Collective Effects

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CERN

Introduction

- COLLECTIVE EFFECTS are responsible for the final intensity limit in most accelerators.

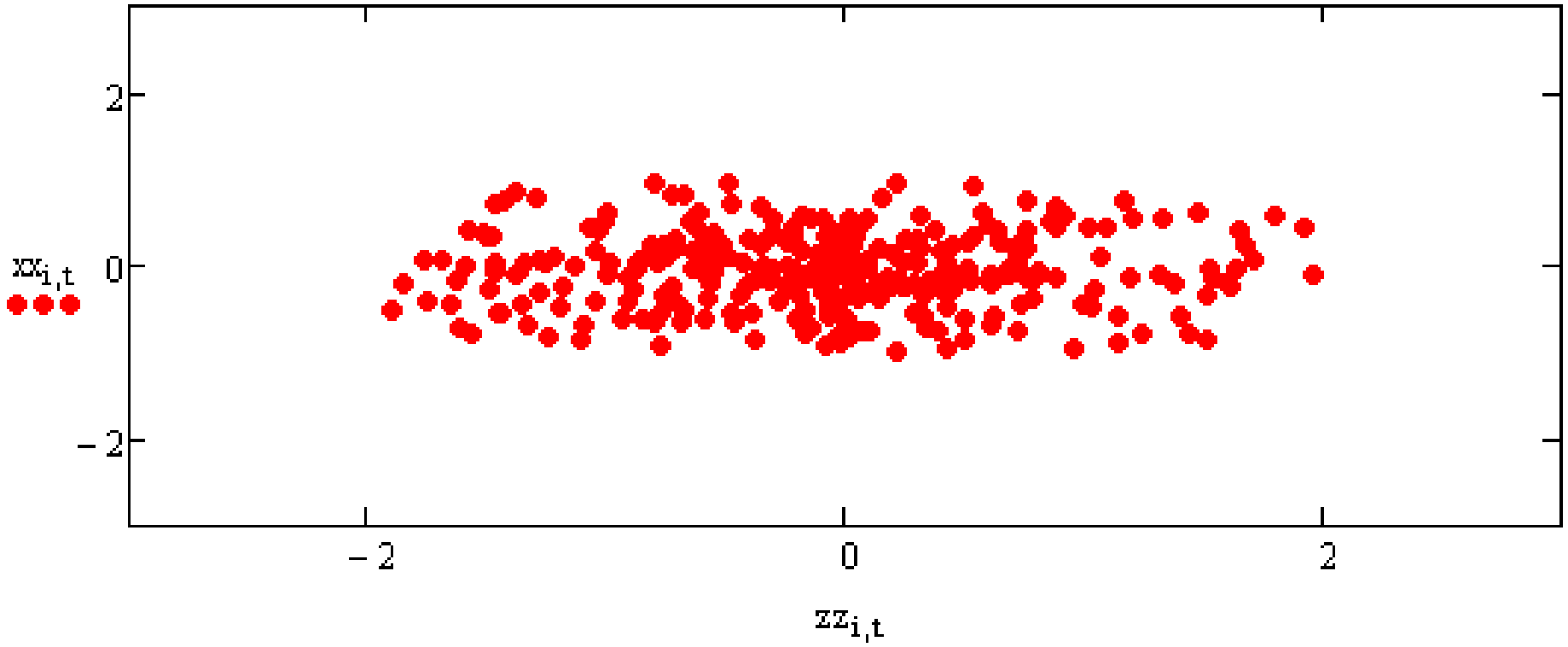
- Why is that?
  - The beams in our accelerators are kept and controlled by electromagnetic fields (Magnets, radio frequency,..).
  - Beams consist of charged particles (protons, electrons, ions..) which create their proper electromagnetic fields.
  - Adding up a lot of particles in a bunch create intense e.m. fields which are competing with the controlling fields. This result in naughty “collective” effects. (If they are too many, the particles will start to act ‘collectively’ to make life difficult)

Introduction

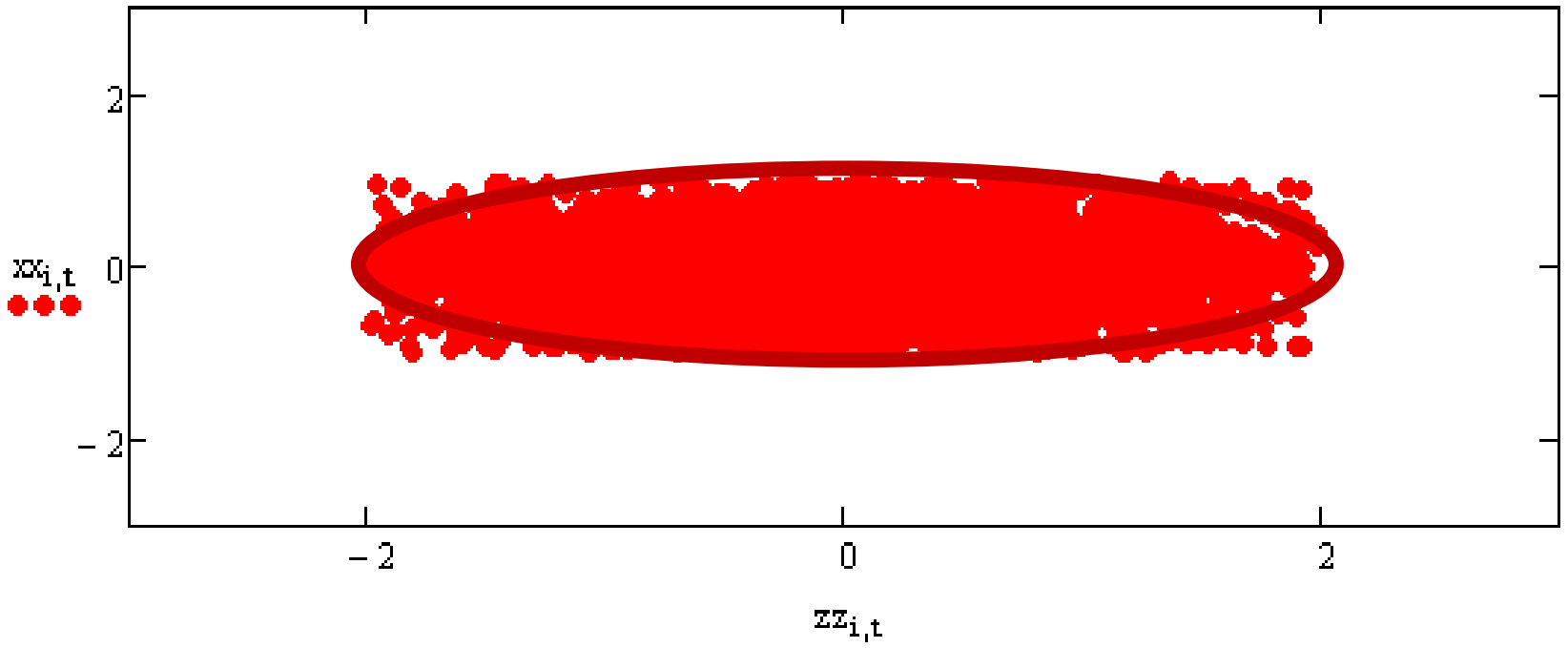
- This lecture is about the consequences of pushing too much particles in a bunch, such as:
  - Space charge effects
  - Wakefields resulting in:
    - Longitudinal coupled bunch and single bunch instabilities
    - Transverse coupled bunch instabilities
    - Head tail instability
- But first: reminder of basic particle motion in a bunch (a bee story)

Busy bees

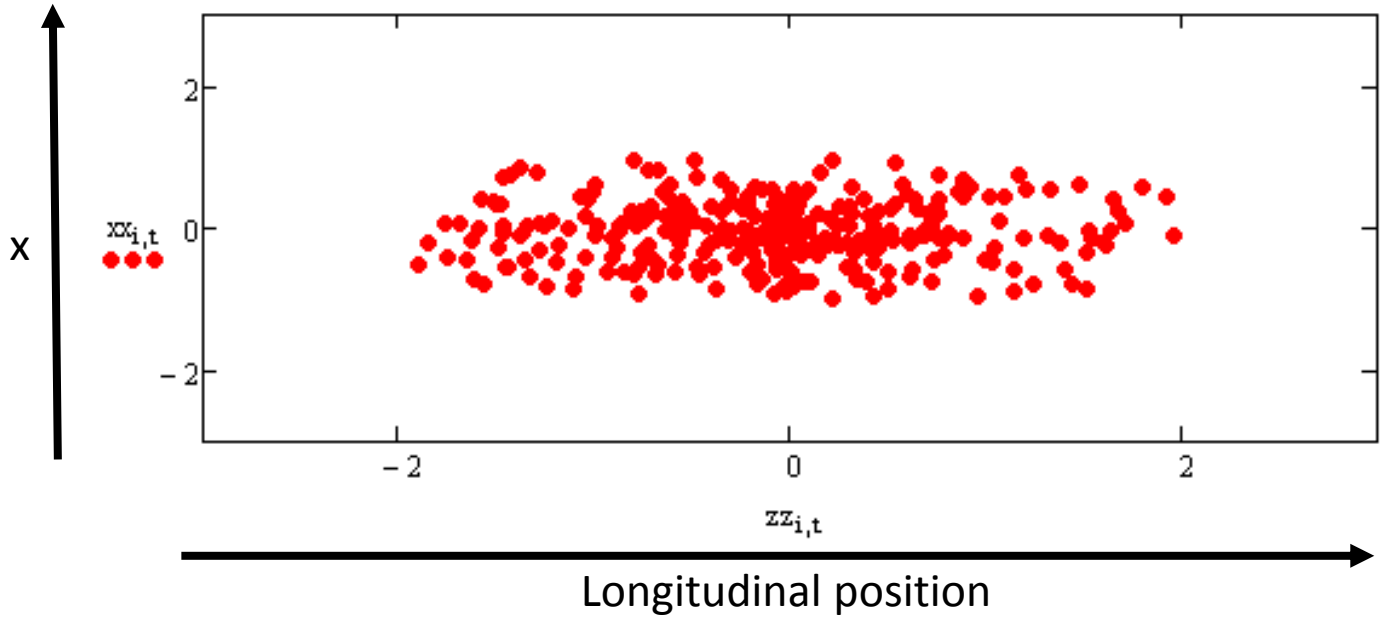
A bunch is not a static thing; particles move around like bees in a swarm.



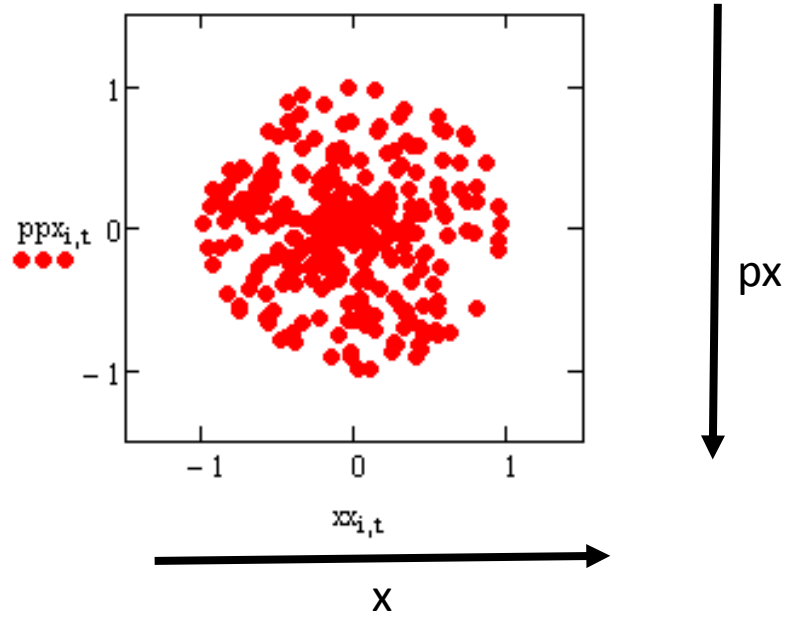
A stable envelope



Order in the chaos



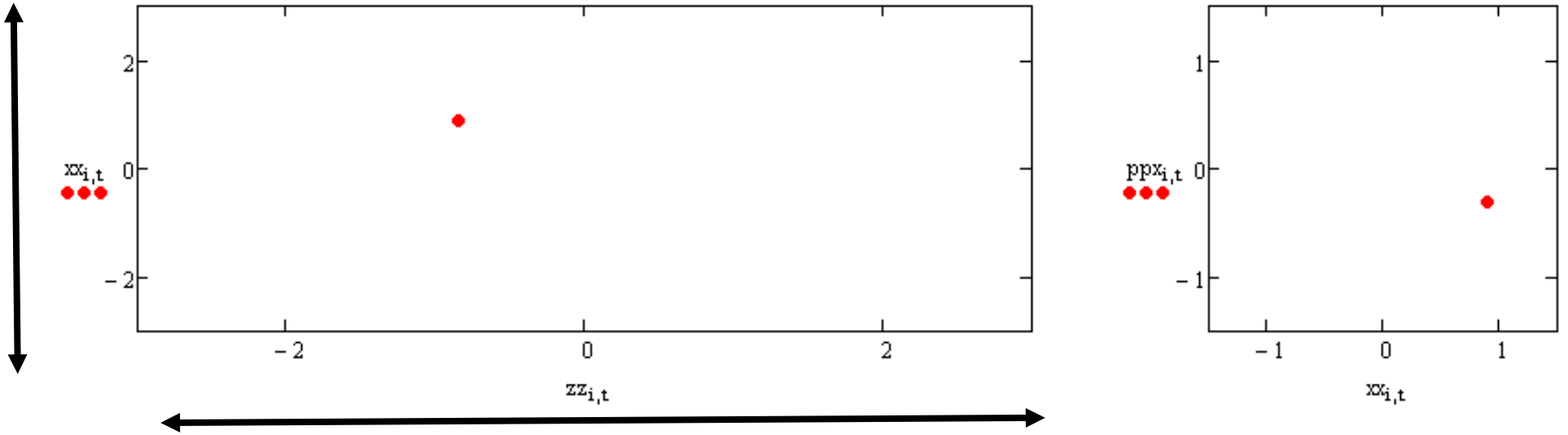
Phase space



The orderly motion of a single bee

Transverse oscillations horizontal or vertical

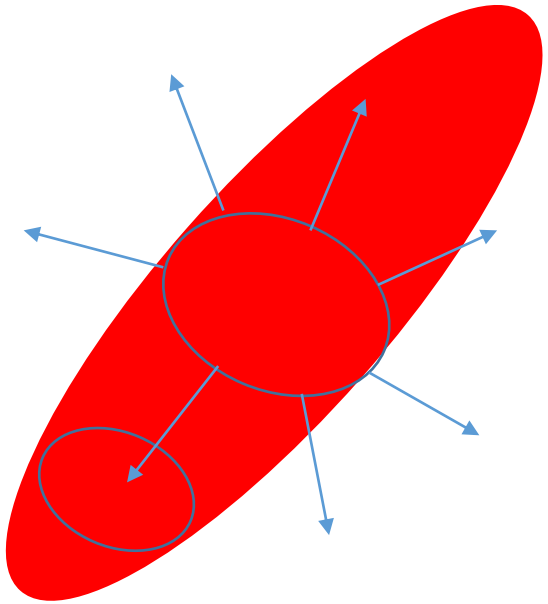
Frequency : betatron tune, Qh, Qv



Longitudinal oscillations

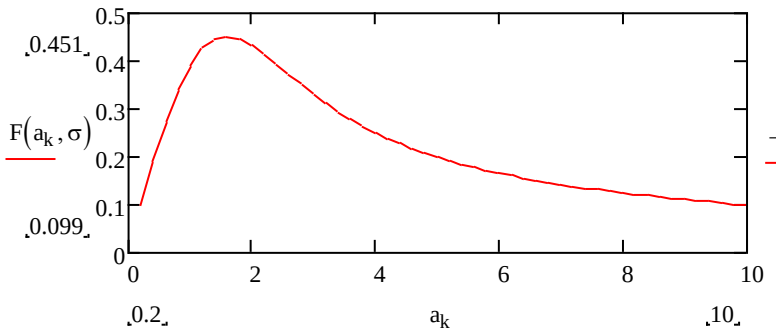
Frequency : synchrotron tune, Qs.

Space charge (origin collective, result single bunch)

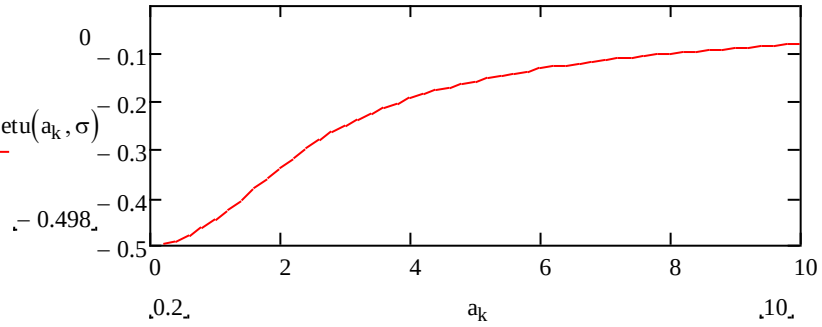


Protons in a bunch repel each other resulting in a de-focusing force.

This causes a betatron tune shift which is different for particles close to the center and particles at the outside of the bunch.



Force as function of amplitude

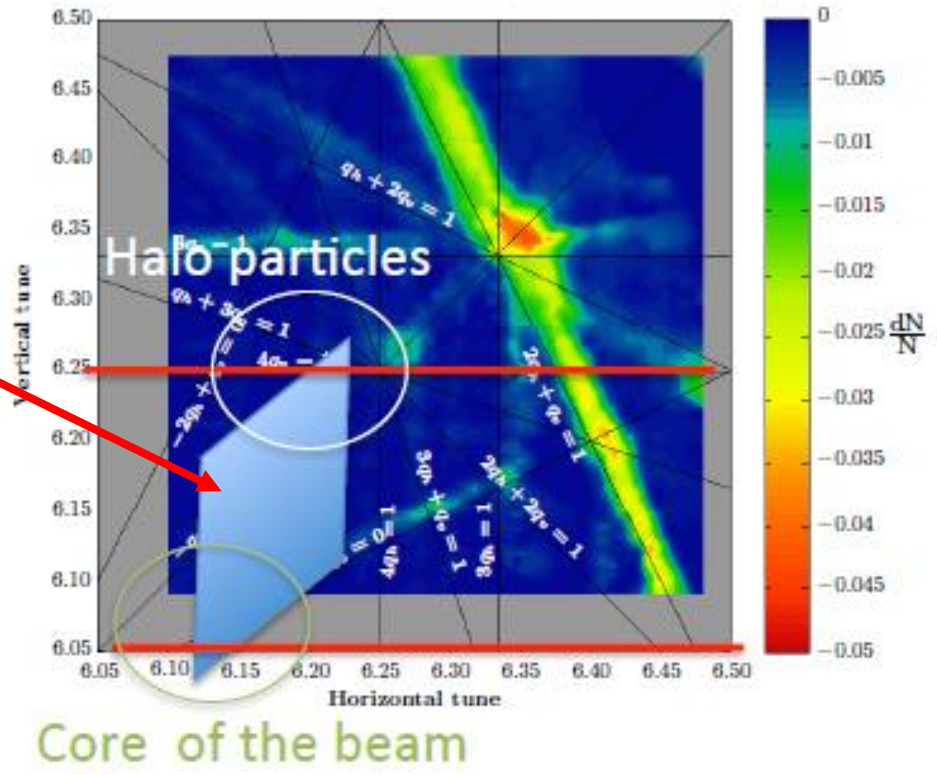


Tune shift as function of amplitude

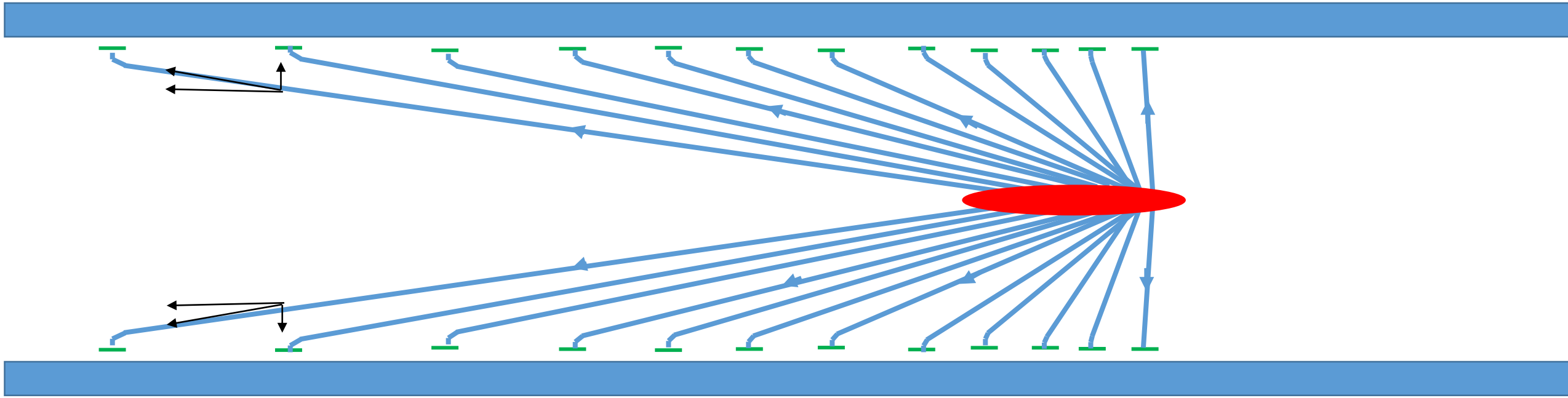
Space charge

$$dQ \sim \frac{N}{\sigma_s \cdot \varepsilon} \cdot \left(\frac{E_0}{E}\right)^3$$

- Tune spread makes it difficult to avoid resonances
- Depends strongly on energy: it is an important performance limiter for low energy accelerators
- Make bunches as long as possible



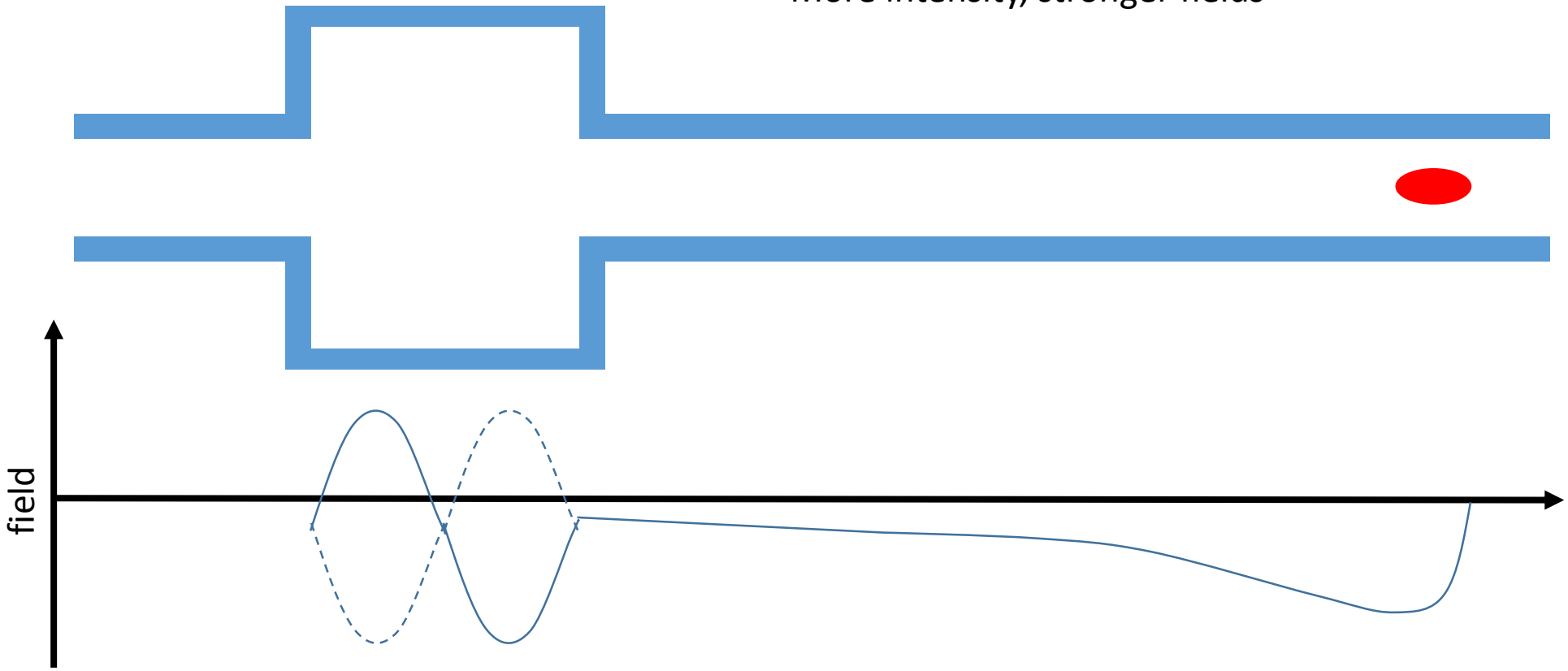
Wakefields: field induced by bunch in the vacuum chamber



Wakefields

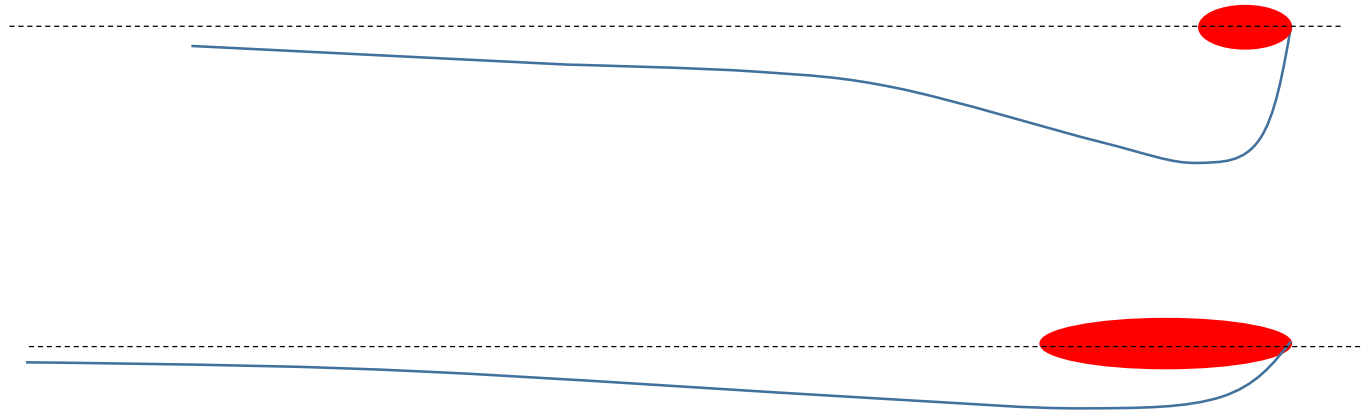
In cavity like structures standing waves are provoked leading to longer lasting wakefields.

More intensity, stronger fields



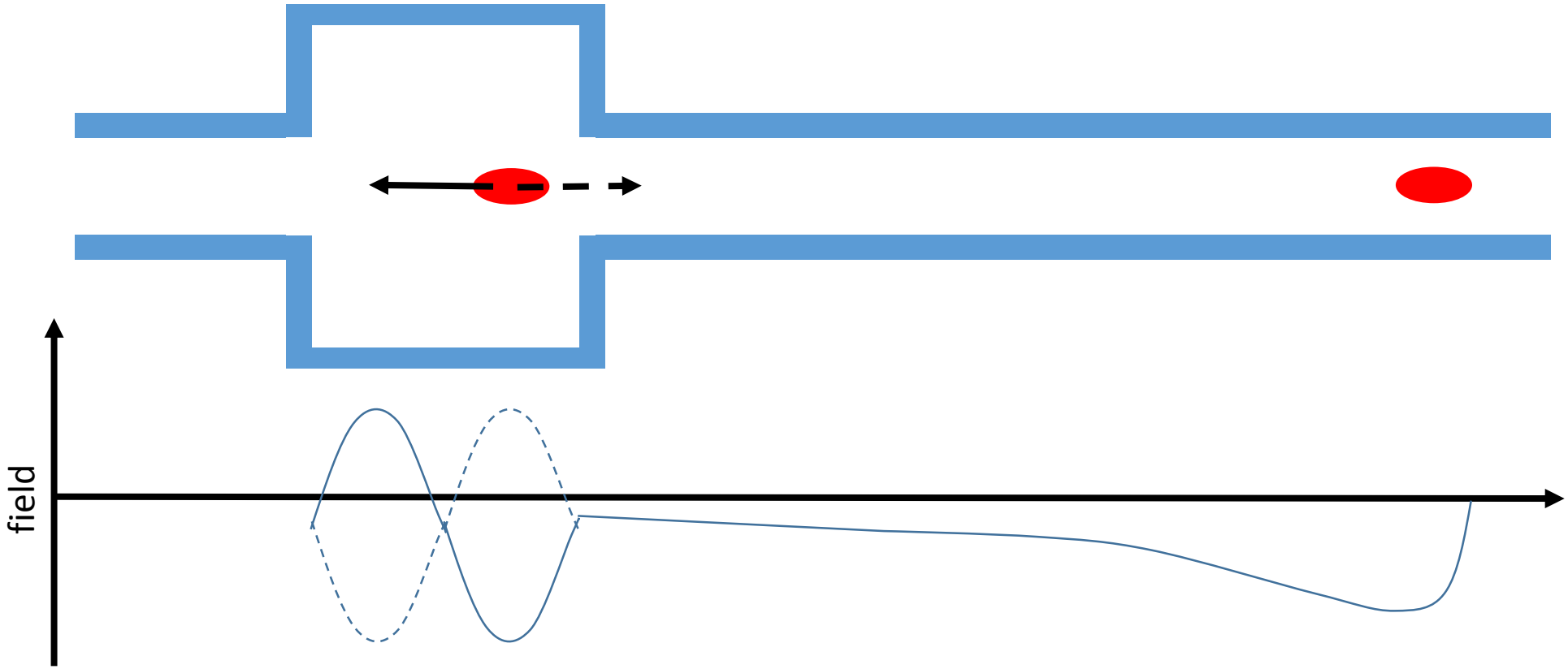
An important fact about Wake fields

Longer bunches induce weaker fields

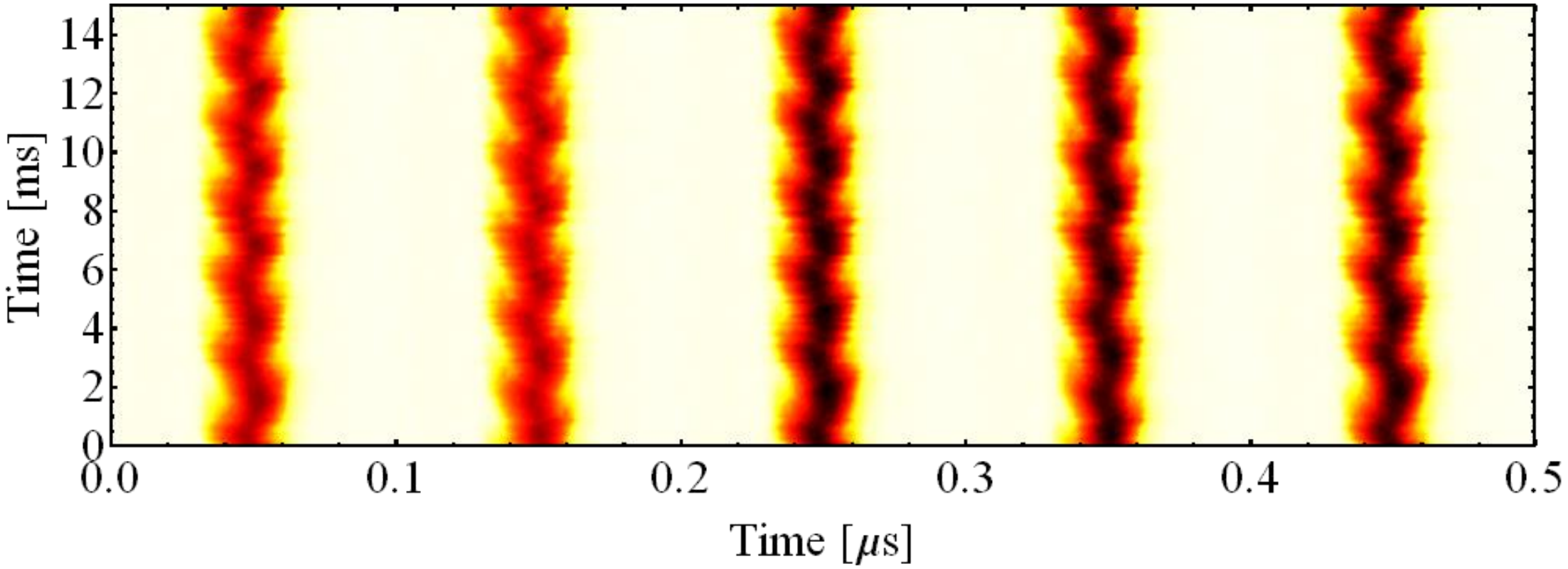


Longitudinal coupled bunch modes

Bunches can be (de)-accelerated by the wake field of preceding bunches.

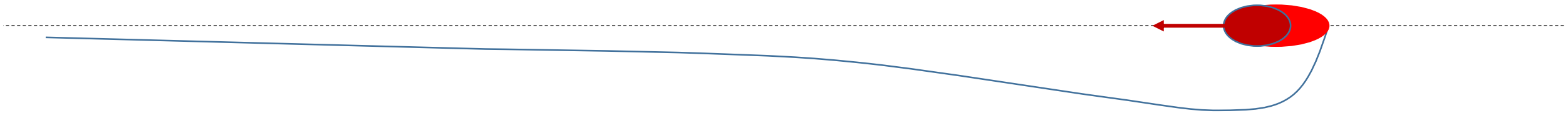


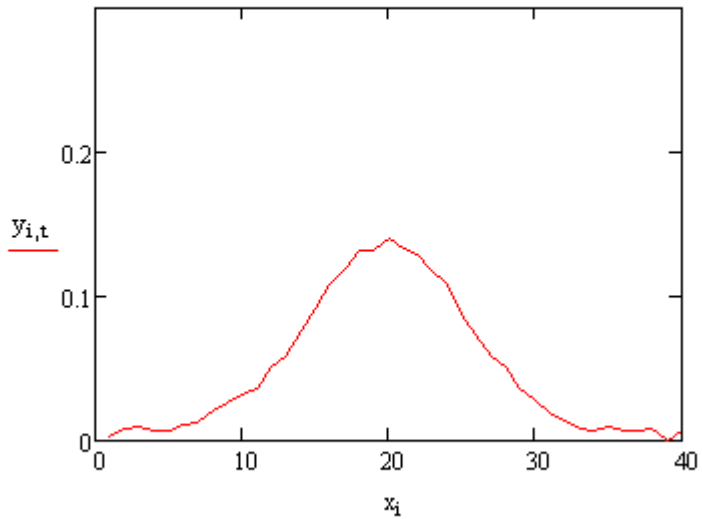
Longitudinal coupled bunch instability in the PS.



Courtesy L. Ventura, H. Damerau

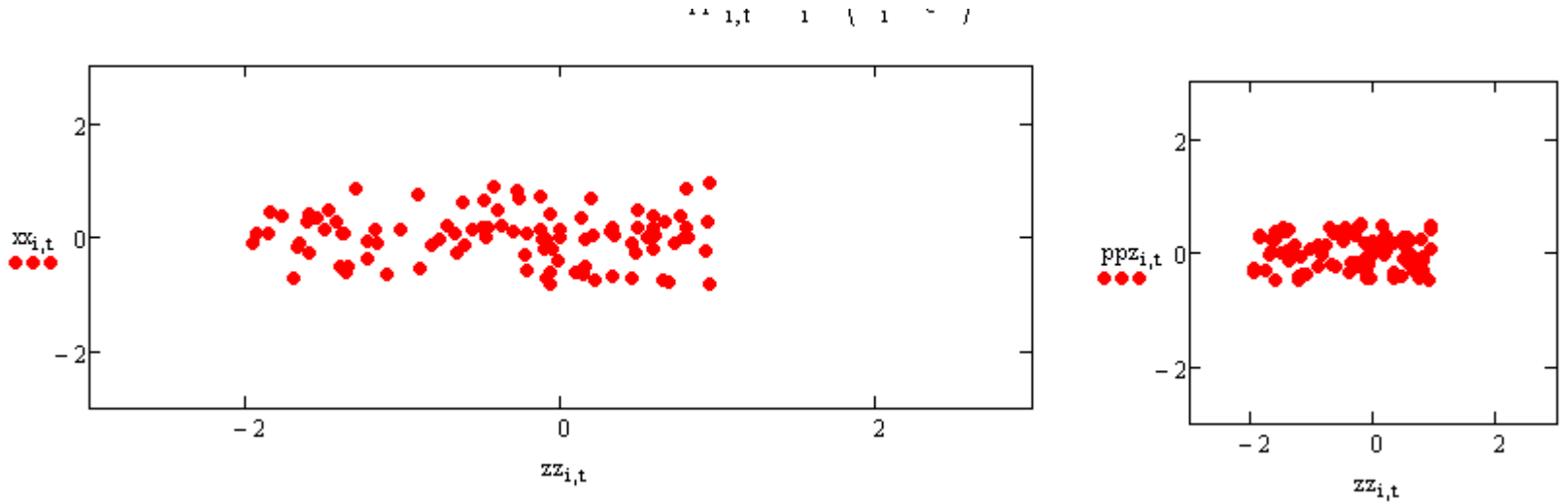
Longitudinal single bunch instability





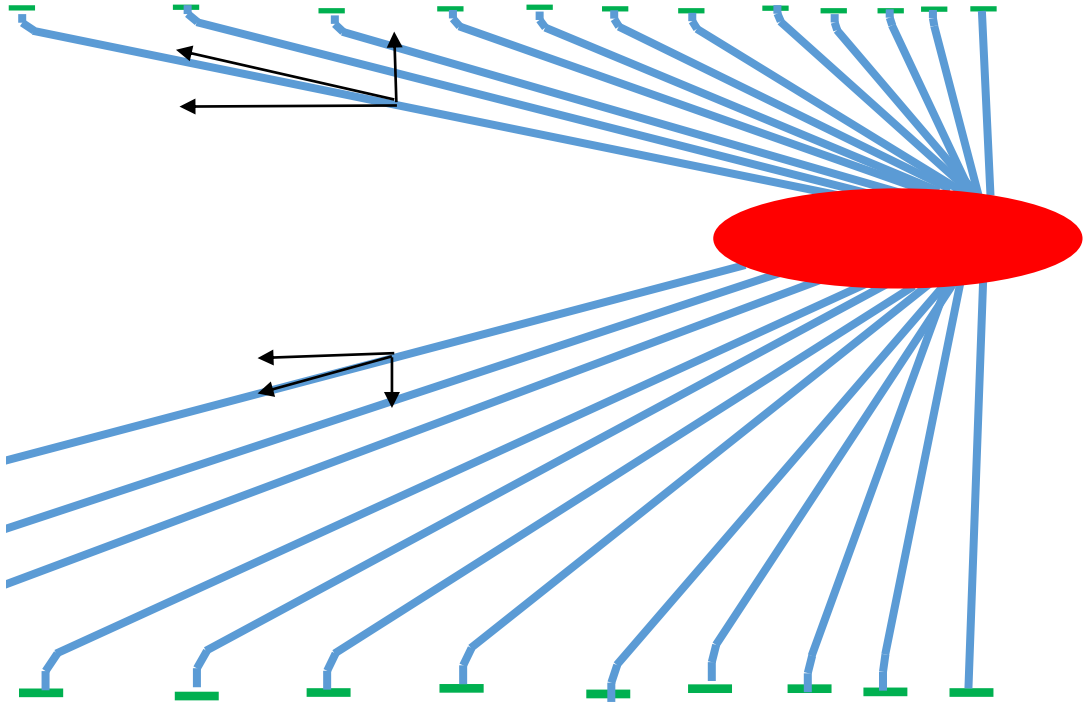
Longitudinal single bunch instability

Envelope is changing in real space and phase space -> coherent motion

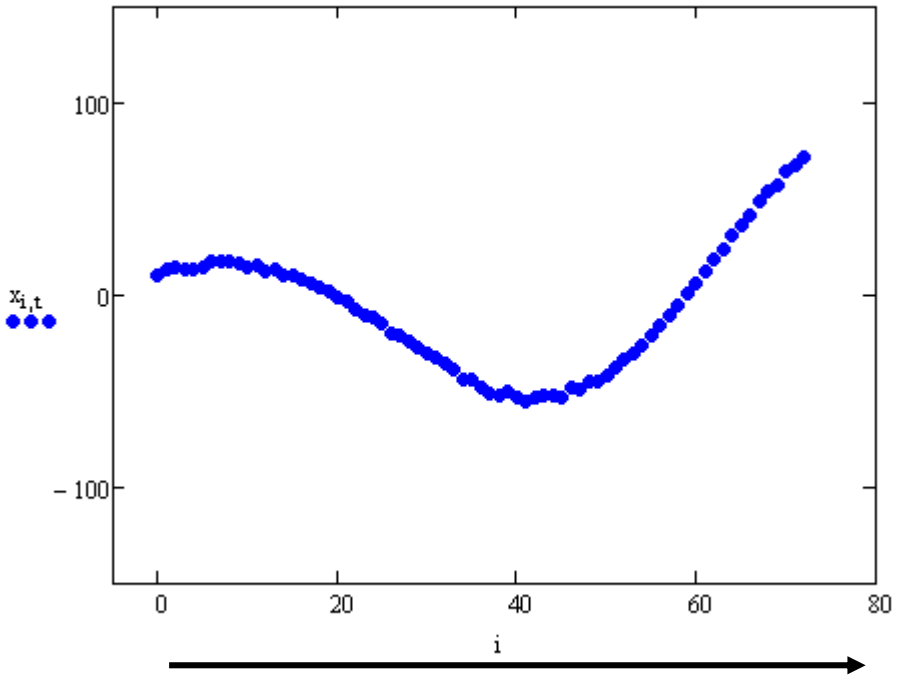


Transverse instabilities

When the bunch is off center a net transverse wakefield is created



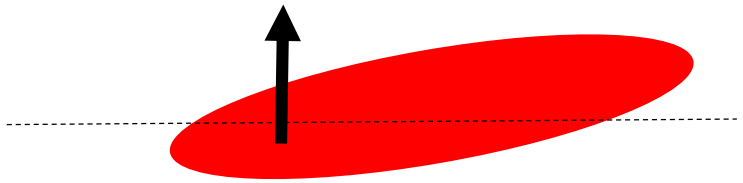
Transverse coupled bunch mode



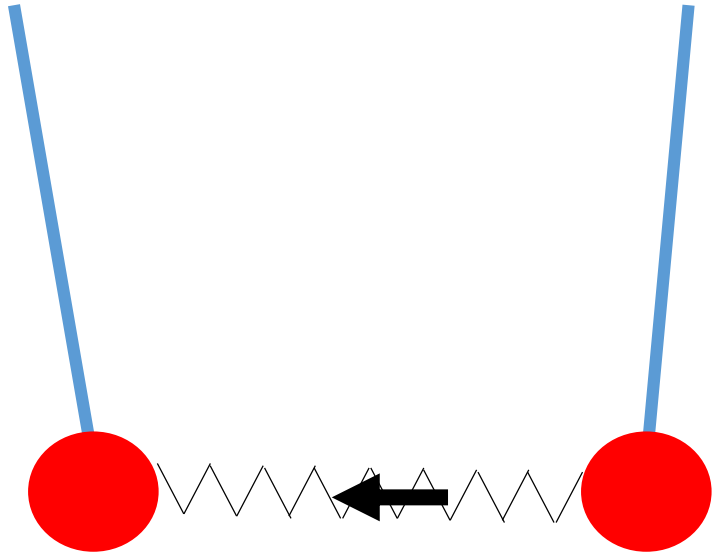
72 bunches

Bunches will receive a transverse kick depending on the transverse position of the previous bunches.

One way coupling between oscillators

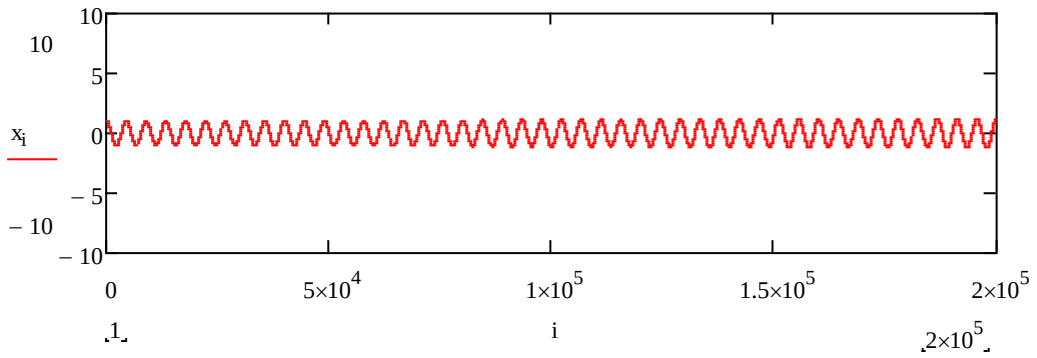


The tail sees a force depending on the position of the head

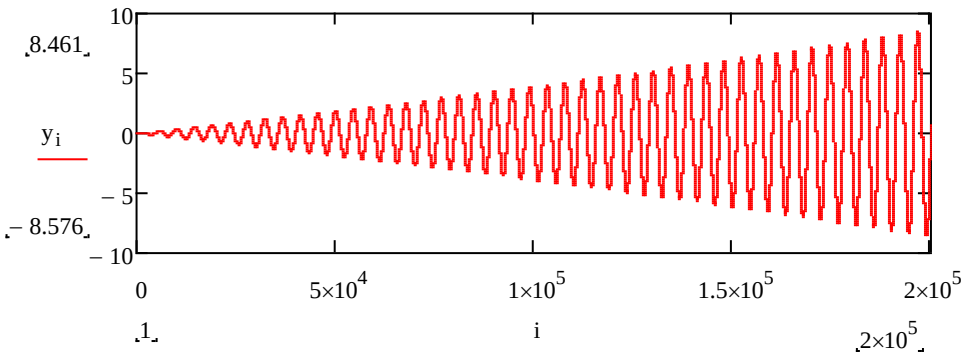


One way coupling from head to tail

A small oscillation form the head induces an increasing oscillation of the tail

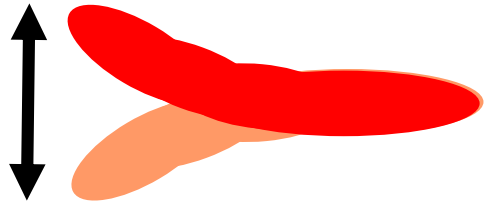


HEAD



TAIL

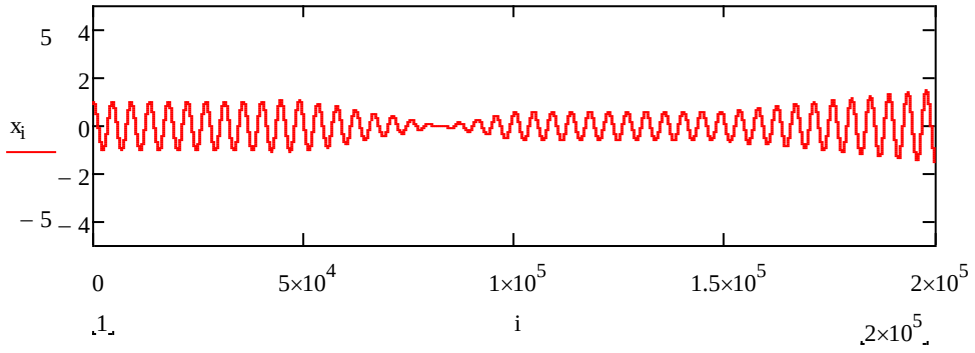
‘Beam break up’ or ‘Fast head Tail’

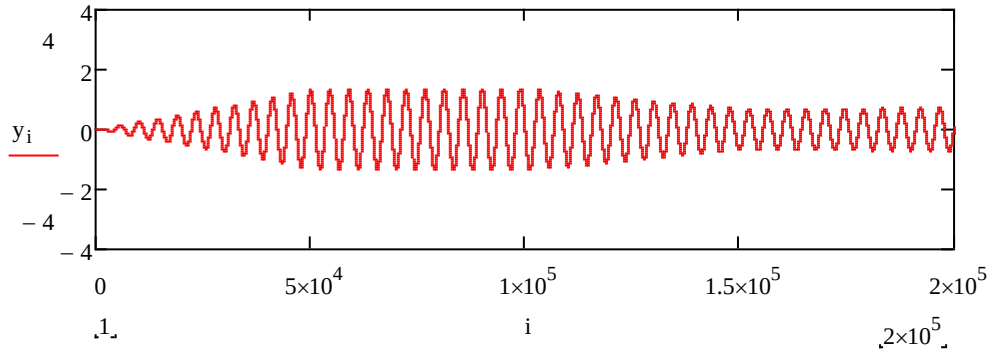


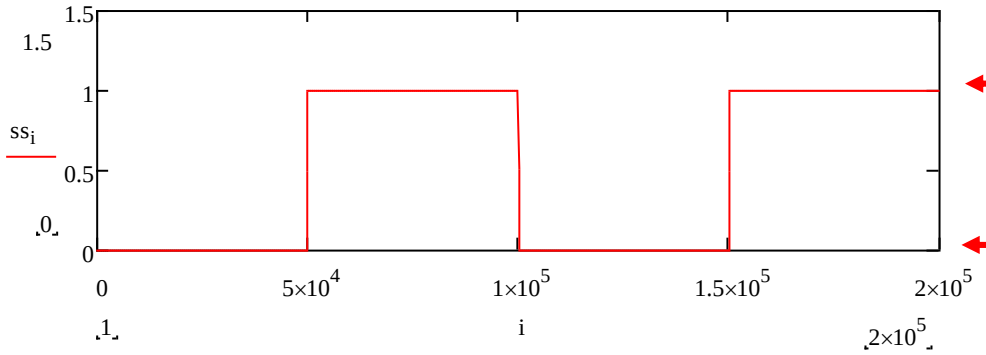
- Happens mainly in LINAC’s
- Can happen also in large circular accelerators if strong enough to develop in a few turns.

Head and tail interchanging position

Low intensity

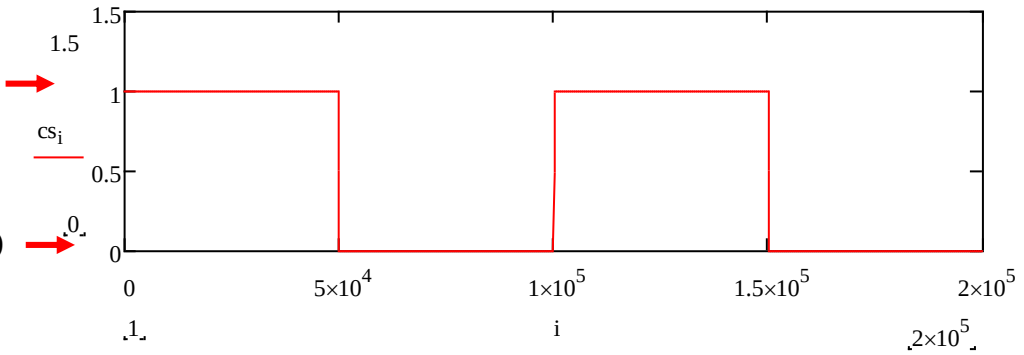






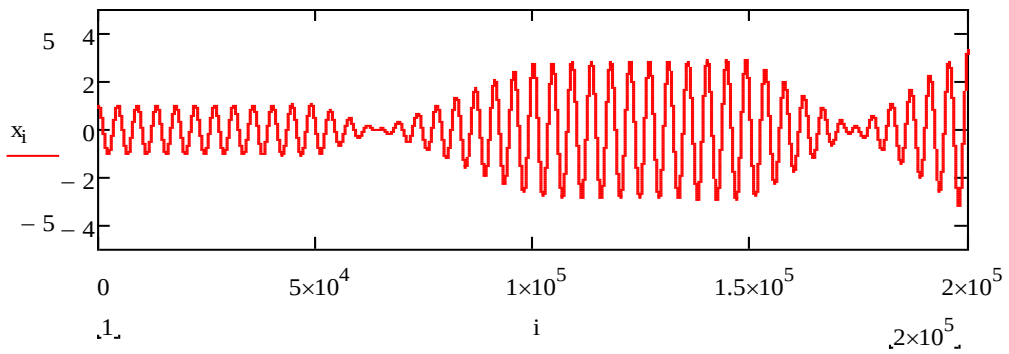
TAIL

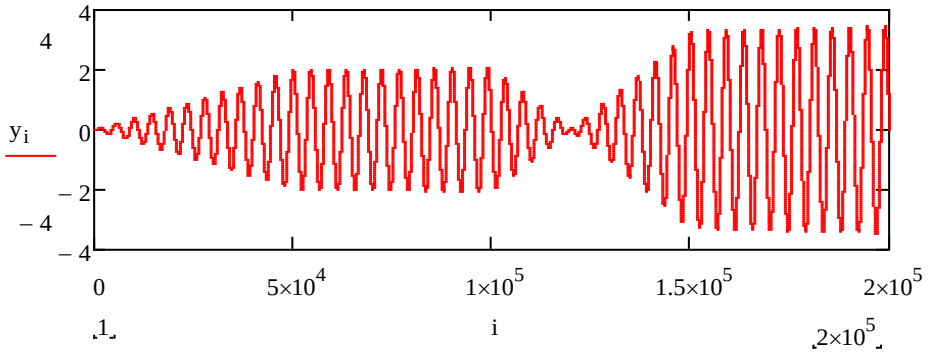
HEAD

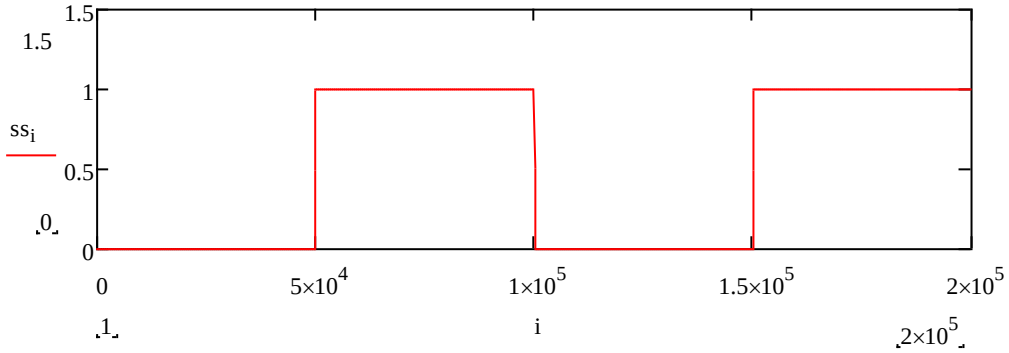


Head and tail interchanging position

High intensity (strong coupling)

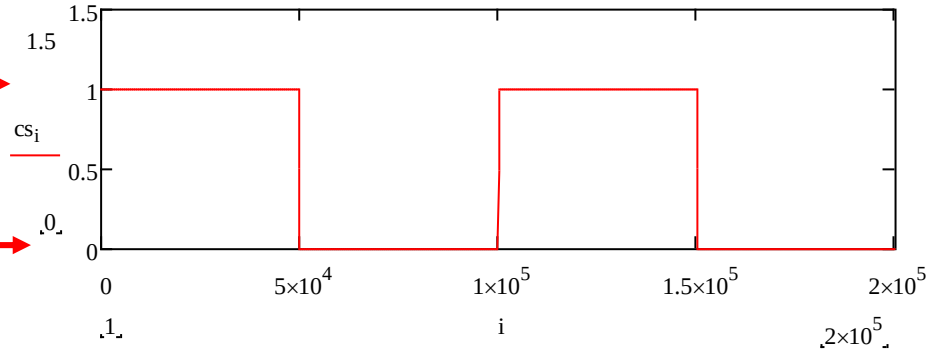




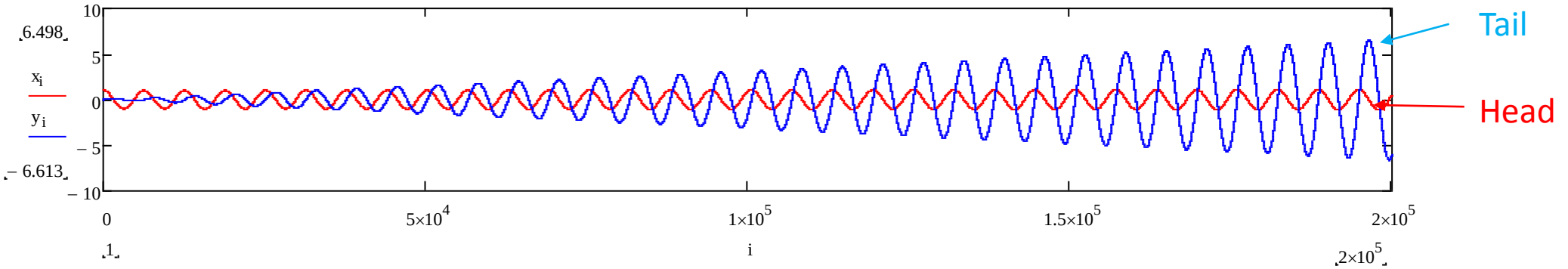


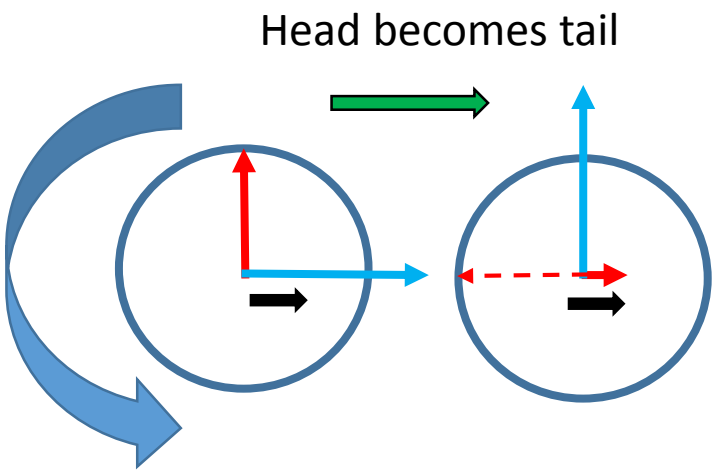
TAIL

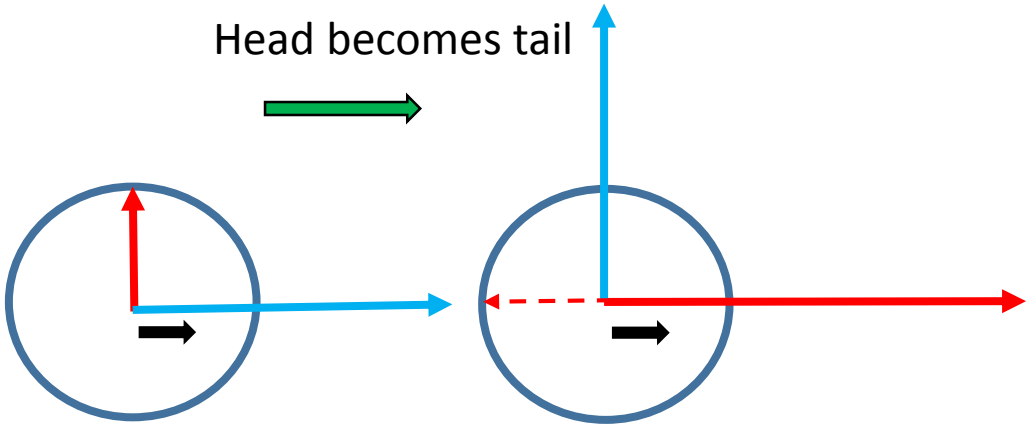
HEAD

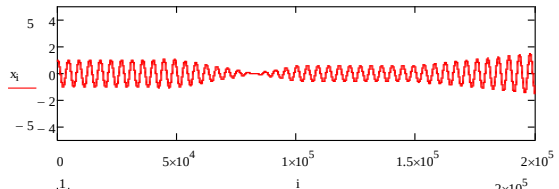


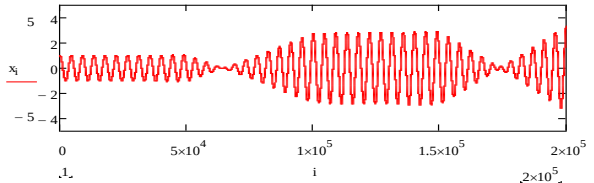
A picture of what is happening



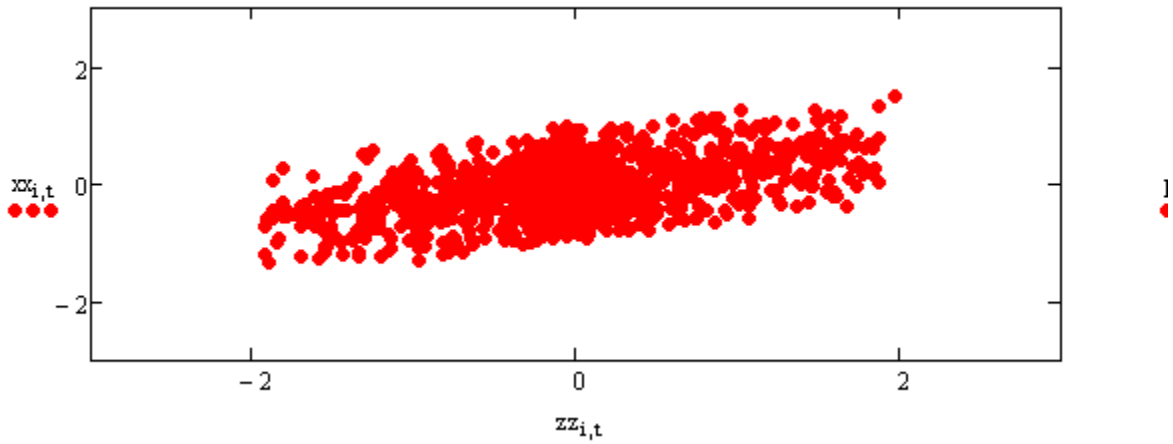








Head tail instability, how it looks like

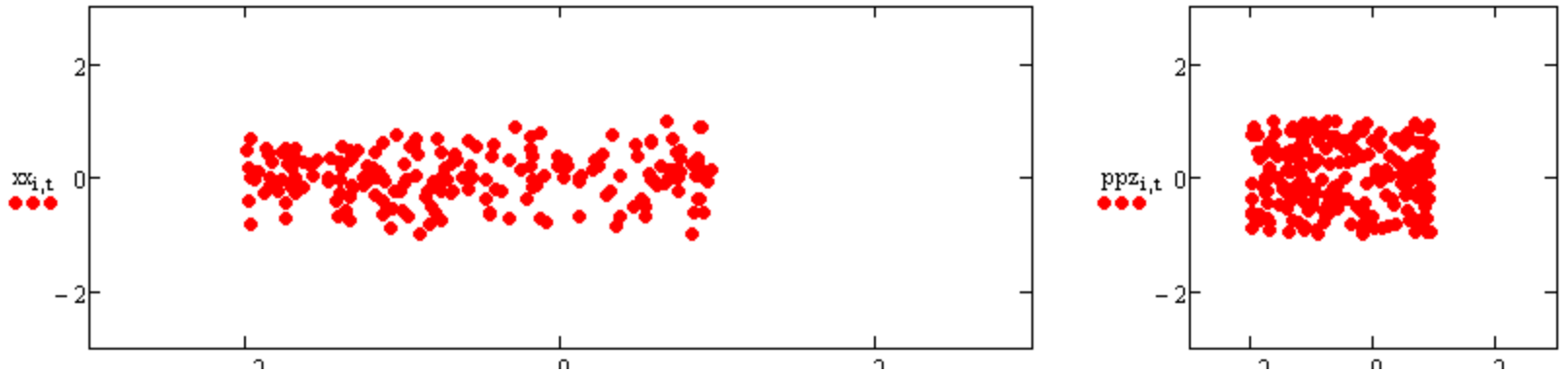


How to fight these instabilities?

- Make a smooth vacuum pipe to avoid strong wakefields.
- Maximize bunch length to minimize the peak wake field.
- Create a frequency spread (make them walk out of step),using chromaticity or non linear magnets
- Active damping with a feedback. Measure position and kick to put bunch back in place.

- These measures have all their limitations: limited tune spread to avoid resonances, limited power and bandwith in feedbacks, …

Damping with frequency spread



Summary

- The fields created by high intensity bunches create undesirable effects which limit the performance.
- In low energy accelerators the defocusing force created by the charges, create a tune spread and put particles on resonances.
- Wakefields, induced by intense bunches, result in a coupling force between bunches resulting in instabilities (coupled bunch)
- Wakefield variations over the length of the bunch create longitudinal single bunch instabilities and transverse head tail instabilities.

- Remark: other mechanisms can create similar coupling forces such as e-cloud and beam-beam.