Motivation and Overview

(an introduction to the lectures and a few things to remember)

- quantitative treatment in lectures -

Werner Herr
CERN

Intensity (density) limitations - Issues

- Brick wall - threshold effects (e.g.):
  - Instabilities and beam loss (TMCI, ...)
  - Performance degradation (beam-beam limit, ...)
- Build up and evolution of problems and issues (e.g.):
  - Incoherent collective and single particle effects (diffusion, lifetime, halo, emittance growth, ...)
  - Practical problems (operation, technical limits, protection, ...)

Intensity → intensity, current, brightness

- Good performance of machines require good understanding of the limitations
- We discuss in this school (necessarily incomplete):
  - Circular and linear machines
  - Single and multi particle effects
  - Single and multiple beams
  - Low and high energy beams
  - Diagnostics: high brightness and intensity
  - Numerical and simulation tools

CAS is rather ambitious:

Go beyond standard (general) textbooks, many problems still intensively studied and tools are developped:

- Impedance calculations and measurements
- Treatment of collective effects, modelling, ...
- Non-linear beam dynamics
- Beam-beam effects, e-cloud, ions, ...
- Diagnostics, observations and mitigations
- ....

Bibliography (very selective):

[AC1] A. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*, World Scientific Publishing, 1993.

[AC2] A. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering*, World Scientific Publishing, 1998.

[LN400] M. Dienes, M. Month, S. Turner (eds), *Frontiers of Particle Beams: Intensity Limitations*, Joint US-CAS Topical Course, Lecture Notes in Physics 400, Springer 1992.

[BZ1] B. Zotter and S. Kheifets, *Impedances and Wakefields in High Energy Particle Accelerators*, World Scientific, 1997.

[CAS2011] *Proceedings of the CERN Accelerator School: High Power Hadron Machines*, Bilbao, Spain, 24. May - 2. June 2011, edited by Roger Bailey, CERN-2013-001 (CERN, Geneva, 2013).

[CAS2013] *Proceedings of the CERN Accelerator School: Advanced Accelerator Physics*, Trondheim, Norway, 28. - 29. August 2013, edited by W. Herr, CERN-2014-009 (CERN, Geneva, 2014), DOI: http://dx.doi.org/10.5170/CERN-2014-009.

→ Bibliography in individual lectures

→ And: Thanks to everybody who provided many of the figures

Categories of limitations:

- Incoherent single and multi particle effects, mostly slow
- Collective <u>incoherent</u> effects
- Collective <u>coherent</u> effects, often fast
- More than one beam: beam-beam effects, electron cloud, beam gas interactions, ...
- Practical considerations

Particles and beams are sources of em-fields and affect the dynamics of other particles interacting with these fields

Categories of interactions:

- Interaction of particles within a bunch (e.g. direct space charge, IBS, ..)
- Interaction of particles with other bunches (e.g. coupled bunches)
- Interaction with other "beams" (e.g. beam-beam , electron cloud)
- Interaction with the accelerator elements (e.g. magnetic fields)
- Interaction with the environment

→ We can expect: more particles more troubles ...

Interaction with environment

- Impedances and wake fields
- Image space charge forces and Resistive wall
- Cavities and beam pipes, induced fields and Higher Order Modes
- Restgas scattering
- Synchrotron radiation (e.g. build up of e-cloud)

Impedances and wake-fields

In the presence of elements (e.g. beam pipe): fields interact with the vacuum chamber

Described by the impedance and wake-fields

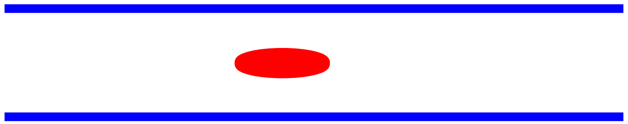
The fields affect particles travelling behind: wake-fields

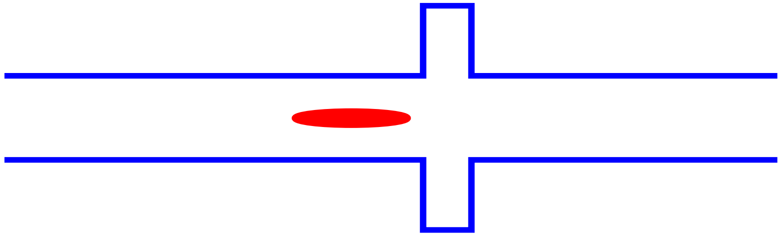
For ultra-relativistic particle: dominant effect

Very good knowledge essential (computation and measurements), needed for reliable modelling of the effects and mitigation

A few types of interactions with the environment (very schematic)

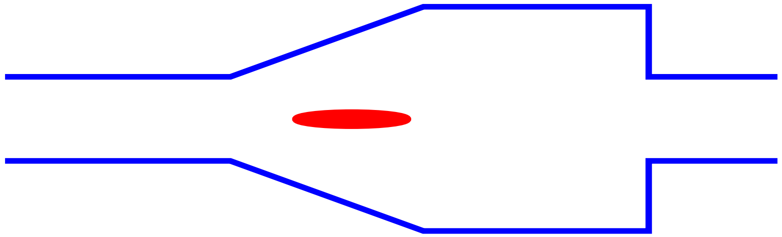
Resistive wall:



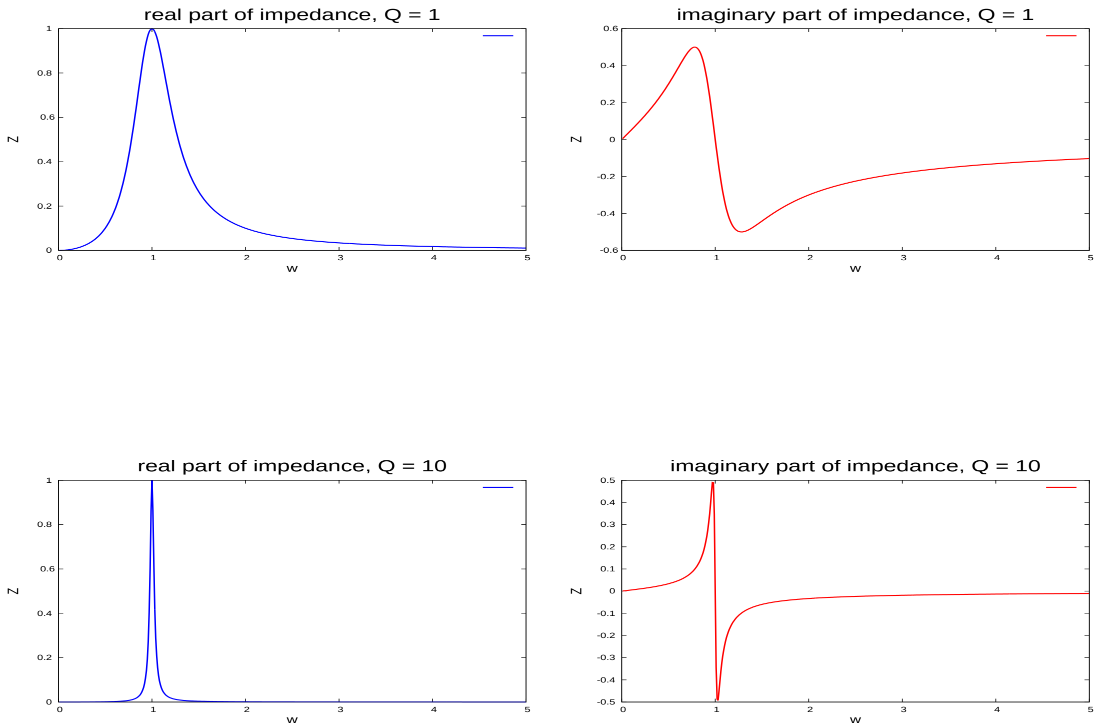


Resonator (narrow-band, slow decay, high Q)

Transitions (broad-band, fast decay):



Example: $Z_{||}$ narrow band resonators,   different quality factors



For an actual cavity: impedance (smooth) sum over large number of resonators

→ ”broad band impedance”

Impedances and wake fields

- Source of many collective effects, detailed knowledge essential to understand beam stability, we see:
  - Induced fields → incoherent and coherent tune shifts
  - Instabilities (details later)
  - Heating, parasitic losses
- Growth rates etc. from wake fields increase with increasing intensities, ”self-inflicted” damping such as decoherence etc. remain fixed, this sucks

→ Must expect strong dependence on intensity

Short and long range wake fields

Examples:

Short range, decays over length of one bunch → only intra-bunch modes: head-tail

Long range, decays over many bunches (or even several turns) → multi bunch and multi-turn instabilities

Heating of the beam pipe

Actually, an old effect:

used to heat pipelines and railroad tracks

origin are : resistivity, skin effect and magnetic induction

In accelerators: usually unwanted ..

Single particle effects

- Resonances, dynamic aperture and beam halo
- Intra beam scattering, Touschek effect
- Restgas scattering
- For ions: change of charge state
- For leptons: quantum excitation, lifetime, (anti-)damping

Non-linear effects and resonances

Presence of non-linear fields

e.g. non-linear machine elements, beam-beam, space charge, ...

- Resonances
- Reduced dynamic aperture
- Emittance growth, particle loss, reduced lifetime, ...

Touschek effect and IBS

Both intensity dependent effects

Touschek effect

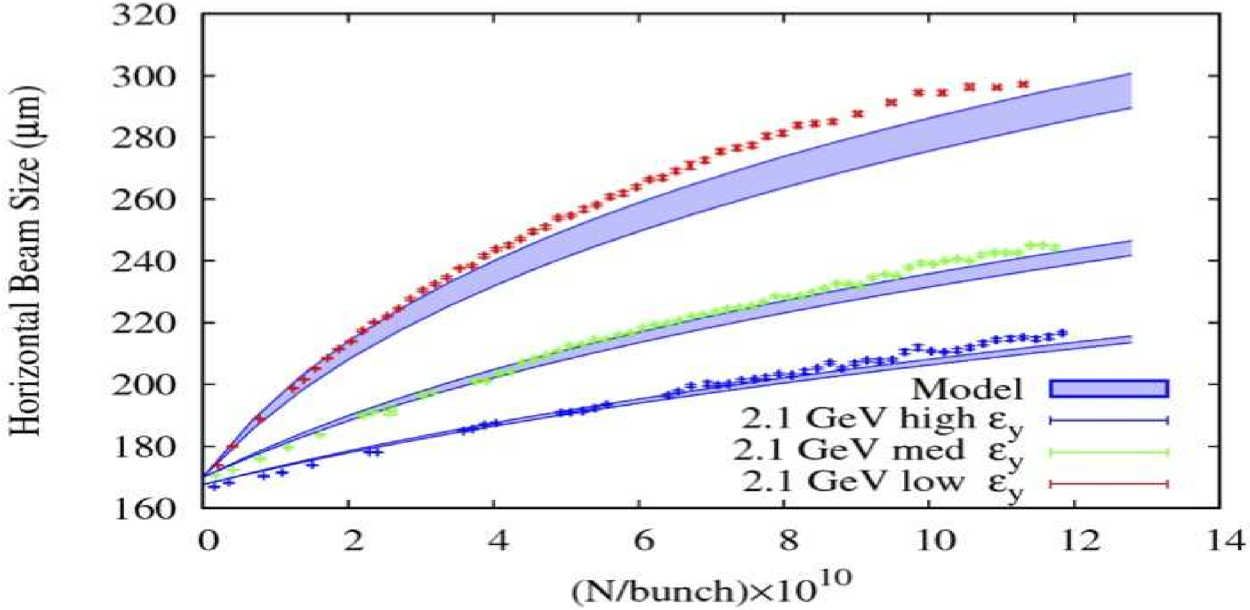
- Single scattering effect, possible particle loss

IBS

- Multiple Coulomb scattering, diffusion and growth of emittance(s)

  Both observed in many machines. CERN: ISR, SPS, AA, ..

- Important for small emittances and high intensity



Observed emittance growth as function of beam emittances and intensities (Cornell)

Longitudinal space charge

Unbunched beams:

- Only transverse fields by symmetry

Bunched beams (or non-uniform longitudinal distribution):

- Modulation of forces along the motion
- Also longitudinal fields

Longitudinal Instabilities

- Robinson instability
- Micro-wave instability
- Coupled bunch instability
- Negative mass instability

Robinson instability

One of the most fundamental instabilities

Single bunch, driven by longitudinal impedance

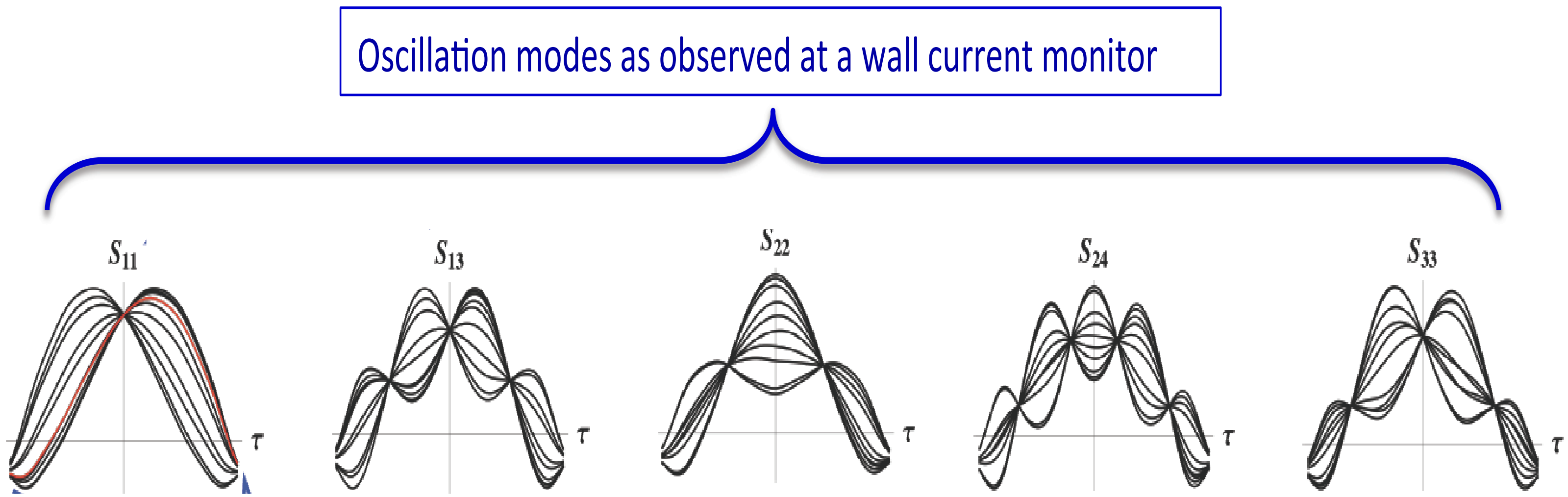
Relevant when: $\omega_r \ \approx \ h \cdot \omega_0$

Can considerably reduce the intensity threshold

Stability considerations for low and high intensity

Single bunch modes

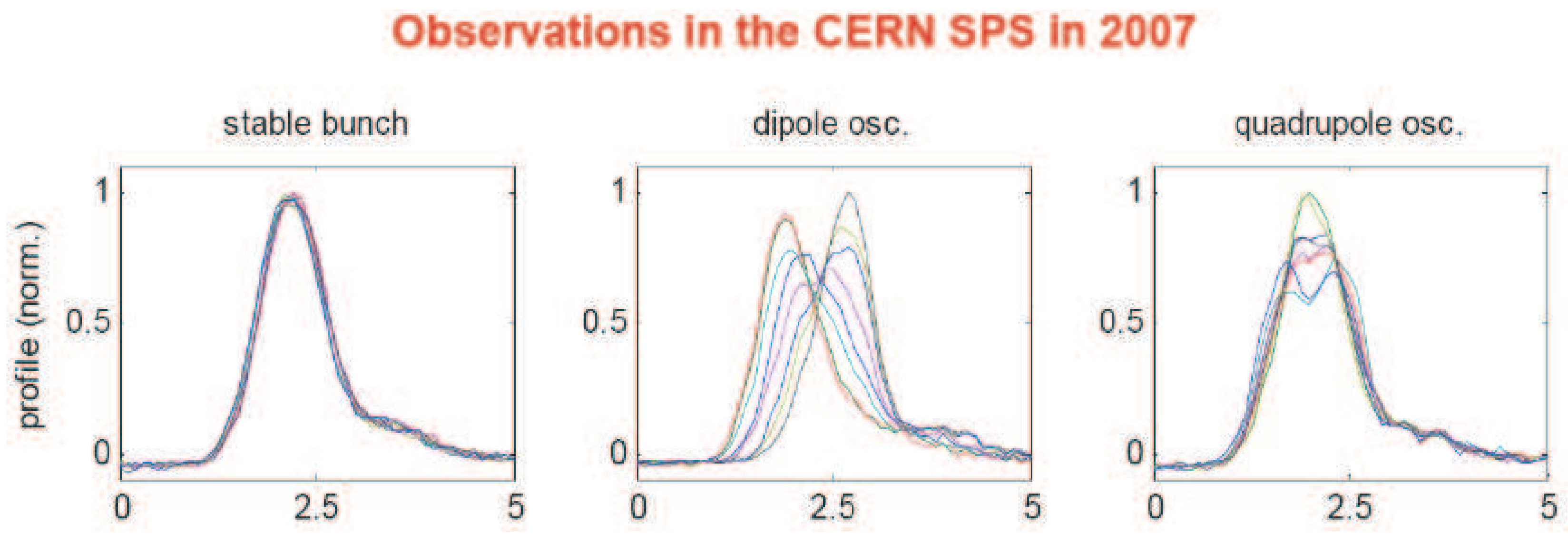
- Many modes of oscillations (measured in SPS, 2007)
- Frequency shift with intensity → threshold and limit
- Micro-wave instability



Example:

Longitudinal modes, simulated

Different modes, different number of modes



Example:

Profile of longitudinal modes, measured in SPS

Coupled bunch modes and instability

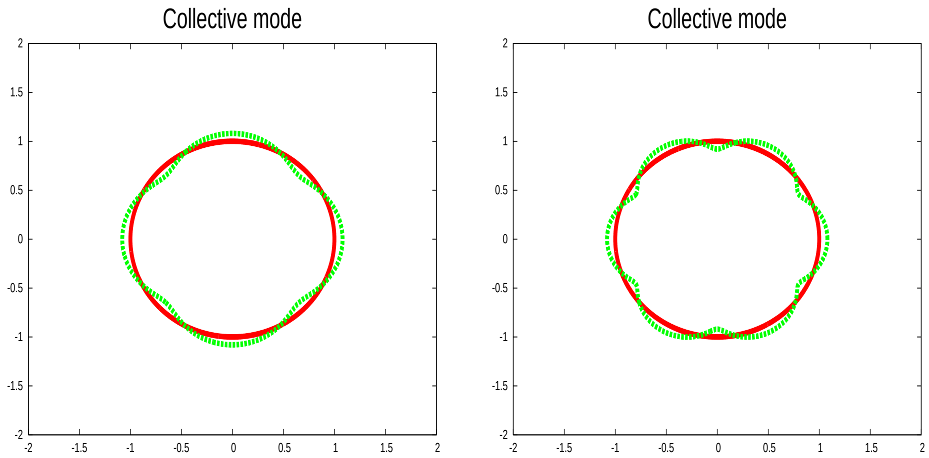
- Coupled (rigid) bunches show many different modes

  $m = 0, 1, ..$

- With many bunches: many modes that are potentially unstable, even for low intensity. Makes the prediction of a threshold difficult

Unbunched beams - transverse

Transverse modes wave pattern around the machine, different velocities



Keywords: Fast waves and Slow waves, related to orbital harmonics. Different behaviour concerning possible instabilities

Negative mass instability - longitudinal

- Particle at $v \approx c$ do not travel much faster when accelerated
- Above transition: particles seem to experience an attractive force (negative mass)
- Result: (longitudinal) self-bunching and particle loss
- Determines an intensity threshold

  and: unbunched beams unstable above transition

Related: effects in flat galaxies ...

Bunched beams

- Transverse modes and instabilities
- Longitudinal modes and instabilities
- Transverse Head-tail instability
- Longitudinal Head-tail instability
- Coupled bunch instability
- Mode coupling and beam break-up

Transverse direct space charge

Single particle effect due to interactions with the collective fields of a bunch

Features:

- Strong energy dependence $(1/\gamma^2)$
- Affects incoherent motion (not coherent) and optics
- Proportional to intensity and inversely proportional to emittance
- Always defocusing in both planes and produces tune spread (can be rather large)

- Dynamics can be:

    Emittance dominated

    Space charge dominated (depends on intensity)

→ A strong limit for High Intensity - Low Emittance beams

(see lecture by G. Franchetti)

Image fields

- Beam induced image charges in the wall
- Move along with the beam
- No dependence on emittance
- Do not disappear for higher energies
- Affects incoherent <u>and</u> coherent motion

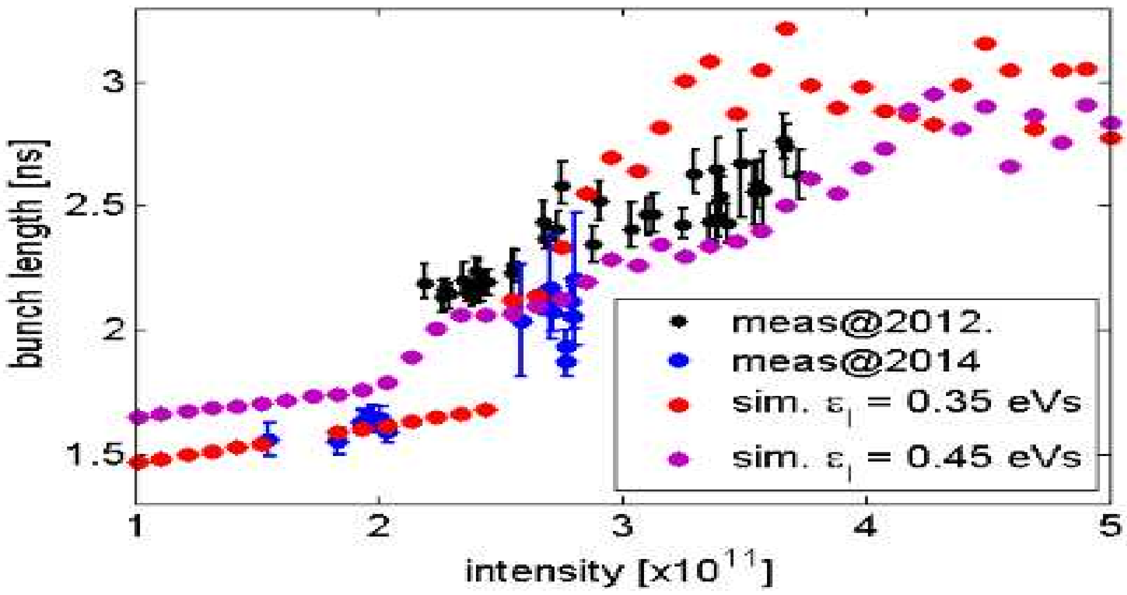
Micro-wave instability

The term is used for:

Bunched/unbunched beams, transverse and longitudinal

some effects:

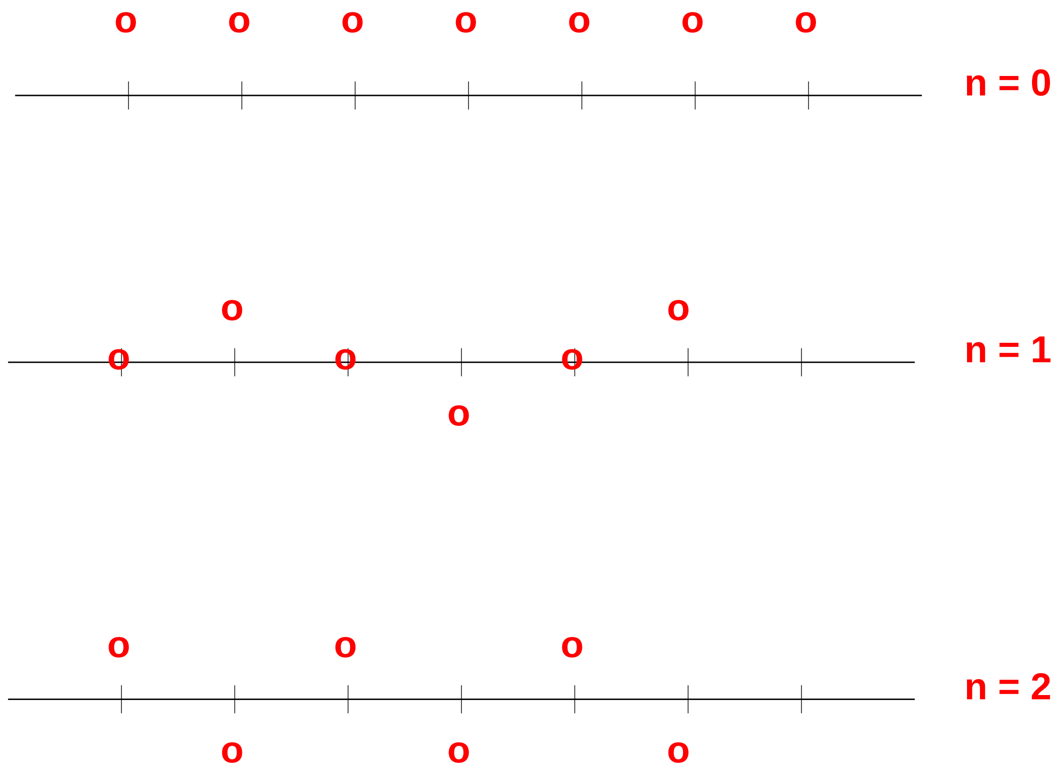
- Often: wakefield wavelength shorter than bunch length
- Single (short) bunches, fast blow-up
- Bunch lengthening
- Typically a threshold behaviour



Observed and simulated bunch lengthening in SPS, caused by vacuum flange impedance

Clear dependence on intensity

Transverse coupled bunch modes

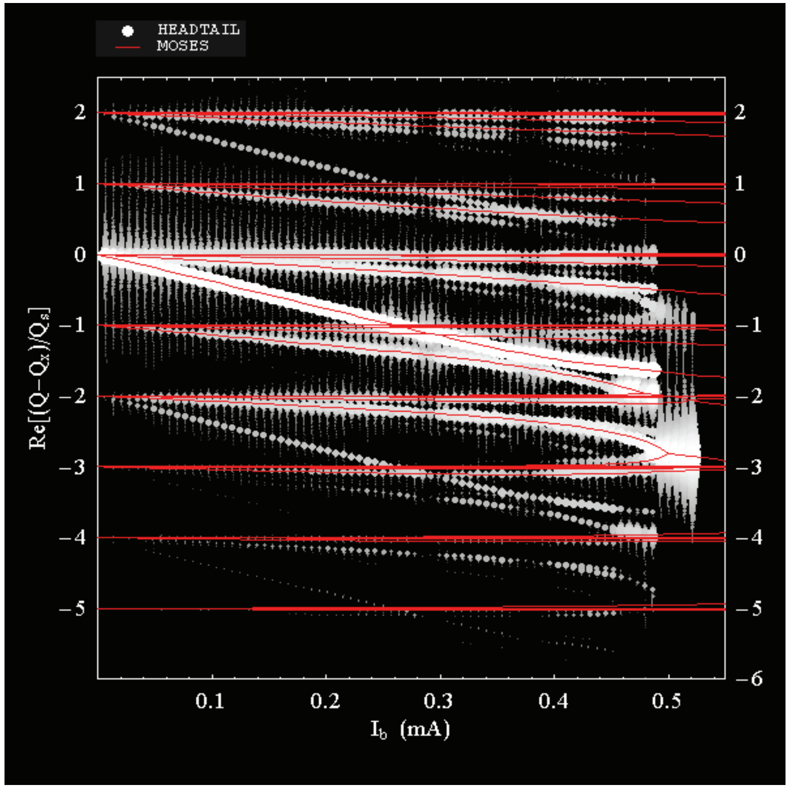


- Very schematic transverse oscillation of bunches in a train

Transverse mode coupling instability (TMCI)

Also known as: *Fast Head – Tail Instability*

- Frequencies of two neighboring modes approach (and eventually become equal) → clear intensity dependence
- Threshold for the intensity, can be very severe in lepton machines (LEP, large number of cavities)
- Also observed in hadron machine: SPS



Example:

Transverse Mode coupling (simulation)

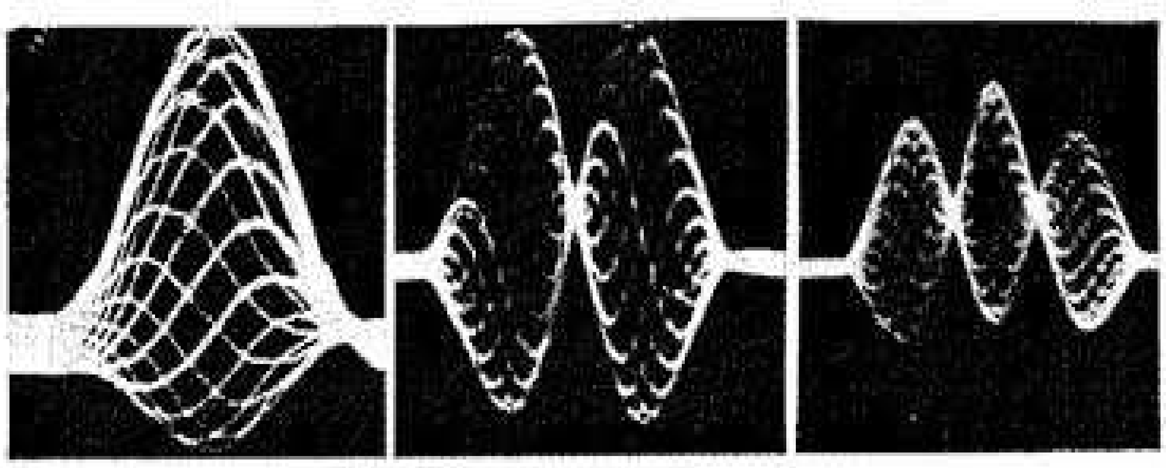
Visible onset of instability when modes have equal frequencies

Head-tail instability

Important: frequency spectrum of impedance, need good knowledge

Observations: plenty (PS, PS Booster, LEP, SPS,..)

- In contrast to TMCI: no intensity threshold, always unstable for negative chromaticity

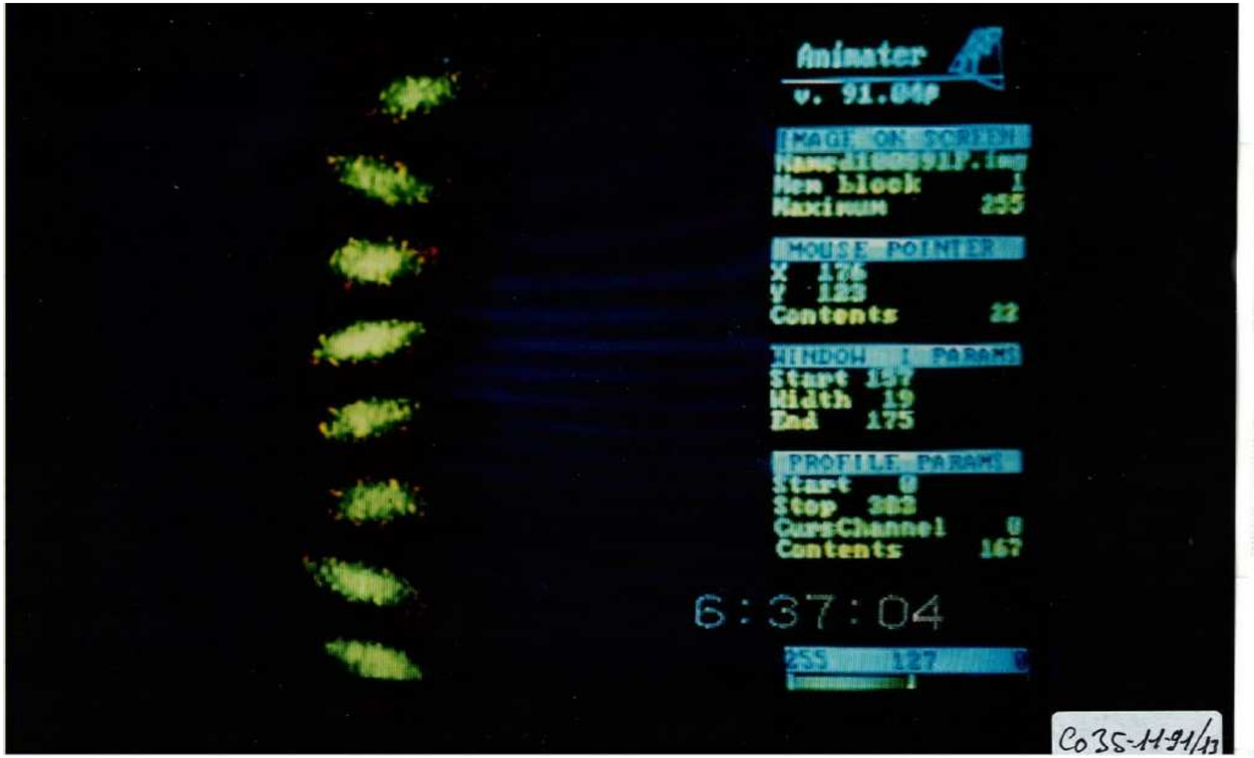


Example:

Head-tail modes (CERN PS, 1974)

m = 0, m = 1, m = 2

Shape of bunches changes along the length

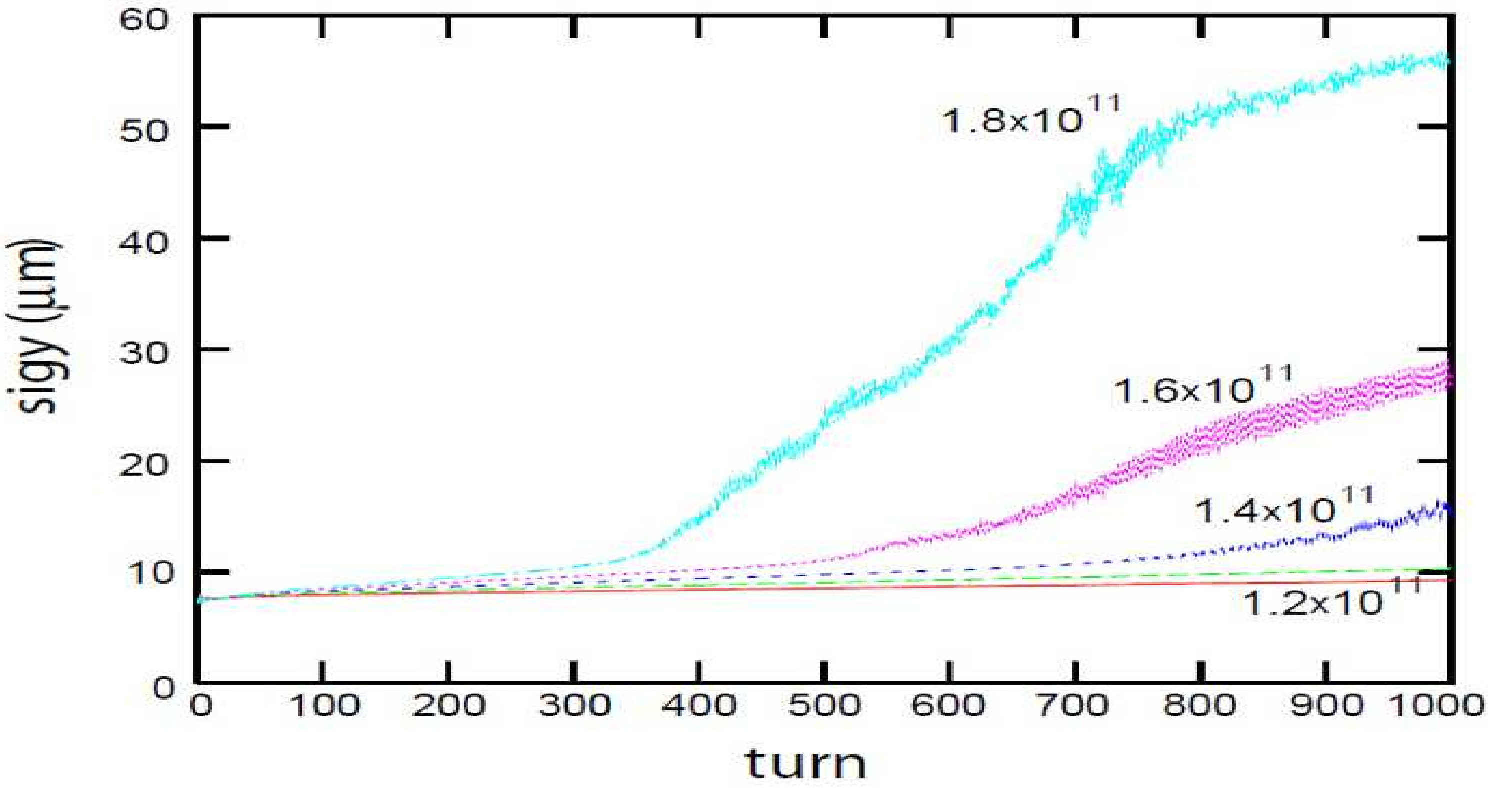


Example (same bunch, turn by turn, measured with streak camera):

Head-tail mode m = 1 (CERN LEP)

Electron cloud

- Interaction of synchrotron radiation with environment
- Effect on successive bunches, instabilities and emittance growth
- Depends on bunch pattern (distance) and intensity
- Single bunch effect: density increase head to tail (PEP)



Example:

Vertical (single bunch) beam size growth as function of intensity due to electron cloud (PEP)

Low energy beams

- Primary effect: space charge $\frac{1}{\gamma^2}$ (intensity !)
- Beam transfer
- Acceleration from low energy can cause problems at transition

Consequences crossing transition:

- Stable phase move on other side of RF wave
- $\Delta p/p \rightarrow \infty$
- Bunch length gets short
- Synchrotron frequency goes to zero
- RF bucket gets large

Instabilities in LINACS

- Wake potentials:
  - Longitudinal wakes $\rightarrow$ energy loss
  - Transverse wakes $\rightarrow$ transverse deflection
- Resonant cavities: fundamental and Higher Order Modes (HOM)
- Other challenges: beam loading

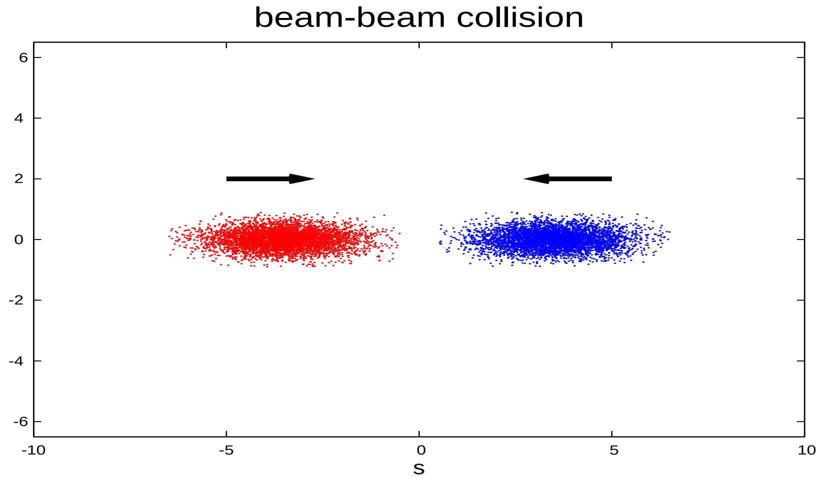
Space charge in LINACS

- At low energies will limit the intensity
- Example: SNS
- An issue: emittance growth, matching
- Lower energy linacs often ”part” of particle sources, see later

Beam break-up (BBU) in linacs

- Transverse displacement causes wakes and deflect trailing particles in a bunch
- Dipolar and Quadrupolar beam break-up occur
- Both limiting the bunch intensity, may be a hard limit for linear colliders
- Cumulative ..

Beam-beam collision



Typically:

- **0.001% (or less) of particles collide**
- **99.999% (or more) of particles are distorted**

Beam-beam effects

Remember:

$$\mathcal{L} = \frac{N_1 N_2 f n_B}{4\pi\sigma_x\sigma_y} = \frac{N_1 N_2 f n_B}{4\pi \cdot \sigma_x\sigma_y}$$

- **Effects are important for present and future machines (RHIC, LHC, FCC, ...)**
- **See lecture by Tatiana Pieloni and Xavier Buffat**

Beam-beam effects in colliders

Very non-linear fields from other beam

Very local, unlike direct space charge

Fields depend on intensity and current

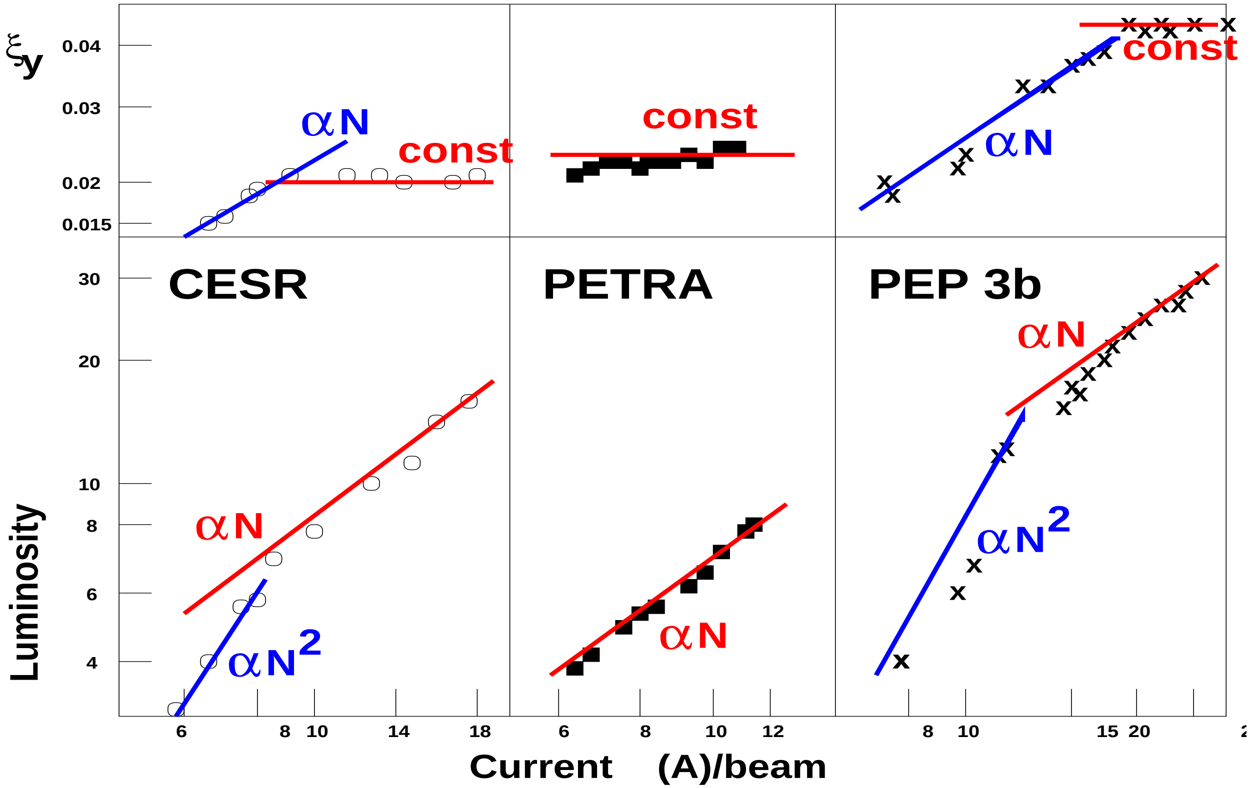
Many consequences on beam dynamics:

- Incoherent effects
- Coherent effects
- Leptons versus hadrons, very different behaviour

Beam-beam effects - Incoherent effects

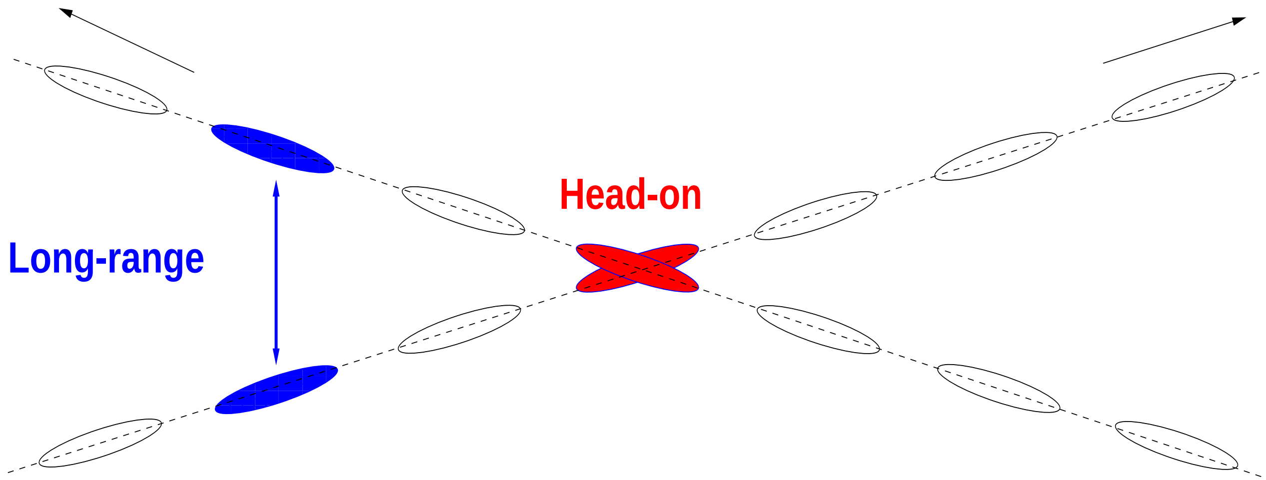
- Many observations available
- Intensity dependent tune shift and spread (non-linearity) much smaller than direct space charge)
- In e+e- colliders: intensity dependent beam-beam limit
- For hadrons: reduced dynamic aperture and bad lifetime (head-on and long range effects exhibit very different behaviour).
- Additional complications: synchro-betatron coupling, bunch to bunch differences, ...

Examples: beam-beam limit



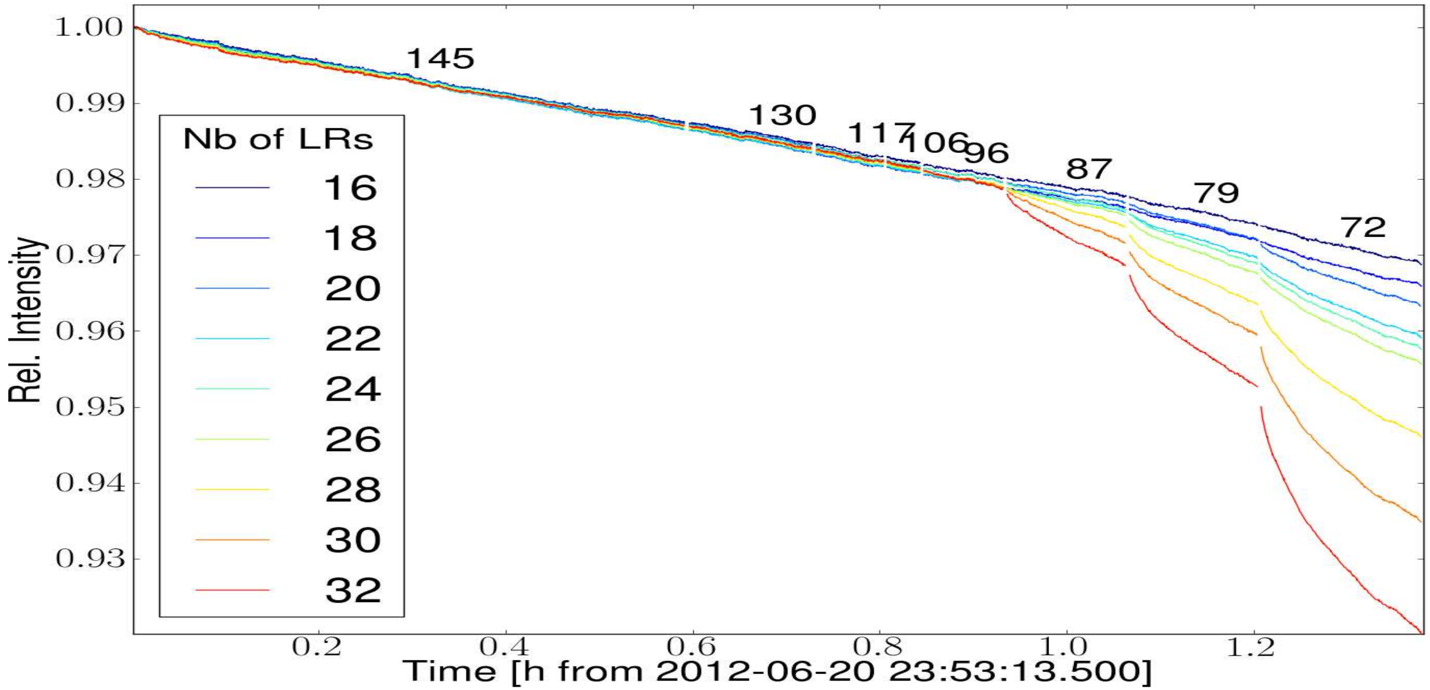
Beam-beam tune shift saturates above a threshold intensity

Crossing angles (example LHC)



- Particles experience distant (weak) forces
- Separation typically 6 - 12 σ

➡ We get so-called long range interactions



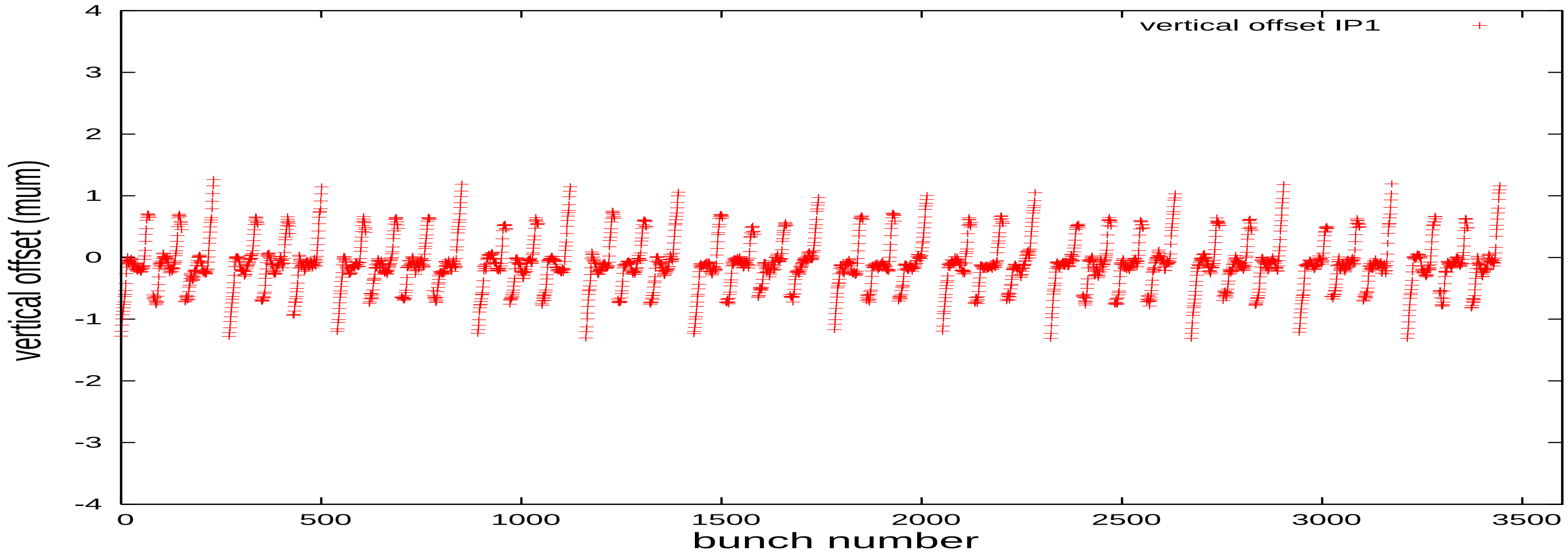
Stepwise reduction of long range separation (crossing angle)

Bunch losses depend on number of long range interactions ("PACMAN" bunches, see lecture by T. Pieloni)

Beam-beam effects - Coherent effects

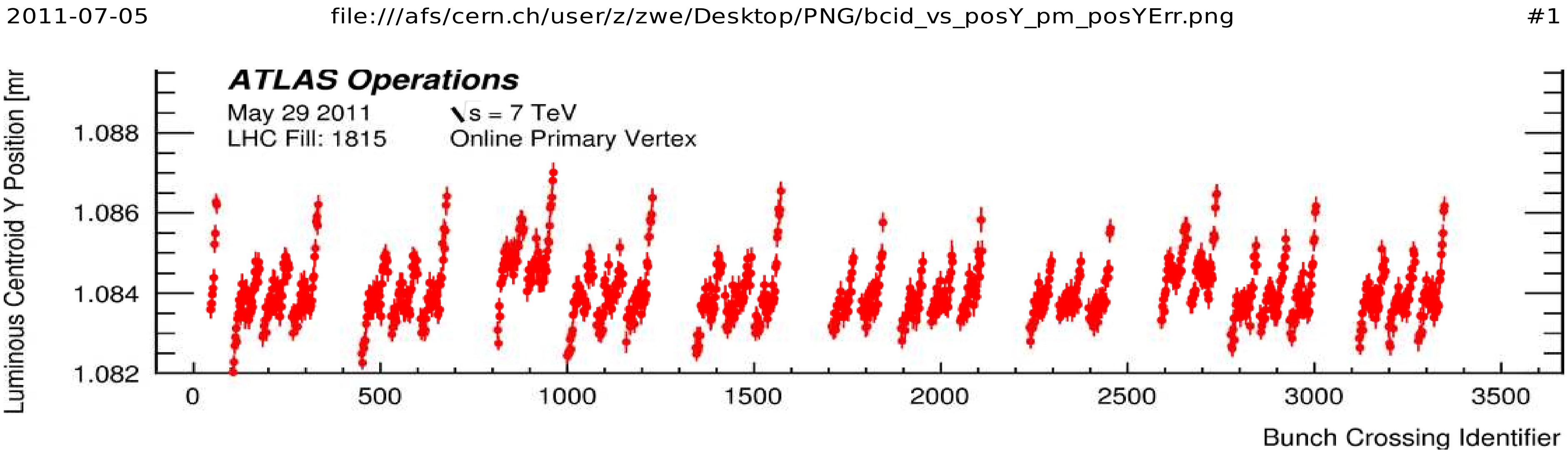
- Coherent beam-beam modes:
  - Can be excited by head-on and long range interactions
  - Complications for beams with many bunches and irregular filling schemes
- Other coherent effects:
  - From bunch to bunch: different tunes and chromaticity
  - Coherent deflection causes orbit distortions: different from bunch to bunch

PACMAN Orbit effects: calculation



- Vertical offset expected at collision point in IP1
- Predicted orbits from self-consistent computation (2003)
- Cannot be resolved with beam position measurement, but ..

PACMAN Orbit effects: measurement



- **Measured vertex centroid in ATLAS detector**
- **Very good agreement with computation**

Other Beam-beam effects

- Linear colliders (no experimental data)
- Beam-beam compensation
- Beamstrahlung
- Beam-beam for continuous beams
- Asymmetric beams (energy, particle type, ..)
- Synchrobetatron coupling

Limitations at the sources

(we have dedicated schools)

- Applications require different particle types
- Sources are the driver for all following accelerators (in particular: colliders are doomed without proper sources)
- Must:
  - Produce sources with high quality, e.g. emittance (divergence !), pulse length and brightness
  - Extraction must produce correct beam for next stage of accelerator (and remove unwanted particles)
  - With strong space charge: First stage linac lattice must be tuned to a specific current

- Examples of sources: thermionic or photocathodes
- Some particles are hard to produce: $\bar{p}$, ions, polarized beams
- Example limitations:
  - Heating and cathode charge, emittance
  - Space charge, low energy beam transport with high intensity
  - Laser power

Practical considerations

- Vacuum
- Cryogenics (for SC devices)
- High power synchrotron radiation (leptons)
- Beam loss and machine protection, radiation damage
- Collimation of high brightness beams
- and USERS ?

Vacuum

(we have dedicated schools)

- Should allow long beam lifetime (colliders !)
- Electrons: collision with residual gas $\rightarrow$ bremsstrahlung

Beam loss and machine protection

(we have dedicated schools)

Must consider:

- Large stored energy in storage rings (e.g. LHC)
- Large beam power in linear machines (e.g. SNS linac)
- High intensity beams in light sources
- Other safety issues: medical accelerators
- Important: diagnostics !

Diagnostics and instrumentation

(we have dedicated schools)

Without proper diagnostics:

- Instabilities etc. cannot be observed
- Instabilities etc. cannot be cured
- Vital also for machine protection

The importance is just too obvious !

Numerical modelling

Basics to understand and to improve

- Beam dynamics as well as machine elements
  (impedance, magnetic fields, ...)
- Very good input parameters to have reliable predictions
- New tools may be necessary, and are constantly developped

Mitigation of limitations

- Passive mitigation

  Reduction of impedance, shielding, etc.

  Proper choice or parameters (Q, Q’, ..)

  Landau damping

- Active mitigation

  Feedback systems

  Compensation scheme (e.g. non-linear forces)

(Almost) last but not least ...

Not a limitation from the accelerator, but we have users:

- Applications may require maximum intensity, brightness, ...
- Experiments for particle Physics (e.g. LHC)
  - Require ”clean” collision signature
  - To many simultaneous interactions unwanted (see lecture by Lenny, e.g. nominal LHC: maximum $\approx$ 20 - 30), limits the maximum desirable luminosity (bunch spacing !!)

Summary

- Plenty of limitations to look at during this school
- Not complete, but attempts a contemporary treatment
- Hope you are sufficiently motivated