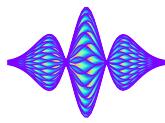




Intrabunch motion in the presence of mode coupling



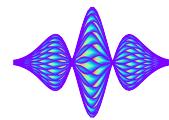
E. Métral (15 min)

Slides presented by X. Buffat (many thanks!)





Intrabunch motion in the presence of mode coupling



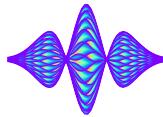
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- ◆ See references
 - * E. Métral, Intrabunch motion, PRAB-2021: <https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.24.014401>
 - * E. Métral, Intrabunch motion, Virtual (Zoom) APT seminar @ FNAL, Chicago, USA, 09/02/2021:
<https://ad.fnal.gov/ADSeminars/SeminarsArchive/APTSeminars-2021.html>
 - * E. Métral and X. Buffat, Intrabunch motion with both impedance and beam-beam using the circulant matrix approach, IPAC-2022: <https://accelconf.web.cern.ch/ipac2022/papers/wepotk062.pdf>

Intrabunch motion in the presence of mode coupling



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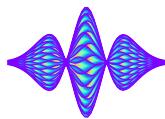
- ◆ See references
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INTRODUCTION

A transverse mode coupling instability (TMCI) can be observed in the presence of impedance only [1], impedance and tune spread [2], impedance and beam-beam [3], electron cloud [4], impedance and space charge [5]. These insta-

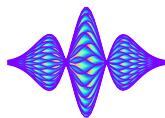


Introduction and motivation



- ◆ **QUESTION:** How can we explain theoretically such **asymmetric pictures** of transverse coherent single-bunch instabilities?

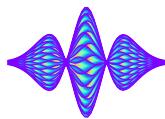
Introduction and motivation



- ◆ **QUESTION:** How can we explain theoretically such **asymmetric pictures** of transverse coherent single-bunch instabilities?

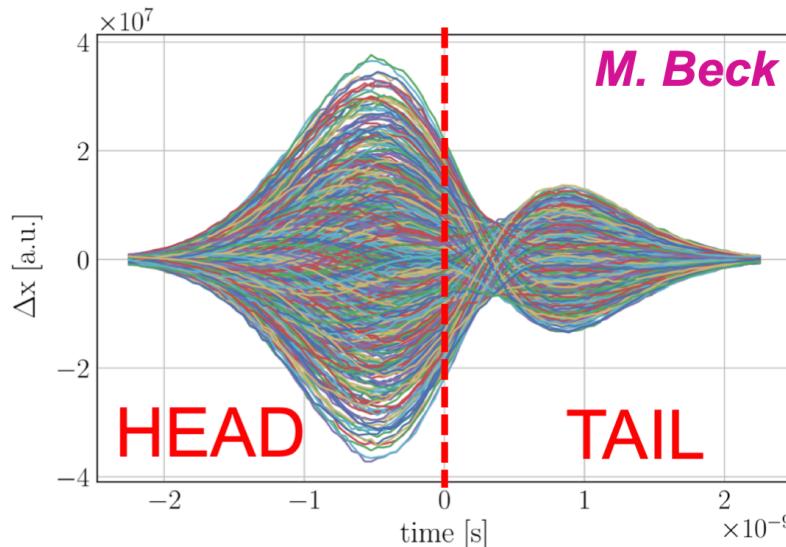
PyHEADTAIL simulations: impedance only

Introduction and motivation

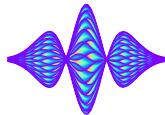


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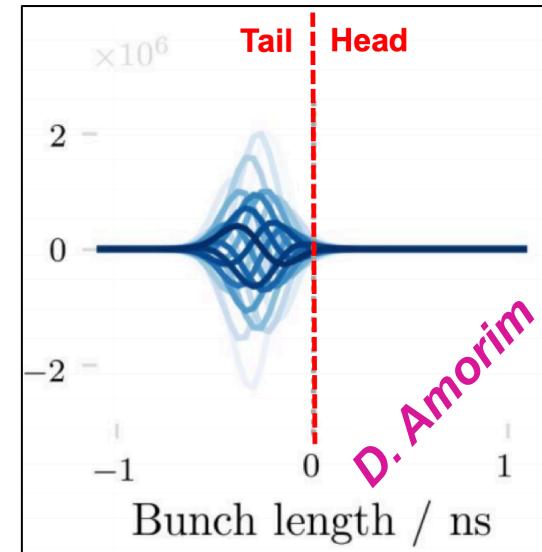
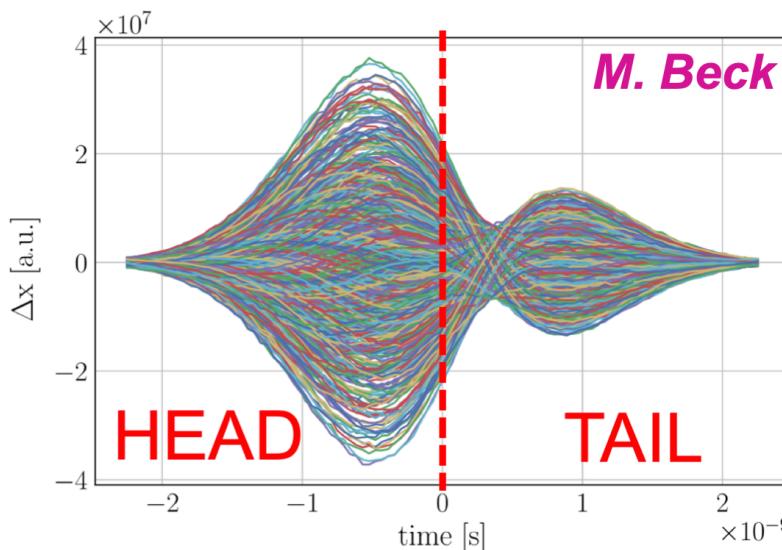


Introduction and motivation



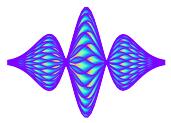
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PyHEADTAIL simulations: impedance only



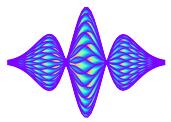


Introduction and motivation

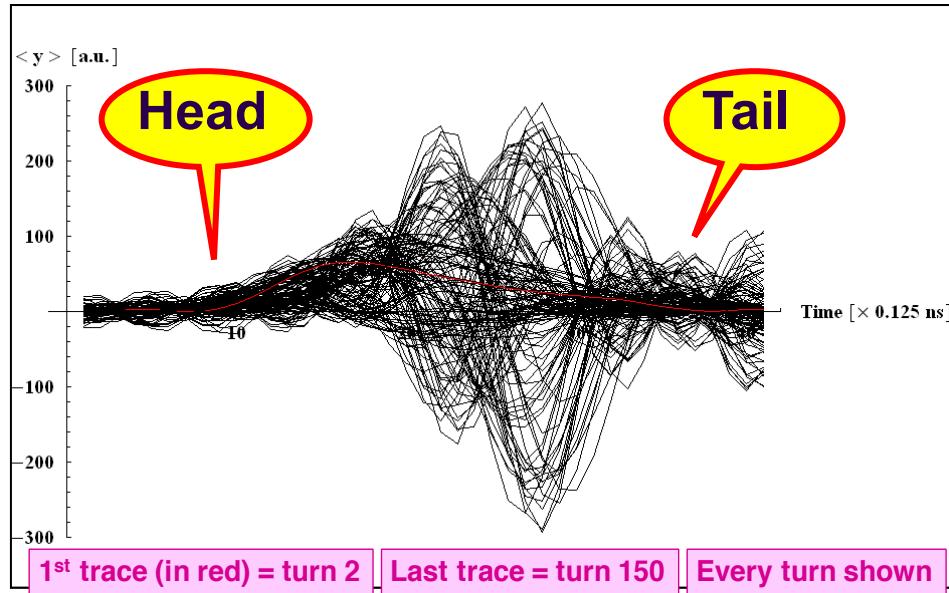


CERN SPS (Q26) measurements: impedance + space charge

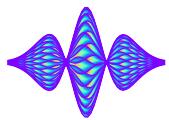
Introduction and motivation



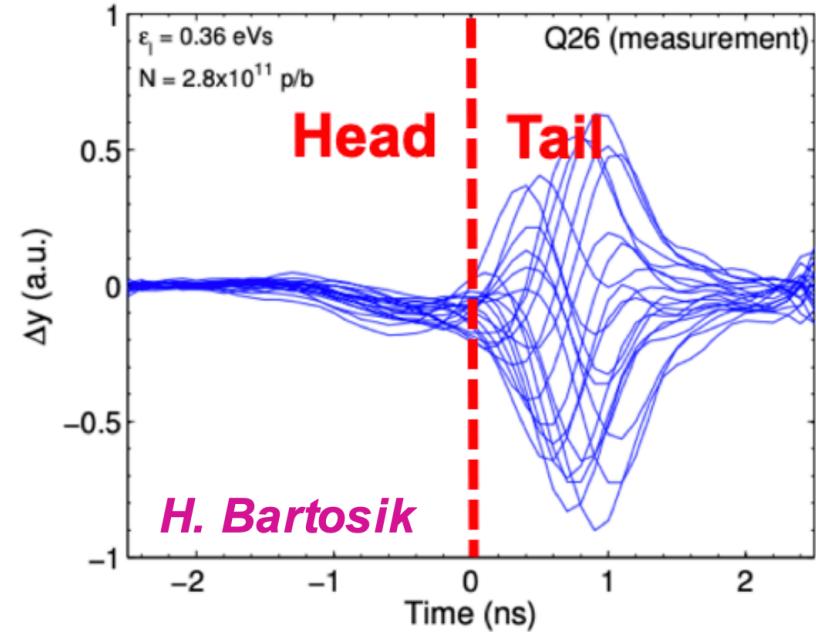
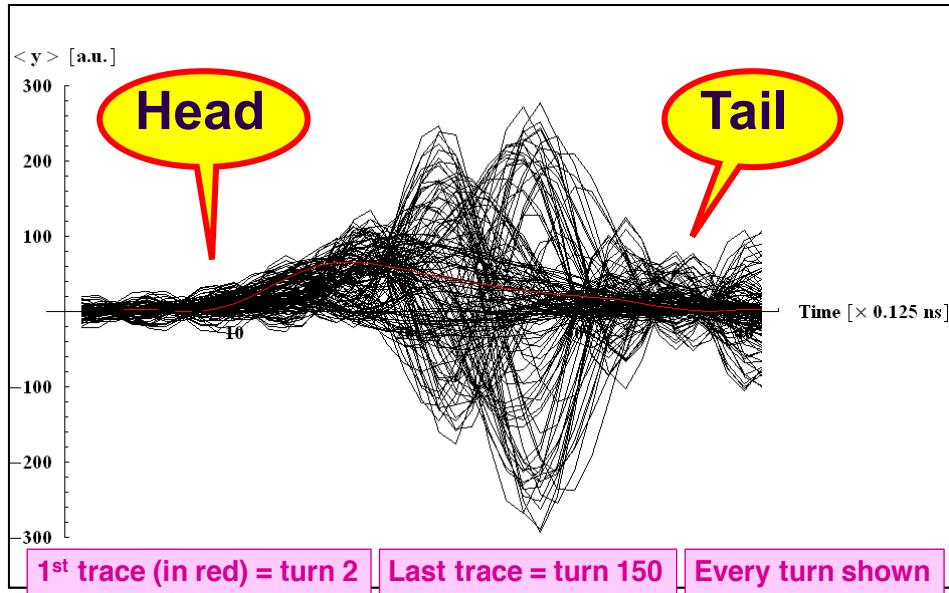
CERN SPS (Q26) measurements: impedance + space charge



Introduction and motivation

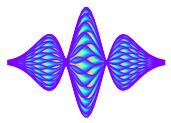


CERN SPS (Q26) measurements: impedance + space charge



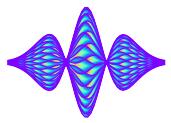


Introduction and motivation



CERN PS (left) and PSB (right) measurements: impedance + space charge

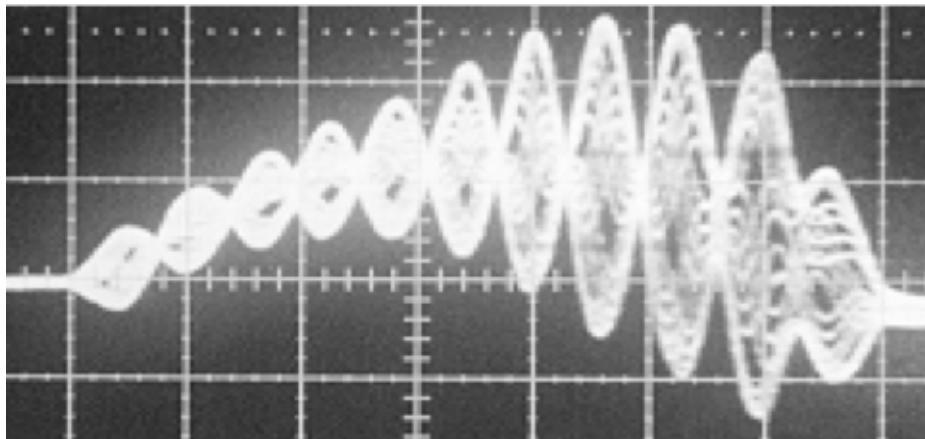
Introduction and motivation



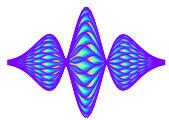
CERN PS (left) and PSB (right) measurements: impedance + space charge

Head

Tail



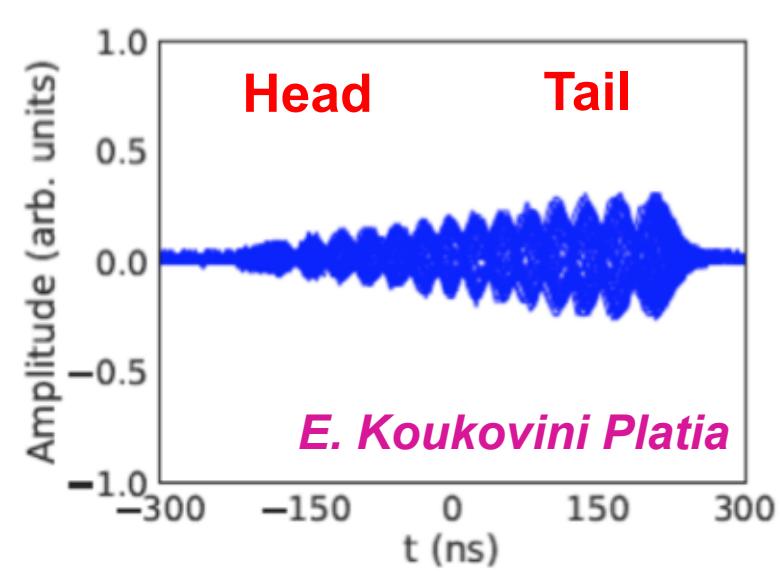
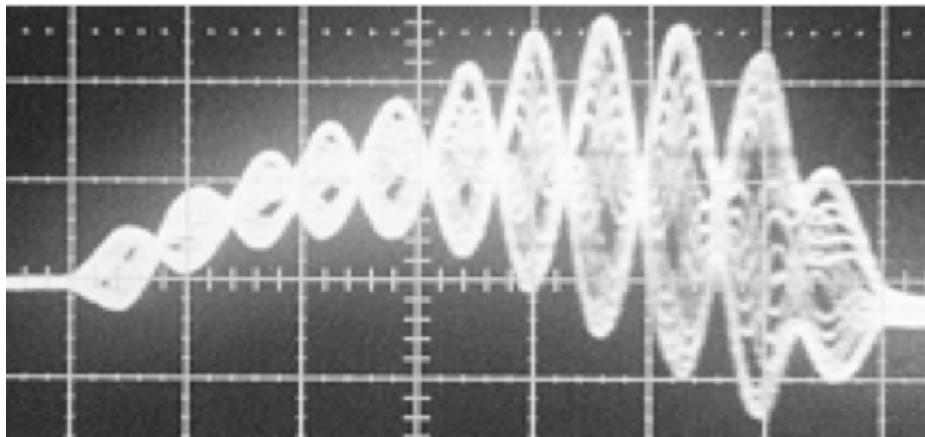
Introduction and motivation



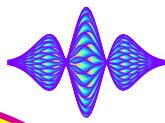
CERN PS (left) and PSB (right) measurements: impedance + space charge

Head

Tail



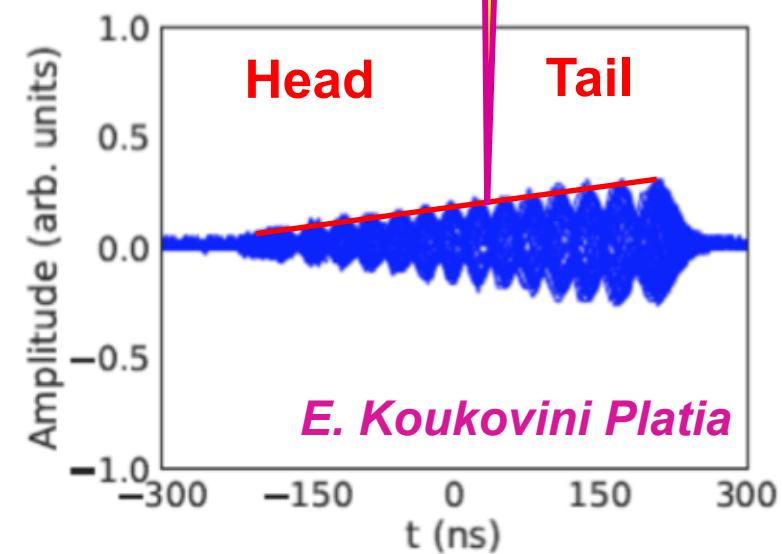
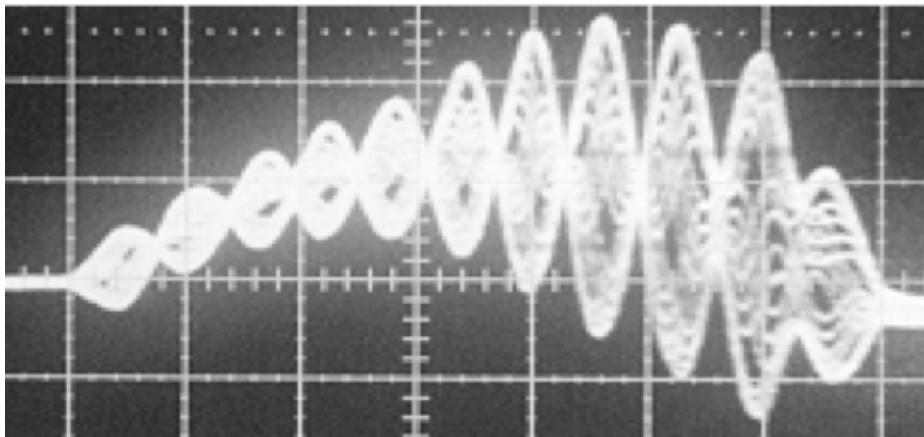
Introduction and motivation



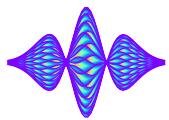
CERN PS (left) and PSB (right) measurements: impedance + space charge

Head

Tail



Introduction and motivation



More pictures from
the PS (1999)

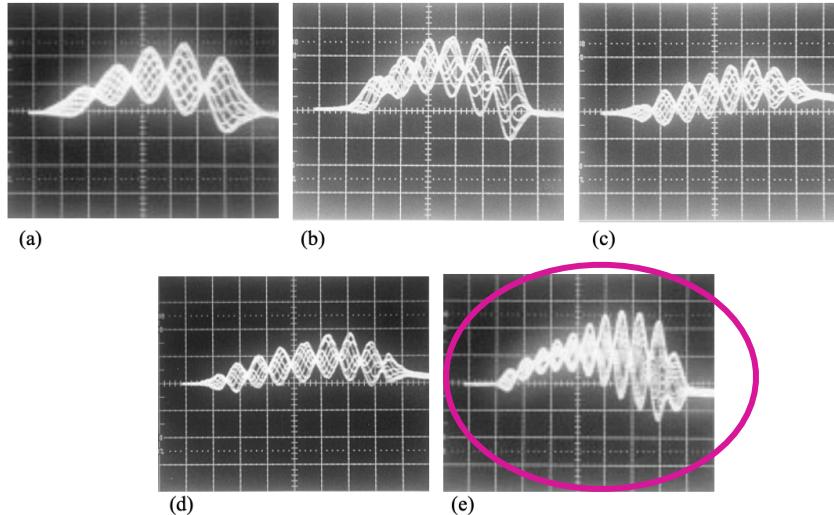
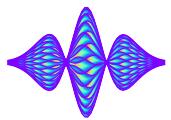


FIGURE 6. ΔR signal from a radial beam-position monitor during 20 consecutive turns. Time scale: 20 ns/div. (a) Nominal single-bunch beam with $Q_h = 6.08$, $Q_v = 6.32$, $\xi_x \approx -0.5$ and $\xi_y \approx -1.5$. (b) $Q_h = 6.18$, $Q_v = 6.21$, $\xi_x \approx -0.7$ and $\xi_y \approx -1.7$. (c) $Q_h = 6.21$, $Q_v = 6.18$, $\xi_x \approx -1.1$ and $\xi_y \approx -0.3$. (d) $Q_h = 6.21$, $Q_v = 6.16$, $\xi_x \approx -1.2$ and $\xi_y \approx 0.1$. (e) Ultimate single-bunch beam with $Q_h = 6.20$, $Q_v = 6.16$, $\xi_x \approx -1.3$ and $\xi_y \approx 0.1$.

Introduction and motivation



More pictures from
the PSB (2019)

E. KOUKOVINI-PLATIA *et al.*

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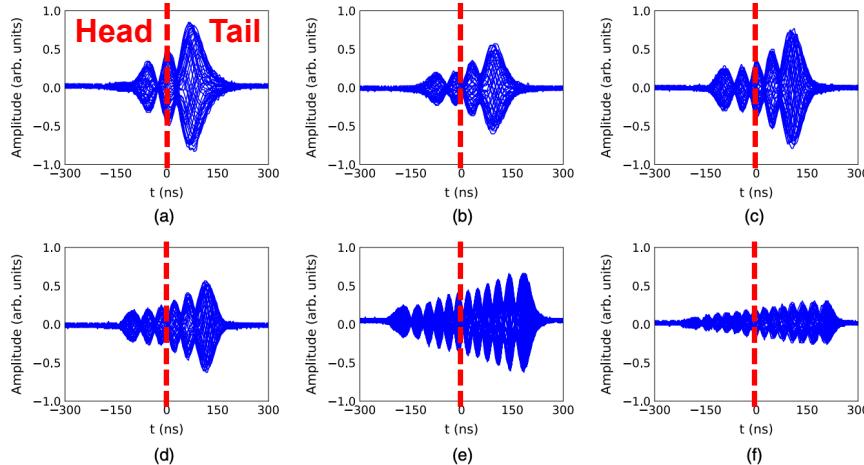
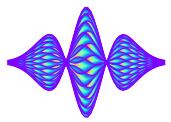


FIG. 6. Head-tail modes as recorded by the horizontal pick-up for a single bunch in the PSB and horizontal tune of 4.28. For chromaticity ξ_x close to the natural value, a radial mode $m = 2$ is detected [Fig. 6(a)]. As chromaticity increases in absolute value, the radial mode number increases up to $m = 13$ for the maximum sextupole strength [Fig. 6(f)]. The intensity is fixed at $N = 3 \times 10^{12}$ p for all cases. (a) $\xi_x = -0.7$, $m = 2$, (b) $\xi_x = -1.1$, $m = 3$, (c) $\xi_x = -1.3$, $m = 4$, (d) $\xi_x = -1.6$, $m = 5$, (e) $\xi_x = -2.5$, $m = 11$, (f) $\xi_x = -2.7$, $m = 13$.

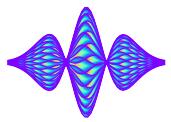


Introduction and motivation

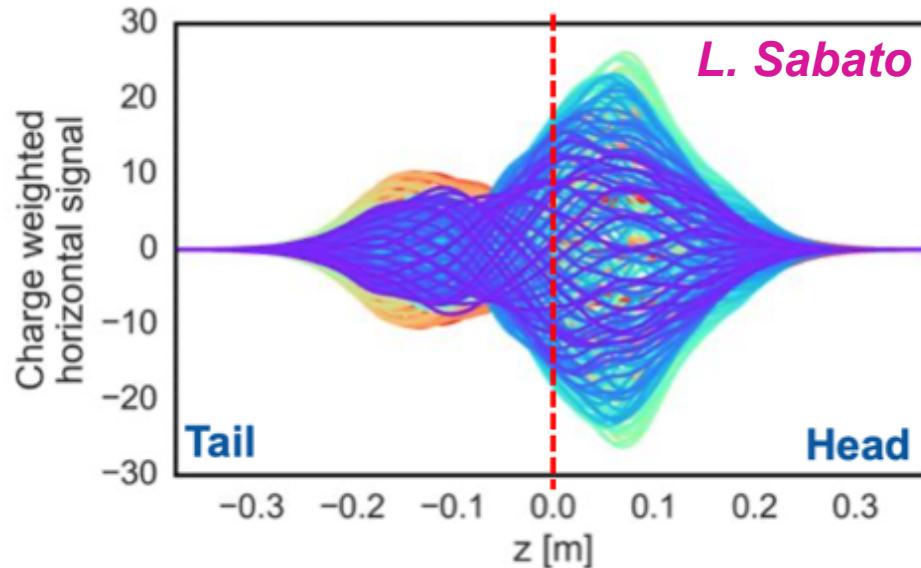


PyHEADTAIL simulations: e-cloud only

Introduction and motivation

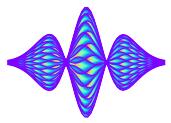


PyHEADTAIL simulations: e-cloud only



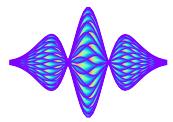


Introduction and motivation

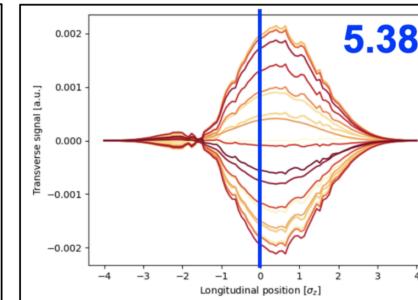
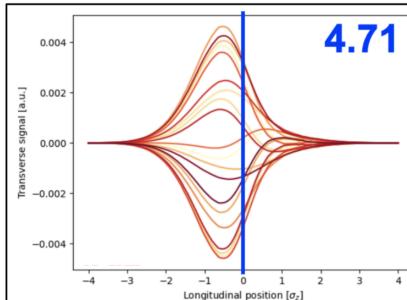
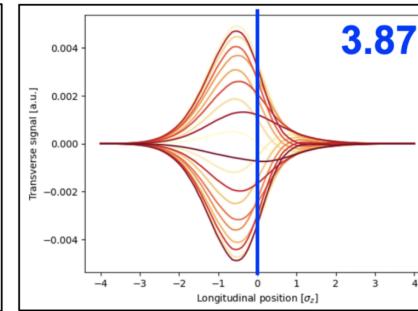
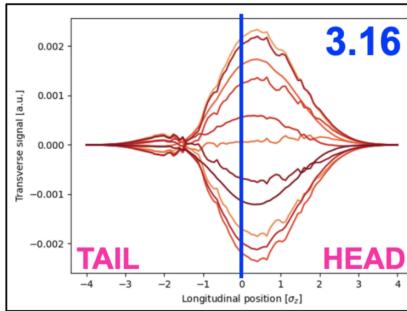


Simulations from Circulant Matrix Approach: impedance + beam-beam

Introduction and motivation

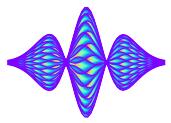


Simulations from Circulant Matrix Approach: impedance + beam-beam



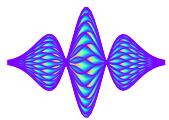


Introduction and motivation

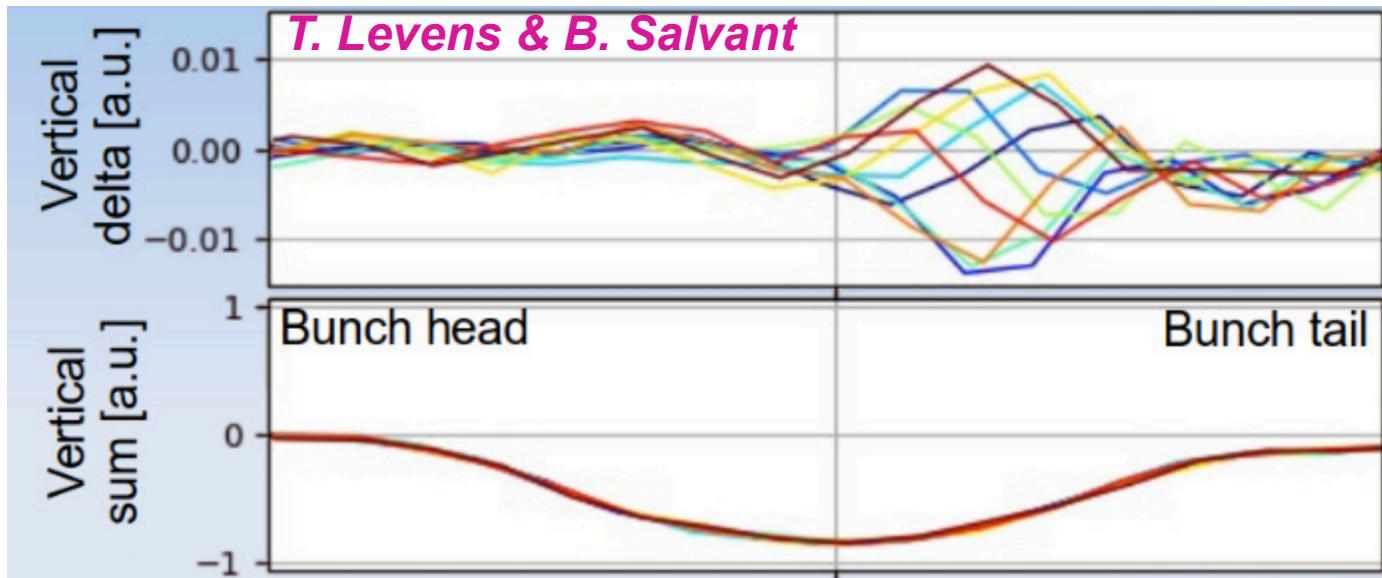


CERN LHC measurements: “16L2 instability” (vacuum non-conformity)

Introduction and motivation

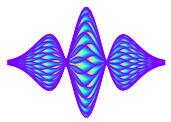


CERN LHC measurements: “16L2 instability” (vacuum non-conformity)



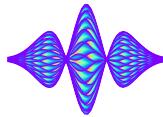


Introduction and motivation

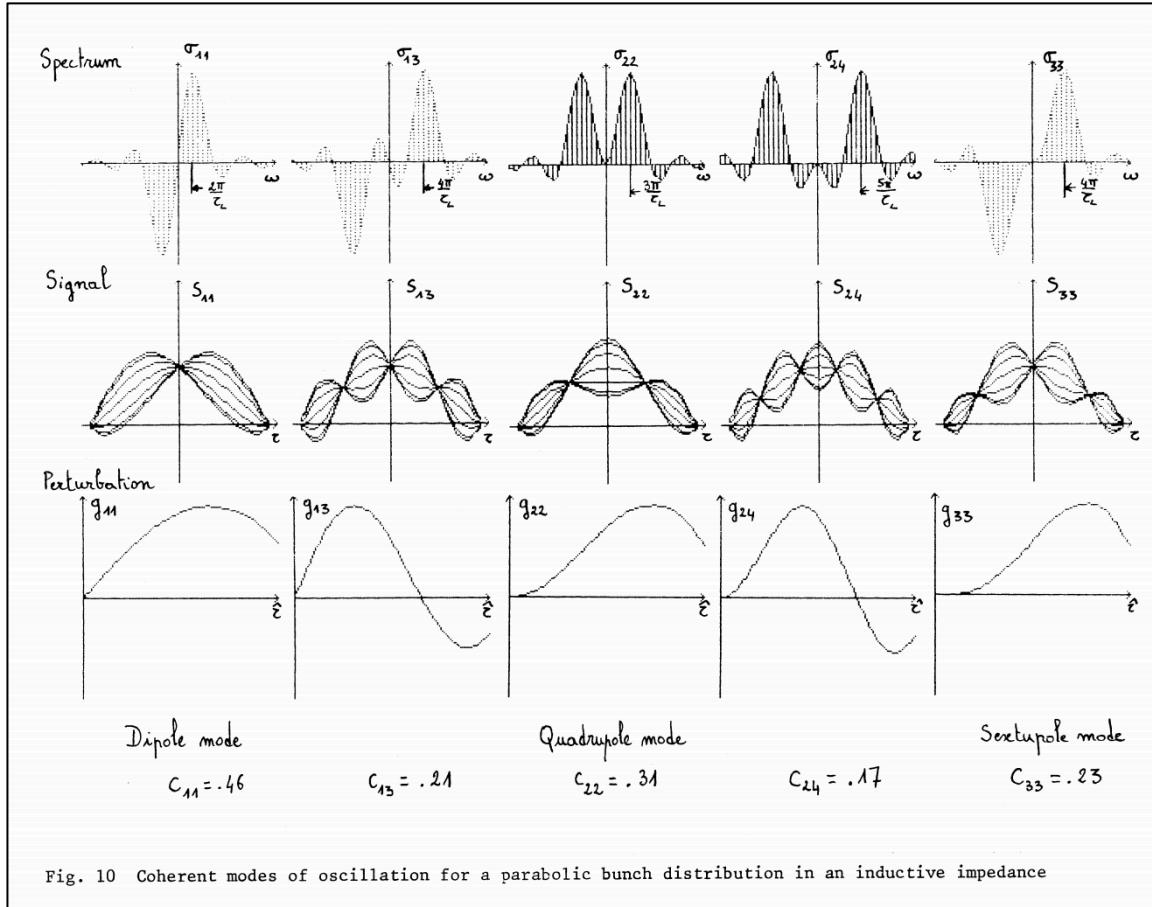


=> **ANSWER:** By mode coupling (interaction between several modes)

Reminder for independent modes

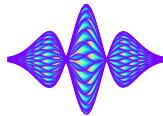


LONGITUDINAL

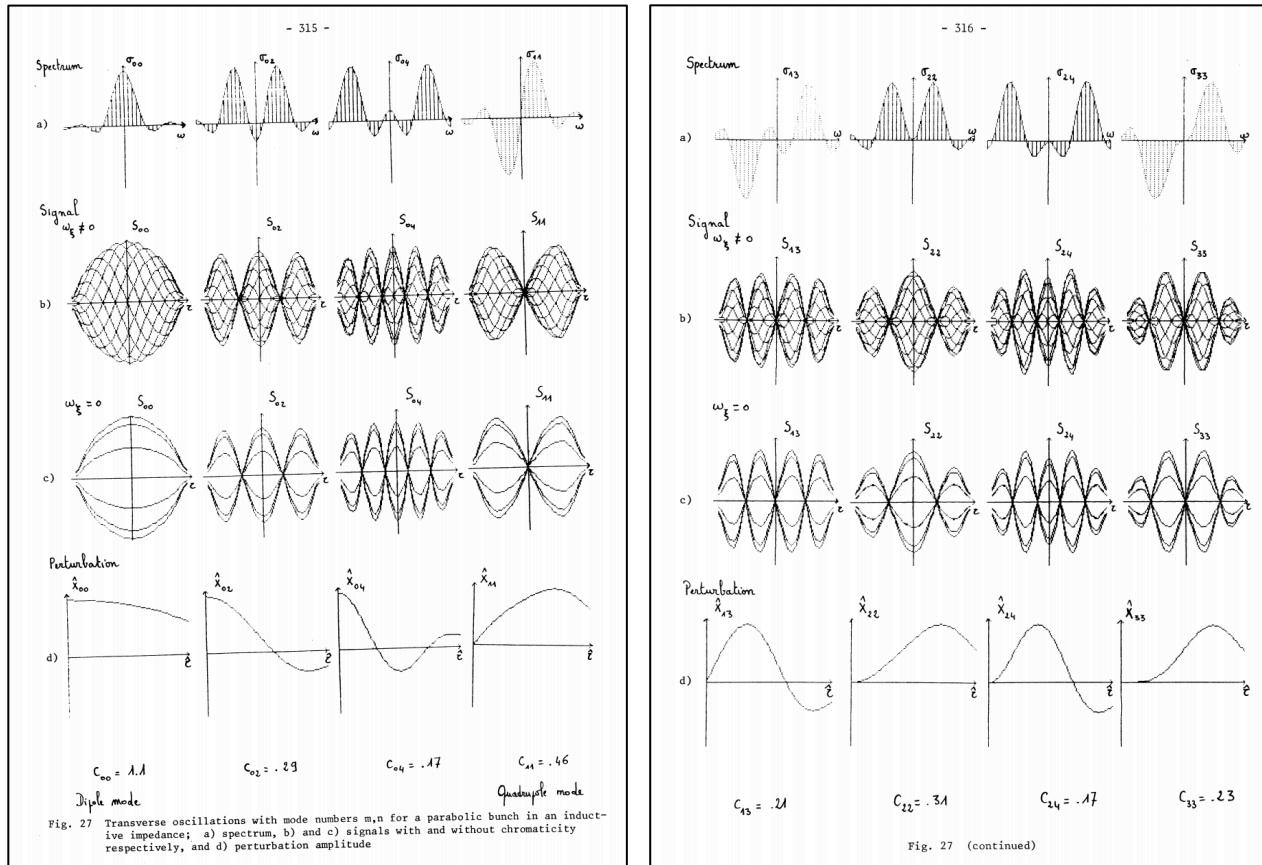


J.L. Laclare. *Bunched beam coherent instabilities.*
 Technical Report CERN-1987-003-V-1, CERN, 1987
[\(https://cds.cern.ch/record/611596/files/p264.pdf\)](https://cds.cern.ch/record/611596/files/p264.pdf)

Reminder for independent modes

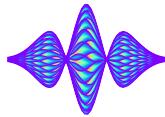


TRANSVERSE



J.L. Laclare. *Bunched beam coherent instabilities.*
 Technical Report CERN-1987-003-V-1, CERN, 1987
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Reminder for independent modes



E. MÉTRAL

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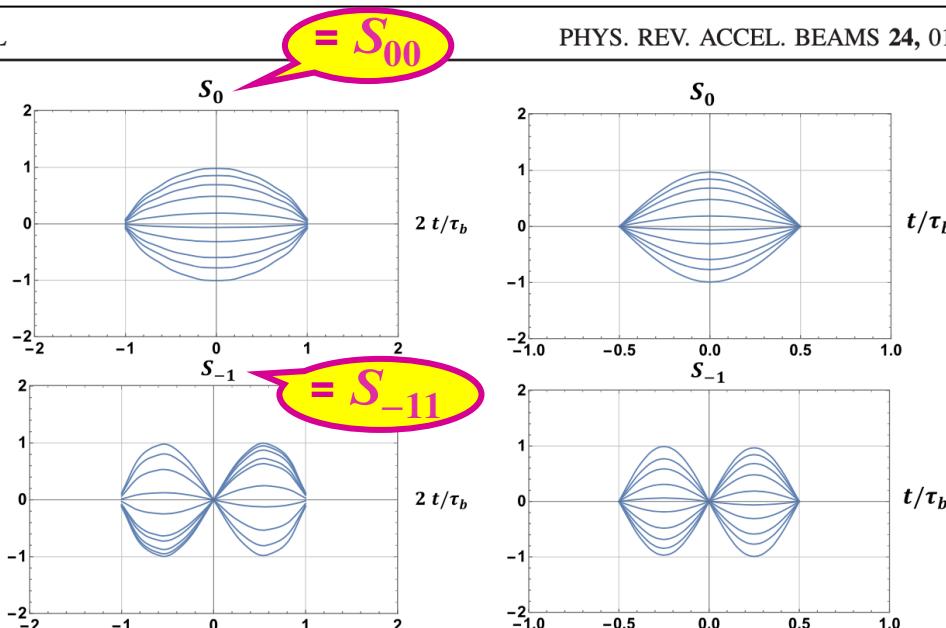


FIG. 1. Left: intrabunch signal deduced from the solutions of the eigenvalue problem at low intensity using the GALACTIC Vlasov solver for the case of a bunch with a longitudinal “water-bag” distribution [1] interacting with a purely inductive impedance [2]; right: approximation by sinusoidal modes given by Eqs. (1) and (2) [3]. Here, t is the time, τ_b is the full (4-sigma) bunch length and the head of the bunch is on the left while the tail is on the right.

For $Q' = 0$

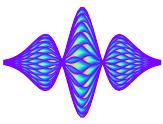
they are called standing-wave patterns. As can be seen in Fig. 1 (right) and as discussed by Sacherer in [3], these intrabunch signals can be well approximated by

$$S_0(t, n) = \cos\left(\frac{\pi t}{\tau_b}\right) \cos(2\pi n Q), \quad (1)$$

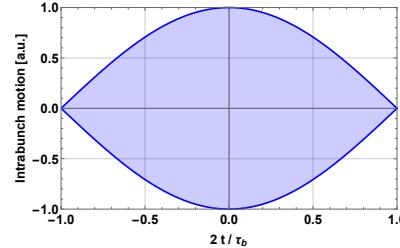
$$S_{-1}(t, n) = \sin\left(\frac{2\pi t}{\tau_b}\right) \cos(2\pi n Q), \quad (2)$$

where t is the time, n the turn number, τ_b the full (4-sigma) bunch length and Q the transverse tune.

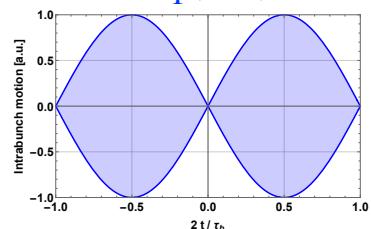
Reminder for independent modes



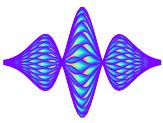
$S_0(t, n)$



$S_1(t, n)$

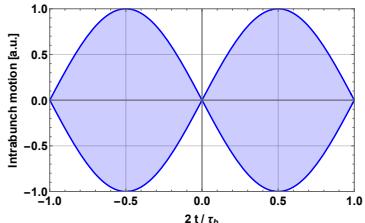


Reminder for independent modes

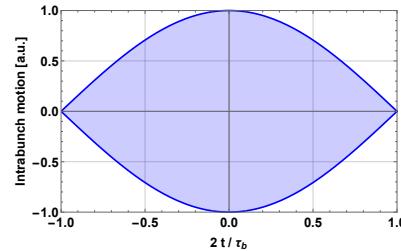


Let's speak now
only in number of
nodes (positive
number only)

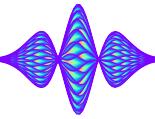
$S_1(t, n)$



$S_0(t, n)$

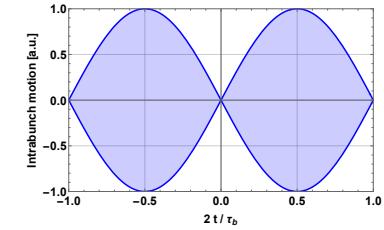


Reminder for independent modes

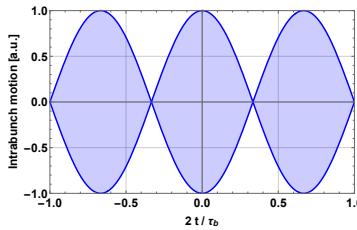


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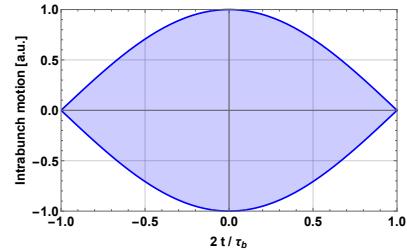
$S_1(t, n)$



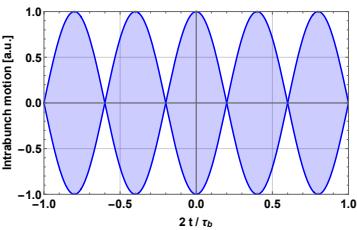
$S_2(t, n)$



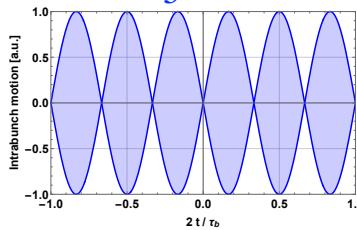
$S_0(t, n)$



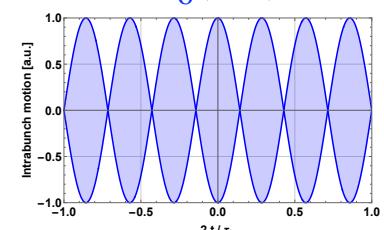
$S_4(t, n)$



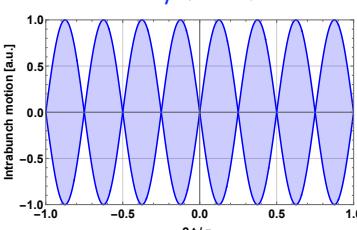
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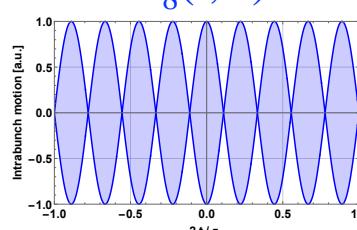
$S_6(t, n)$



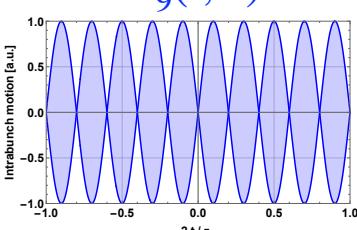
$S_7(t, n)$



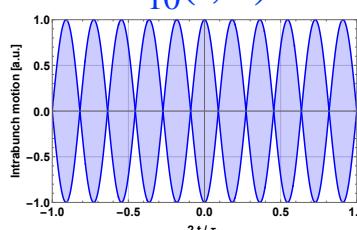
$S_8(t, n)$

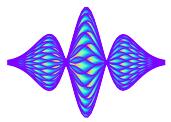


$S_9(t, n)$



$S_{10}(t, n)$



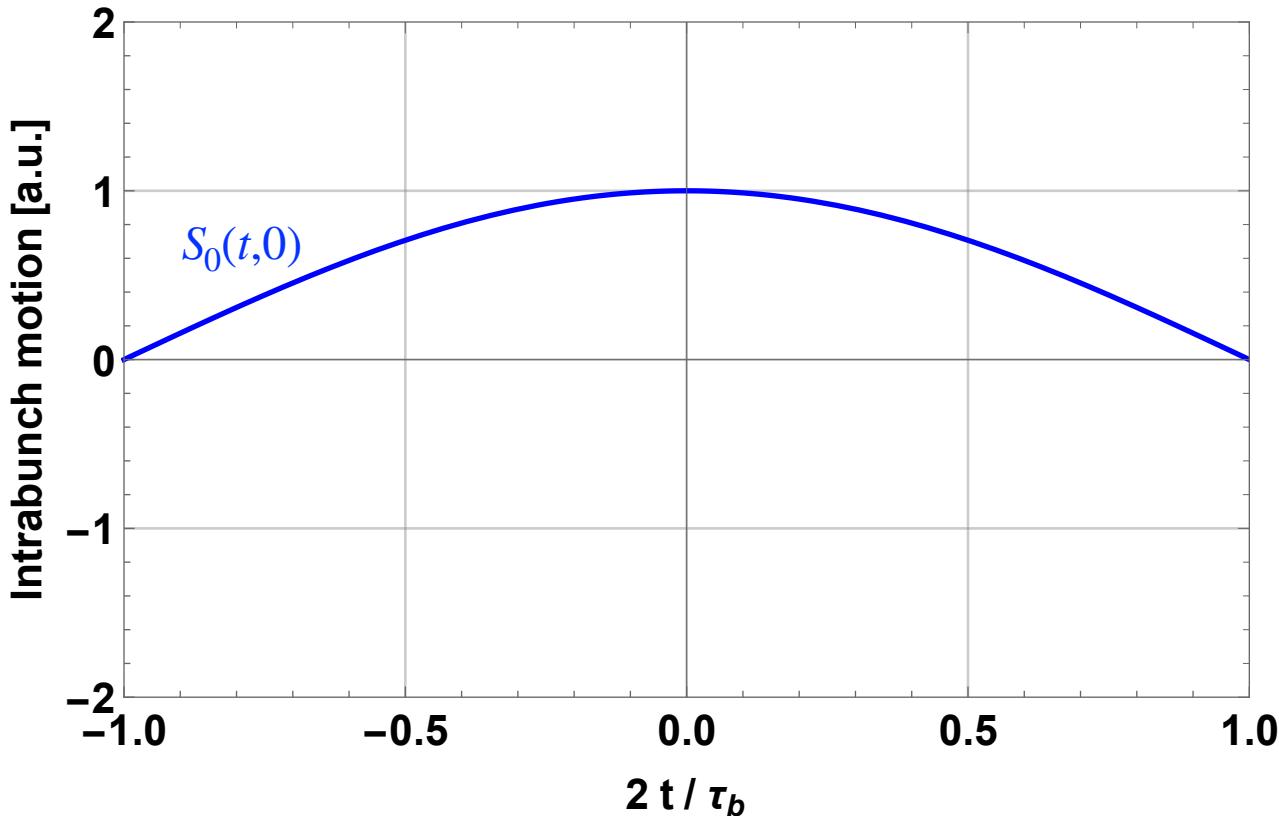
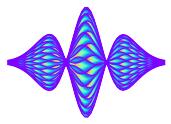


WITHOUT MATHS:

Which kind of possible pictures of intrabunch motion can we already anticipate when several modes interact?

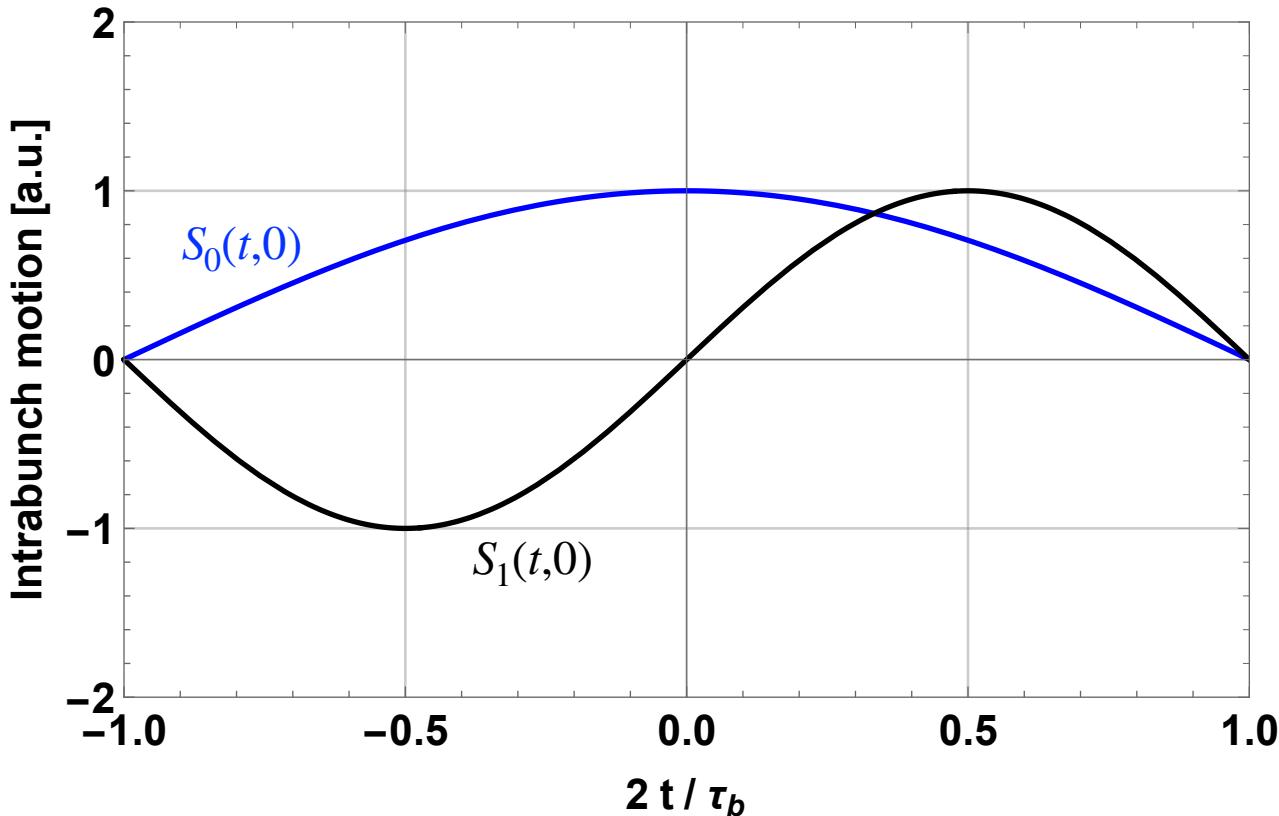
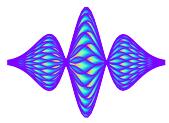
2 consecutive modes

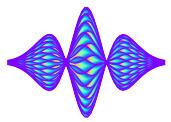
=> 1st case with mode 0 and mode 1



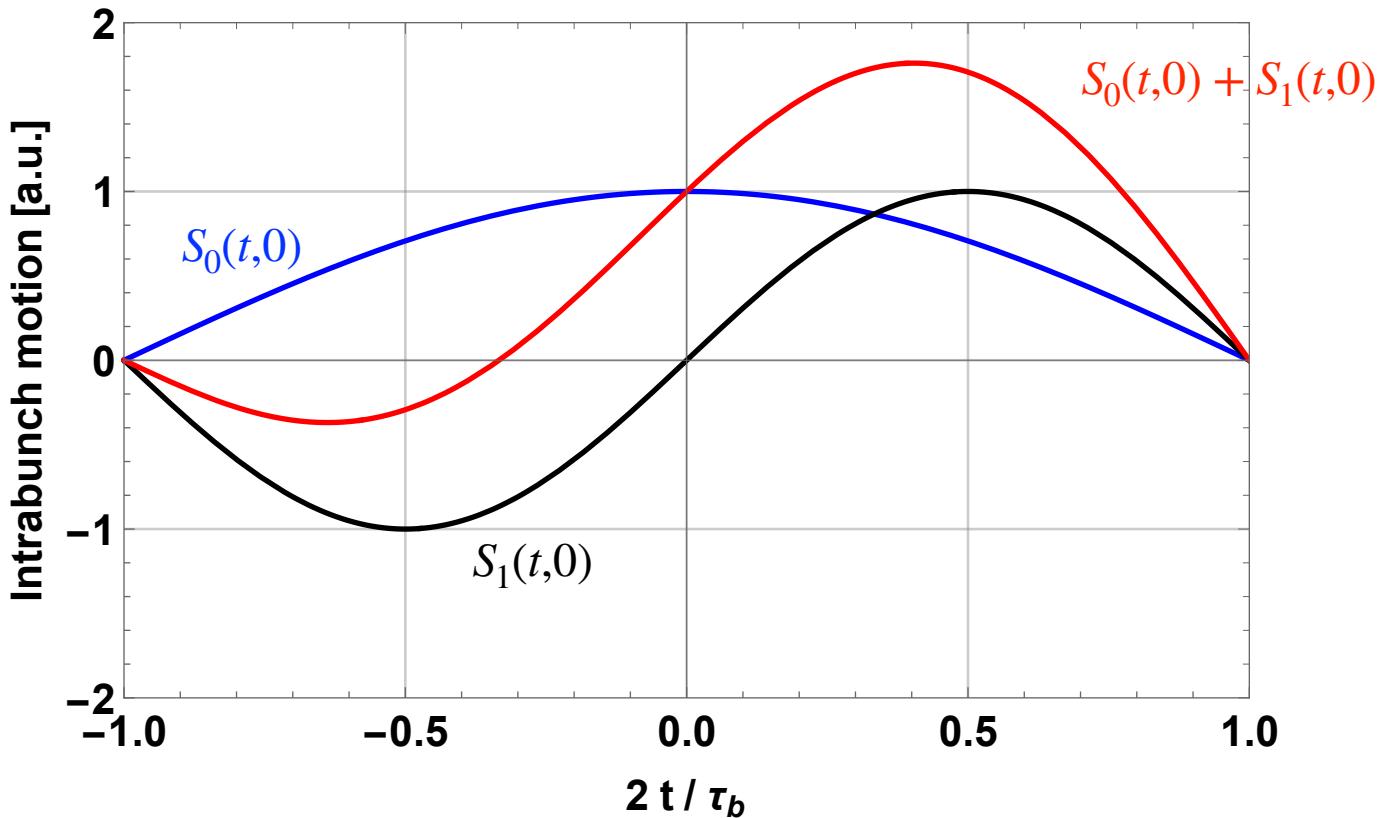
2 consecutive modes

=> 1st case with mode 0 and mode 1



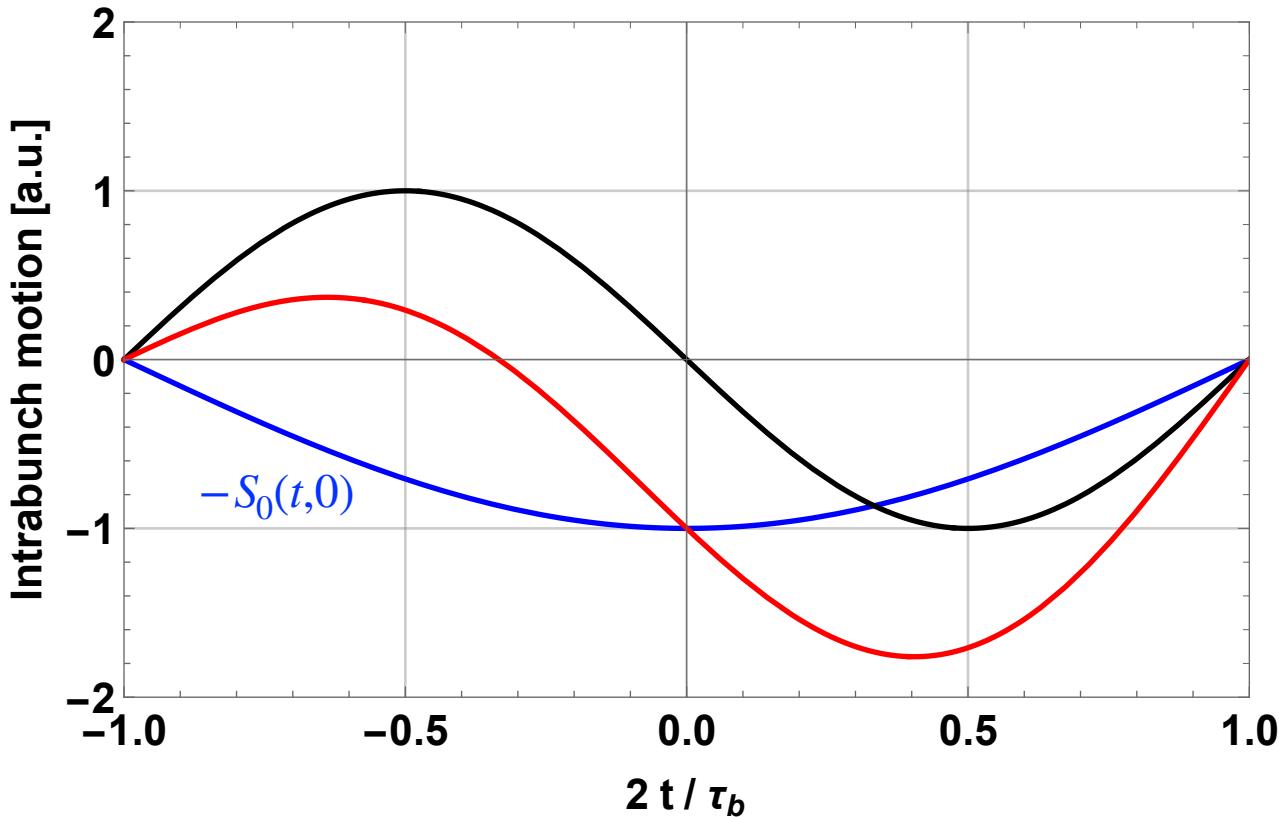
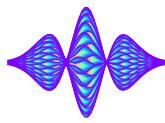


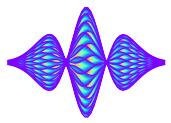
2 consecutive modes => 1st case with mode 0 and mode 1



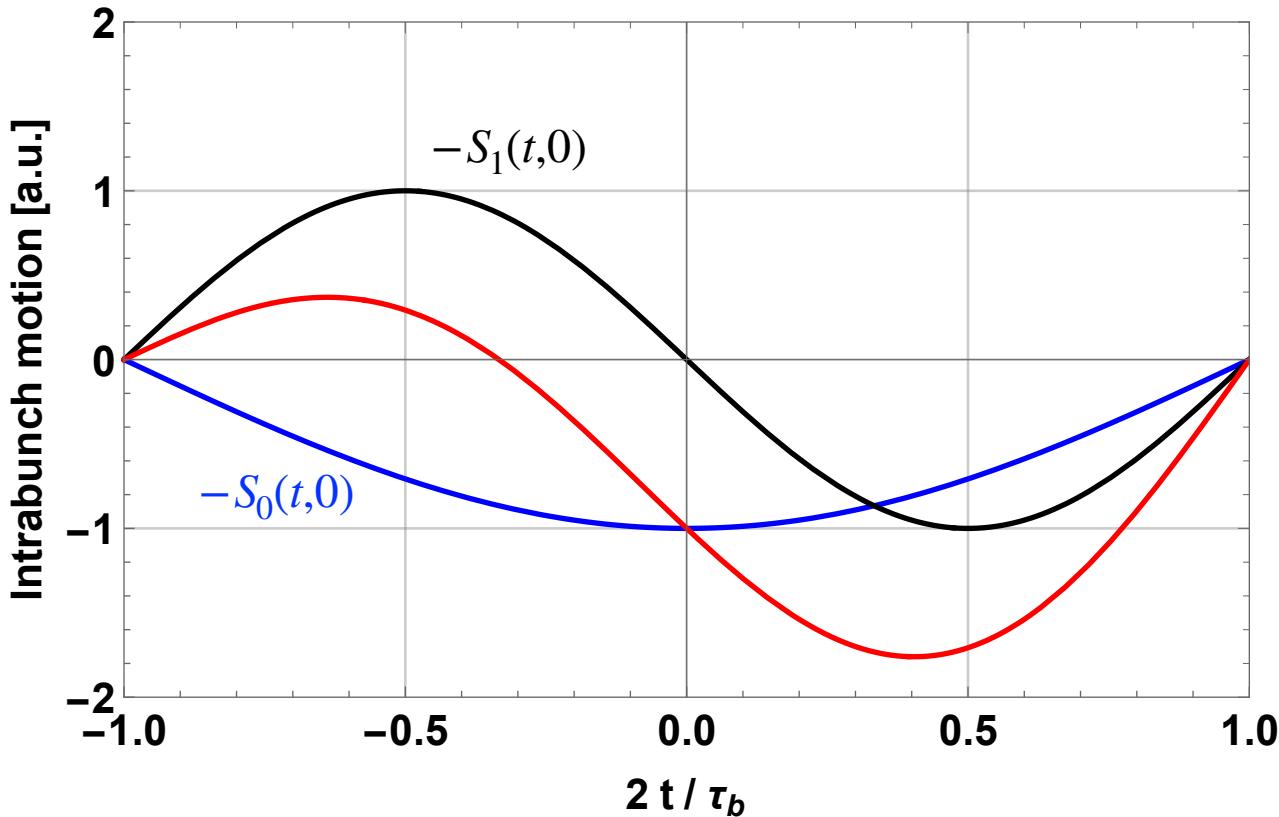
2 consecutive modes

=> 1st case with mode 0 and mode 1



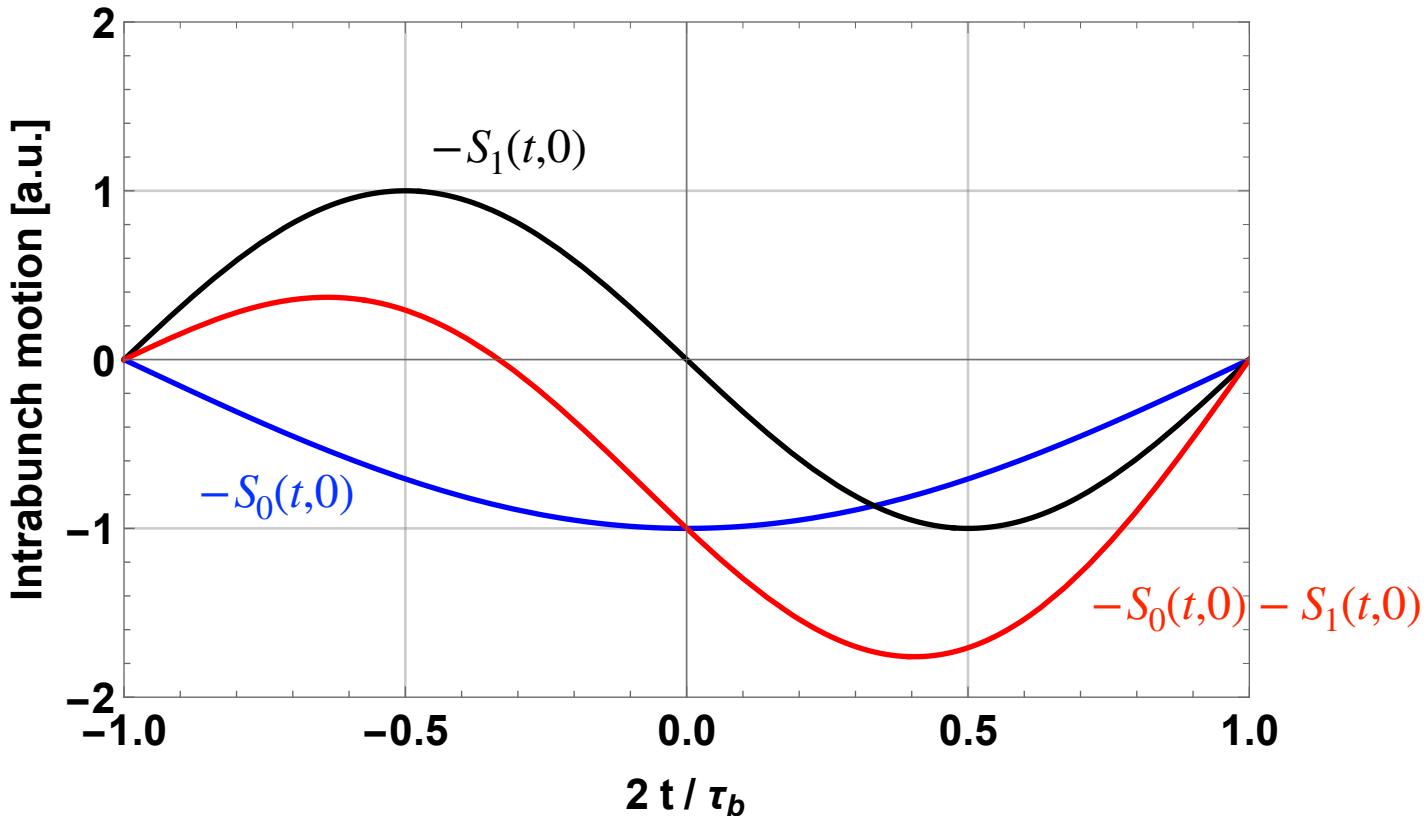
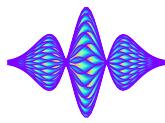


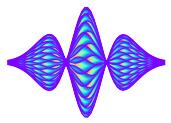
2 consecutive modes => 1st case with mode 0 and mode 1



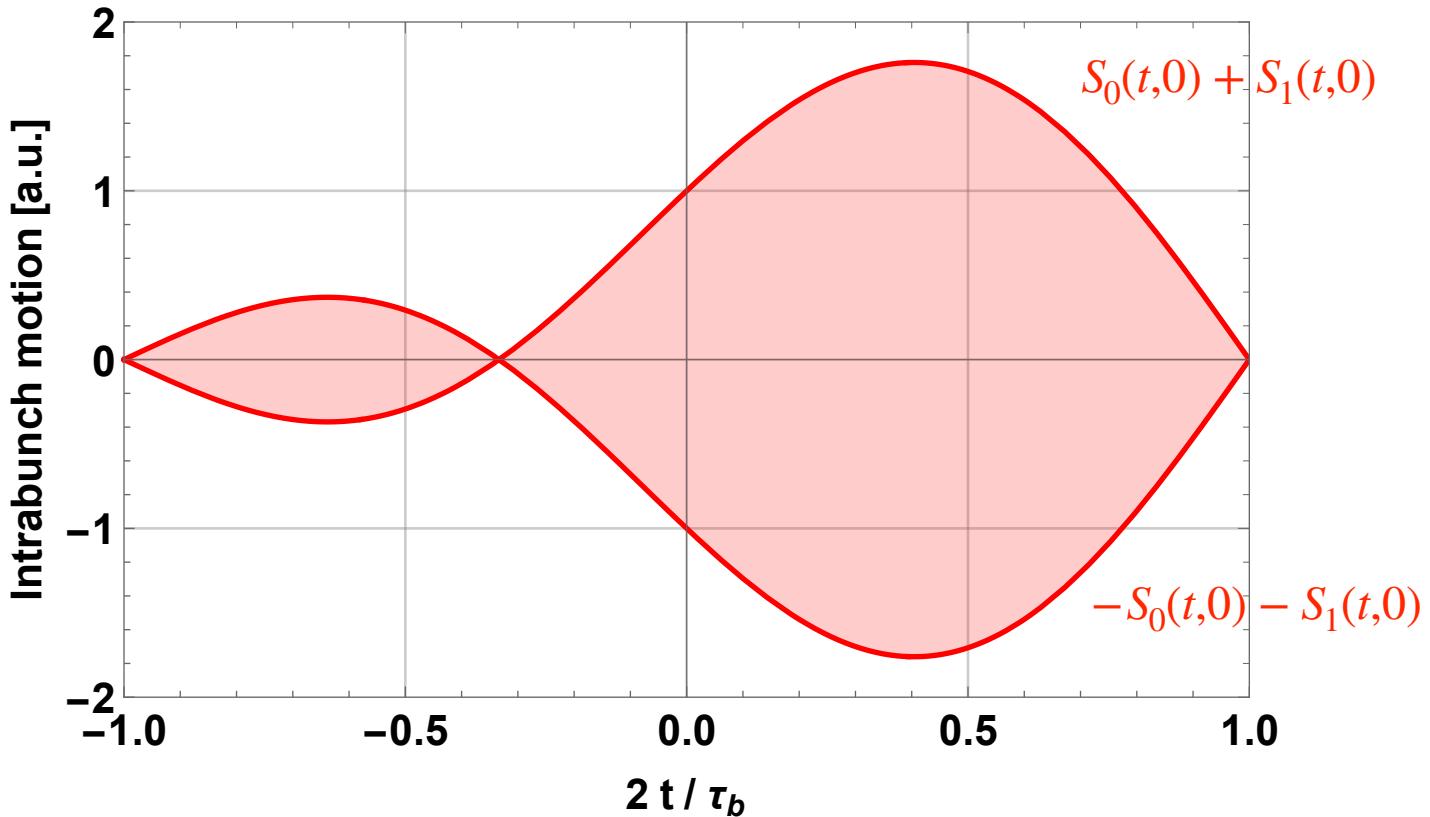
2 consecutive modes

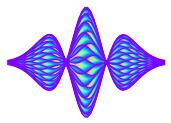
=> 1st case with mode 0 and mode 1



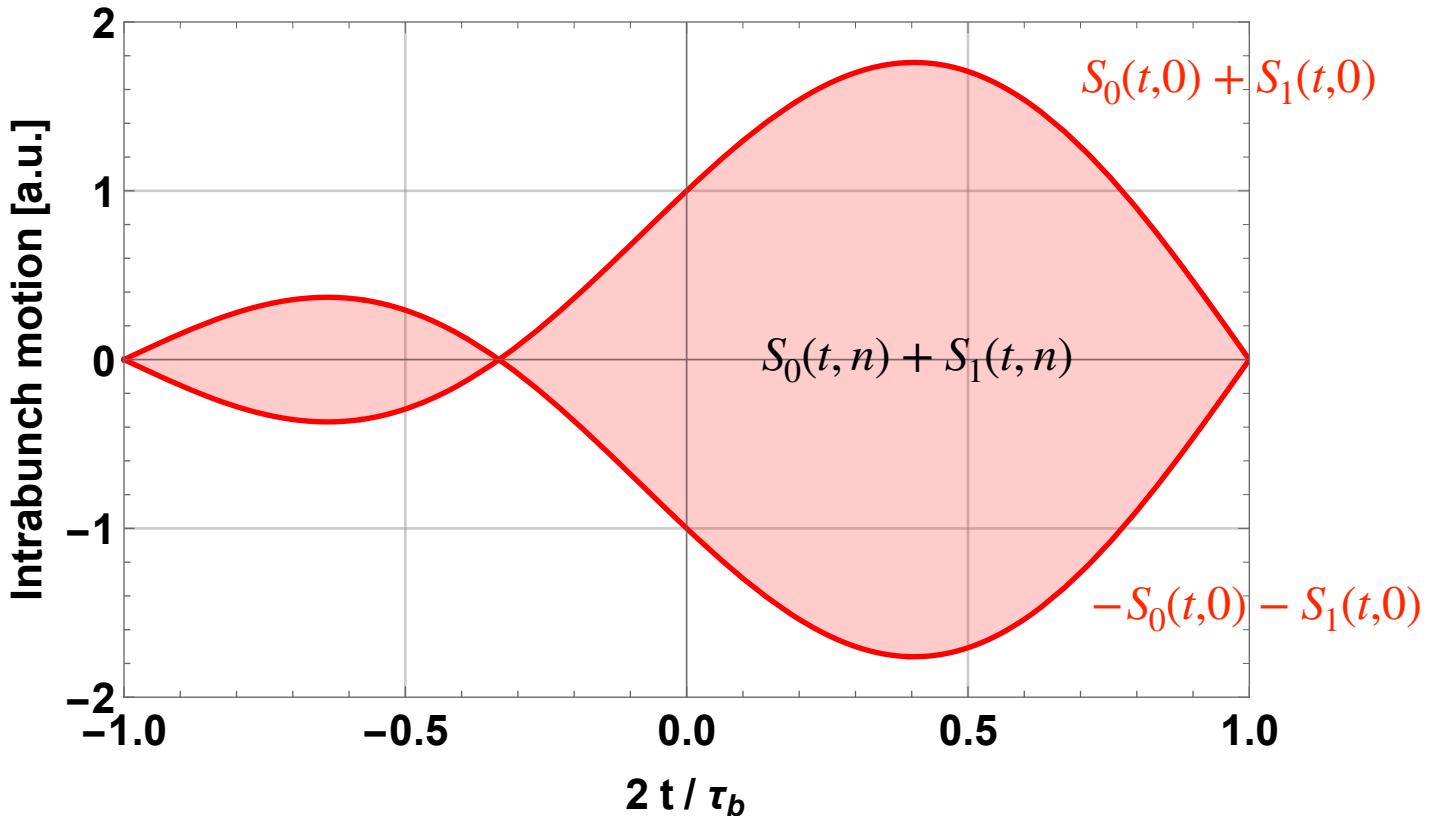


2 consecutive modes => 1st case with mode 0 and mode 1

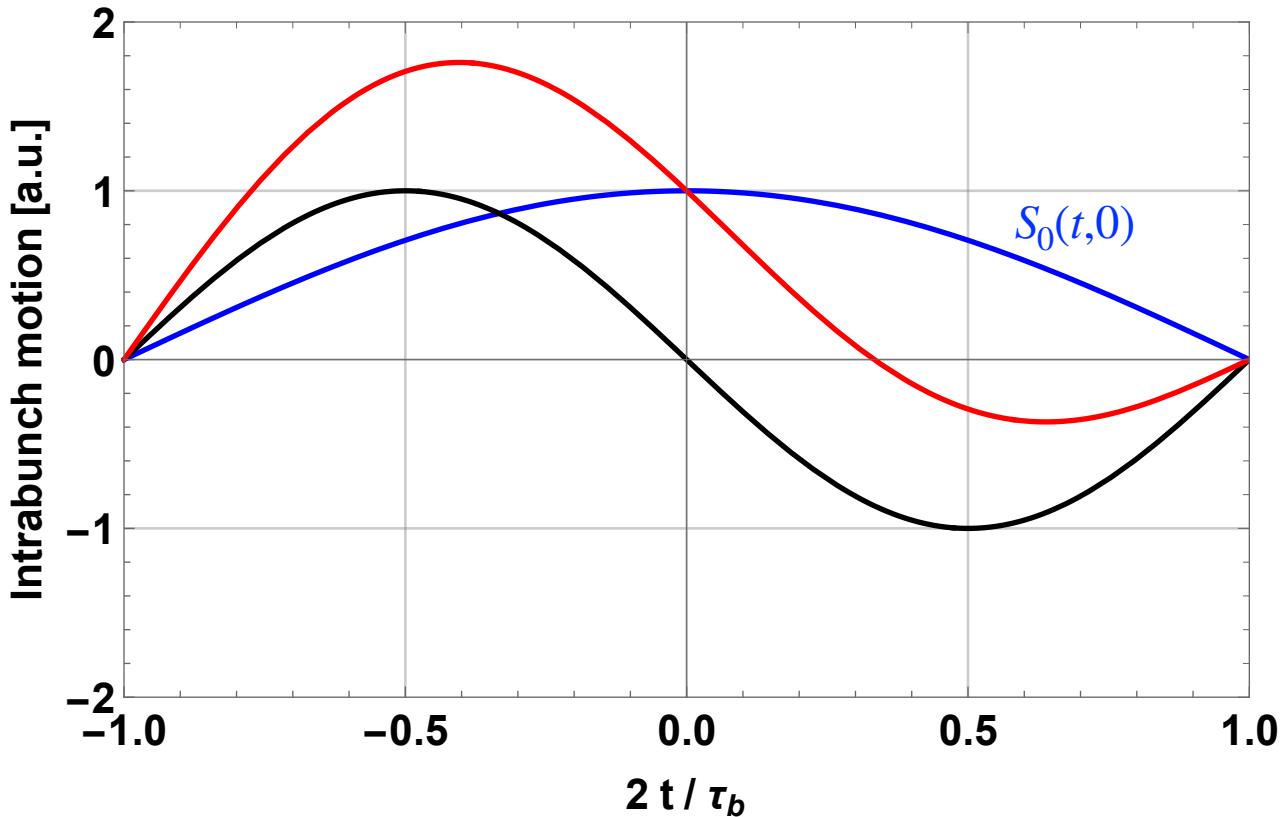


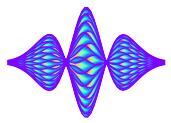


2 consecutive modes => 1st case with mode 0 and mode 1

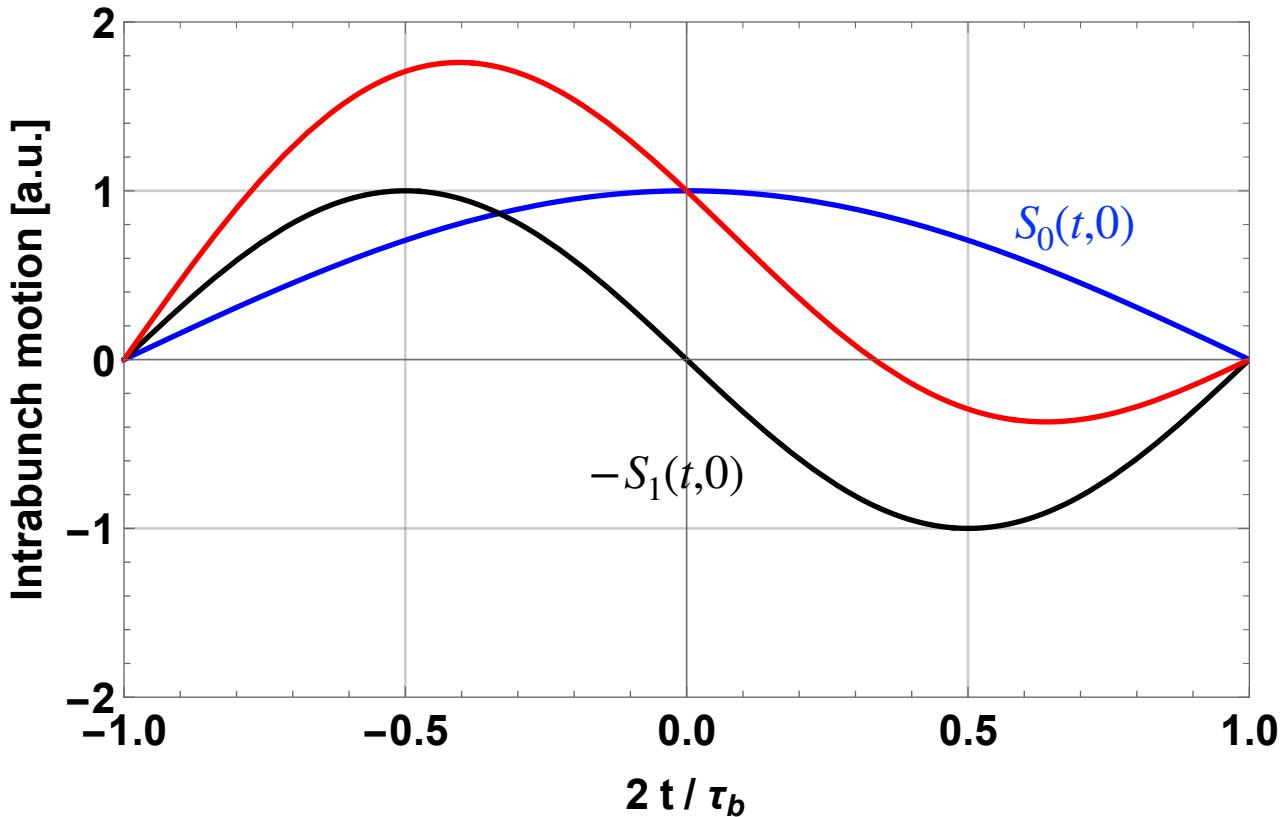


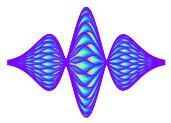
2 consecutive modes => 1st case with mode 0 and mode 1



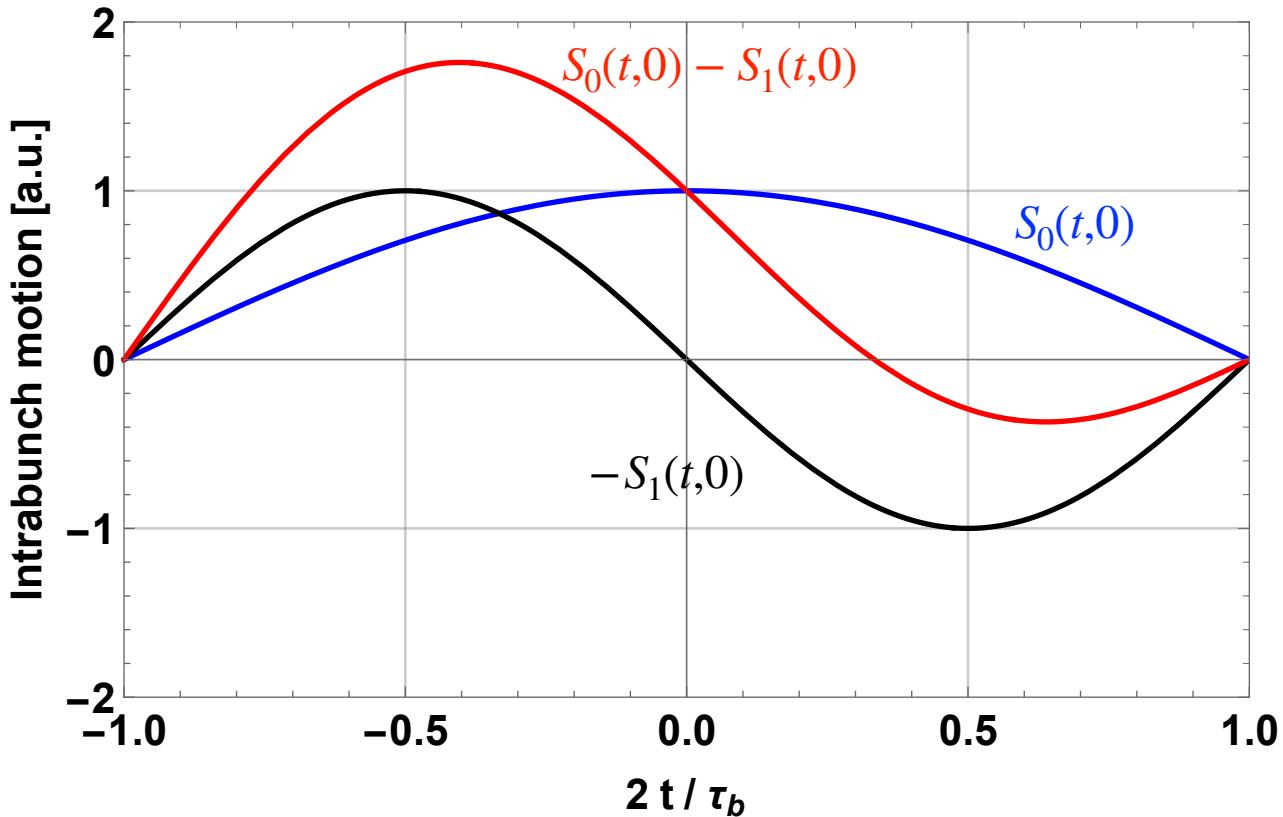


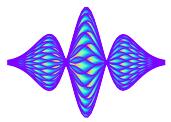
2 consecutive modes => 1st case with mode 0 and mode 1



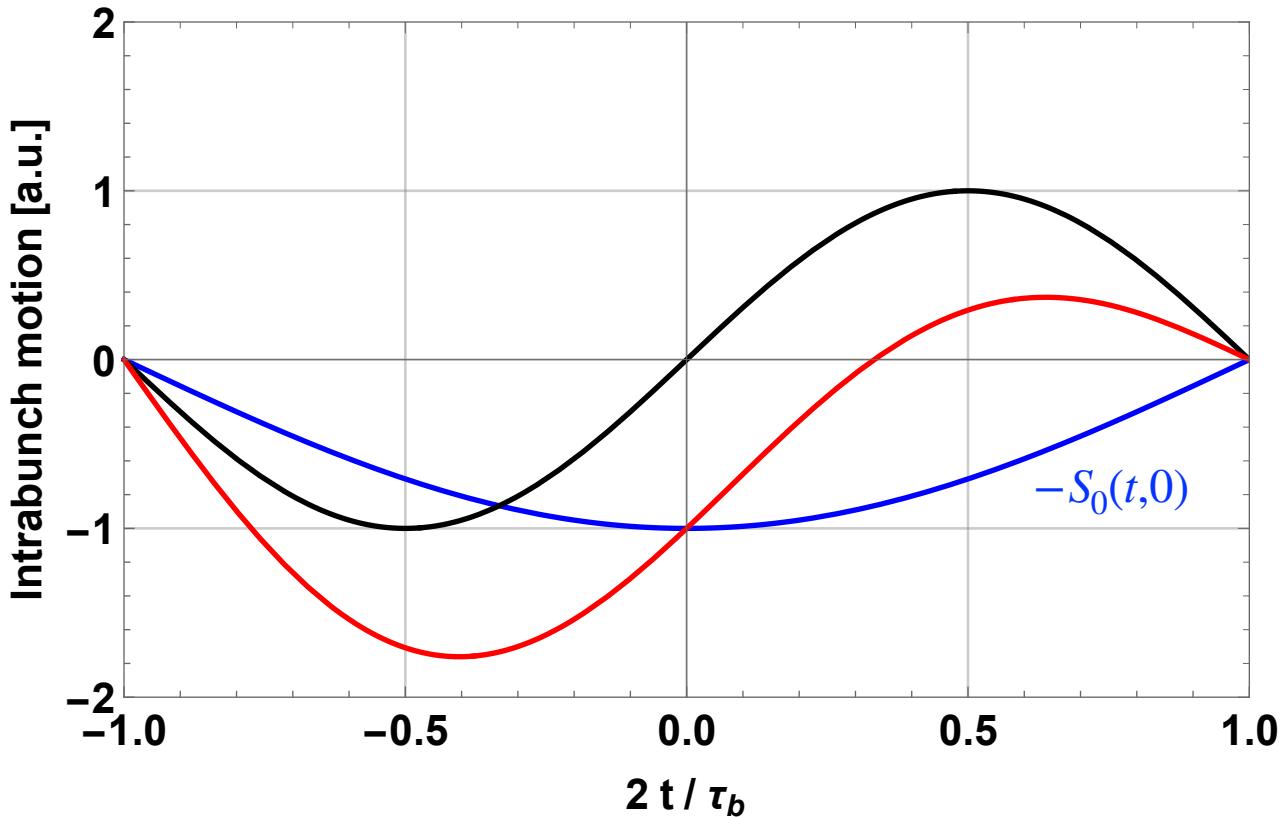


2 consecutive modes => 1st case with mode 0 and mode 1



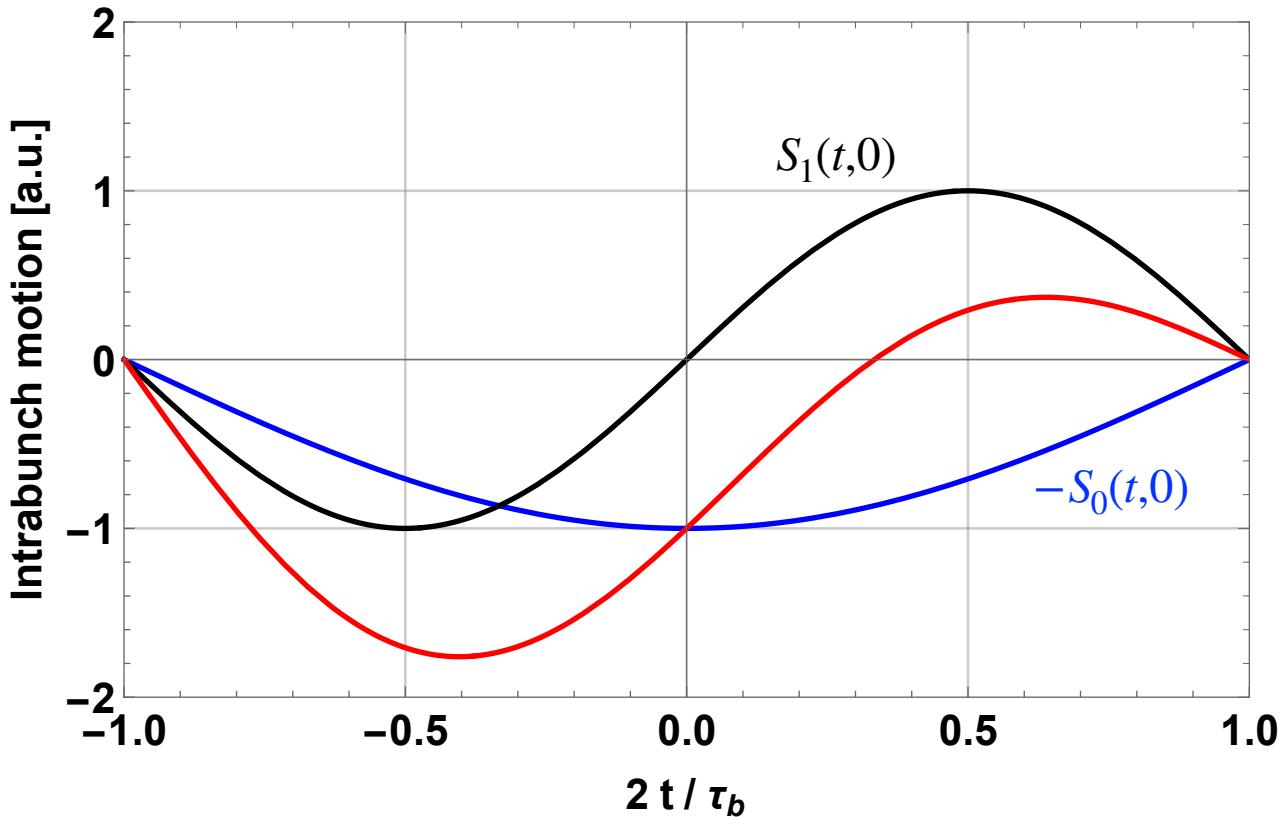
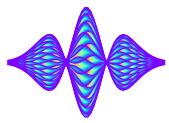


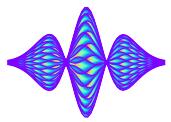
2 consecutive modes => 1st case with mode 0 and mode 1



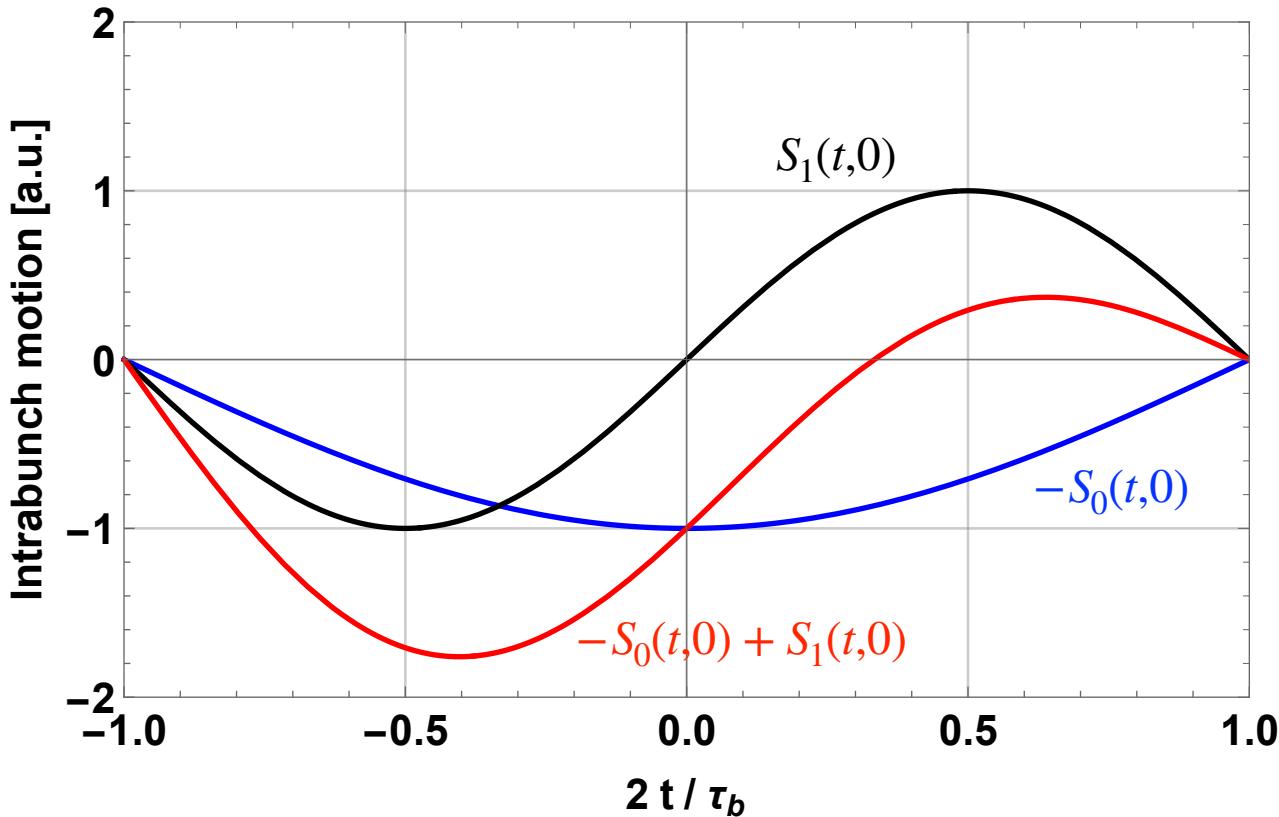
2 consecutive modes

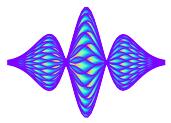
=> 1st case with mode 0 and mode 1



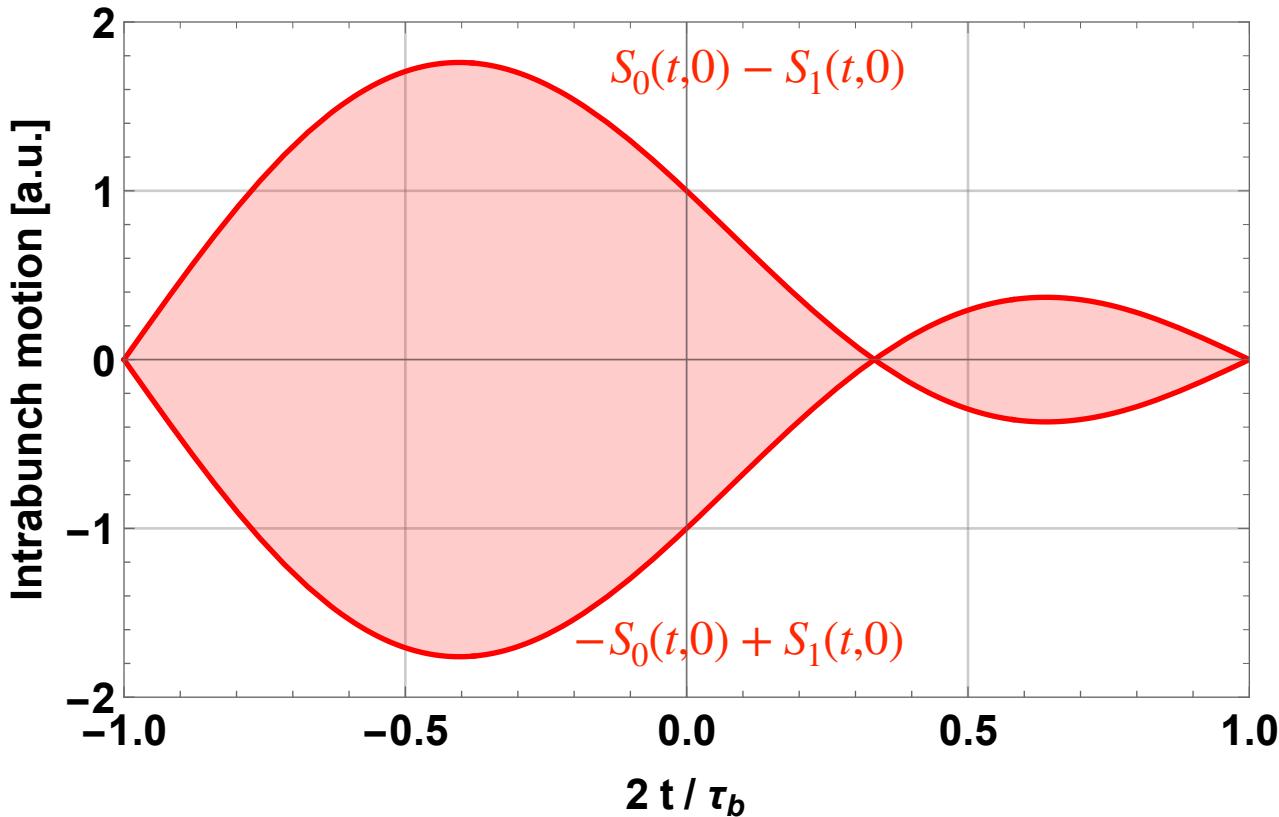


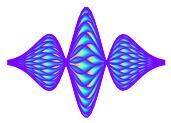
2 consecutive modes => 1st case with mode 0 and mode 1



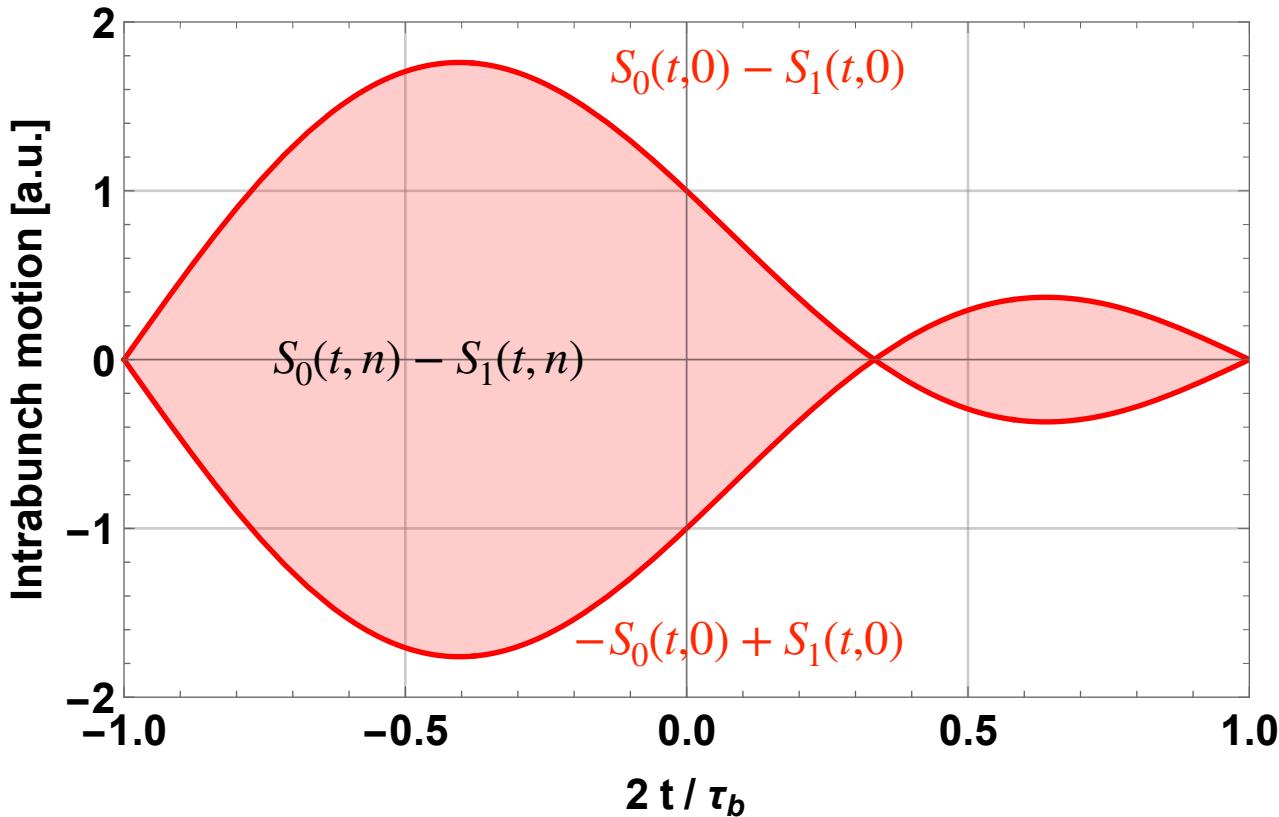


2 consecutive modes => 1st case with mode 0 and mode 1



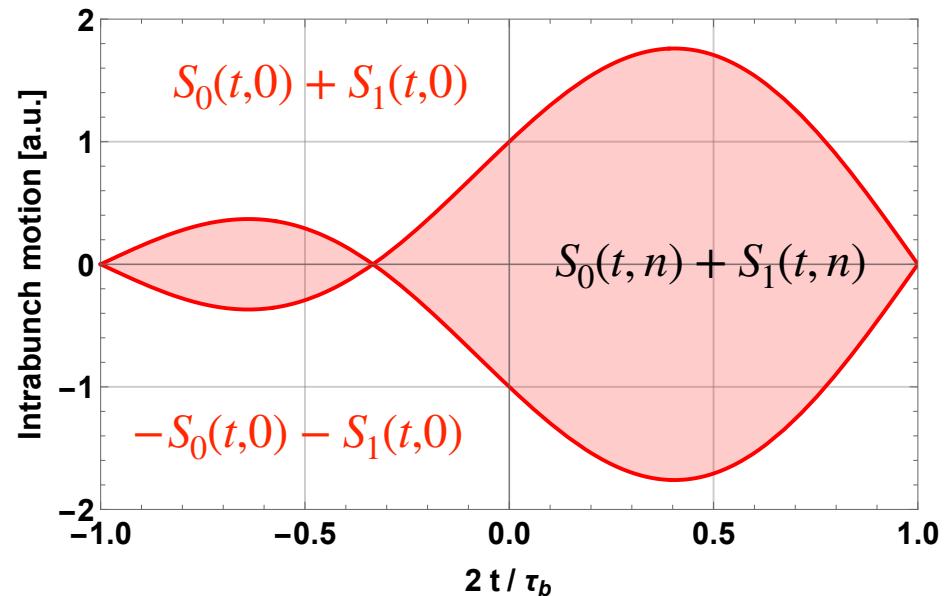
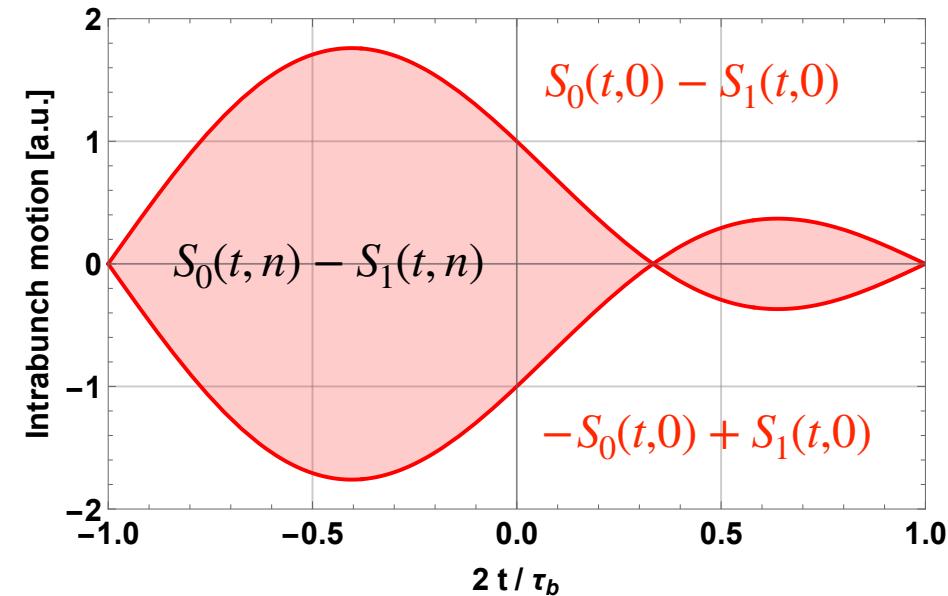
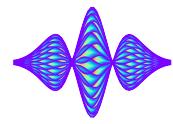


2 consecutive modes => 1st case with mode 0 and mode 1



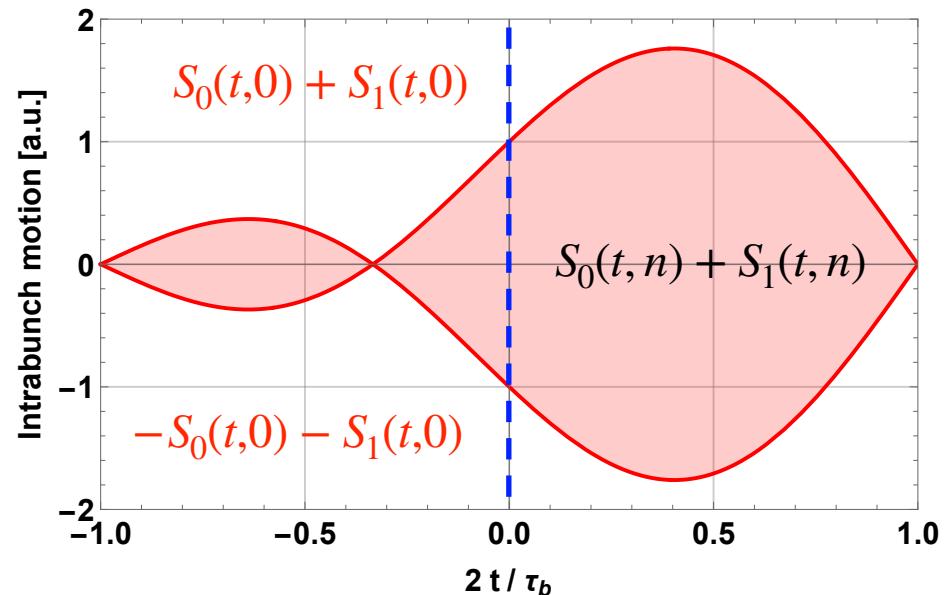
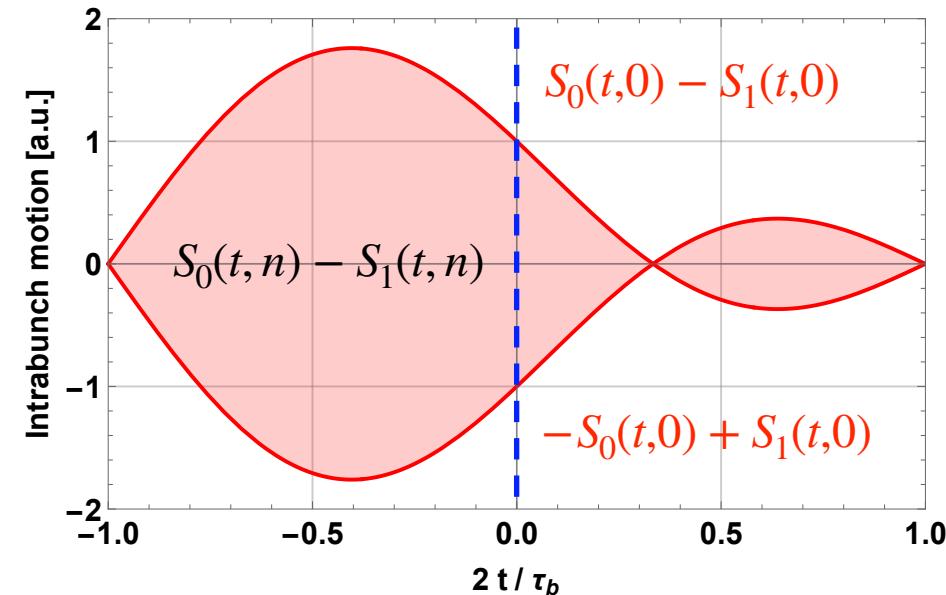
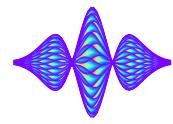
2 consecutive modes

=> 1st case with mode 0 and mode 1

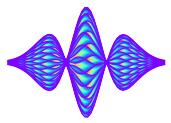


2 consecutive modes

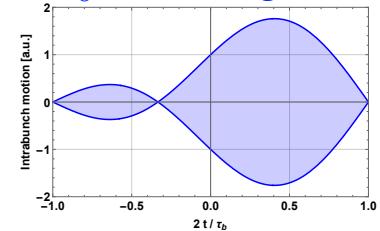
=> 1st case with mode 0 and mode 1

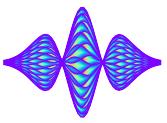


2 consecutive modes => General case



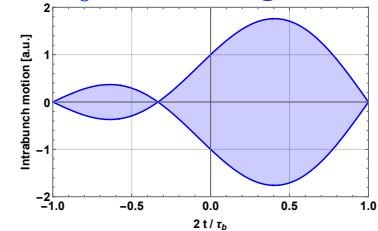
$$S_0(t, n) + S_1(t, n)$$



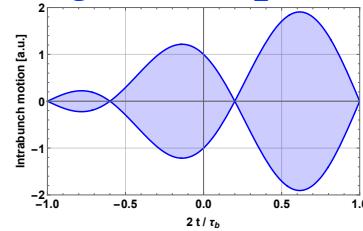


2 consecutive modes => General case

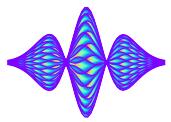
$$S_0(t, n) + S_1(t, n)$$



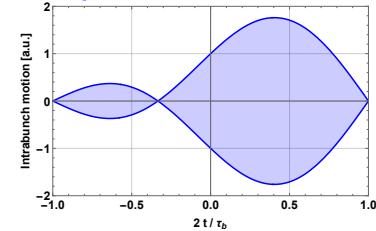
$$S_1(t, n) - S_2(t, n)$$



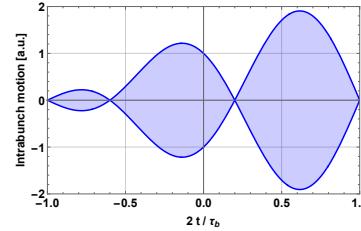
2 consecutive modes => General case



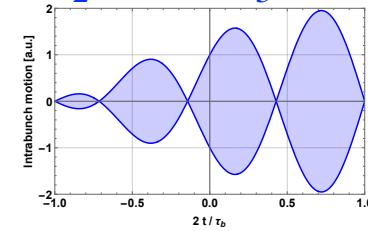
$$S_0(t, n) + S_1(t, n)$$



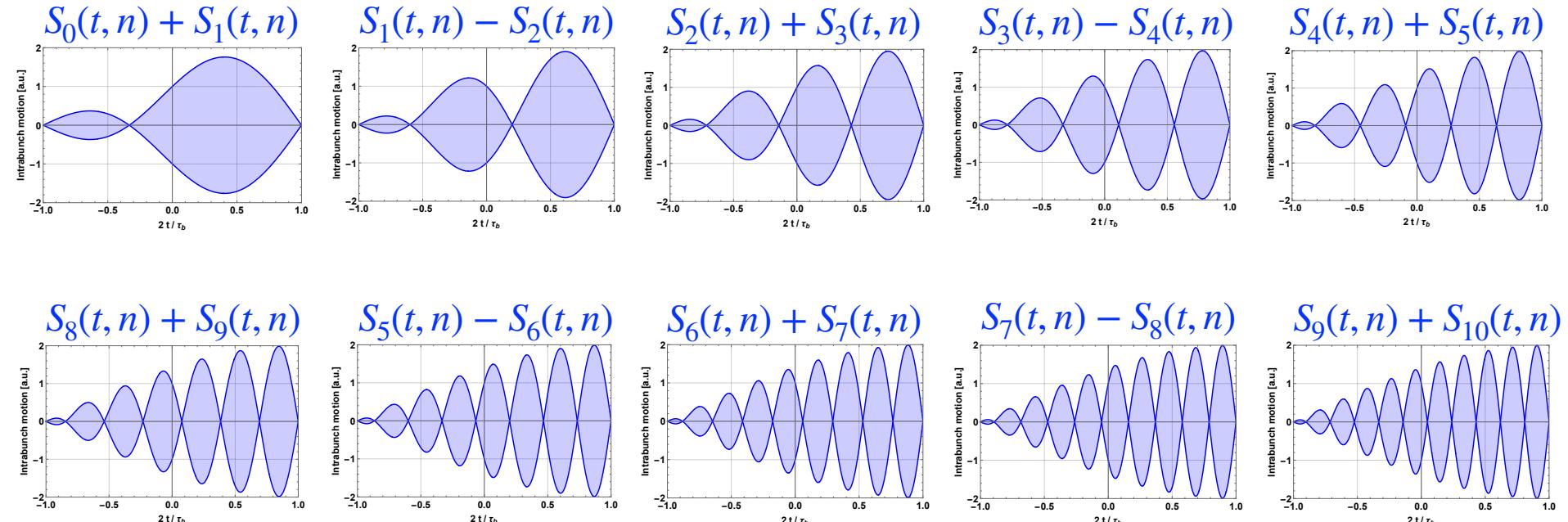
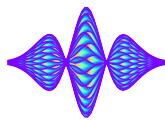
$$S_1(t, n) - S_2(t, n)$$



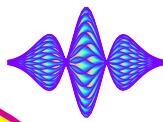
$$S_2(t, n) + S_3(t, n)$$



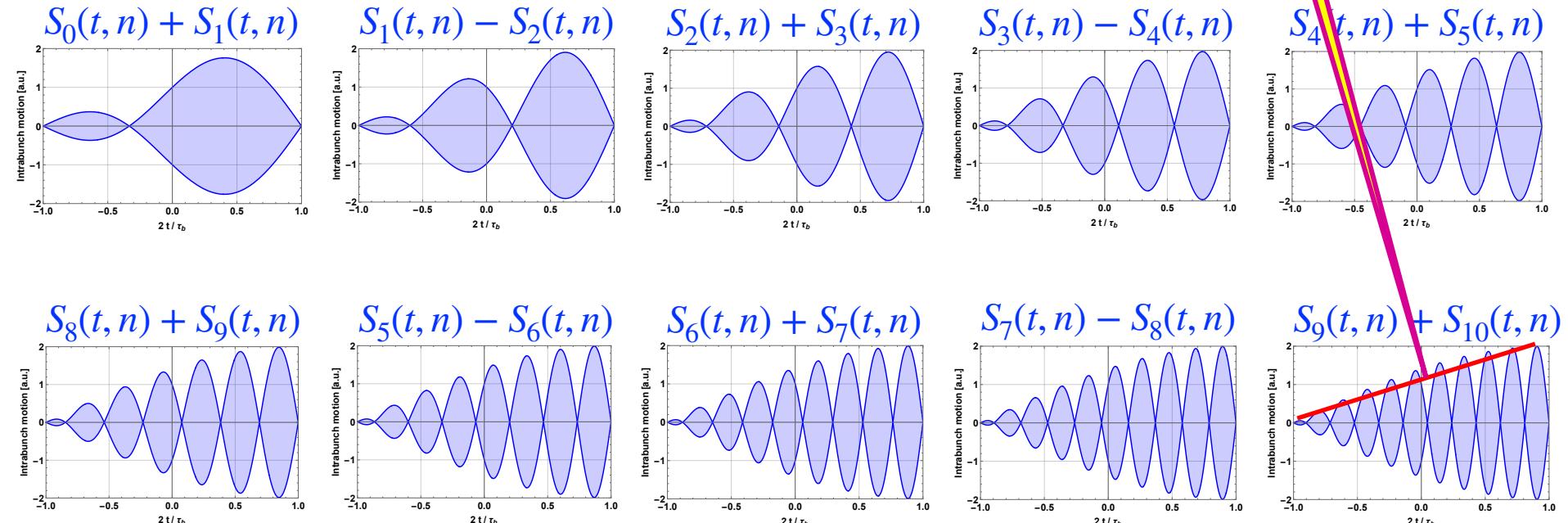
2 consecutive modes => General case



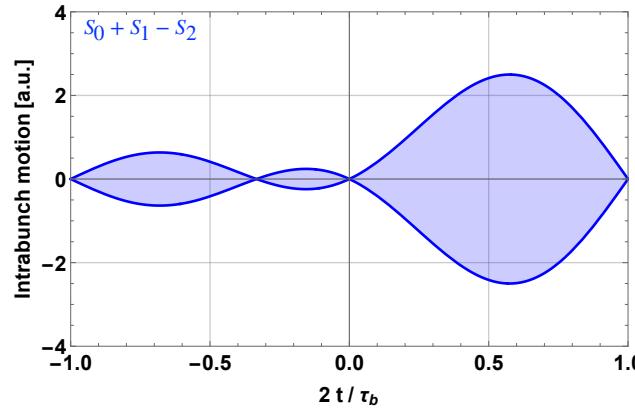
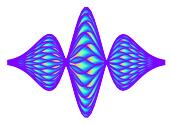
2 consecutive modes => General case



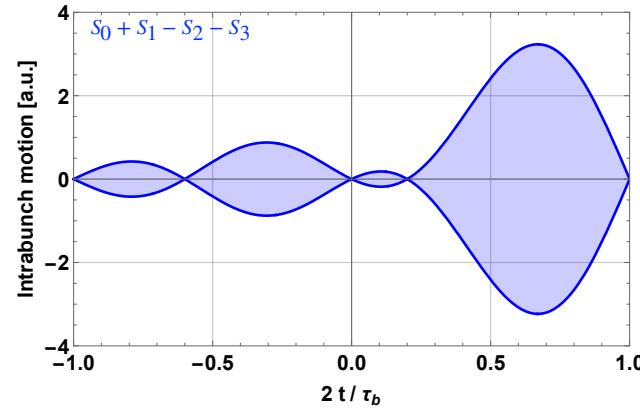
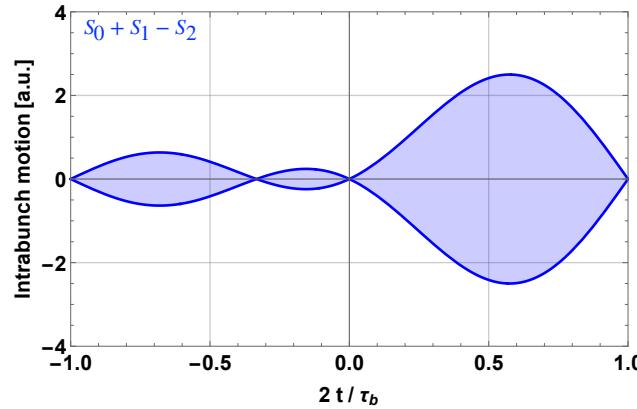
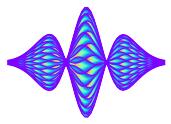
~ Linear increase
along the bunch
(and 10 nodes)



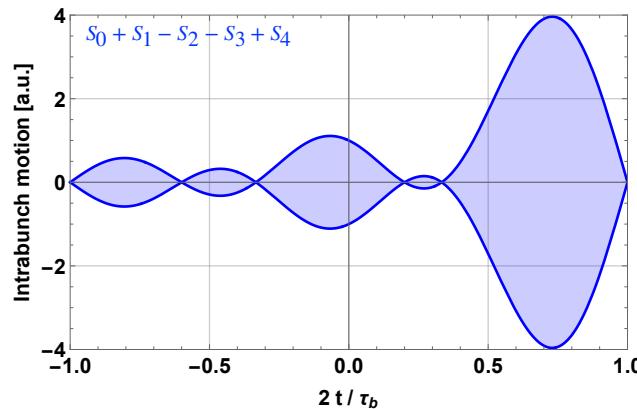
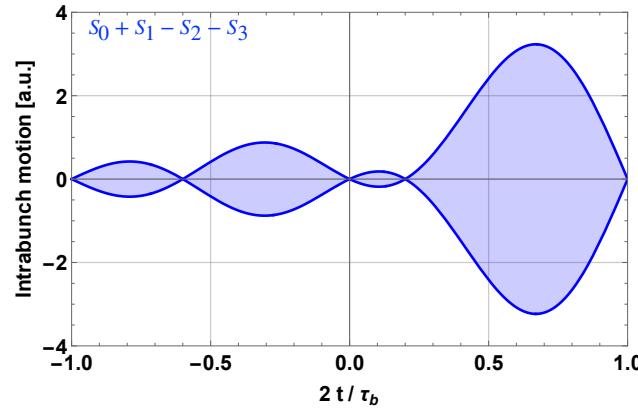
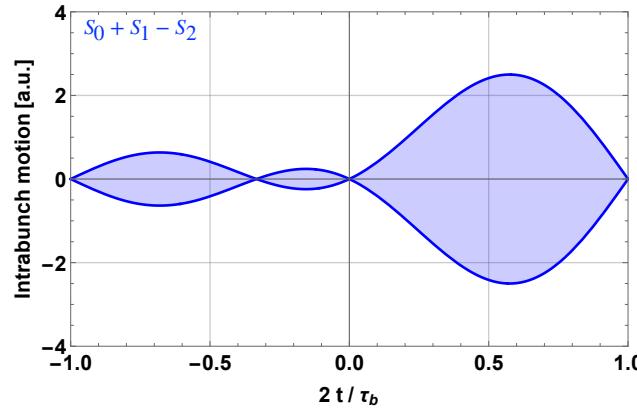
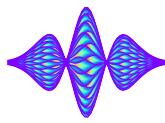
With many modes



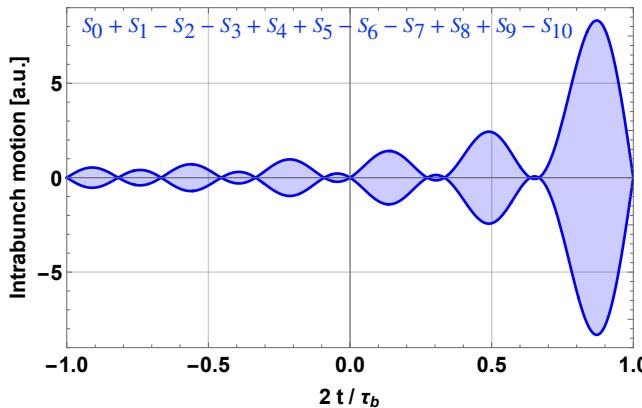
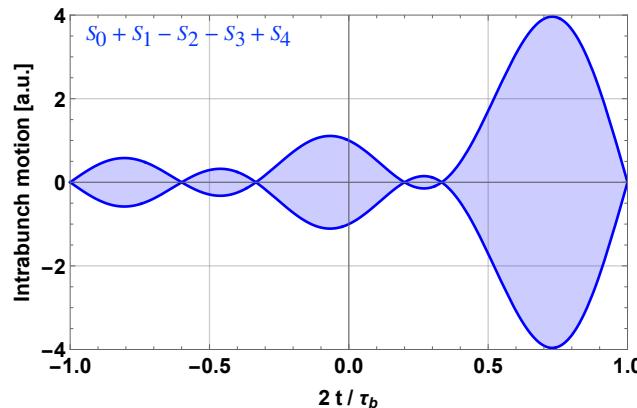
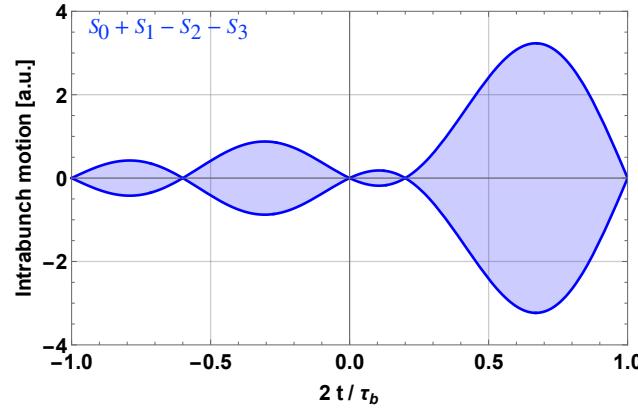
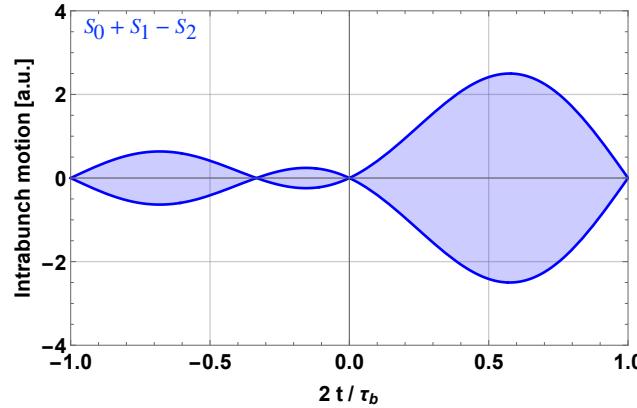
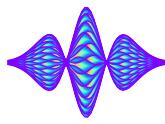
With many modes



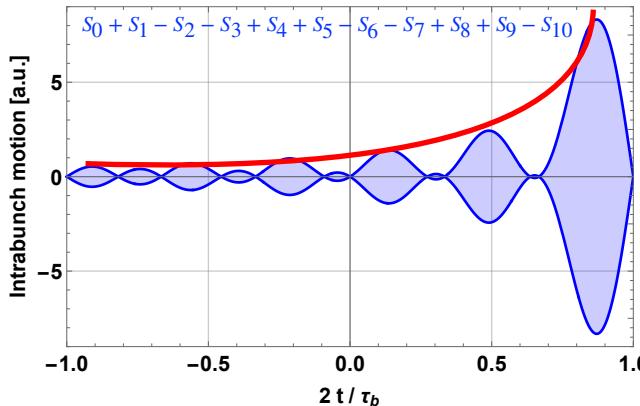
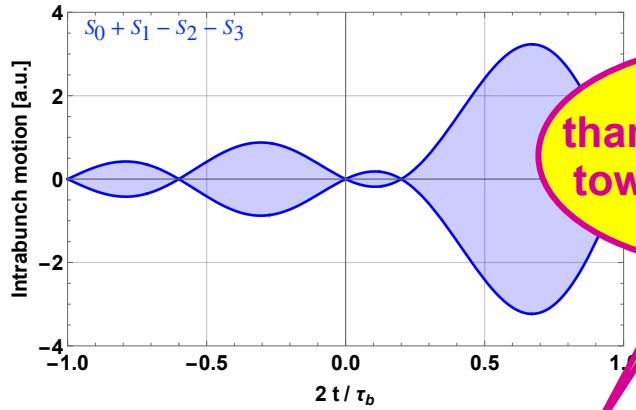
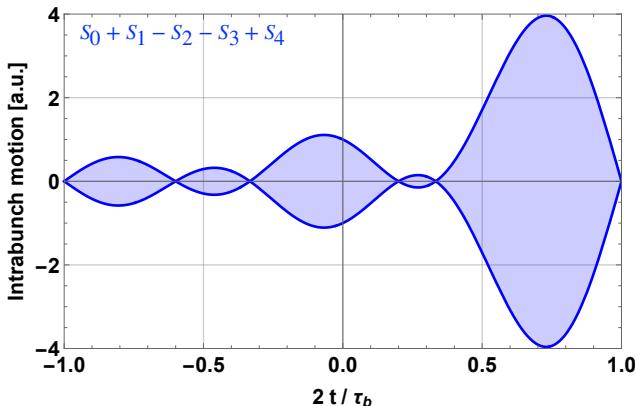
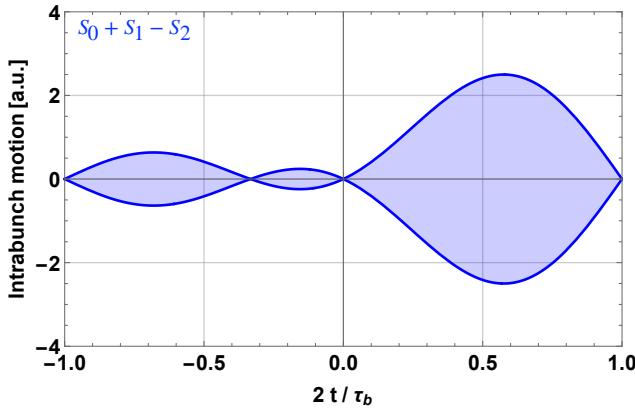
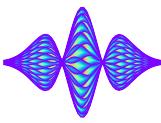
With many modes

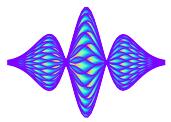


With many modes



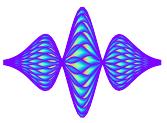
With many modes





WITH MATHS:

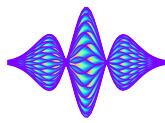
Which kind of pictures of intrabunch motion do we obtain from the GALACTIC Vlasov solver (with impedance only)?



$$\sigma(l) = \sum_{i,j=-\infty}^{\infty} a_{ij} \sigma_{ij}(l)$$

$$\frac{\Delta Q}{Q_s} a_{kl} = H a_{ij}$$

GALACTIC VLASOV SOLVER (impedance only)

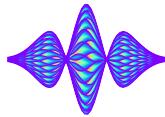


$$\sigma(l) = \sum_{i,j=-\infty}^{\infty} a_{ij} \sigma_{ij}(l)$$

Low-intensity
Eigenvectors (for
independent
modes)

$$\frac{\Delta Q}{Q_s} a_{kl} = H a_{ij}$$

GALACTIC VLASOV SOLVER (impedance only)



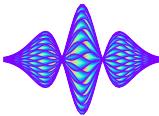
$$\sigma(l) = \sum_{i,j=-\infty}^{\infty} a_{ij} \sigma_{ij}(l)$$

Low-intensity
Eigenvectors (for
independent
modes)

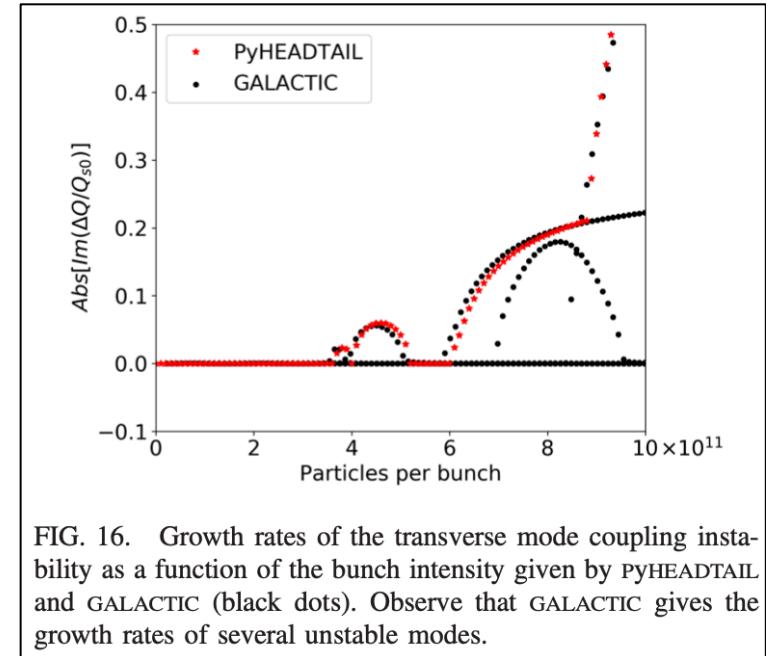
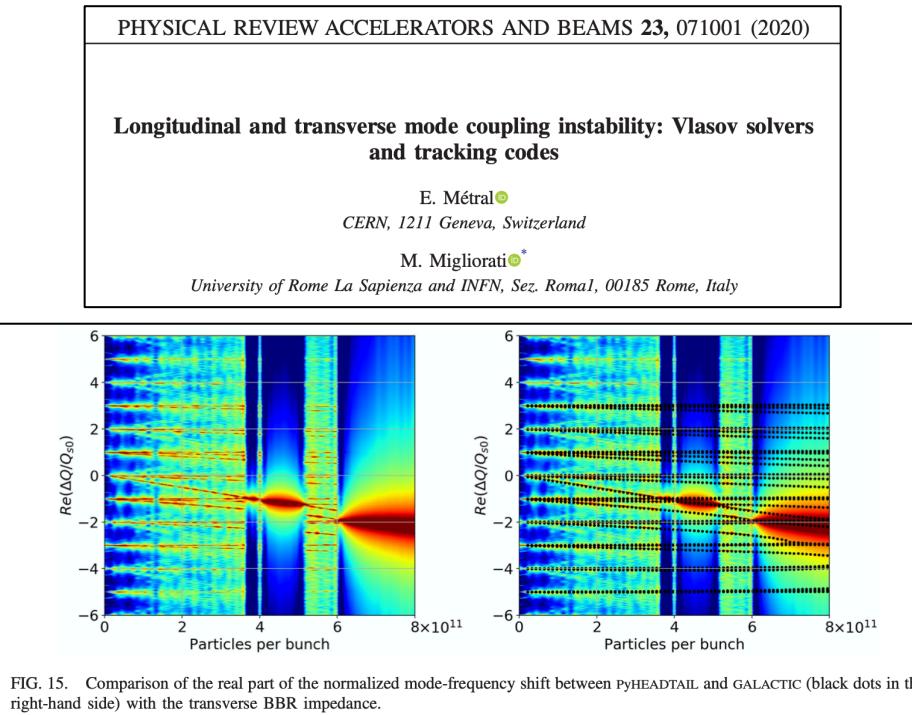
Matrix to be diagonalised:

- 1) Eigenvalues give the mode frequency shifts (Re and Im)
- 2) Eigenvectors give the coefficients a_{ij} to be used in the equation above to be able to plot the intrabunch signal

$$\frac{\Delta Q}{Q_s} a_{kl} = H a_{ij}$$

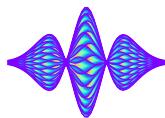


- GALACTIC was explained and benchmarked against the PyHEADTAIL macroparticle tracking code in this PRAB paper

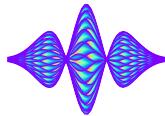




GALACTIC VLASOV SOLVER (impedance only)



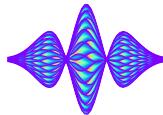
- ◆ Any number of modes can be treated with GALACTIC, but, to be able to clearly see what happens when the bunch intensity is increased, **the simple case of 2 modes (0 and -1) is discussed in detail below**



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2×2 matrix also used to describe
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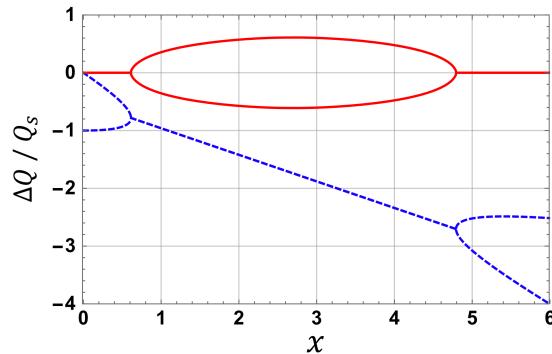
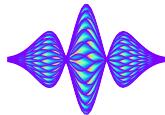


FIG. 4. Eigenvalues of the matrix of Eq. (5) with x a normalized parameter proportional to the bunch intensity [19]: real part in blue (dashed line) and imaginary part in red (full line).

GALACTIC VLASOV SOLVER (impedance only)



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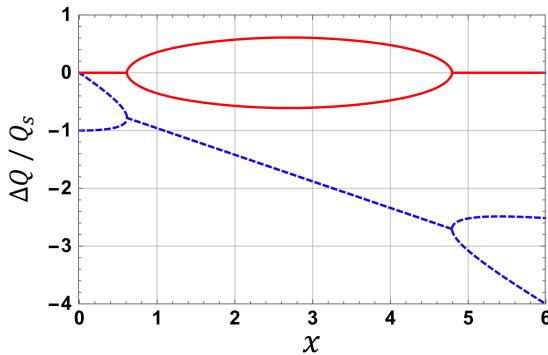


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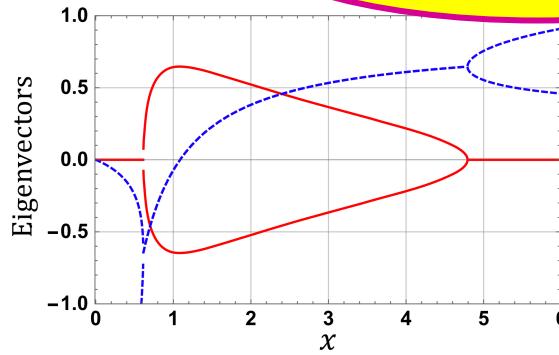
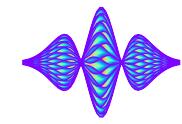
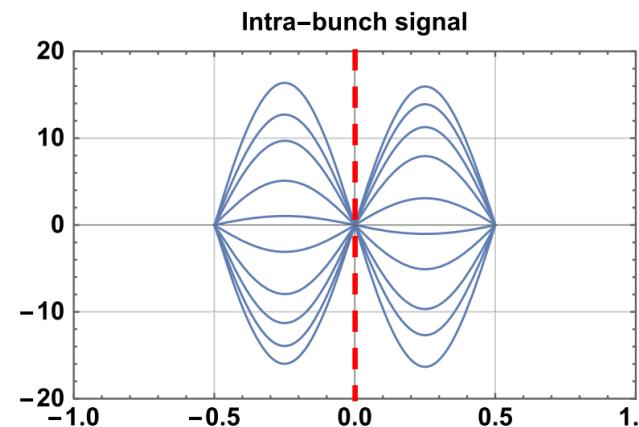
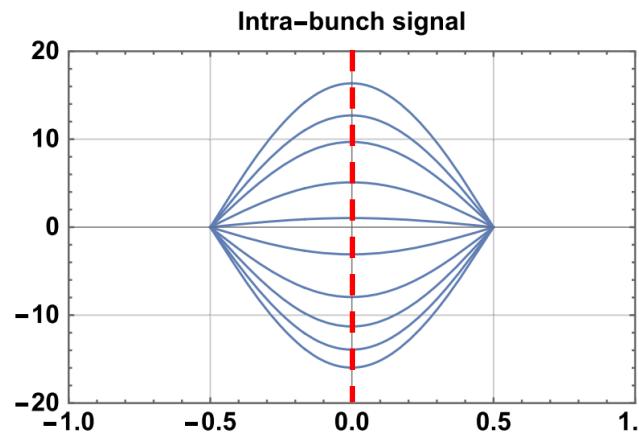
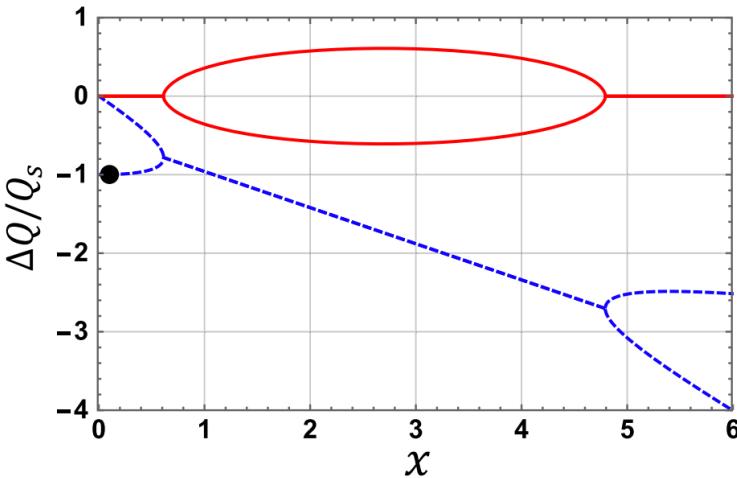
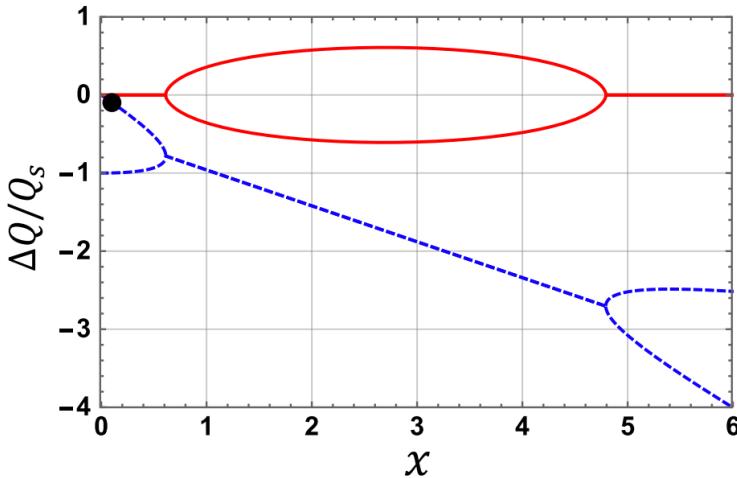
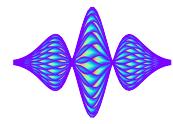
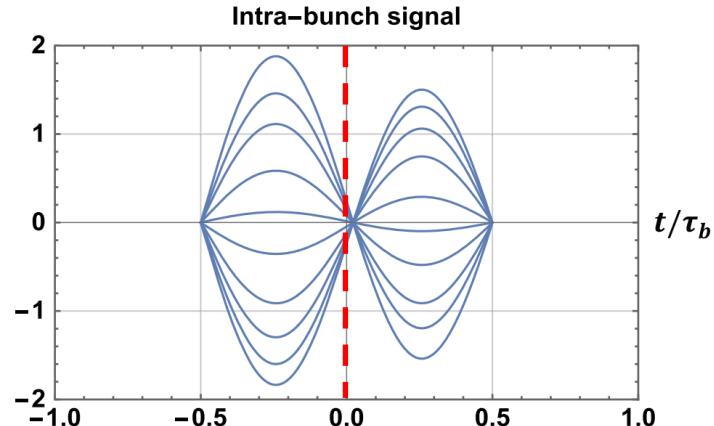
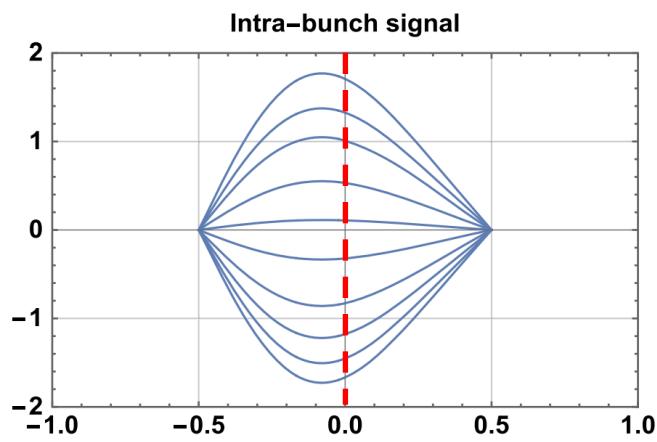
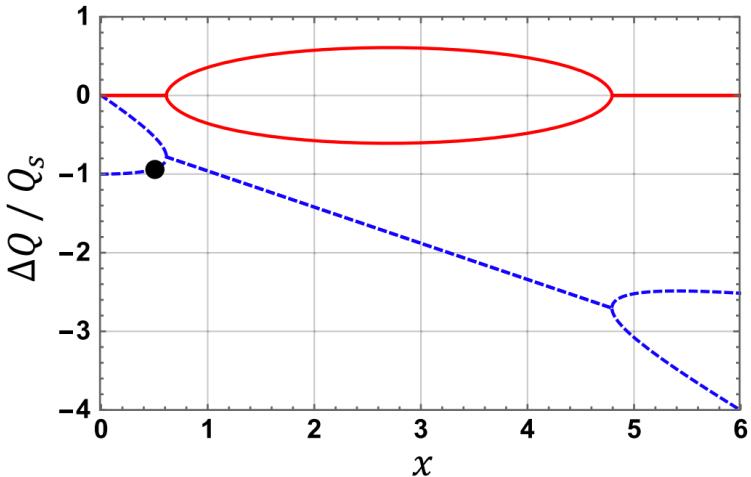
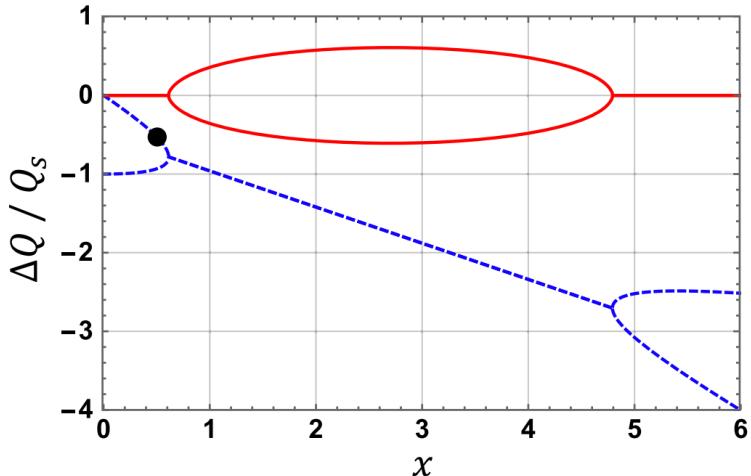
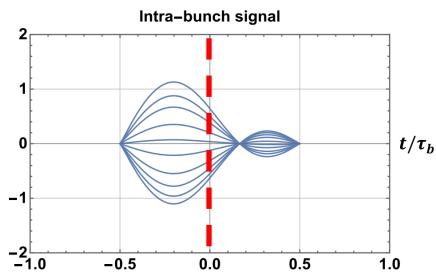
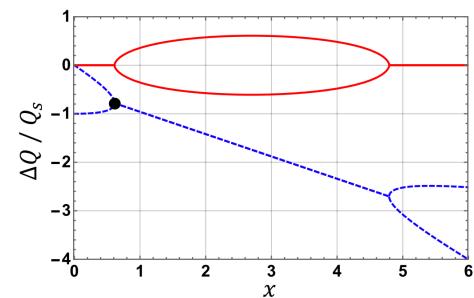
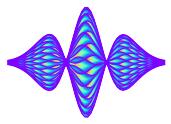
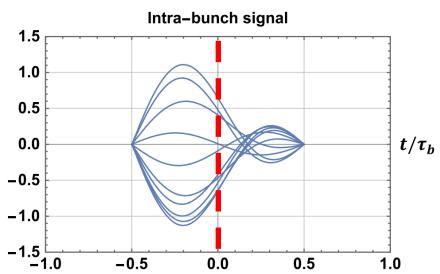
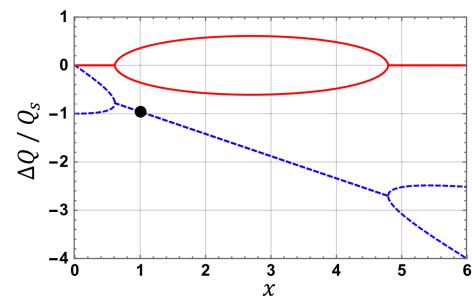
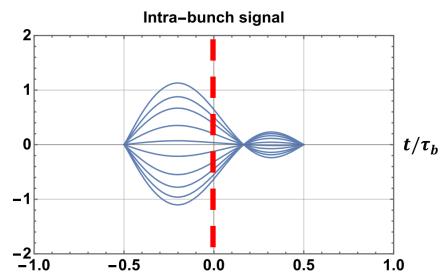
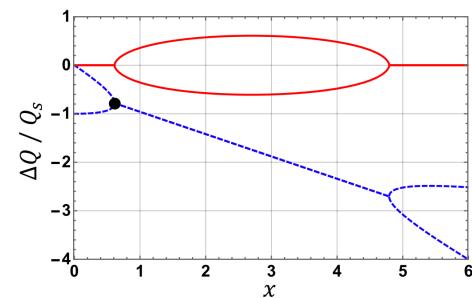
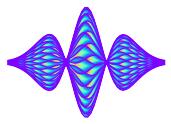


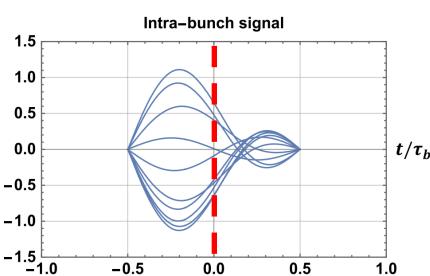
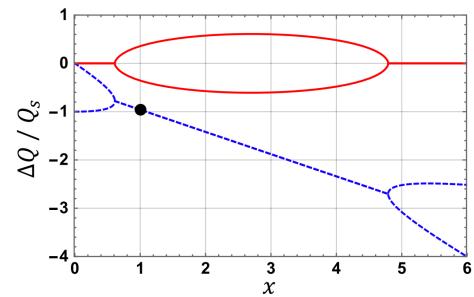
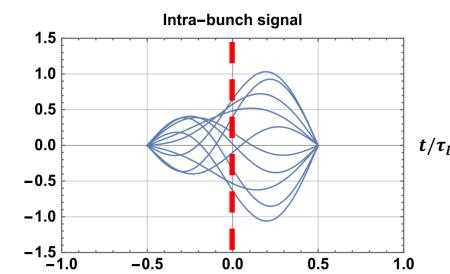
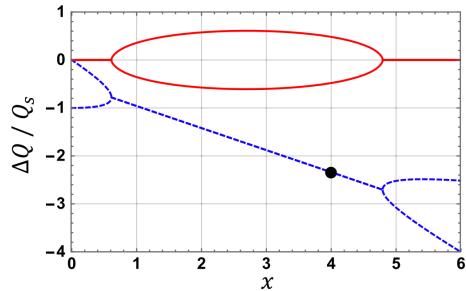
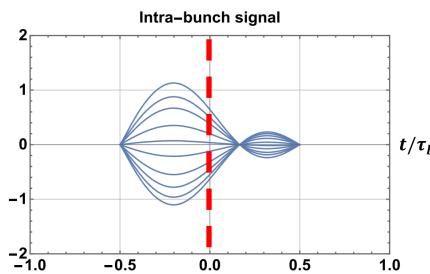
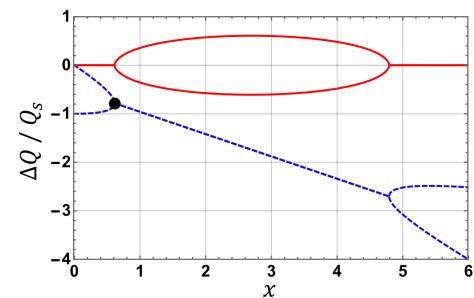
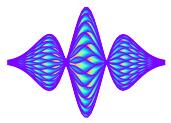
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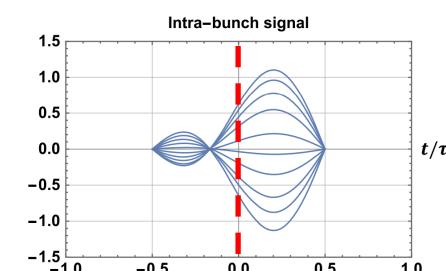
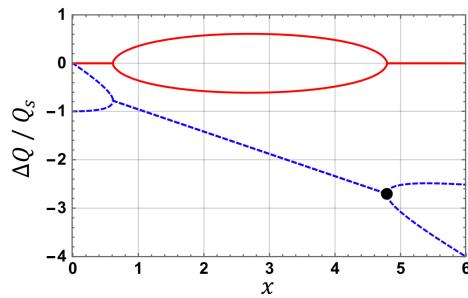
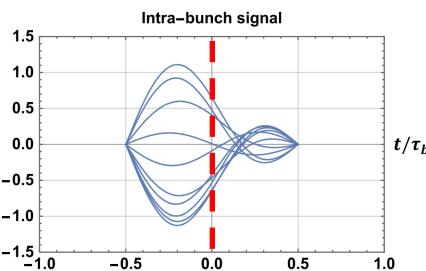
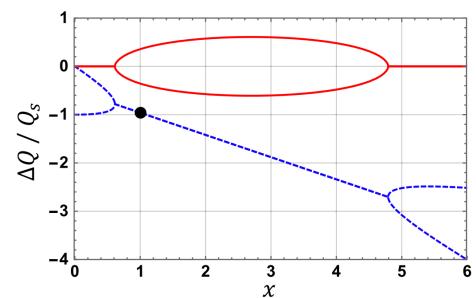
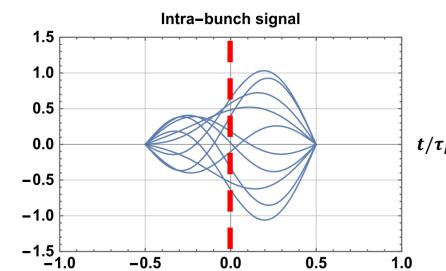
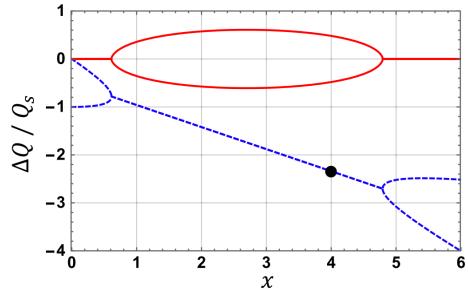
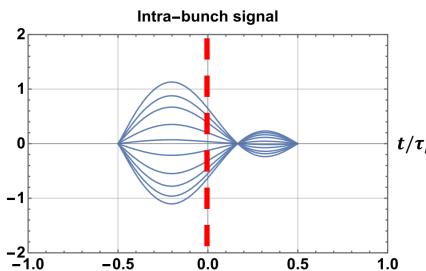
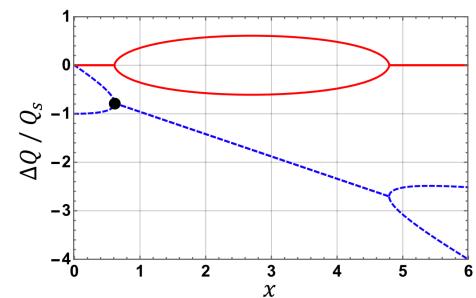
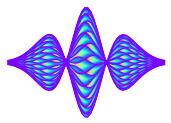


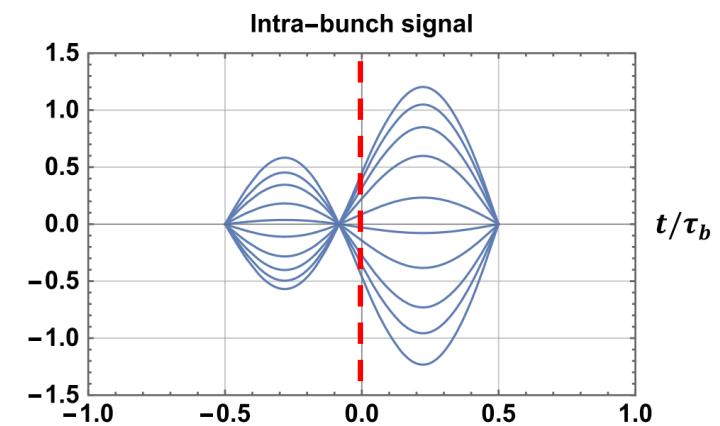
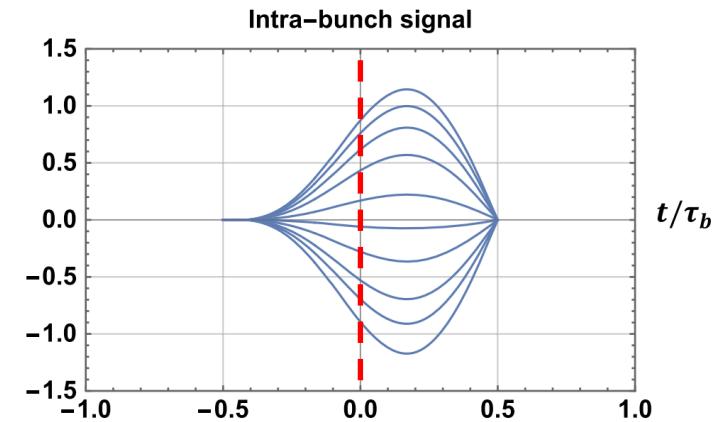
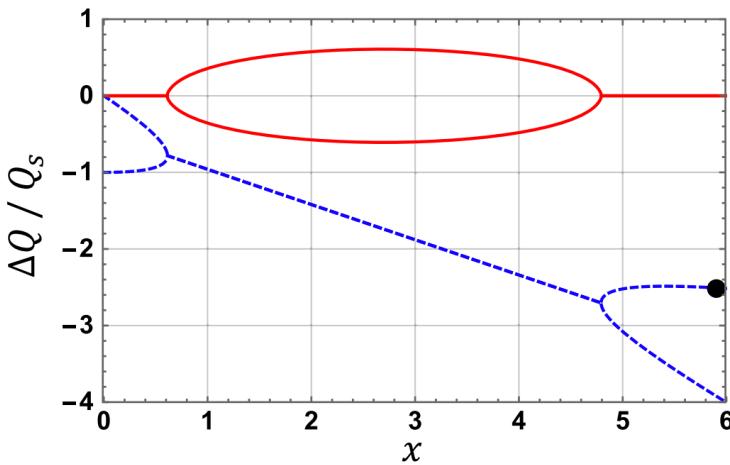
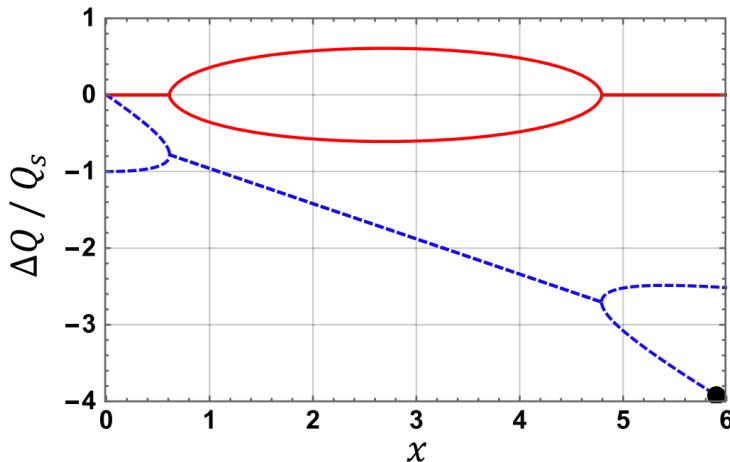
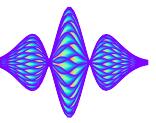


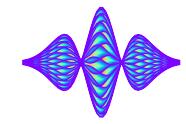
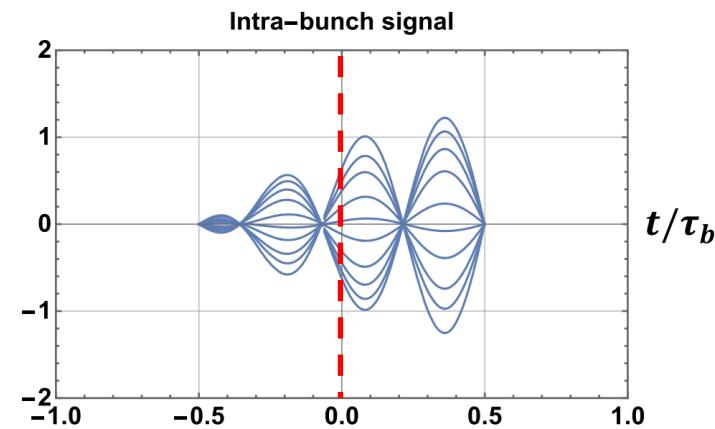
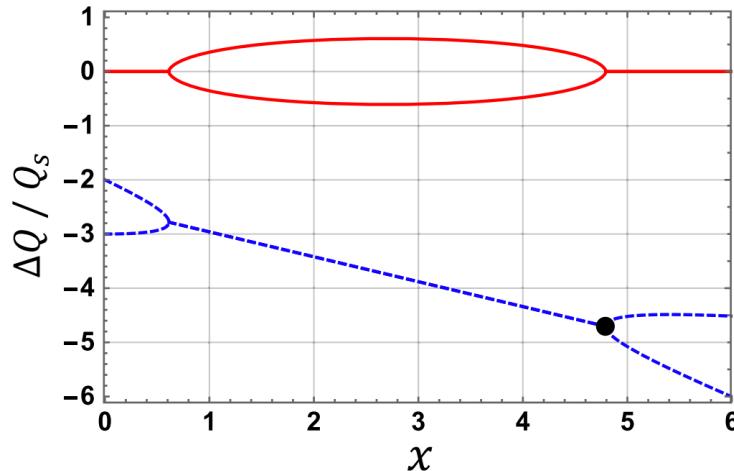


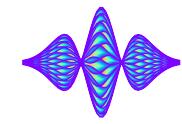
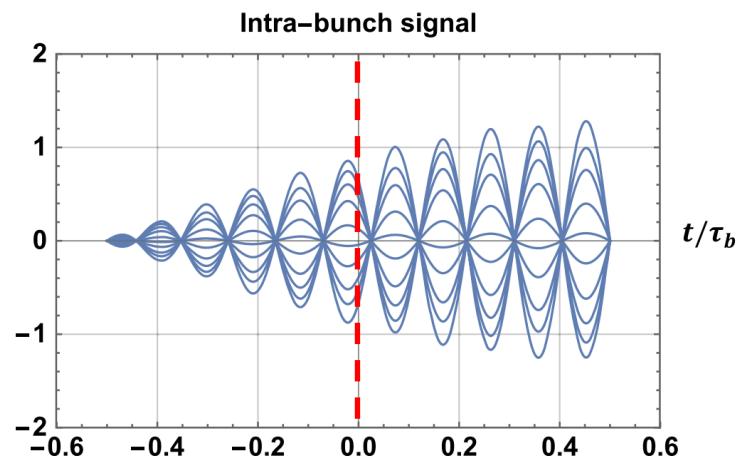
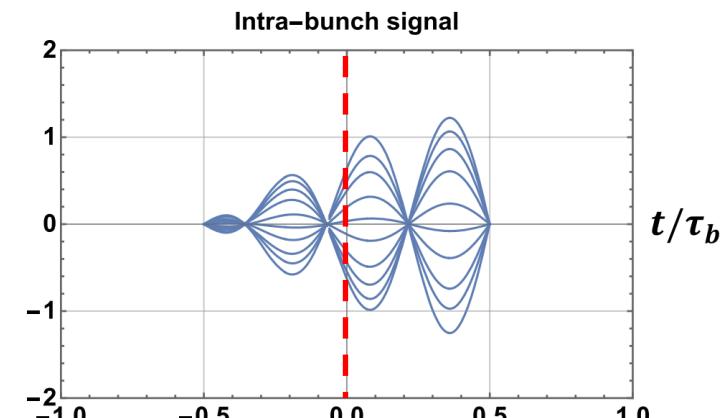
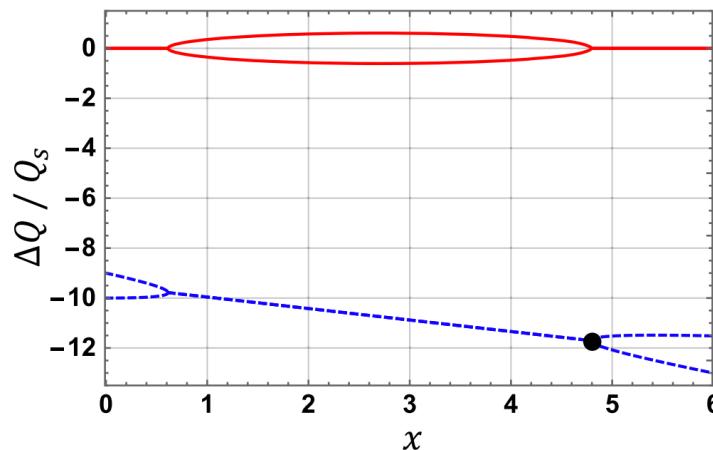
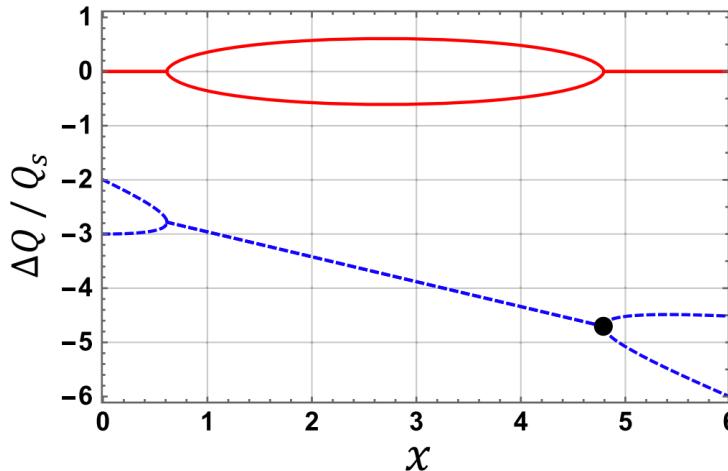






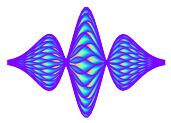




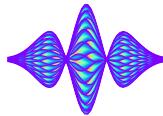




Conclusion



Conclusion

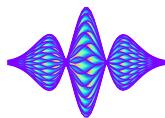


TAKE-HOME MESSAGE

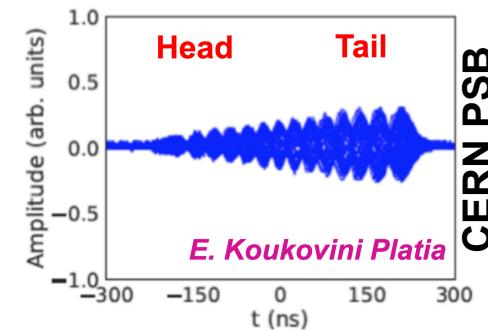
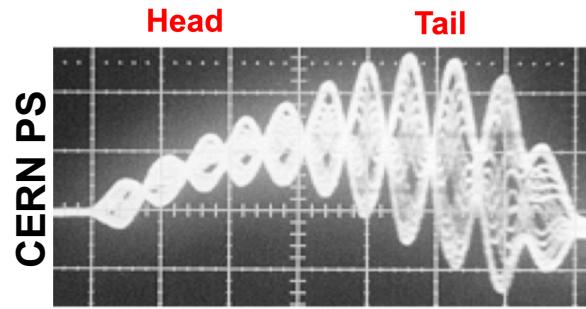
Mode coupling (interaction between several modes) explains why/how different kinds of asymmetric intrabunch signals are observed (in both measurements and simulations) with

- * Impedance
- * Impedance and space charge
- * Impedance and beam-beam
- * Electron cloud

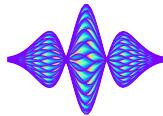
Outlook



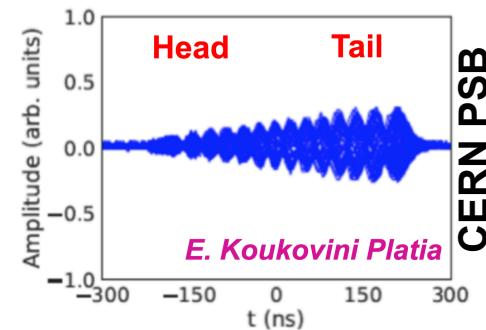
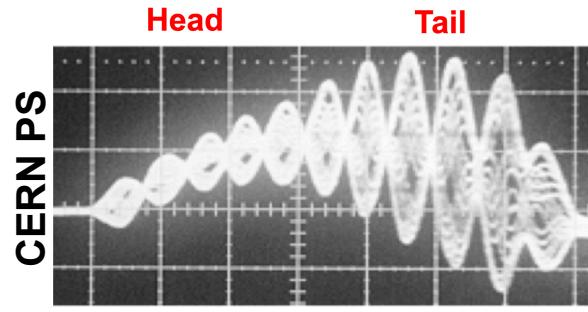
- ◆ The measurements of intrabunch motion in both the CERN PS and PSB (in strong space charge regime) have not been reproduced by simulations yet, such as e.g.



Outlook

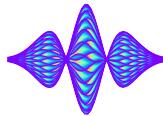


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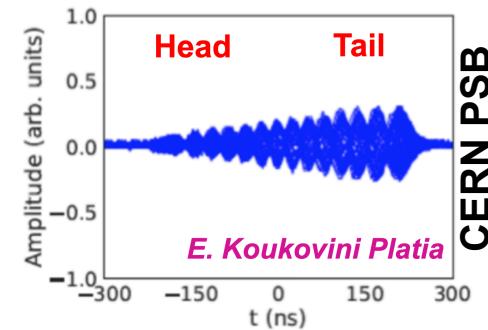
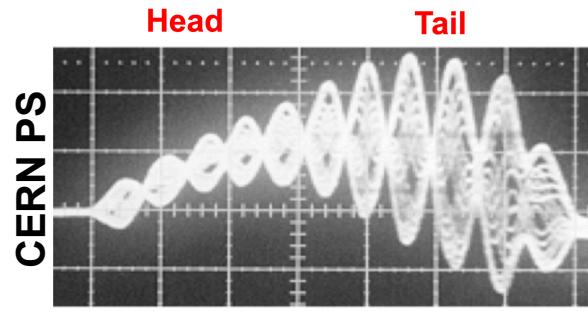


- * It would therefore be great to try and do so

Outlook

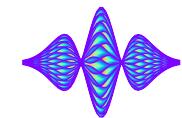


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- * It would therefore be great to try and do so
- * The analysis presented here suggests that **these intrabunch signals should be mainly explained by the interaction between 2 high-order modes => To be confirmed...**

*Thank you very much for your attention
&*



Many thanks to A. Burov for our long-term collaboration

&

This talk is dedicated to Y. Alexahin



PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 034202 (2019)

Convective instabilities of bunched beams with space charge

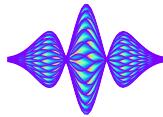
A. Burov^{*}

Fermilab, P.O. Box 500, Batavia, Illinois 60510-5011, USA

(Received 12 July 2018; revised manuscript received 6 December 2018; published 28 March 2019)

**MCBI 2019
workshop in
Zermatt**

Y. Alexahin, Vlasov eigenfunction analysis of space-charge and beam-beam effects, in *ICFA Mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators, Zermatt, Switzerland*, edited by E. Métral, G. Rumolo, and T. Pieloni (2020), p. 193, <https://doi.org/10.23732/CYRCP-2020-009>.



Summary slide, 5th ICFA mini-workshop on Space Charge

Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation
(If relevant, specify type of facility, species, tune shift):

This presentation deals with the general notion (and fundamental observable) of intrabunch motion during a transverse coherent single-bunch instability. In particular, it explains how mode coupling (interaction between several modes) can provide different kinds of asymmetric intrabunch signals (as observed in both measurements and simulations) with 1) Impedance only, 2) Impedance and space charge, 3) Impedance and beam-beam and 4) Electron cloud.

From your perspective, where is the gap regarding space charge effects?
(understanding/control/mitigation/prediction/?)

The long-standing problem of the effect of space charge on transverse coherent instabilities is not fully understood and explained yet, even if a major step was recently achieved by Xavier Buffat, who could reproduce by simulations most of the observables of the CERN SPS instability. Some observations, such as the ones mentioned in the talk at the CERN PS and PSB, remain to be simulated, fully understood and explained.

What is needed to bridge this gap?

Some simulation and theoretical work remain to be performed to fully understand all the CERN instabilities in strong space charge regime (PSB, PS and SPS) and it might be that, as discussed in the past, all of them come from TMCI (with space charge), which would be a very important “new” result and input for the whole community (tbc).