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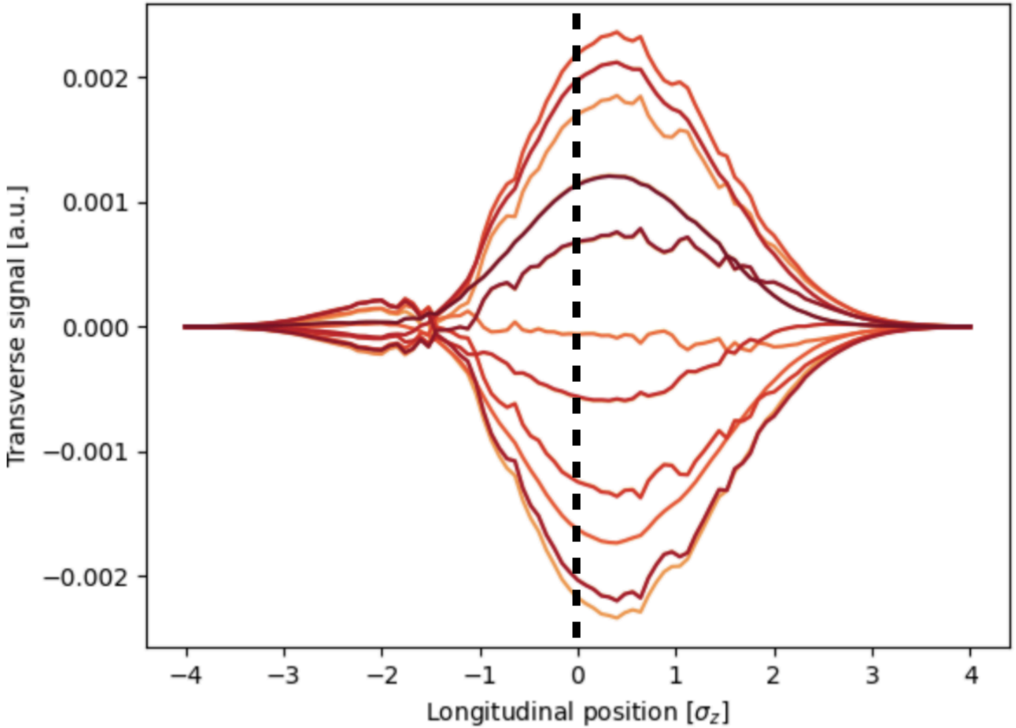

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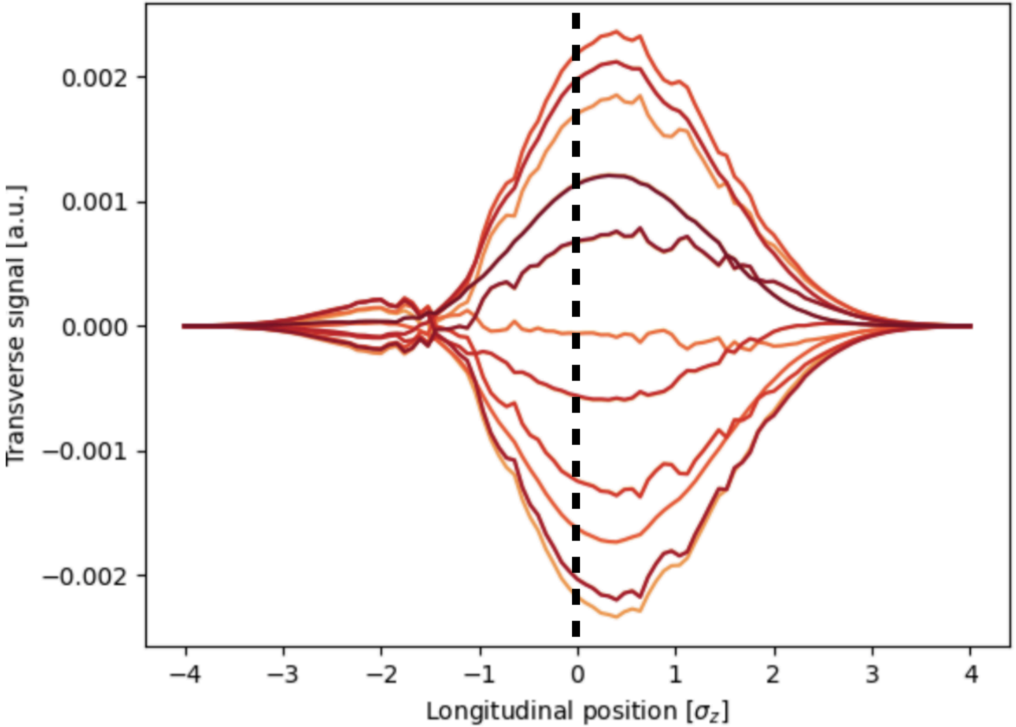

=> See: E. Métral and X. Buffat, Intrabunch motion with both impedance and beam-beam using the circulant matrix approach, IPAC-2022: https://accelconf.web.cern.ch/ipac2022/papers/wepotk062.pdf

Introduction and motivation

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 041002 (2014)

Transverse mode coupling instability of colliding beams

S. White
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N. Mounet and T. Pieloni
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(Received 16 January 2014; published 9 April 2014; corrected 11 April 2014)

In high brightness circular colliders, coherent and incoherent beam dynamics are dominated by beam-beam interactions. It is generally assumed that the incoherent tune spread introduced by the beam-beam interactions is sufficiently large to cure any instabilities originating from impedance. However, as the two counterrotating beams interact they can give rise to coherent dipole modes and therefore modify the coherent beam dynamics and stability conditions. In this case, coherent beam-beam effects and impedance cannot be treated independently and their interplay should be taken into account in any realistic attempt to study the beam stability of colliding beams. Due to the complexity of these physics processes, numerical simulations become an important tool for the analysis of this system. Two approaches are proposed in this paper: a fully self-consistent multiparticle tracking including particle-in-cell Poisson solver for the beam-beam interactions and a linearized model taking into account finite bunch length effects. To ensure the validity of the results a detailed benchmarking of these models was performed. It will be shown that under certain conditions coherent beam-beam dipole modes can couple with higher order headtail modes and lead to strong instabilities with characteristics similar to the classical transverse mode coupling instability originating from impedance alone. Possible cures for this instability are explored both for single bunch and multibunch interactions. Simulation results and experimental evidences of the existence of this instability at the LHC will be presented for the specific case of offset collisions.

DOI: 10.1103/PhysRevSTAB.17.041002 PACS numbers: 29.20.-c, 29.27.-a, 07.05.Tp

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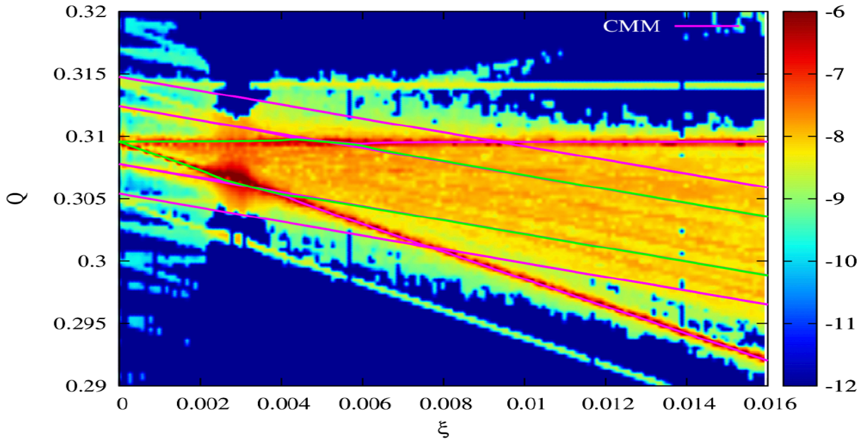

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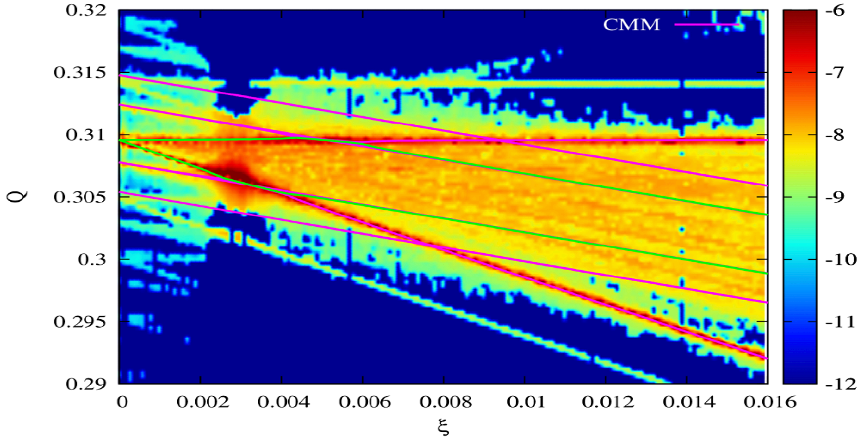

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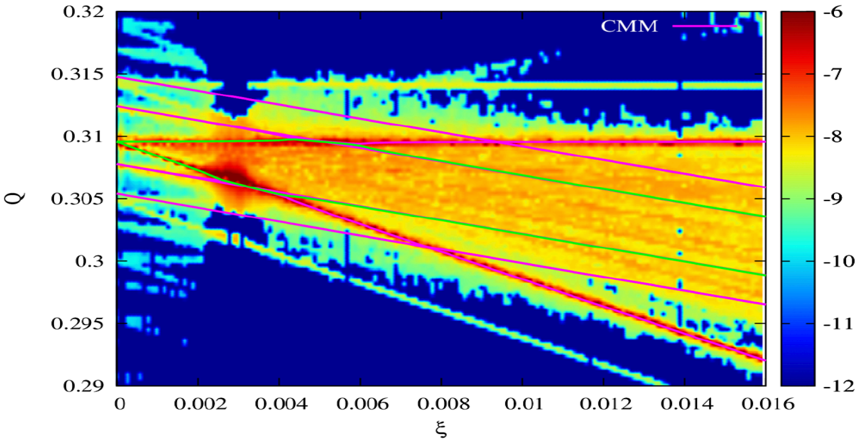

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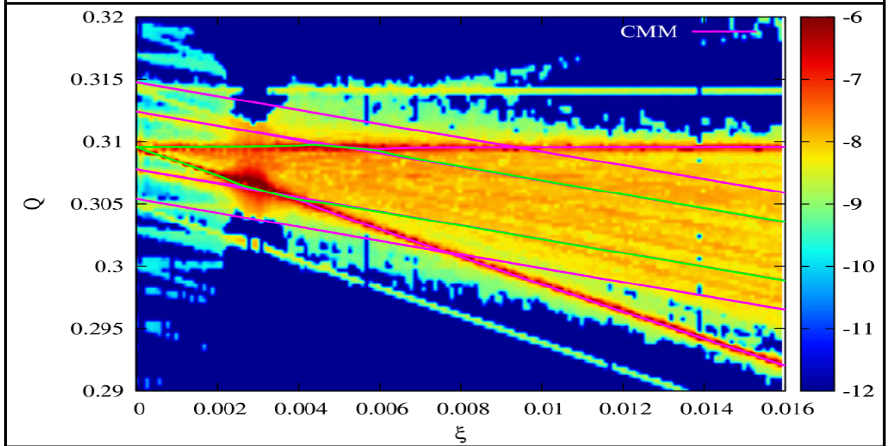

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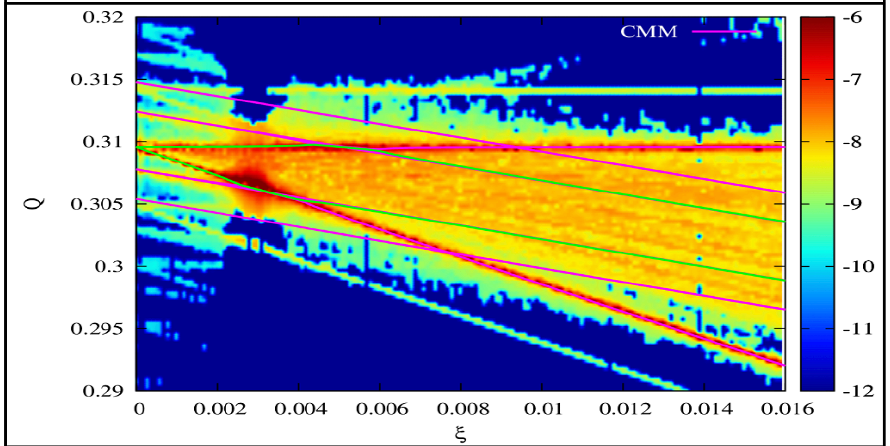

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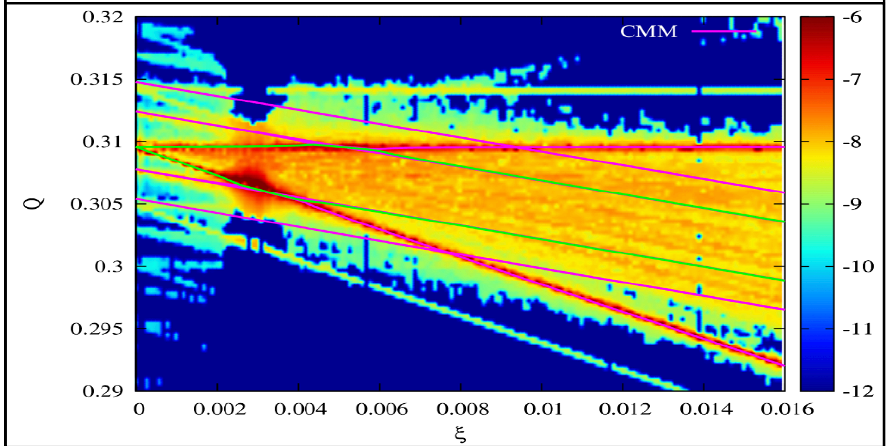

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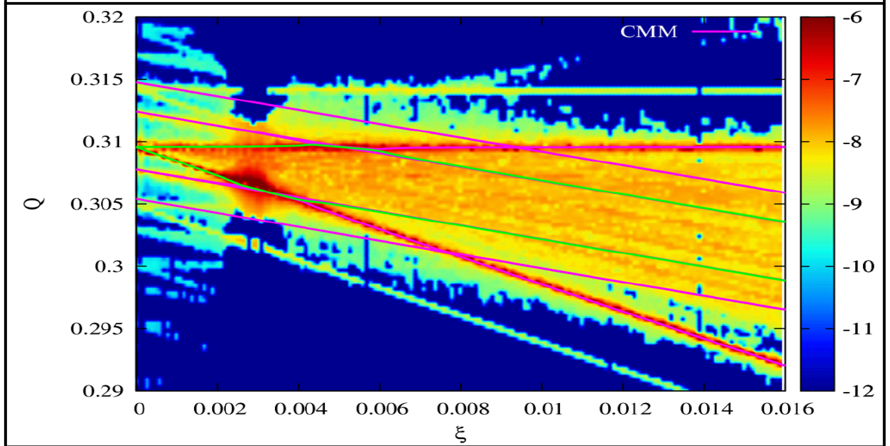

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$$\frac{\Delta Q}{Q_s} a_{kl} = H a_{ij}$$

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Matrix to be diagonalised:

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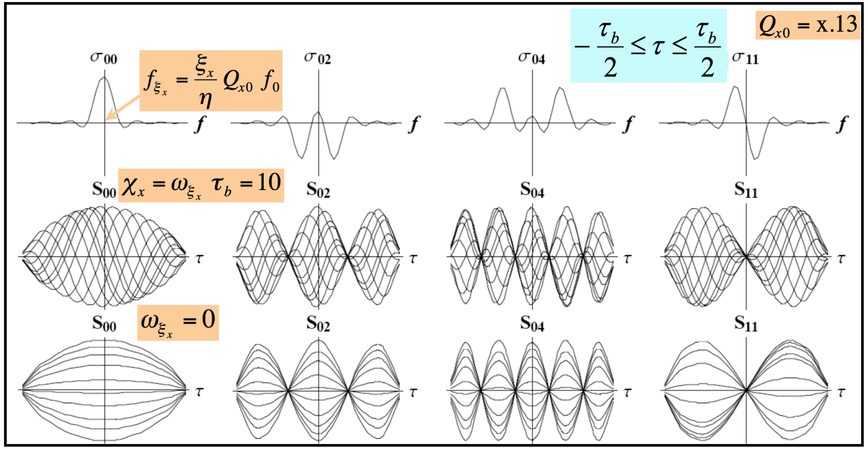

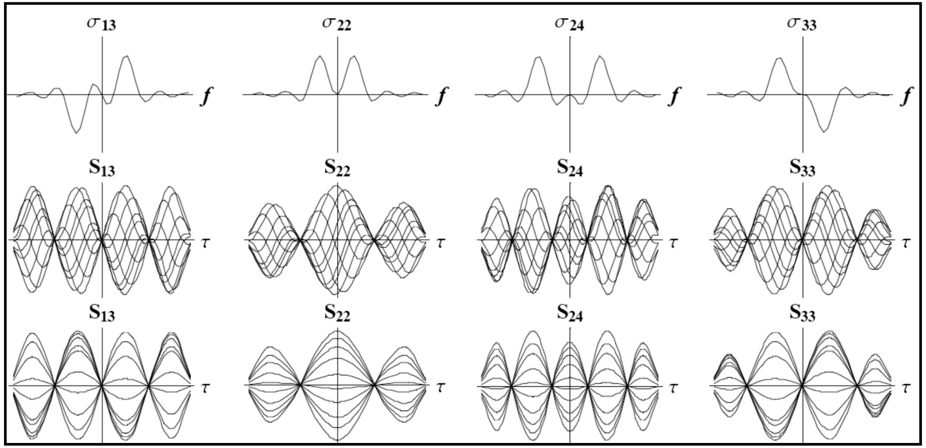

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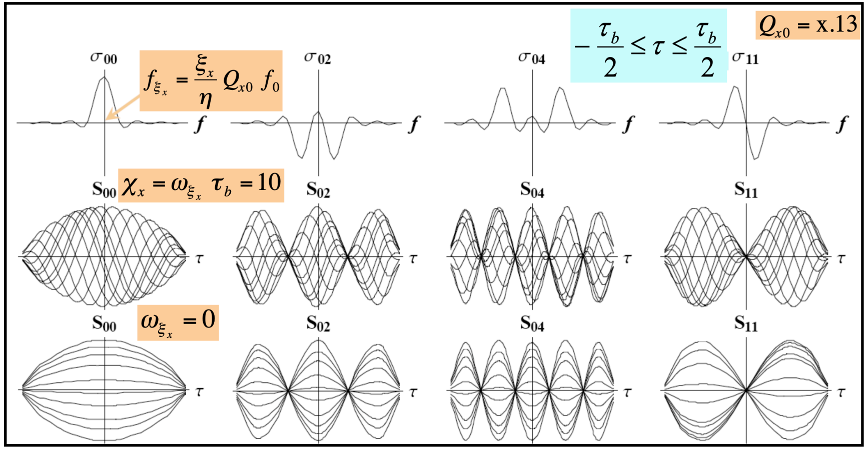

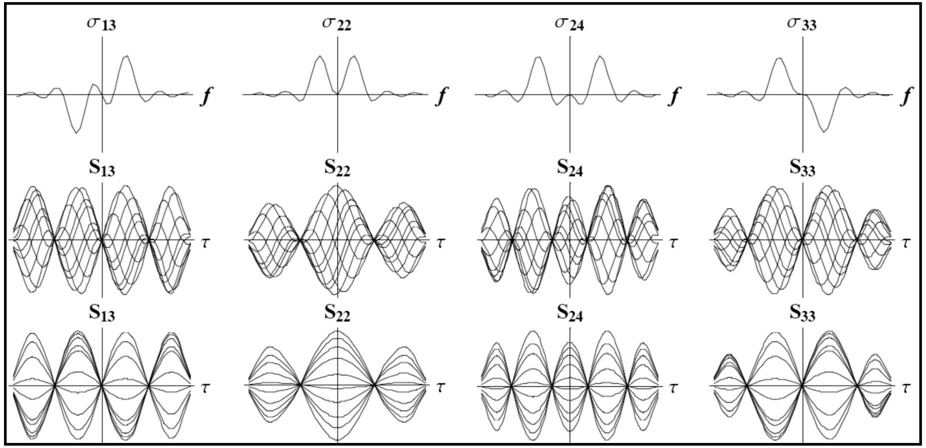

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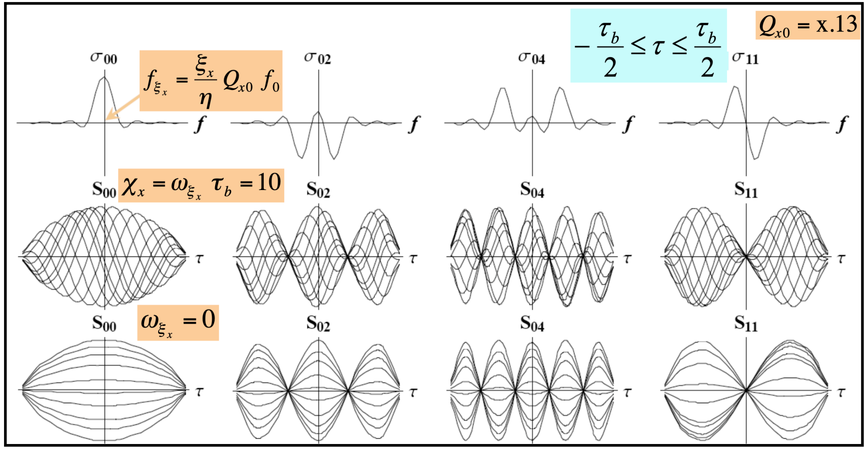

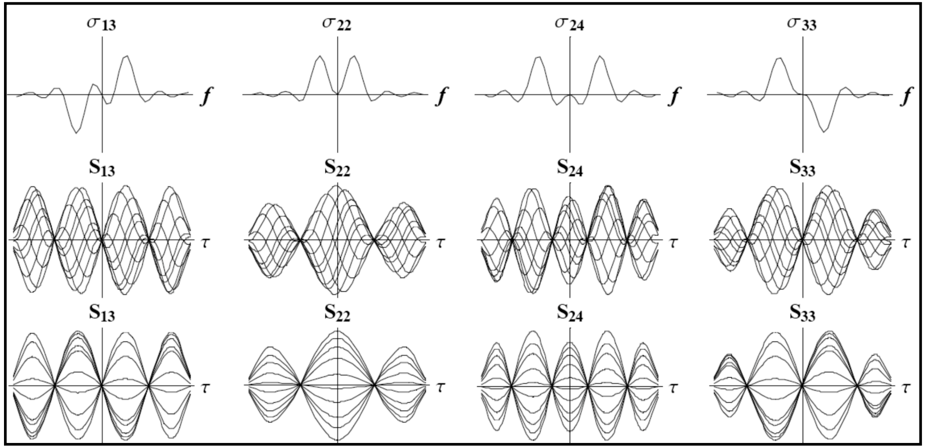

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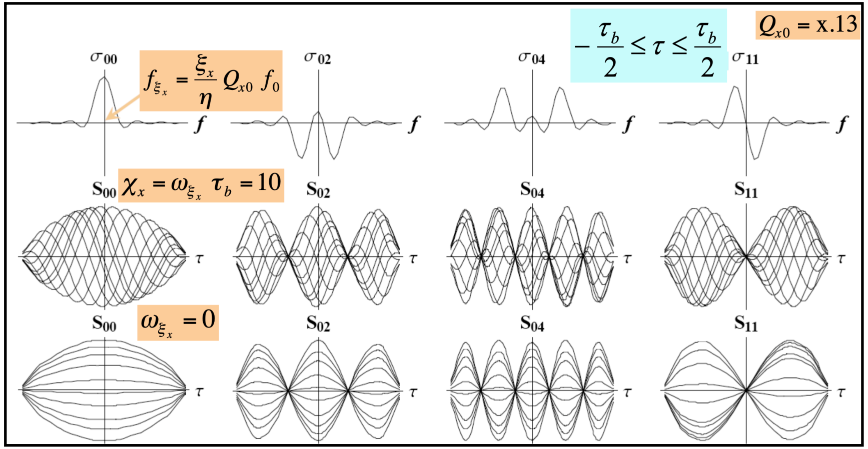

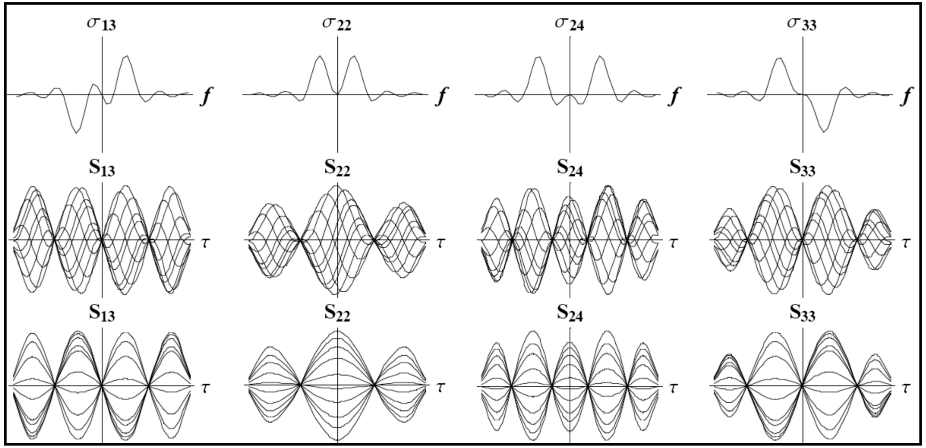

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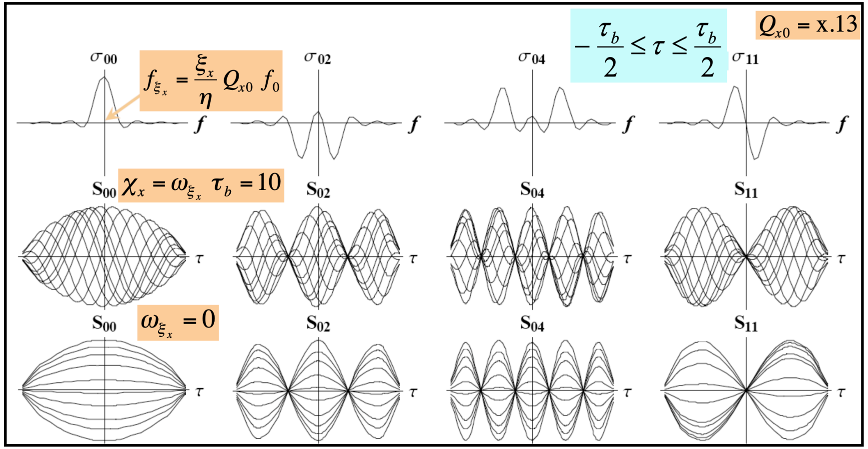

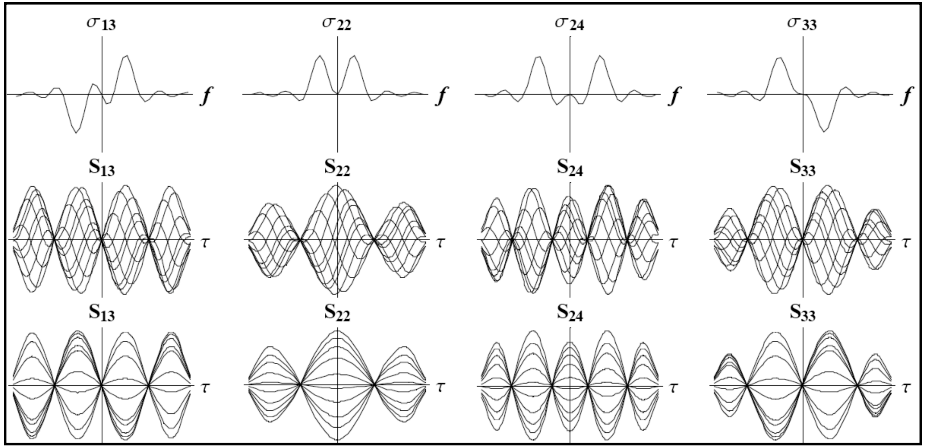

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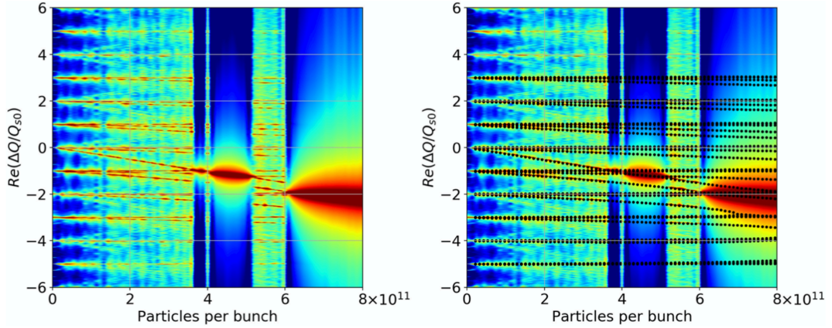

FIG. 15. Comparison of the real part of the normalized mode-frequency shift between PyHEADTAIL and GALACTIC (black dots in the right-hand side) with the transverse BBR impedance.

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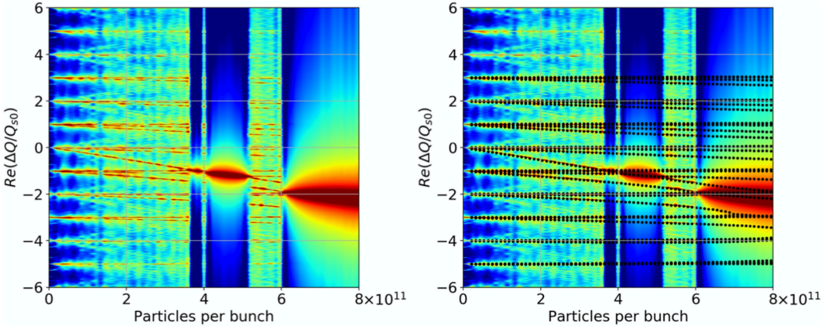

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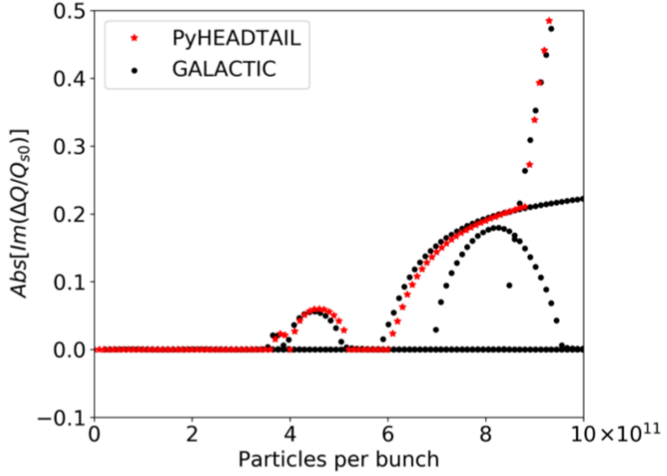

FIG. 16. Growth rates of the transverse mode coupling instability as a function of the bunch intensity given by PyHEADTAIL and GALACTIC (black dots). Observe that GALACTIC gives the growth rates of several unstable modes.

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$$H = \begin{bmatrix} -1 & -0.23jx \\ -0.55jx & -0.92x \end{bmatrix}$$

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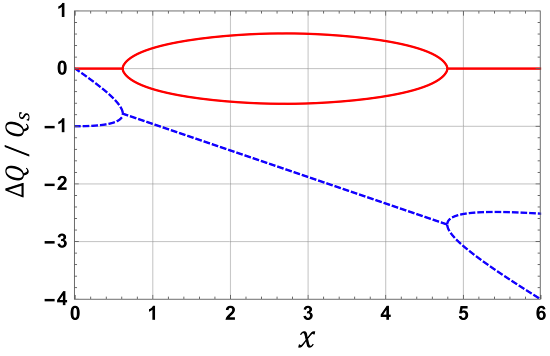

FIG. 4. Eigenvalues of the matrix of Eq. (5) with x a normalized parameter proportional to the bunch intensity [19]: real part in blue (dashed line) and imaginary part in red (full line).

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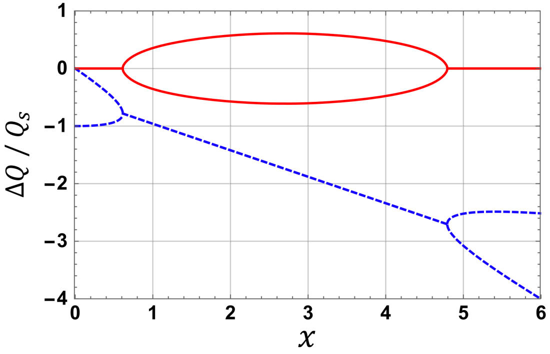

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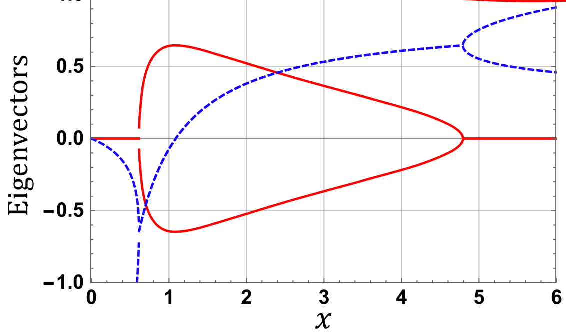

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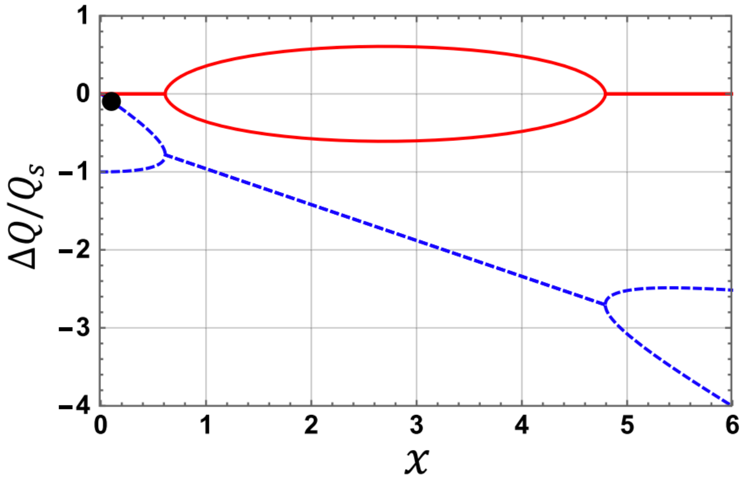
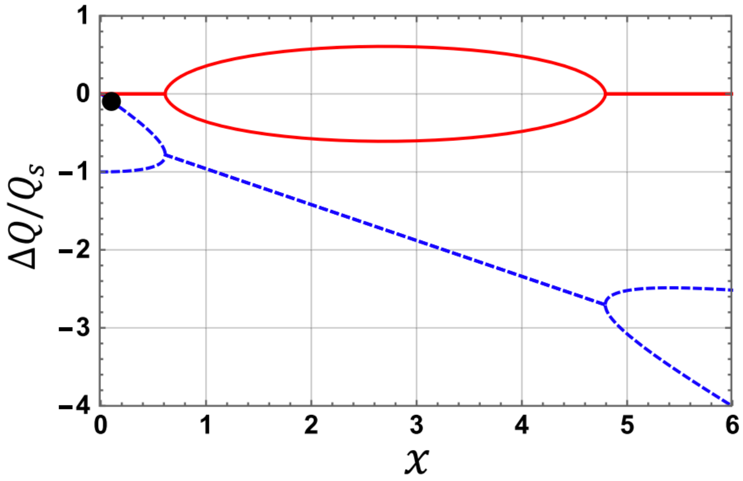
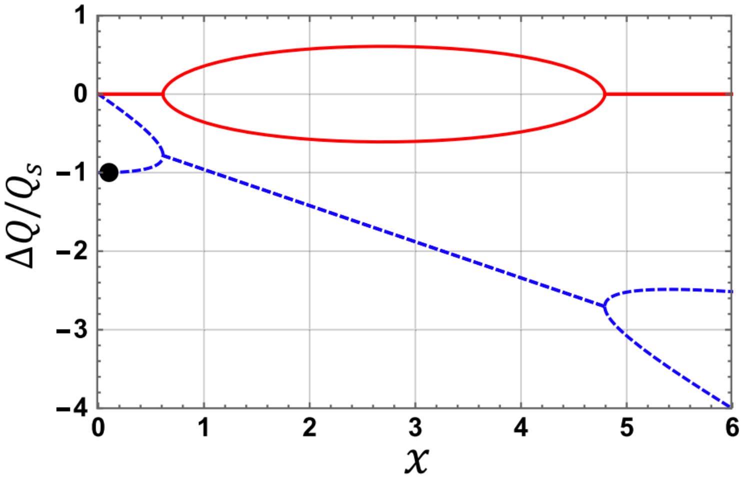


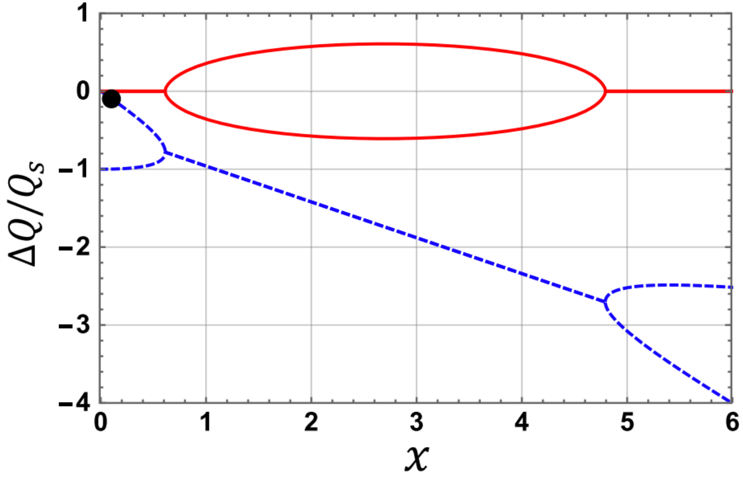
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
$\Delta Q/Q_s$
x

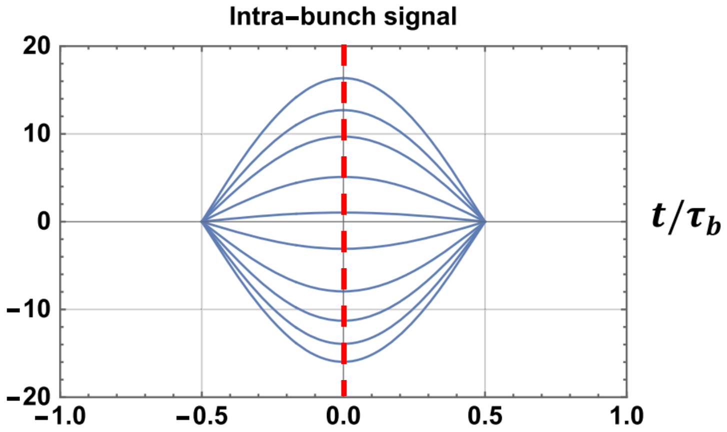


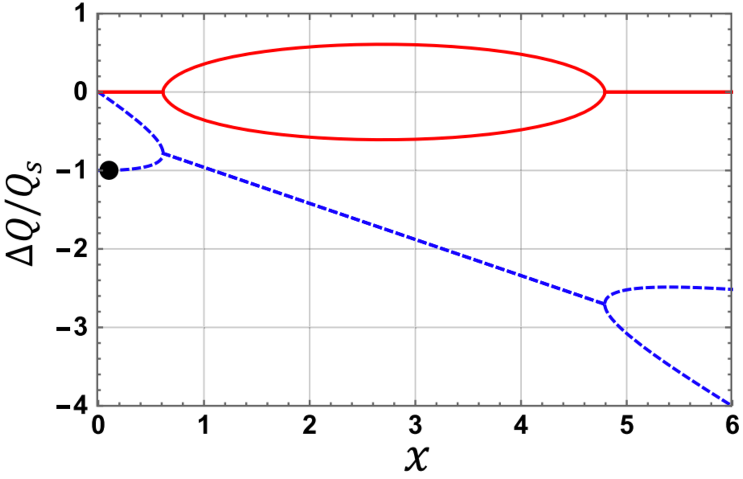
ΔQ/Q_s
x
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6

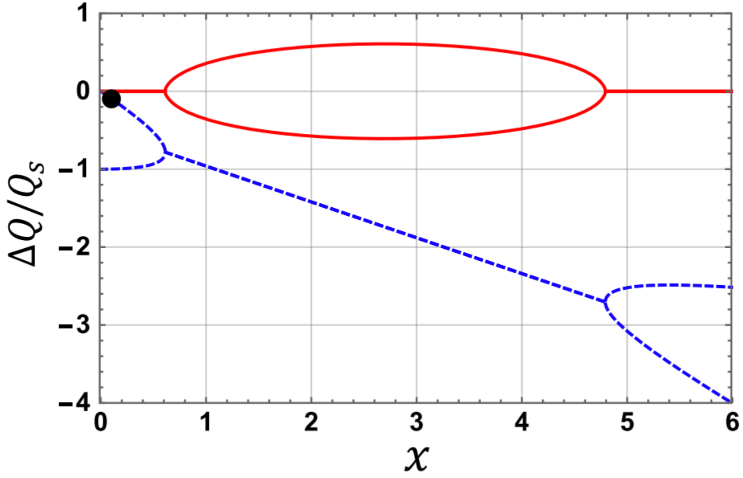


ΔQ/Q_s
x
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6

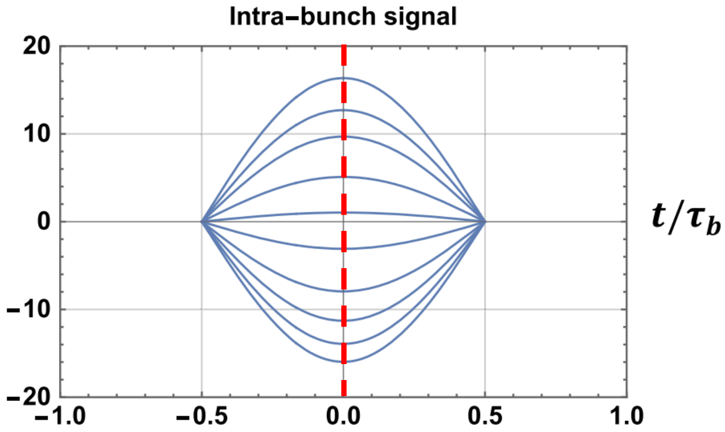

1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
$\Delta Q/Q_s$
x


Intra–bunch signal
20
10
0
−10
−20
−1.0
−0.5
0.0
0.5
1.0
t/τ_b

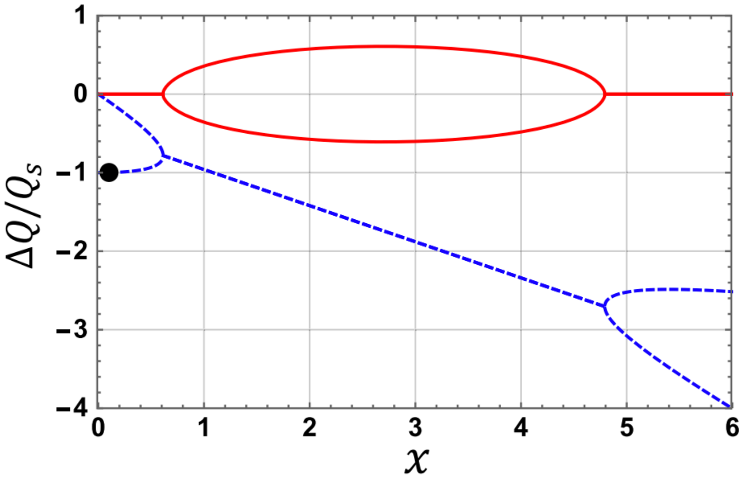

1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
$\Delta Q/Q_s$
x



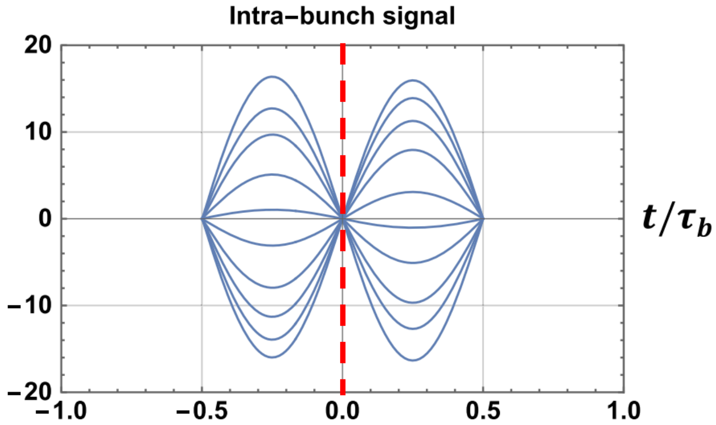
ΔQ/Qs
x



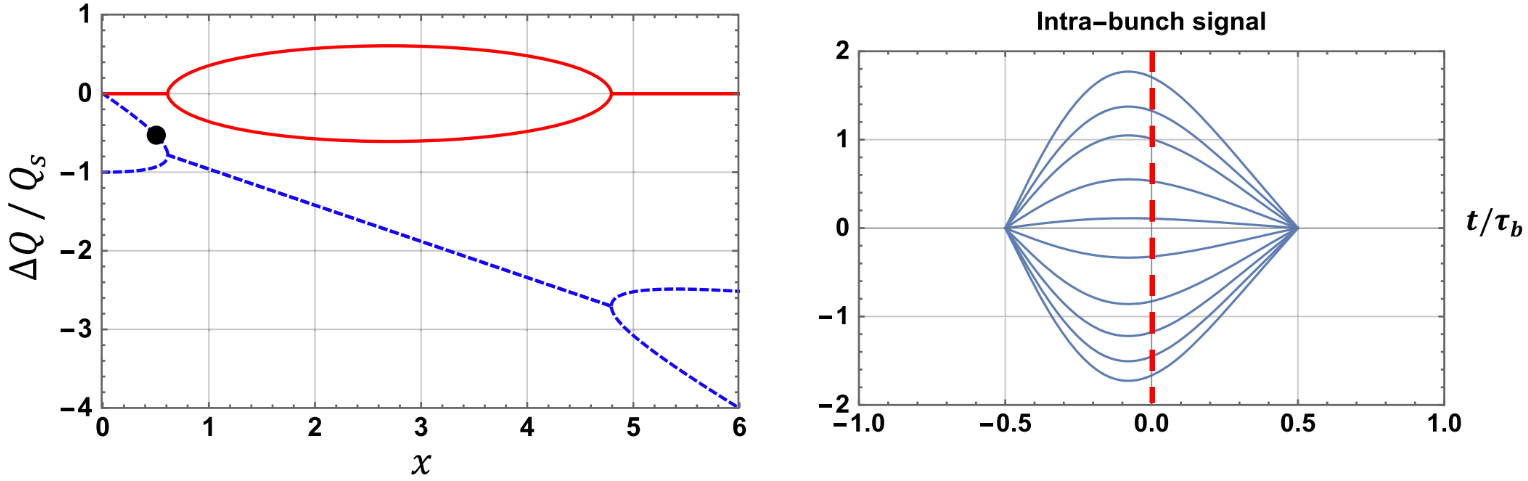
Intra-bunch signal
t/τb



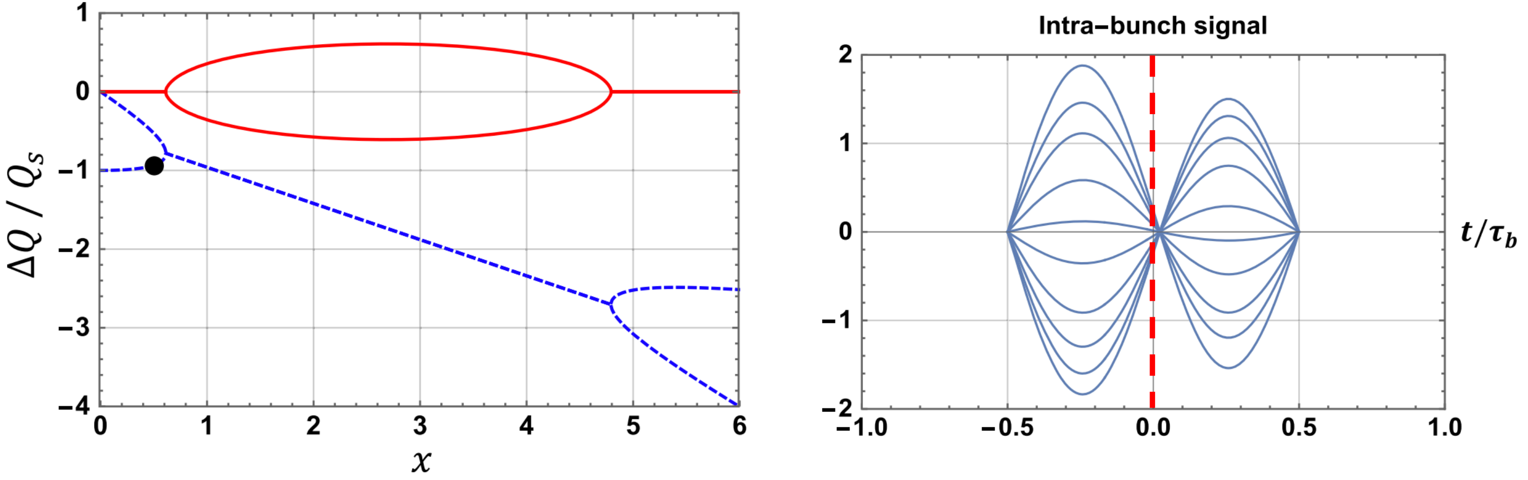
ΔQ/Qs
x



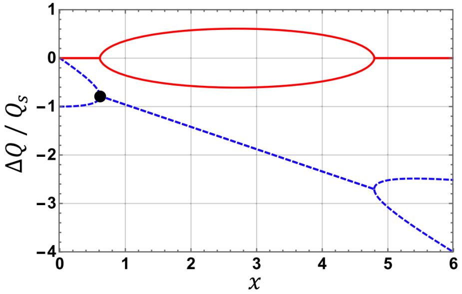
Intra-bunch signal
t/τb



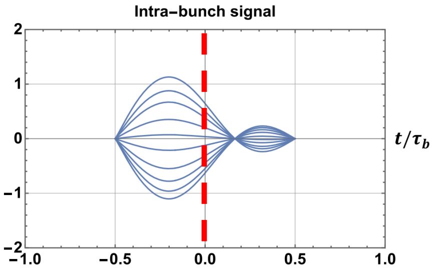
ΔQ / Q_s
x
Intra–bunch signal
t/τ_b



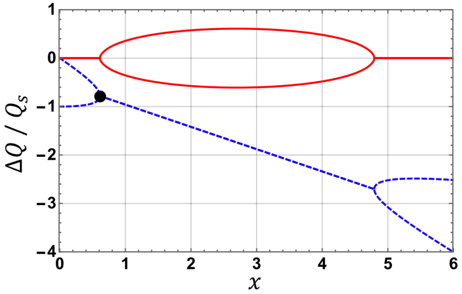
ΔQ / Q_s
x
Intra–bunch signal
t/τ_b



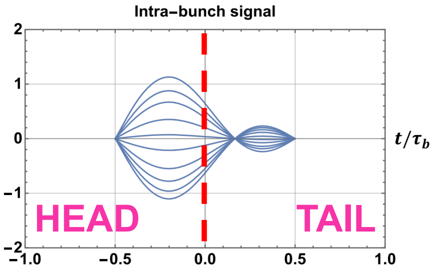
ΔQ / Q_s
x
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6



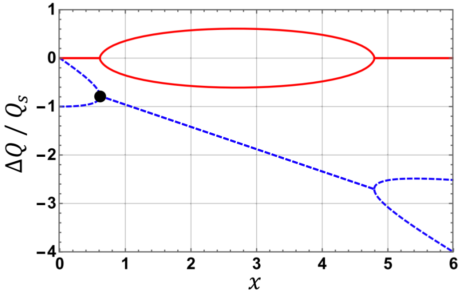
Intra−bunch signal
t/τ_b
2
1
0
−1
−2
−1.0
−0.5
0.0
0.5
1.0



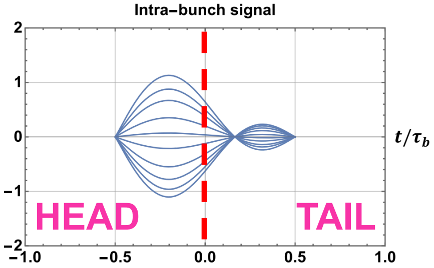
$\Delta Q\ /\ Q_s$
x



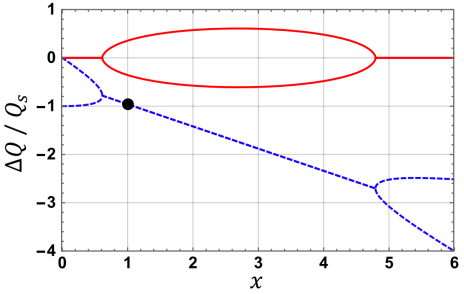
Intra-bunch signal
t/τ_b
HEAD
TAIL



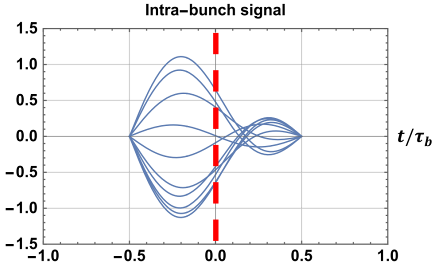
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
ΔQ / Q_s
x



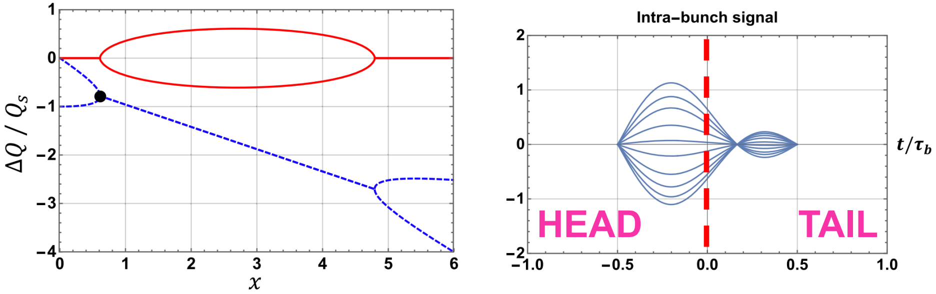
Intra−bunch signal
2
1
0
−1
−2
−1.0
−0.5
0.0
0.5
1.0
t/τ_b
HEAD
TAIL

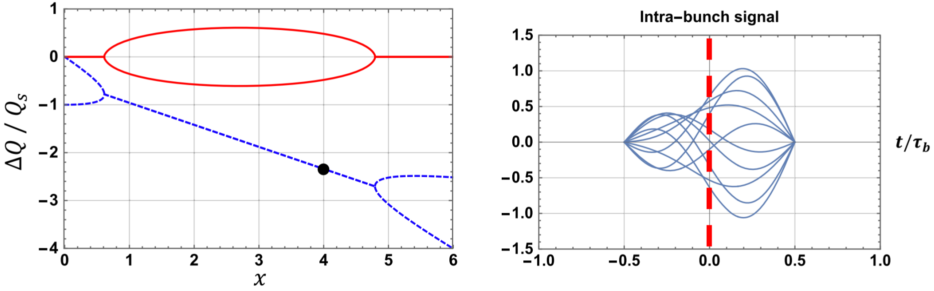


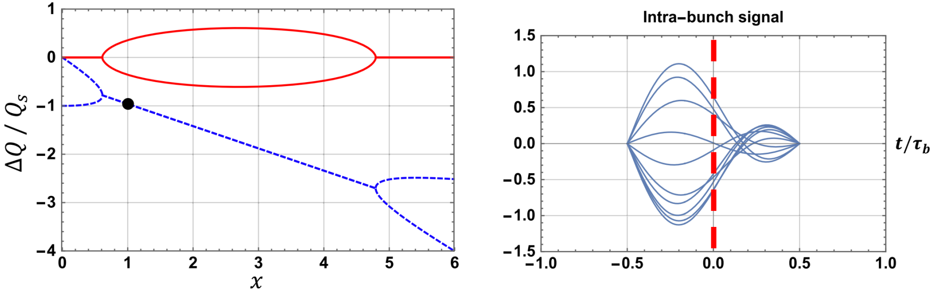
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
ΔQ / Q_s
x

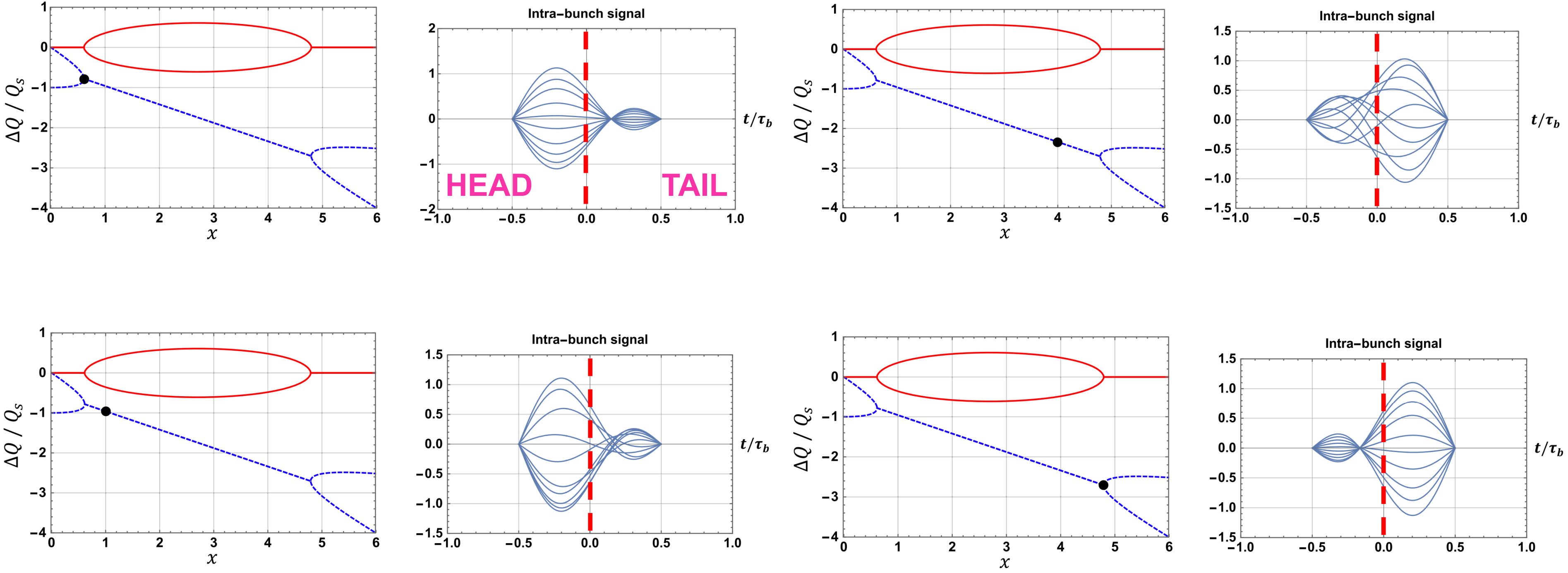


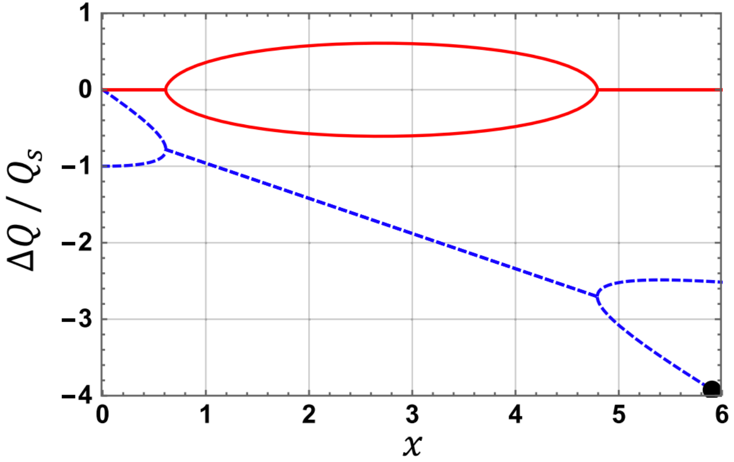
Intra−bunch signal
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
t/τ_b


$\Delta Q \,/\, Q_s$
x
Intra−bunch signal
HEAD
TAIL
t/τ_b

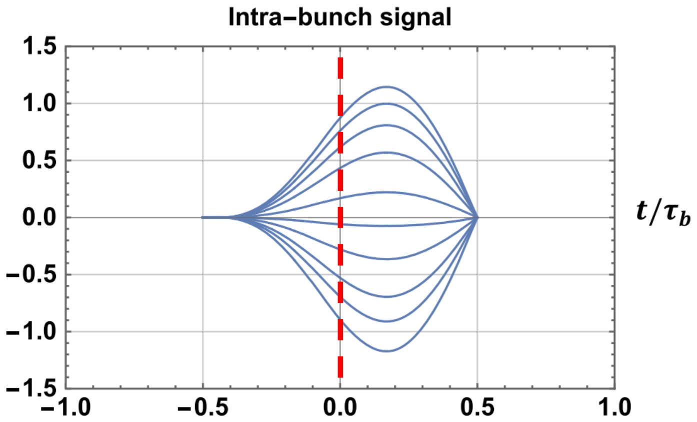

$\Delta Q \,/\, Q_s$
x
Intra−bunch signal
t/τ_b


$\Delta Q \,/\, Q_s$
x
Intra−bunch signal
t/τ_b

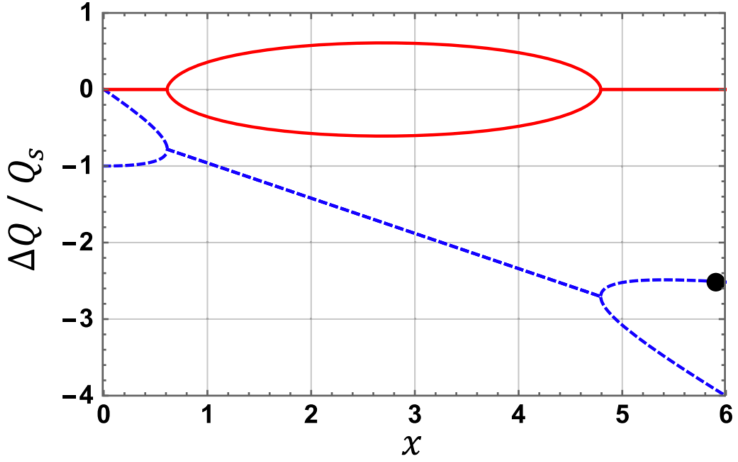

ΔQ / Q_s
x
Intra−bunch signal
HEAD
TAIL
t/τ_b
ΔQ / Q_s
x
Intra−bunch signal
t/τ_b
ΔQ / Q_s
x
Intra−bunch signal
t/τ_b
ΔQ / Q_s
x
Intra−bunch signal
t/τ_b



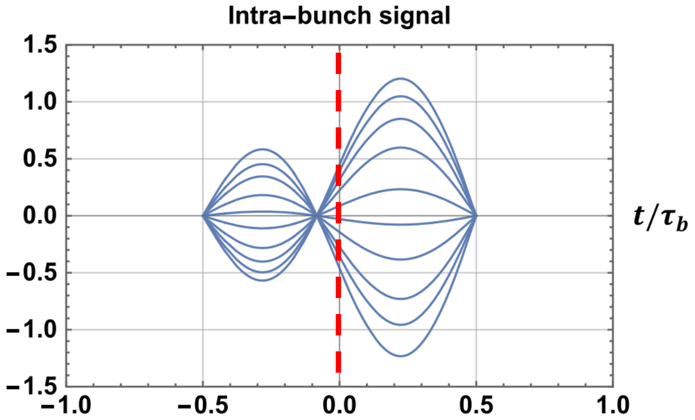
1
0
−1
−2
−3
−4
0 1 2 3 4 5 6
x
$\Delta Q\ /\ Q_s$



Intra−bunch signal
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0 −0.5 0.0 0.5 1.0
t/τ_b



1
0
−1
−2
−3
−4
0 1 2 3 4 5 6
x
$\Delta Q\ /\ Q_s$



Intra−bunch signal
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0 −0.5 0.0 0.5 1.0
t/τ_b

TMCI with both impedance and beam-beam

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- **CMM** = Circulant Matrix Model

TMCI with both impedance and beam-beam

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  - ★ 1st **introduced in 1993** by V.V. Danilov and E.A. Perevedentsev in "Feedback system for elimination of the transverse mode coupling instability" (https://cds.cern.ch/record/253913/files/CM-P00061155.pdf)

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CERN SL/93-38 (AP)

Feedback System for Elimination of the Transverse Mode Coupling Instability

V.V. Danilov and E.A. Perevedentsev
SL Division, CERN*

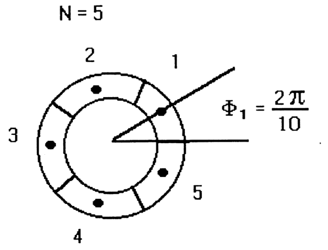


Figure 1: Division of the longitudinal phase space into mesh elements for the hollow beam model. Here $N = 2k + 1 = 5$.

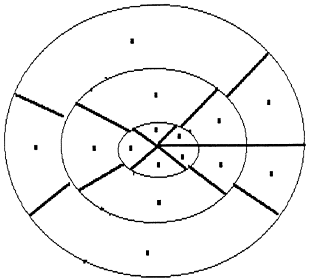


Figure 2: The mesh elements for radial modes.

TMCI with both impedance and beam-beam

★ We start with the study of the centroid motion of each discretized element, or beamlet, in the transverse plane and the goal is to obtain the full one-turn matrix. Then, **the properties of the dynamical system are studied via the eigenvalues (and eigenvectors) of the full one-turn matrix**

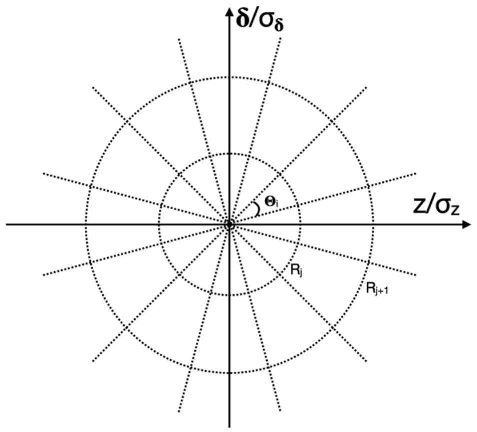


FIG. 2. Illustration of the discretization of the longitudinal phase space in slices and rings within the CMM.

TMCI with both impedance and beam-beam

- ★ We start with the study of the centroid motion of each discretized element, or beamlet, in the transverse plane and the goal is to obtain the full one-turn matrix. Then, **the properties of the dynamical system are studied via the eigenvalues (and eigenvectors) of the full one-turn matrix**
- ★ **CMM is very versatile** and can be used with impedance (driving and detuning), transverse feedback, beam-beam, second-order chromaticity, space charge, etc.

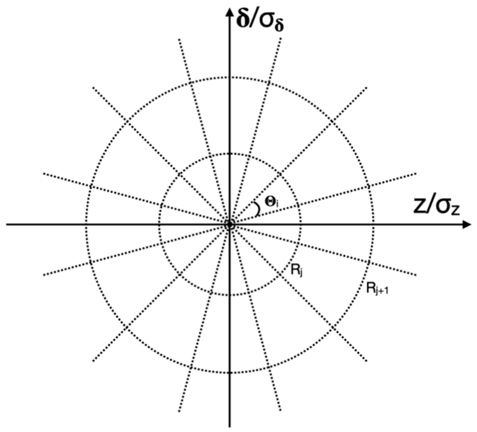
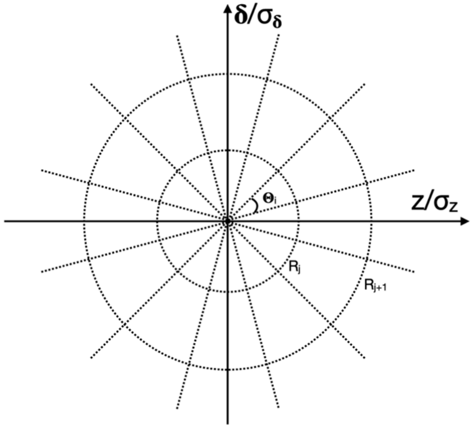


FIG. 2. Illustration of the discretization of the longitudinal phase space in slices and rings within the CMM.

TMCI with both impedance and beam-beam

- ★ We start with the study of the centroid motion of each discretized element, or beamlet, in the transverse plane and the goal is to obtain the full one-turn matrix. Then, **the properties of the dynamical system are studied via the eigenvalues (and eigenvectors) of the full one-turn matrix**
- ★ **CMM is very versatile** and can be used with impedance (driving and detuning), transverse feedback, beam-beam, second-order chromaticity, space charge, etc.
- ★ These effects have been implemented in a code called **BIMBIM** started by X. Buffat during his PhD thesis (https://cds.cern.ch/record/1987672/files/CERN-THESIS-2014-246.pdf)



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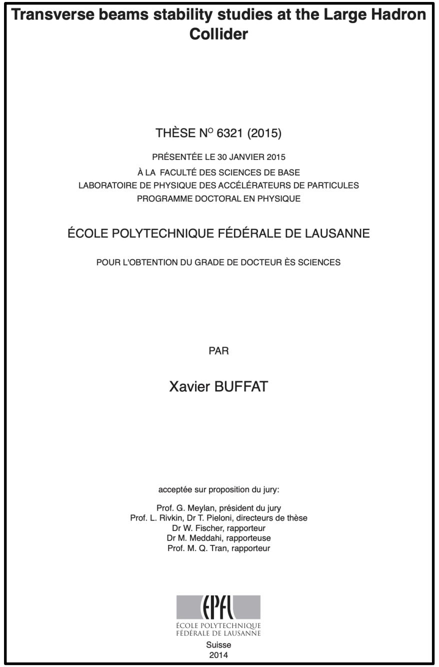


Transverse beams stability studies at the Large Hadron Collider

THÈSE N° 6321 (2015)

PRÉSENTÉE LE 30 JANVIER 2015
À LA FACULTÉ DES SCIENCES DE BASE
LABORATOIRE DE PHYSIQUE DES ACCÉLÉRATEURS DE PARTICULES
PROGRAMME DOCTORAL EN PHYSIQUE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Xavier BUFFAT

acceptée sur proposition du jury:

Prof. G. Meylan, président du jury
Prof. L. Rivkin, Dr T. Pieloni, directeurs de thèse
Dr W. Fischer, rapporteur
Dr M. Meddahi, rapporteuse
Prof. M. Q. Tran, rapporteur

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Suisse
2014

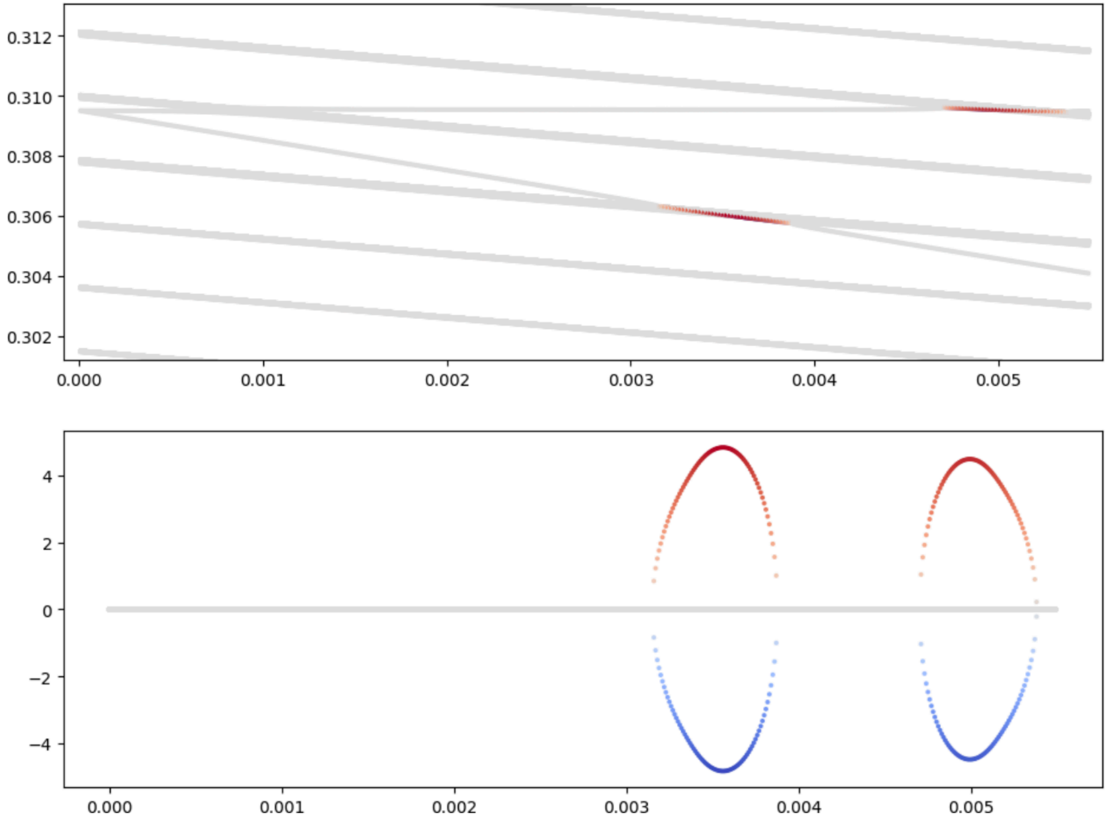
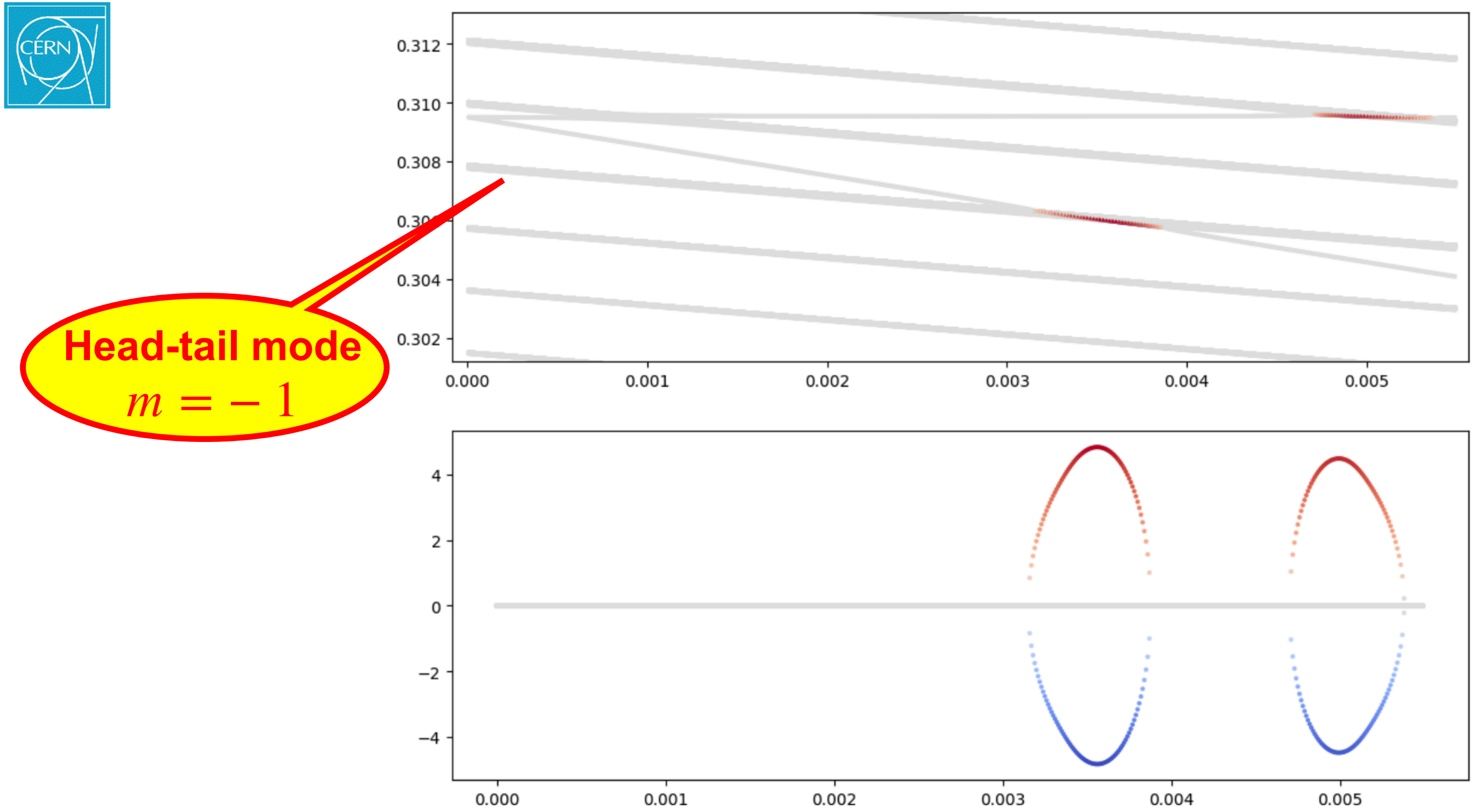


Figure 3: Usual TMCI plots with the real part (top) and imaginary part (bottom) of the eigenvalues as a funtion of the beam-beam parameter, for the case of both impedance and beam-beam.



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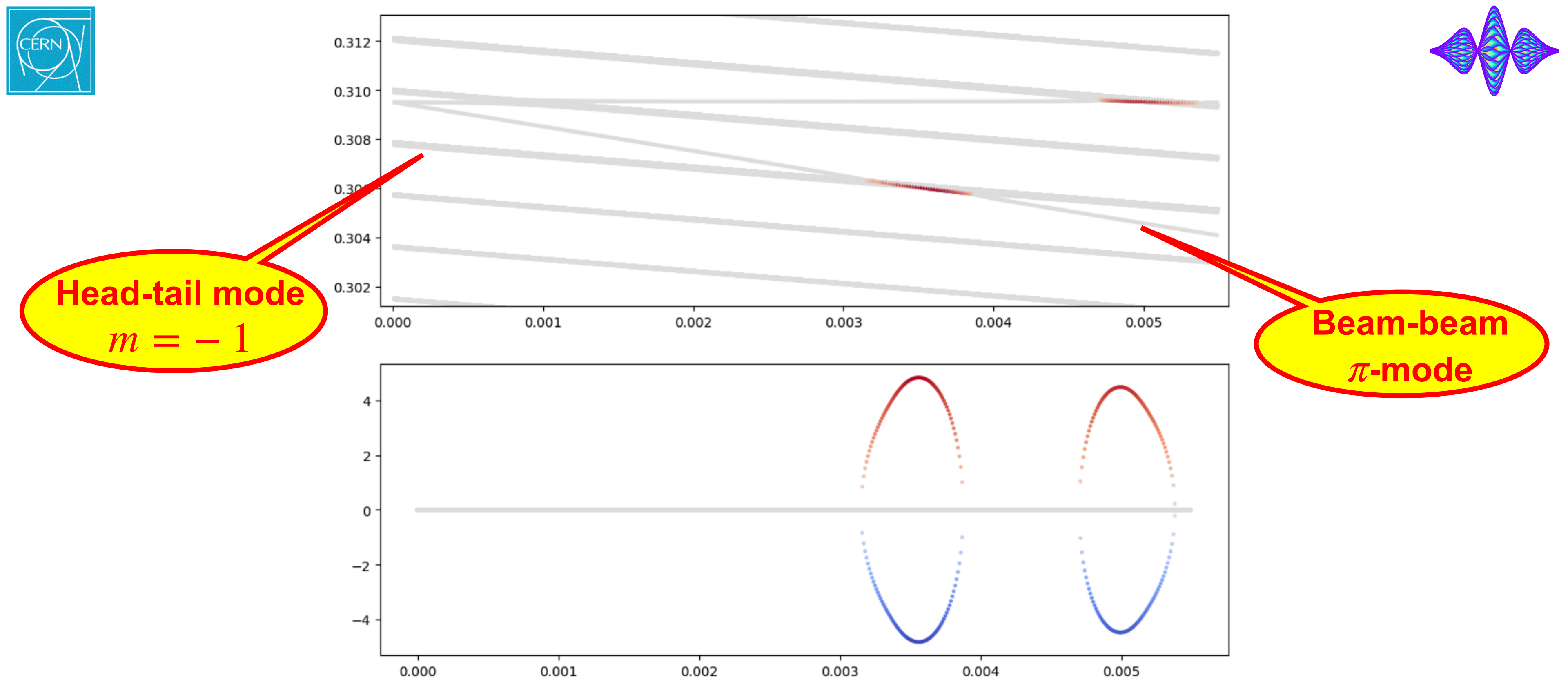

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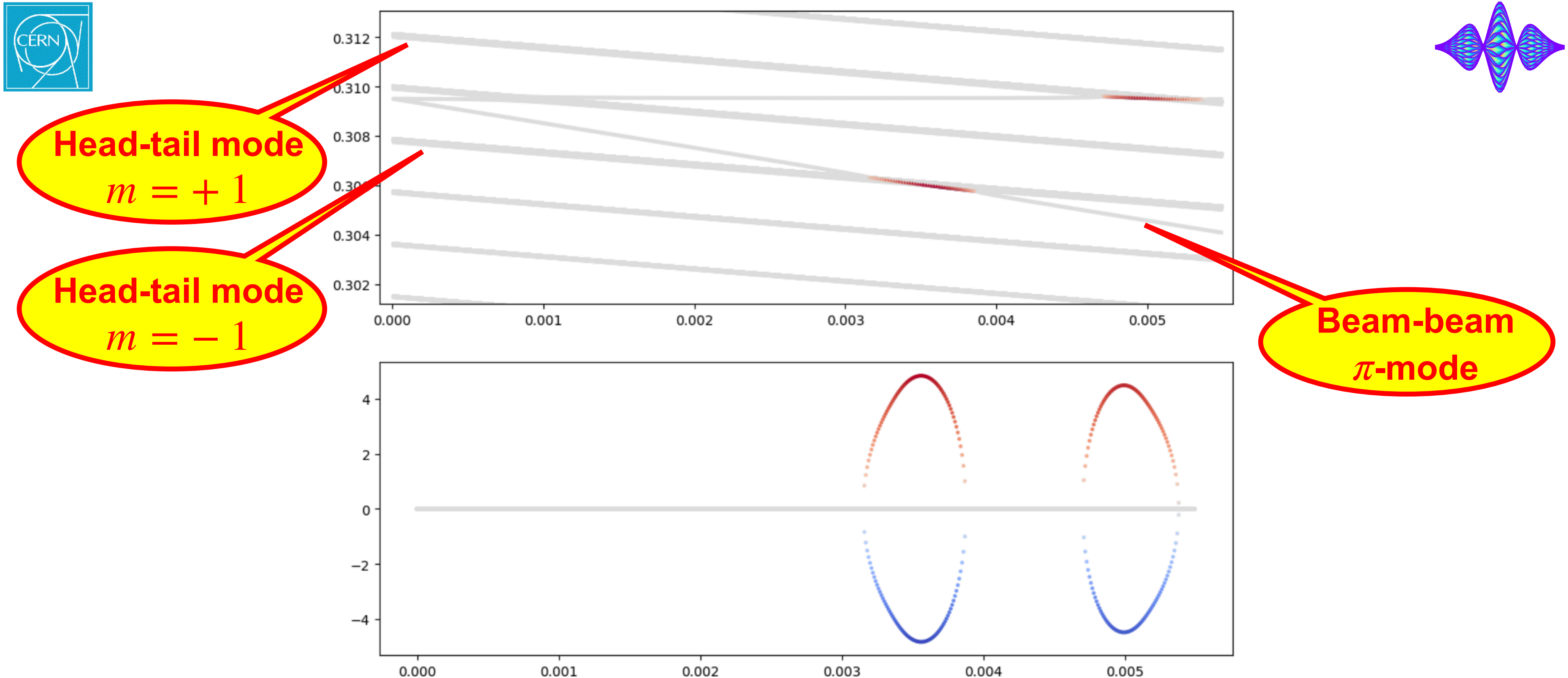

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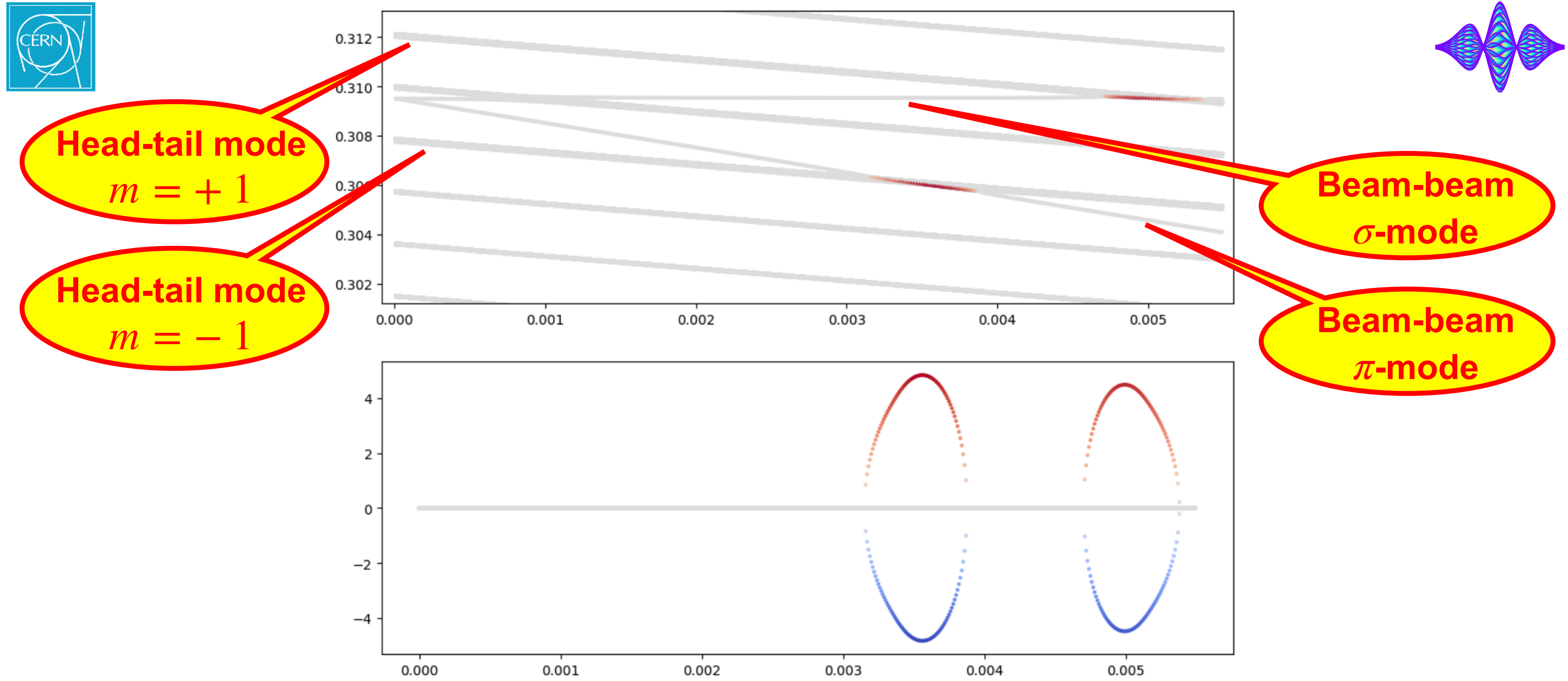

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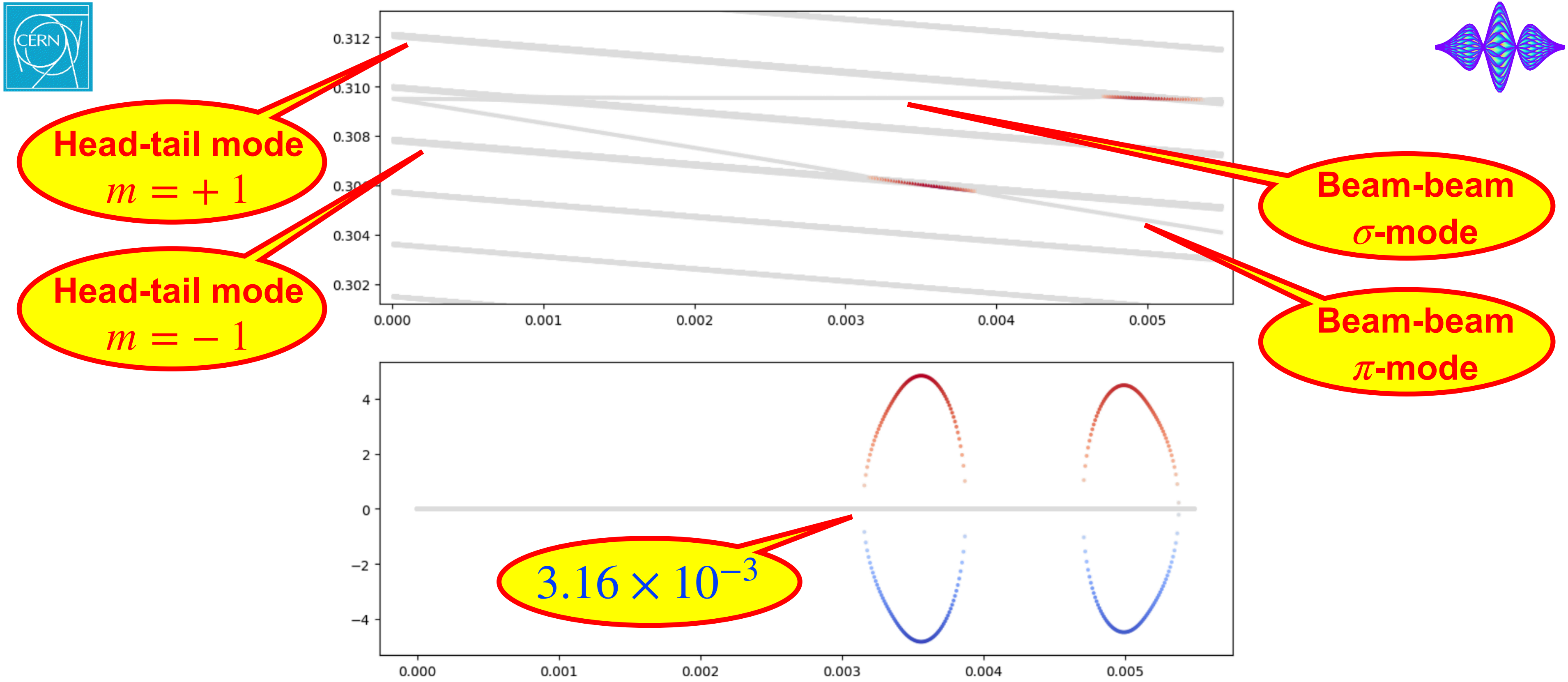

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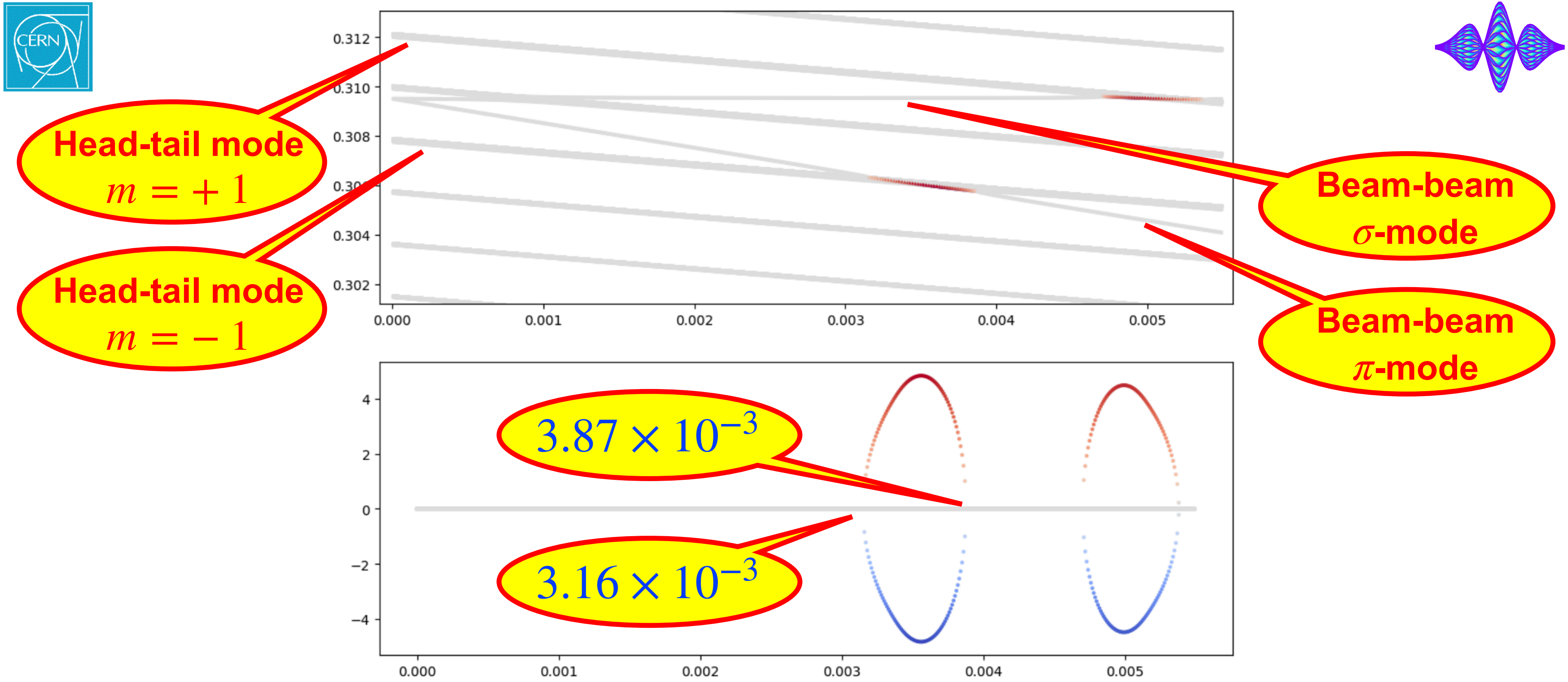

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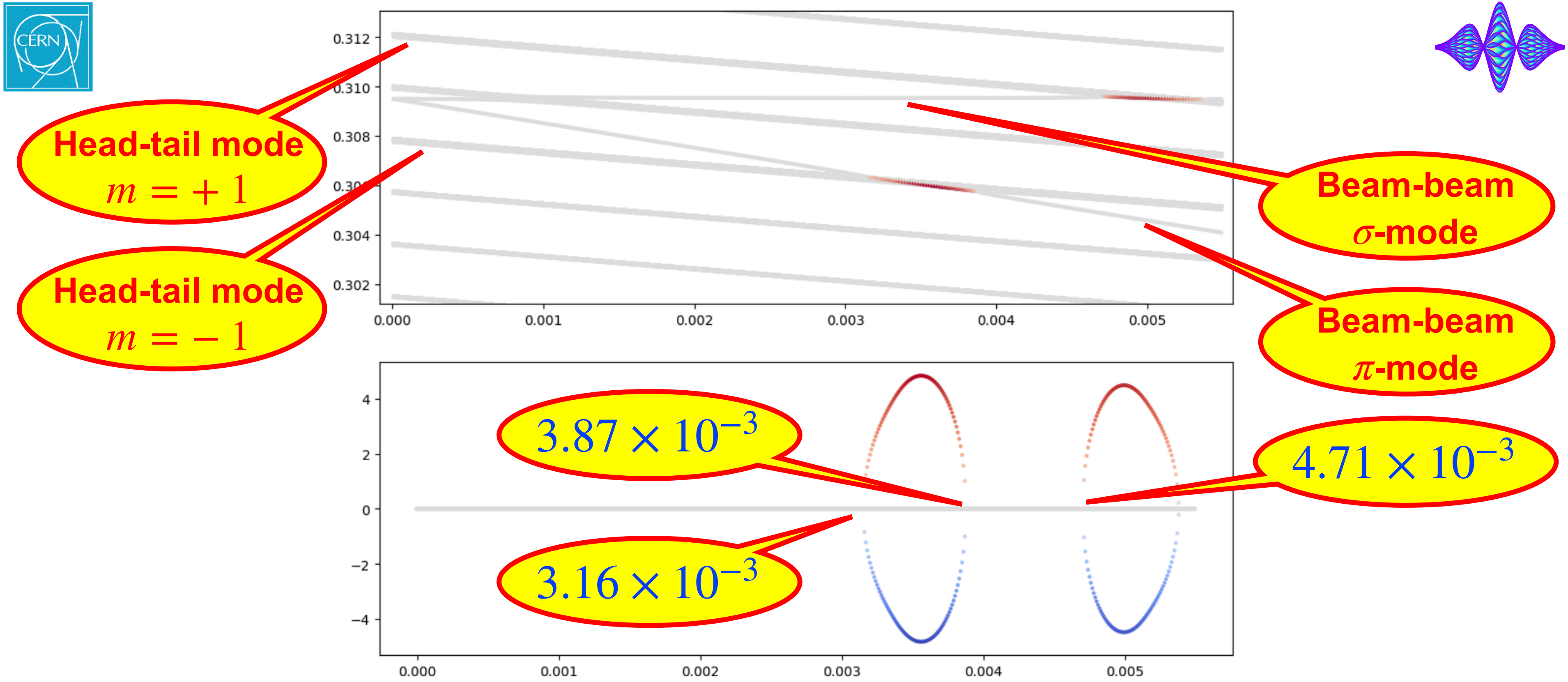

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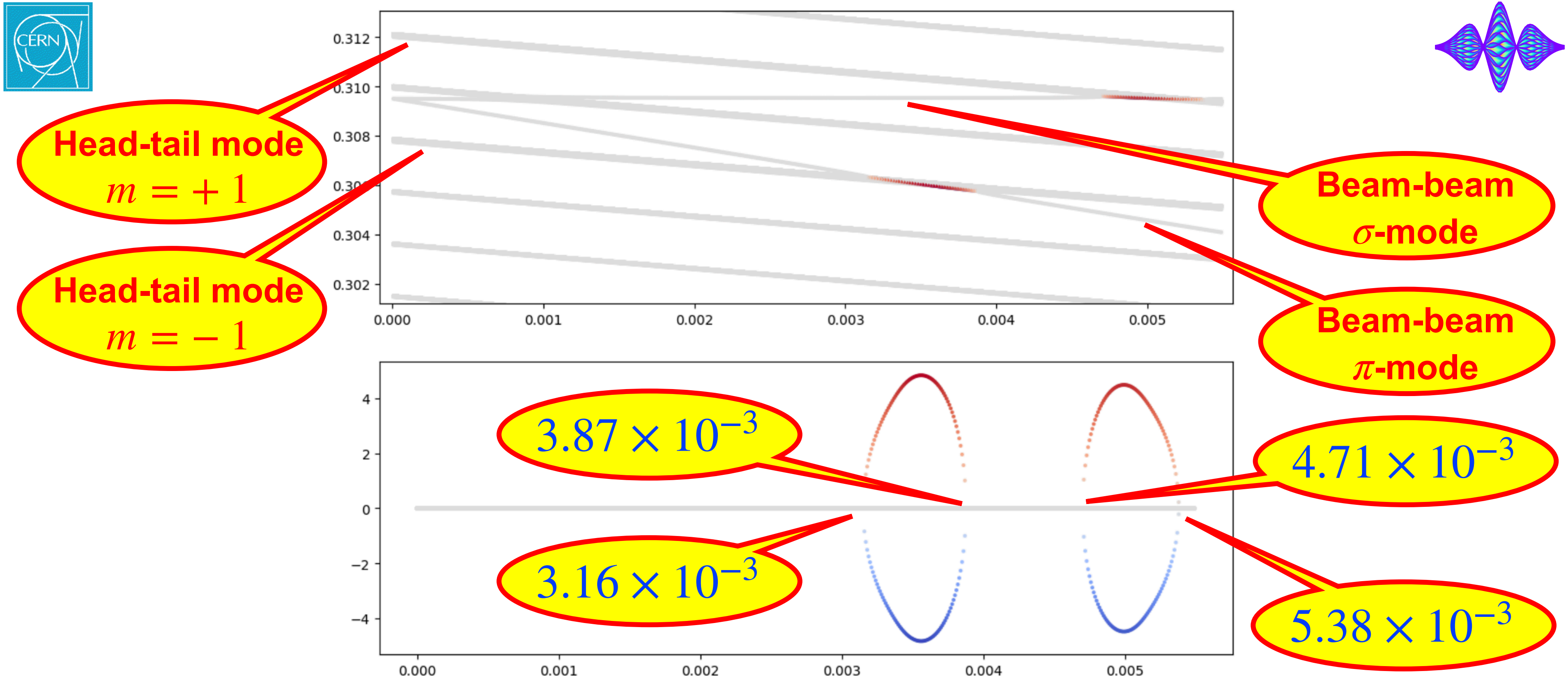

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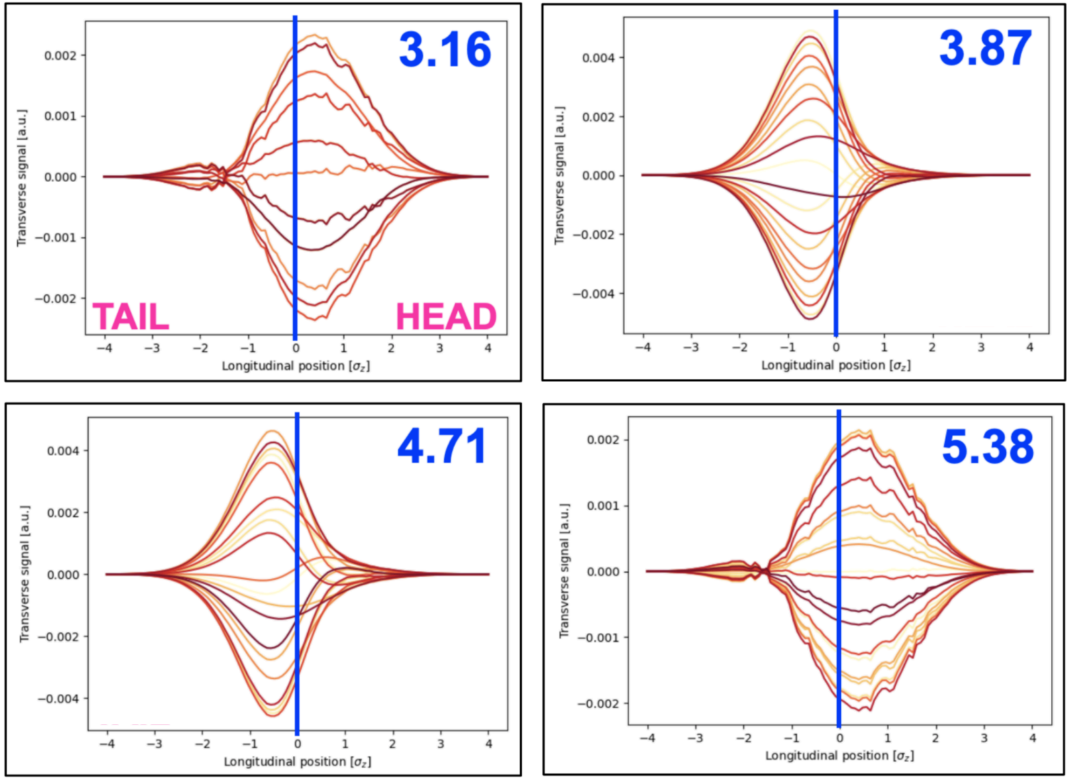
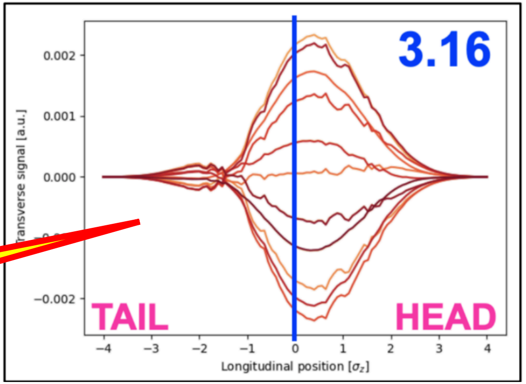
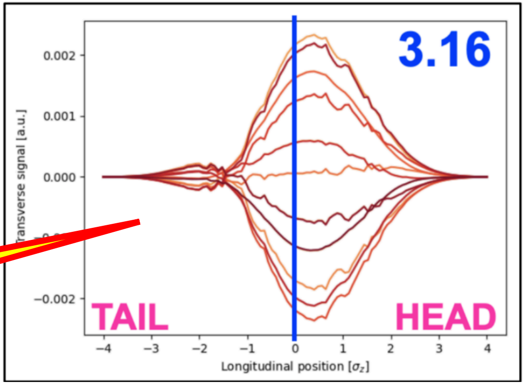


Figure 4: Signals of transverse intrabunch motion, for beam 1, with both impedance and beam-beam for the 4 beam-beam parameters corresponding to the TMCI intensity thresholds of Fig. 3: (top left) 3.16×10^{-3}; (top right) 3.87×10^{-3}; (bottom left) 4.71×10^{-3}; (bottom right) 5.38×10^{-3}.



Very similar to the case with impedance only



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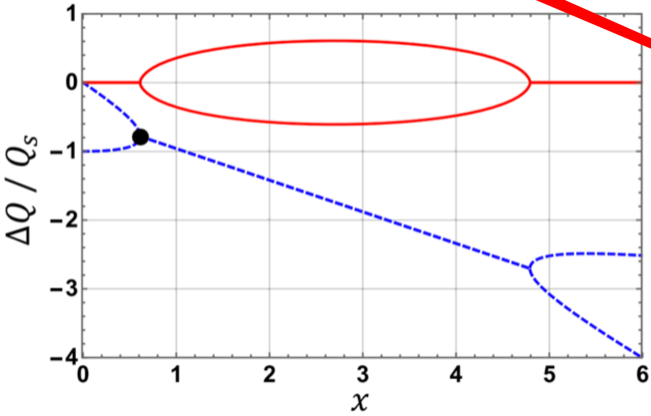

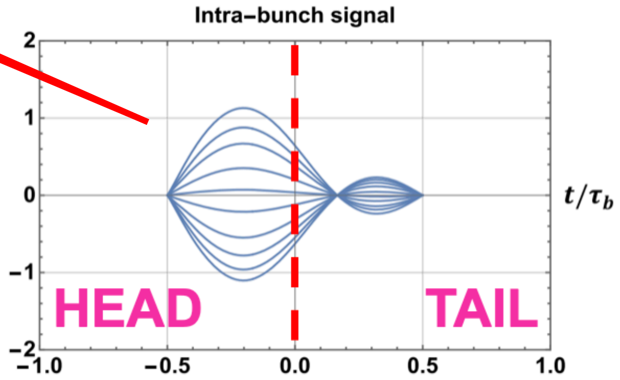

This case can be predicted without maths…

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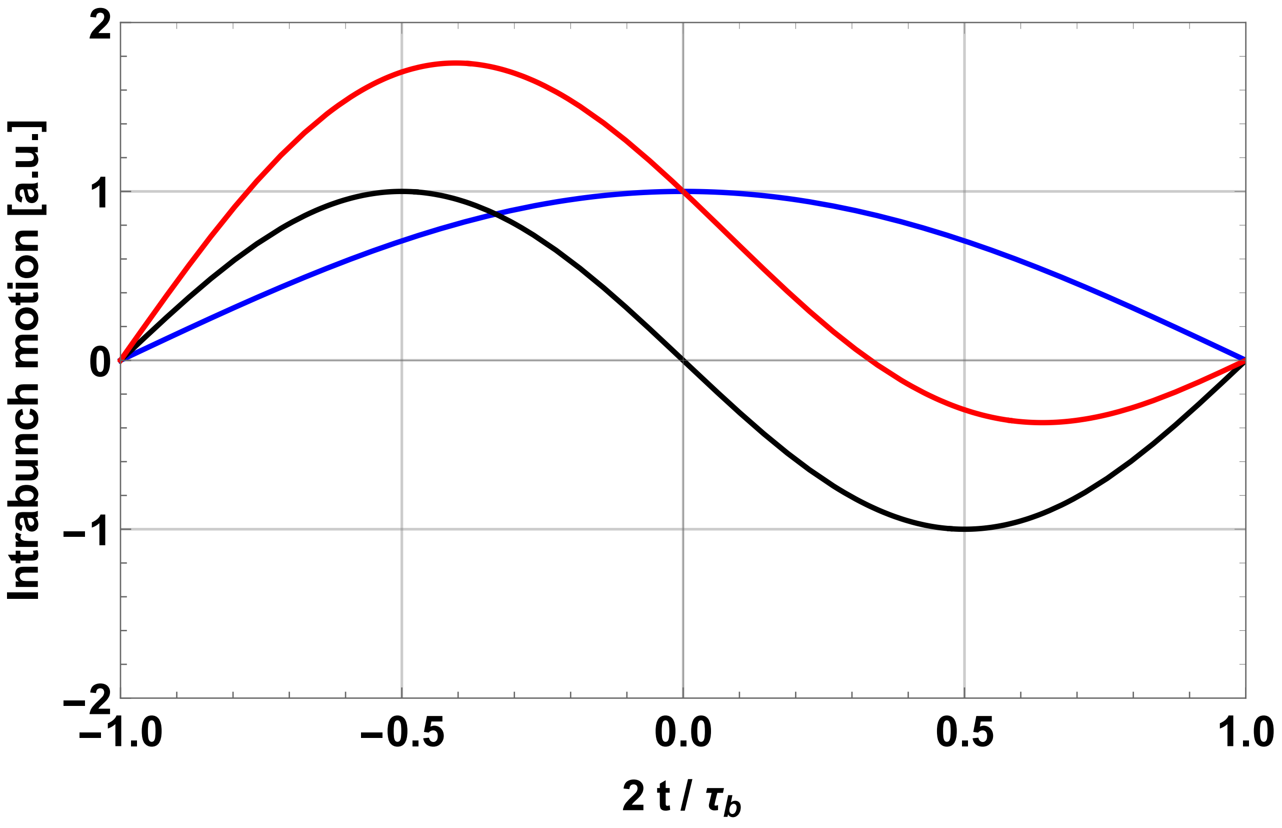
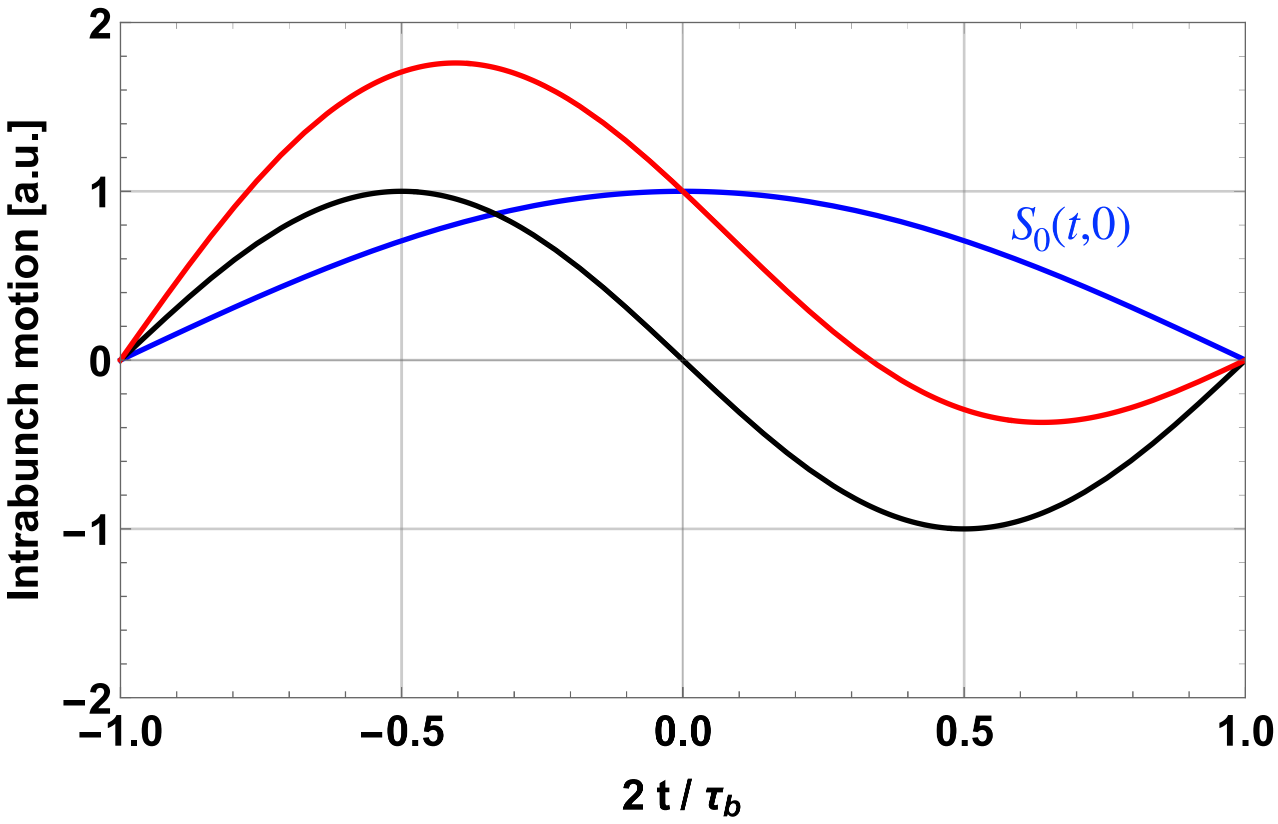


This case can be predicted without maths…



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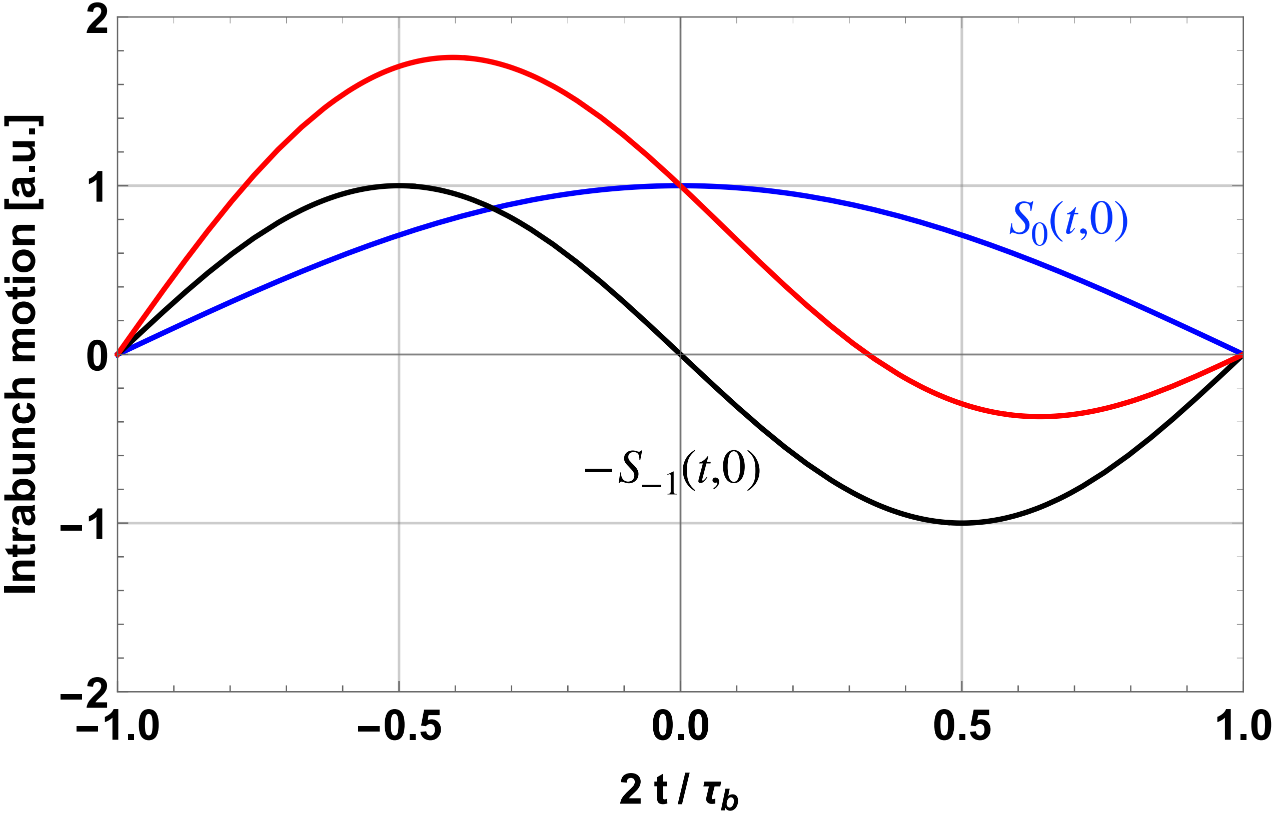
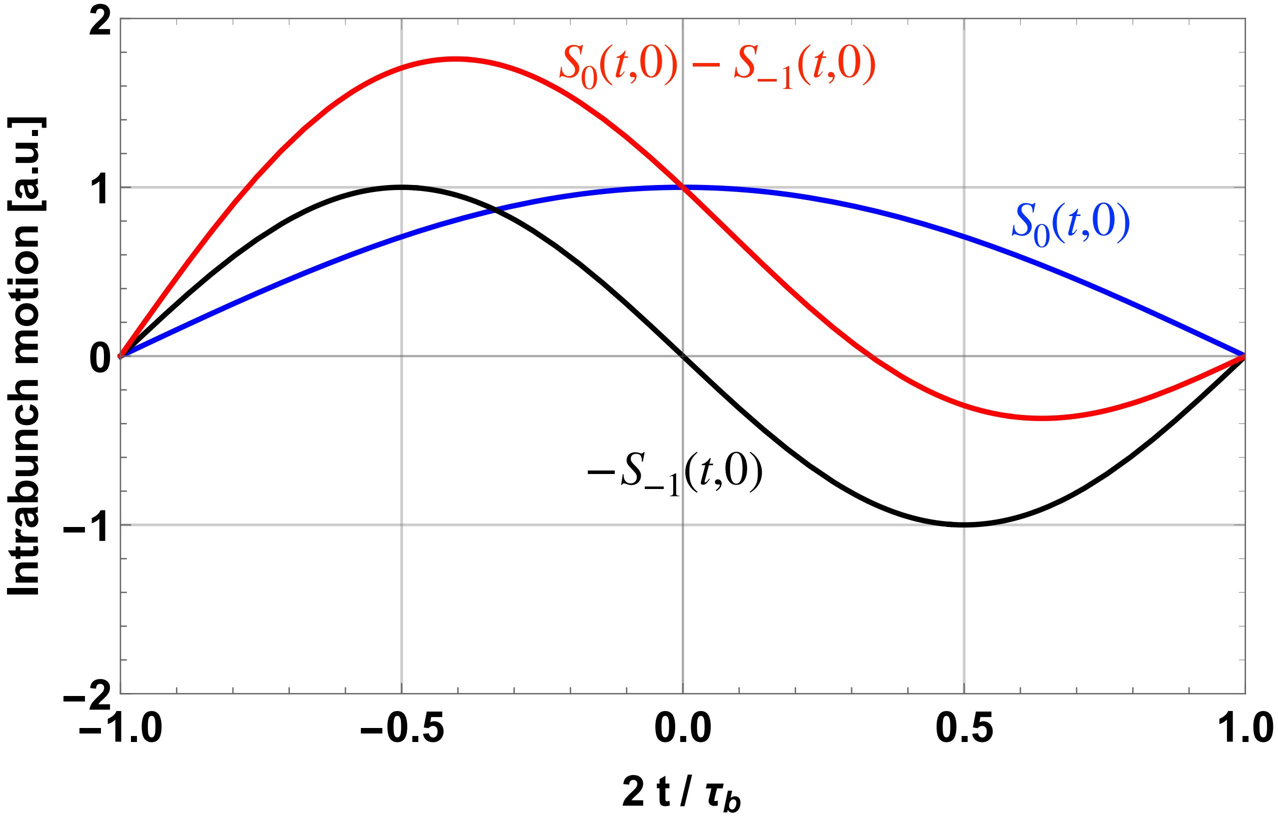
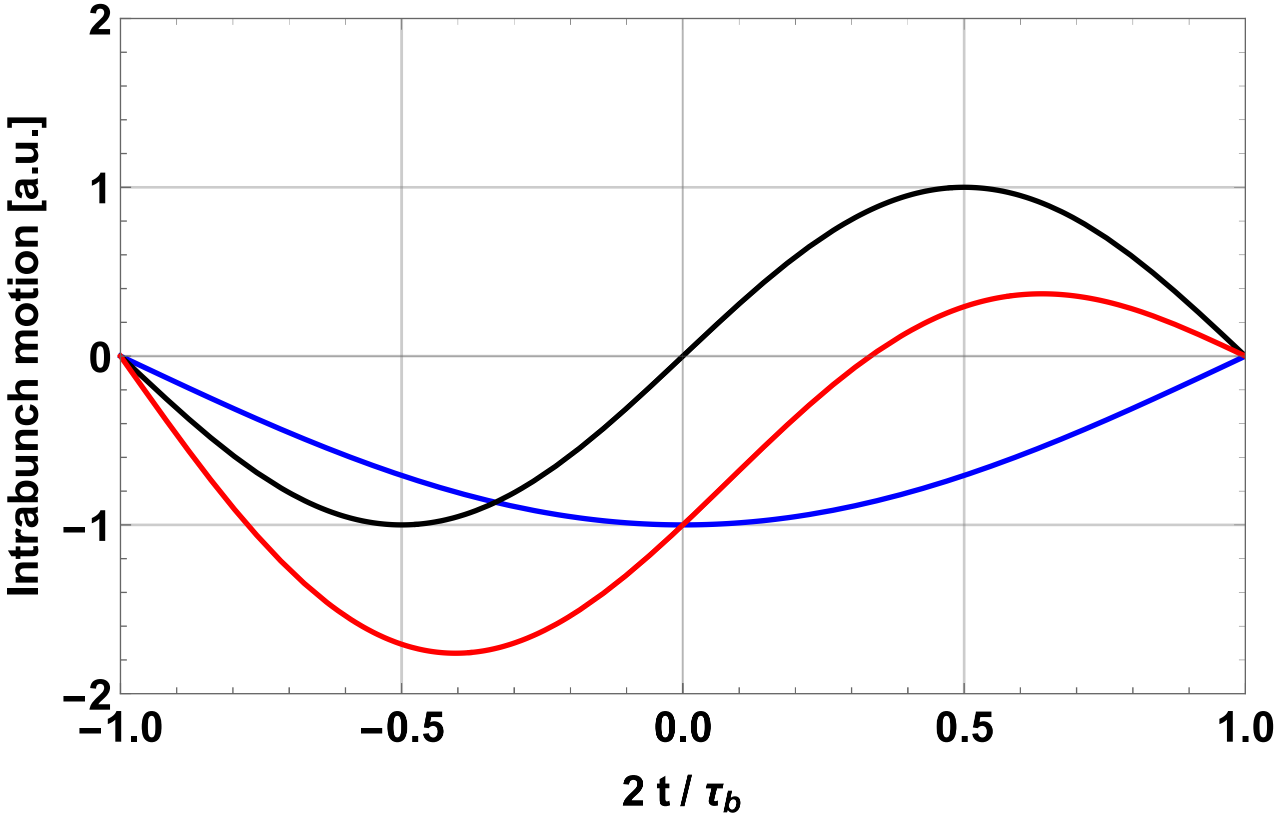


This case can be predicted without maths…



This case can be predicted without maths…



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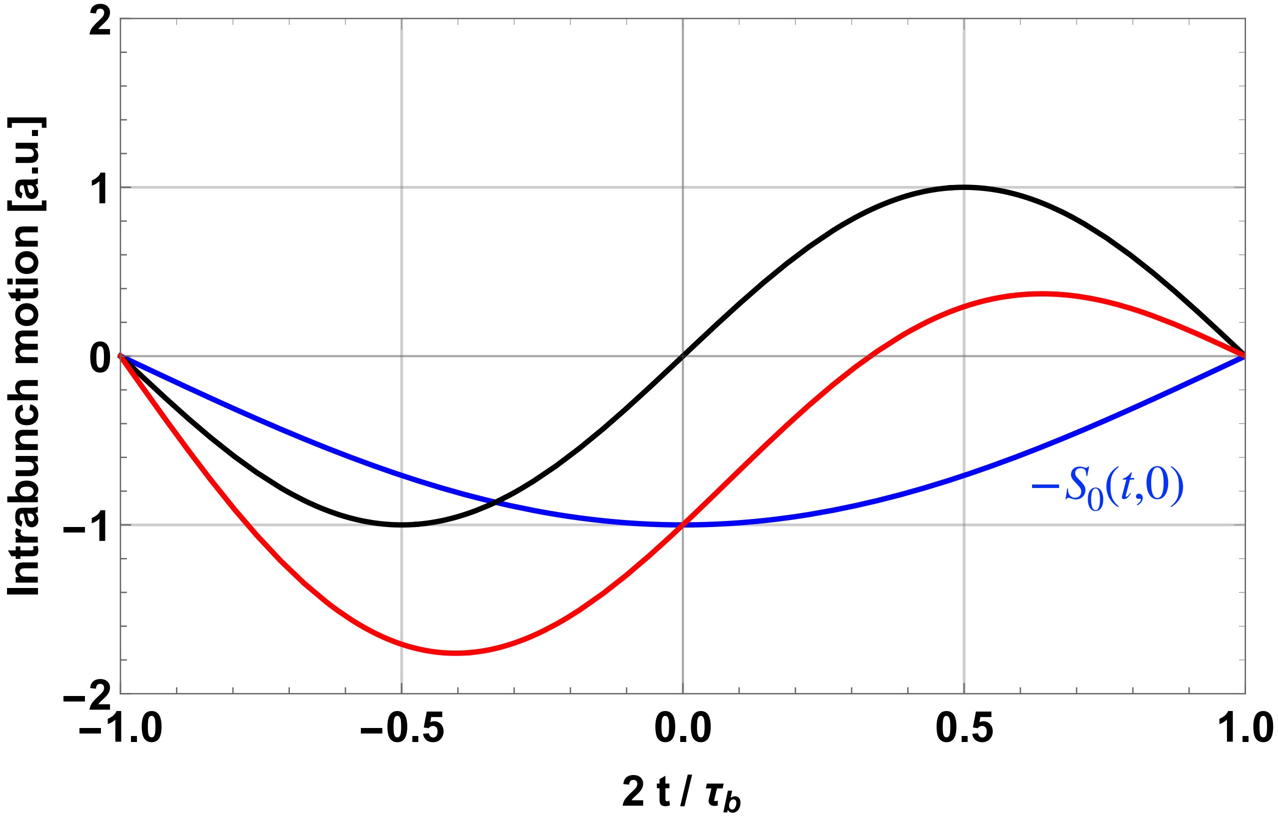

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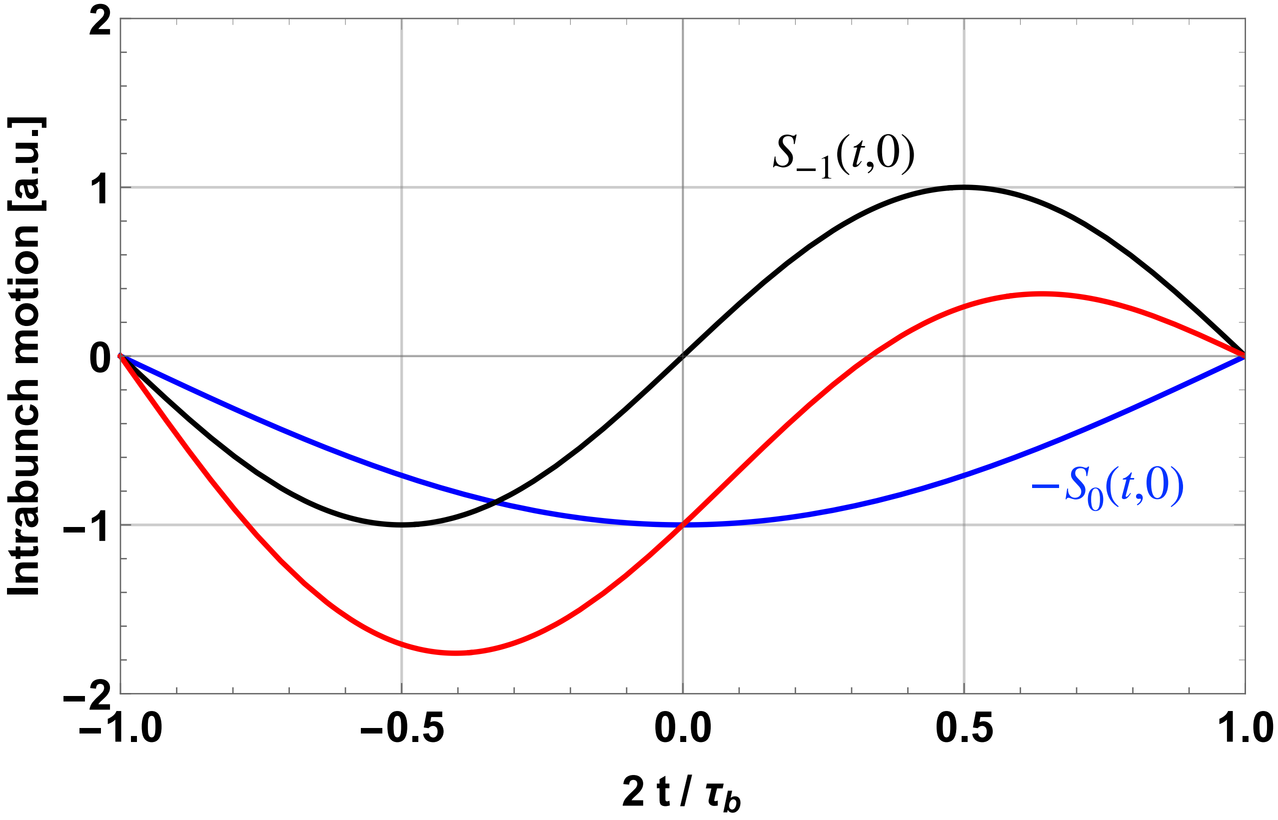

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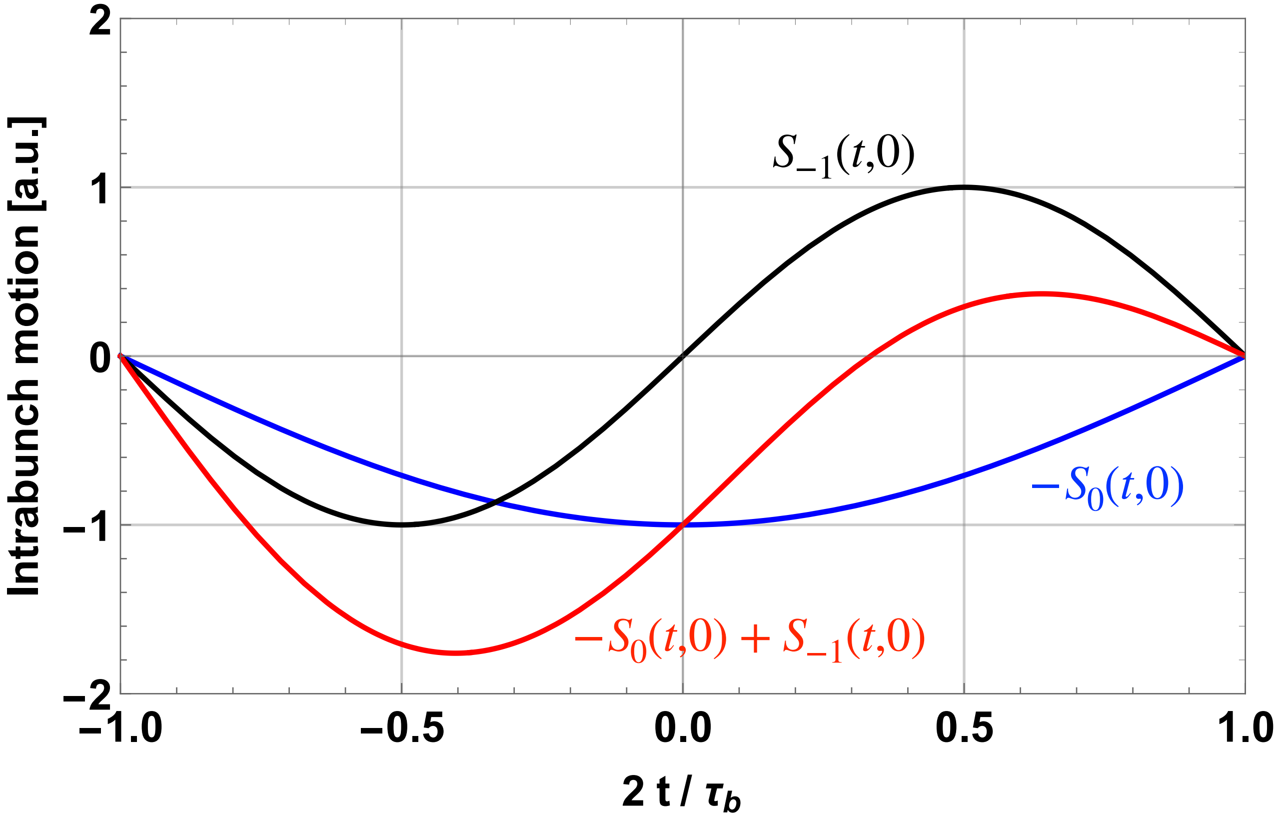

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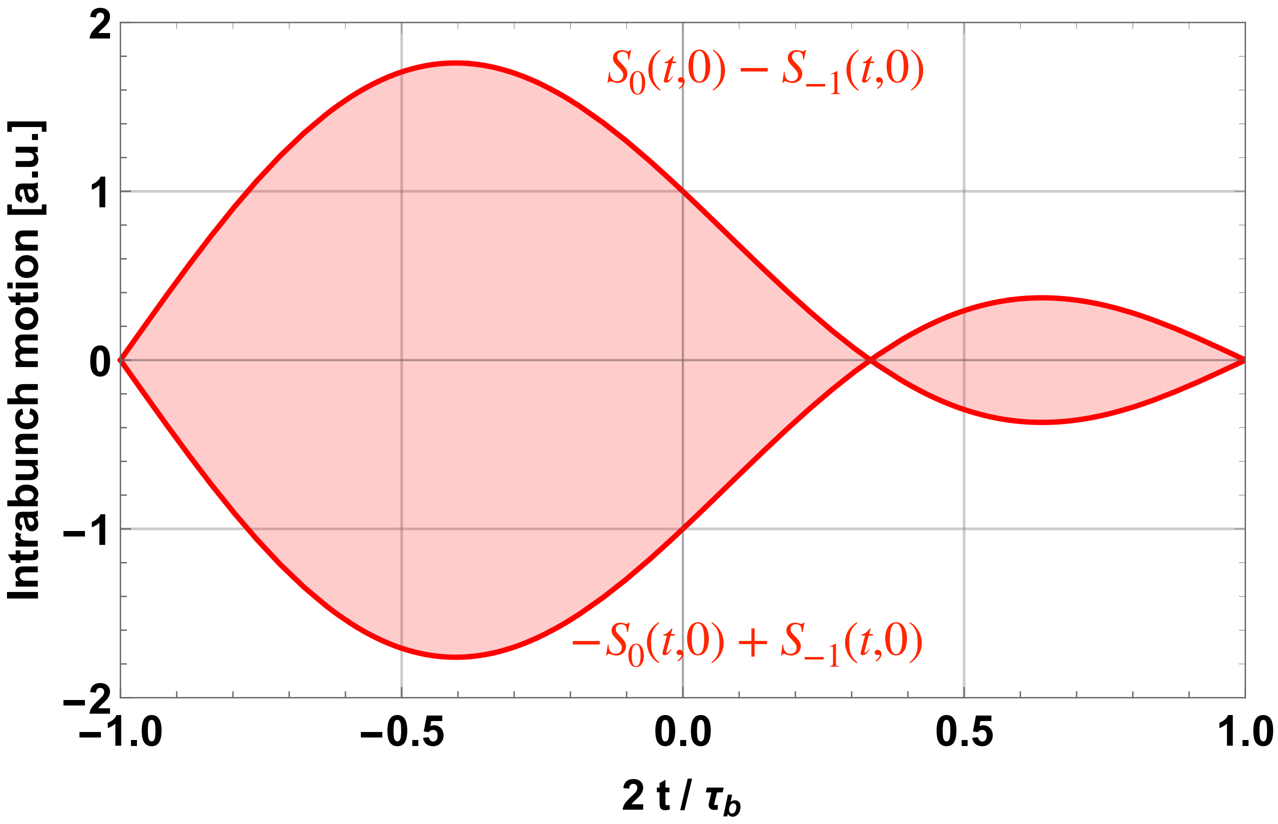

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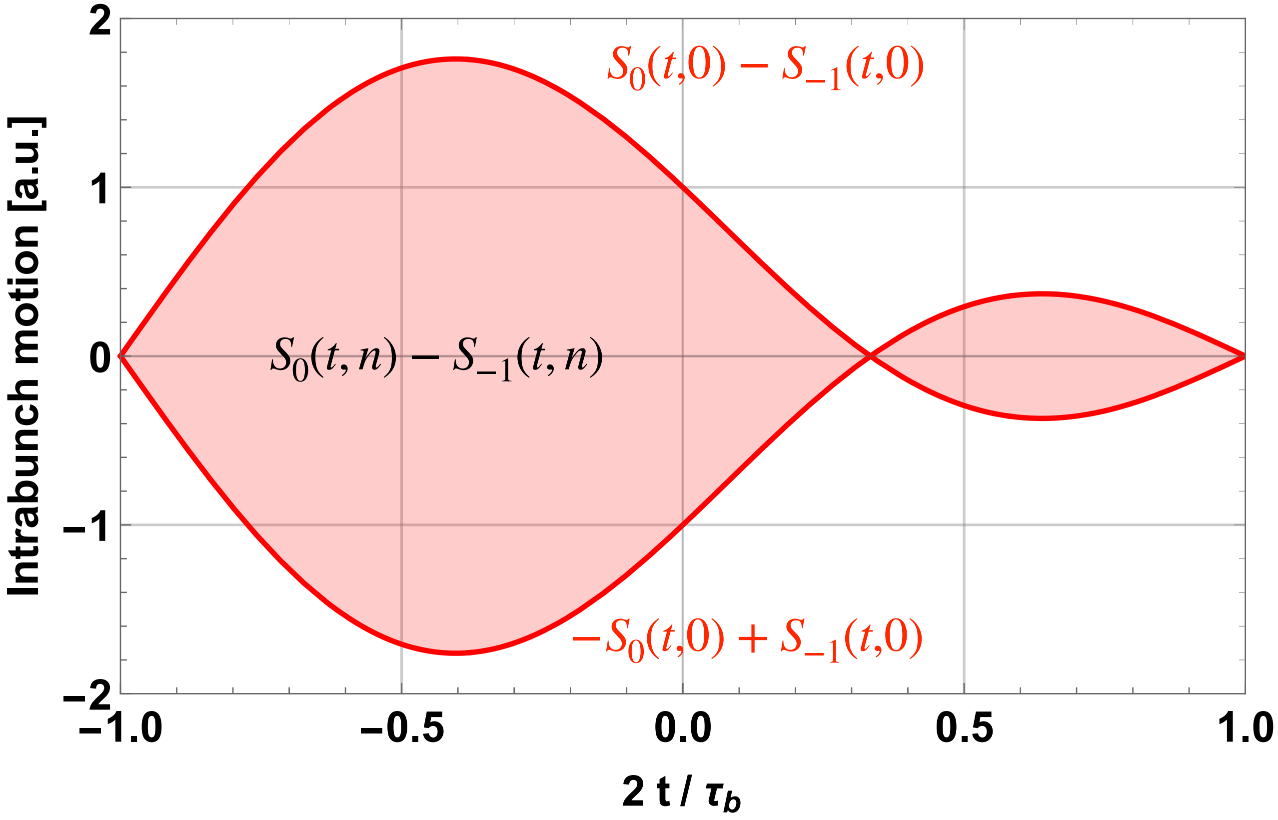

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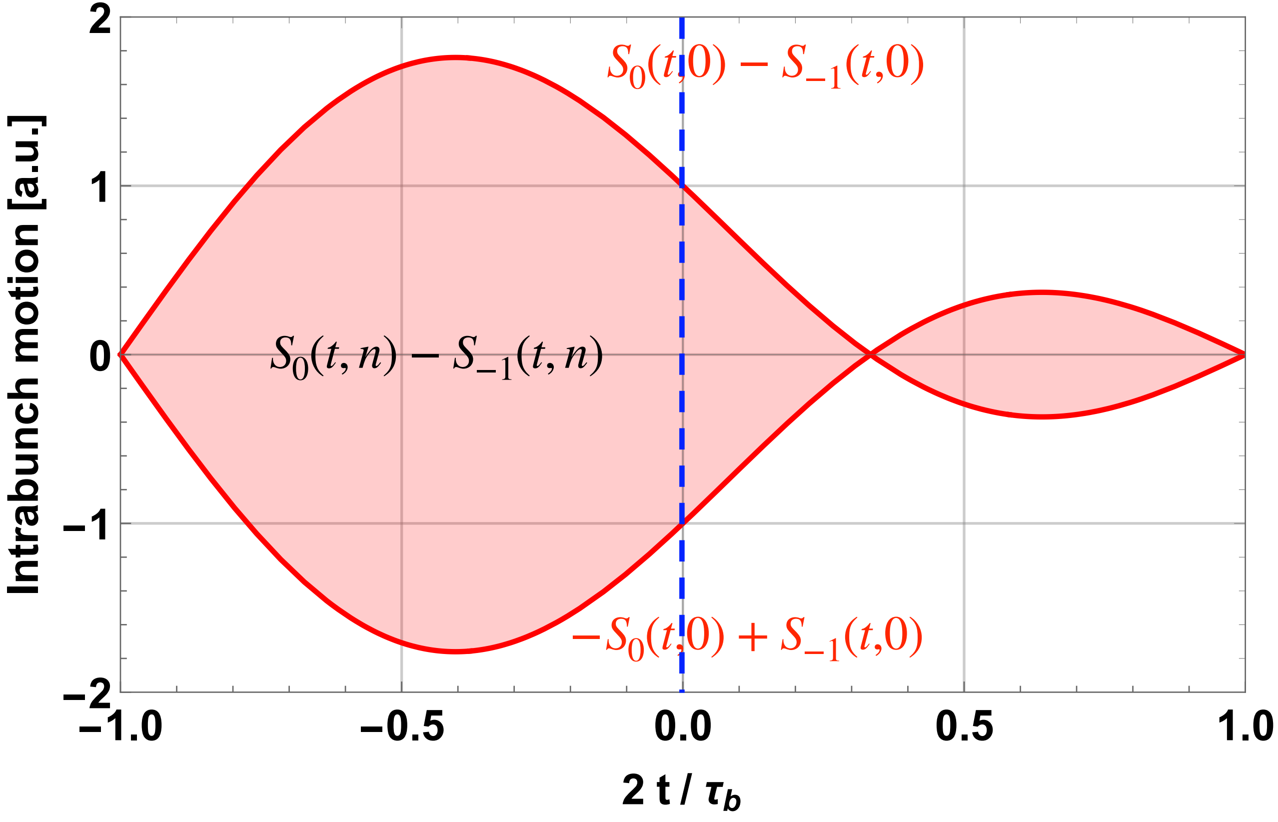

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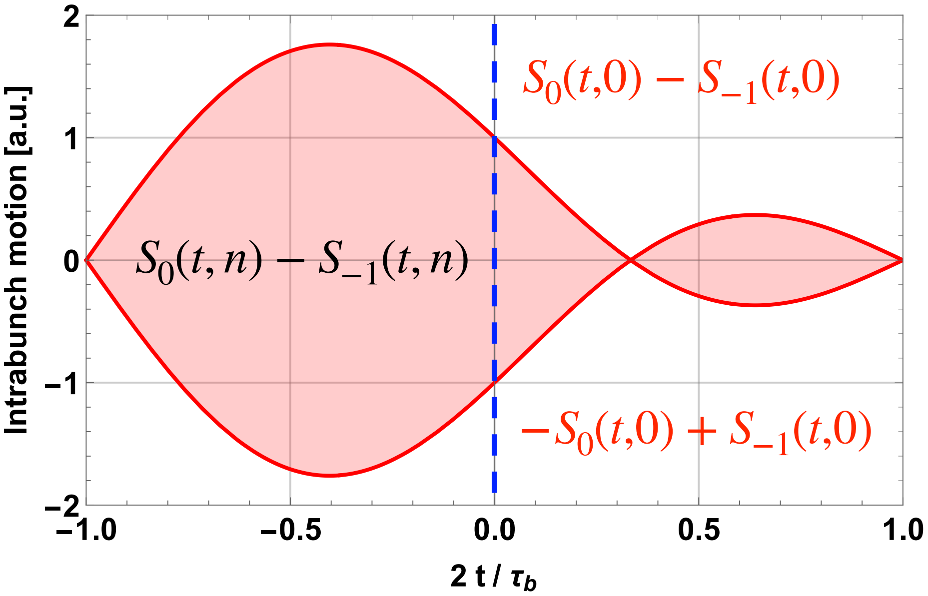

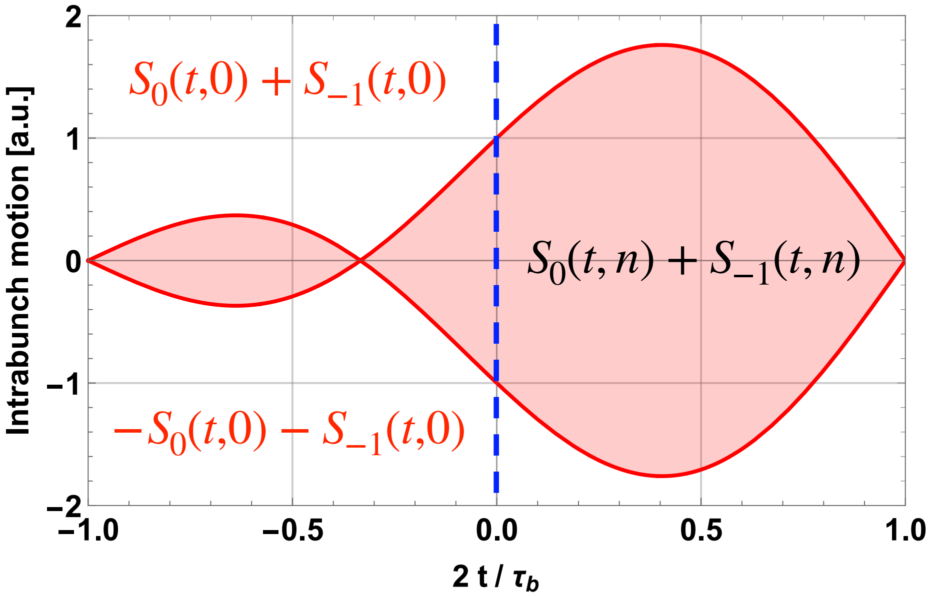

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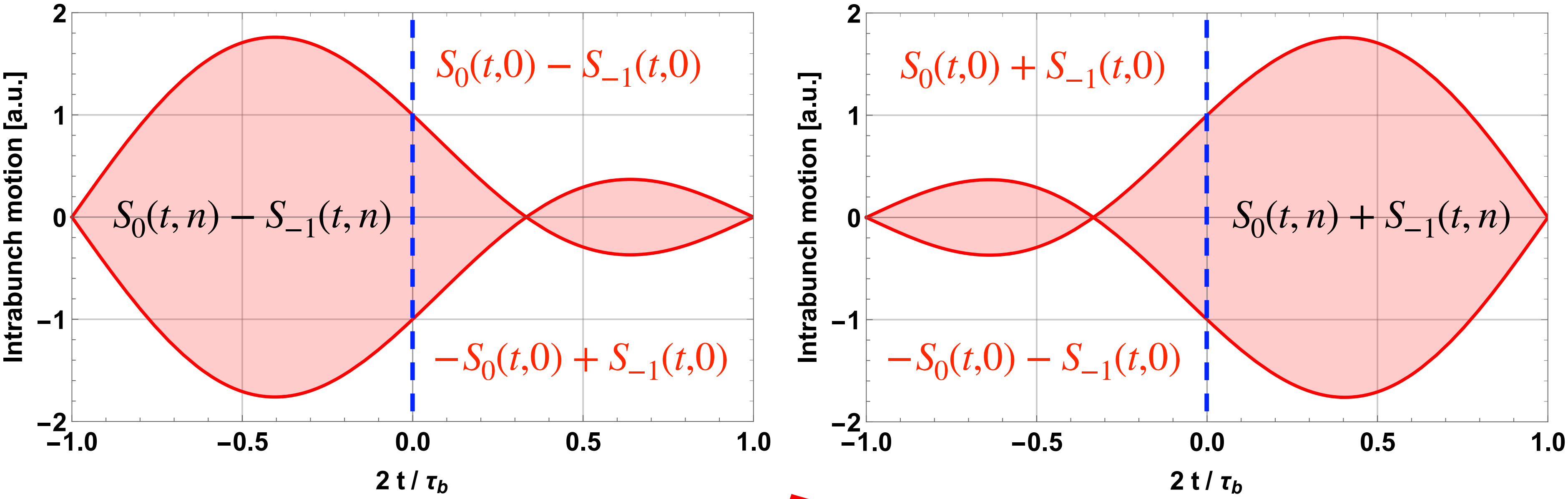


And similarly for the modes 0 and +1

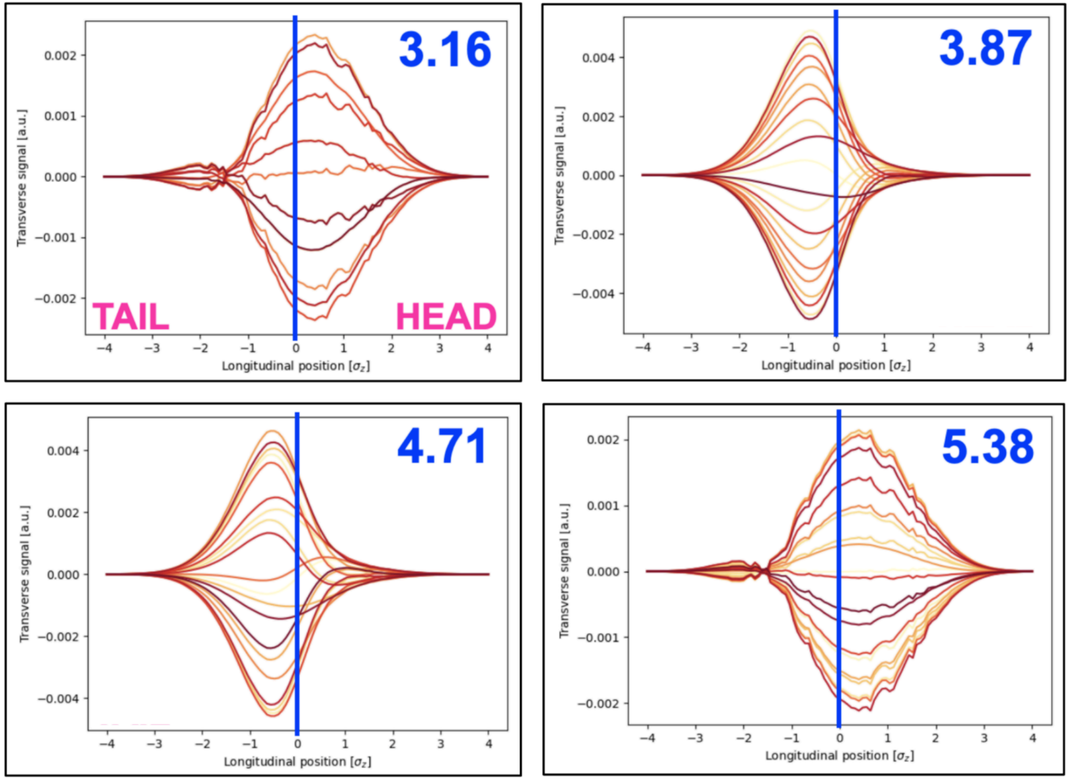
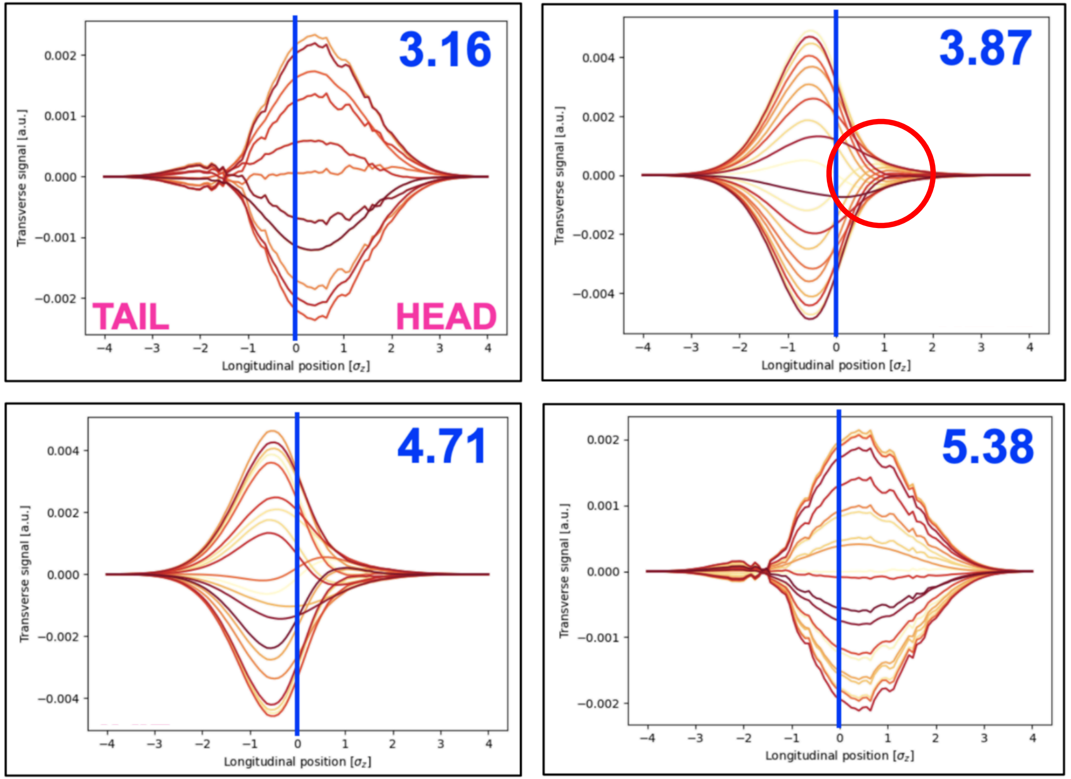


Figure 4: Signals of transverse intrabunch motion, for beam 1, with both impedance and beam-beam for the 4 beam-beam parameters corresponding to the TMCI intensity thresholds of Fig. 3: (top left) 3.16×10^{-3}; (top right) 3.87×10^{-3}; (bottom left) 4.71×10^{-3}; (bottom right) 5.38×10^{-3}.



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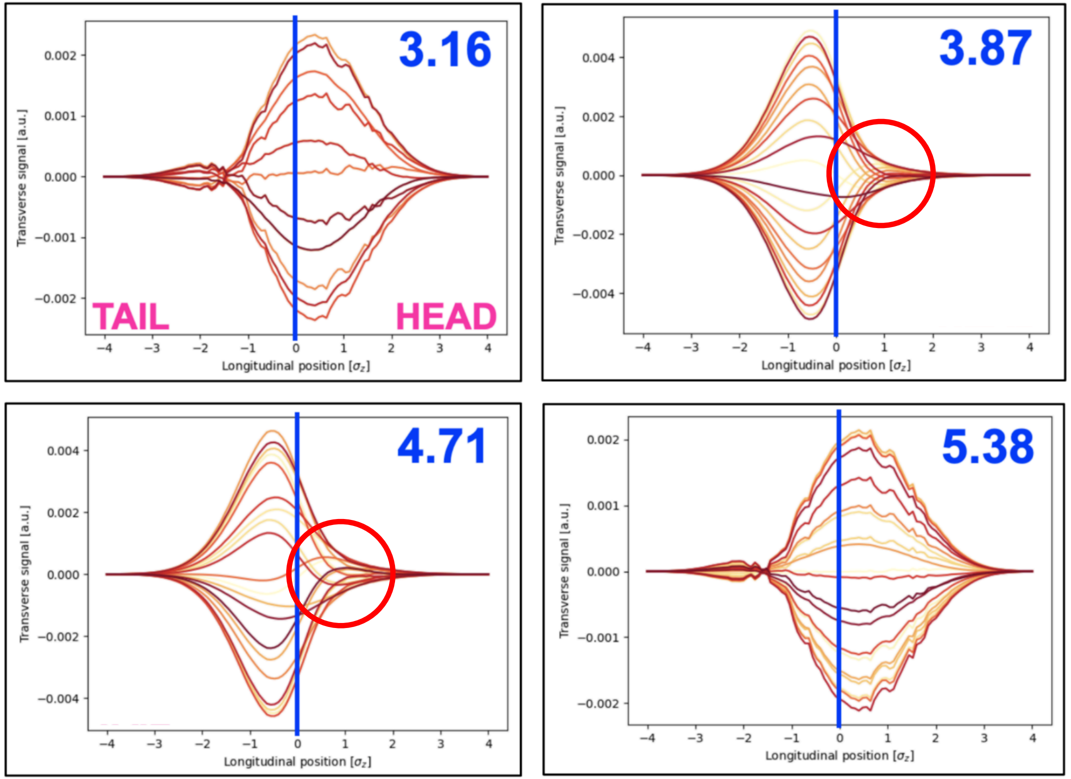

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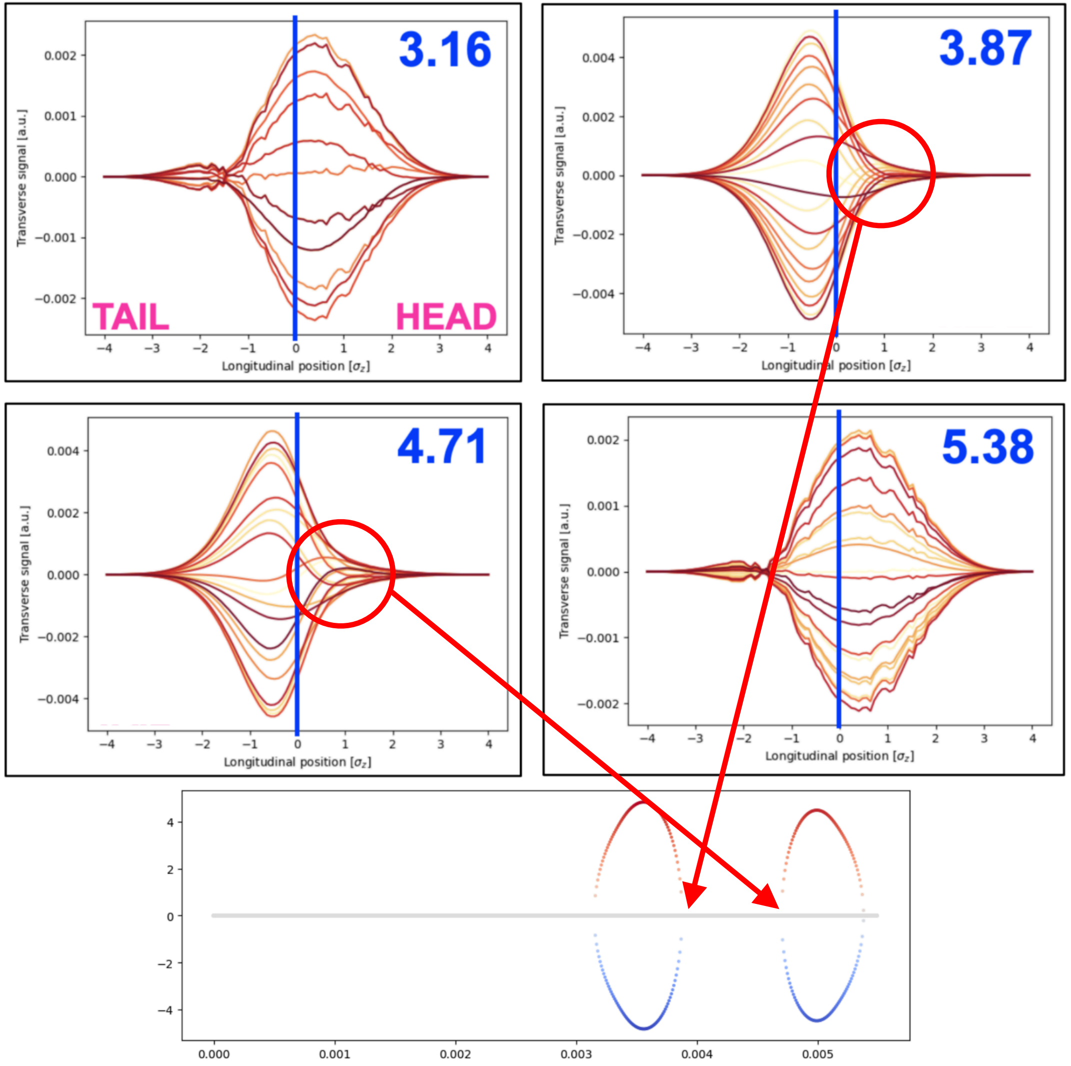
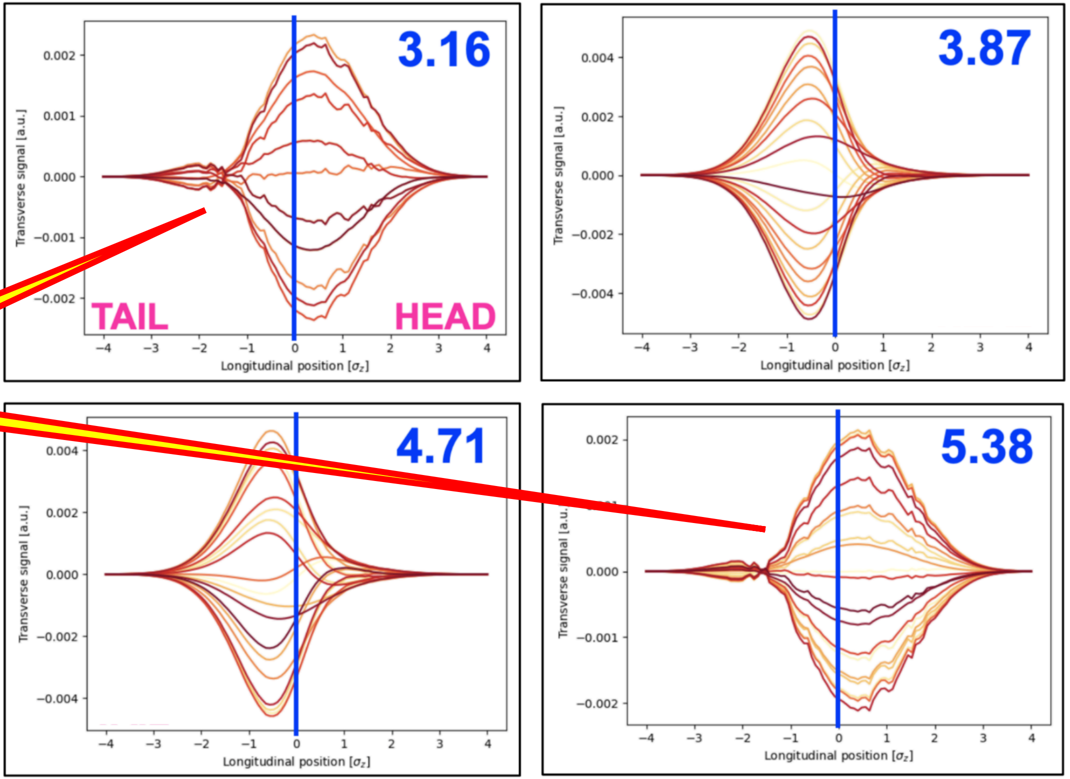


3.16
TAIL
HEAD
3.87
4.71
5.38
Transverse signal [a.u.]
Longitudinal position [σ_z]

Very similar intrabunch signals for 1st mode coupling and 2nd mode decoupling



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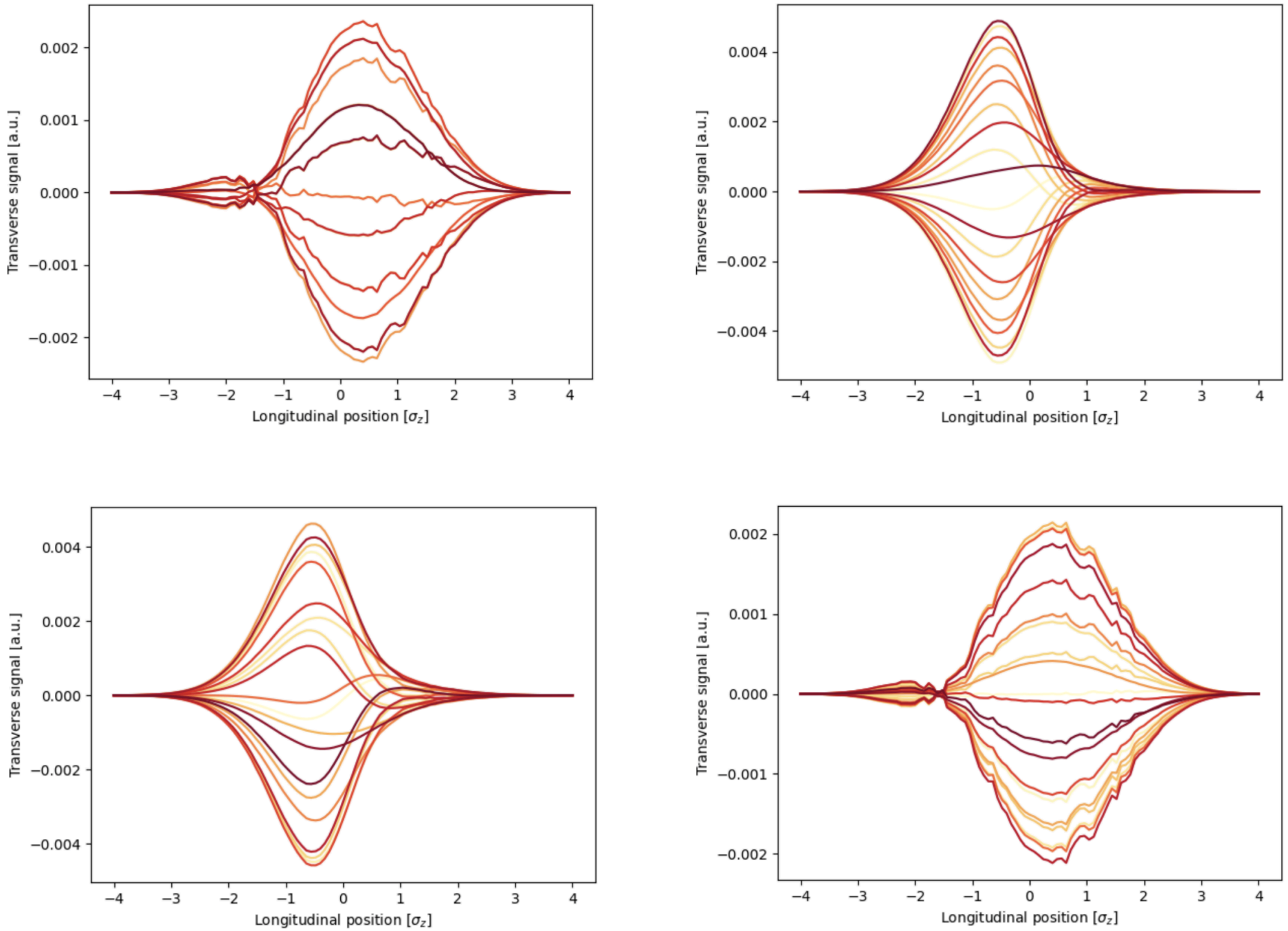
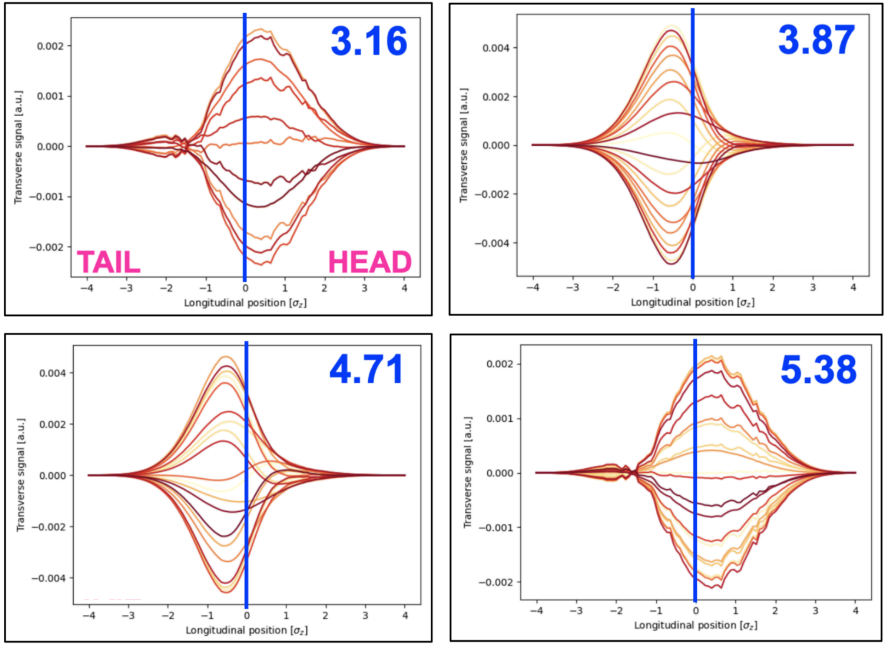


Figure 5: Same as Fig. 4 but for beam 2.



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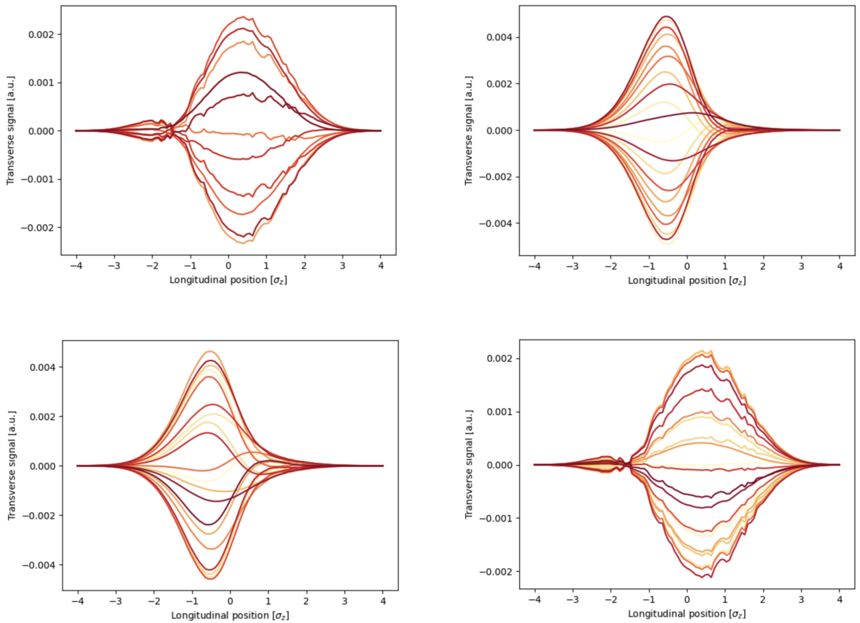

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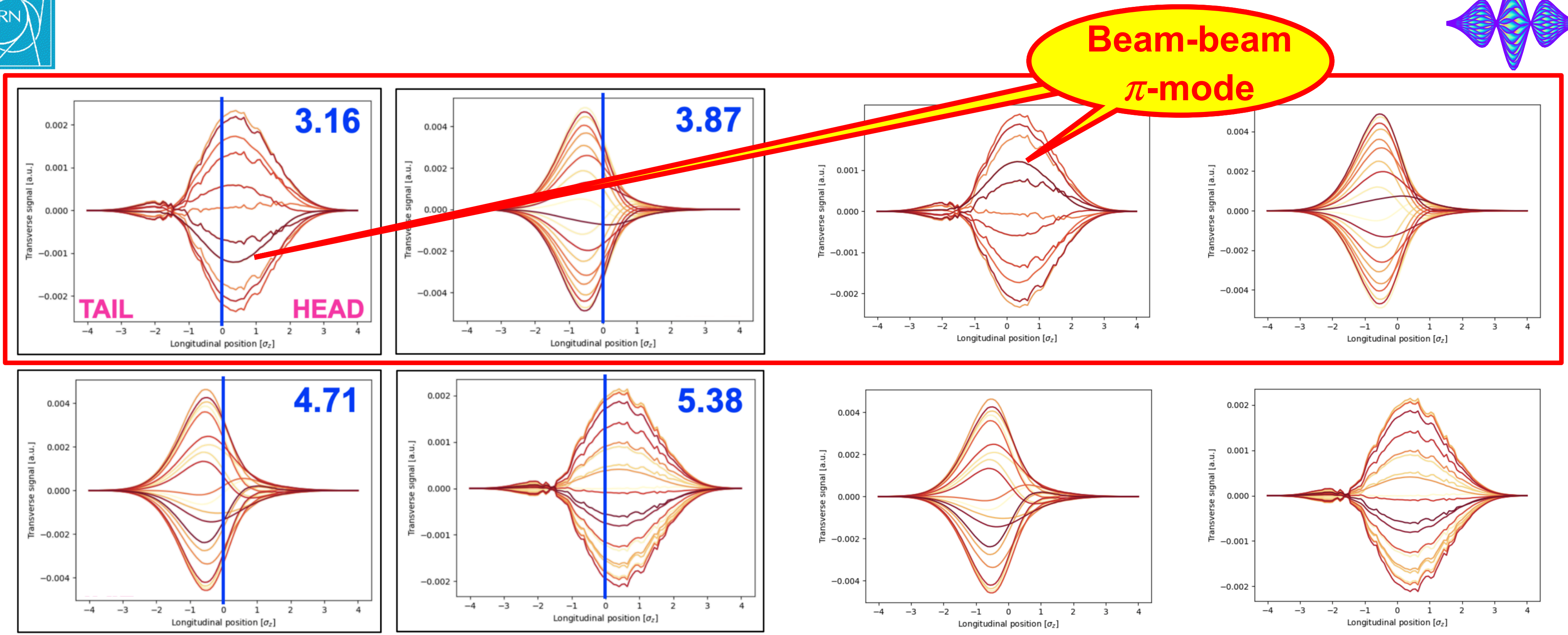

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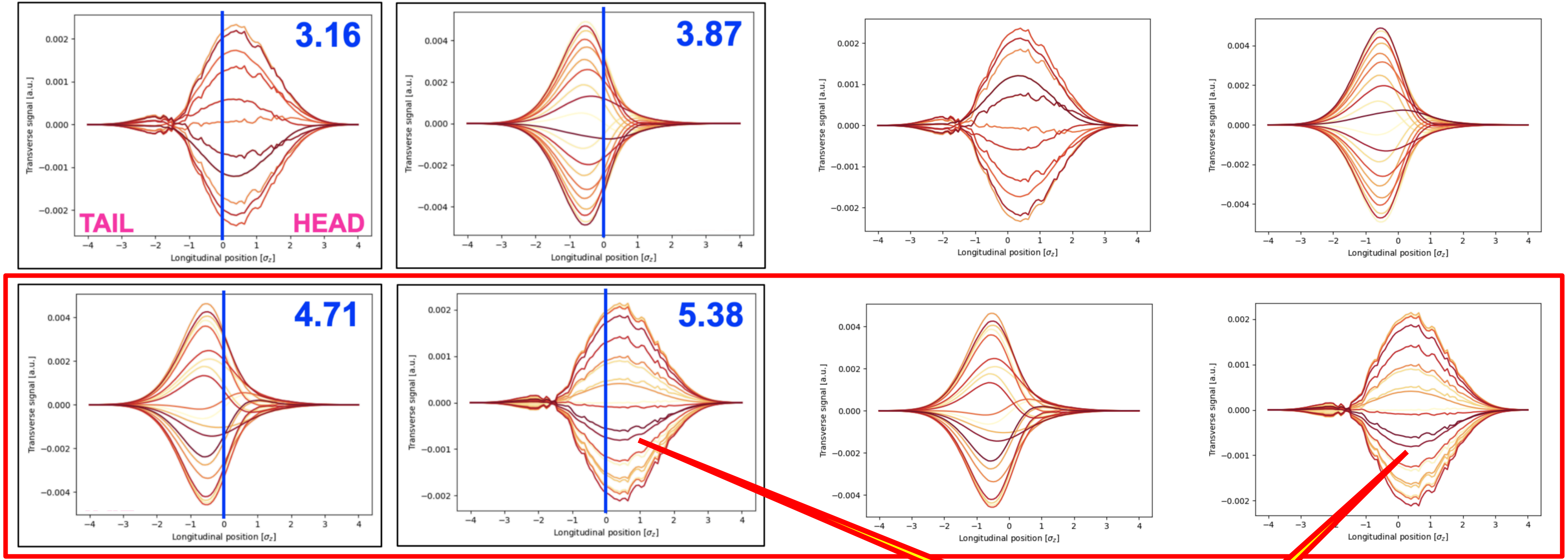

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Take-home messages

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- The evolution of the intrabunch motion with intensity is a fundamental observable with high-intensity high-brightness beams
- Exactly at the mode coupling (or mode decoupling) threshold between 2 modes, the intrabunch signal is the sum (or difference) of the intrabunch signals of the 2 unperturbed modes (leading to asymmetric pictures with new fixed points)!

APPENDIX

(Some other TMCI intrabunch pictures with impedance and space charge; impedance only; e-cloud)

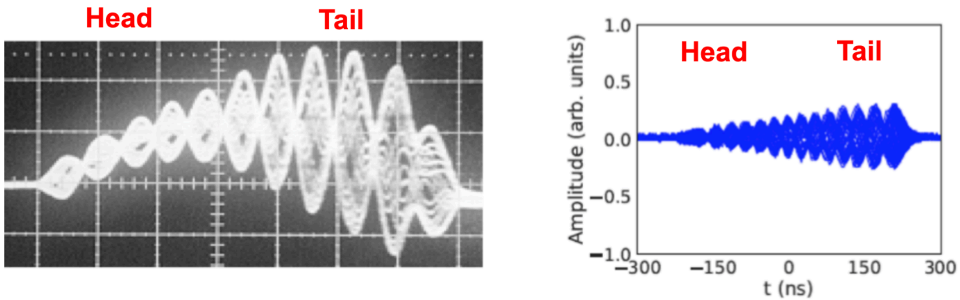
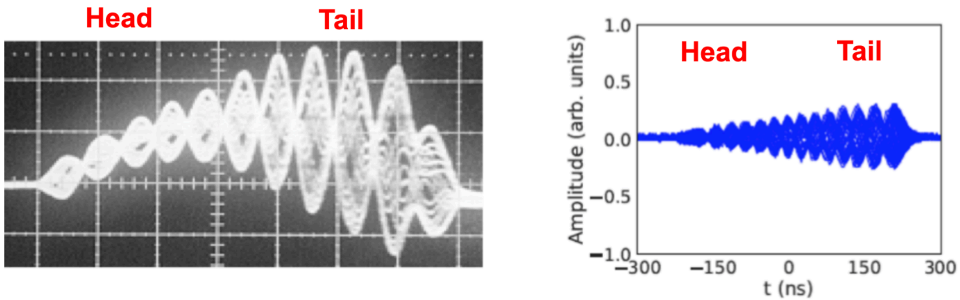


Figure 3: Measurements at the CERN PS [8] (left) and PSB (right, courtesy of E. Koukovini Platia [9]) in the presence of both impedance and strong space charge.



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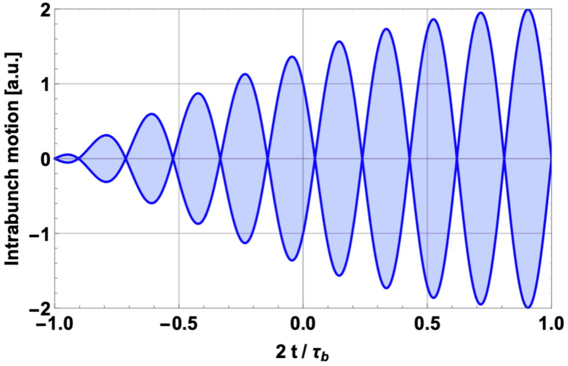

Figure 8: Addition of the approximated low intensity sinusoidal modes $S_9(t,n)$ and $S_{10}(t,n)$ for all the possible number of turns n [2].

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 034202 (2019)

Convective instabilities of bunched beams with space charge

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For a single hadron bunch in a circular accelerator at zero chromaticity, without multiturn wakes and without electron clouds and other beams, only one transverse collective instability is possible, the mode-coupling instability (TMCI). For sufficiently strong space charge (SC), the instability threshold of the wake-driven coherent tune shift normally increases linearly with the SC tune shift, as independently concluded by several authors using different methods. This stability condition has, however, a very strange feature: at strong SC, it is totally insensitive to the number of particles. Thus, were it correct, such a beam with sufficiently strong SC, being stable at some intensity, would remain stable at higher intensity, regardless of how much higher. This paper suggests a resolution of this conundrum: while SC suppresses the TMCI, it introduces head-to-tail convective amplifications, which could make the beam even less stable than without SC, even if all the coherent tunes are real, i.e., all the modes are stable in the conventional *absolute* meaning of the word. This is done using an effective new method of analysis of the beam's transverse spectrum for arbitrary space charge and wake fields. Two new types of beam instabilities are introduced: the saturating convective instability and the absolute-convective instability.

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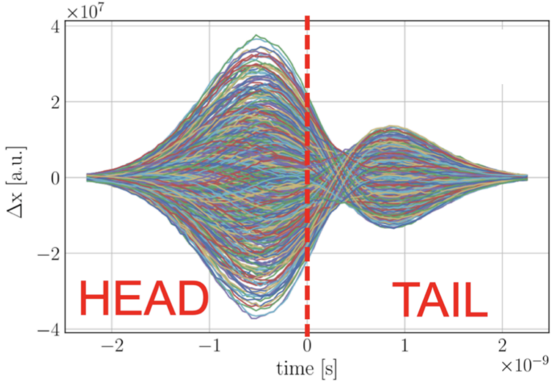
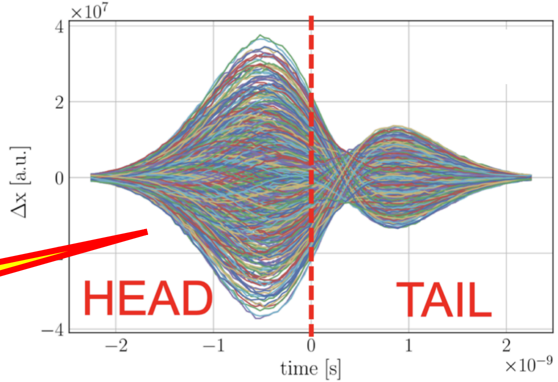


Figure 1: PyHEADTAIL [4] simulations with impedance only: CERN SPS (left, courtesy of M. Beck [5])



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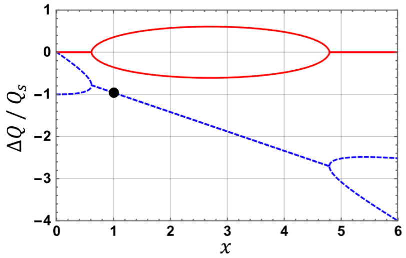
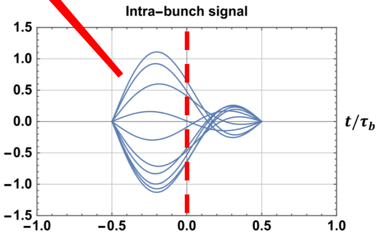
"Just above" TMCI threshold





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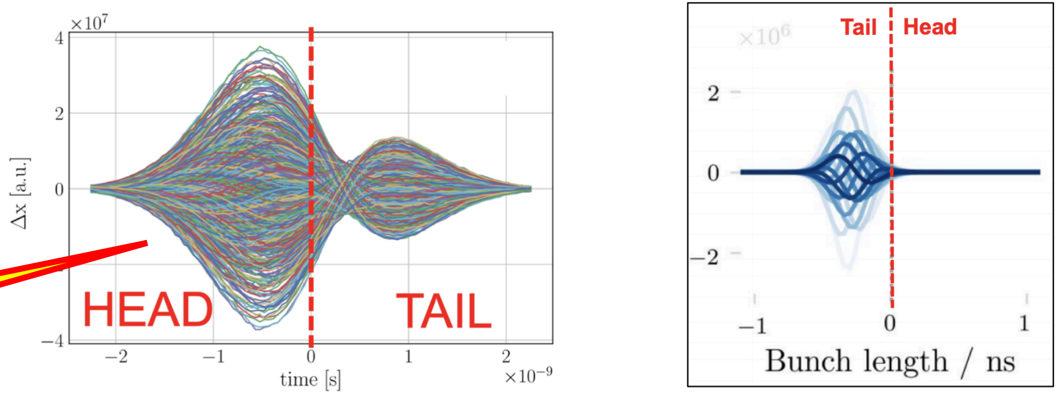

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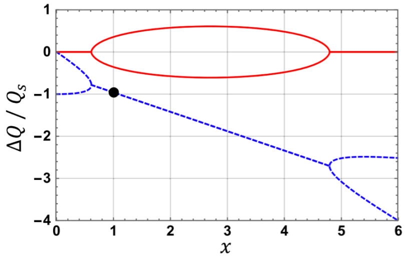

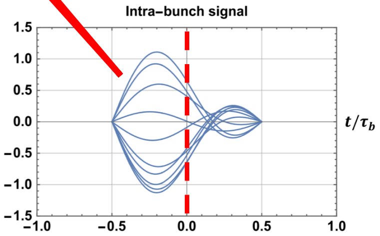

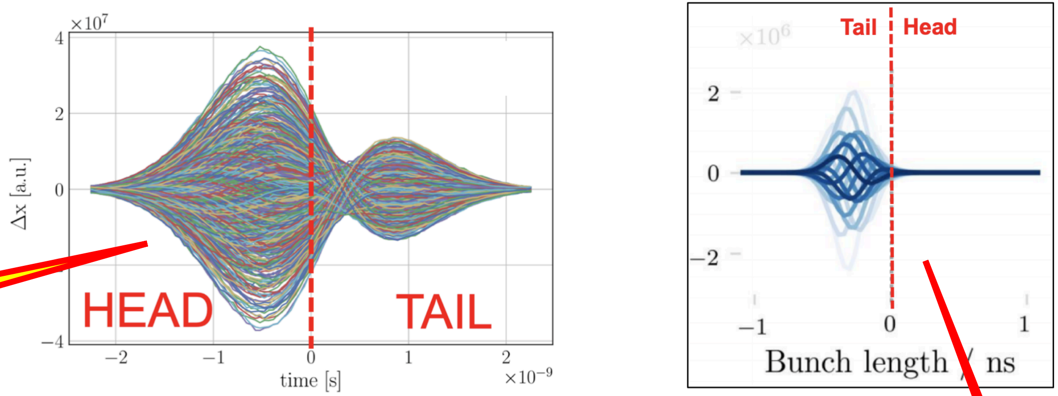

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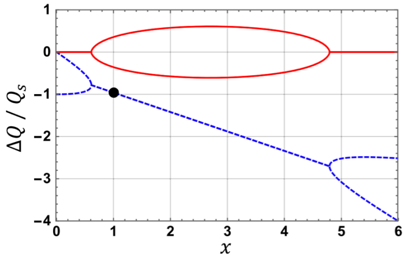
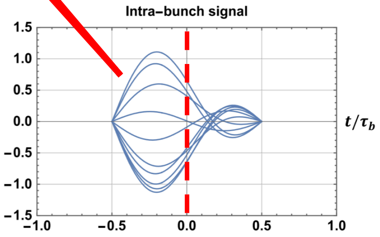




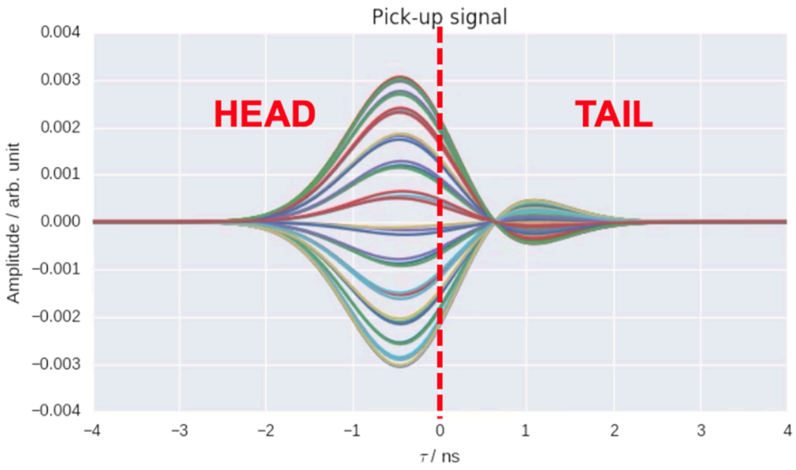
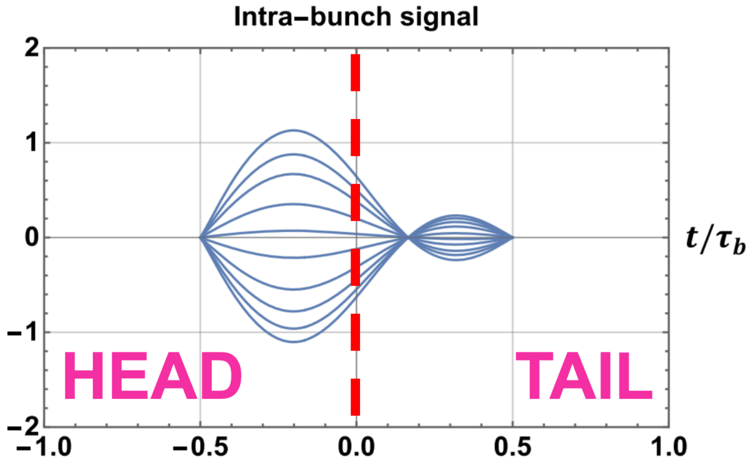


FIG. 3. Simulated (with the DELPHI Vlasov solver, using a Gaussian longitudinal profile) transverse intrabunch signal (superimposed turn after turn), as observed from a pickup monitor, for the case of a bunch interacting with an impedance and for the chromaticity $Q' = 0$, when the two modes 0 and -1 start to couple. This figure is courtesy of Amorim [9].



GALACTIC Vlasov solver,
using a “Water-Bag” longitudinal profile

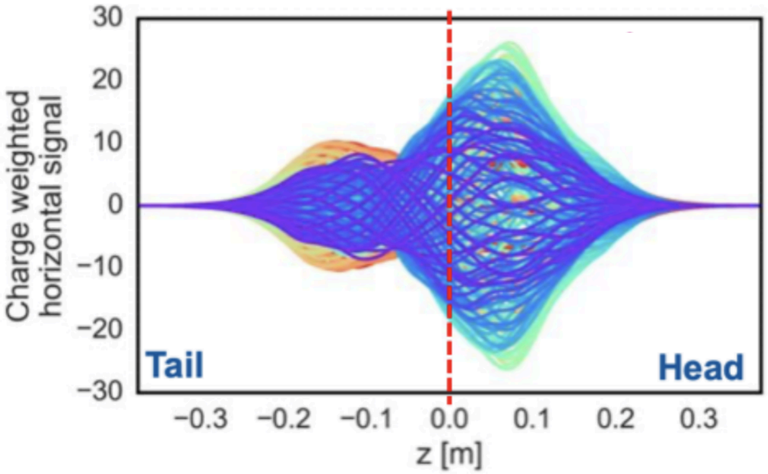
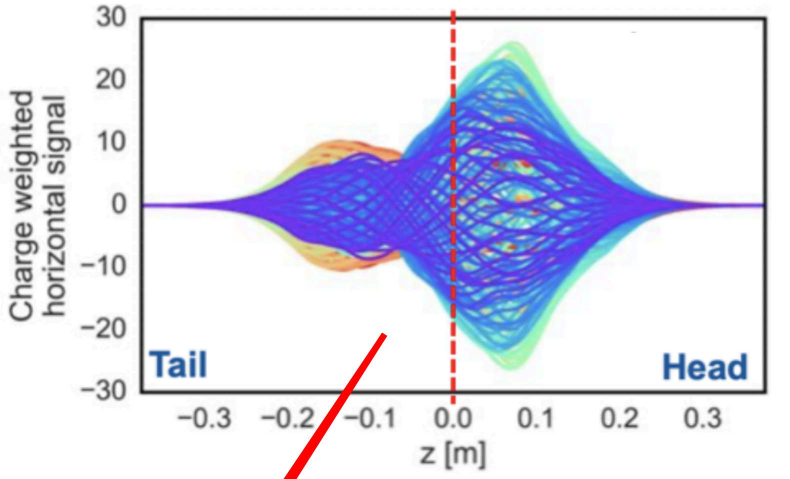


Figure 4: PyHEADTAIL simulations with electron cloud only (courtesy of L. Sabato [10]).



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and to Inès, who will start her Master at EPFL in a few days 🌻