Collective effects in particle accelerators

The CERN Accelerator School

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Collective Effects and Impedances

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Collective forces

Dome of the Swiss Federal Palace

[Wiki]

- **One for all:** The motion of each individual particles define the collective force
- **All for one:** The collective force affects the motion of each individual particle

- The collective forces can affects beams in several ways

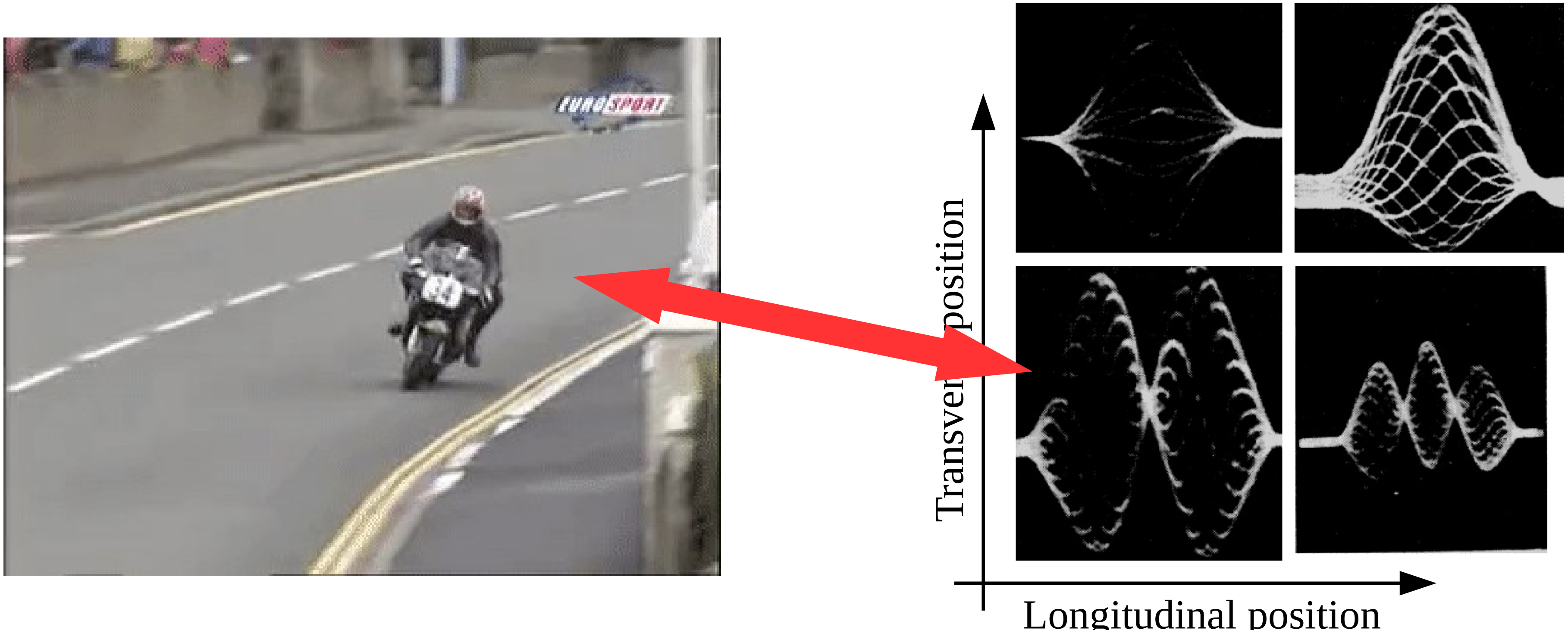
→ They usually limit the quality of the beams that can be achieved with a given machine, such that understanding and control of collective effects directly relates to performance reach

→ In some cases the collective force is used to achieve a given purpose

Content

- Collective instabilities
  - Study case: Electromagnetic wake fields and the head-tail instability
  - Damping mechanisms
- Non-linear collective effects
  - Poincaré section, resonances and chaos
  - Beam-beam and space-charge effects
- Scattering effects
- Summary

Real life instability vs beam instabilities



- At high speed, the motorbike holds a lot of energy flowing in a given direction
- If a mechanism allows for even a small transfer of this energy to a mode of oscillation of the bike, the pilot has no chance to contain the oscillation

→ **instability**

- Particle beams also holds a lot of energy flowing in a given direction
- Several mechanism can transfer the longitudinal energy into modes of oscillation
- Beams have much more modes of oscillation than bikes...

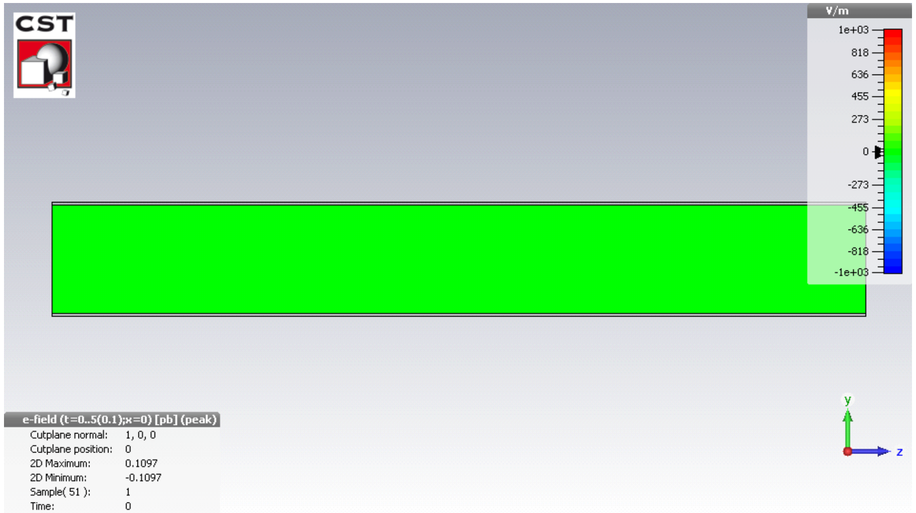
Wake fields on Lake Neuchatel

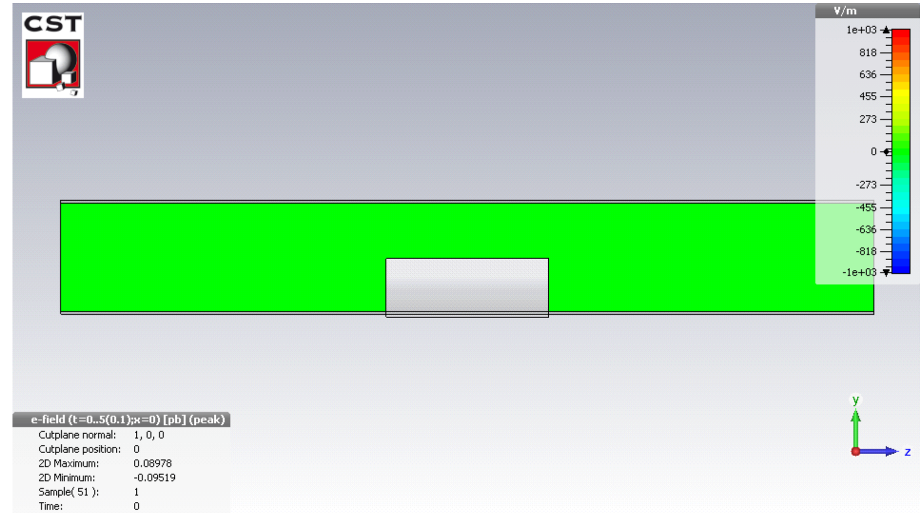
Witness

Source

Wake fields in particle beams

[Wake]

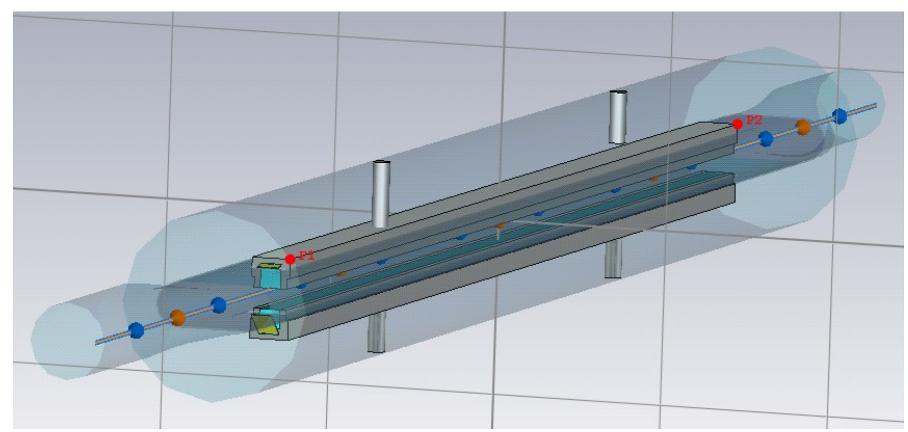




- Just like a boat travelling on a lake, a charge particle travelling through space generates a wake, in the form of an electromagnetic field rather than a wave on water

  → For particles travelling close to the speed of light, the wake affects only particles behind the source

- Structures in/around the beam pipe can generate complex behaviour (electromagnetic waves, trapped modes, …)

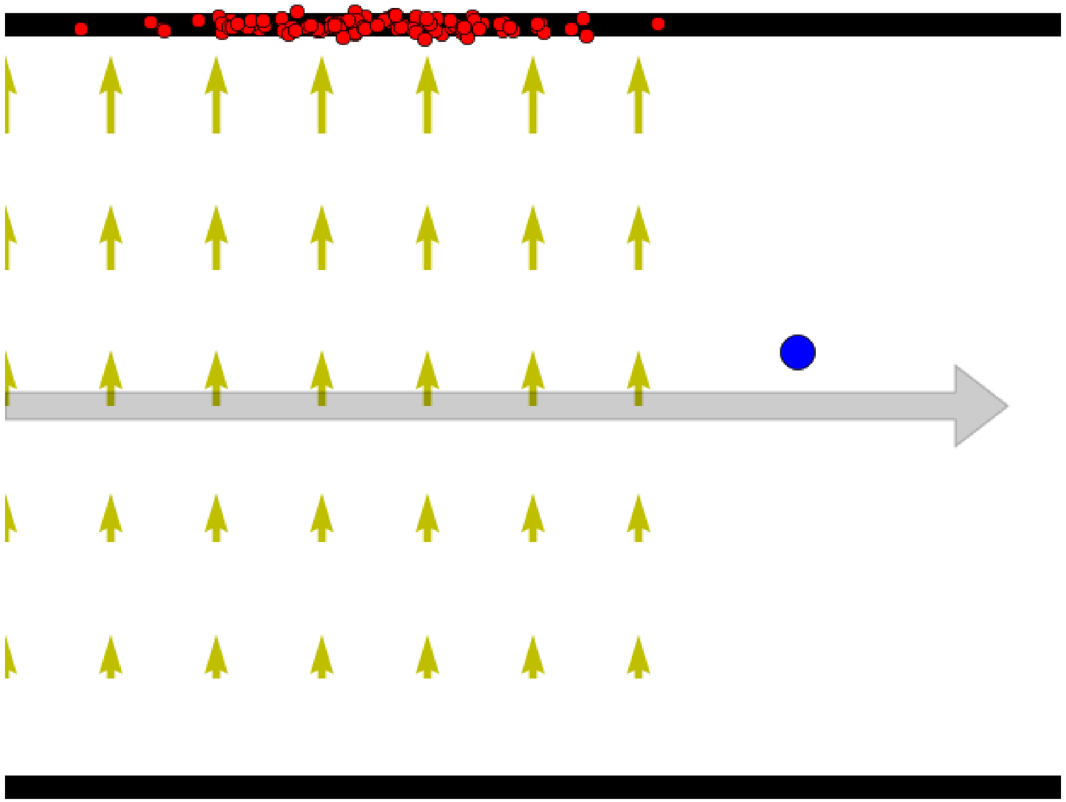


LHC collimator model

Wake fields: A naive but effective approach

- Image charges are attracted by the beam at the surface of surrounding elements
  - These charges interact with the material, which depends on its property (resistivity, capacity, shape, smoothness, …)

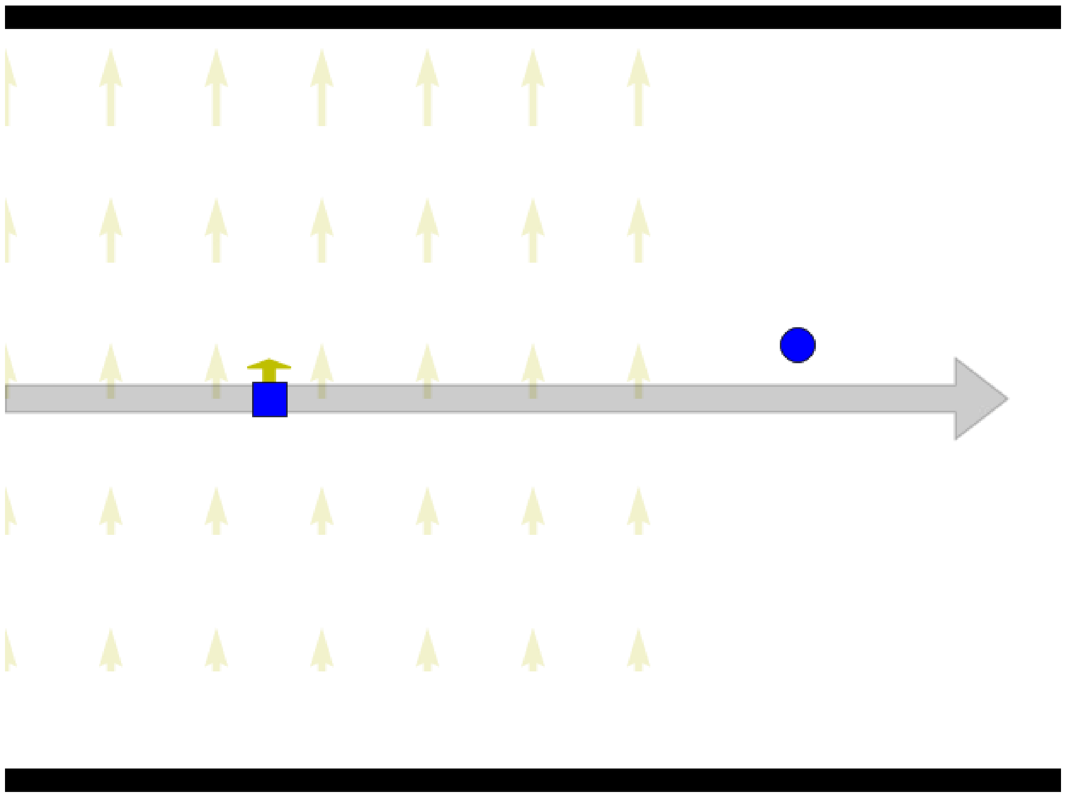
Wake fields: A naïve but effective approach



- If the beam oscillates, the density of the image charges vary on both sides with its oscillation

  → The fields generated behind the source particle also varies, with the natural frequency of the source particle!

Beam breakup

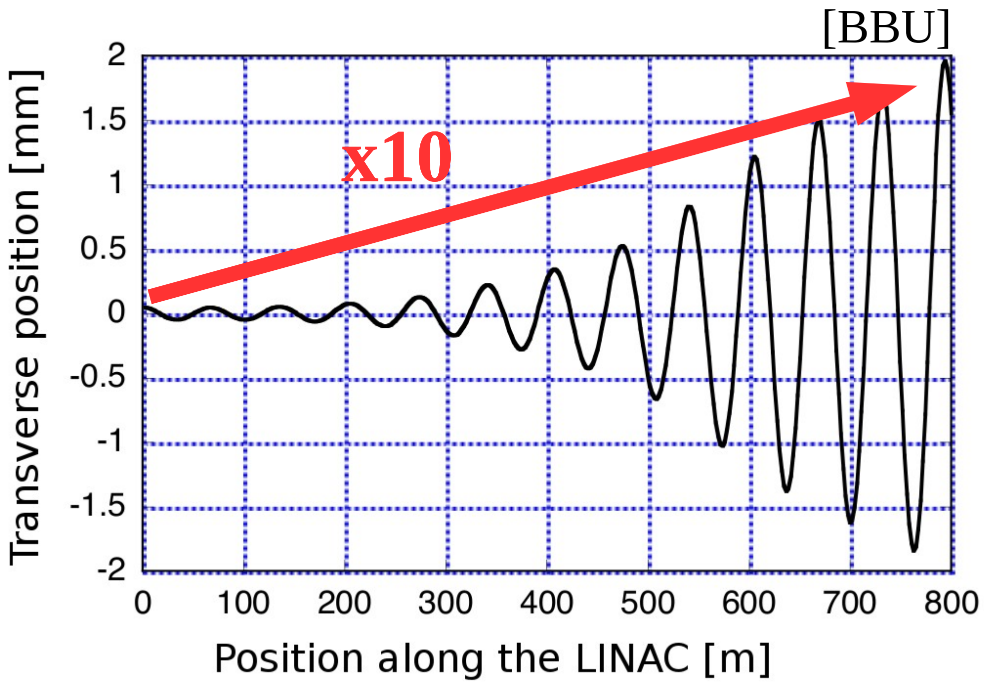


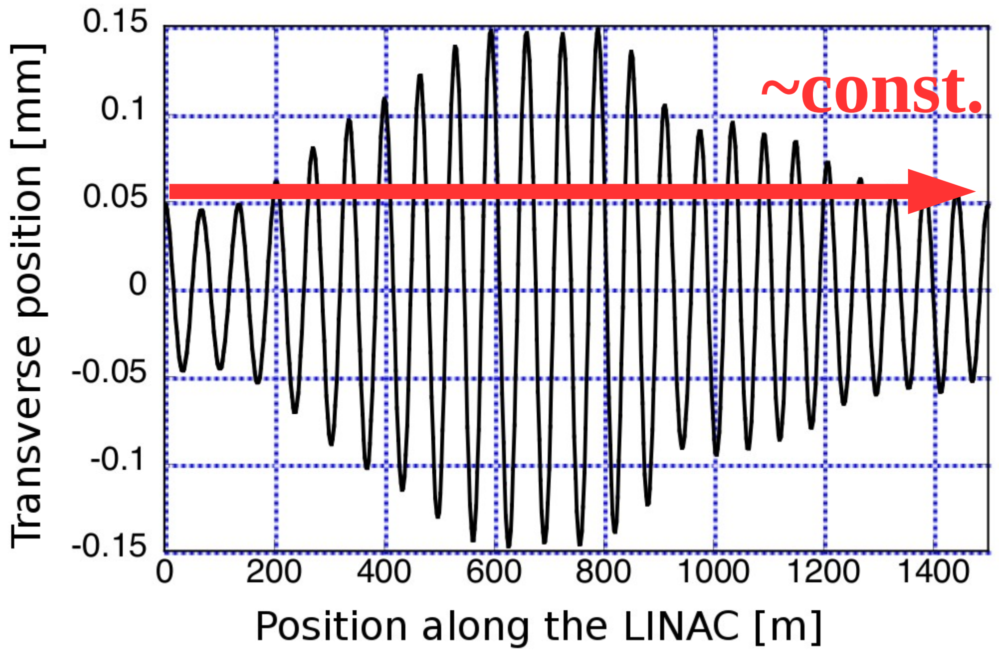
- In a LINAC (or a machine featuring slow synchrotron motion), the particles do not oscillate longitudinally

  → A trailing particle feels the oscillating field

  → Since its natural frequency is the same as the one of the source particle, it is driven to higher and higher amplitude

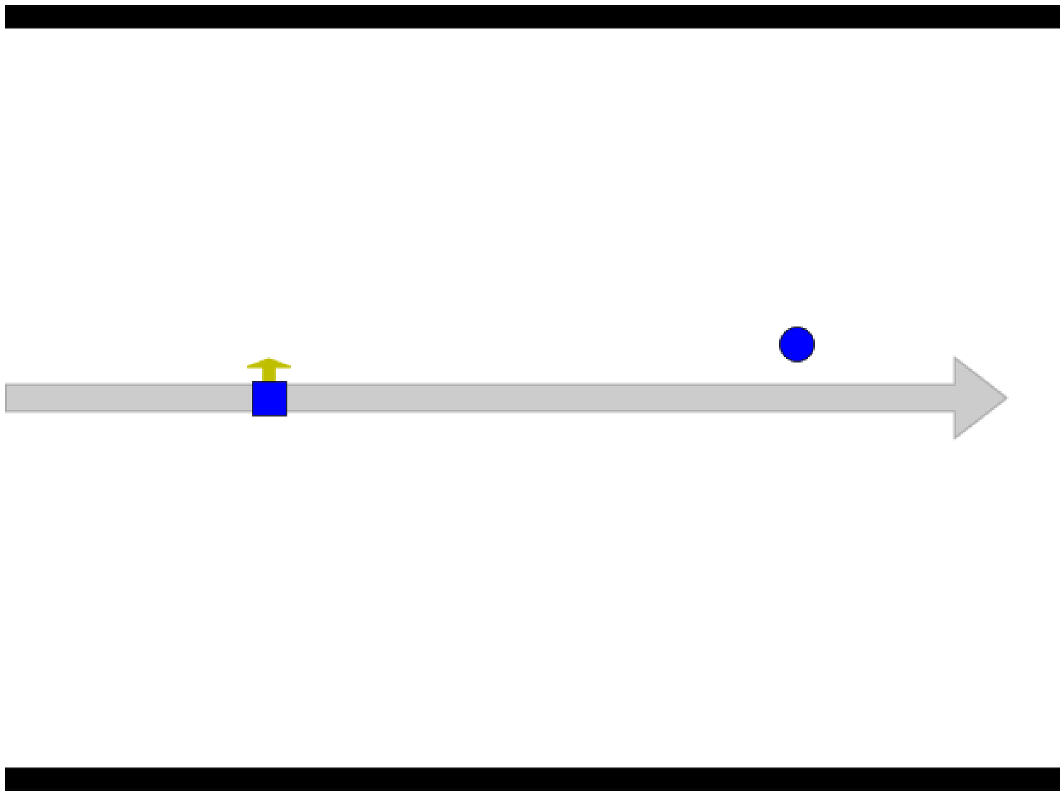
Beam breakup





- An initial perturbation is amplified through the LINAC
- Mitigations involve:
  - Minimising wake fields (i.e. electromagnetic design of the elements in the beam line)
  - Minimising misalignments
  - Minimising initial perturbations (injection steering)
  - Introducing a spread in frequency with non-linear fields (BNS damping)

The head-tail instability

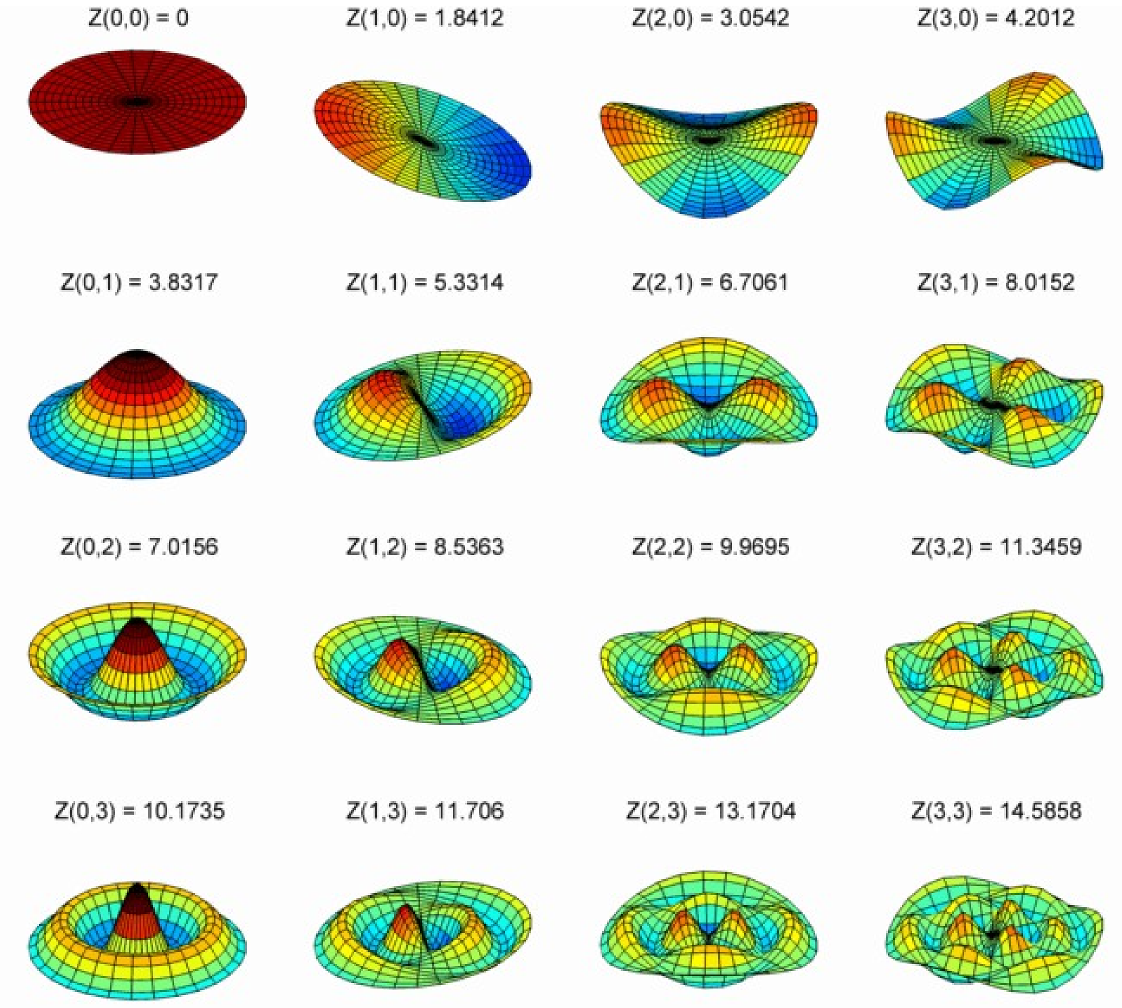


- Considering longitudinal oscillation:
  - When the square particle is trailing, it is driven by the round particle's wake field, and vice-versa when it overtakes the round particle
  - The amplitude of the two particles is self-amplified → Collective instability

The head-tail instability

- In practice we have more than 2 particles: we need to consider distributions of particles and their modes of oscillations

→ Most theories start with Vlasov / Fokker-Plank equations and a decomposition of the motion in radial and azimuthal mode in phase space

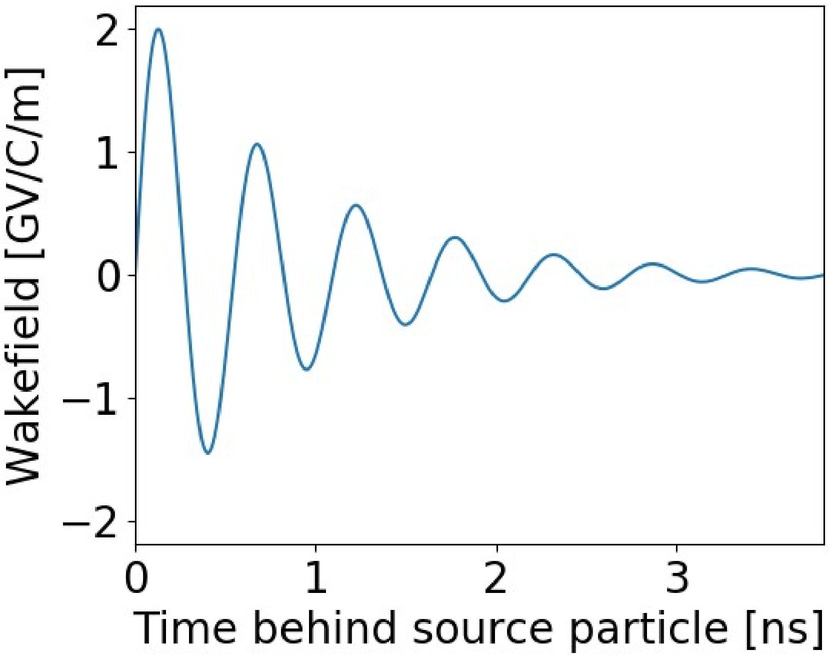


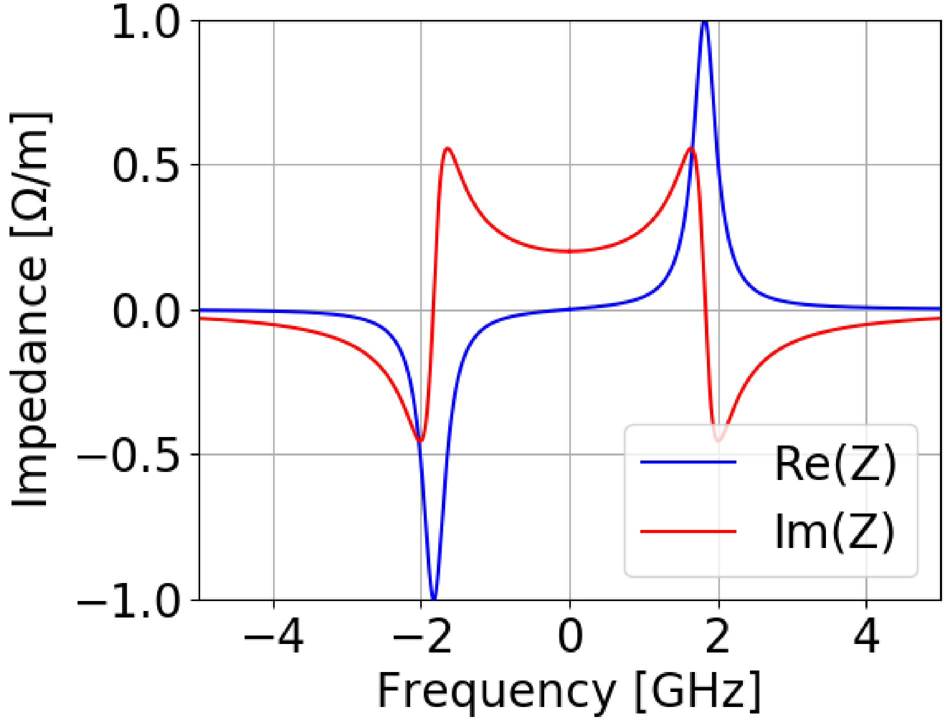
[Wiki]

Wakefield, impedance and effective impedance

- The wake fields are often described in term of their Fourier transform
  → The beam coupling impedance

Example: Resonator





Wakefield, impedance and effective impedance

- The impedance is a particularly interesting quantity, as its impact on a given mode of oscillation be estimated based on its product with the mode spectrum → Sacherer tune shift [Sacherer]

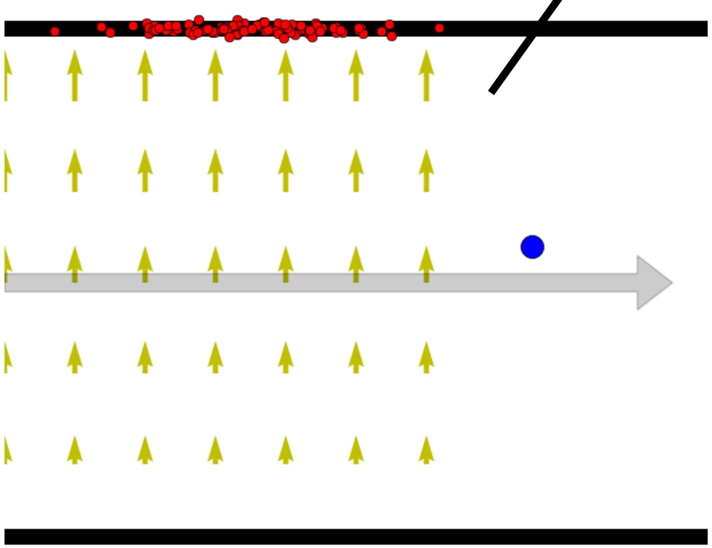
Frequency and growth rate of the instability

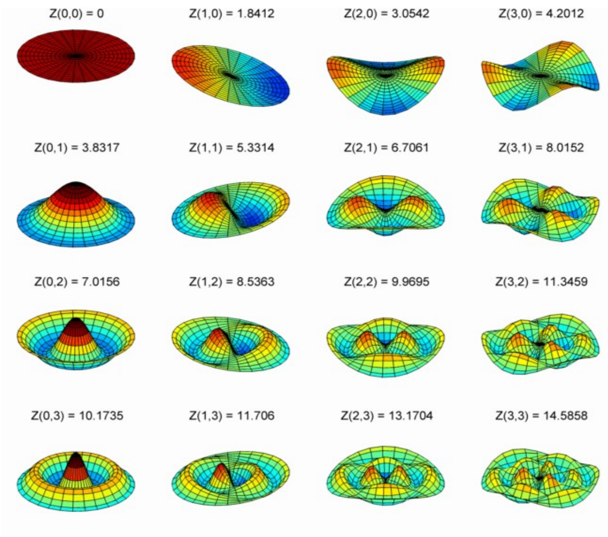
Chromaticity plays an important role for head-tail instabilities

$$\Delta Q \propto \sum_{k=-\infty}^{\infty} Z(\omega_k) H(\omega_k - \omega_\xi) \propto Z_{\text{eff}}$$

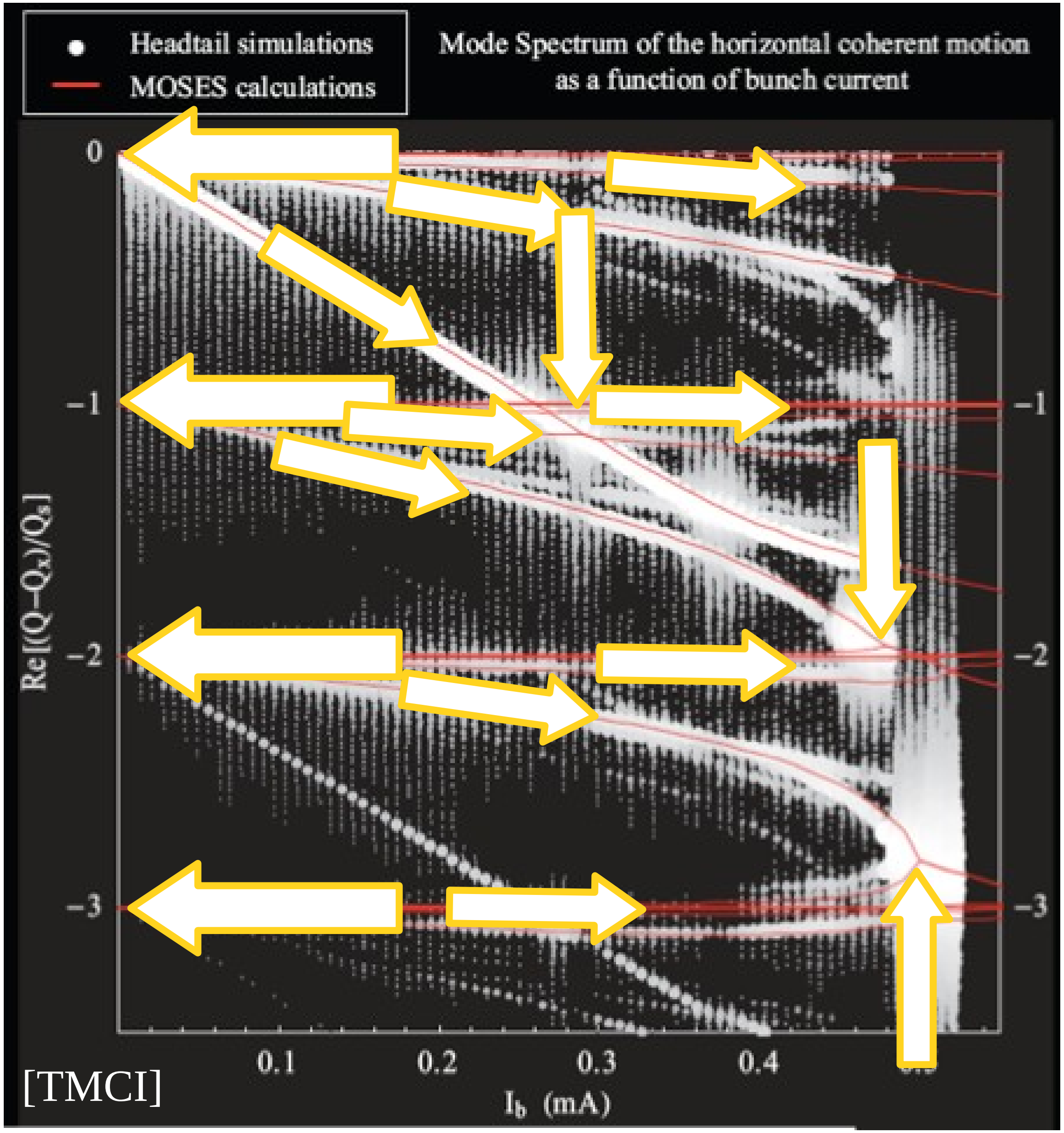
Impedance

Oscillation spectrum





The strong head-tail instability or Transverse Mode Coupling Instability (TMCI)



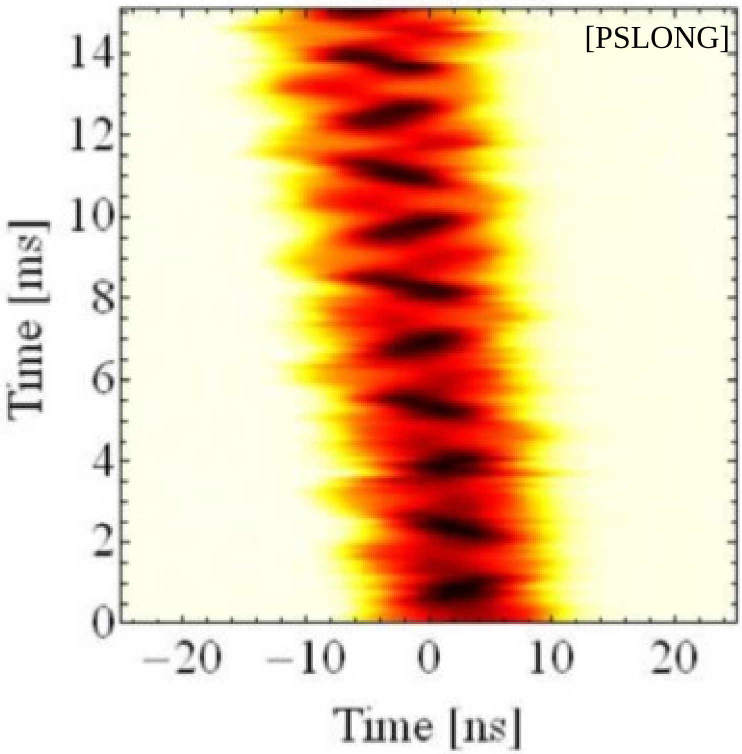
- In the high intensity regime, the effect is no longer linear with the intensity / impedance

  → The various modes are strongly perturbed

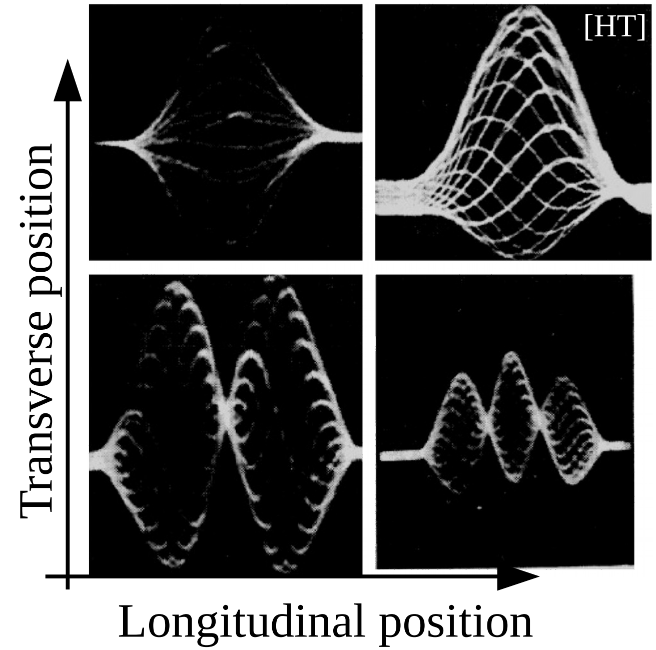
  → Mode coupling generates strong instabilities

- Self-consistent models or macro-particle simulations are needed to describe such configurations

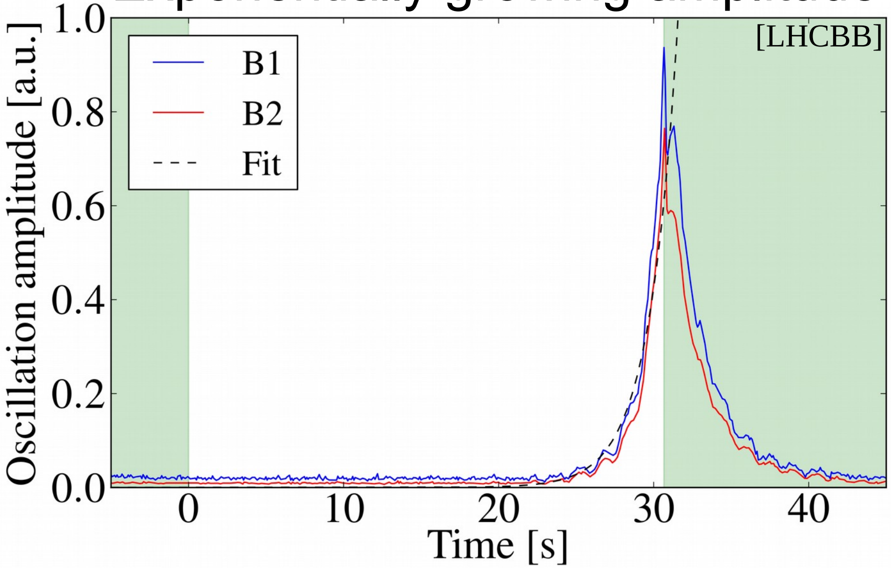
Experimental characteristics



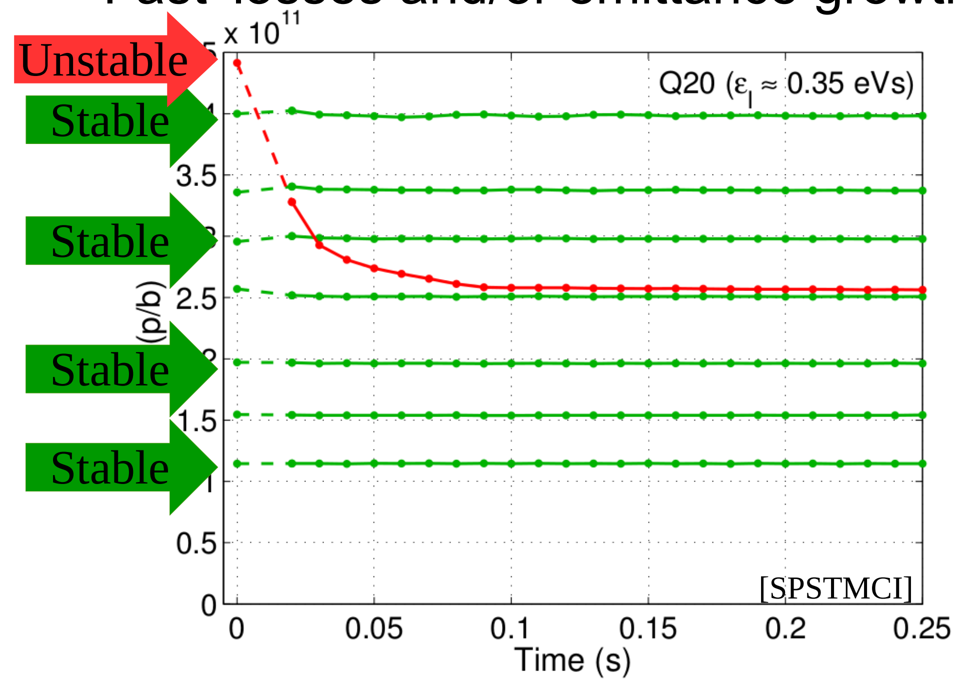
Oscillation of the density or transverse position along the bunch / beam



Exponentially growing amplitude

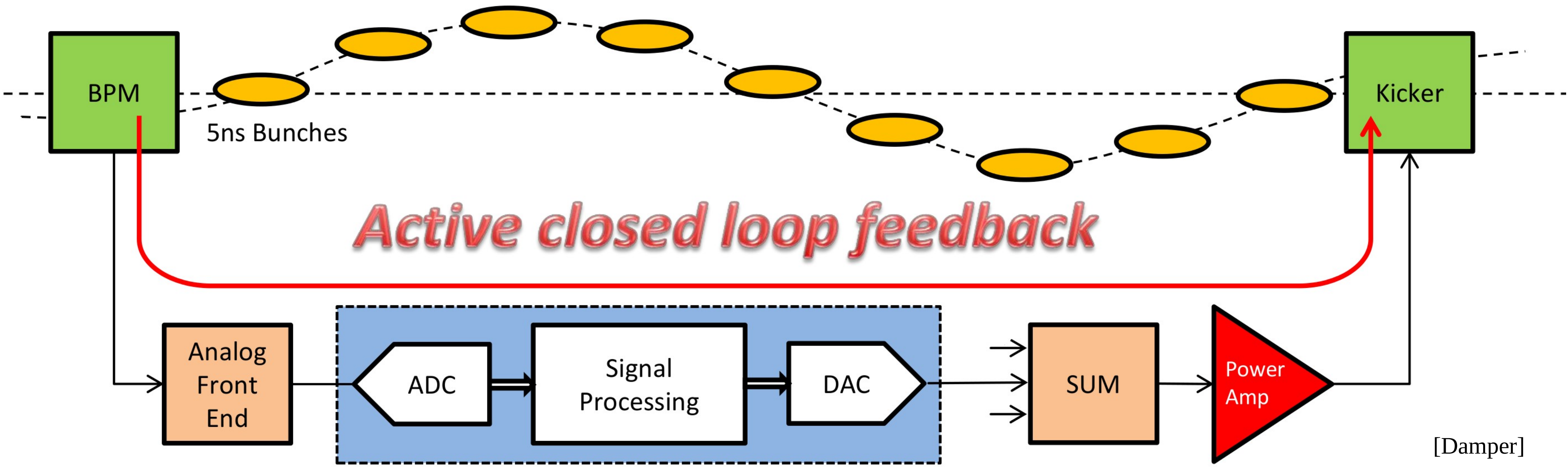


'Fast' losses and/or emittance growth



Active feedbacks (dampers)

- There exists a variety of instabilities generated by wake fields. In addition, other collective interactions generate even more instability mechanisms... → **Stabilisation is always needed!**



[Damper]

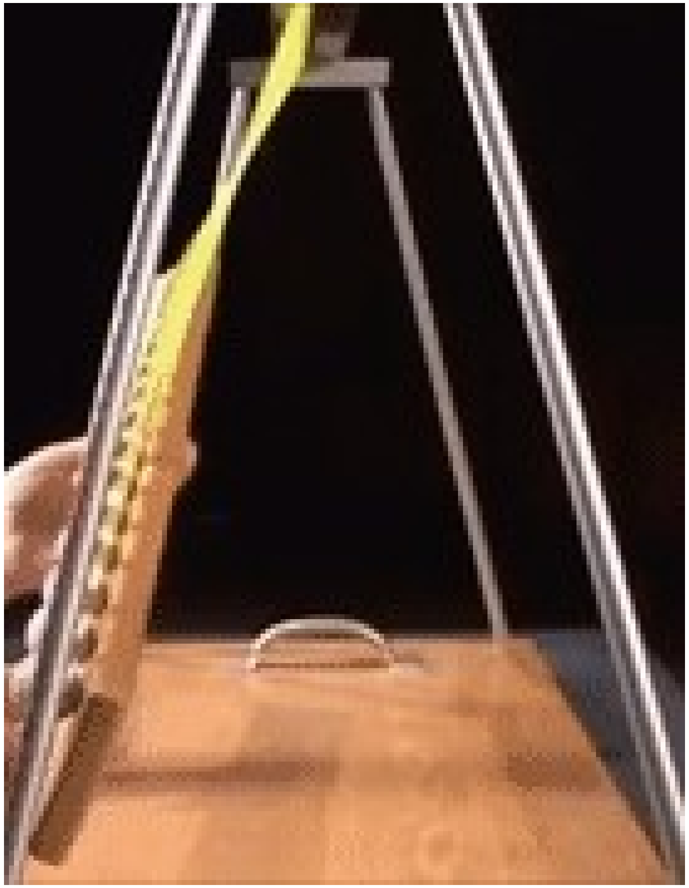
- By measuring the beam position and acting back on the beam (within the next few turns), several instabilities can be suppressed
  - Most coupled bunch instabilities are cured with an active feedback
  - Instabilities with intrabunch motion are technologically more challenging (high bandwidth)

  → Landau damping is still needed in most machines

Decoherence and Landau damping

- In the presence of a tune spread, the particles tend to desynchronize in time
  - Organised motion slowly get dis-organised as times goes

    → **decoherence**



- By dis-organizing the particles, the tune spread prevents collective instabilites

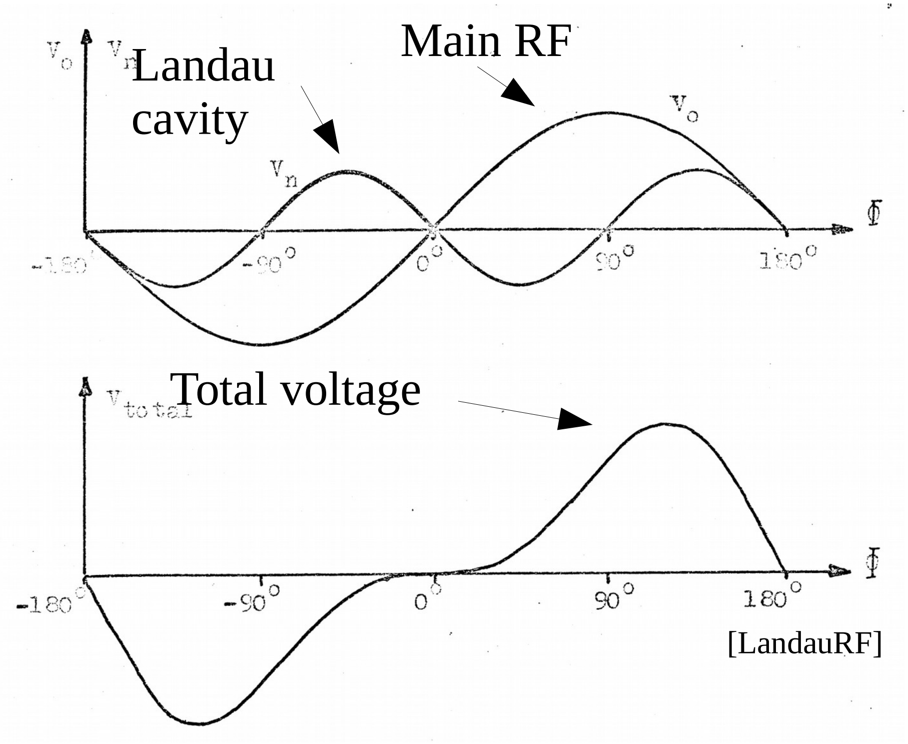
  → **Landau damping**

  - Initially discovered in plasmas, Landau damping is essential to most particle accelerators

Landau cavities and octupoles

- In order to increase the longitudinal tune spread, RF cavities of higher frequencies can be used to enhance the non-linear behaviour → Landau cavities

- In order to increase the transverse tune spread, non-linear magnets can be used → Landau octupoles



[LandauRF]

[Octupole]

- Some collective forces generate a significant tune spread (space-charge, beam-beam) that generates Landau damping → They can be beneficial !

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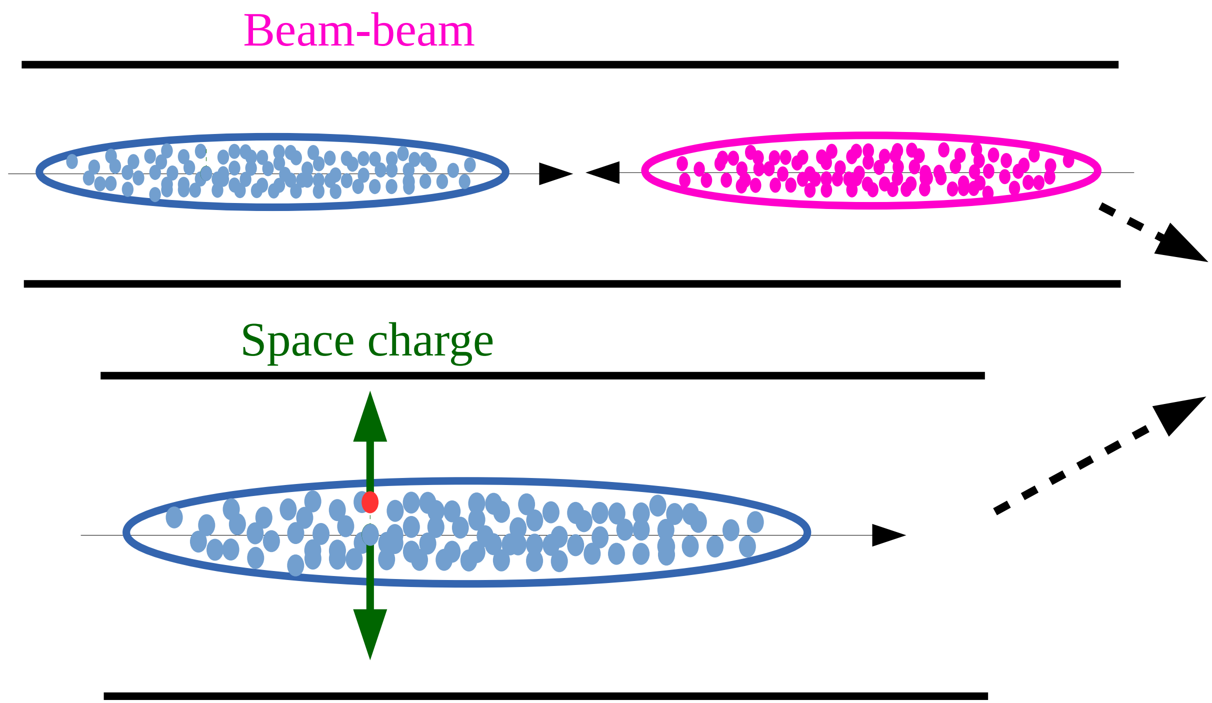
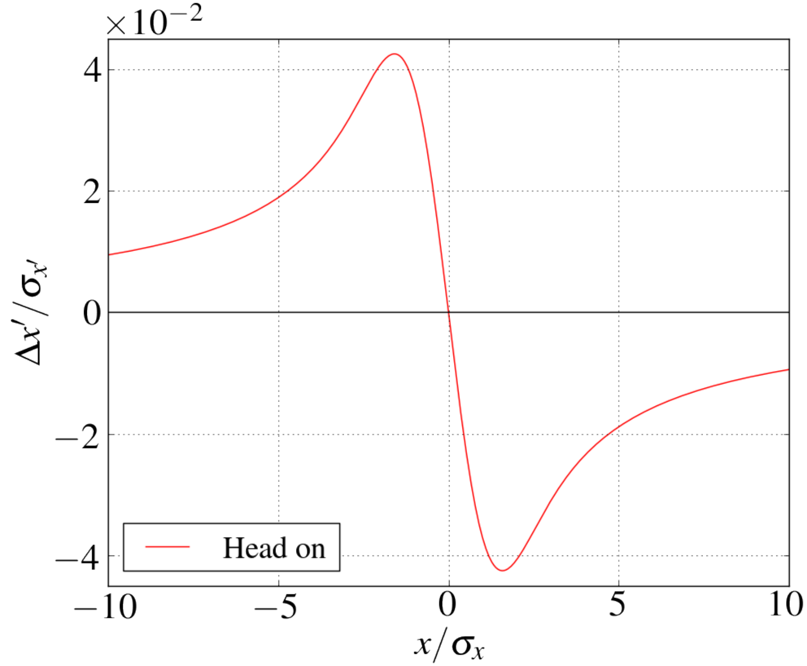
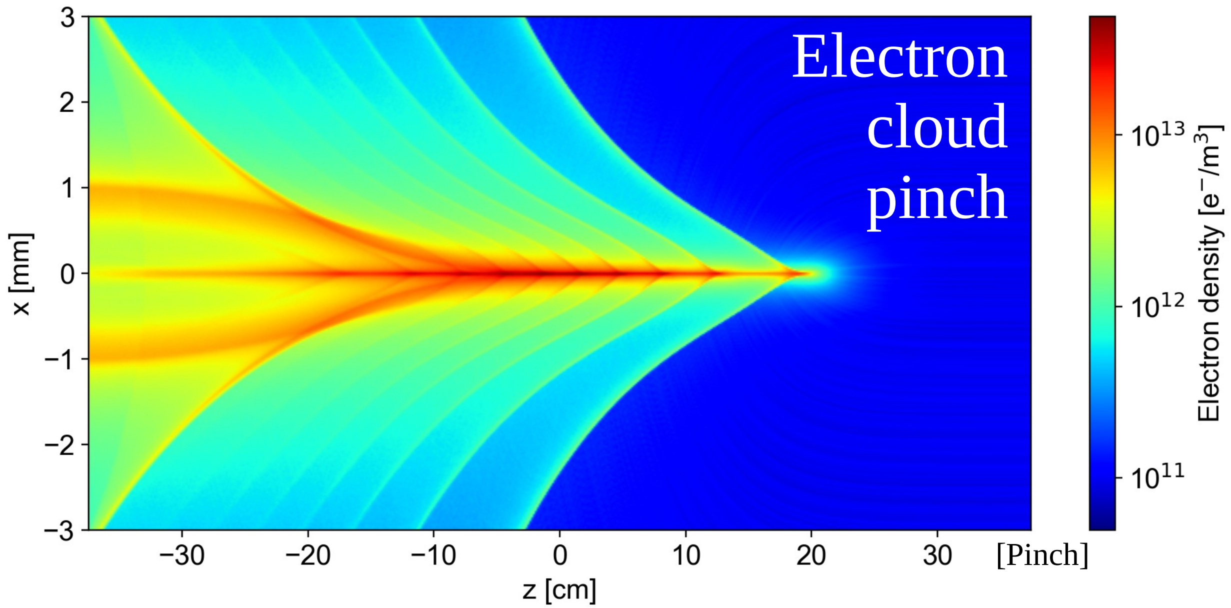
Non-linear collective force

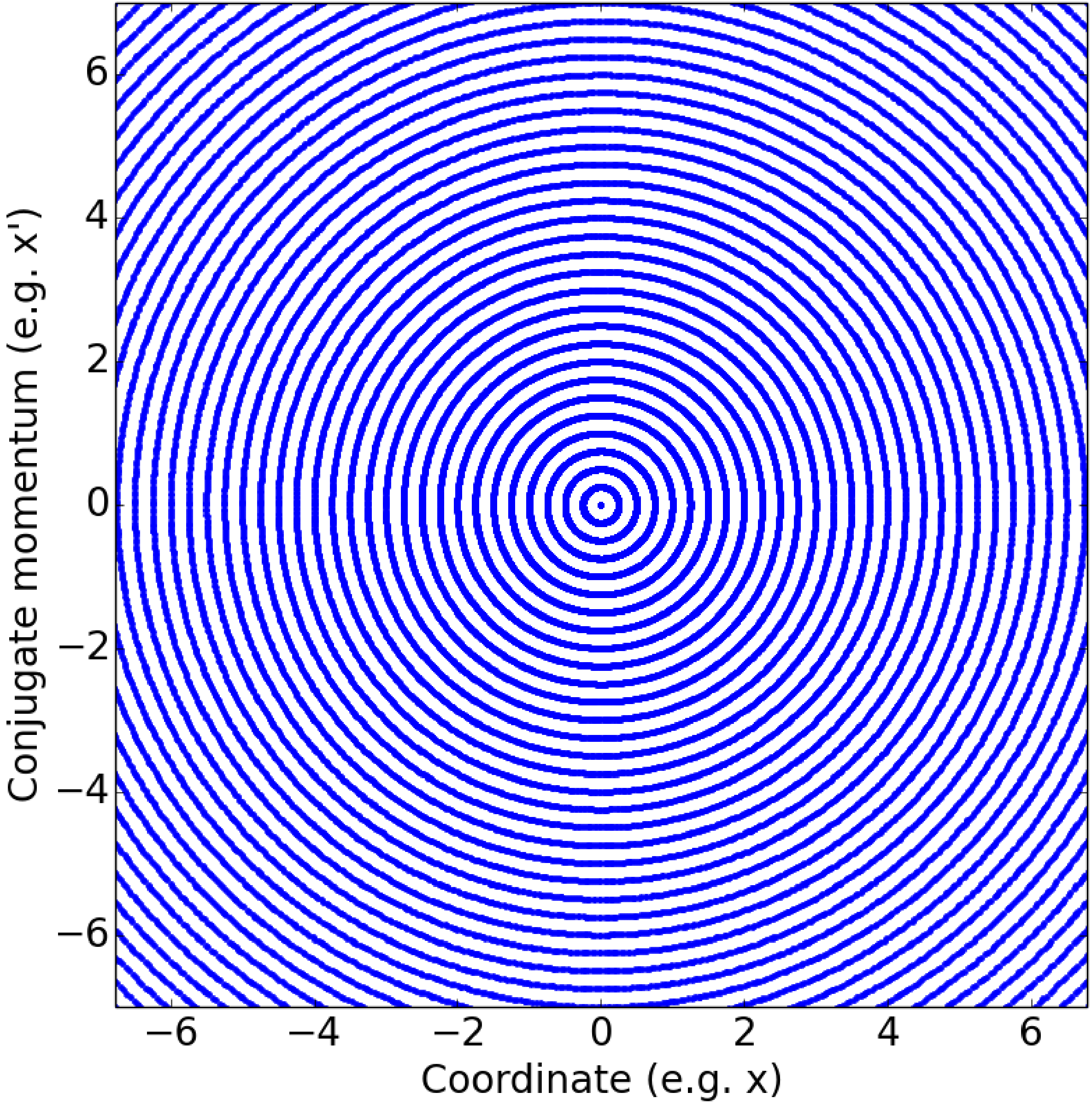




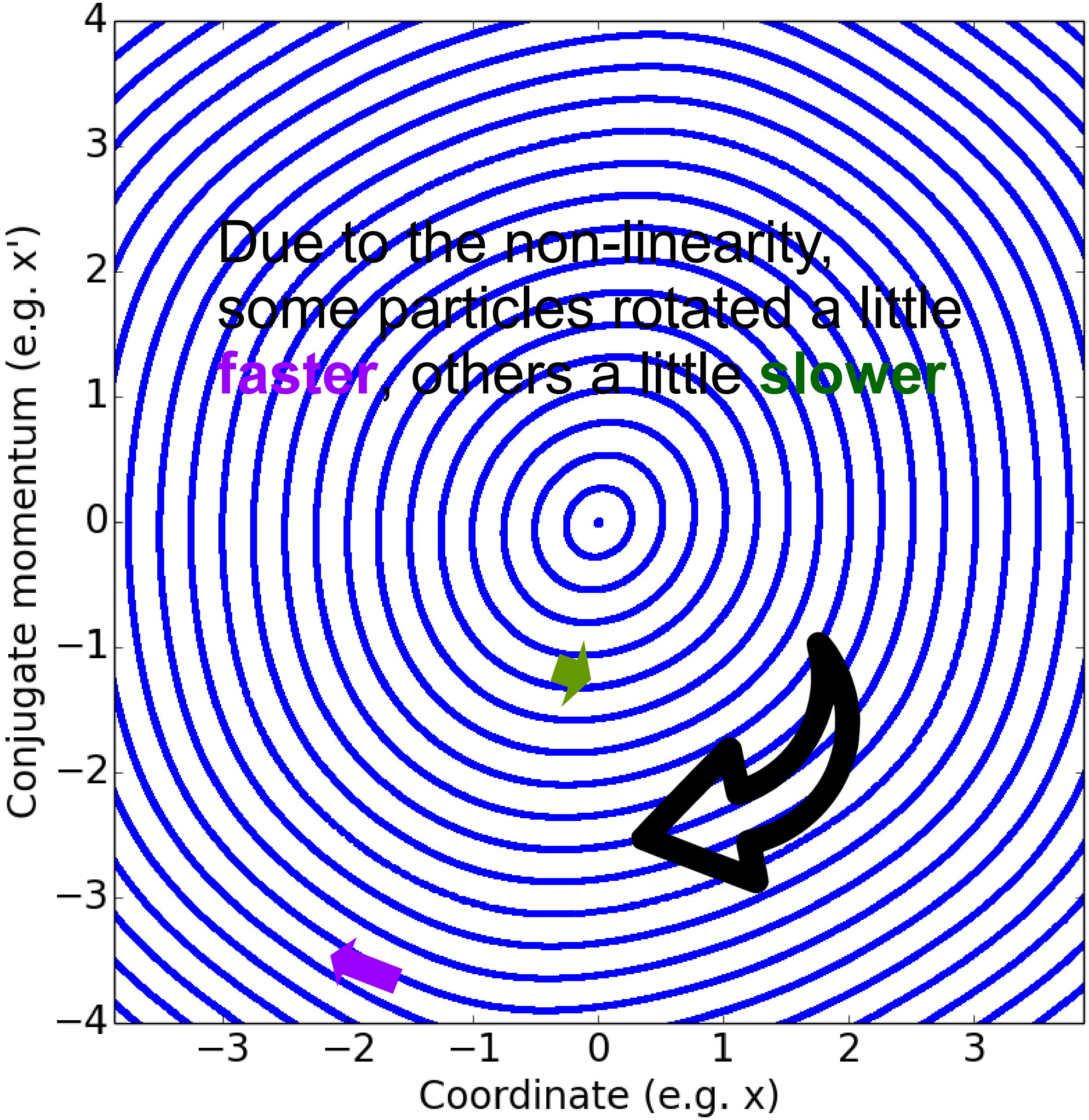


Poincaré section (phase space)

Regular trajectories → Long beam lifetime



'Weakly' non-linear motion

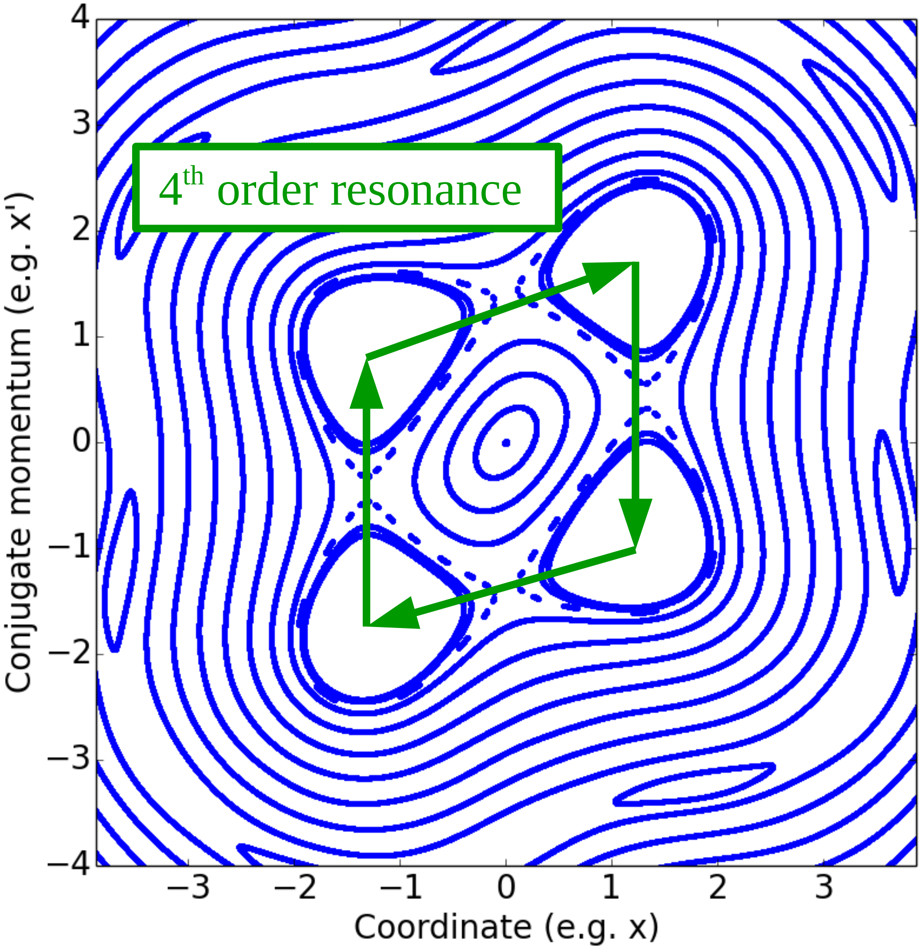


- The non-linearity generates a 'tune spread', i.e. particles oscillate at different frequencies

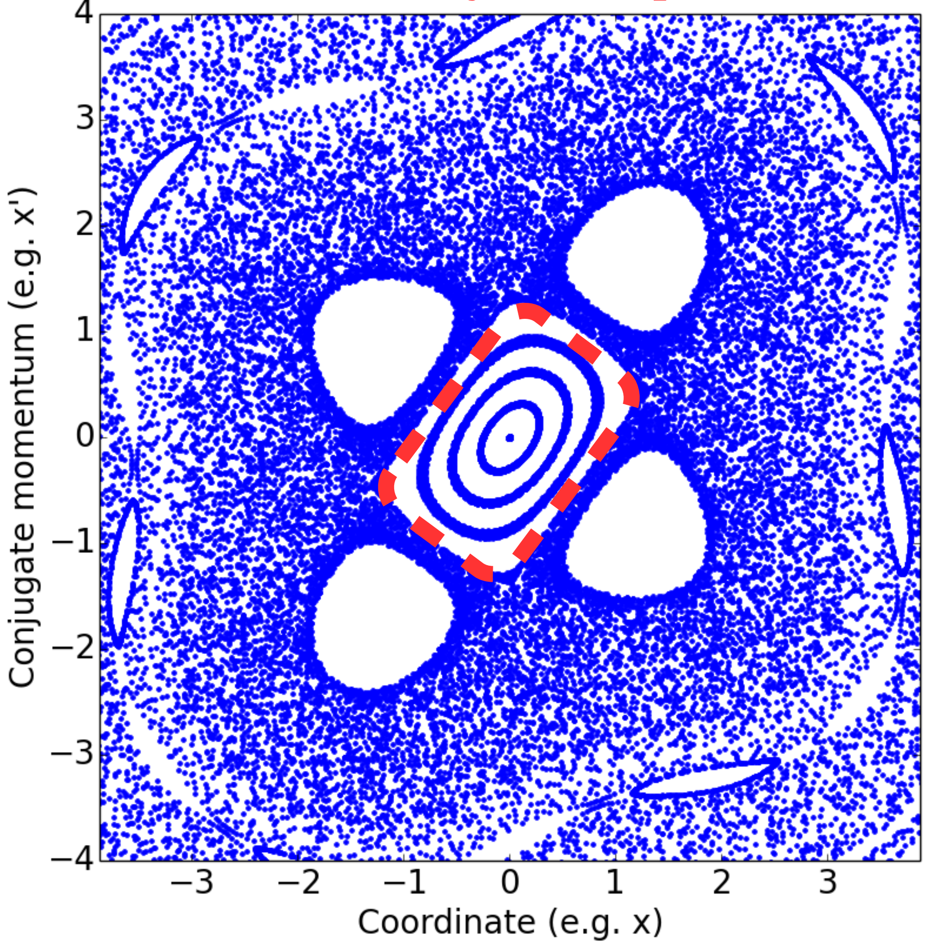
  → Landau damping!

- Nevertheless the trajectories can remain regular and the beam lifetime preserved

Resonances and chaos



The limit of regular motion is called the **dynamic aperture**

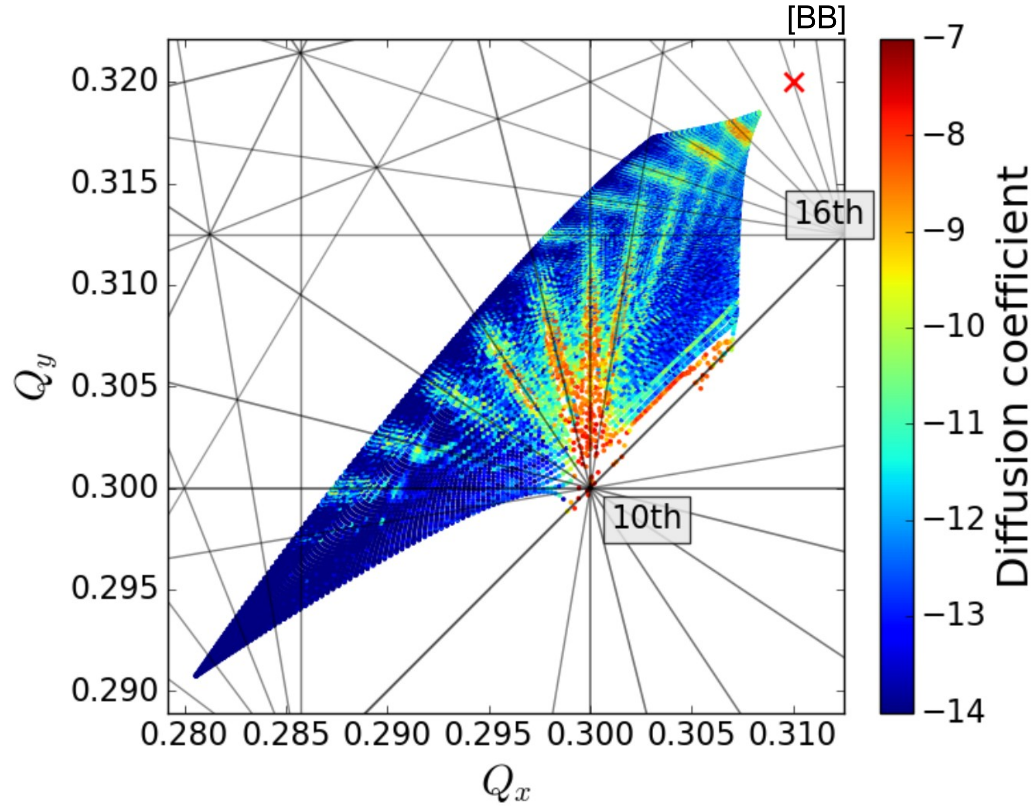


- Resonances distort the particles' trajectories
- Under some conditions, the trajectories become chaotic

→ Emittance growth and beam losses

Tune footprint

- High luminosity usually comes with strong beam-beam effects
  - The non-linearity of the force generates a tune spread that can be visualised in a 'tune diagram' and compared to resonance conditions
  - It is not possible to avoid all resonance, but some are worst than others



- In a comparable manner, space-charge forces limit the brightness of the beam in low energy machines (i.e. low relativistic gamma)
- A careful design allows for a minimisation of these effects is key to achieve high performance (working point, injection energy, separation scheme, ...)
  - In addition, several compensation schemes exists for either space-charge or beam-beam effects, usually acting on the tune spread and/or the resonances with special devices (multipole magnet, electron lens, wires)

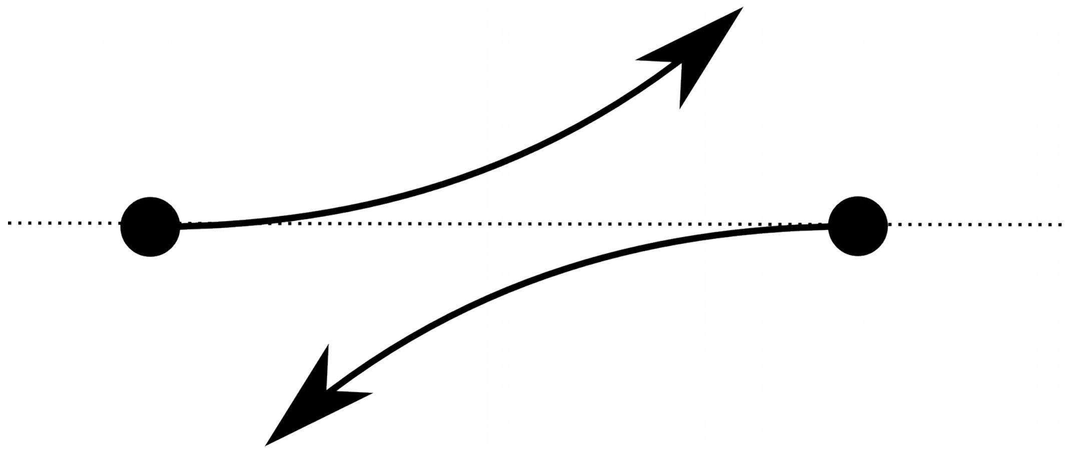
Content

Scattering

- 'Far' interactions between particles in a beam are well modeled by the space-charge fields, however close interactions (scattering events) lead to a redistributions of the momentum in 3D

  → Multiple random small angle deflections: Emittance growth! (**Intrabeam** scattering)

  → One single deflection may send one of the particles out of the machine acceptance: Beam losses! (**Touschek** scattering)

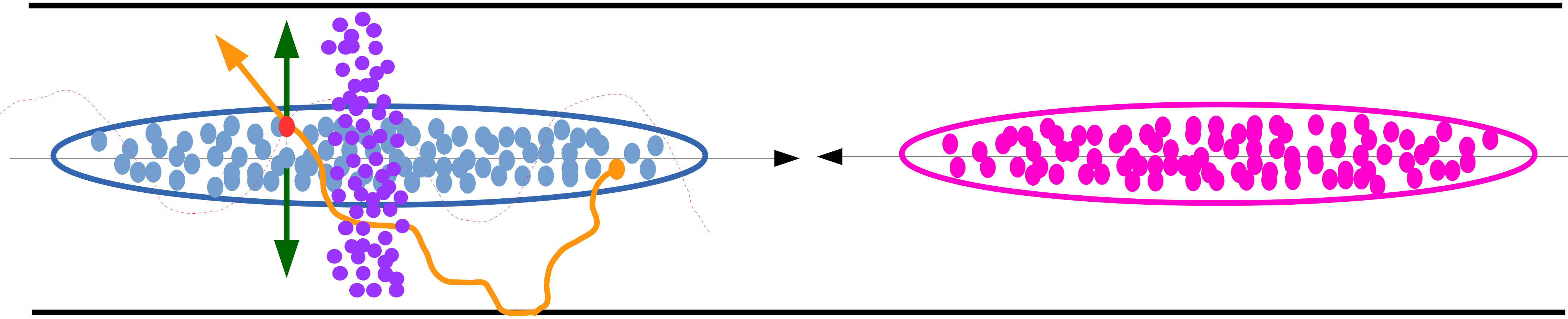


- The amount of these events depends on the beam property (scattering is more likely in denser beam, i.e. at lower relativistic gamma)
- The redistribution, thus the IBS growth rates in the different planes, depends on the machine optics (dispersion, transverse coupling)
- Other types of scattering can lead to emittance growth or losses (e.g. small angle deflections in beam-beam interactions or on rest gas particles)

Summary : Collective interactions

Direct electromagnetic interaction of the particles in the beams : Space-charge effects, intrabeam scattering / Touschek scattering

Electromagnetic interaction with other species : Electron clouds, ions



Electromagnetic interaction of the particles in the beams through an interaction with surrounding elements (Vacuum chamber, beam screen, RF cavities, collimators, beam instrumentation, …) : Wake fields / Impedance

Electromagnetic interaction with another beam : Beam-beam effects, electron cooling, electron lens

Summary: Impact on the beam

- Collective force can deteriorate the beam quality in several ways
  - Beam instabilities
  - Non-linear effects
  - Scattering effect
- The performance of a machine is usually limited by collective effects, their understanding and mitigation is the key to maximise the potential of a given machine
  - Optics (tune, chromaticity, transition energy, ...)
  - Active feedbacks
  - Passive mitigations (Landau cavities, Landau octupoles, resonance and/or tune spread compensators)
  - Electromagnetic design of every element
  - Surfaces exposed to the beam

Not treated today

- Dissipation of the collective force (Beam loading, RF/electron cloud heating)
- Wake field acceleration → see E. Gschwendtner on Thursday next week
- Beam-beam disruption → see S. Stapnes also on Thursday
- Free electron laser
- Coherent synchrotron radiation

Good lecture notes on this topic

- Proceedings of the CAS-CERN Accelerator School on Intensity Limitations in Particle Beam
https://e-publishing.cern.ch/index.php/CYRSP/issue/view/37

- A. Chao, **Physics of Collective Beam Instabilities in High Energy Accelerators** (Wiley, 1993) and **Lecture Notes on Special Topics in Accelerator Physics** (SLAC-PUB-9574)
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