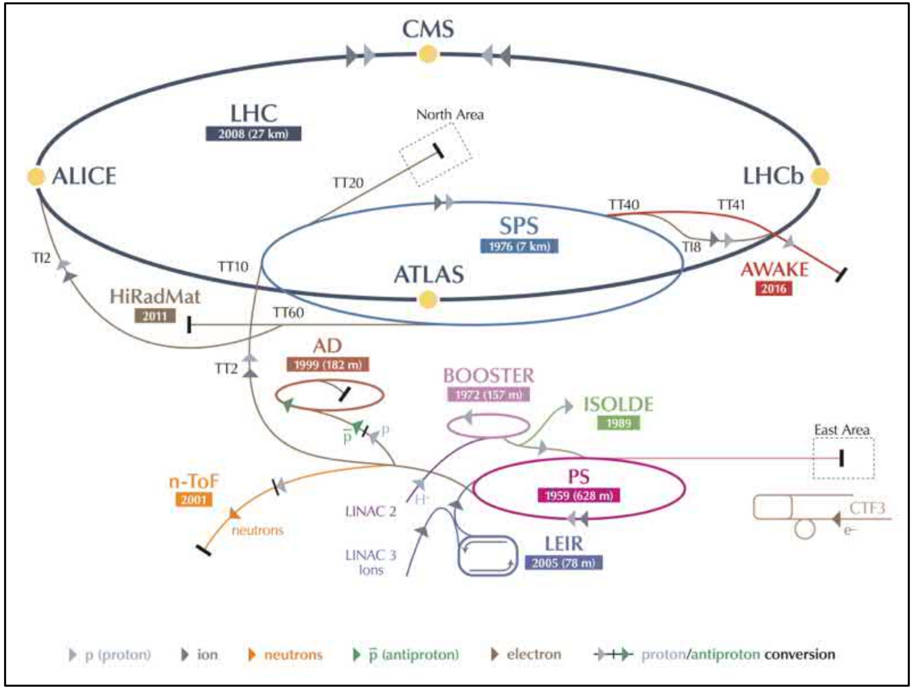
Alex Chao Symposium

E. Métral (Elias.Metral@cern.ch)

- Section leader of the CERN BE-ABP-HSC section (Hadron Synchrotron Collective/Coherent effects)
- Deputy director of the JUAS school (Joint Universities Accelerator School)

https://conf.slac.stanford.edu/alexchaosymposium/agenda



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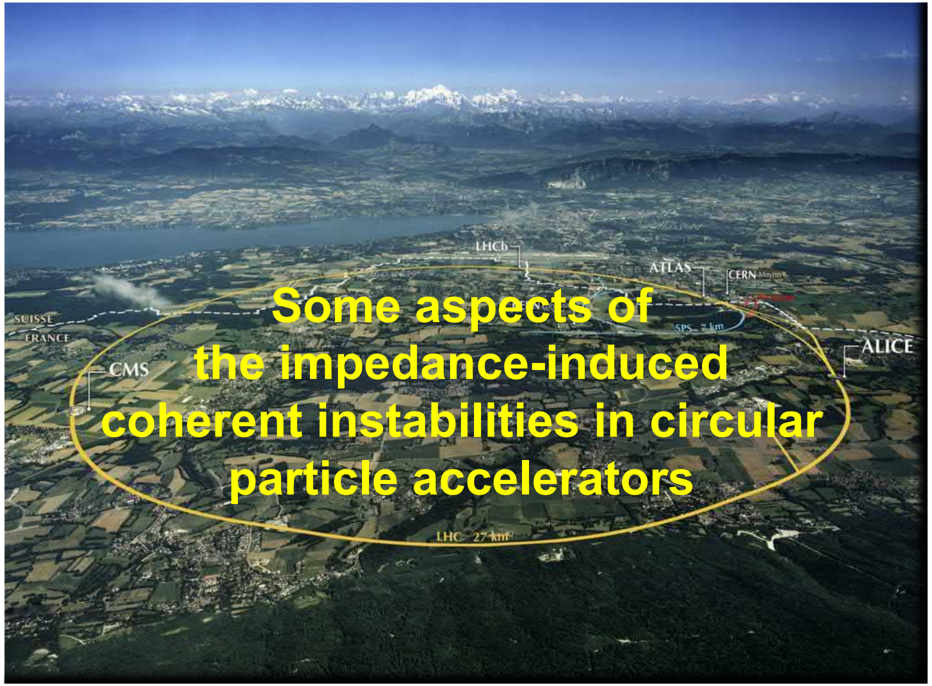
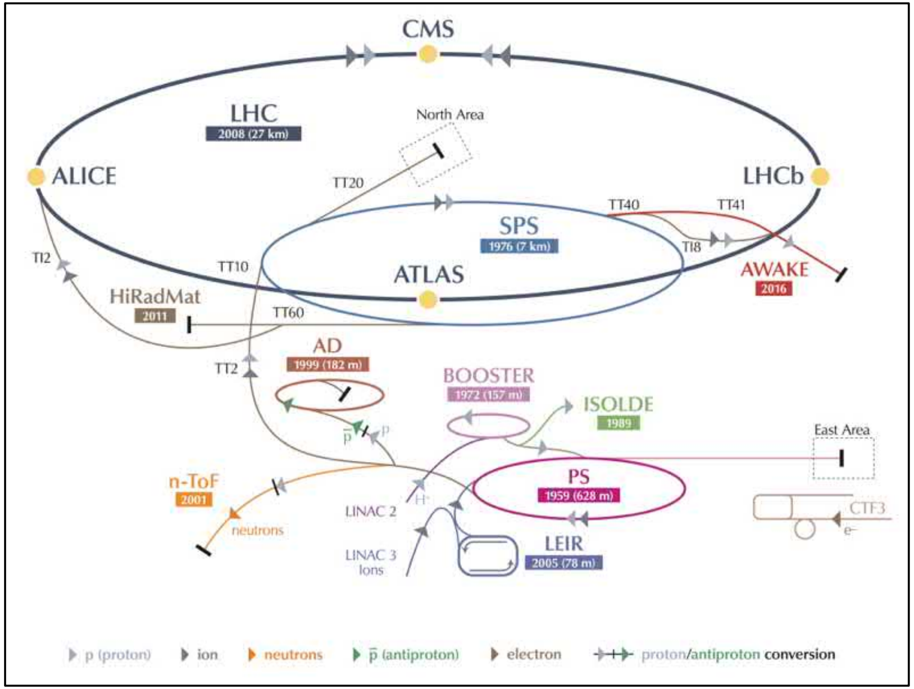
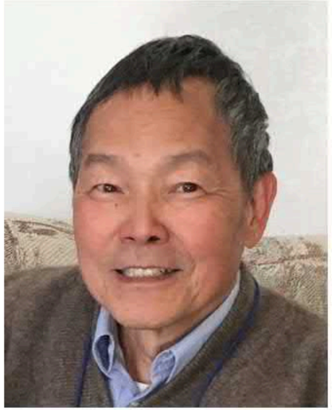




IPAC 2018 prize for Alex Chao:
I had the pleasure to be there and listen to him

Robert R. Wilson Prize for Achievement

The Robert R. Wilson Prize for Achievement recognizes and encourages outstanding achievement in the physics of particle accelerators.



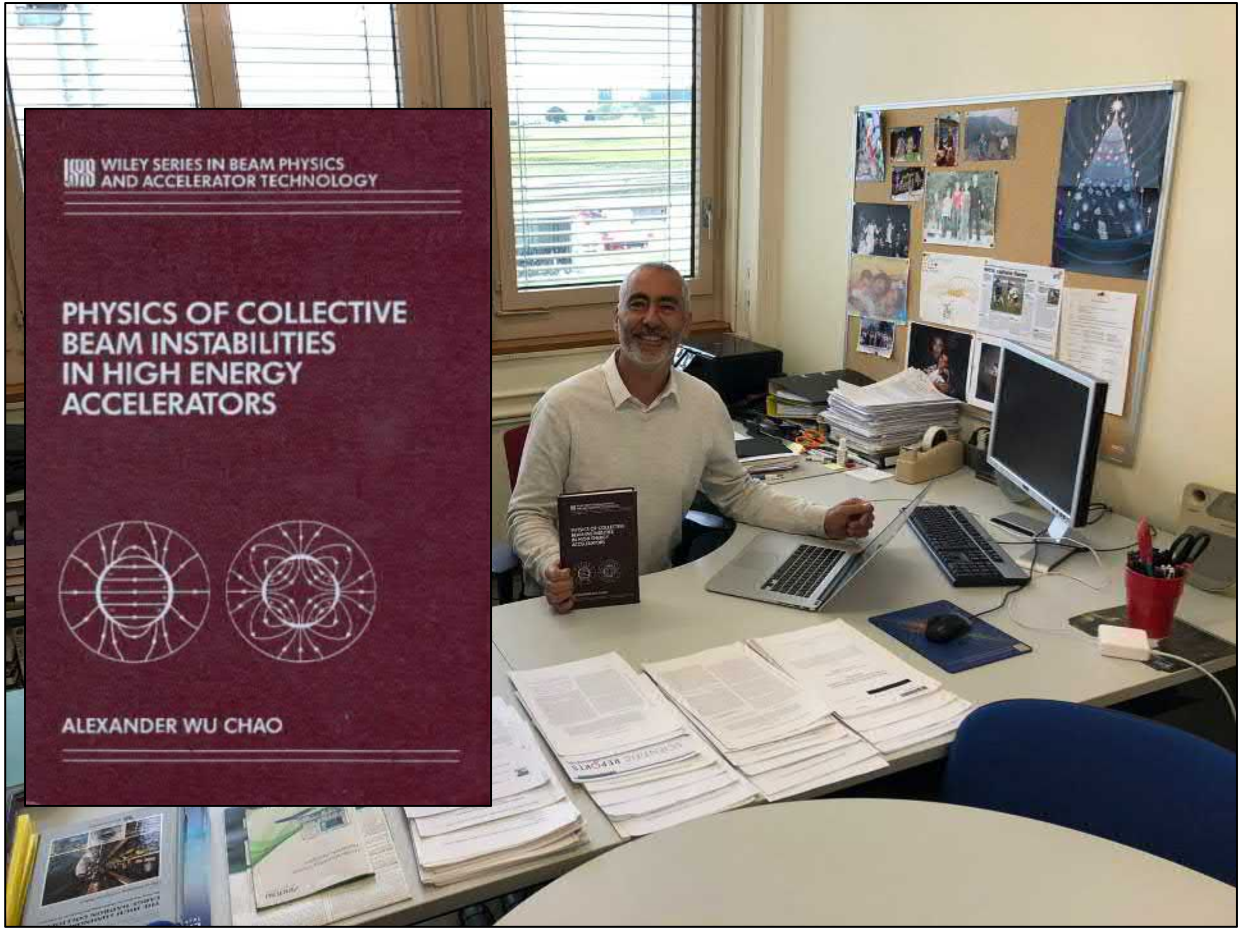
Recipient

Alexander Wu Chao
SLAC National Accelerator Laboratory

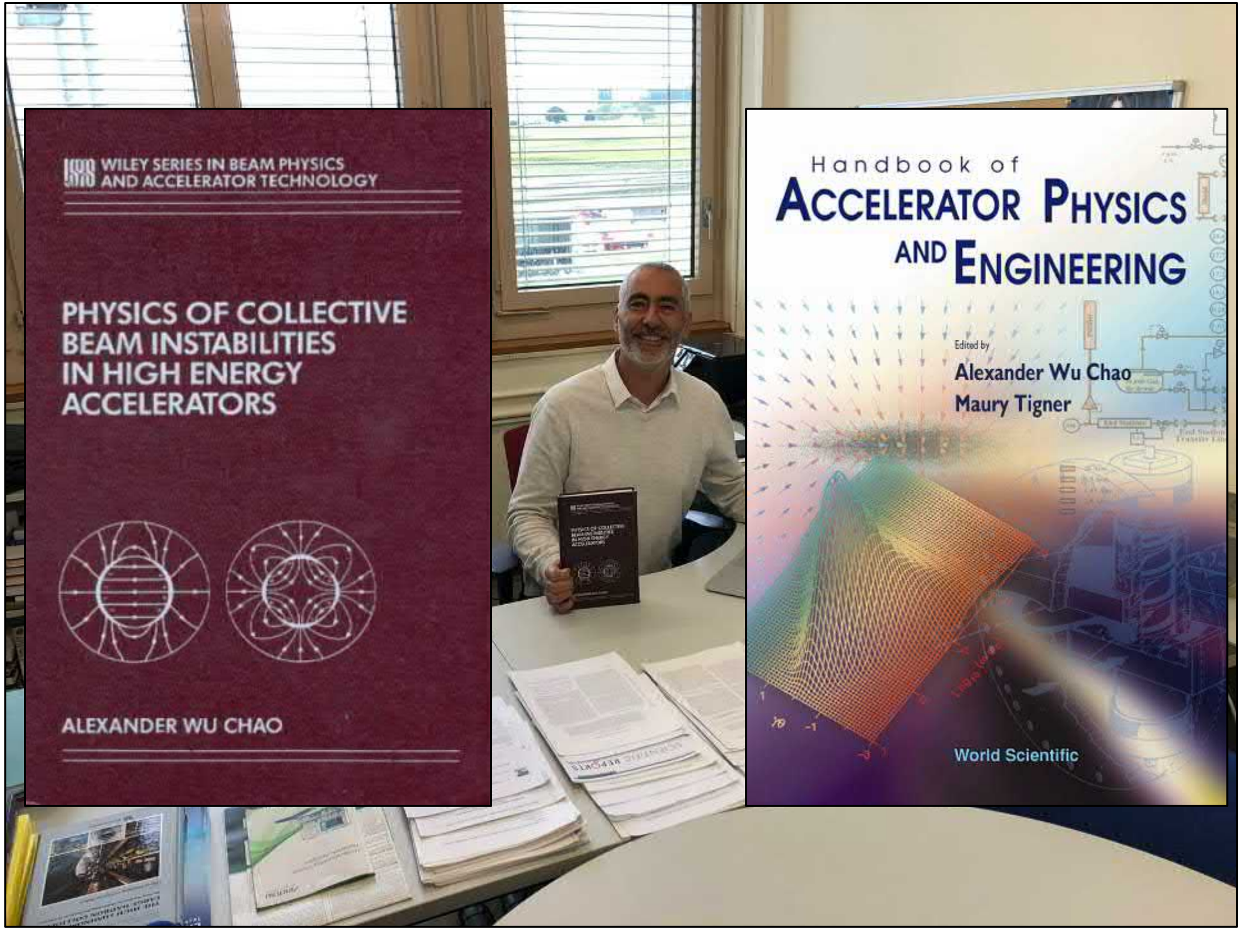
"for insightful, fundamental and broad-ranging contributions to accelerator physics, including polarization, beam-beam effects, nonlinear dynamics, and collective instabilities, for tireless community leadership and for inspiring and educating generations of accelerator physicists."

"The Chao" bible

"The Chao" bible



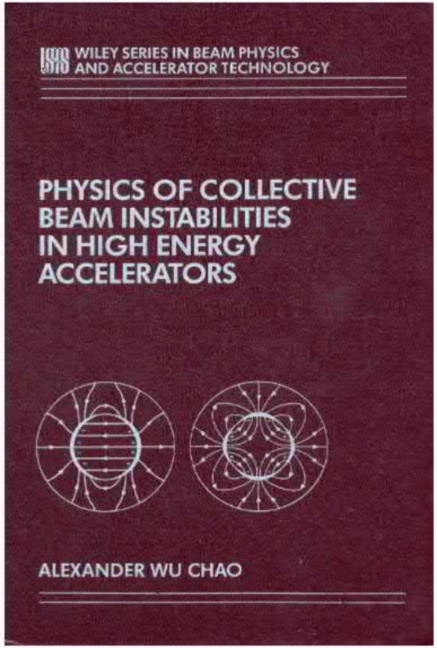
“The Chao” bible



HEADTAIL macroparticle tracking code (2002)
F. Zimmermann
G. Rumolo
EPFL team (C. Tambasco, T. Pieloni, L. Coyle, M. Schenk)
WILEY SERIES IN BEAM PHYSICS AND ACCELERATOR TECHNOLOGY
PHYSICS OF COLLECTIVE BEAM INSTABILITIES IN HIGH ENERGY ACCELERATORS
ALEXANDER WU CHAO
Handbook of ACCELERATOR PHYSICS AND ENGINEERING
Alexander Wu Chao
Maury Tigner
World Scientific
N. Biancacci
X. Buffat
C. Zannini
N. Mounet
B. Salvant
E. Koukovini Platia
S. Antipov
L. Giacomel
G. Iadarola

On-line book (371 pages):

http://www.slac.stanford.edu/~achao/wileybook.html



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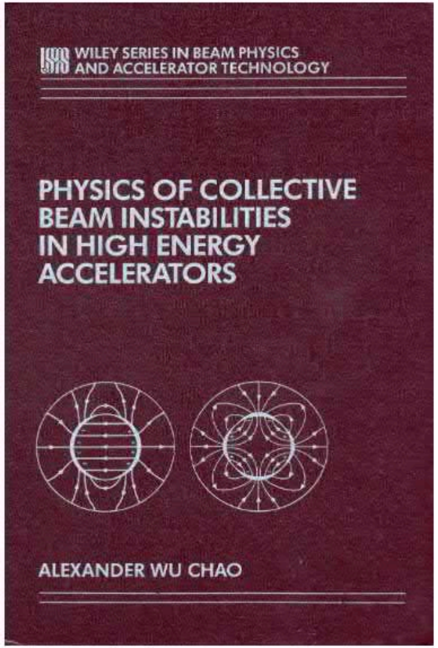

$$\begin{aligned} \text{dynamical system} &= \text{beam} + \text{surroundings}, \\ \text{mediator of interaction} &= \text{wake field}. \end{aligned} \tag{1.1}$$

"The Chao" bible came perfectly on time for me (1993): I started my PHD in 1996…

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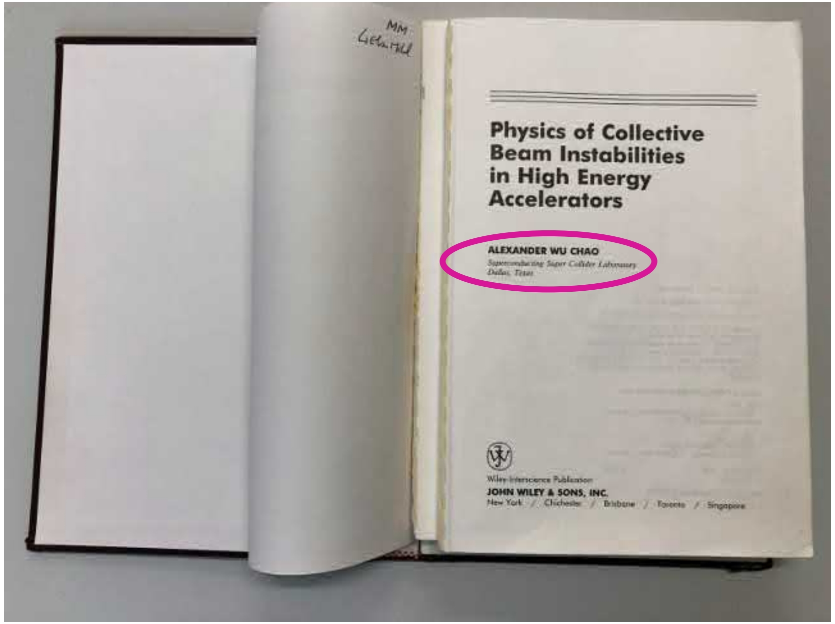
- I spent my first few months reading and re-deriving it (with cgs units!)



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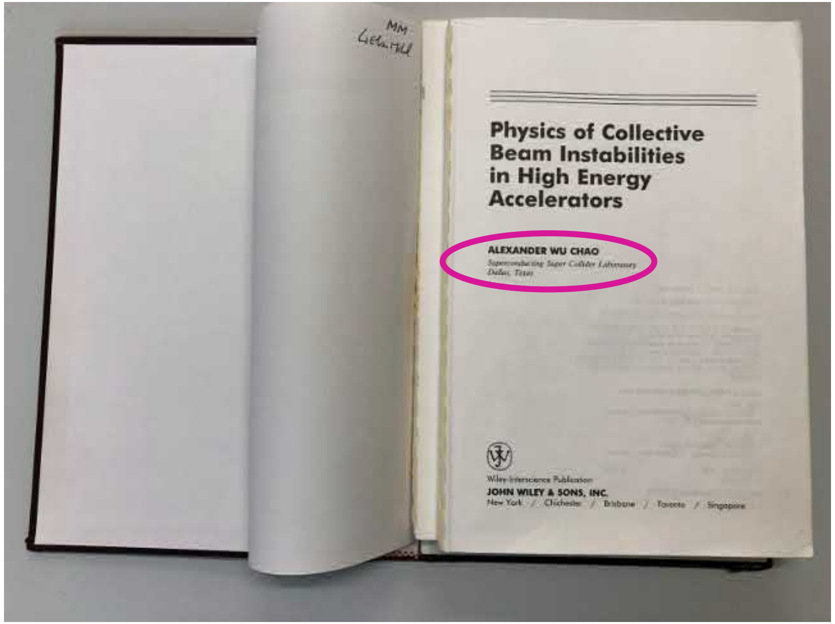

> this volume—the subject of collective beam instabilities in accelerators. Over the years, I have learned and been fascinated by this subject, and it is this fascination that I would like to share with the reader.

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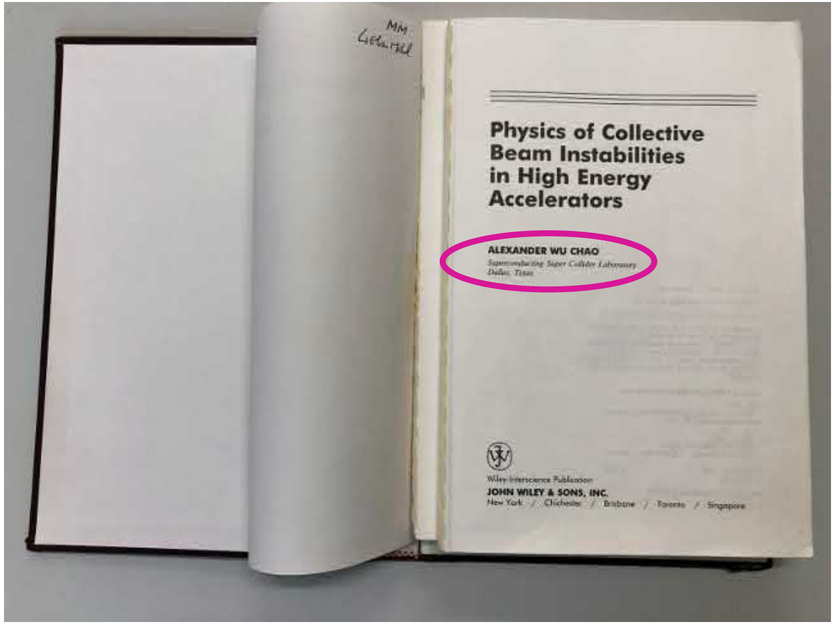

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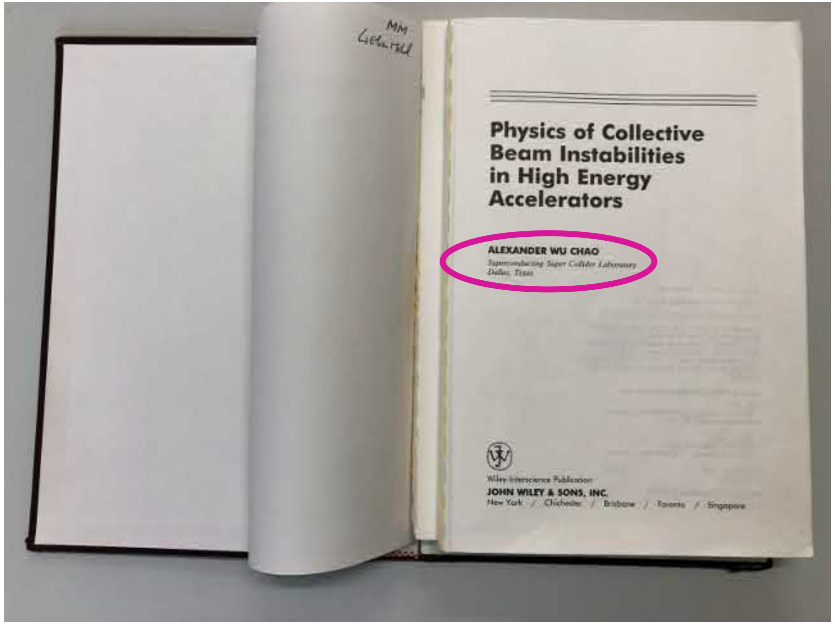

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- Another complementary approach is e.g. from J.L. Laclare (CAS-1985)

BUNCHED BEAM COHERENT INSTABILITIES

J.L. Laclare
Laboratoire National Saturne, 91191 Gif-sur-Yvette Cedex, France

ABSTRACT

In this chapter, we will deal with coherent longitudinal and transverse instabilities. It is a collective phenomenon which prevents one from increasing the current circulating in an accelerating device without losing the beam or spoiling its characteristics.

My PHD supervisor: D. Möhl

DIETER MÖHL – PROMINENT SCIENTIST AND WONDERFUL TEACHER

(1936-2012)

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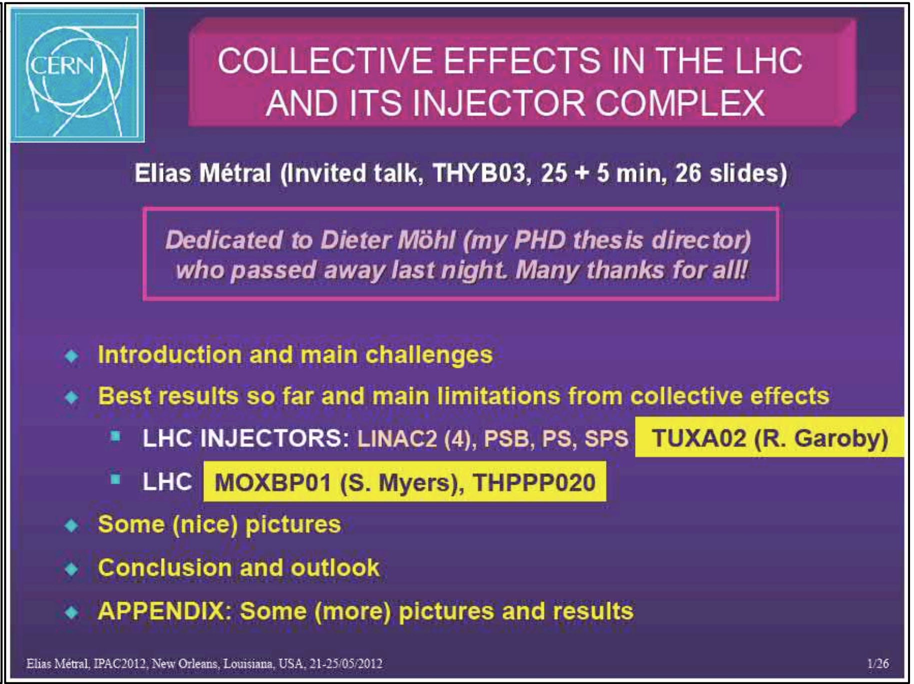

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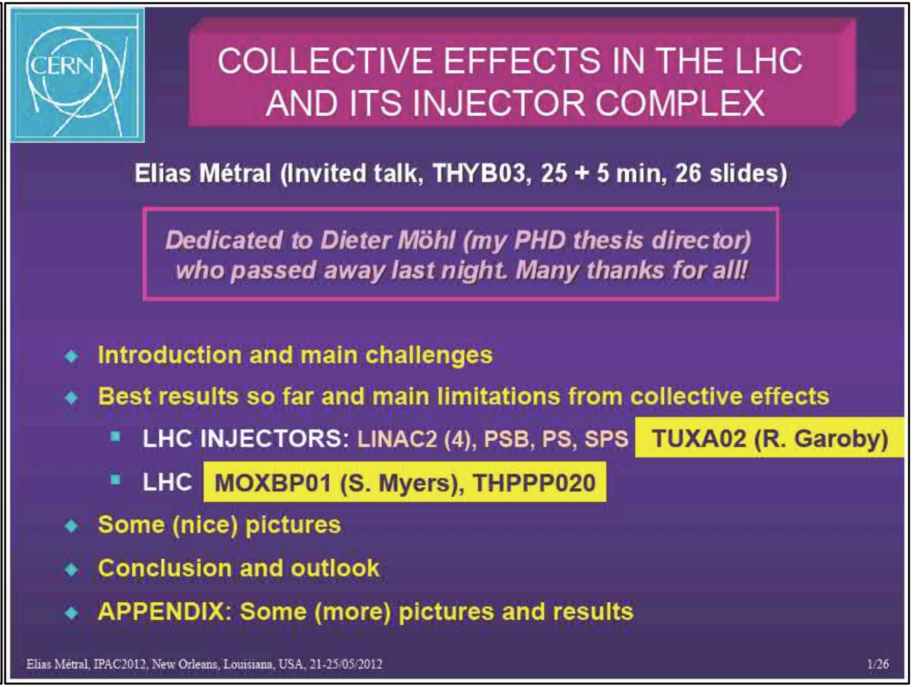

THE USE OF RF-KNOCKOUT FOR DETERMINATION OF THE CHARACTERISTICS OF THE TRANSVERSE COHERENT INSTABILITY OF AN INTENSE BEAM*

Dieter Möhl+ and Andrew M. Sessler

See Chao's footnote p. 263 (1971)

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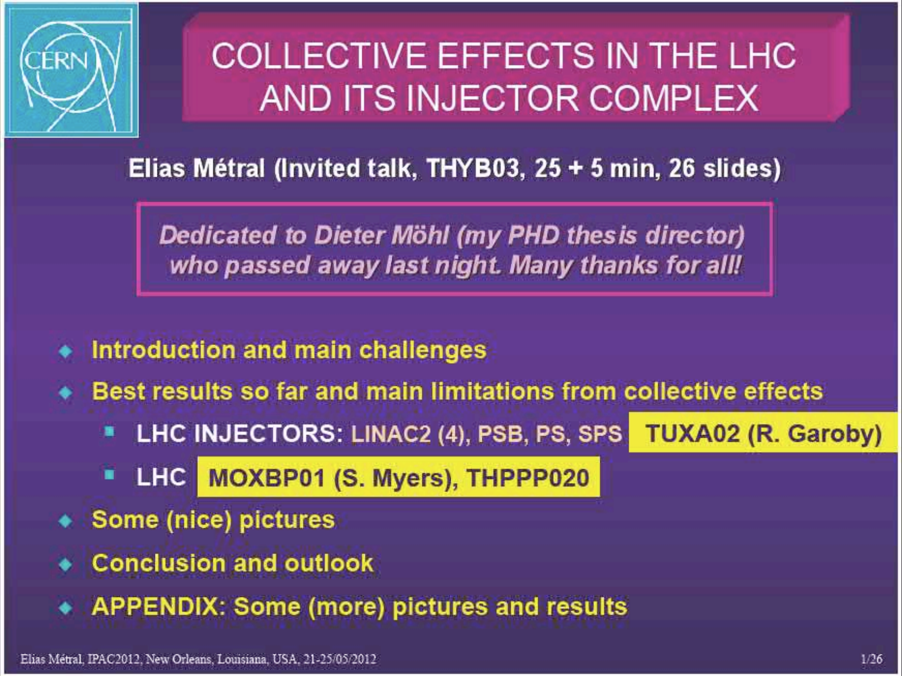

Beam Transfer Function (BTF)

THE USE OF RF-KNOCKOUT FOR DETERMINATION OF THE CHARACTERISTICS OF THE TRANSVERSE COHERENT INSTABILITY OF AN INTENSE BEAM*

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See Chao's footnote p. 263 (1971)

A.M. Sessler and V.G. Vaccaro

pipe as shown in Figure 2.1(a) and (c). The Fourier transform of the wake function is called the *impedance*. The idea of representing the accelerator environment by an impedance was introduced by Sessler and Vaccaro.[19] *1967*

A.M. Sessler and V.G. Vaccaro

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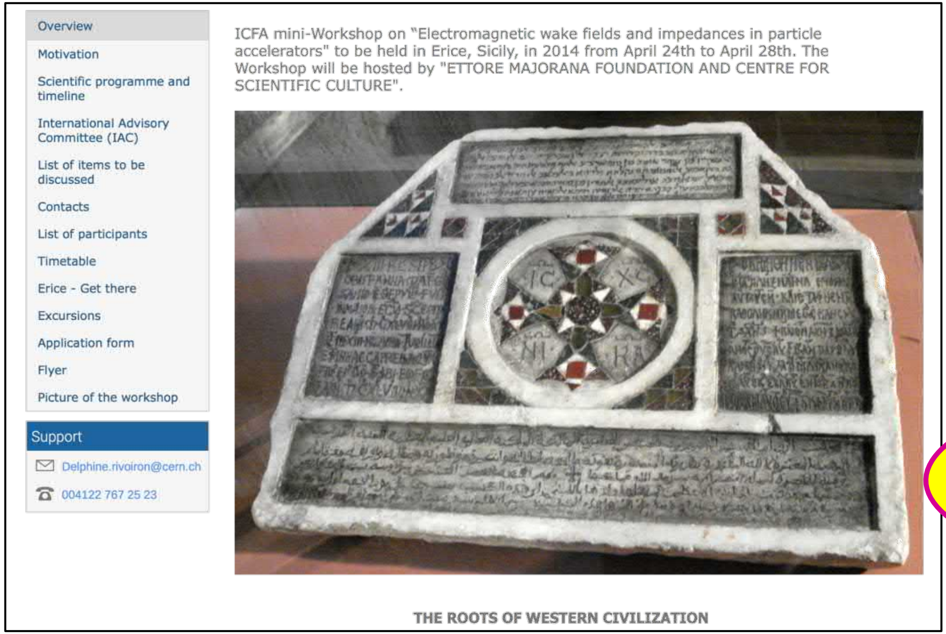


Impedance workshop, Erice, Sicily, 24-28/04/2014

IPAC19 prize for V.G. Vaccaro

The Xie Jialin Prize for outstanding work in the accelerator field, with no age limit.

Prof. Vittorio Giorgio VACCARO

'For his pioneering studies on instabilities in particle beam physics, the introduction of the impedance concept in storage rings and, in the course of his academic career, for disseminating knowledge in accelerator physics throughout many generations of young scientists."

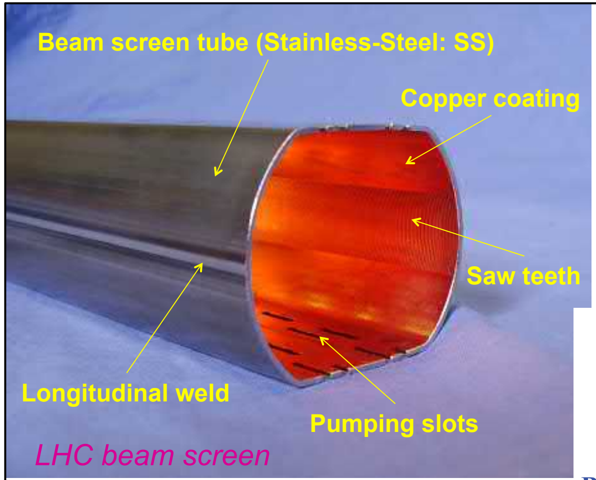
Just few words on him, as he could not join us…

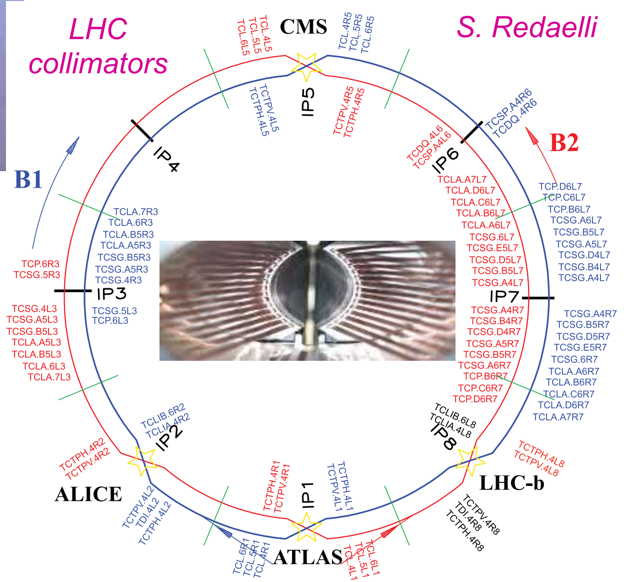
E. Métral

E. Métral, IPAC'19, Melbourne, Australia, 23/05/2019

See also https://ipac2019.vrws.de/talks/thaplm2_talk.pdf

Example of the LHC "wall impedance"





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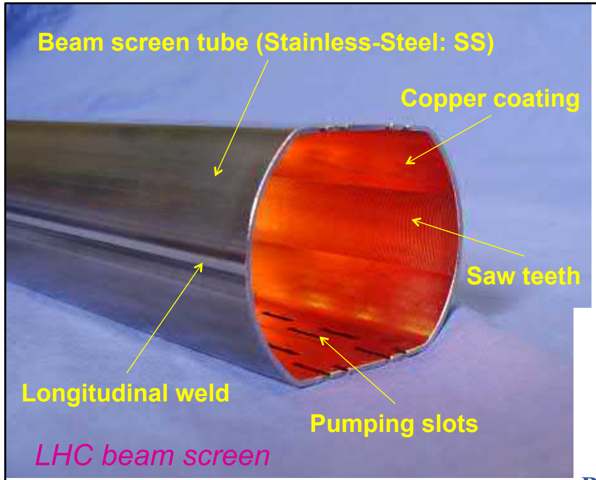

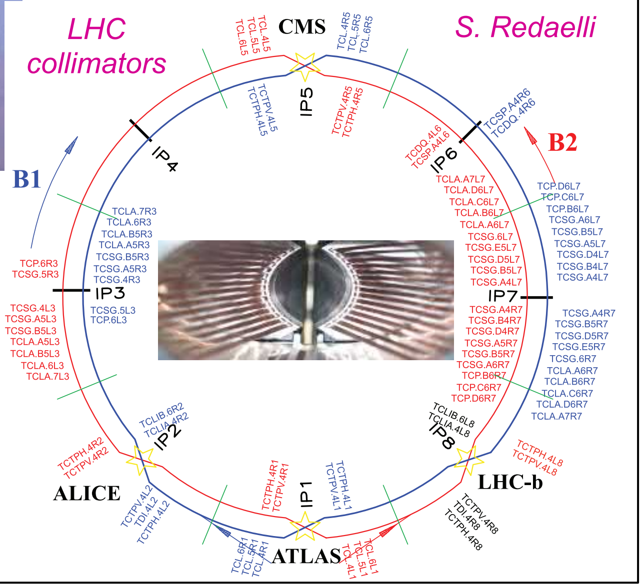

[6]This is meant to be the particle energy at injection. In a circular accelerator, it is usually during the low energy operation that the beam is least stable. The beam usually becomes more stable when accelerated to higher energies.

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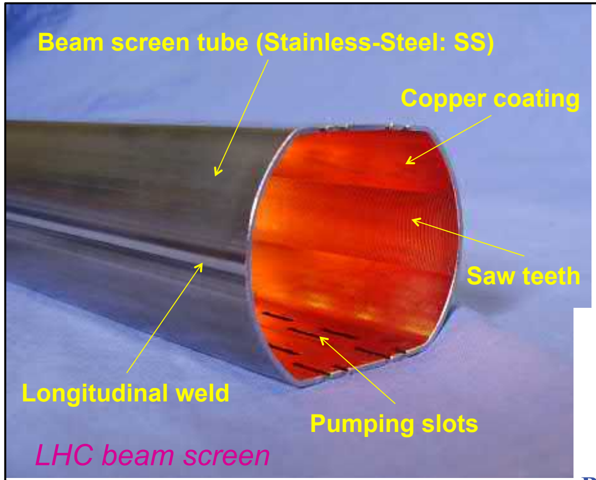

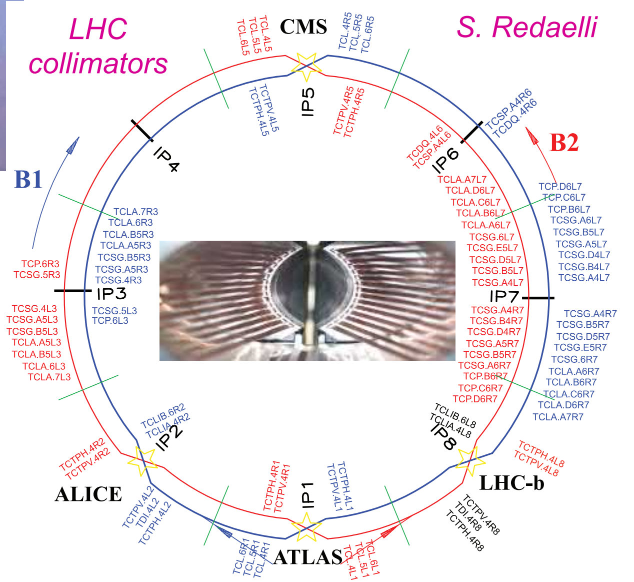

[6] This is meant to be the particle energy at injection. In a circular accelerator, it is usually during the low energy operation that the beam is least stable. The beam usually becomes more stable when accelerated to higher energies.

=> In the LHC, the collimators are closed during acceleration and the impedance becomes much bigger at high energy… and Landau damping from octupoles less effective due to the smaller transverse beam size…

Example of the LHC “wall impedance”

- Despite the fact that the impedance is more than 50 years old, a lot of work has been done, in the last 2 decades, on 5 aspects

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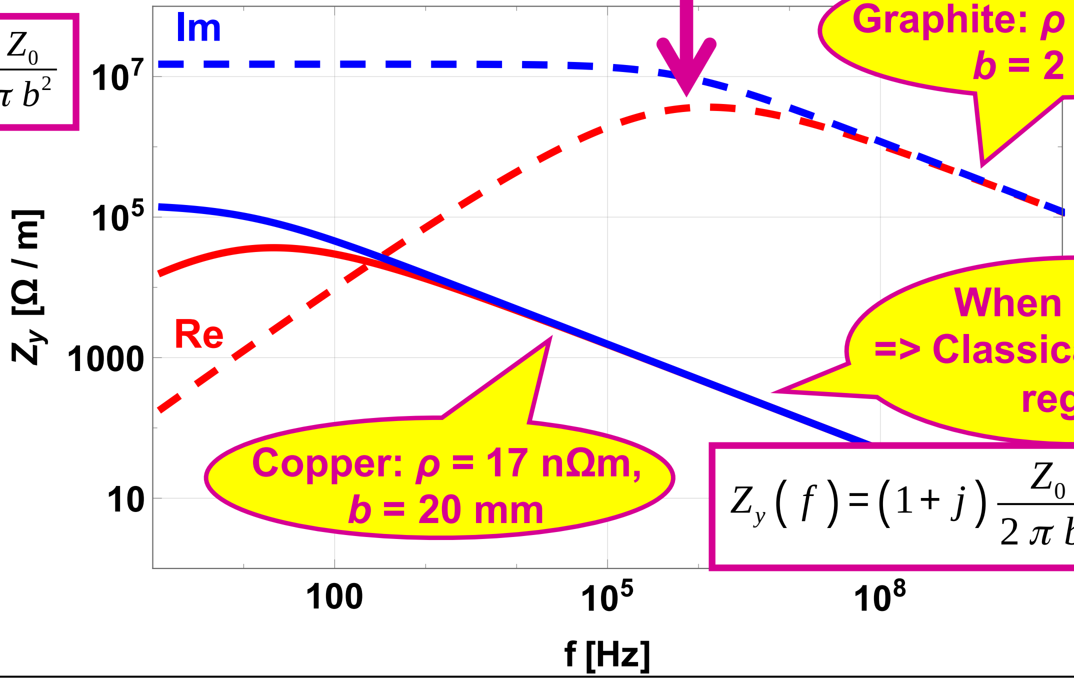
  - Effect of the detuning impedance in non axi-symmetric structures and generalisation of the Yokoya form factors
  - Effect of the relativistic velocity factor
  - Effect of the number of layers and coatings

Example of the LHC "wall impedance"

Assuming a 1 m long round beam pipe

$$f_{\max,\mathrm{Re}} \approx \frac{\rho}{b^2} \times \frac{1}{\pi \mu_0}$$

$$Z_y\left(f \rightarrow 0\right) = \frac{j Z_0}{2 \pi b^2}$$



Graphite: *ρ* = 10 µΩm, *b* = 2 mm

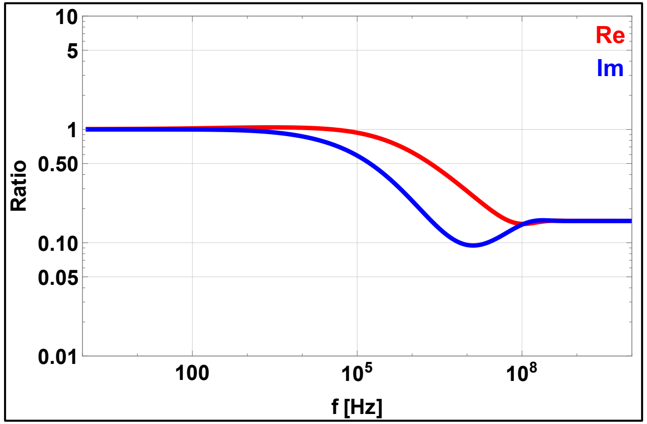
When Re = Im => Classical thick-wall regime

Copper: *ρ* = 17 nΩm, *b* = 20 mm

$$Z_y\left(f\right) = \left(1 + j\right) \frac{Z_0}{2 \pi b^3} \delta_{SkinDepth}\left(f\right)$$

Example of the LHC “wall impedance”

Stainless steel beam pipe with 20 mm radius and 10 µm copper coating (room temp.)

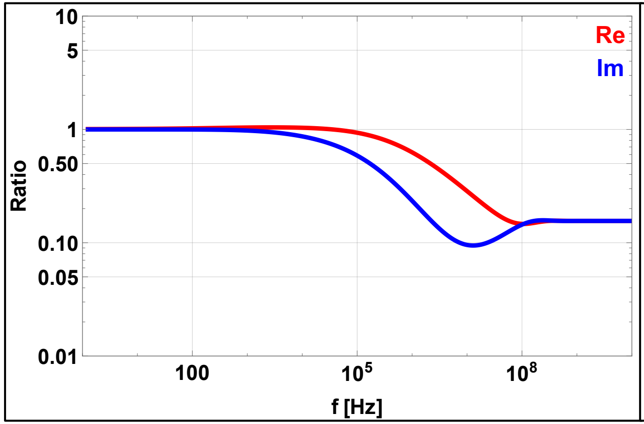


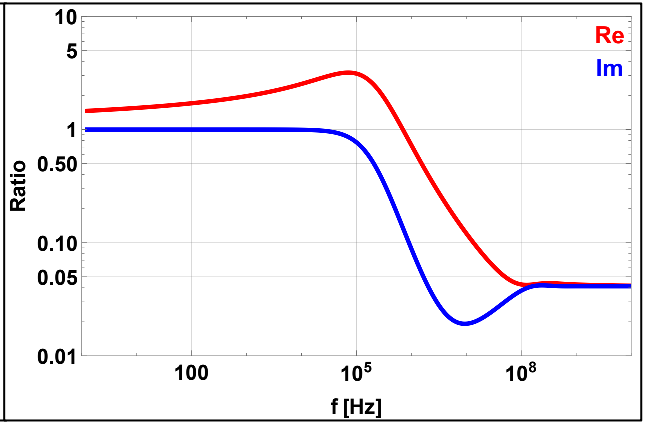
$$\text{Ratio} = \frac{Z_y\left(\text{with coating}\right)}{Z_y\left(\text{without coating}\right)}$$

Example of the LHC "wall impedance"

Stainless steel beam pipe with 20 mm radius and 10 µm copper coating (room temp.)

Graphite beam pipe with 2 mm radius and 10 µm copper coating (room temp.)

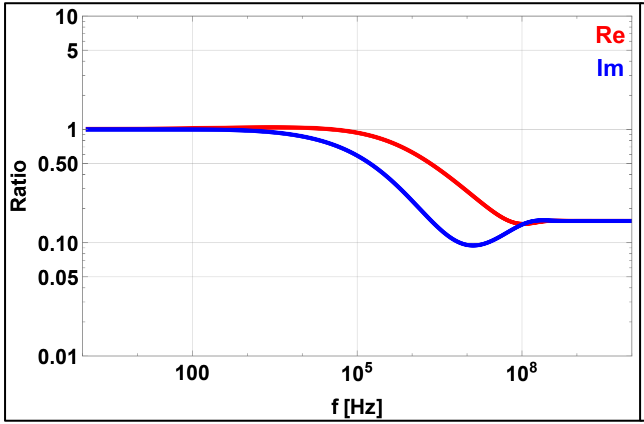




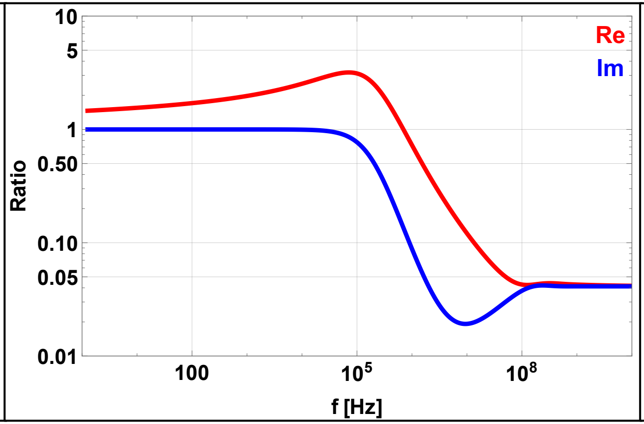
$$\text{Ratio} = \frac{Z_y(\text{with coating})}{Z_y(\text{without coating})}$$

Example of the LHC "wall impedance"

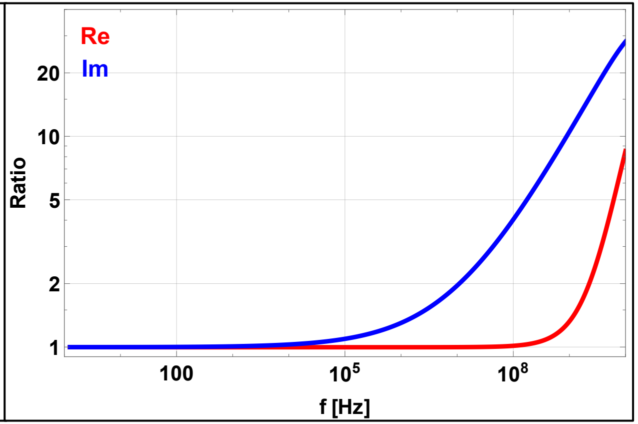
Stainless steel beam pipe with 20 mm radius and 10 µm copper coating (room temp.)



Graphite beam pipe with 2 mm radius and 10 µm copper coating (room temp.)



Copper (room temp.) beam pipe with 20 mm radius and 10 µm graphite coating



$$\text{Ratio} = \frac{Z_y\left(\text{with coating}\right)}{Z_y\left(\text{without coating}\right)}$$

Wake field accelerators

As $|z|$ increases, W'_m and W_m may change signs and the wake forces become beneficial. In particular, W'_0 may become negative at some finite distance behind the head of the beam. Therefore, if one injects two beam bunches into the accelerator and if the separation of the two bunches is chosen strategically, the trailing bunch can be *accelerated* by the wake field of the leading bunch. This leads to the idea of *wake field accelerators*. We will

E. Métral - G. Rumolo - T. Pieloni, MCBI2019 workshop, Zermatt, Switzerland, 23-27/09/2019

Closing remarks for the MCBI2019 workshop

E. Métral, G. Rumolo and T. Pieloni

Yong Ho Chin 1958–2019

A foremost accelerator physicist

Albert Hofmann 1933–2018

An expert in all things colliders

1^{st} talk from MCBI 2019 by M. Migliorati

Acknowledgements

- First studies of impedance-induced instabilities were developed in the early 70s, and even before, with the initial concepts of dispersion relations and coupling impedance

- Some influential people who made the story of this important, intriguing and always in fashion topic of particle accelerators are:
  - A. Chao, C. Pellegrini, A. M. Sessler, V. Vaccaro, F. Sacherer, J. L. Laclare, B. Zotter, K. Yokoya, Y. Chin, J. Haissinski, A. Hoffmann, V. K. Neil, L. J. Laslett, M. Sands, E. D. Courant, …

… and, of course, also many colleagues participating to this workshop!

Mitigation of Coherent Beam Instabilities in particle accelerators 23/09/2019 Pag. 6

1st talk from MCBI 2019 by M. Migliorati

Acknowledgements

- How to summarize in 30 minutes more than 50 years of studies, works and experiments on collective effects?
- A considerable amount of papers on many refereed journals have been, and continue to be, published
- Also books have been written on this subject, as:
  - A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators
  - K. Y. Ng, Physics of Intensity Dependent Beam Instabilities
  - …

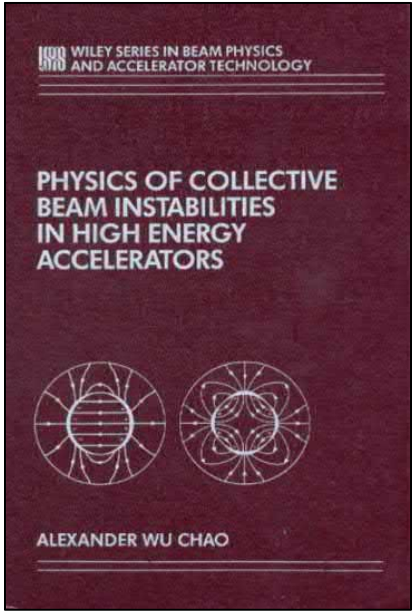
A short phrase to summarize the work that has been done could be:

"Particle Accelerators Work and are Successful"

Are we just lucky? After 50 years it couldn't be only a coincidence …

Mitigation of Coherent Beam Instabilities in particle accelerators 23/09/2019 Pag. 10

Impedance-induced coherent instabilities



Beam Break-Up instability in linacs

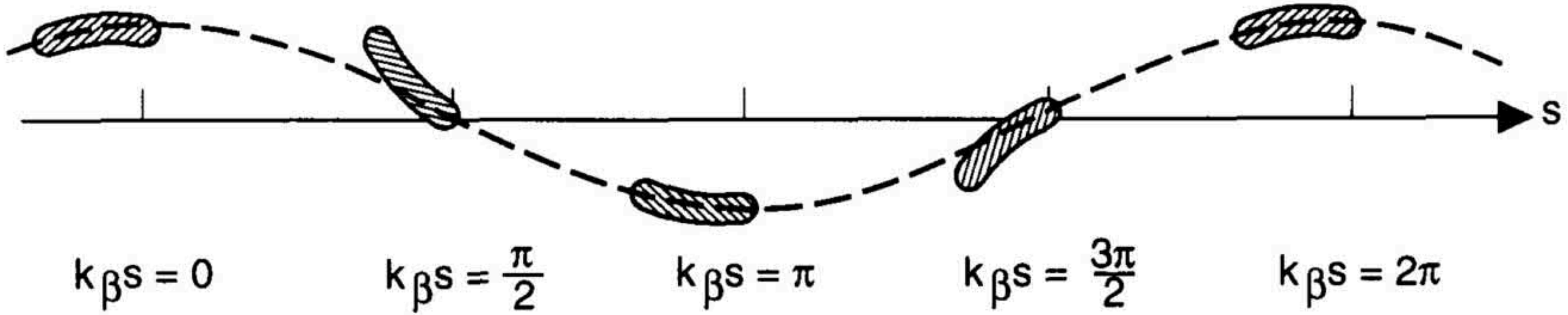


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

Beam Break-Up instability in linacs

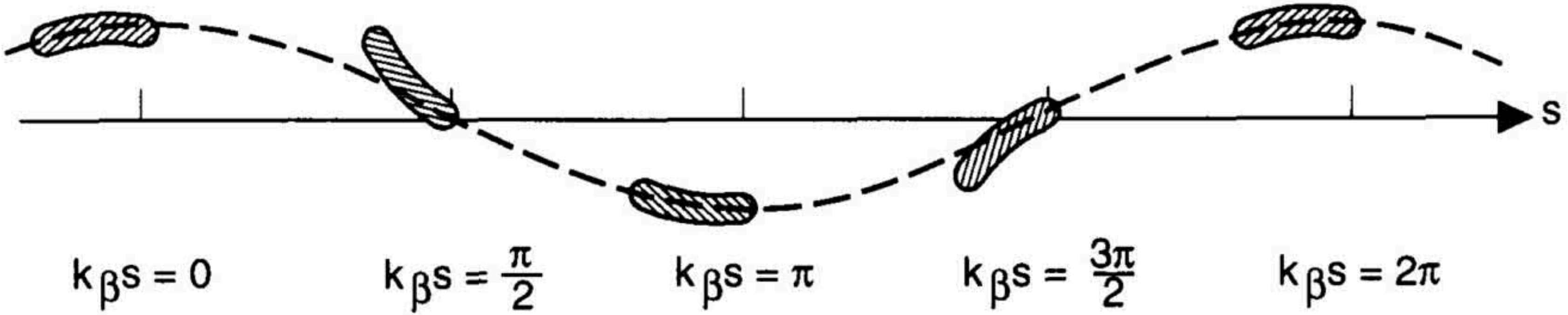


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

section. The first observation of this beam breakup effect was made on the SLAC linac.[5]

[5] R. B. Neal and W. K. H. Panofsky, Science **152**, 1353 (1966); W. K. H. Panofsky and M. Bander, Rev. Sci. Instr. **39**, 206 (1968).

Instabilities in circular machines

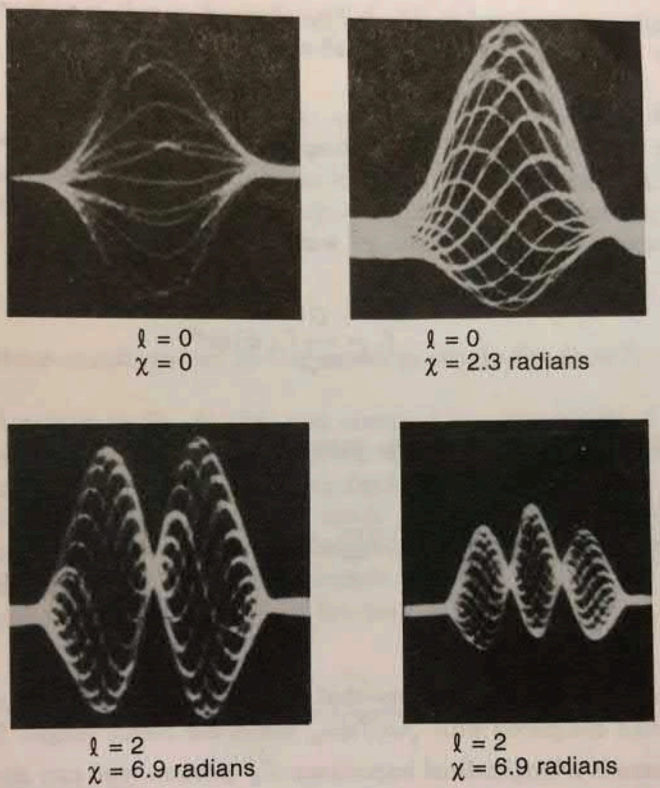
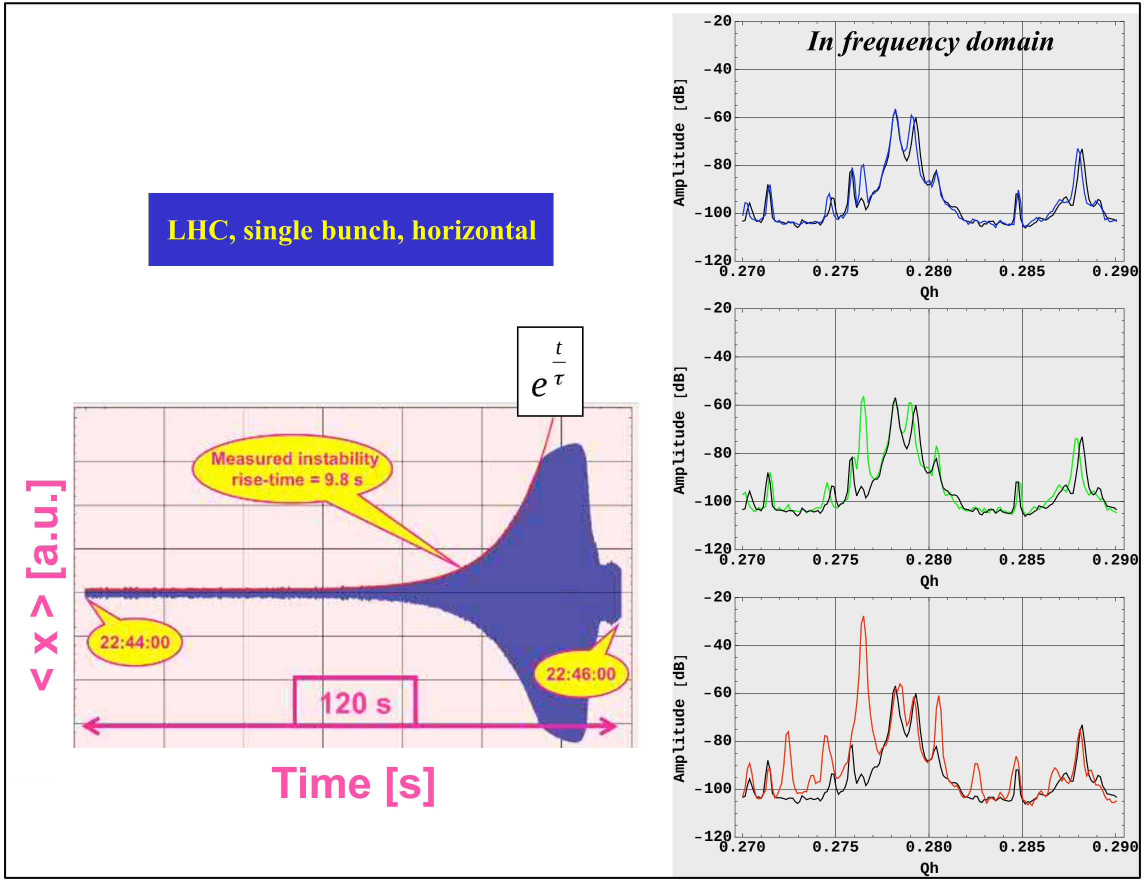
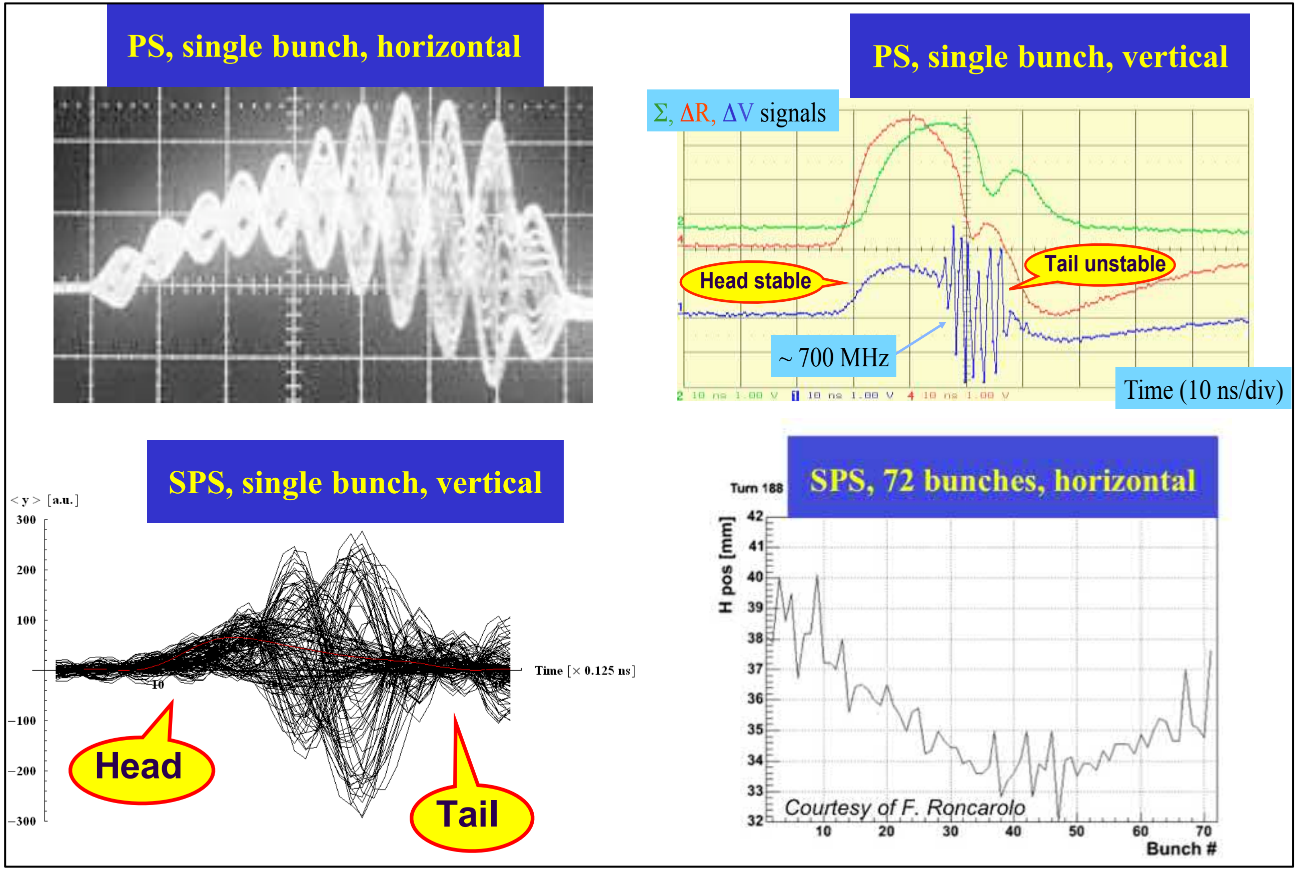


Figure 6.32. Transverse beam oscillation modes observed at the CERN PS Booster. The head-tail phase χ is properly defined for the observed bunch shape. (Courtesy Jacques Gareyte, 1992).

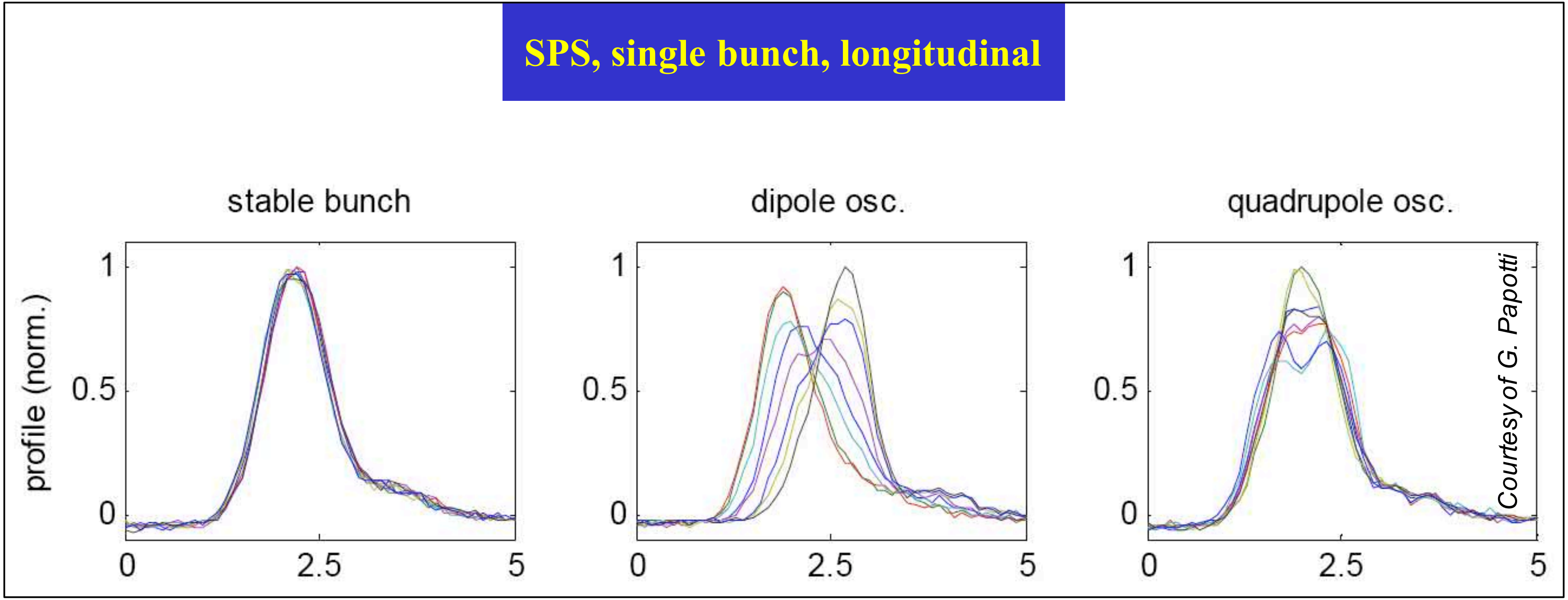
Instabilities in circular machines



Instabilities in circular machines



Instabilities in circular machines



F. Sacherer and the mode analysis

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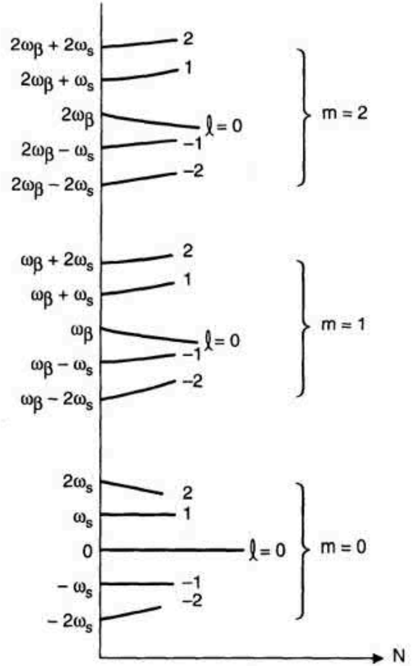


Figure 6.2. Sketch of the dependence of the mode frequencies on the intensity N for a short bunched beam. Ignoring the radial modes, a mode is specified by its transverse mode index m and longitudinal index l. When $N = 0$, the mode frequencies are given by $m\omega_\beta + l\omega_s$. As N increases, the mode frequencies shift, obeying some general rules mentioned in the text.

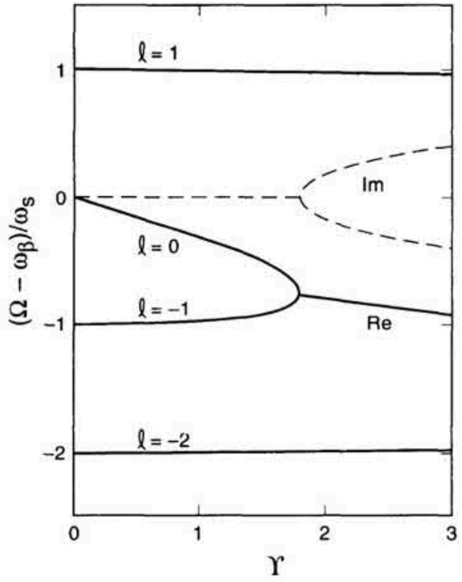
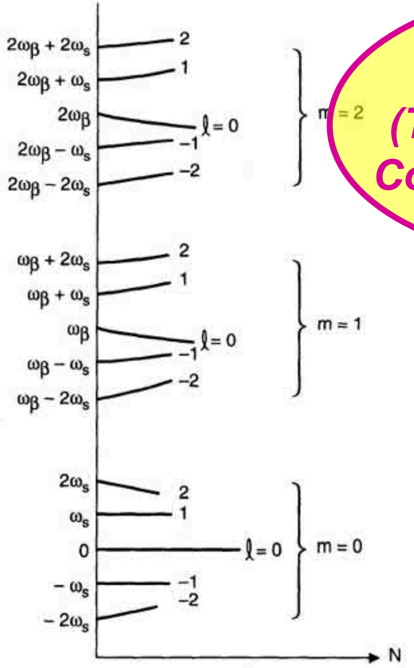


Figure 6.37. Transverse mode frequencies $(\Omega - \omega_\beta)/\omega_s$ versus the parameter Υ for an air-bag beam and an impedance (6.215). The instability threshold is located at $\Upsilon_{th} \approx 1.8$. At the threshold, the $l = 0$ mode frequency has shifted down from ω_β by $\sim 0.8\omega_s$. The dashed curves are the imaginary part of the mode frequencies for $l = 0$ and $l = -1$. This graph can be compared with Figure 4.8 for the two-particle model.

F. Sacherer and the mode analysis

criterion for the beam. The mode analysis that we will follow was largely developed by Sacherer[2] and extended by others.[3] We will also mention work



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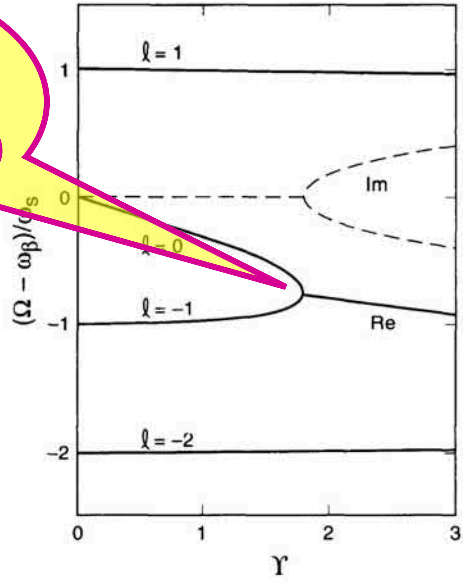
TMCI

(Transverse Mode-Coupling Instability)



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F. Sacherer and the mode analysis

our 10^{12}-particle system. In this approach, the motion of the beam is described by a superposition of modes, rather than a collection of individual particles.

F. Sacherer and the mode analysis

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TNB:UNPLANNED BIVIES

TNB: Forgotten Hero - Frank Sacherer 1940-1978

By Duane Raleigh

Search Wikipedia for "Frank Sacherer," and you'll find … nothing, at least not in English. Google him and the first listing is often "Find a Grave," which tells you that he was born in 1940, was a theoretical physicist and a Yosemite rock climber who died in a mountaineering accident. You will also read that his death was a "grievous loss" to CERN, the organization that operates the Large Hadron Collider, a 27-kilometer-long ring that can smash atoms together at near light speed and recently discovered the so-called "God Particle," the sub-atomic bit that is said to hold the physical fabric of the universe together.

Frank Sacherer was one of the fathers of free climbing. Photo by Glen Denny.

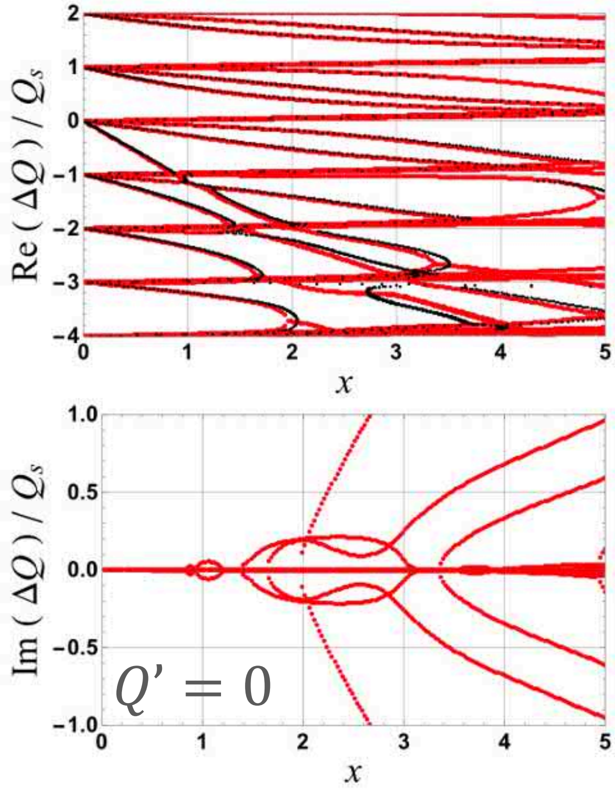
Most climbers, if they have heard of Sacherer at all, know him only as the first ascentionist of *Sacherer Cracker*, a stout 5.10 that goes from fingers to offwidth at the base of El Cap. But even to most of those people, Sacherer is simply part of a route name, like the Salathé of *Steck/Salathé*. Who he was, and his impact on climbing is largely unknown.

TNB BLOG

Examples of TMCI & LMCI => Vlasov solvers GALACTIC and GALACLIC

Examples of TMCI & LMCI => Vlasov solvers GALACTIC and GALACLIC

TIC (BB Resonator, $f_r \tau_b = 2.8$)



Results in black are from Laclare (only real parts)

Examples of TMCI & LMCI => Vlasov solvers GALACTIC and GALACLIC

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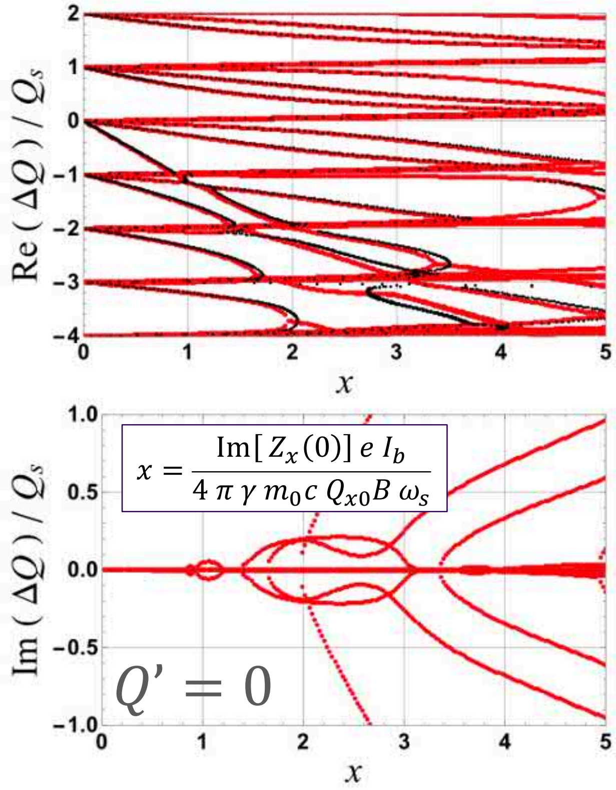

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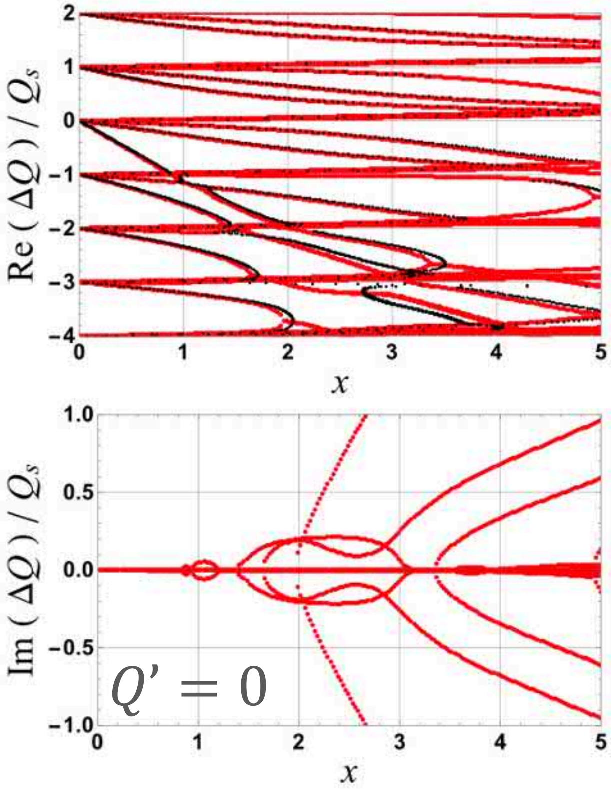
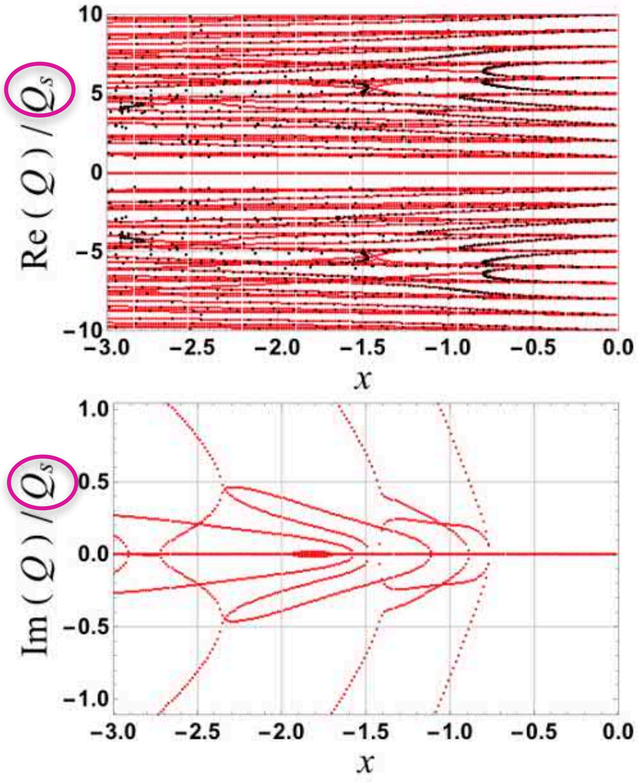


LIC (similar BBR) **without PWD**



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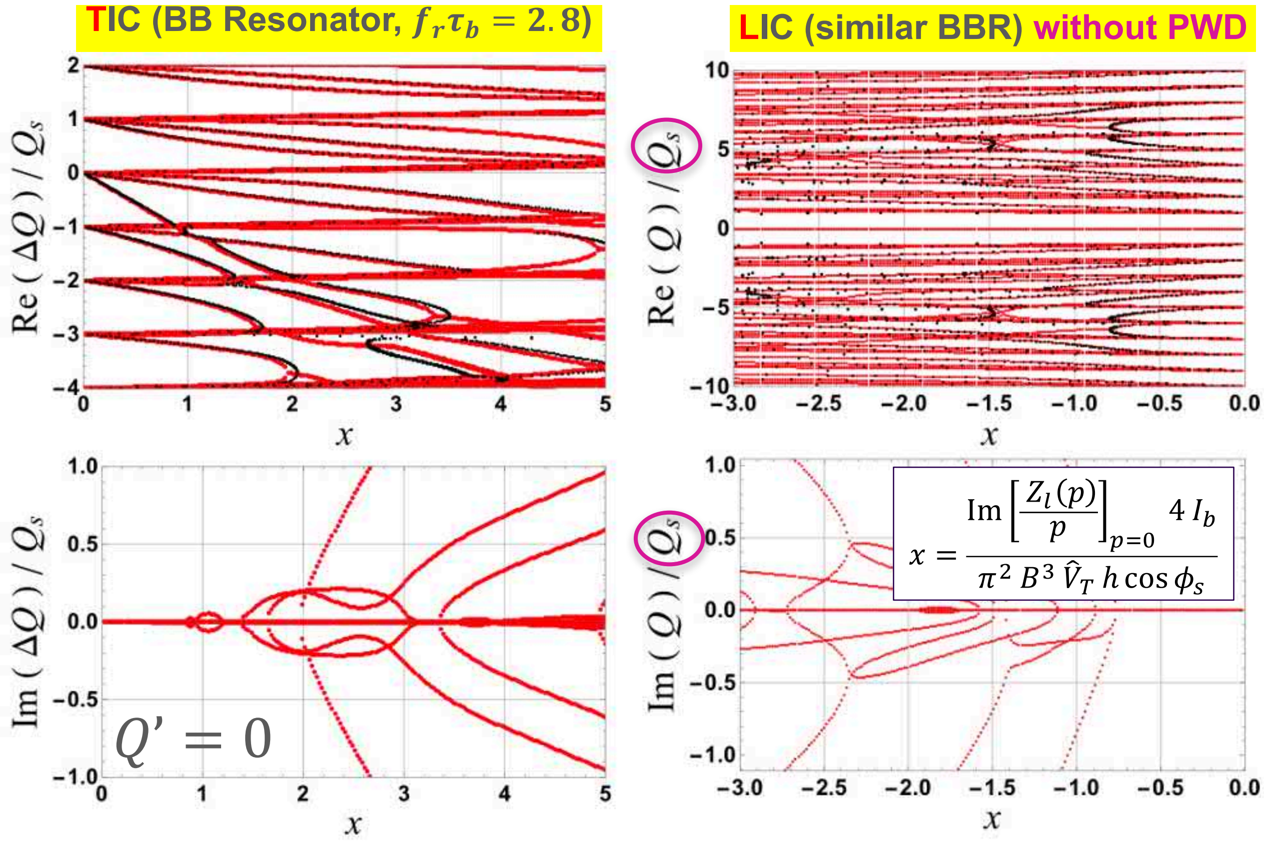
Examples of TMCI & LMCI => Vlasov solvers GALACTIC and GALACLIC

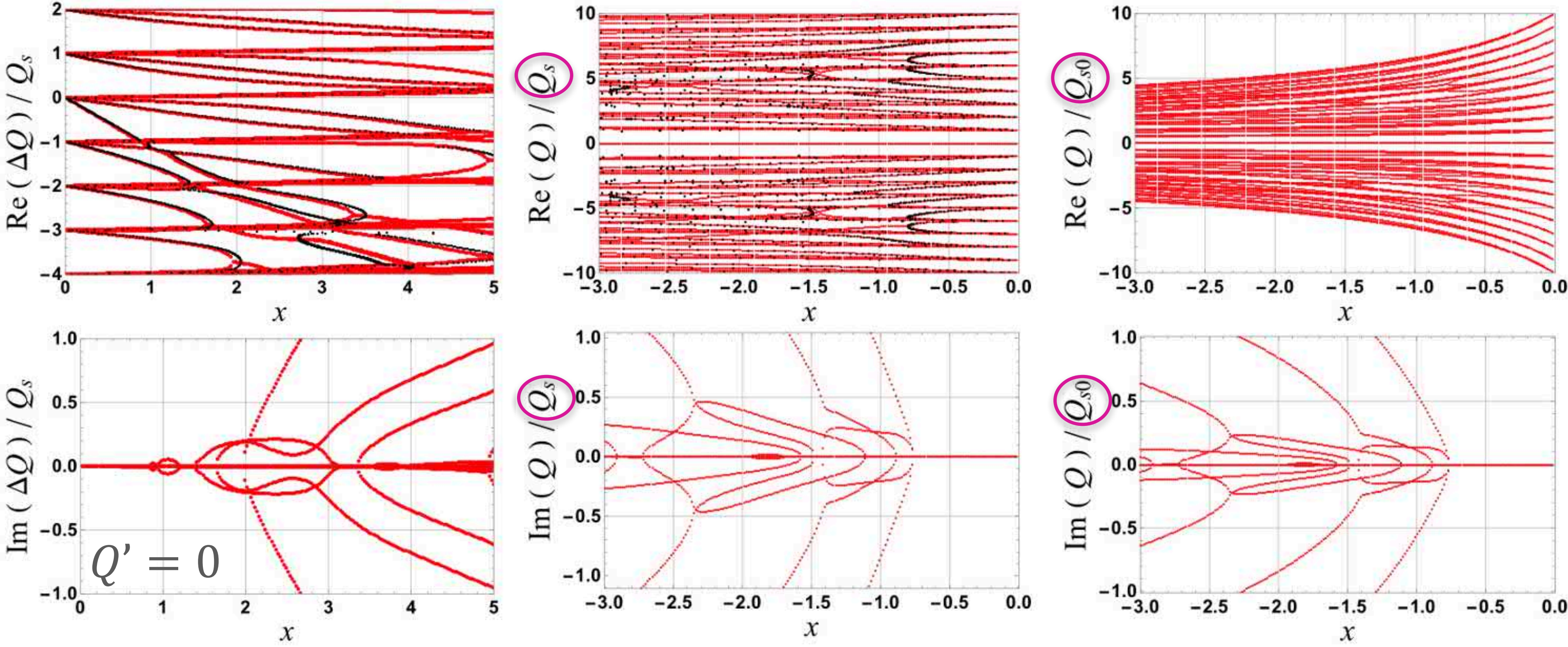


$$x = \frac{\mathrm{Im}\left[\frac{Z_l(p)}{p}\right]_{p=0} \; 4\, I_b}{\pi^2\, B^3\, \hat{V}_T\, h \cos\phi_s}$$

Results in black are from Laclare (only real parts)

Examples of TMCI & LMCI => Vlasov solvers GALACTIC and GALACLIC

TIC (BB Resonator, $f_r \tau_b = 2.8$) | **LIC (similar BBR) without PWD** | **LIC (similar BBR) with PWD**



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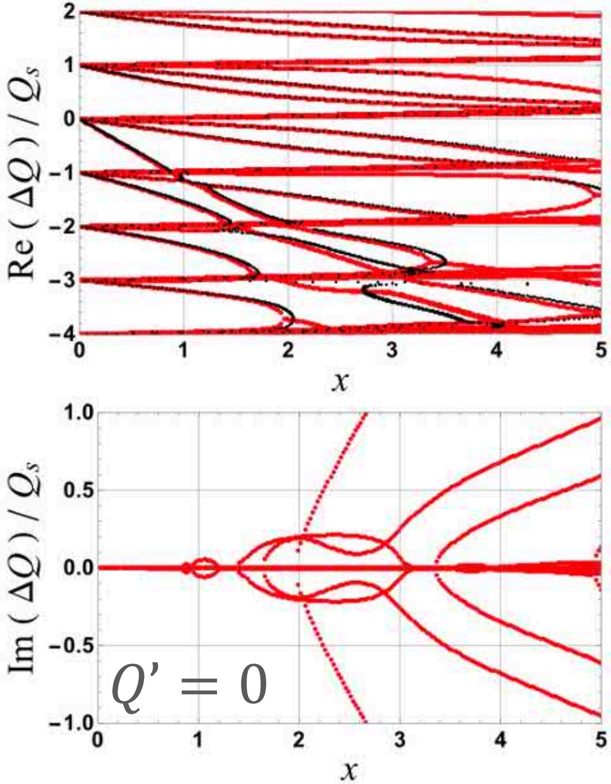
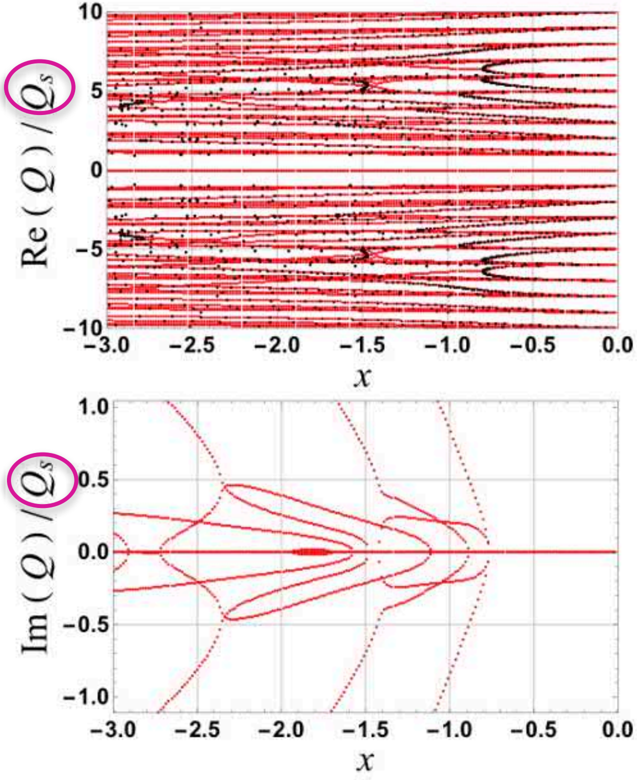
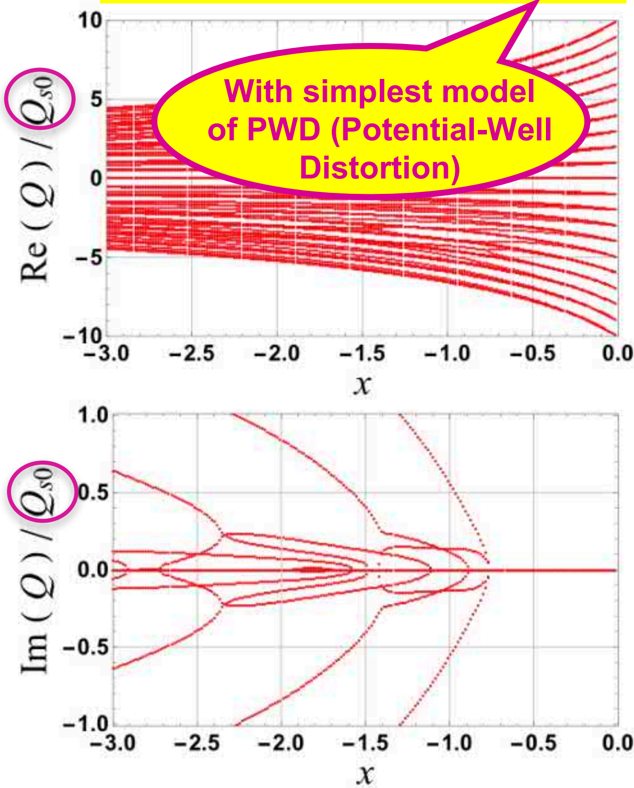


LIC (similar BBR) without PWD



LIC (similar BBR) with PWD



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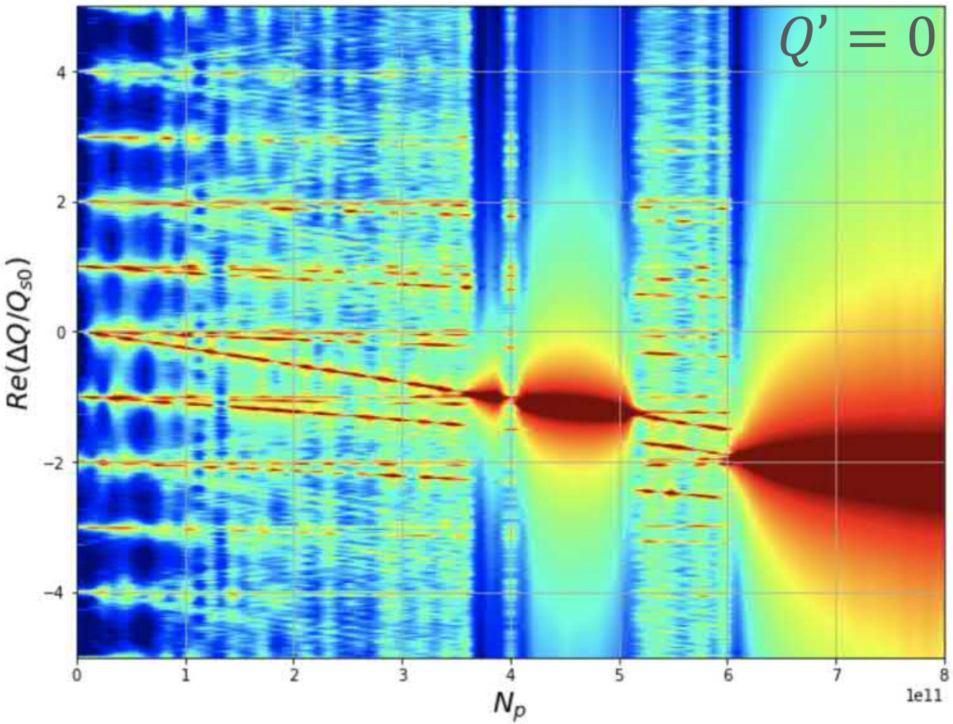
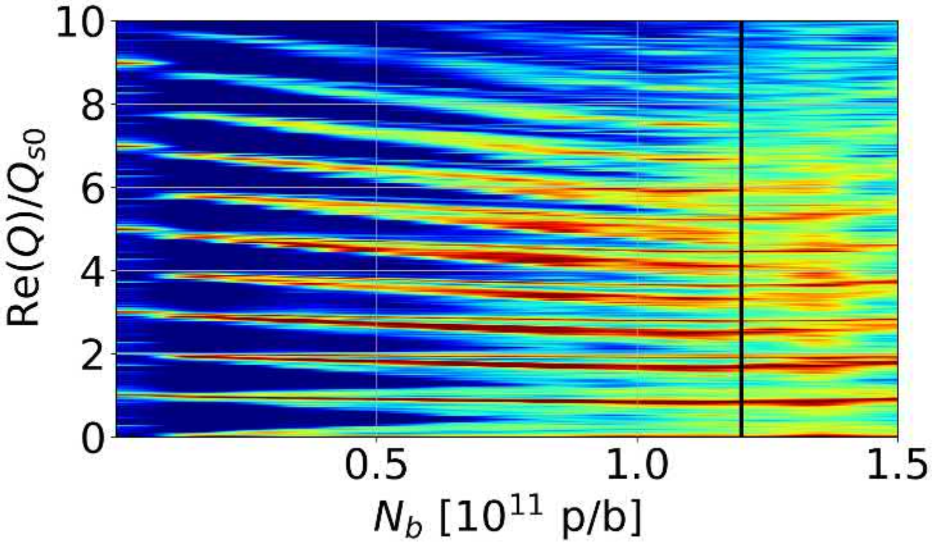
Examples of TMCI & LMCI => Comparison with tracking codes

PyHEADTAIL $(f_r \tau_b = 2.7)$ SBSC $(f_r \tau_b = 2.7)$

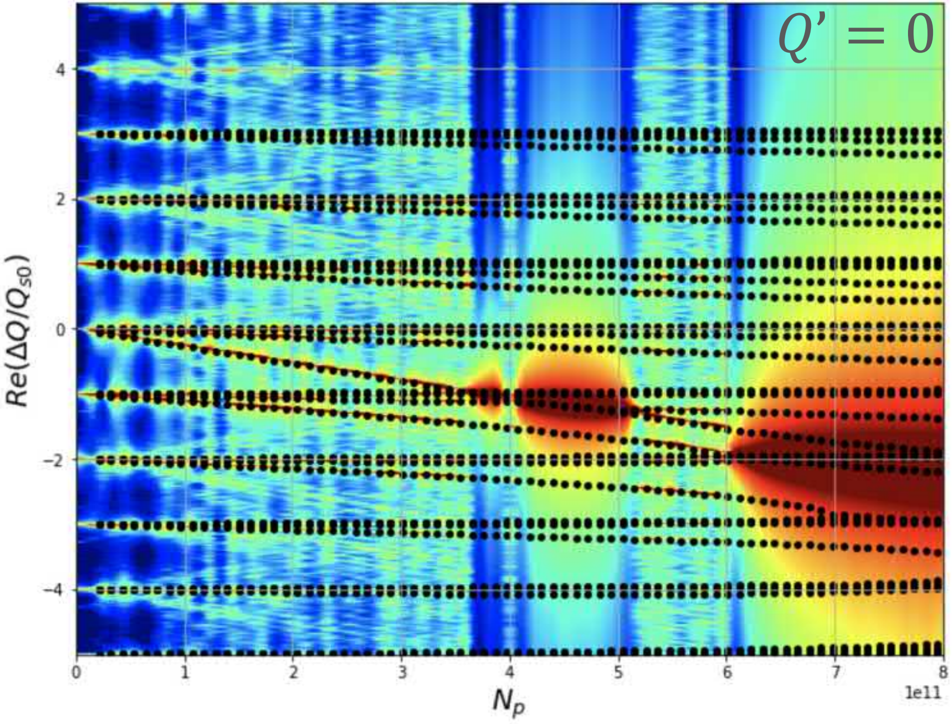




PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)

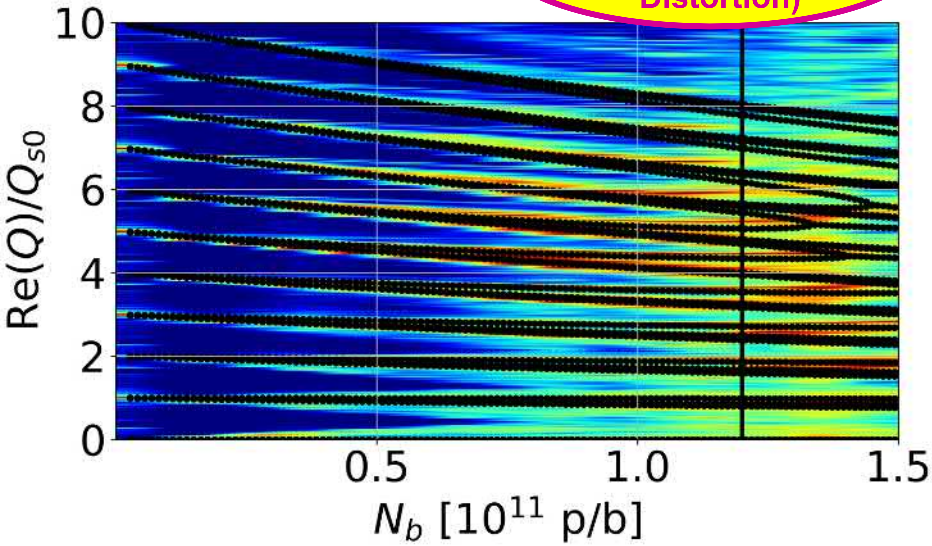
Examples of TMCI & LMCI => Comparison with tracking codes

PyHEADTAIL $(f_r \tau_b = 2.7)$
vs. GALACTIC (in black)



SBSC $(f_r \tau_b = 2.7)$
vs. GALACLIC (in black)

With simplest model of PWD (Potential-Well Distortion)



PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)

Examples of TMCI & LMCI => Comparison with tracking codes

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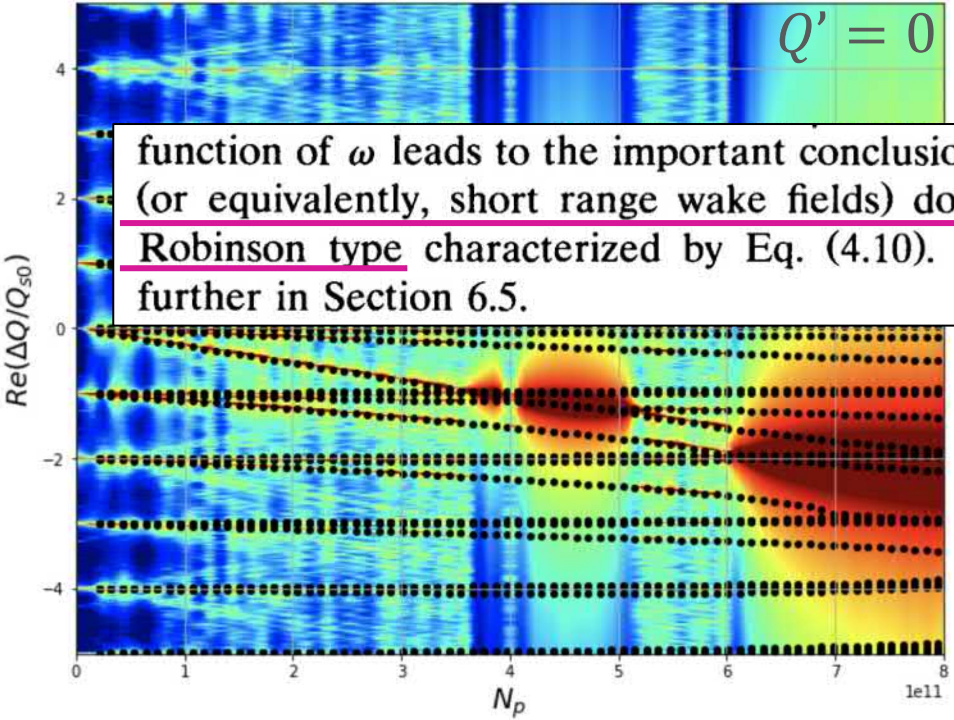
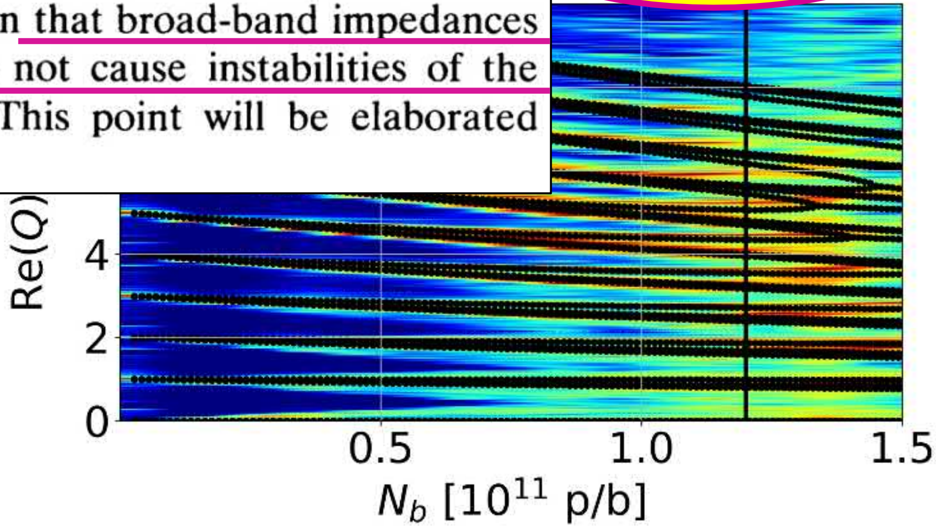


function of ω leads to the important conclusion that broad-band impedances (or equivalently, short range wake fields) do not cause instabilities of the Robinson type characterized by Eq. (4.10). This point will be elaborated further in Section 6.5.

With simplest model of PWD (Potential-Well Distortion)



PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)

Examples of TMCI & LMCI => Comparison with tracking codes

PyHEADTAIL $(f_r \tau_b = 2.7)$ vs. GALACTIC (in black)

SBSC $(f_r \tau_b = 2.7)$ vs. GALACLIC (in black)

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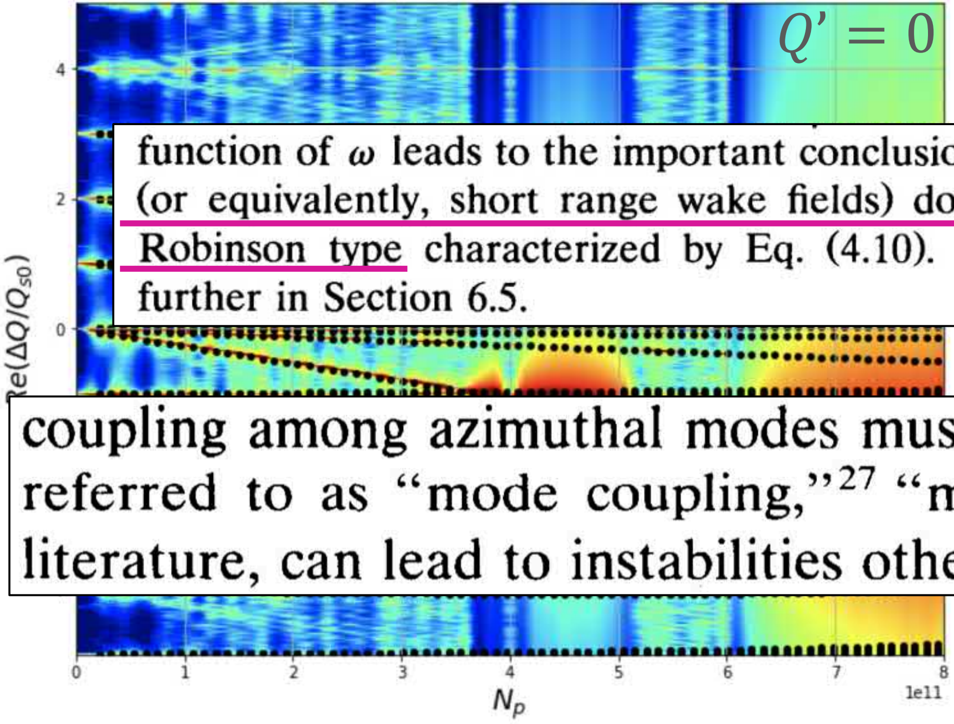

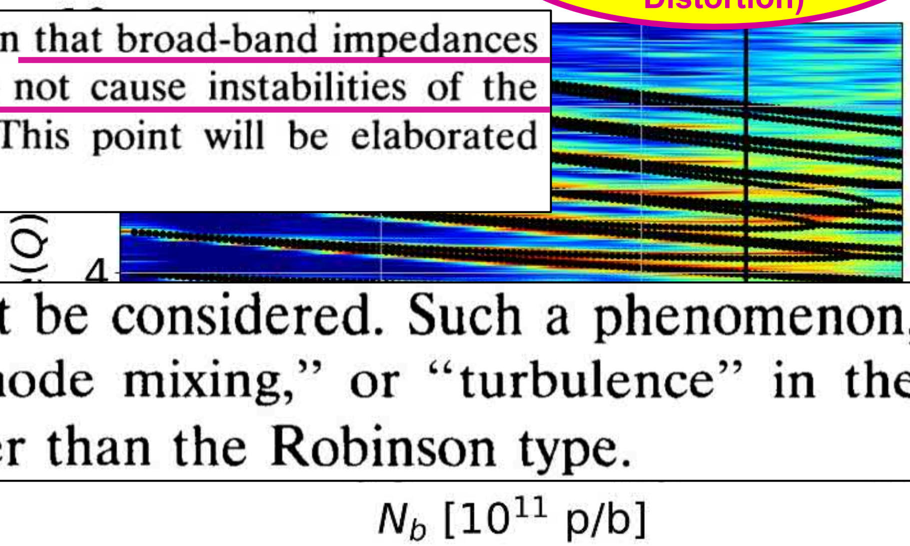

function of ω leads to the important conclusion that broad-band impedances (or equivalently, short range wake fields) do not cause instabilities of the Robinson type characterized by Eq. (4.10). This point will be elaborated further in Section 6.5.

coupling among azimuthal modes must be considered. Such a phenomenon, referred to as "mode coupling,"[27] "mode mixing," or "turbulence" in the literature, can lead to instabilities other than the Robinson type.

PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)

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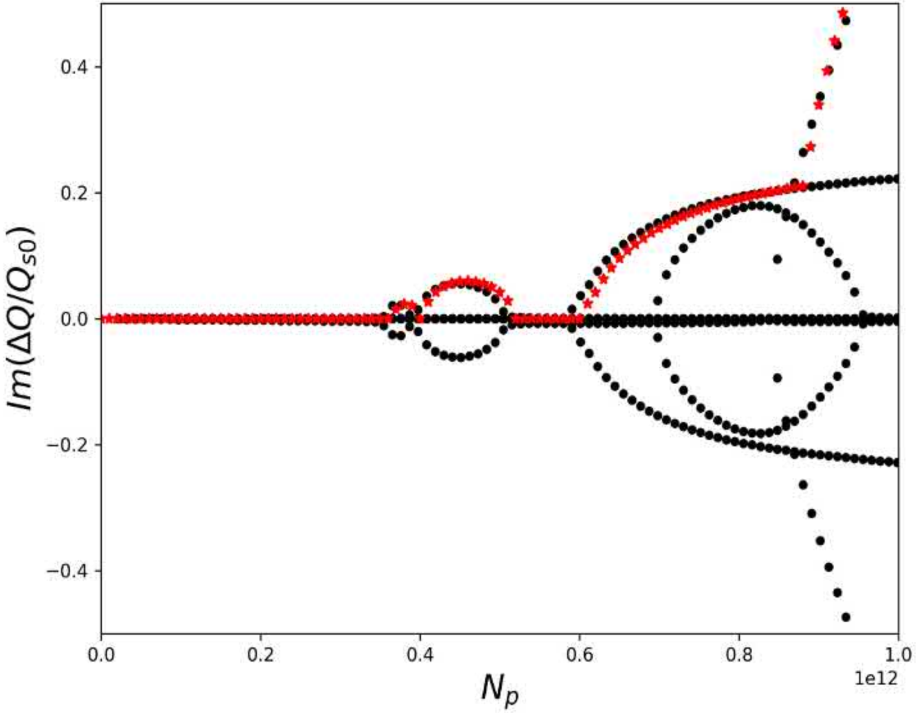
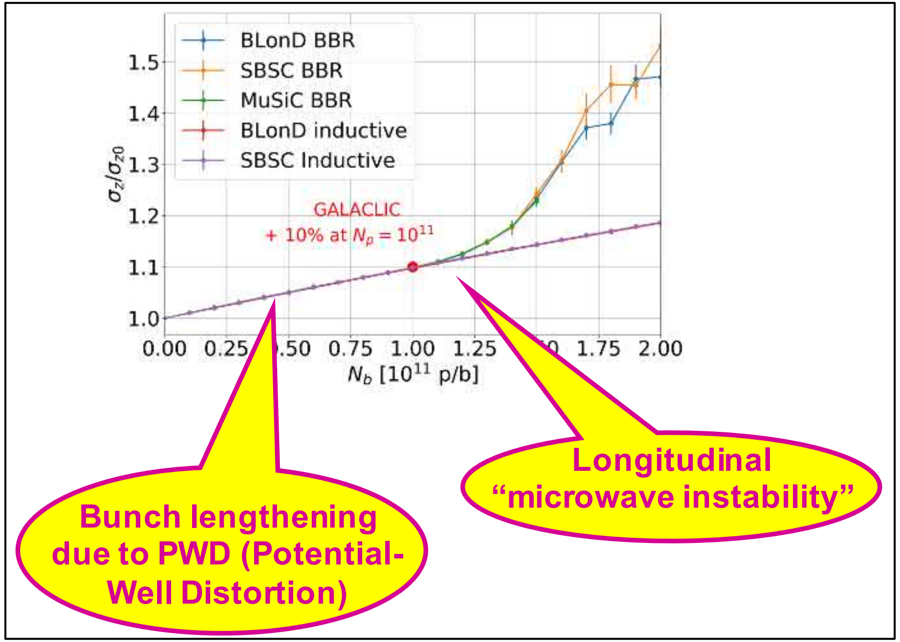


SBSC $(f_r \tau_b = 2.7)$
vs. GALACLIC (in black)

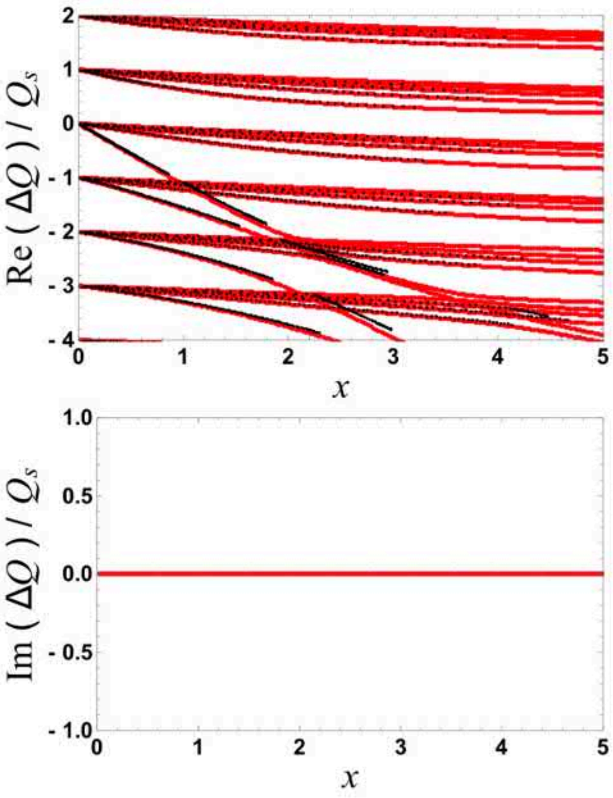


PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)

Neither TMCI nor LMCI w/o real part of impedance

Neither TMCI nor LMCI w/o real part of impedance

GALACTIC with constant inductive impedance



Results in black are from Laclare (only real parts)

Signals observed at Pick-Up electrodes

Signals observed at Pick-Up electrodes

Transverse: low-intensity with constant inductive impedance

Signals observed at Pick-Up electrodes

Transverse: low-intensity with constant inductive impedance

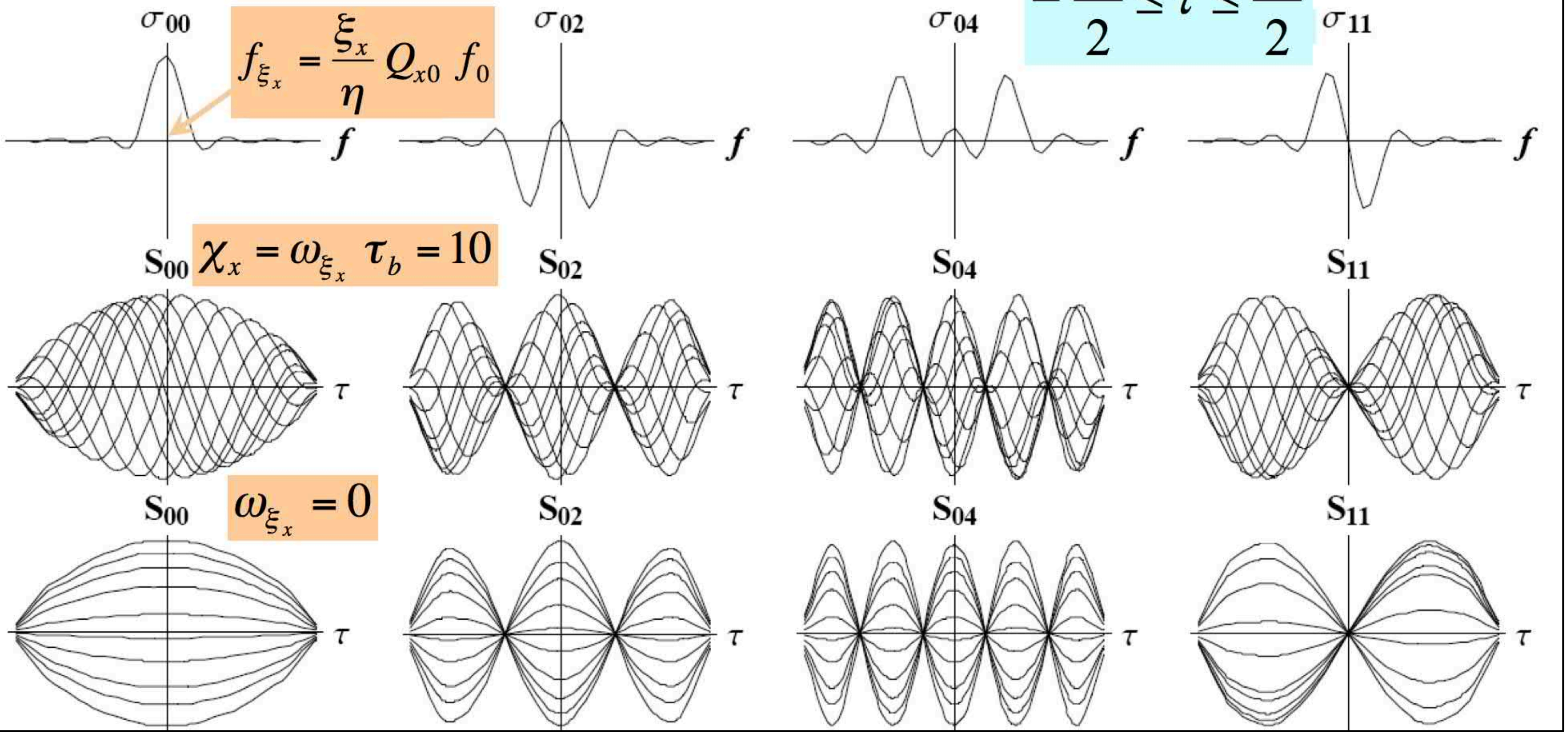
$$-\frac{\tau_b}{2} \leq \tau \leq \frac{\tau_b}{2}$$

$$Q_{x0} = \text{x}.13$$

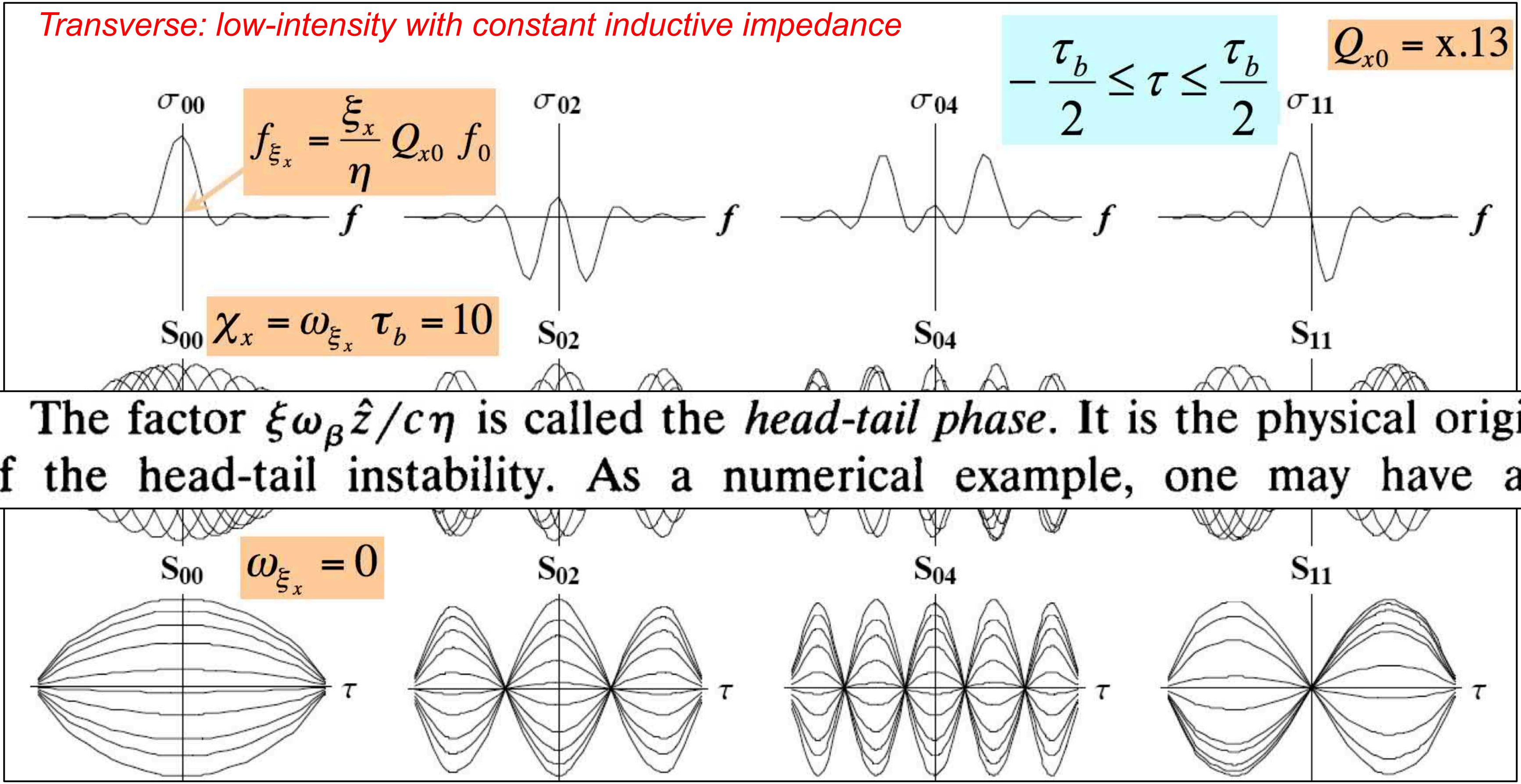
$$f_{\xi_x} = \frac{\xi_x}{\eta} Q_{x0} \, f_0$$

$$\chi_x = \omega_{\xi_x} \, \tau_b = 10$$

$$\omega_{\xi_x} = 0$$



Signals observed at Pick-Up electrodes

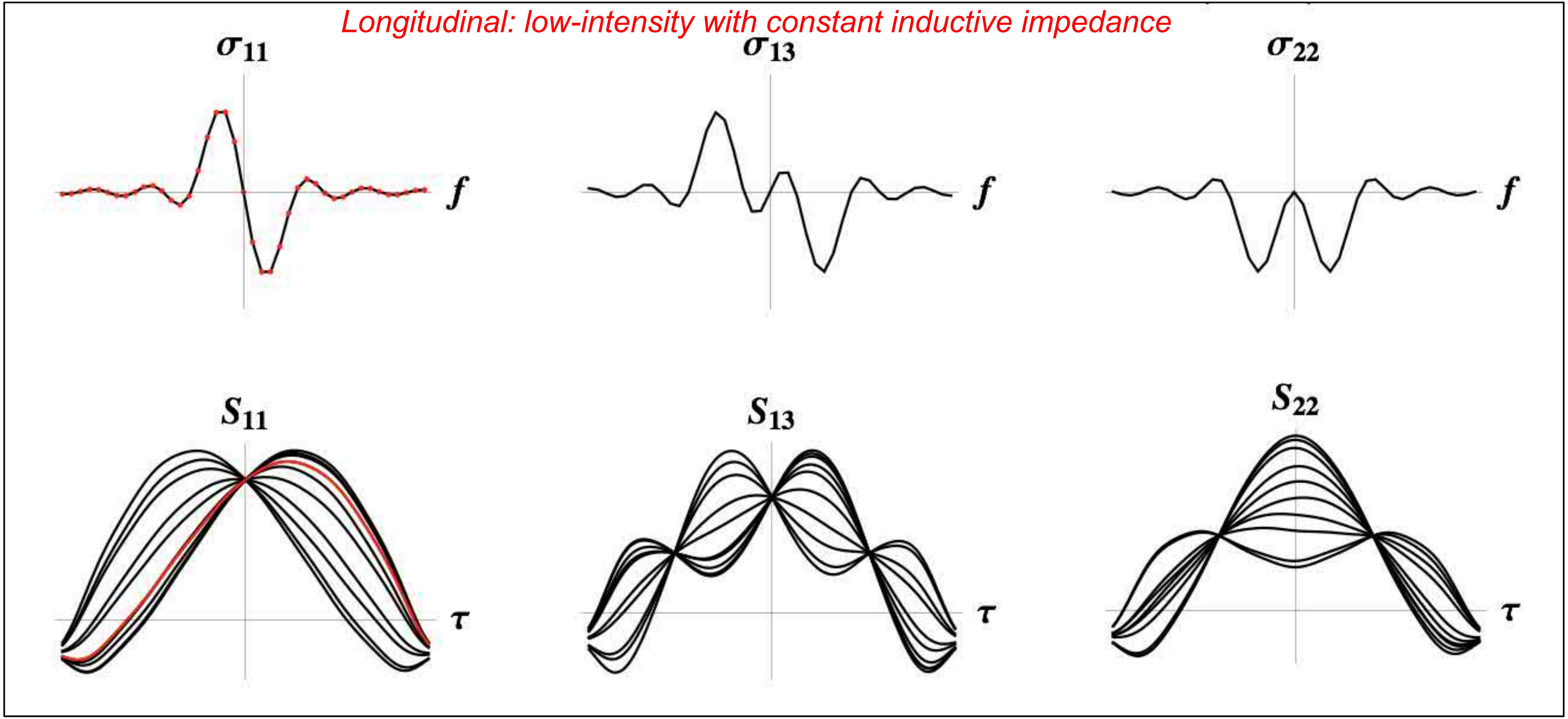


The factor $\xi \omega_\beta \hat{z}/c\eta$ is called the *head-tail phase*. It is the physical origin of the head-tail instability. As a numerical example, one may have an

Signals observed at Pick-Up electrodes

Longitudinal: low-intensity with constant inductive impedance

Signals observed at Pick-Up electrodes

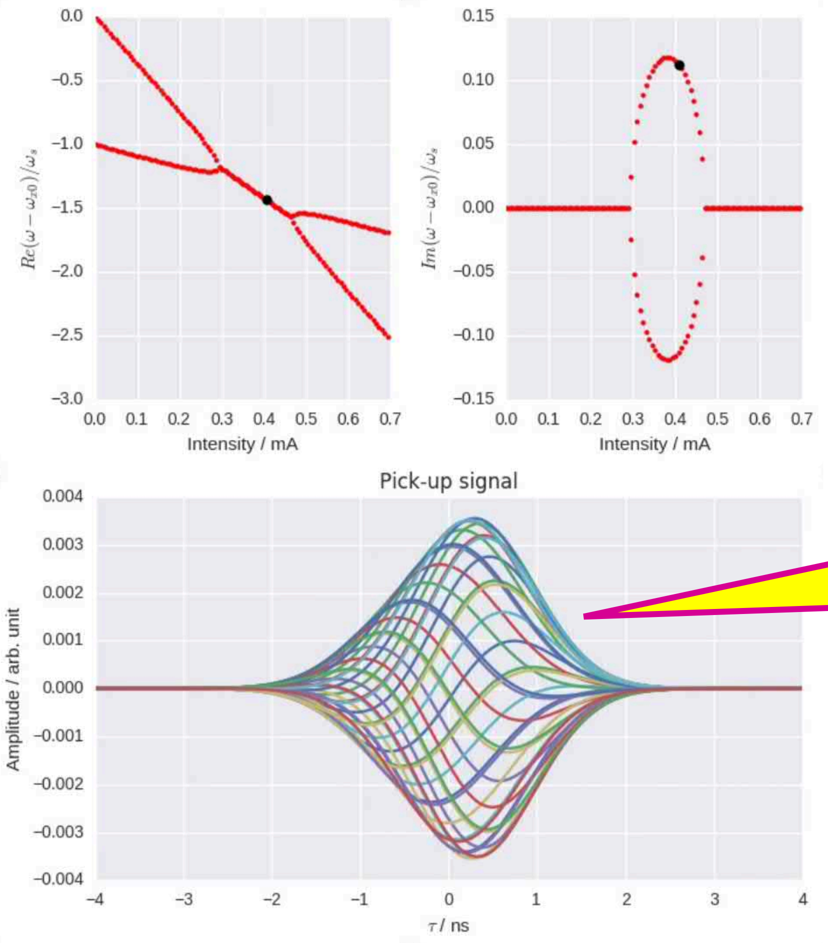


Signals observed at Pick-Up electrodes

Transverse: high-intensity

Signals observed at Pick-Up electrodes

Transverse: high-intensity

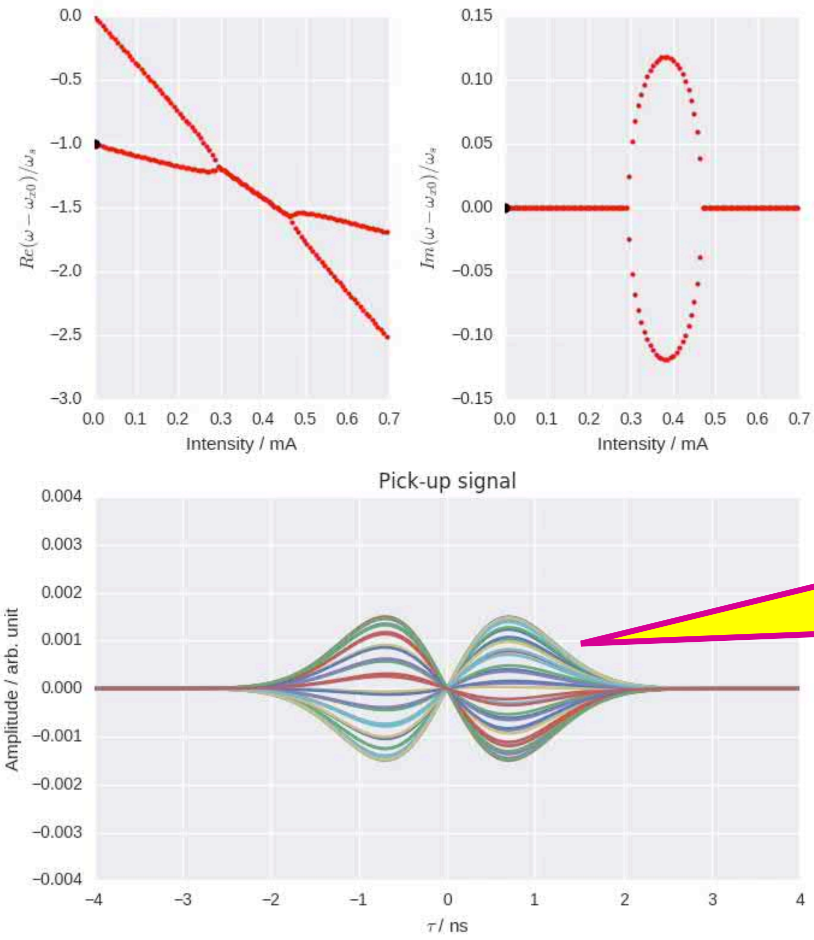


Example from the DELPHI Vlasov solver (N. Mounet, 2014)

D. Amorim

Signals observed at Pick-Up electrodes

Transverse: high-intensity



Example from the DELPHI Vlasov solver (N. Mounet, 2014) => Movie

D. Amorim

Landau damping (and BNS damping for linacs)

CHAPTER 5

Landau Damping

As the previous chapters demonstrated, there are a large number of collective instability mechanisms acting on a high intensity beam in an accelerator, demanding a wide range of (sometimes conflicting) stability conditions. Yet the beam as a whole seems basically stable, as evidenced by the existence of a wide variety of working accelerators, many of them with demanding beam intensities. One of the reasons for this fortunate outcome is *Landau damping*,[1] which provides a natural stabilizing mechanism against collective instabilities if particles in the beam have a small spread in their natural (synchrotron or betatron) frequencies. The purpose of the present chapter is

Landau damping (and BNS damping for linacs)

CHAPTER 5

Landau Damping

[11] V. Balakin, A. Novokhatsky, and V. Smirnov, *Proc. 12th Int. Conf. High Energy Accel.*, Fermilab, 1983, p. 119.

[12] The mechanism of BNS damping is not to be confused with that of Landau damping, to be discussed in Chapter 5. They have little in common other than the fact that both involve a frequency spread in the bunch population.

As the previous chapters demonstrated, there are a large number of collective instability mechanisms acting on a high intensity beam in an accelerator, demanding a wide range of (sometimes conflicting) stability conditions. Yet the beam as a whole seems basically stable, as evidenced by the existence of a wide variety of working accelerators, many of them with demanding beam intensities. One of the reasons for this fortunate outcome is *Landau damping*,[1] which provides a natural stabilizing mechanism against collective instabilities if particles in the beam have a small spread in their natural (synchrotron or betatron) frequencies. The purpose of the present chapter is

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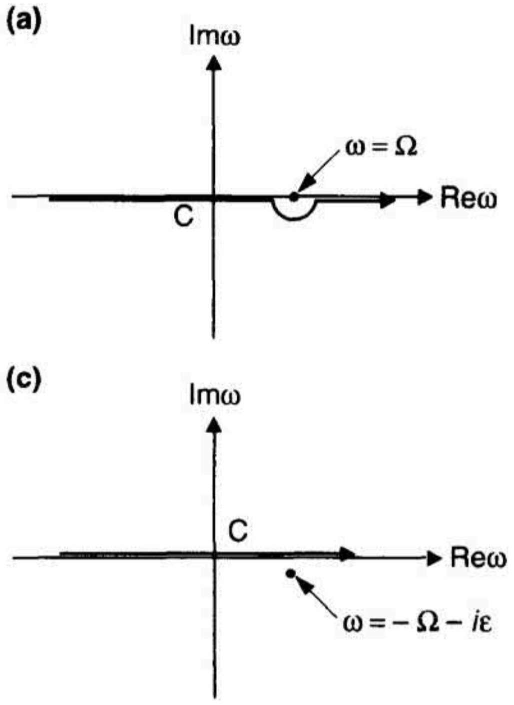

Figure 5.4. Contours in the complex ω-plane: (a) for Eq. (5.40); (b) for Eq. (5.41); (c) for Eq. (5.45) when $\Omega < 0$. The contours can be closed either in the upper half plane or the lower half plane provided $\rho(\omega)$ converges sufficiently rapidly as $|\omega| \to \infty$.

The connection (5.43) has the physical meaning of considering a force that has a time dependence of $\exp(-i\Omega t + \epsilon t)$, i.e., a force that grows with time at an infinitesimal rate. This means the driving force has not been in existence since $t = -\infty$, which has the same effect as introducing explicit initial conditions as far as removing the singularity is concerned.

50-page article for a special edition of IEEE Transactions on Nuclear Science for the 50th anniversary of the PAC conference (originally launched by IEEE in 1965)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016 1001

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REFERENCES

Out of 293

[1] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*. New York: Wiley, 1993, p. 371 [Online]. Available: http://books.google.fr/books?id=MjRoQgAACAAJ.

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VI. Conclusion

Beam instabilities have been studied for several decades and many intricate phenomena have been revealed. They were very often treated separately in the past but since some time the need to study several mechanisms together appeared, to try and better explained the reality of our accelerators. With the increasing power of our computers this becomes easier but the need to continue and develop theories remains, to have a better understanding of the interplays between all these effects, which is the current challenge in the study of beam instabilities.

New kinds of instabilities: 2 examples

“ISR instability” (due to resistive Transverse Dampers)

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- Resistive and reactive Transverse Damper (**TD**)

$$\Delta Q_{TD} = \frac{e^{j\,\phi}}{2\,\pi\,d}$$

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- $\boldsymbol{\phi}$ = betatron phase advance between Pick-Up and Kicker
- $\boldsymbol{d}$ = damper damping time in machine turns (=2/G, G=gain)

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“ISR instability” (due to resistive Transverse Dampers)

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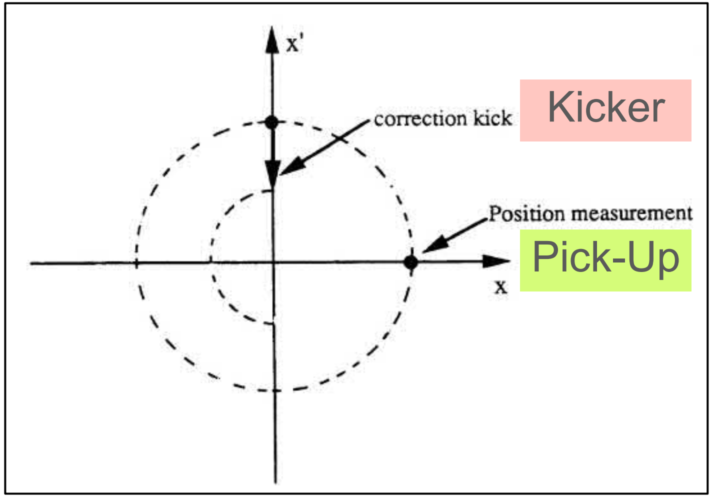

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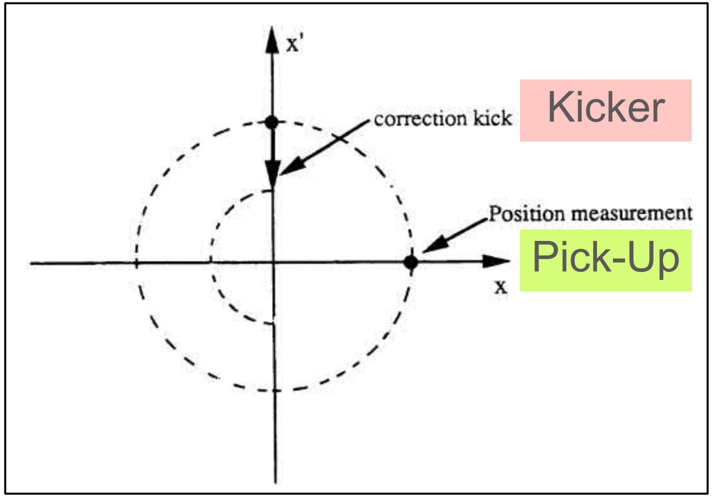

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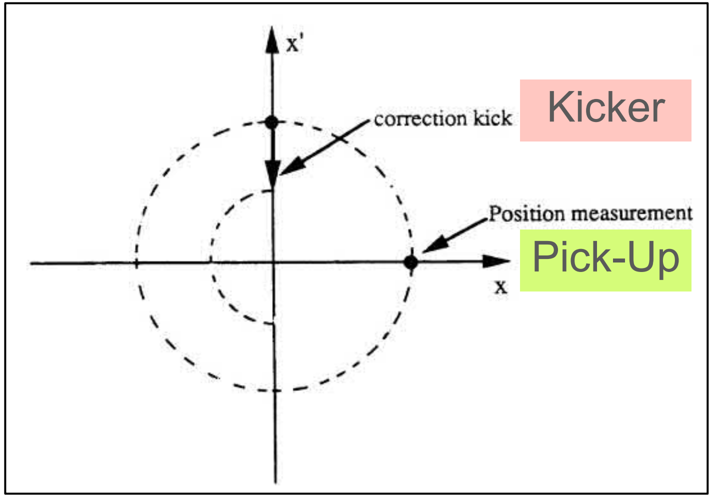
- If $\phi = 0°$ => **TD** is called "**reactive**": in this case, mode 0 is shifted (which can raise the intensity threshold in the presence of TMCI between modes 0 and -1)

"ISR instability" (due to resistive Transverse Dampers)

- Resistive and reactive Transverse Damper (**TD**)



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- ϕ = betatron phase advance between Pick-Up and Kicker
- d = damper damping time in machine turns (=2/G, G=gain)

  - If $\phi = 90°$ => **TD** is called "**resistive**": it is a conventional damper/feedback system, which damps the centre-of-charge motion of the beam

introducing a *reactive* feedback system—rather than the conventional system, which is resistive—that shifts the $l = 0$ mode frequency so as to delay the merging, the instability threshold may be raised. In the presence

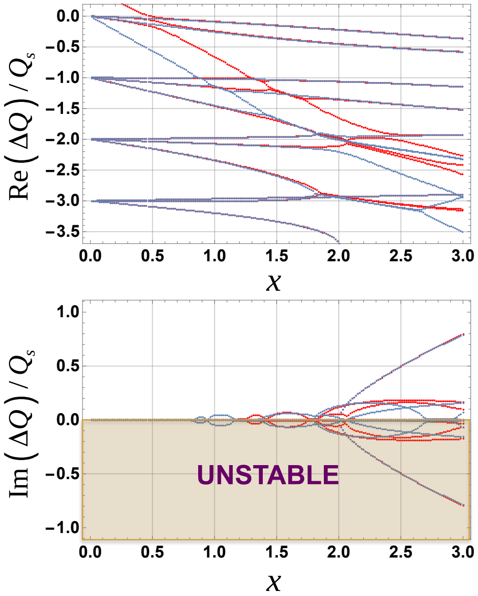
"ISR instability" (due to resistive Transverse Dampers)

Long-bunch regime: ~ CERN SPS

$(f_r \tau_b = 2.8, Q' = 0)$

No **TD**

Reactive **TD**



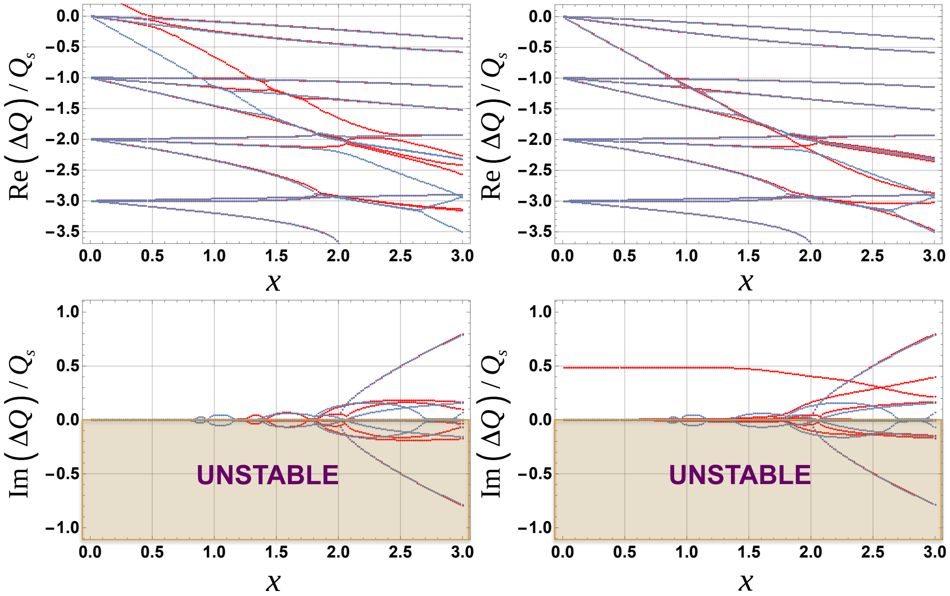
"ISR instability" (due to resistive Transverse Dampers)

Long-bunch regime: ~ CERN SPS

$(f_r \tau_b = 2.8, Q' = 0)$

No **TD** / Reactive **TD**

No **TD** / Resistive **TD**



“ISR instability” (due to resistive Transverse Dampers)

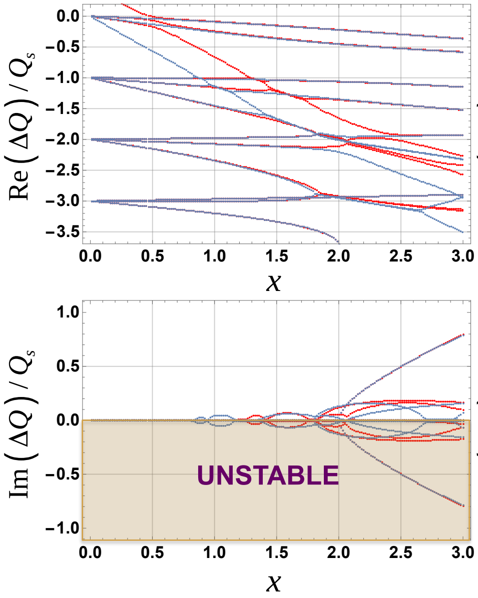
Long-bunch regime: ~ CERN SPS

$(f_r\tau_b = 2.8, Q' = 0)$

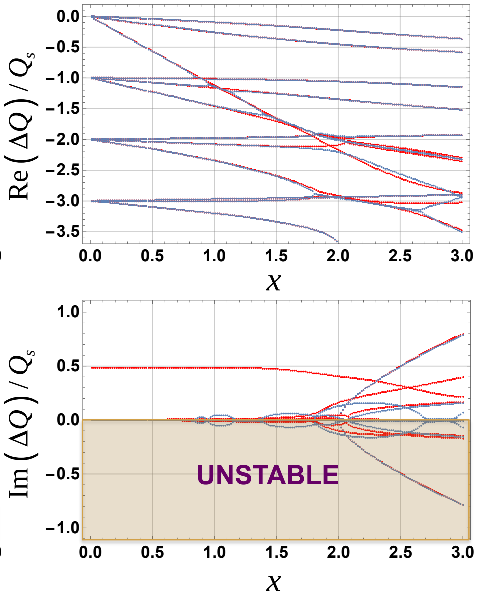
Short-bunch regime: ~ CERN LHC

$(f_r\tau_b = 0.8, Q' = 0)$

No **TD**
Reactive **TD**



No **TD**
Resistive **TD**



No **TD**
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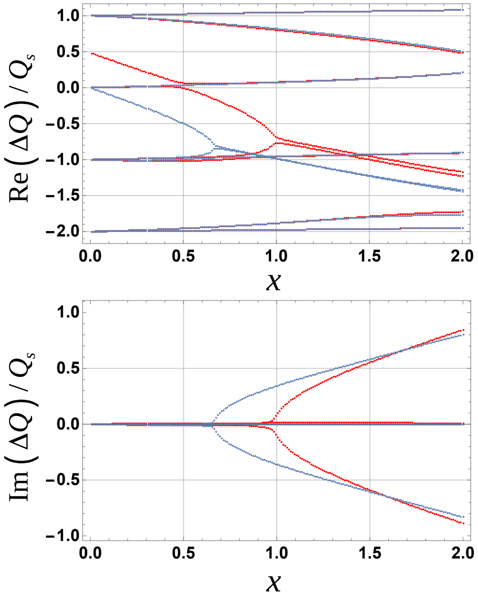

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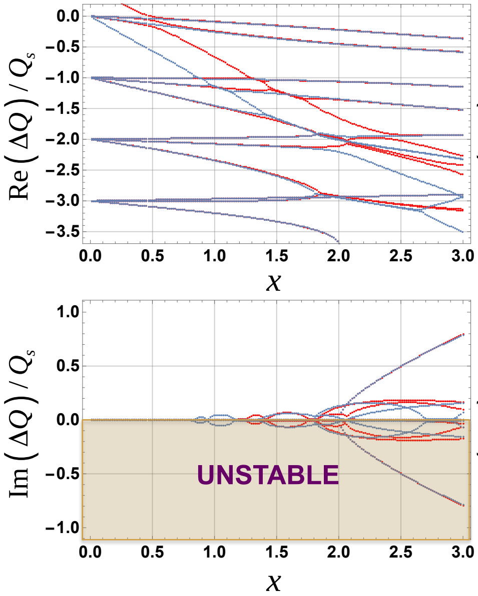
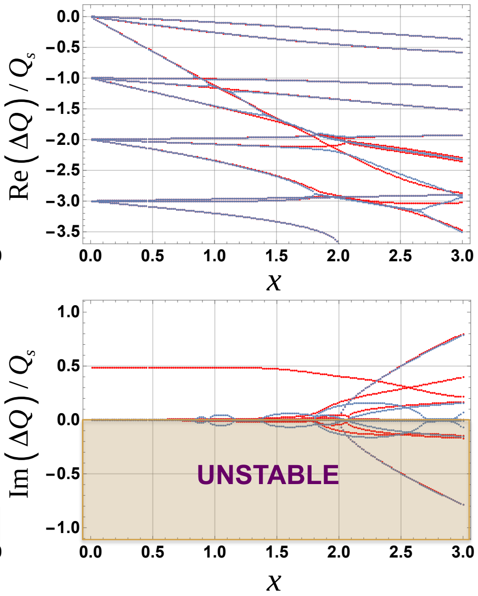


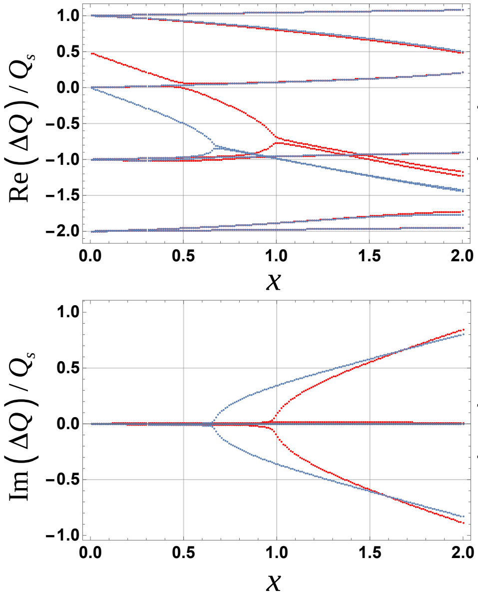
No **TD**
Resistive **TD**



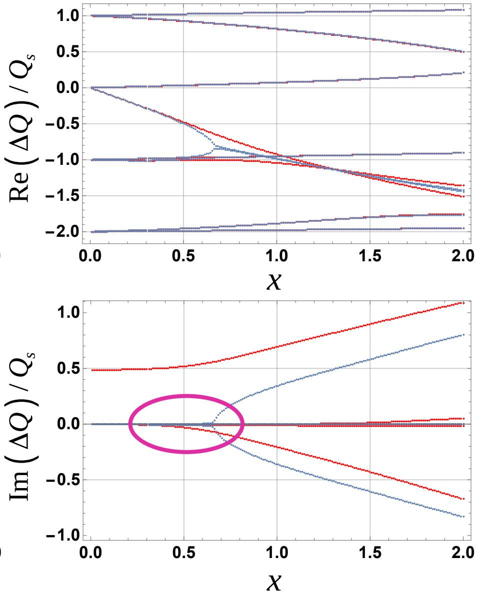
Short-bunch regime: ~ CERN LHC

$(f_r \tau_b = 0.8, Q' = 0)$

No **TD**
Reactive **TD**

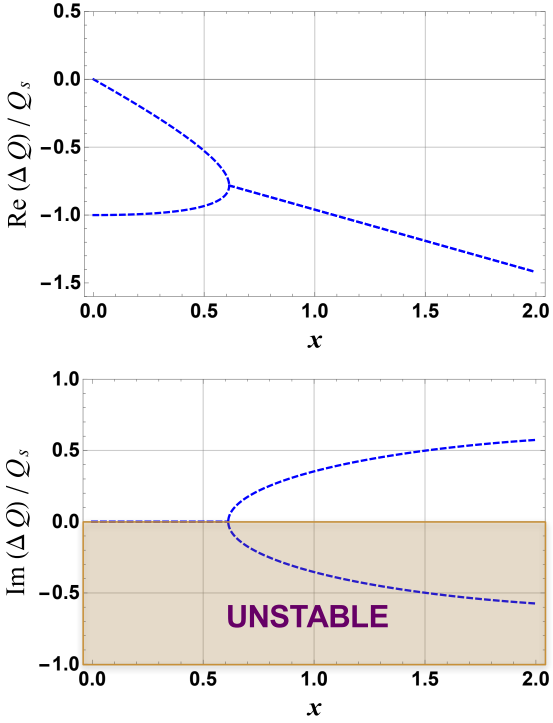


No **TD**
Resistive **TD**



“ISR instability” (due to resistive Transverse Dampers)

- Without TD



“ISR instability” (due to resistive Transverse Dampers)

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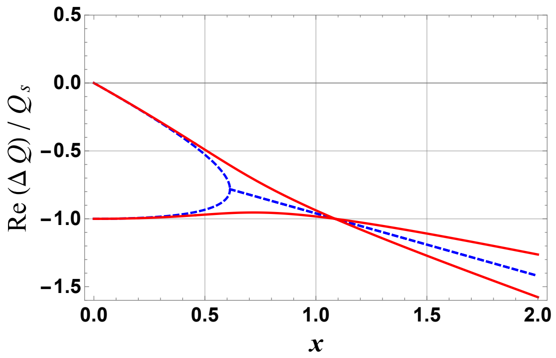
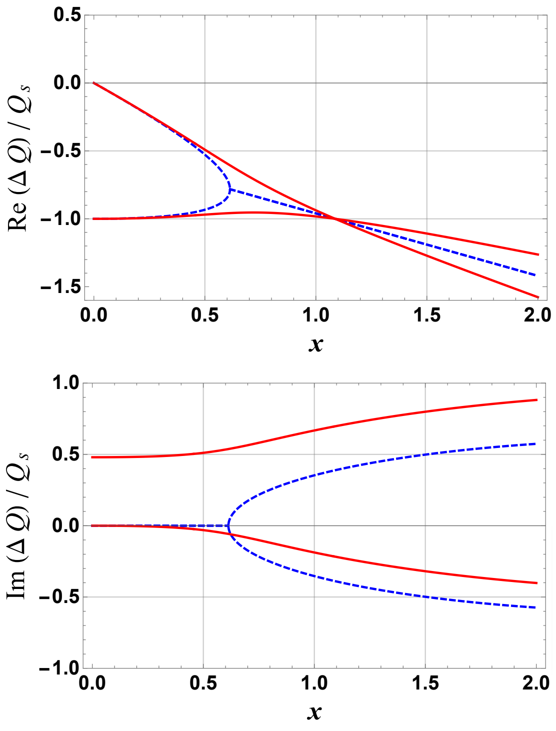


“ISR instability” (due to resistive Transverse Dampers)

- With TD



"ISR instability" (due to resistive Transverse Dampers)

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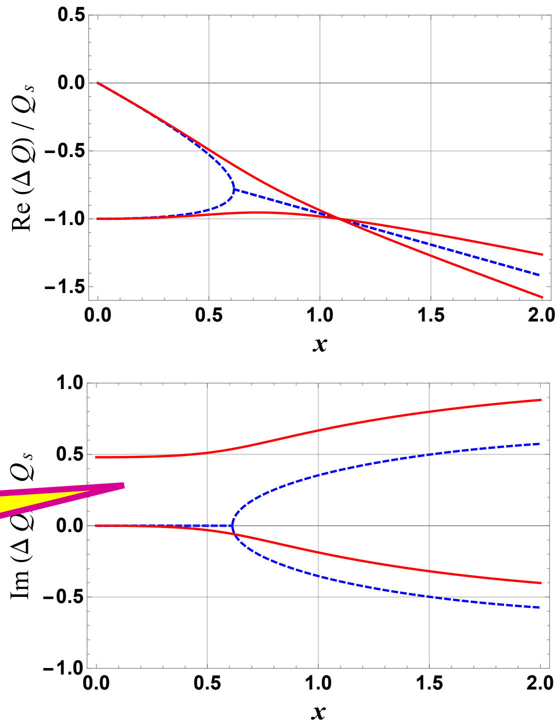
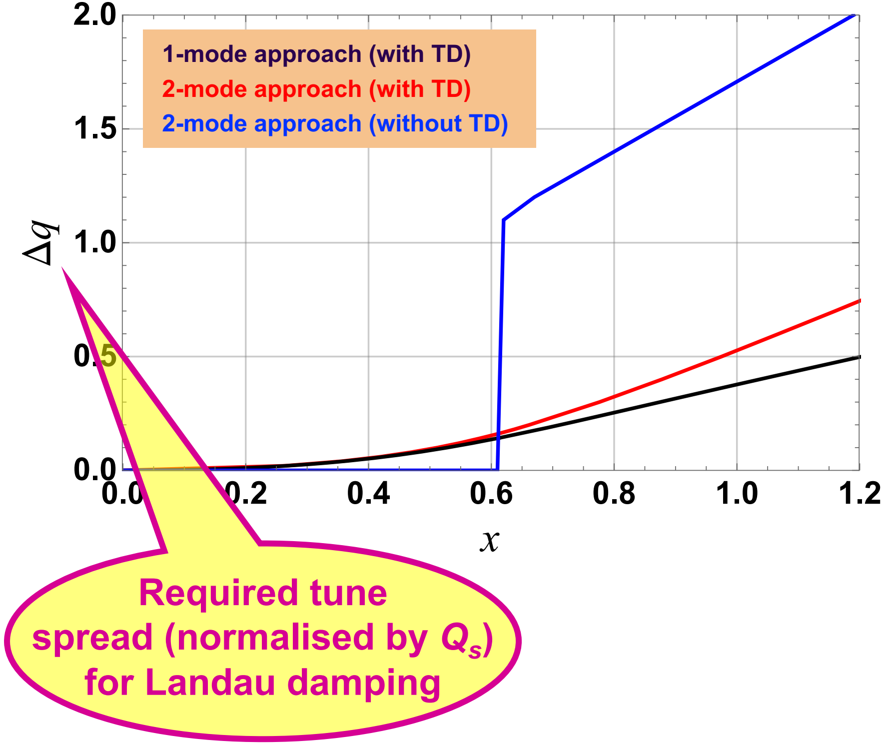
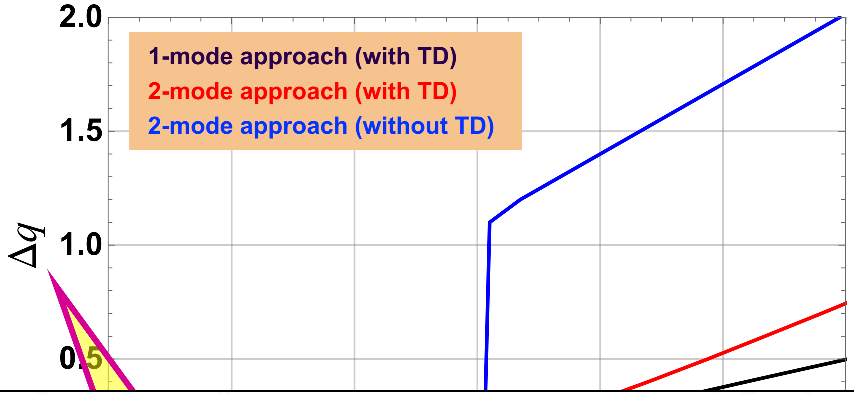


ISR instability
(Imaginary tune Split & Repulsion)

"ISR instability" (due to resistive Transverse Dampers)



"ISR instability" (due to resistive Transverse Dampers)



Although the above analyses assume a one-particle beam, one may venture to apply the result to a two-particle instability. For example, one may conclude that, to substantially raise the strong head-tail instability threshold by Landau damping, it is necessary to have a betatron frequency spread that is comparable to the synchrotron frequency. This is not easy to do in practice, and the conclusion discourages an attempt to Landau damp the strong head-tail instability.

“Coupled head-tail instability” (due to linear coupling)

- Linear coupling can have a beneficial effect for both weak and strong head-tail instabilities if asymmetries between the 2 transverse planes (different impedances, chromaticities, Landau damping, etc.)

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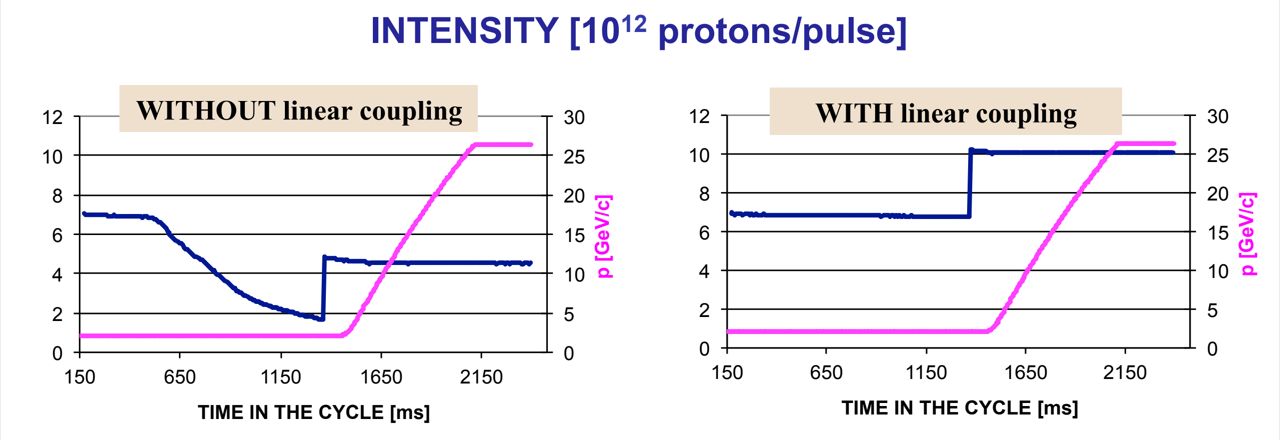
  - Was used in the CERN PS for ~ 15 years



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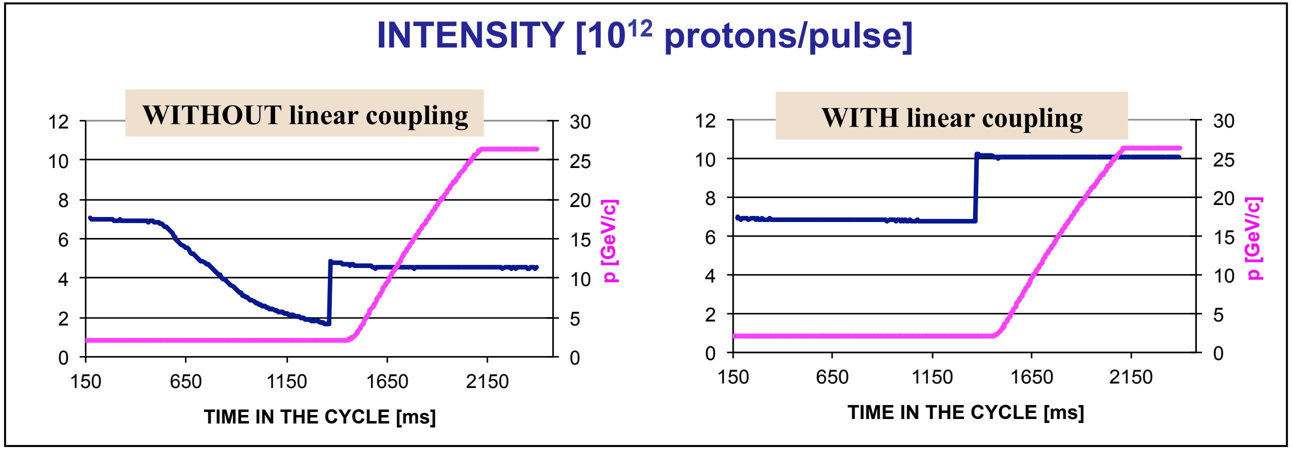

  - Was also observed and used in the past elsewhere: LANL-PSR (with "e-p" instability), BNL AGS (TCBI), CERN SPS & LEP (TMCI), PSB, etc.

“Coupled head-tail instability” (due to linear coupling)

- BUT linear coupling can also have a detrimental effect if coupling is too strong because the coherent tunes are shifted by linear coupling differently compared to the incoherent tunes (providing the Landau damping) due to the nonlinear fields (from octupoles, used to create the tune spread)

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  - Observed also in the LHC

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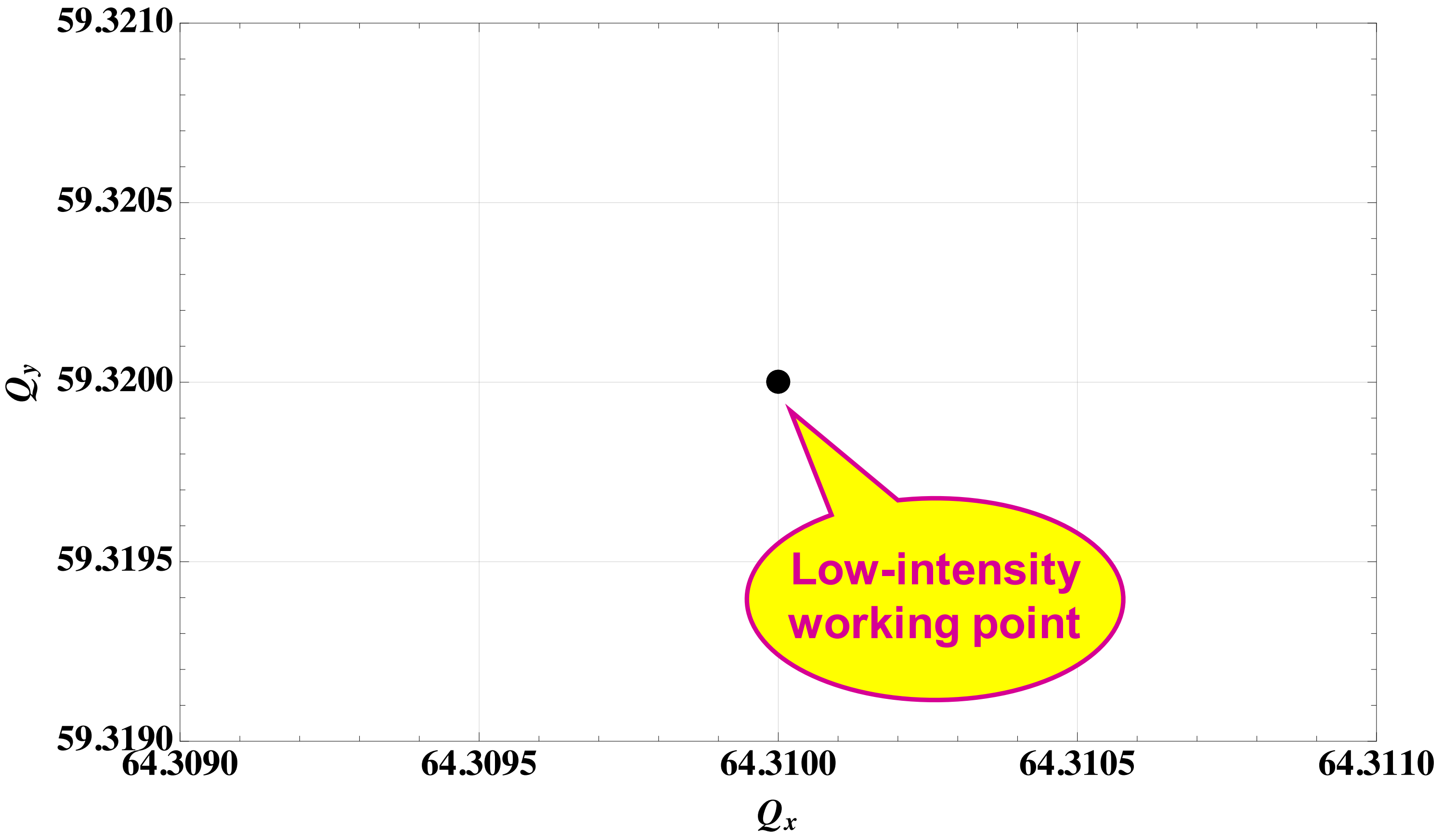

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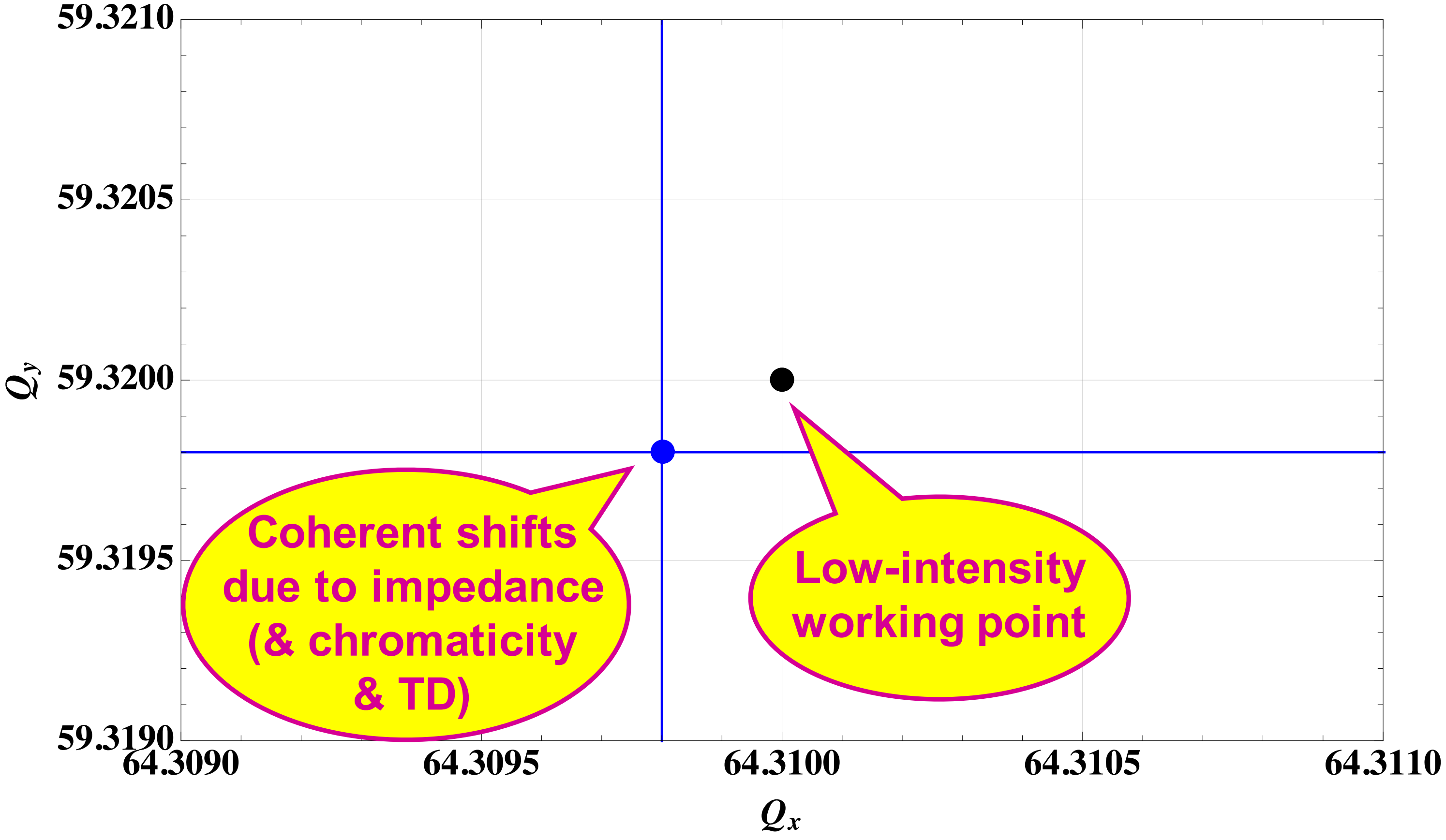

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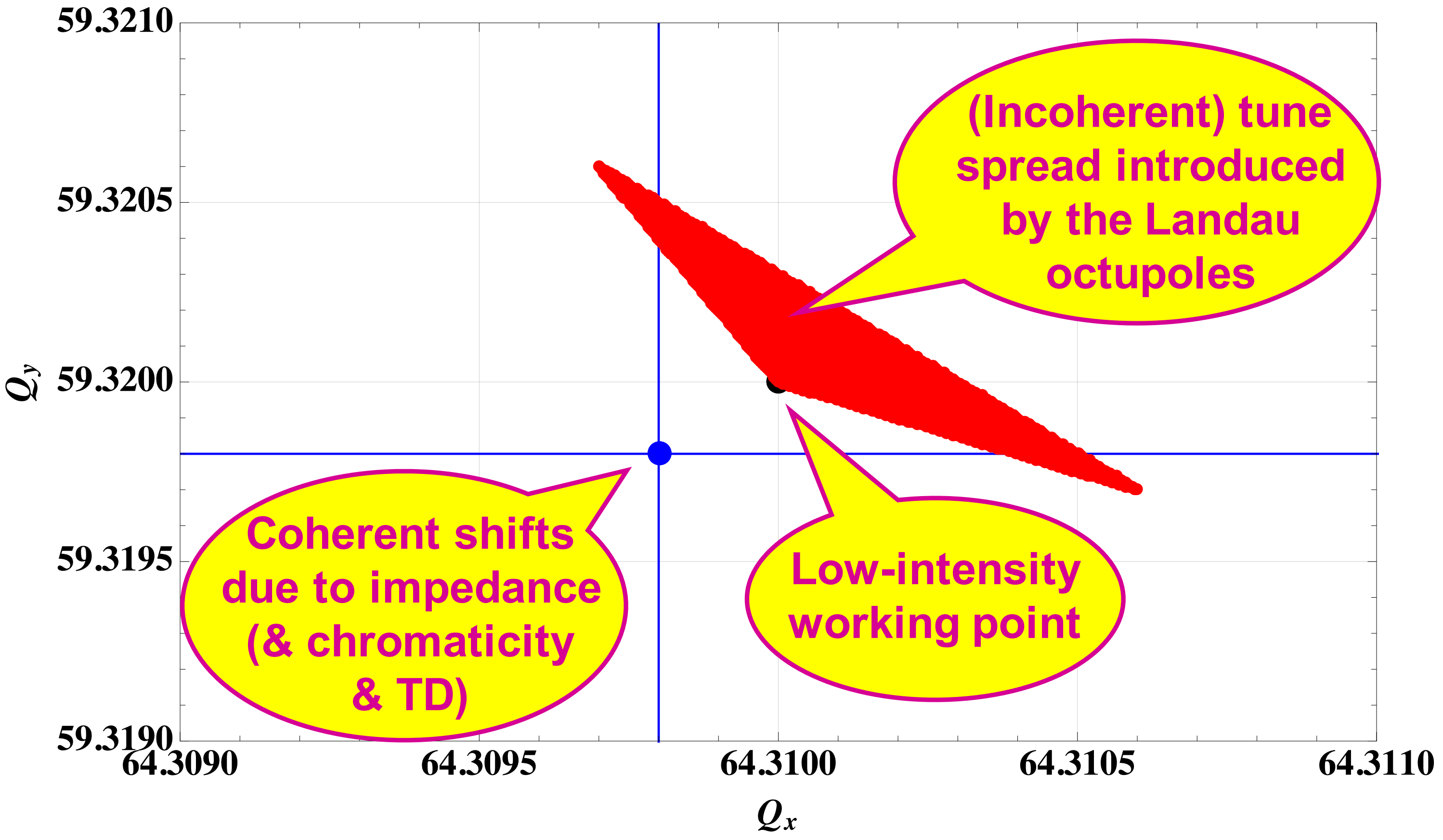

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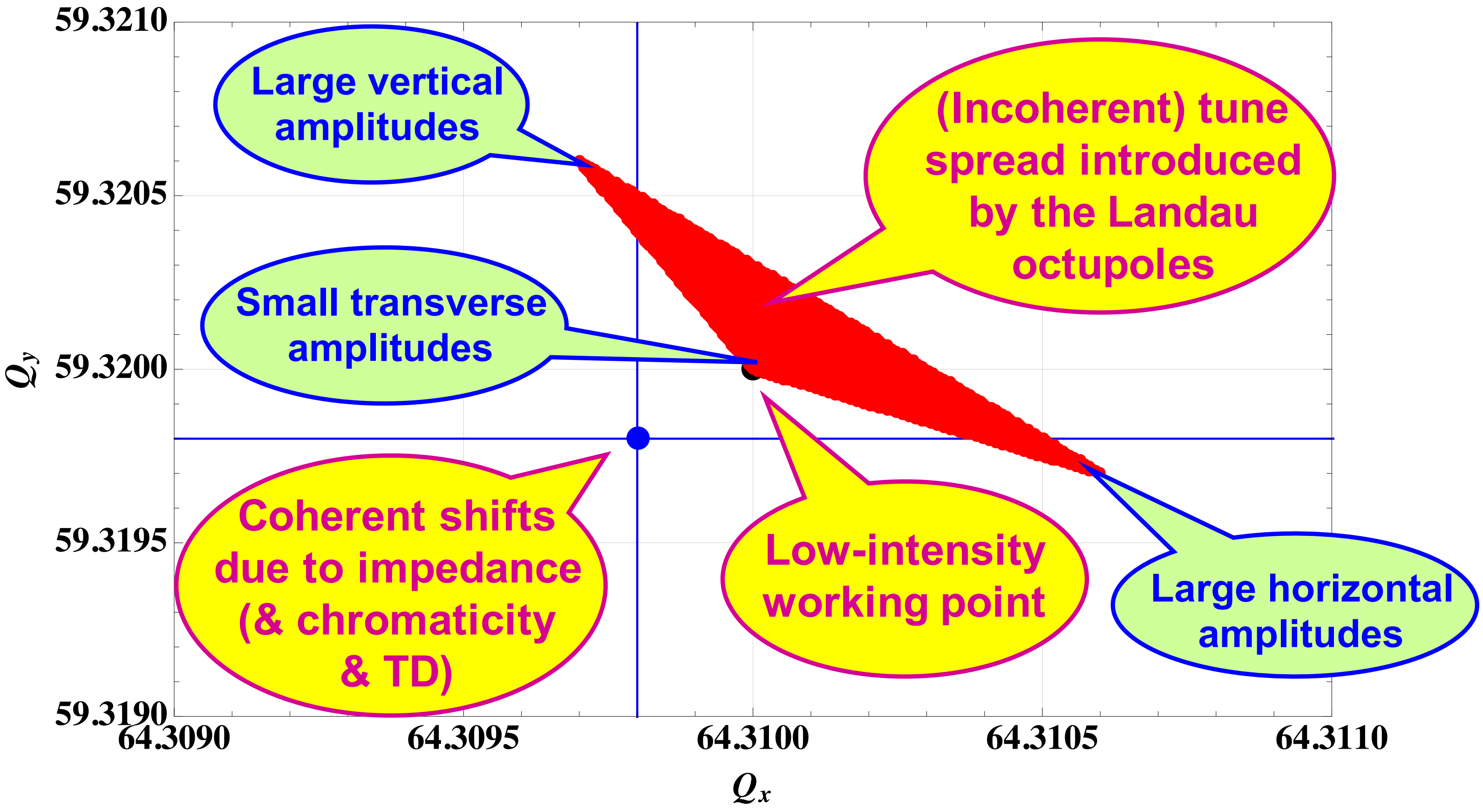
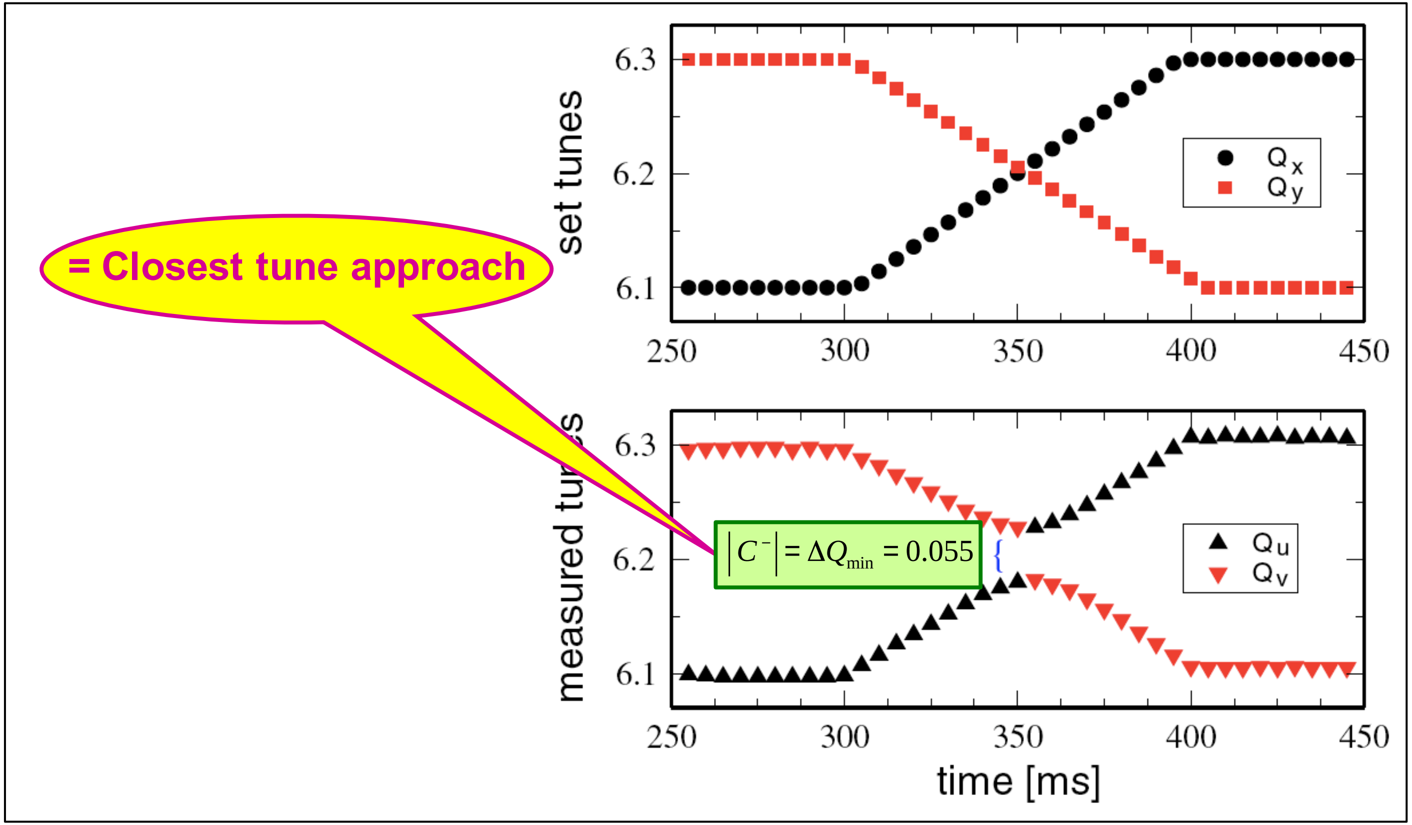
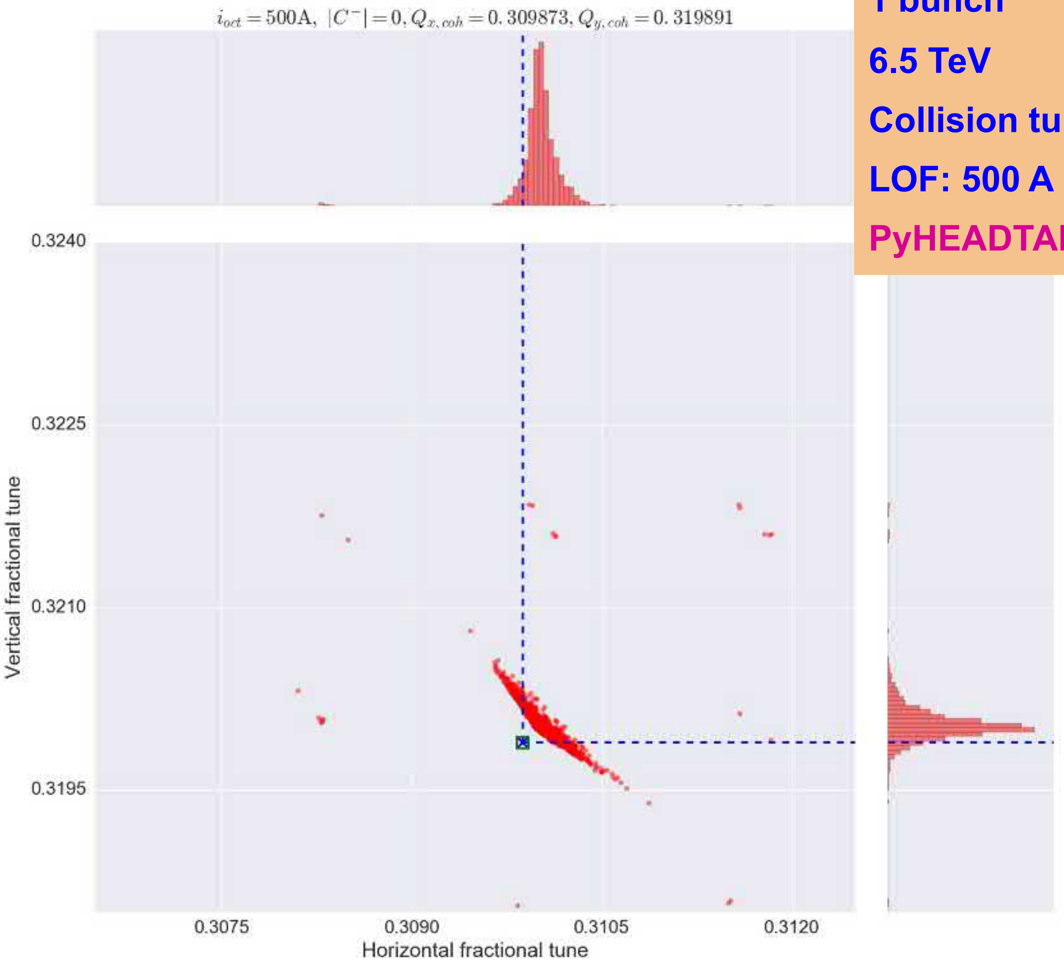


"Coupled head-tail instability" (due to linear coupling)



$\left|C^-\right| = 0$



1 bunch

6.5 TeV

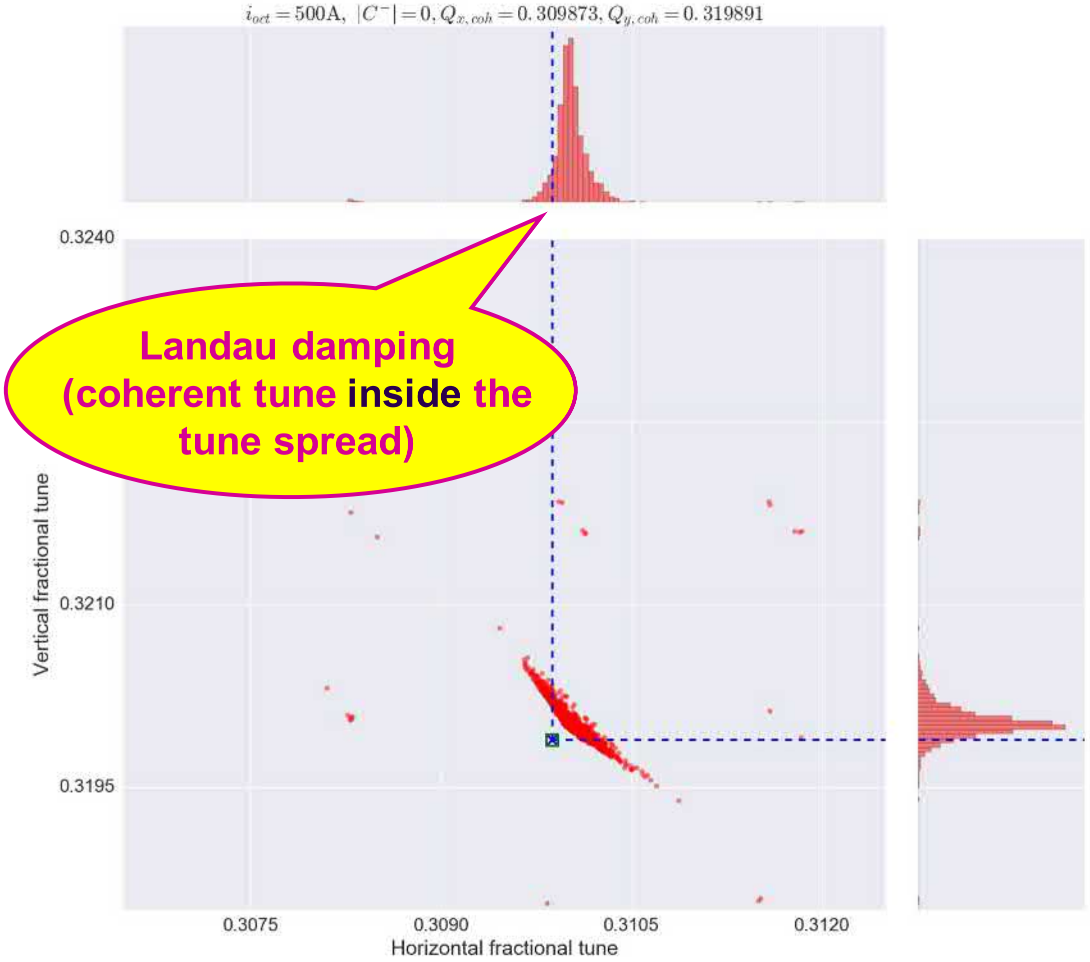
Collision tunes

LOF: 500 A

PyHEADTAIL code

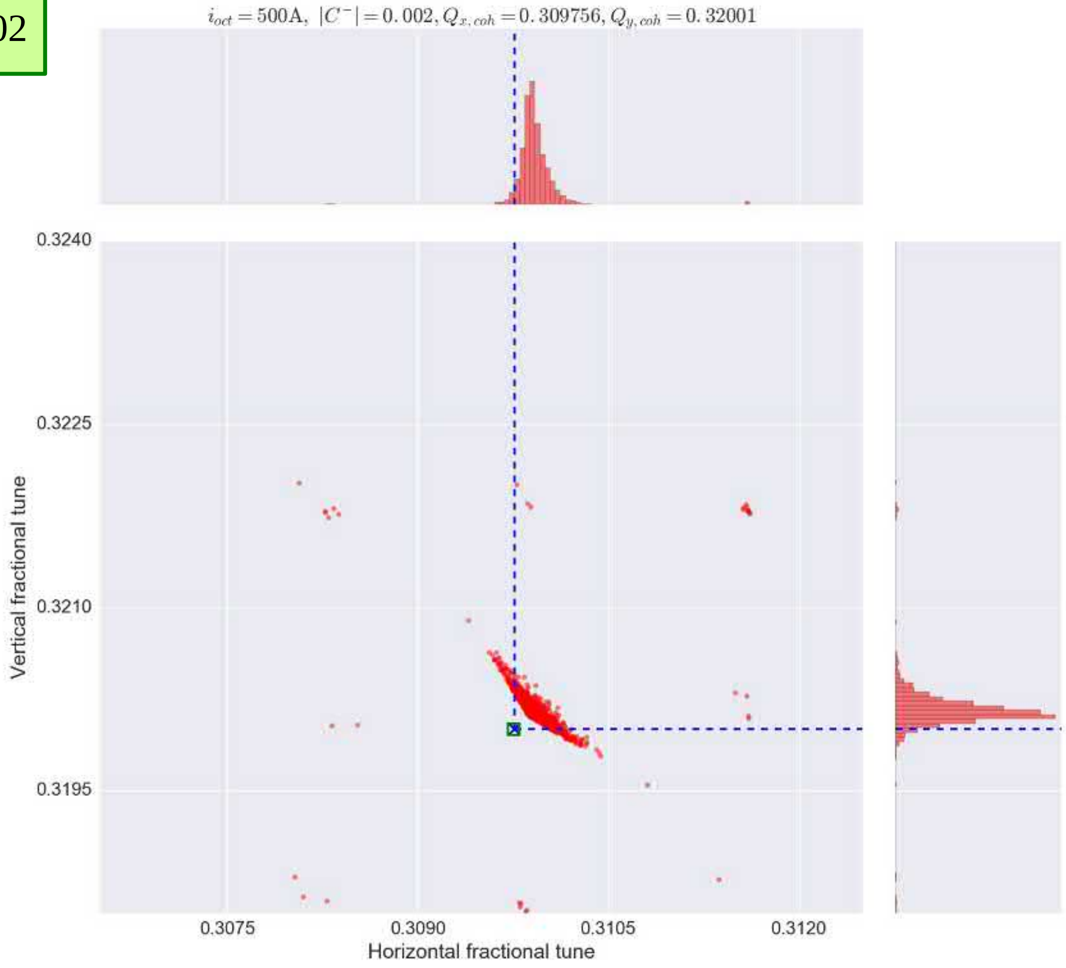
L.R. Carver

$|C^-| = 0$


$i_{oct} = 500\text{A},\ |C^-| = 0, Q_{x,coh} = 0.309873, Q_{y,coh} = 0.319891$
0.3240
0.3210
0.3195
Vertical fractional tune
0.3075
0.3090
0.3105
0.3120
Horizontal fractional tune
Landau damping
(coherent tune inside the
tune spread)

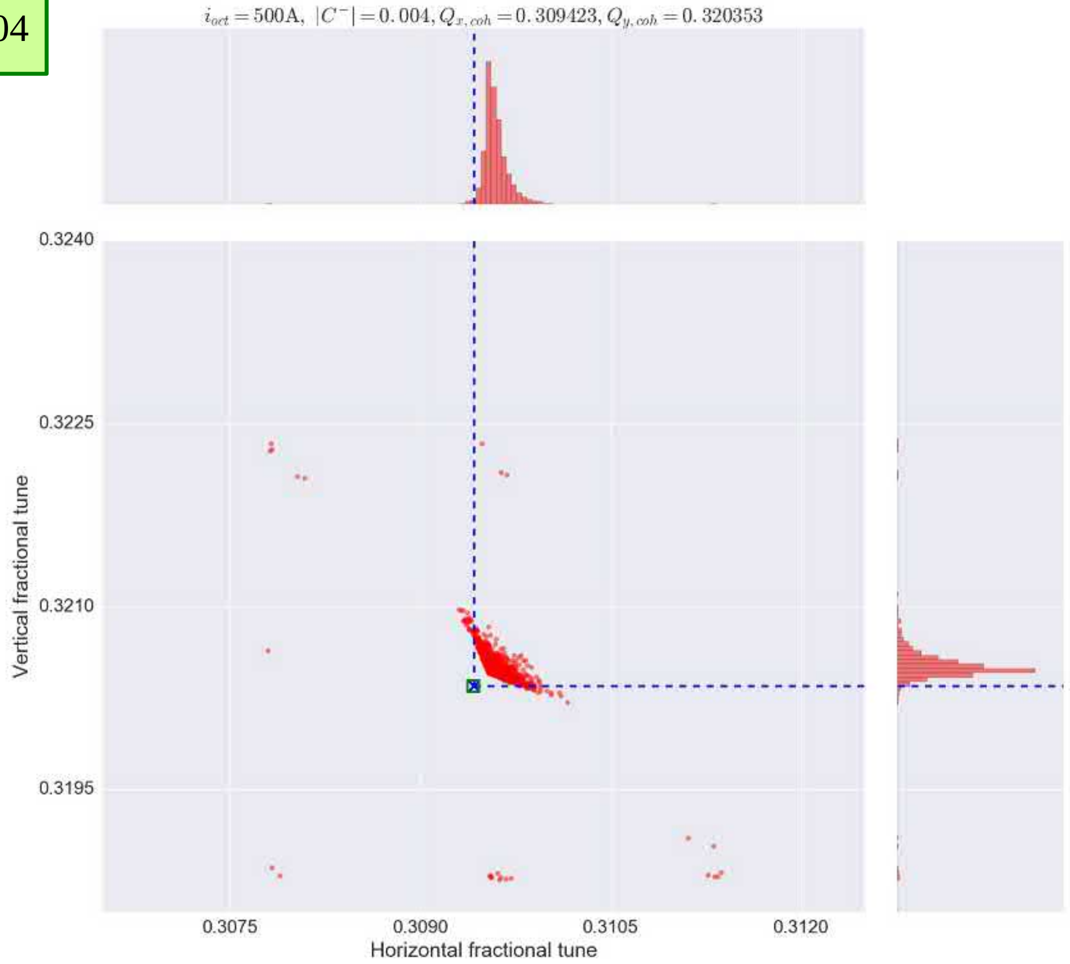
L.R. Carver

$\left|C^{-}\right| = 0.002$



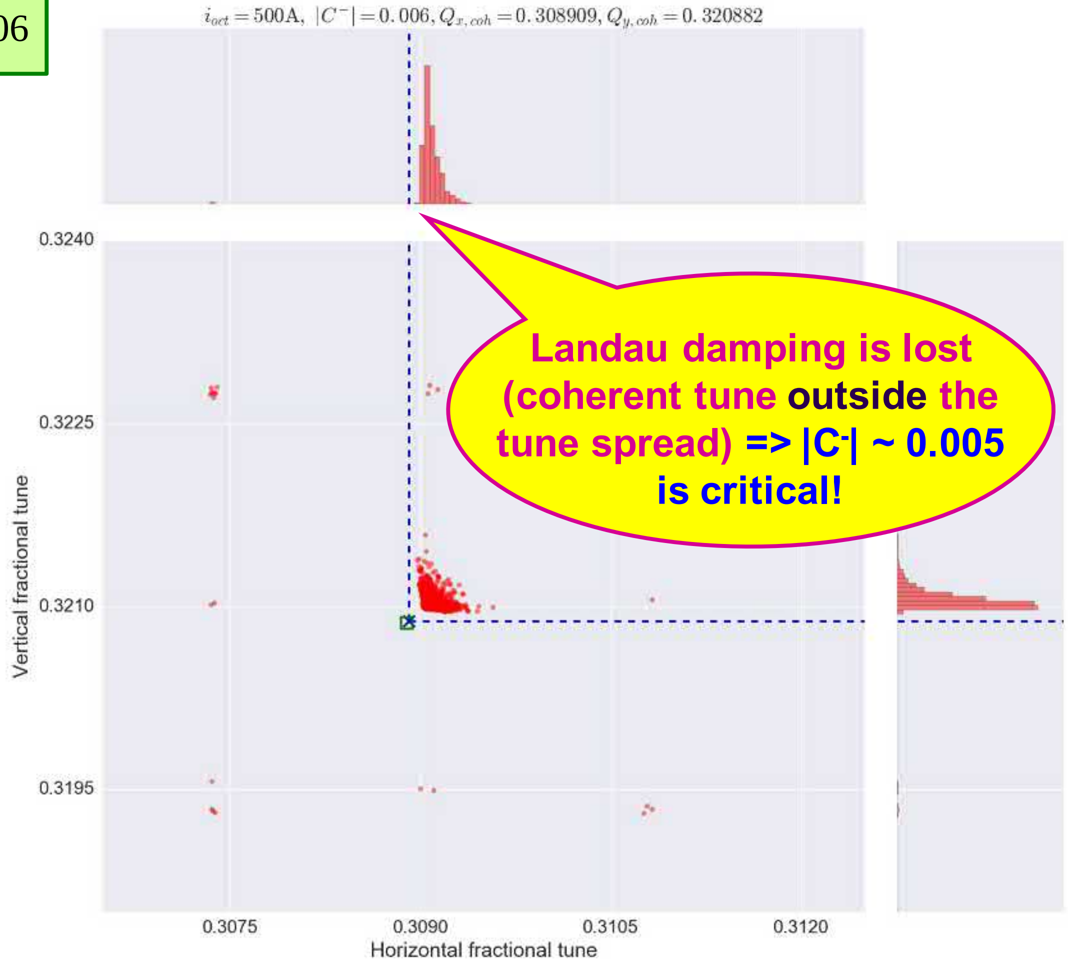
L.R. Carver

$\left| C^- \right| = 0.004$



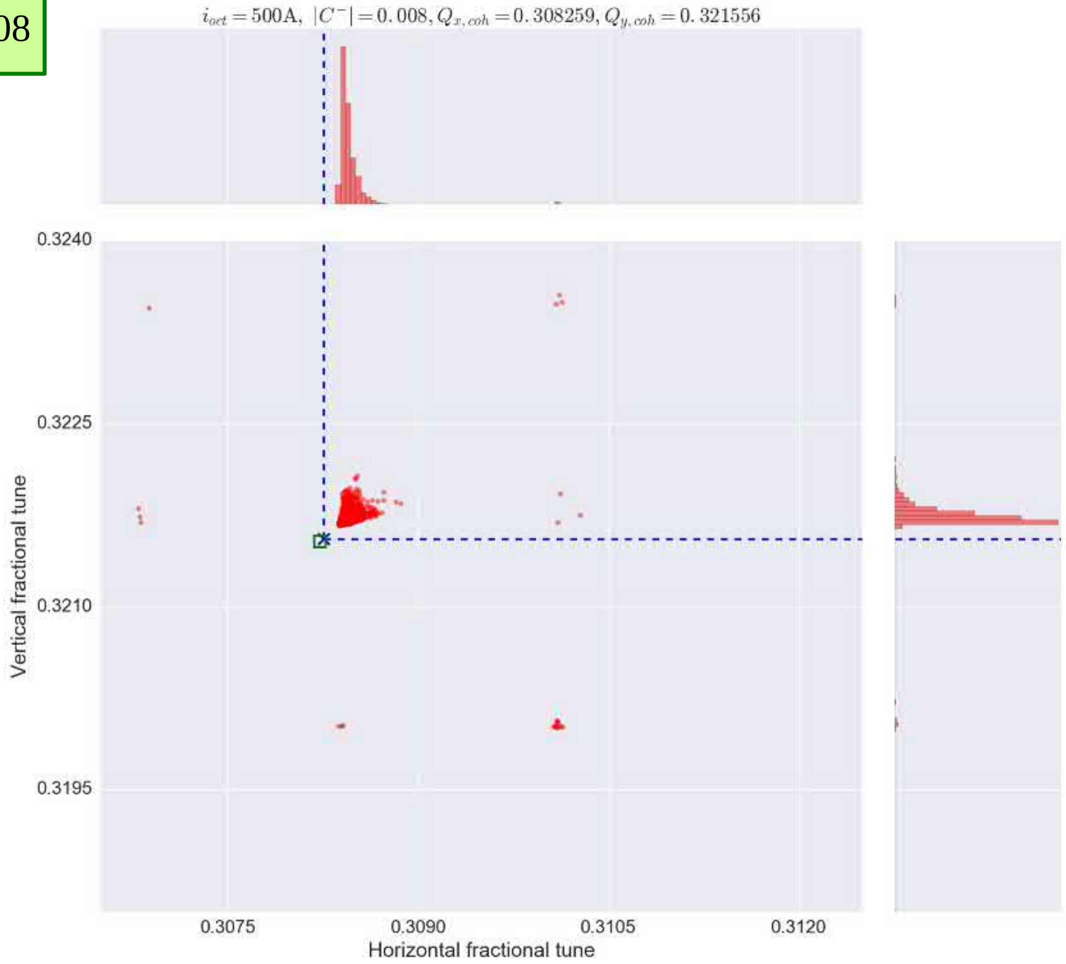
L.R. Carver

$|C^-| = 0.006$



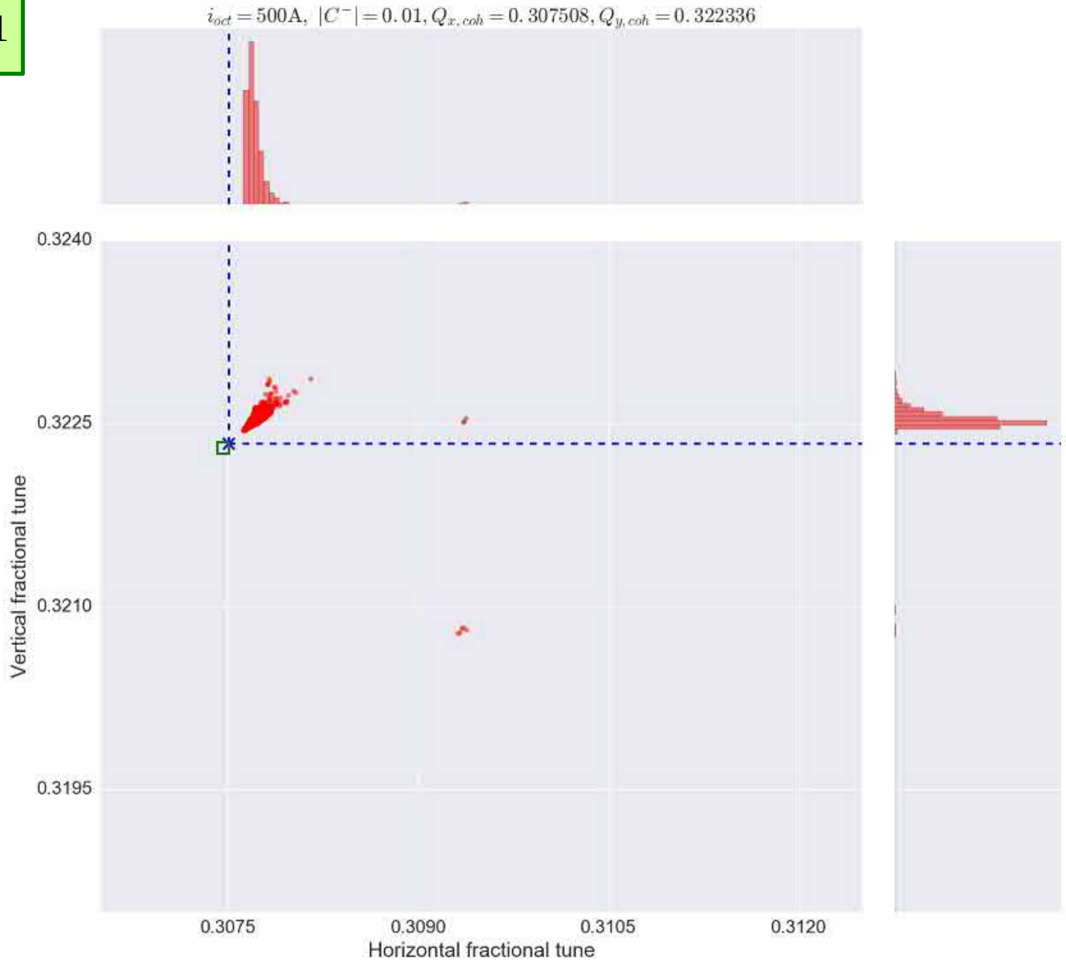
L.R. Carver

$\left| C^- \right| = 0.008$



L.R. Carver

$|C^-| = 0.01$

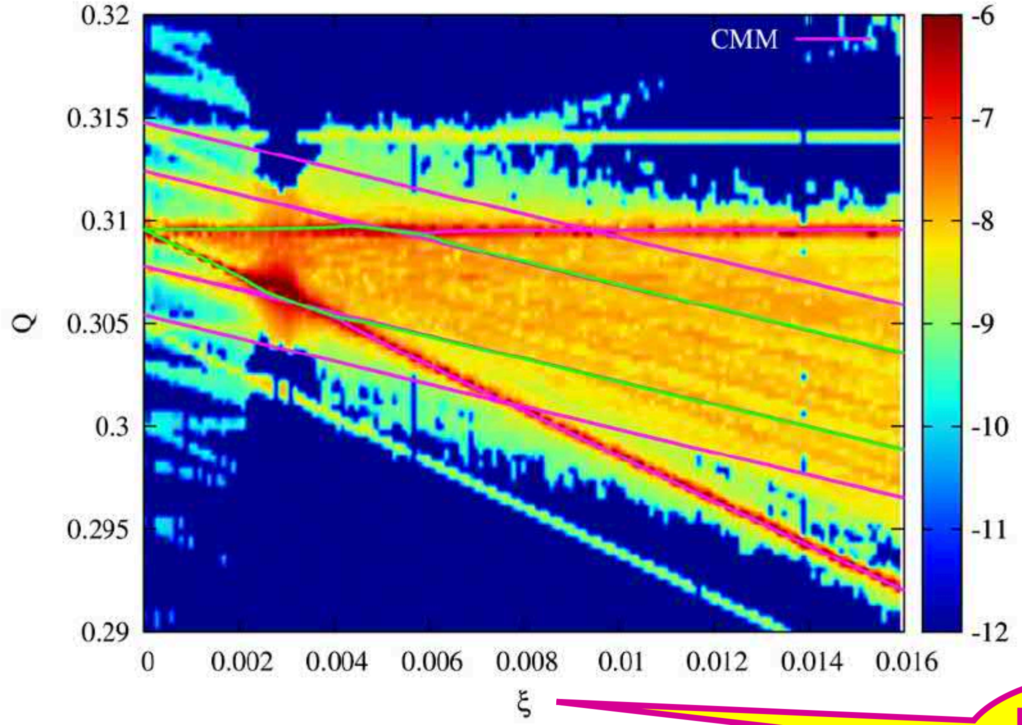


L.R. Carver et al. (PRAB 2018)

L.R. Carver

Many other very interesting mechanisms!

1) Destabilising effect of mode-coupling of colliding beams (beam-beam and impedance)



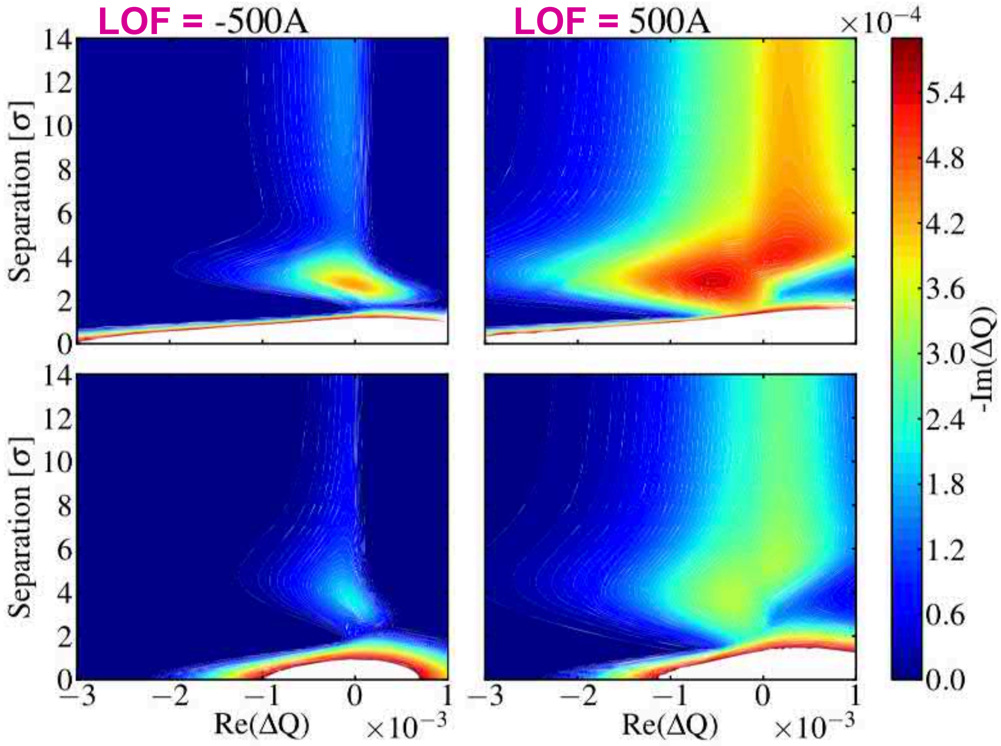
S. White et al. (PRSTAB 2014)

Beam-Beam parameter

2) Destabilising effect of interplay between Landau octupoles and beam-beam

2012

Nominal

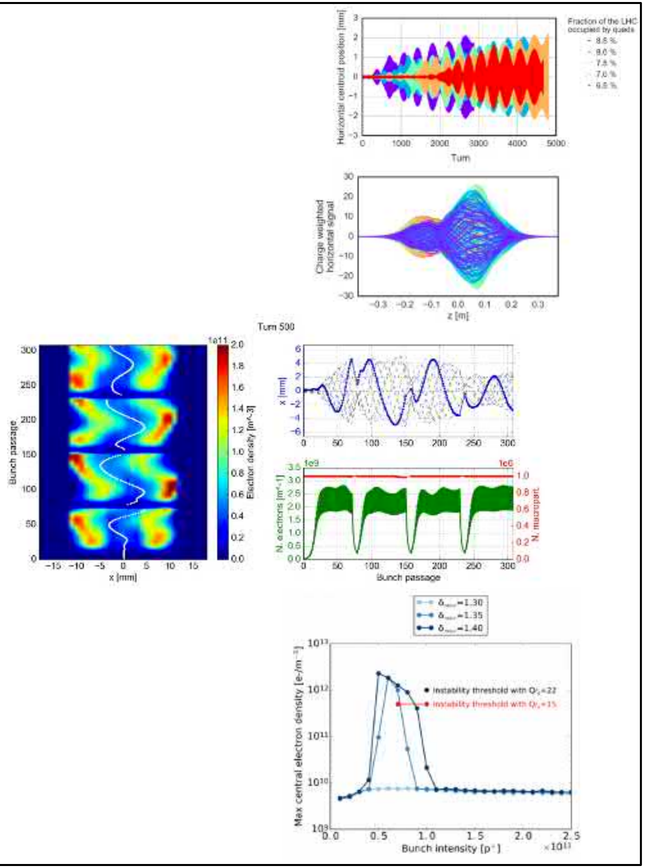


X. Buffat et al. (PRSTAB 2014)

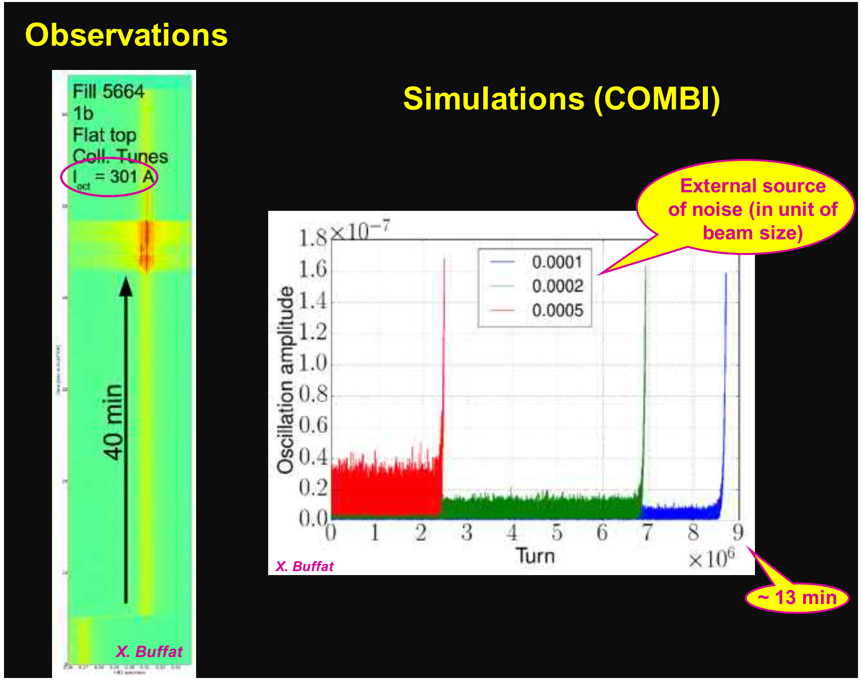
3) Destabilising effects of electron cloud

G. Iadarola et al.

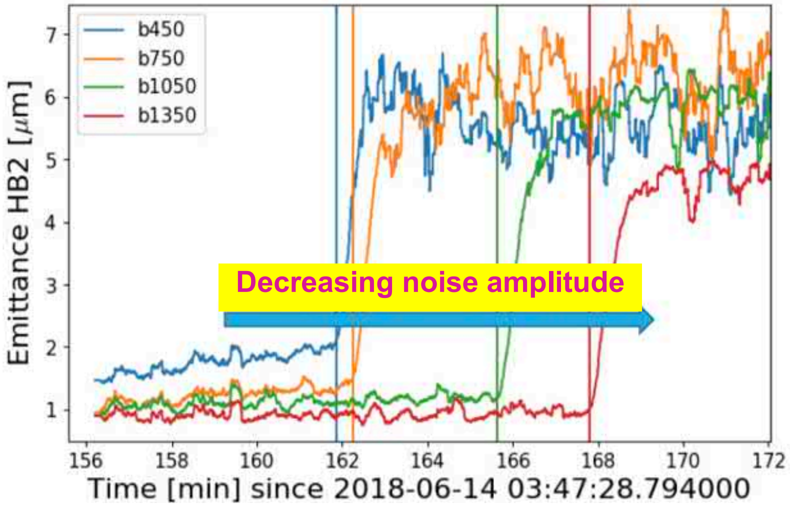
- Quadrupoles explain the observed e-cloud instabilities at injection, similar in H and V (A. Romano et al.)
- Coupled-bunch instabilities driven by e-cloud effects could be simulated for the first time at CERN thanks to new HPC cluster recently deployed for accelerator studies (G. Iadarola et al., 2018)
- Electron cloud buildup driving spontaneous vertical instabilities of stored beams in the Large Hadron Collider (A. Romano et al., PRAB 2018)



4) Destabilising effect of noise



MD in 2018 (X. Buffat et al.)



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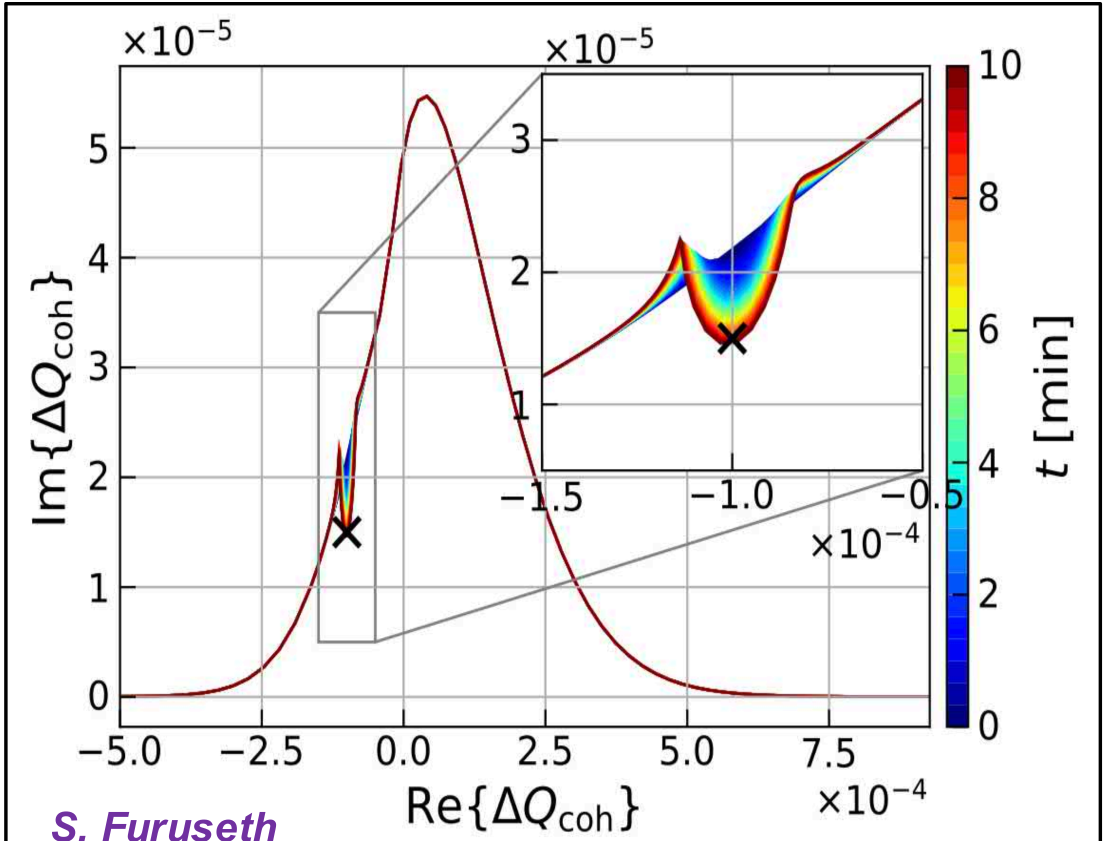
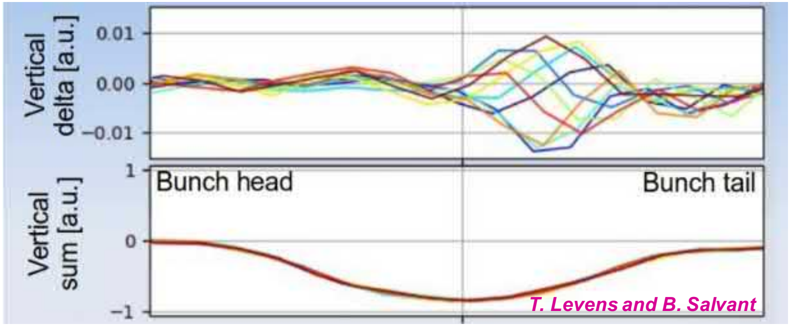


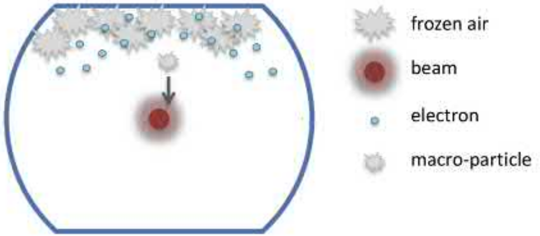
S. Furuseth

5) Destabilising effect of a non-conformity

- "16L2" (half-cell 16 left of Point 2) instability: fastest instability observed in the LHC!

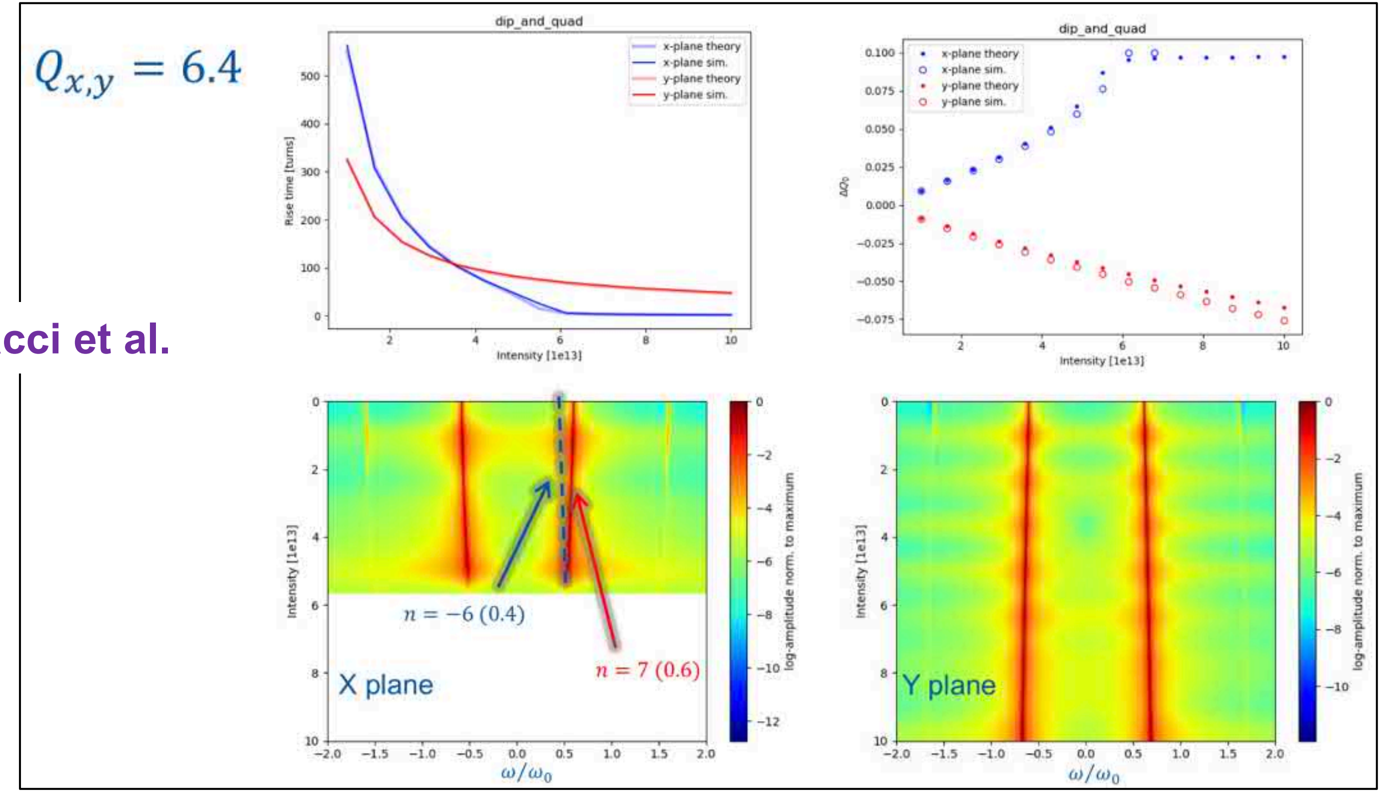


  - 68 premature beam dumps in 2017
  - Limited the number of bunches and intensity per bunch in 2017 and 2018
  - Origin and detailed instability mechanism still under investigation



L. Mether et al.

6) Destabilising effect of detuning impedance on coasting beams ("fast-slow mode coupling instability")



N. Biancacci et al.

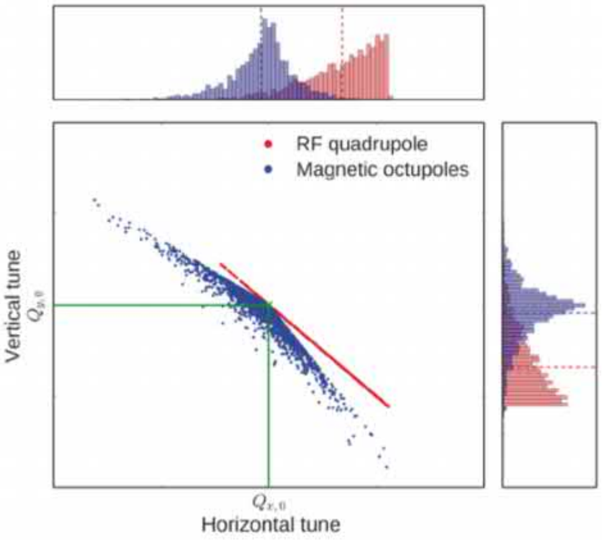
7) Stabilising effect of Q''

- PHD thesis from M. Schenk (supervised by K. Li) recently defended: "A novel approach to Landau damping of transverse collective instabilities in future hadron colliders"
  - Simulations
  - Experiment
  - Theory

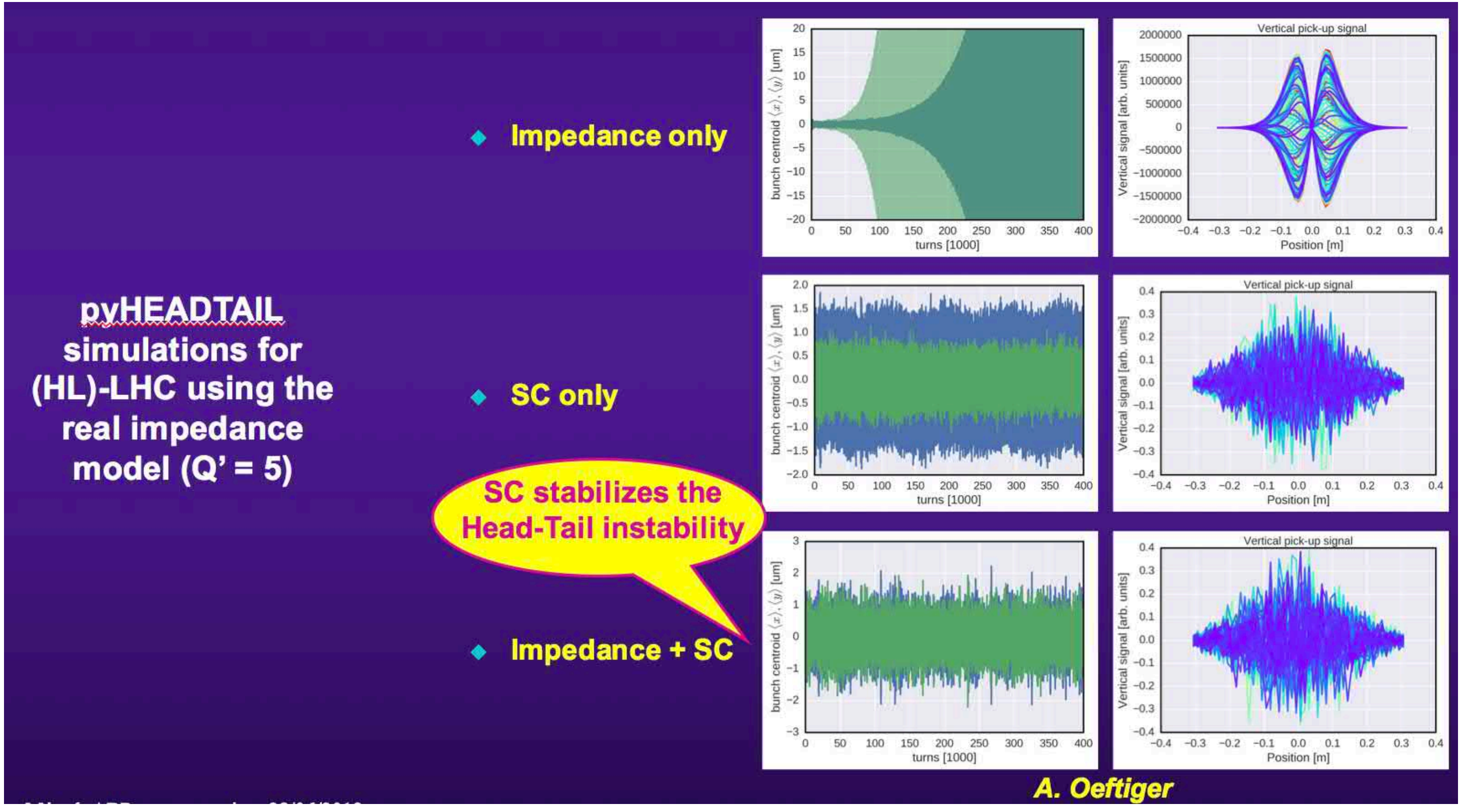
Analysis of transverse beam stabilization with rf quadrupoles
M. Schenk et al., ***PRAB* 20**, *104402, 2017*

Experimental stabilization of transverse collective instabilities in the LHC with 2nd order chromaticity
M. Schenk et al., ***PRAB* 21**, *084401, 2018*

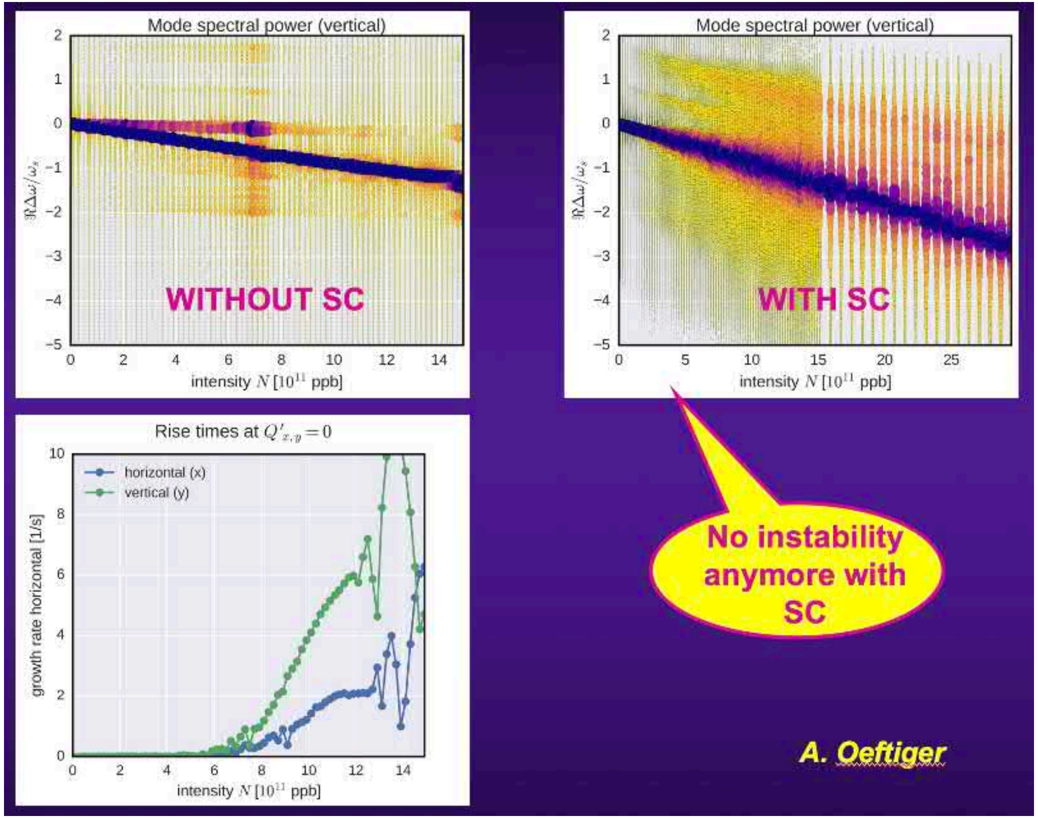
Vlasov description of the effects of nonlinear chromaticity on transverse coherent beam instabilities
M. Schenk et al., ***PRAB* 21**, *084402, 2018*



8) Stabilising effect of space charge in LHC at low energies (weak head-tail: Q’ = 5)



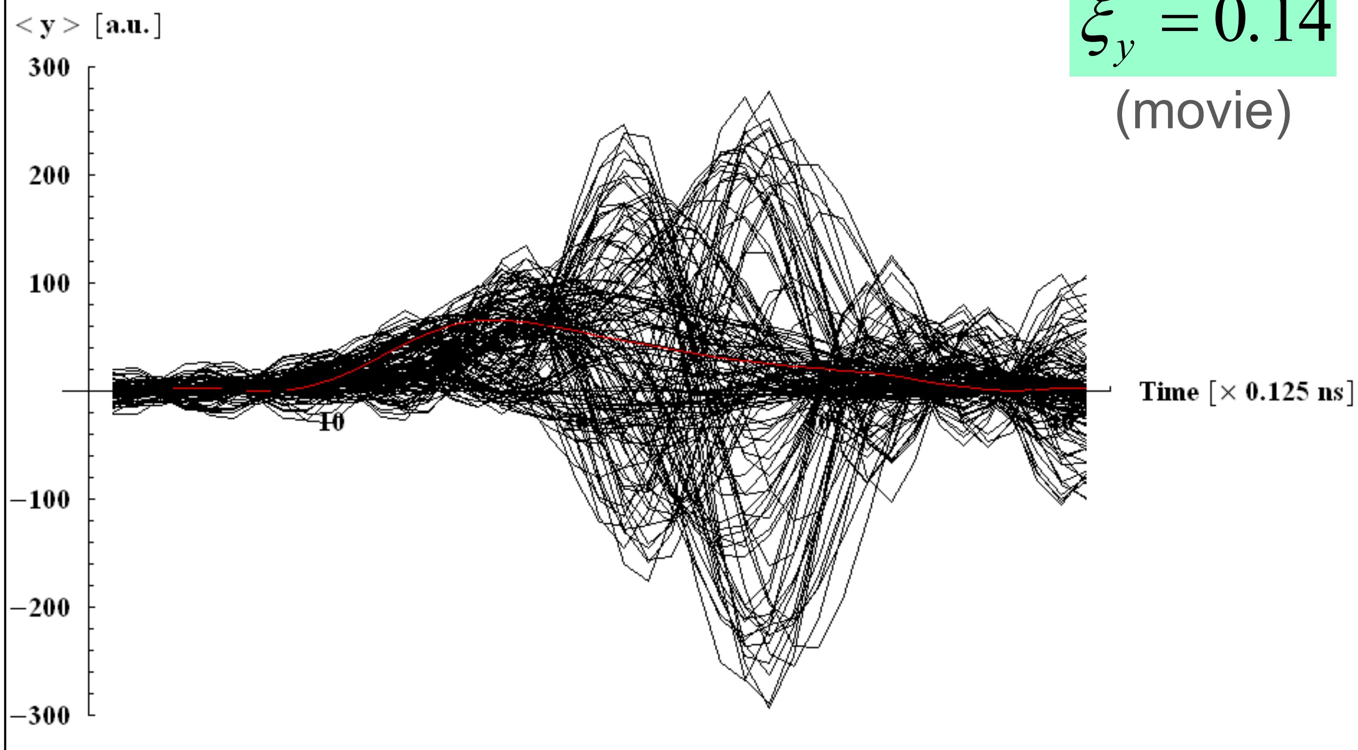
9) Stabilising effect of space charge in LHC at low energies (strong head-tail: Q' = 0)



10) A long-standing problem: effect of space charge on CERN SPS TMCI…

$$\xi_y = 0.14$$

(movie)



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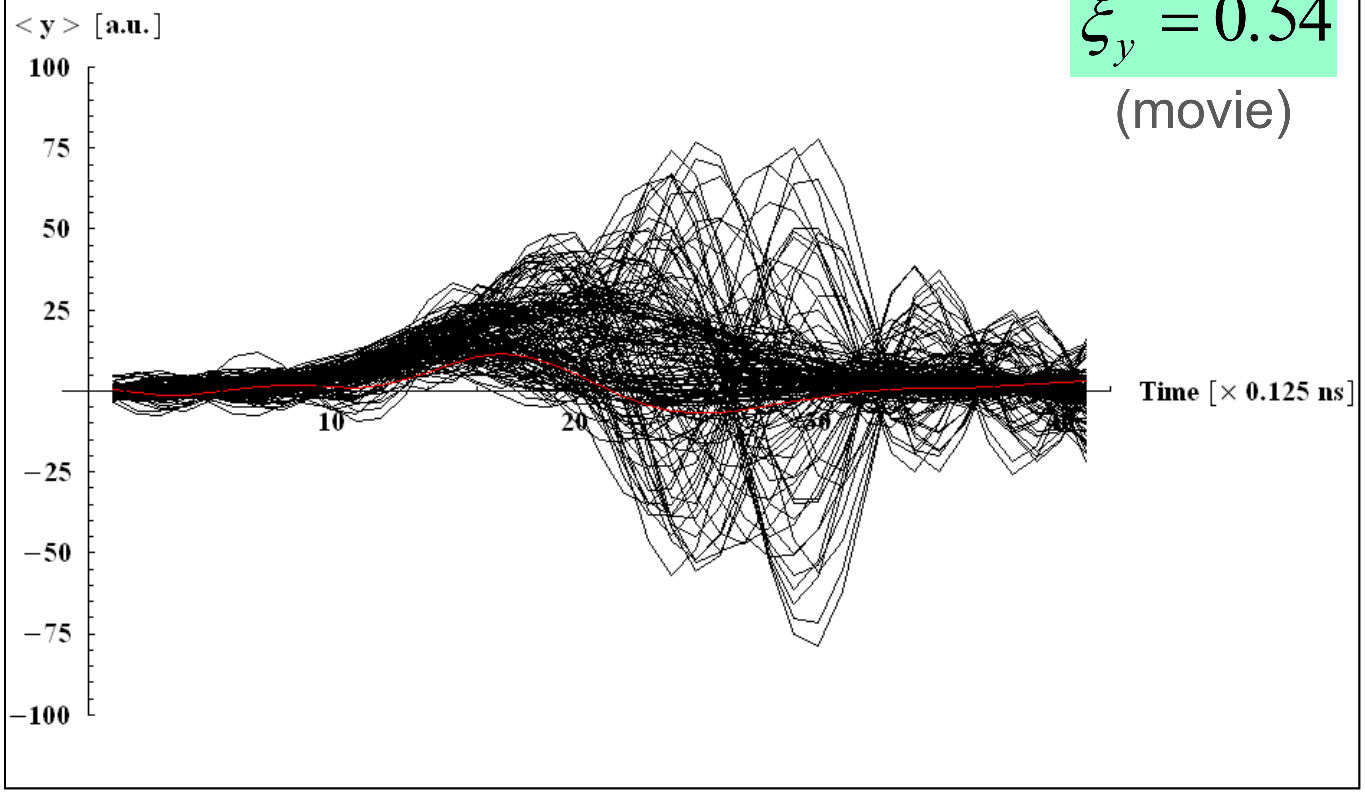

$\xi_y = 0.54$

(movie)

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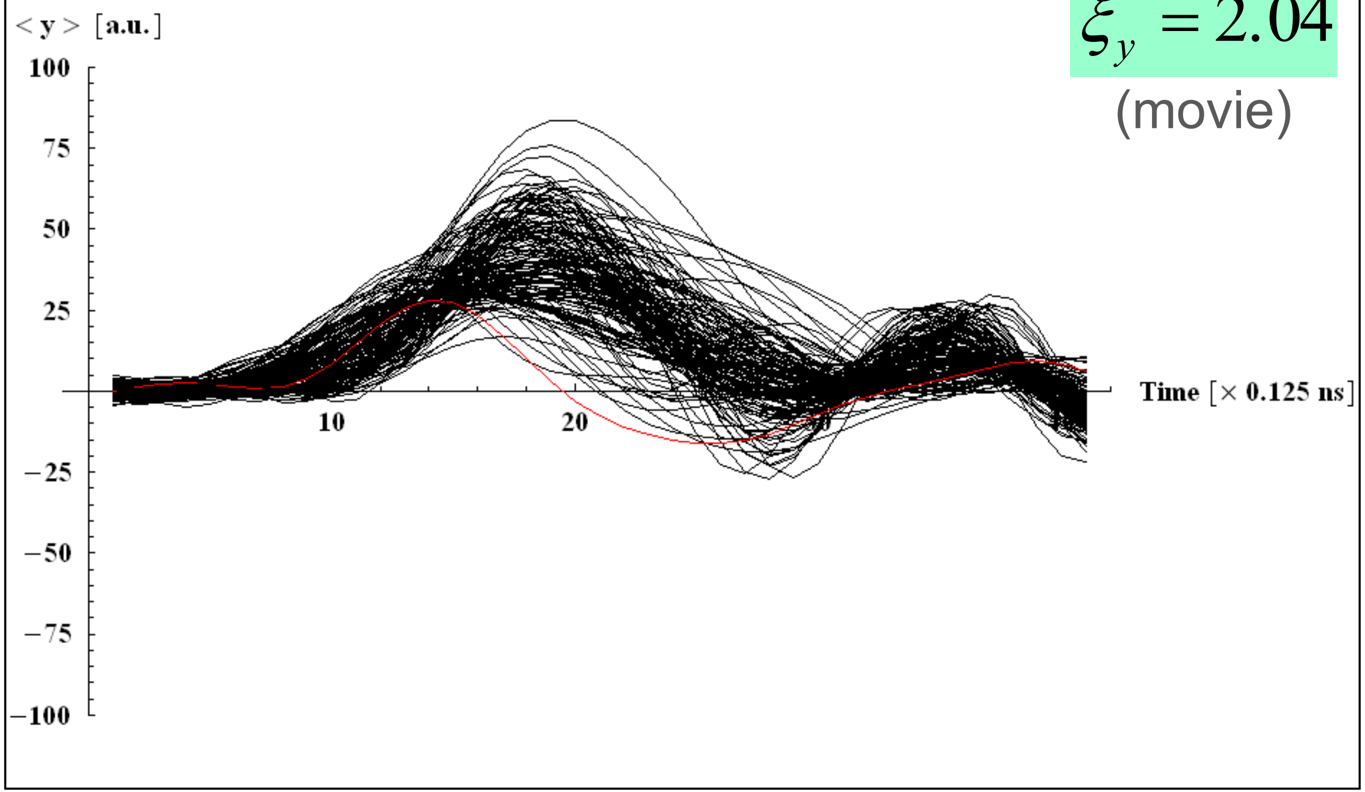

$\xi_y = 2.04$

(movie)

10) A long-standing problem: effect of space charge on CERN SPS TMCI…

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **1**, 044201 (1998)

Fast head-tail instability with space charge

M. Blaskiewicz

Alternating Gradient Synchrotron Department, Brookhaven National Laboratory, Upton, New York 11973-5000

(Received 29 April 1998; published 13 August 1998)

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PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 014201 (2016)

Two particle model for studying the effects of space-charge force on strong head-tail instabilities

Yong Ho Chin
KEK High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki-ken, 305-0801, Japan

Alexander Wu Chao
SLAC Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, California 94025, USA

Michael M. Blaskiewicz
BNL Brookhaven National Laboratory, P.O. Box 5000, Upton, New York 11973-5000, USA
(Received 12 May 2015; published 19 January 2016)

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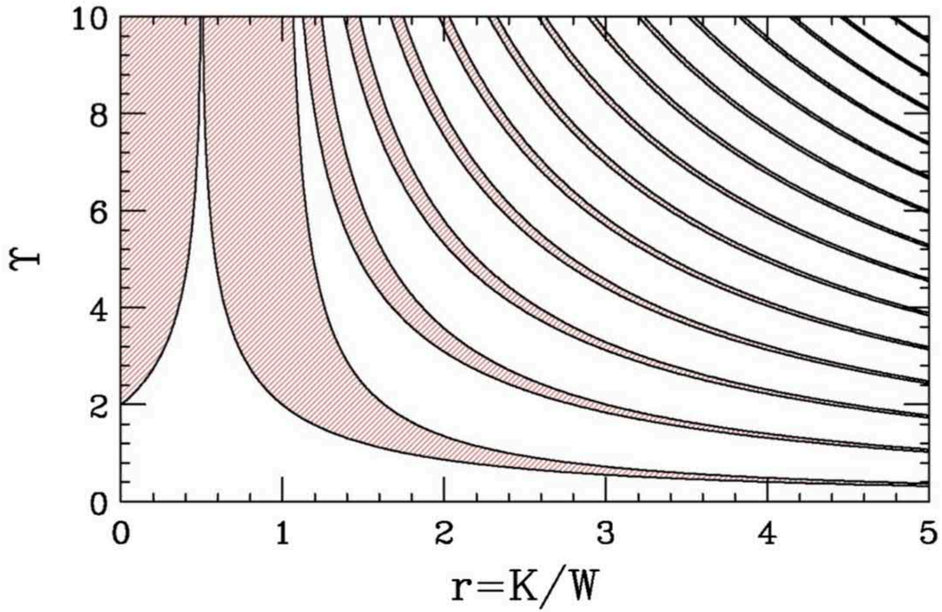
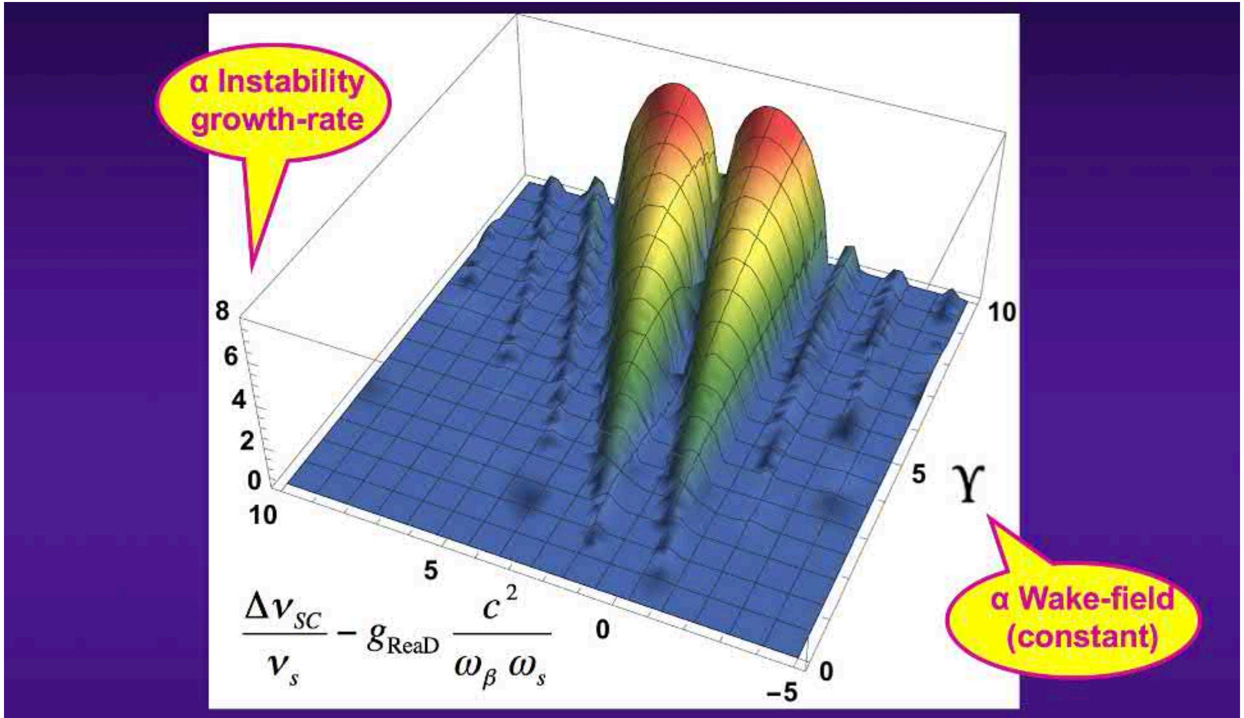


FIG. 3. The stability diagram for the strong space-charge case ($r = K/W \geq 1$). The stability diagram for the weak space-charge case ($r = K/W \leq 1$) is also plotted for completion. Unstable regions are shown shaded.

10) A long-standing problem: effect of space charge on CERN SPS TMCI…



- **Results from Burov_2016 (using a ReaD only) and Chao-Chin-Blaskiewicz_2016 (using SC only) have been recovered and combined**

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- At CERN, it seems that only the LHC (highest energy machine) sees the (beneficial/stabilising) effect of space charge

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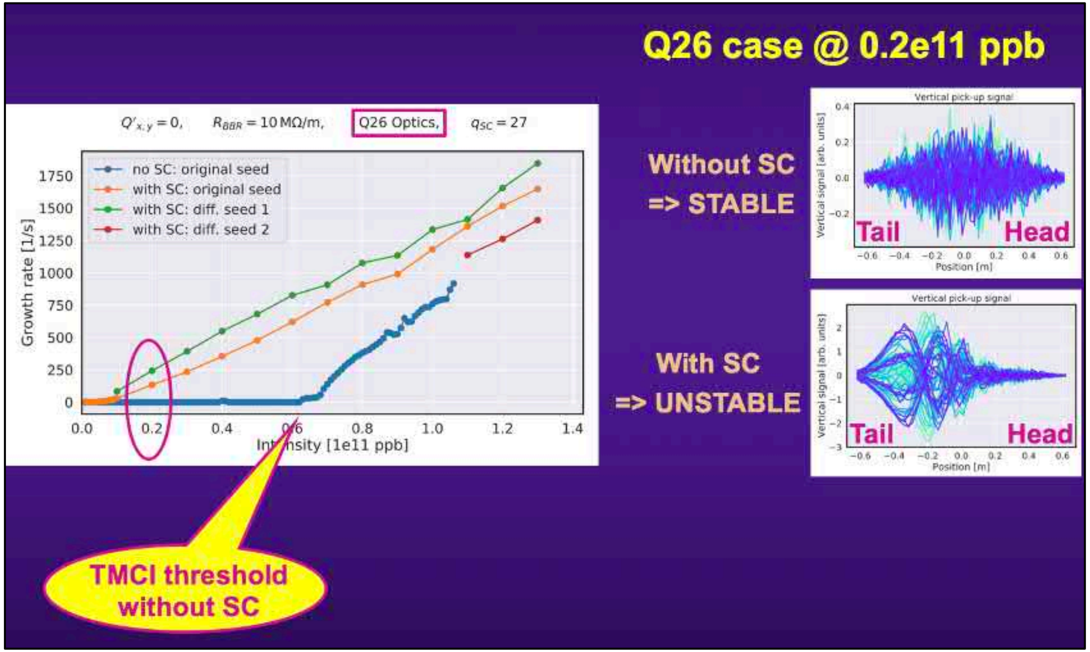
- At CERN, it seems that only the LHC (highest energy machine) sees the (beneficial/stabilising) effect of space charge

- For the SPS TMCI, a destabilising effect has even been revealed with pyHEADTAIL simulations (A. Oeftiger) using a BB resonator. To be continued (using the real impedance model, etc.) => With A. Burov, Y. Alexahin,…



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- BUT the problem has been solved in practice by going farther away from transition (gaining a factor ~ 2.5 in intensity threshold)

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It is interesting to note that Eq. (5.91) for the transverse stability of an unbunched beam gives, up to a numerical factor of the order of unity, the stability condition (4.46) for a bunched beam against the strong head-tail instability when one makes the replacement $\Delta\omega_{1/2} \rightarrow \omega_s$, identifies $|iZ_1^{\perp}/T_0|$ with W_0, and lets N be the number of particles in the bunch. This again supports the observation that synchrotron oscillation has a stabilizing effect against collective instabilities, and ω_s plays for bunched beams a role similar to the one the frequency spread $\Delta\omega_{1/2}$ plays for unbunched beams.

beams. What Eq. (5.99) demonstrates is that the mechanism of the microwave instability is basically the same as that of the strong head-tail instability, which is also called the mode coupling instability in the literature.

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$$\left|Z_1^{\perp}(\omega_c)\right| < Z_0 \frac{\pi \gamma \omega_s \omega_c}{3 N_B r_0 \beta_Z \omega_0 c} \Delta z_{1/2}^2 . \qquad (5.97)$$

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$$\Rightarrow \quad \boxed{N_B^{th} \propto |\eta| \, \varepsilon_L}$$

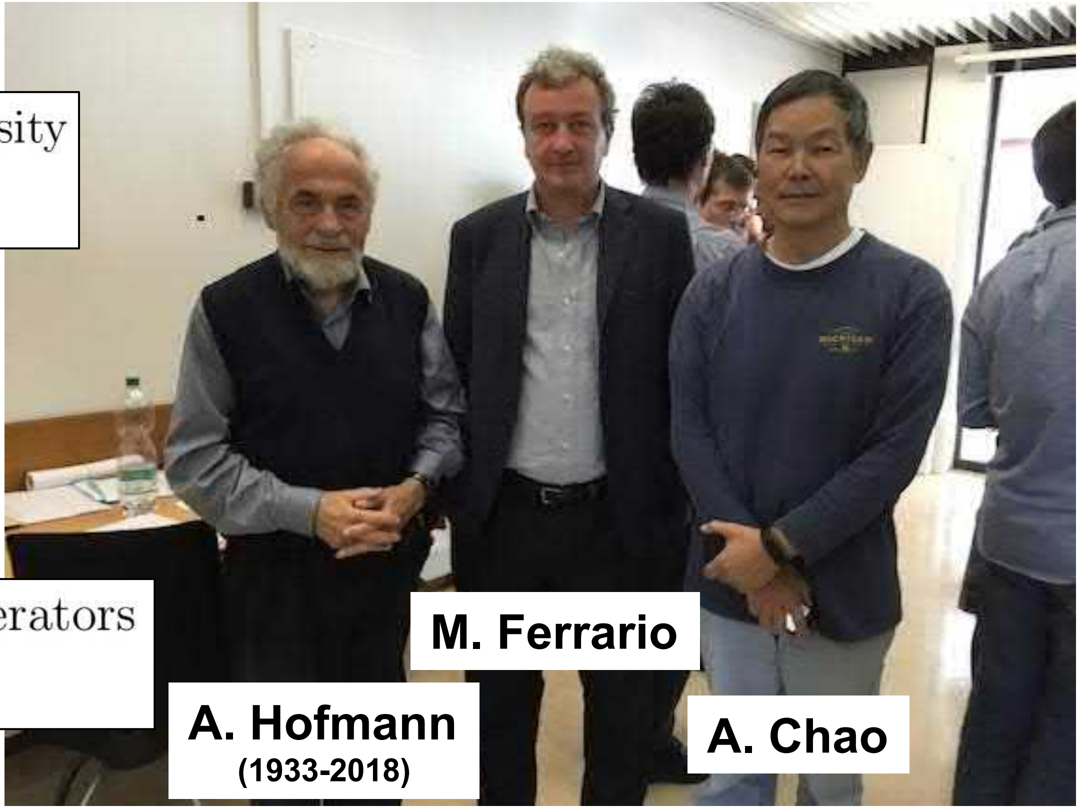
Alex participated to the CAS on "Intensity limitations in particle beams" in 2015 at CERN

Beam Dynamics with High Intensity

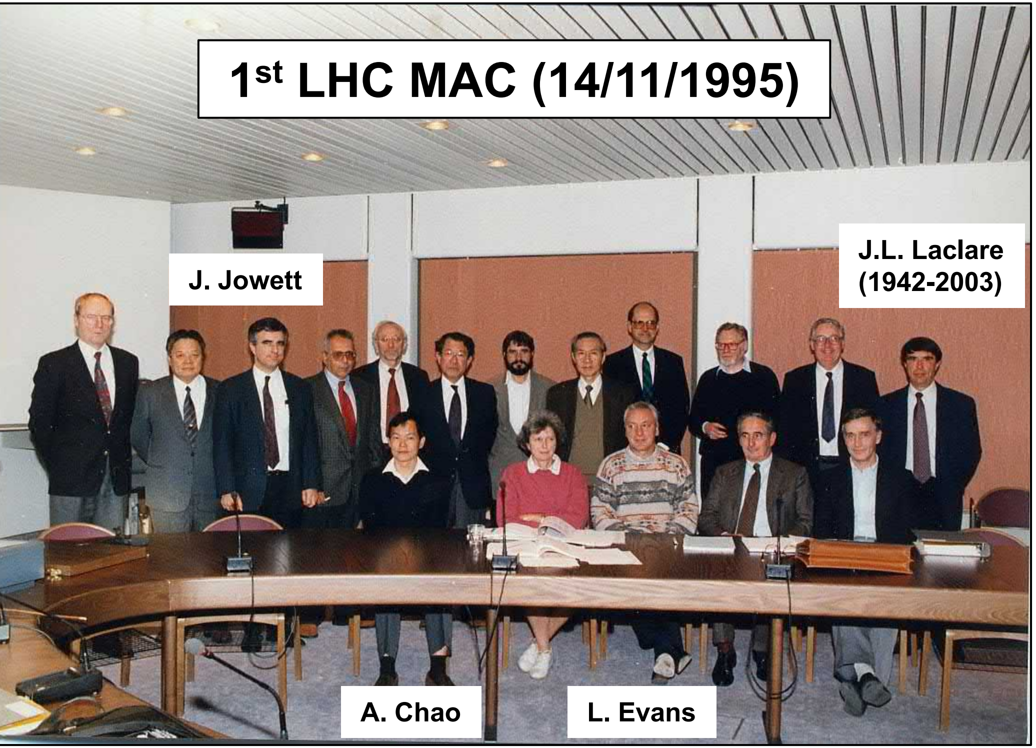
Alex Chao, SLAC

Beam Instabilities in Circular Accelerators

Alex Chao



Alex was also a member of the LHC-MAC for many years, and helped design and construct the LHC with his advice (F. Zimmermann and J. Jowett)



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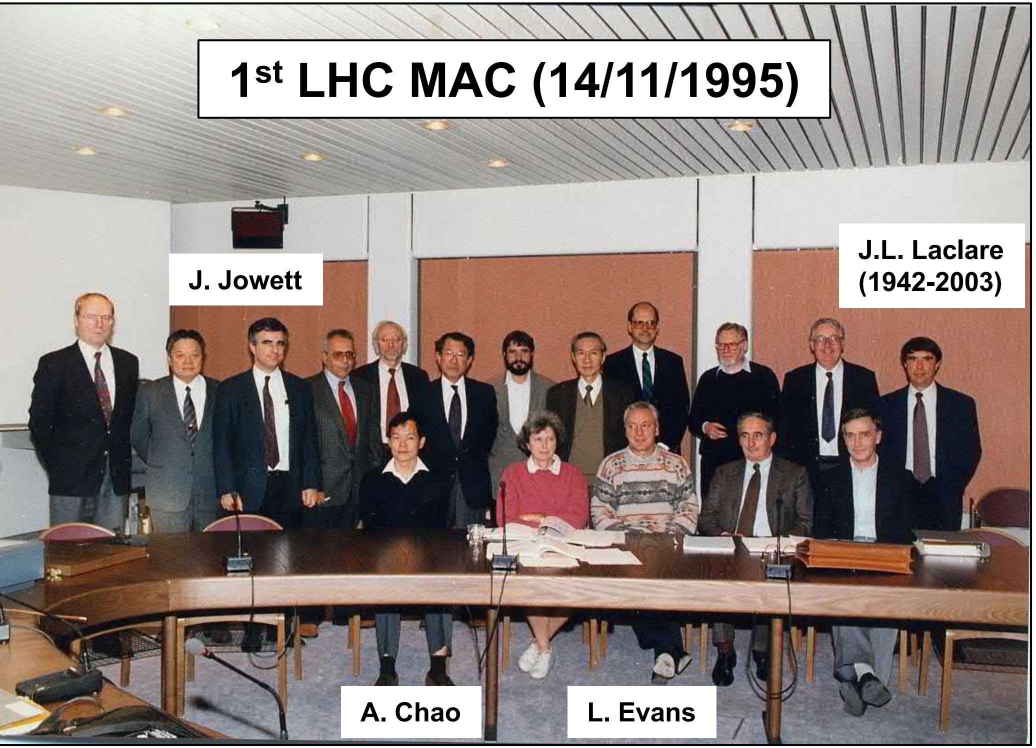

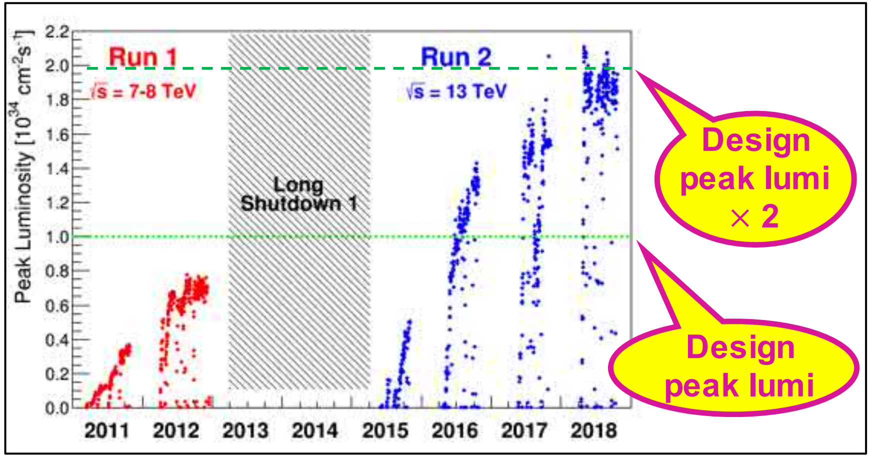

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F. Zimmermann

- "In the fall of 1992… At the SSC, I talked with Alex in his upstairs office about possible options for after my PhD. Alex told me that the two best places in the world for working on accelerator physics were SLAC (in case I were more adventurous to go there from Europe) and CERN. I followed exactly his advice. I first went to SLAC and then to CERN. I will forever be grateful for his excellent guidance.

=> Warm greetings and best wishes to Alex!"

J. Jowett

- "I send Alex my thanks for all his brilliant, influential work, many happy shared occasions since I first met him in 1980 and very best wishes for his retirement"

Conclusion

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  - Etc.

Conclusion

- A lot of progress could be made in the last years but I/we do know what we owe to our fathers and in particular to Alex Chao for having extremely well explained and documented the many impedance-induced instabilities => Many thanks again for that!

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also

> this volume—the subject of collective beam instabilities in accelerators. Over the years, I have learned and been fascinated by this subject, and it is this fascination that I would like to share with the reader.

next generation…

EPFL team
(C. Tambasco, T. Pieloni, L. Coyle, M. Schenk)
HEADTAIL
macroparticle tracking
code (2002)
F. Zimmermann
G. Rumolo
WILEY SERIES IN BEAM PHYSICS AND ACCELERATOR TECHNOLOGY
PHYSICS OF COLLECTIVE BEAM INSTABILITIES IN HIGH ENERGY ACCELERATORS
ACCELERATOR PHYSICS AND ENGINEERING
Alexander Wu Chao
Maury Tigner
World Scientific
N. Biancacci
X. Buffat
MANY THANKS FOR ALL ALEX AND ALL THE BEST FOR THE FUTURE!
C. Zannini
N. Mounet
B. Salvant
E. Koukovini Platia
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L. Giacomel
G. Iadarola