General introduction to multi-particle effects

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USPAS Course on collective effects

Monday, 22.06.2009

Program of the week

	09:00 – 09:55	10:00 – 10:55	11:00 – 11:55	12:00 – 12:55	14:30 – 15:25	15:30 – 17:00
MO 22/06/09 (EM)	Introduction (EM & GR)	Space charge	Envelope equations	Wake fields & impedances	Wake fields & impedances	Tutorials
TU 23/06/09 (GR)	Correction of tutorials	Longitudinal dynamics	Longitudinal dynamics	Longitudinal dynamics	Longitudinal dynamics	Tutorials
WE 24/06/09 (EM)	Correction of tutorials	Transverse dynamics (Coasting)	Transverse dynamics (Coasting)	Transverse dynamics (Bunched)	Transverse dynamics (Bunched)	Tutorials
TH 25/06/09 (GR)	Correction of tutorials	Two-stream effects	Two-stream effects	Numerical modeling	HEADTAIL code	Tutorials
FR 26/06/09	Exam	Exam	Exam			

This introduction aims at giving a general intuitive approach to the multi-particle effects, trying to explain glossary and classification.

All the subjects treated during this lecture will be explained in detail later on during the week

General definition of *multi-particle processes* in an accelerator or storage ring

Class of phenomena in which the evolution of the particle beam cannot be studied as if the beam was a single particle (as is done in beam optics), but depends on the combination of external fields and interaction between particles. Particles can interact between them through

- Self generated fields:

  → Direct space charge fields

  → Electromagnetic interaction of the beam with the surrounding environment through the beam's own images and the wake fields (impedances)

  → Interaction with the beam's own synchrotron radiation

- Long- and short-range Coulomb collisions, associated to intra-beam scattering and Touschek effect, respectively

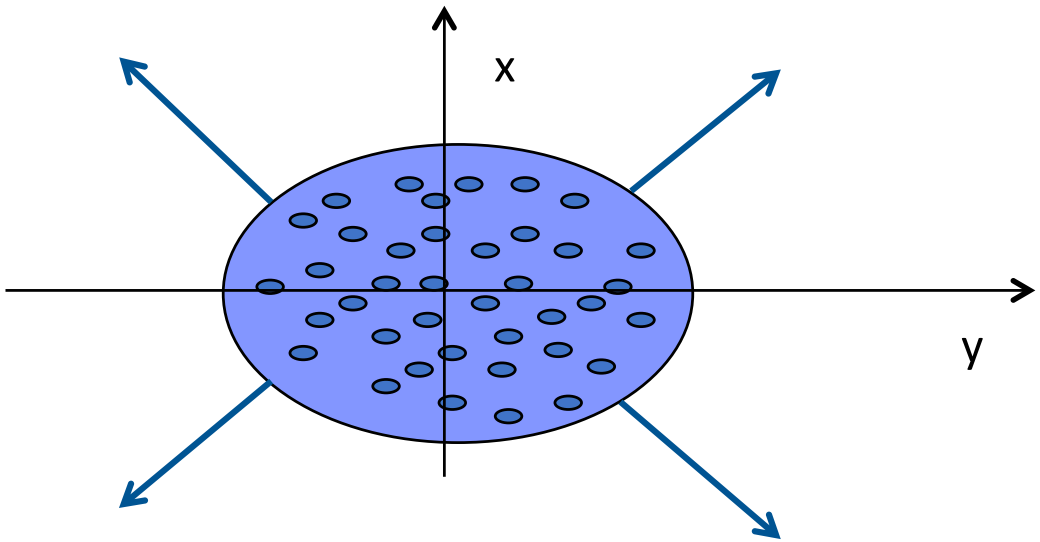
- Interaction of electron beams with trapped ions, proton/positron/ion beams with electron clouds, beam-beam in a collider ring, electron cooling for ions

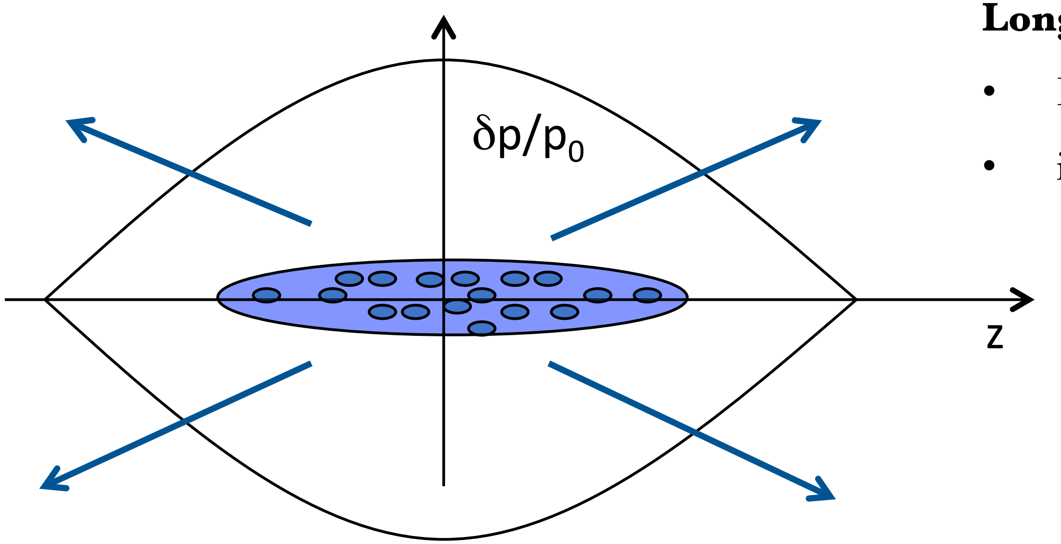
MULTI-PARTICLE PROCESSES ARE DETRIMENTAL FOR THE BEAM (DEGRADATION AND LOSS, SEE NEXT SLIDES)

Direct space charge forces

Transverse space charge

- Force decays like $1/\gamma^2\beta$
- It is always repulsive

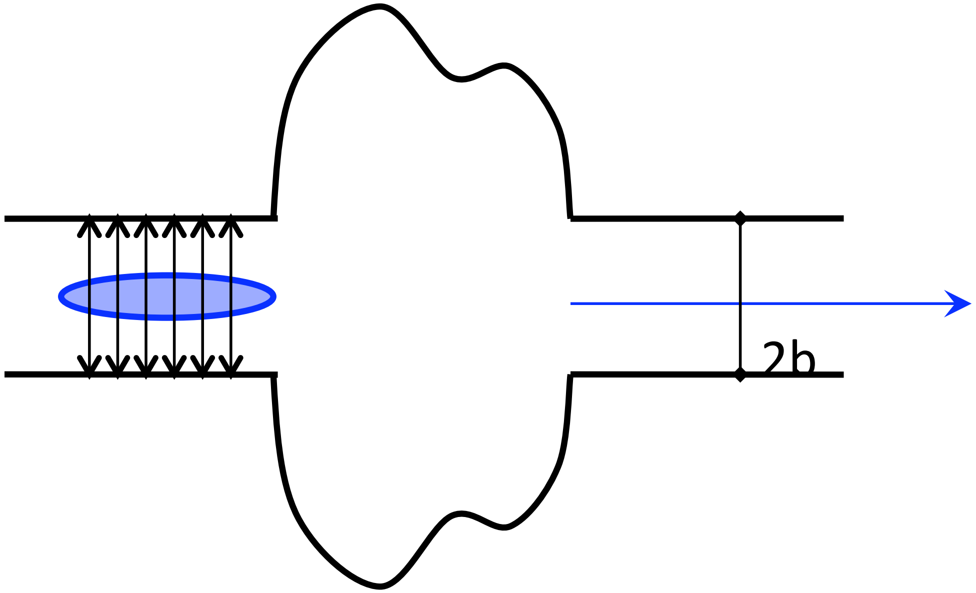


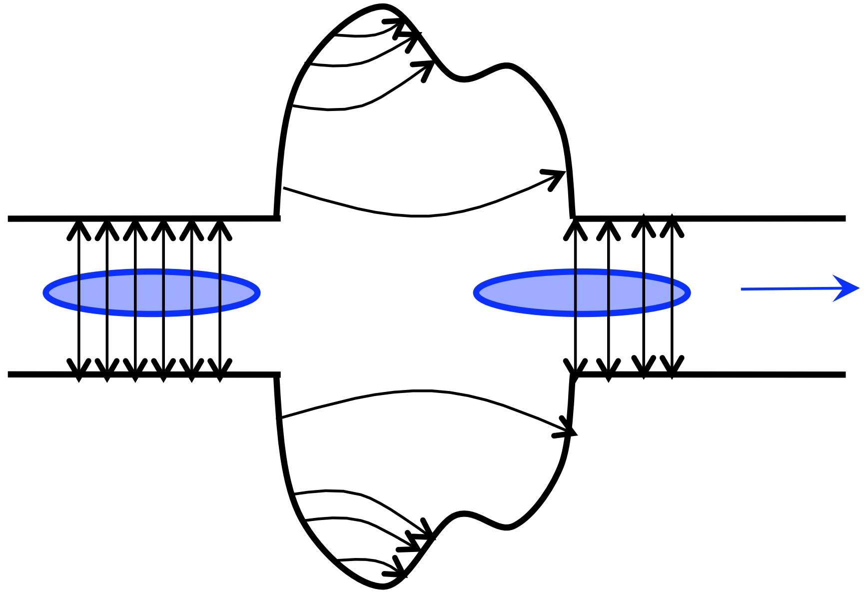


Longitudinal space charge

- Force decays like $1/\gamma^2$
- it can be attractive above transition

Wake fields (impedances)

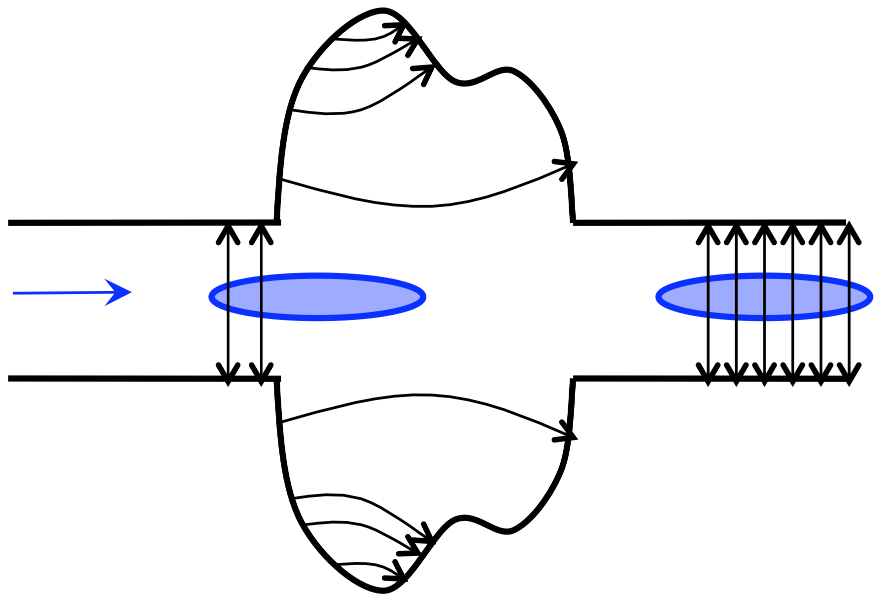




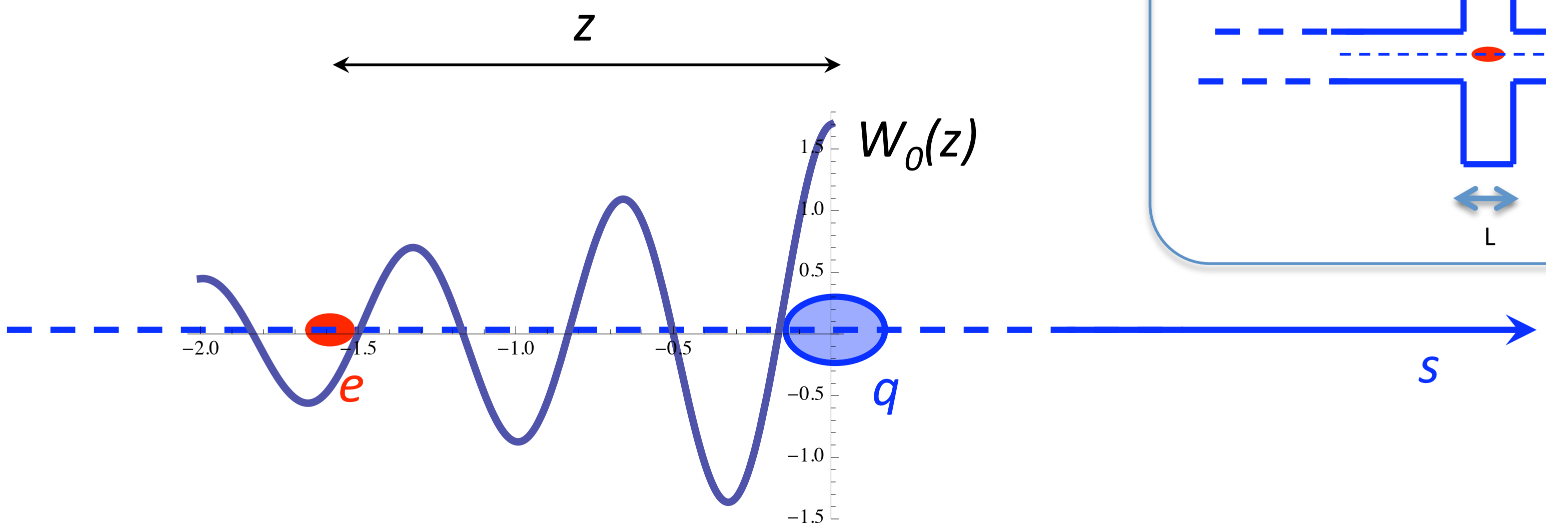
When the beam goes through a discontinuity, it induces an e-m field which keeps ringing after the beam has passed:

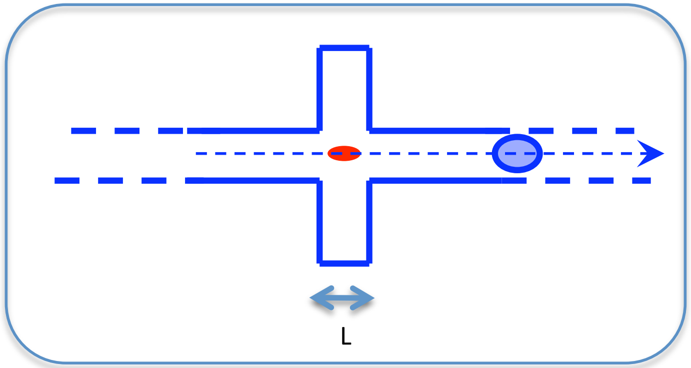
→ Energy loss

→ Effect intra-bunch and on following bunches



Wake fields (impedances)





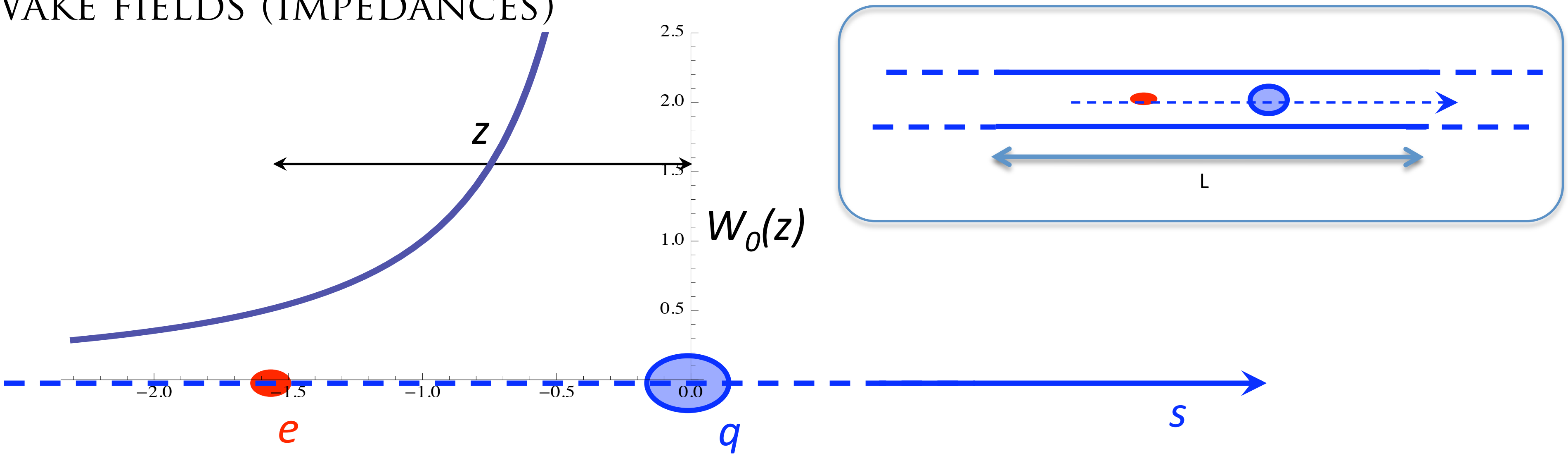
Model:

A particle ***q*** going through a device of length L, ***s (0,L),*** leaves behind an oscillating field and a probe charge ***e*** at distance ***z*** feels a force as a result. The integral of this force over the device defines the ***wake field*** and its Fourier transform is called the ***impedance of the device of length L***.

$$\int_0^L F_{||}(s,z)ds = -eqW_{||}(z) \qquad \int_0^L F_{\perp}(s,z)ds = -eqxW_{\perp}(z)$$

$$Z_{||\,(\perp)}(\omega) \equiv \frac{1}{c}\int_{-\infty}^{\infty} dz\, e^{-i\omega z/c} W_{||\,(\perp)}$$

Wake fields (impedances)



Model (cont's):

The device of length L can also be a segment of accelerator (defined by the simple beam pipe) and the wake is generated by the finite conductivity of the pipe material. In this case the wake field and the impedance are said to be of **resistive wall** type and the integration can be done over L=2π R

$$\int_0^L F_{||}(s,z)ds = -eqW_{||}(z) \qquad \int_0^L F_{\perp}(s,z)ds = -eqxW_{\perp}(z)$$

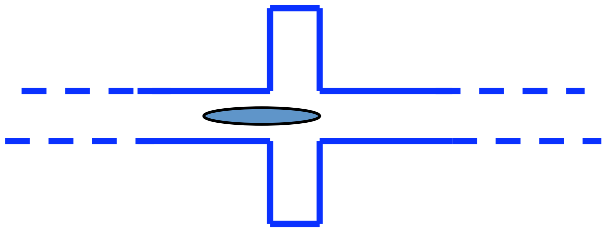
$$Z_{||\,(\perp)}(\omega) \equiv \frac{1}{c}\int_{-\infty}^{\infty} dz\, e^{-i\omega z/c} W_{||\,(\perp)}$$

Wake fields (impedances)

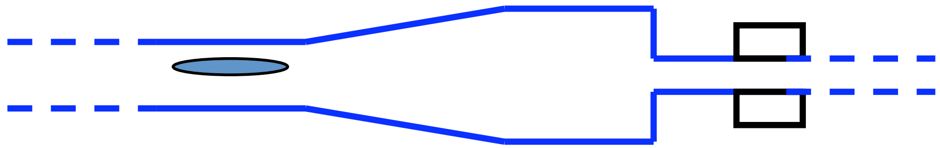
The full ring is usually modeled with a so called total impedance made of three main components:

- Resistive wall impedance

- Several narrow-band resonators at lower frequencies than the pipe cutoff frequency c/b (b beam pipe radius)



- One broad band resonator at $\omega_r \sim c/b$ modeling the rest of the ring (pipe discontinuities, tapers, other non-resonant structures like pick-ups, kickers bellows, etc.)



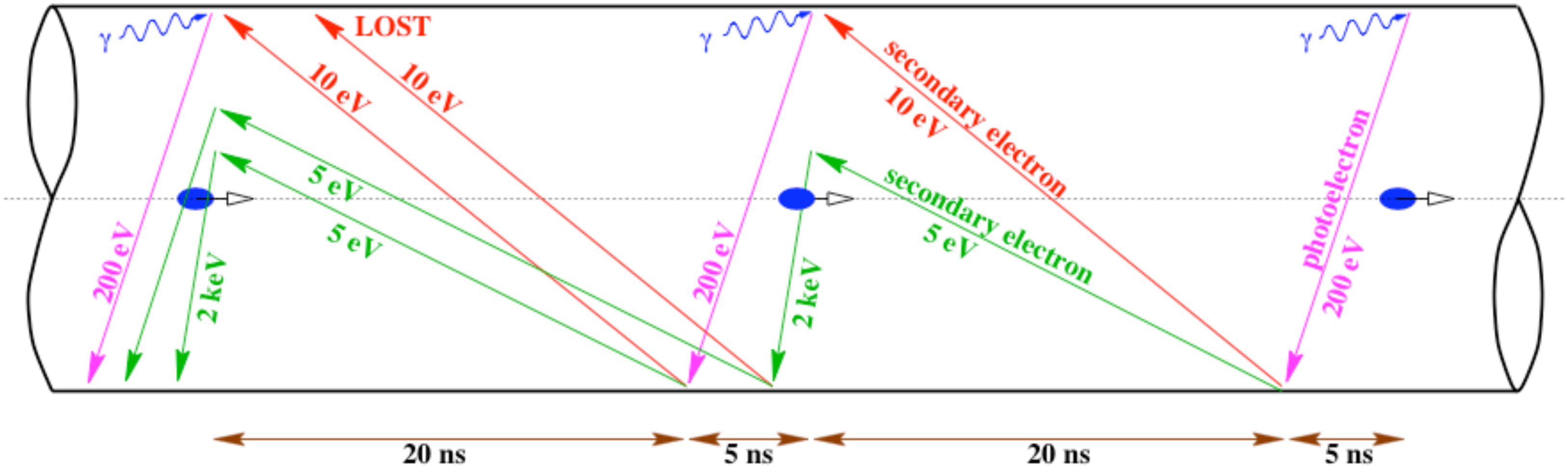
⇒ The total impedance is **allocated to the single ring elements** by means of off-line calculation prior to construction/installation

⇒ **Total impedance** designed such that the nominal intensity is stable

Electron cloud

Principle of electron multipacting:

Example of LHC

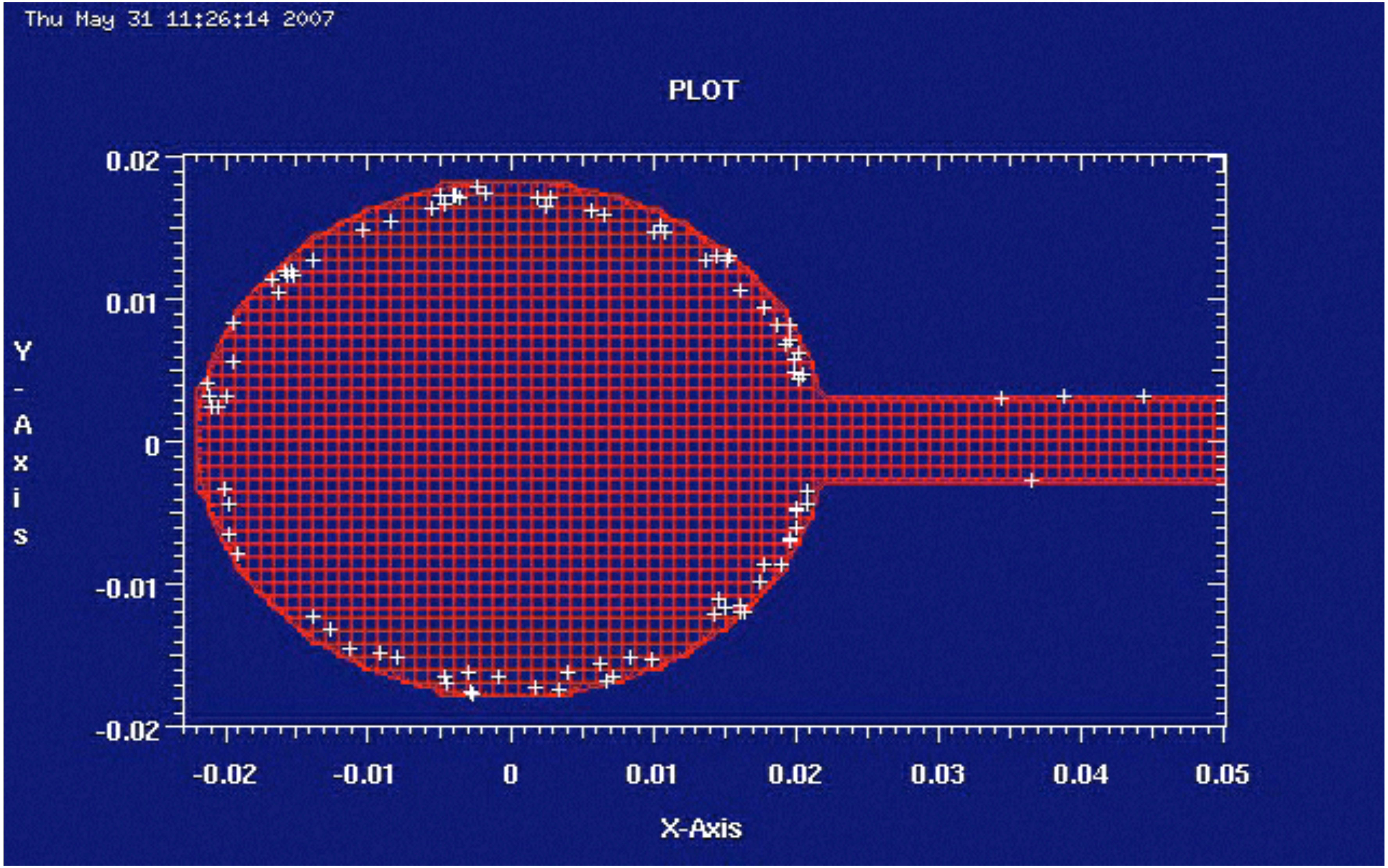


Electron multiplication is made possible by:

- ✓ Electron generation due to photoemission, but also residual gas ionization
- ✓ Electron acceleration in the field of the passing bunches
- ✓ Secondary emission with efficiency larger than one, when the electrons hit the inner pipe walls with high enough energy

Electron cloud

Photoelectrons produced by the synchrotron radiation are accelerated by the bunches and quickly accumulate in the vacuum chamber (example, wiggler of a CLIC damping ring)



Several names to describe these effects...

‚Multi-particle‘ is the most generic attribute. ***‚High-current‘, ‚high-intensity‘, ‚high brightness‘*** are also used because these effects are important when the beam has a high density in phase space (many particles in little volume)

Other labels are also used to refer to different subclasses

- **Collective** effects **(coherent)**:

  → The beam resonantly responds to a self-induced electromagnetic excitation

  → Are **fast** and visible in the beam **centroid motion** (tune shift, instability)

- **Collective** effects **(incoherent)**:

  → Excitation moves with the beam, spreads the frequencies of particle motion.

  → Lead to particle diffusion in phase space and **slow** emittance growth

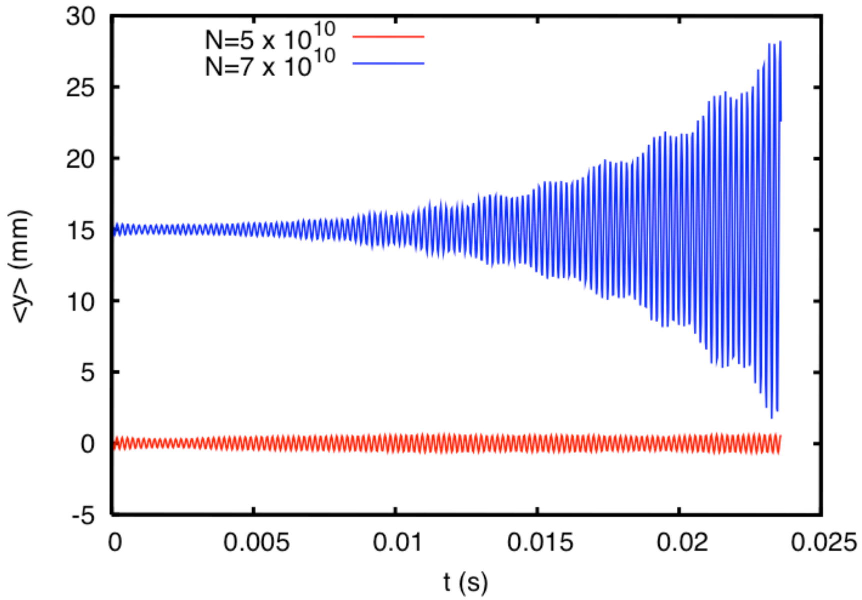
- **Collisional** effects **(incoherent)**:

  → Isolated two-particle encounters have a global effect on the beam dynamics (diffusion and emittance growth, lifetime)

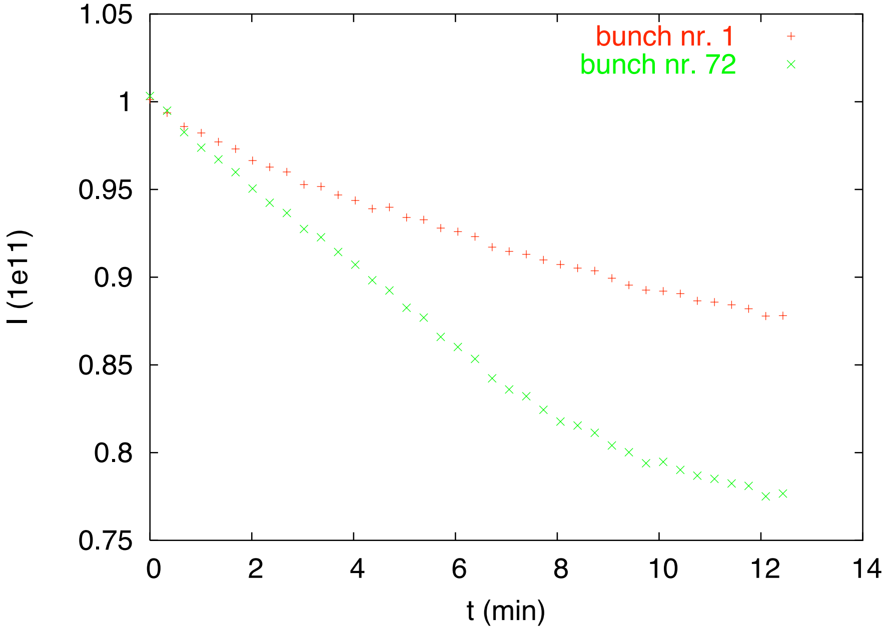
- **Two-stream** phenomena (coherent or incoherent):

  → Two component plasmas needed (beam-beam, pbeam-ecloud, ebeam-ions) and the beam reacts to an excitation caused by another „beam“

Some examples….



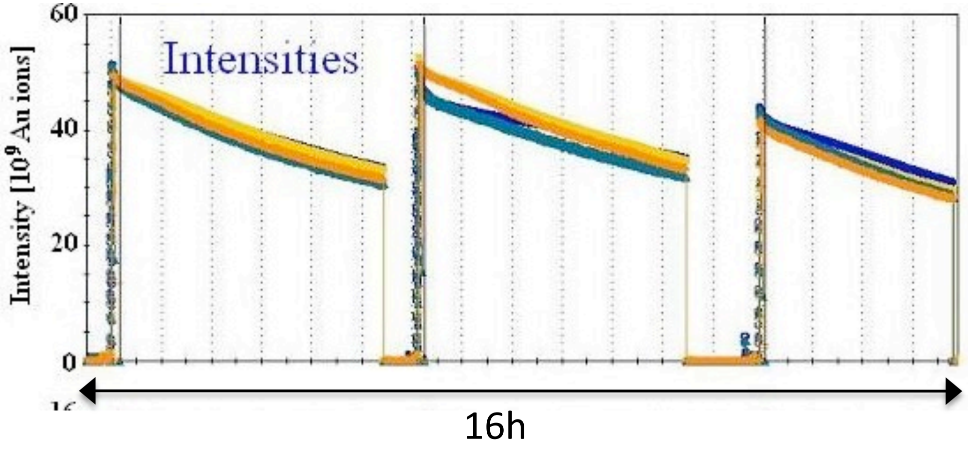
Coherent effect:
When the bunch current exceeds a certain limit (current threshold), the centroid of the beam, e.g. as seen by a BPM, exhibits an exponential growth and the beam is lost within few milliseconds (simulation of an SPS bunch)



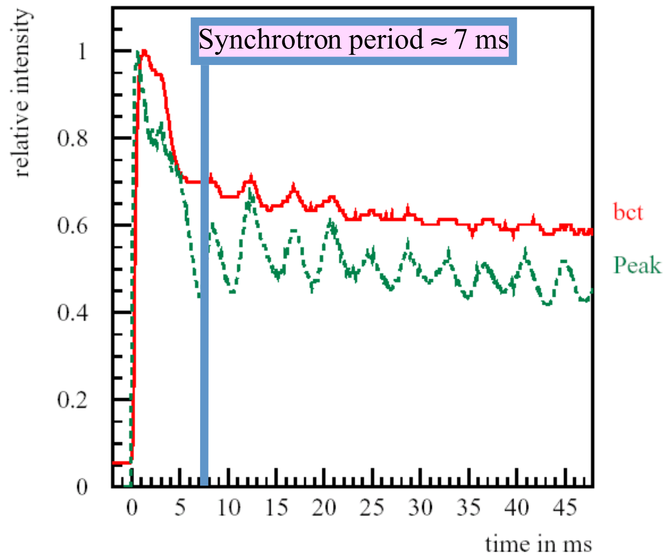
Incoherent effect:
Slow beam loss. First and last bunch of an SPS train of 72 bunches gradually lose their particles (10% and 25%, respectively) over several minutes (data from SPS, 2004)

More examples… (plots show measured beam intensity vs time)

BNL-RHIC, Au-Au operation, Run-4 (2004)



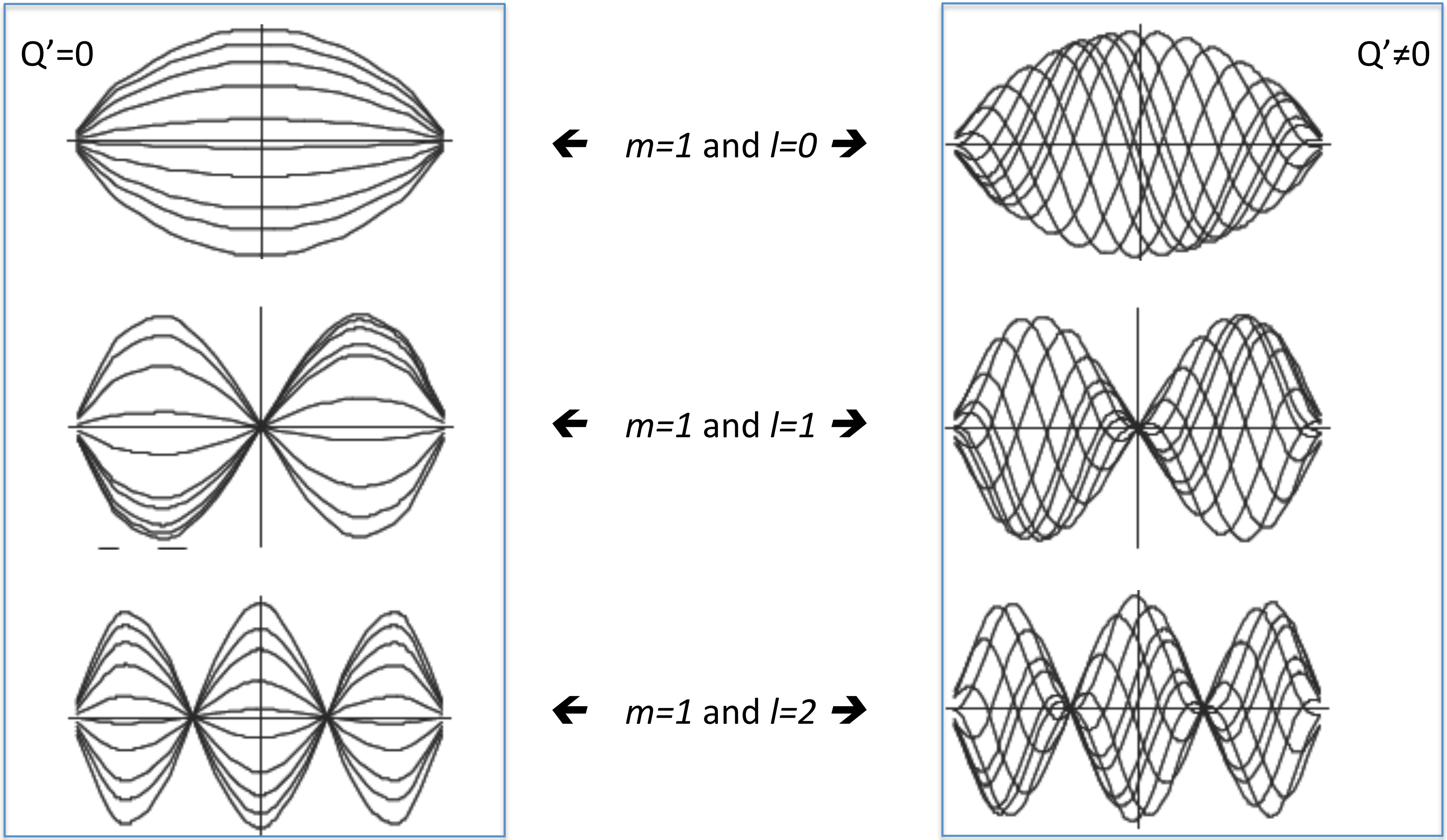
CERN-SPS (II) TMC Instability (2003)



NOTE THE DIFFERENT TIME SCALE ON THESE PLOTS!

Examples of coherent modes seen at a wide-band pick-up (BPM)

- The patterns of the head-tail modes depend on chromaticity



Coherent modes measured at a wide-band pick-up (BPM)

m=1 and *l=0*

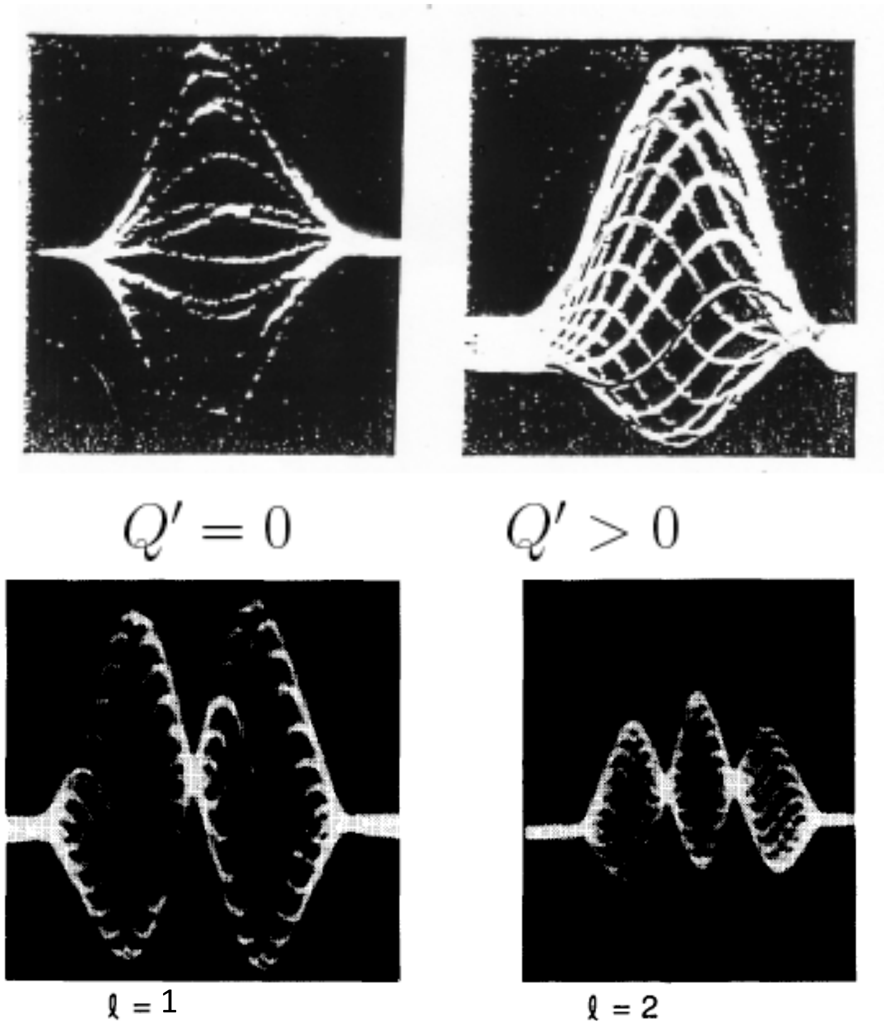


Figure 6.32. Transverse beam oscillation modes observed at the CERN PS Booster. The head-tail phase χ is properly defined for the observed bunch shape. (Courtesy Jacques Gareyte, 1992).

Why are multi-particle effects important ?

The performance of an accelerator is usually limited by a multi-particle effect!!

➔ When the beam current in a machine is pushed above a certain limit (intensity threshold), **intolerable losses or beam quality degradation** appear due to these phenomena

➔ How these effects can affect the beam:

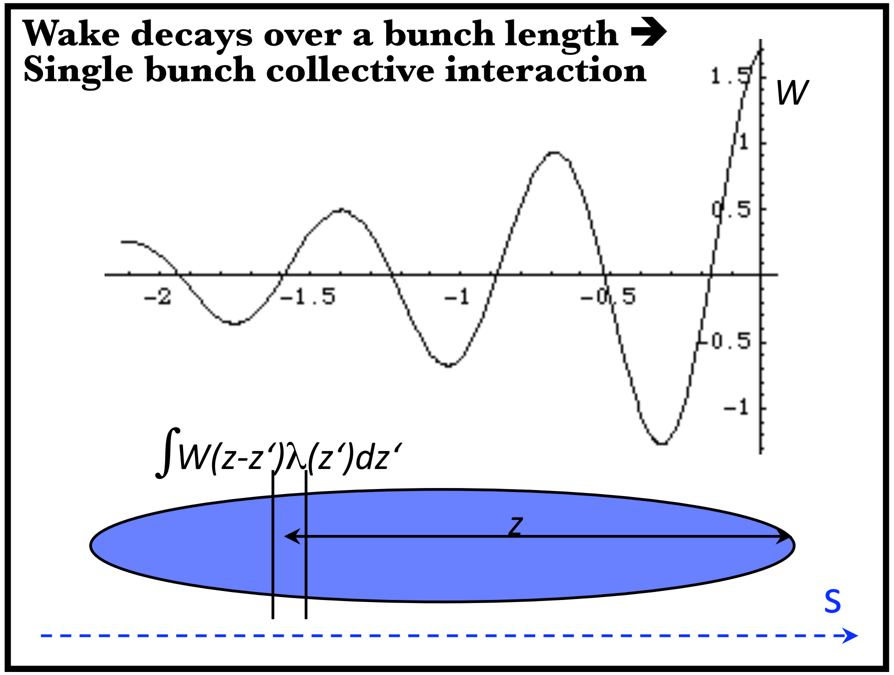
- Coherent effects can be:
  - → Transverse
    - ✓ coherent tune shift
    - ✓ fast beam loss due to instability
  - → Longitudinal (energy loss, bunch lengthening, synchrotron tune shift)
- Incoherent effects can be:
  - → Longitudinal or transverse
    - ✓ emittance growth, incoherent tune shift, tune spread, bad lifetime
- Two-stream phenomena are:
  - → result into coherent or incoherent effects

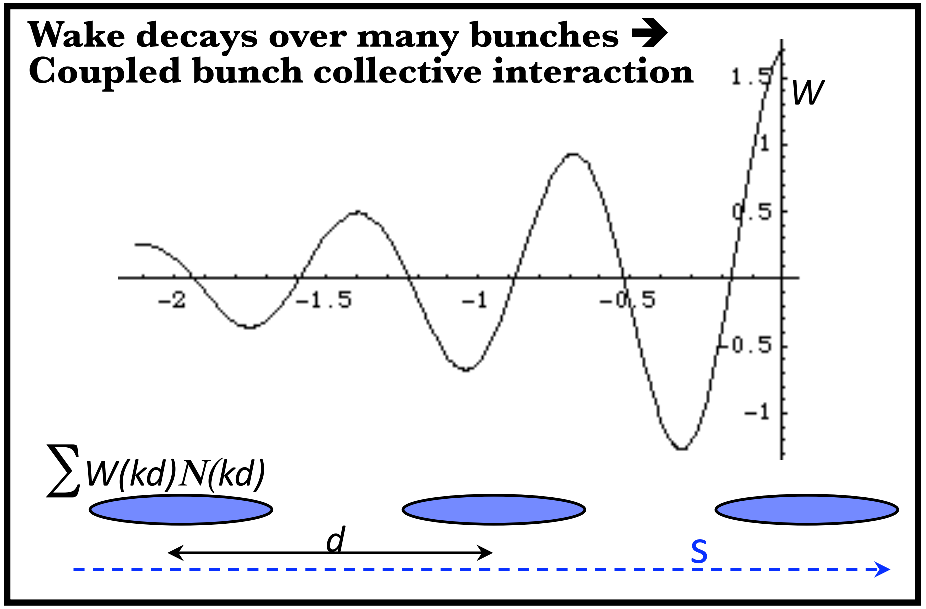
Types of collective effects (I)

- Single or multi-bunch behavior depends on the range of action of the wake fields

  → Single bunch effects are usually caused by short range wake fields (broad-band impedances)

  → Multi bunch or multi-turn effects are usually associated to long range wake fields (narrow-band impedances)





Types of collective effects (II)

- Transverse:

  → Single bunch

  ✓ Rigid bunch instability, head-tail instability

  ✓ Transverse Mode Coupling Instability (TMCI), also referred to as beam break-up or strong (fast) head-tail instability

  ✓ Electron Cloud Instability (ECI)

  → Coupled bunch instability

  ✓ Coupling between subsequent bunches through long range wake fields or electron cloud, Ion Instability, Fast-Ion Instability

- Longitudinal:

  → Single bunch

  ✓ Potential well distortion, energy loss

  ✓ Microwave instability, turbulent bunch lengthening

  → Coupled bunch instability

Difference between multi-particle effects and single-particle resonances

- What they have in common:

  ✓ Both **coherent instabilities** and **resonances** can make the amplitudes of some particles grow in phase space till they are lost hitting the machine aperture

  ✓ Both **incoherent effects** and **resonances** can cause some beam particles to migrate to the large amplitudes and produce emittance growth

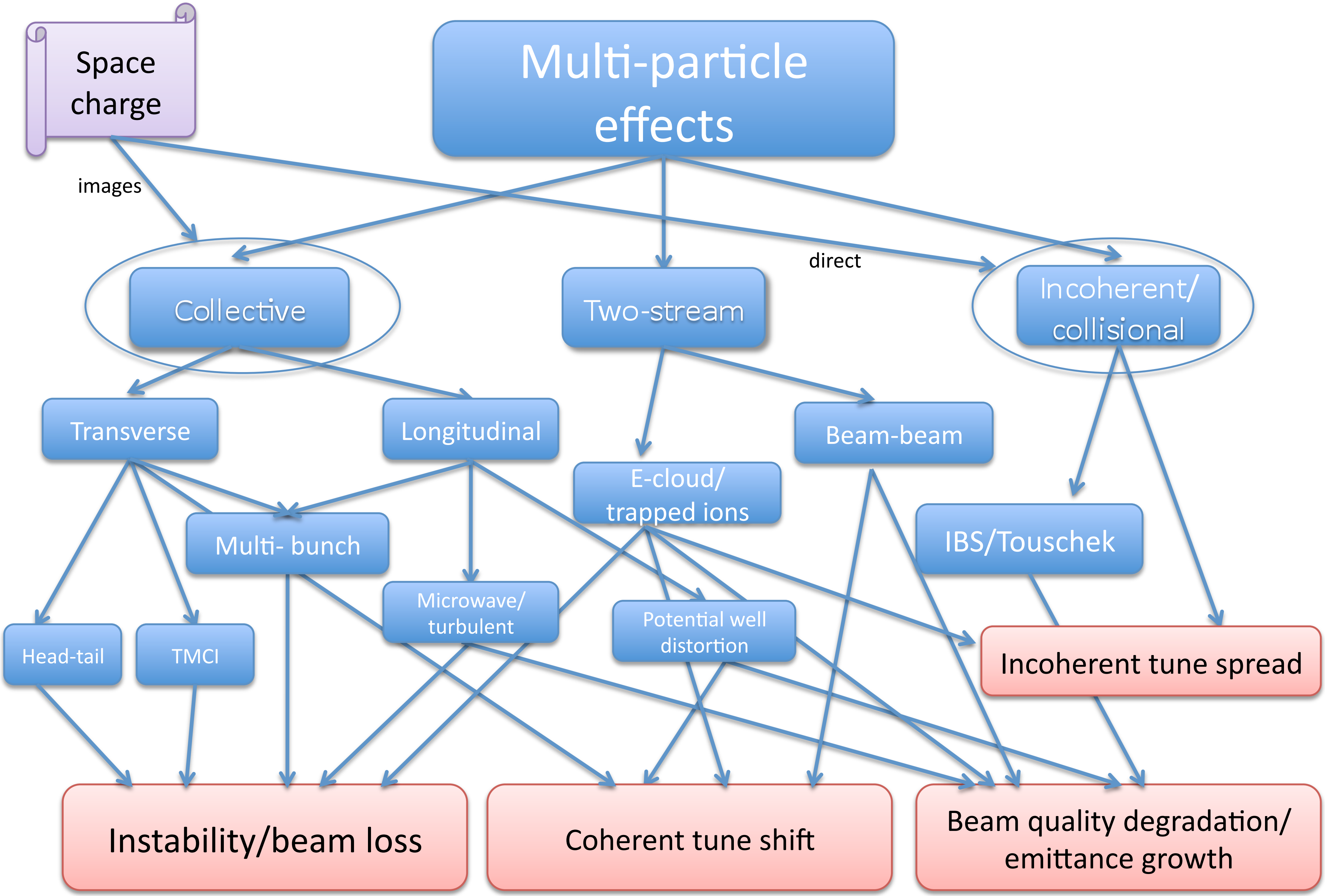
- But they are fundamentally different phenomena....

  → Resonances only depend on the distribution of linear/nonlinear errors in the lattice of a machine and are not the response of a beam to a self-excitation

  → The unstable motion due to a resonance is not intensity dependent and occurs whenever the working point of a machine is badly placed with respect to the resonance lines excited by the distribution of the lattice errors.

  → The theory of linear/nonlinear resonances is based on the single particle dynamics, whereas multi-particle effects can be only described with a kinetic/macroparticle approach (Maxwell/Vlasov system, two- or more-particle models)

  → However, interplays between resonances and multi-particle effects are possible due to the intensity dependent tune shift/spread, which can lead to resonance crossing (static, dynamic or periodic)


Space charge
Multi-particle effects
images
direct
Collective
Two-stream
Incoherent/ collisional
Transverse
Longitudinal
Beam-beam
E-cloud/ trapped ions
IBS/Touschek
Multi- bunch
Microwave/ turbulent
Potential well distortion
Head-tail
TMCI
Incoherent tune spread
Instability/beam loss
Coherent tune shift
Beam quality degradation/ emittance growth