CERN

U.S. Particle Accelerator School

Education in Beam Physics and Accelerator Technology

Collective effects in Beam Dynamics

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http://uspas.fnal.gov/index.shtml

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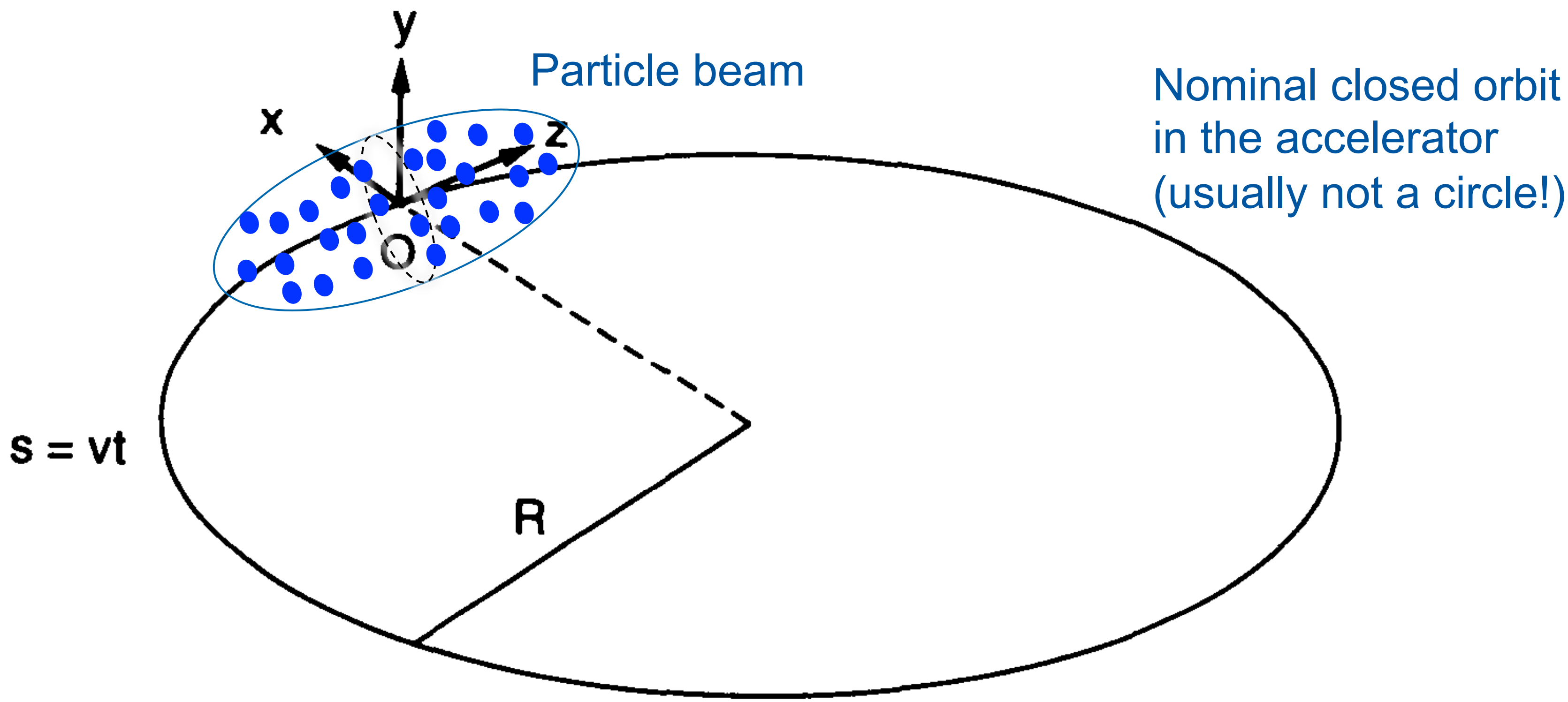
Introduction to collective effects



- Motion of particles is described in reference frame co-moving with synchronous particle (i.e. with nominal momentum on nominal closed orbit, motion determined by external fields)
  - **Transverse** → x (plane of closed orbit) or y (conjugate variables are divergences x' and y')
  - **Longitudinal** → z (conjugate variable is momentum spread δ)
- Volume occupied by beam in phase space (x, x', y, y', z, δ) is called beam emittance

Introduction to collective effects

- A general definition of collective effects
  - Class of phenomena in beam dynamics, in which the evolution of a particle in a beam depends on both the external EM fields and the extra EM fields created by the presence of other particles.

- How other particles can affect a single particle's motion:
  - **Self-induced EM fields**
    - Space charge from beam particles
    - EM interaction of whole beam with surrounding environment
    - EM interaction of whole beam with its own synchrotron radiation
  - **Coulomb collisions**
    - Long range and multiple two beam particle encounters → Intra-beam scattering
    - Short range and single events two beam particle encounters → Touschek effect
    - Elastic and inelastic scattering against residual gas
  - **EM fields from another charge distribution** (generated or not by the beam itself), like a second "beam"
    - Beam-beam in colliders
    - Ion trapping for electron beams
    - Electron clouds for positron/hadron beams
    - Interactions with electron lens or electron cooling system

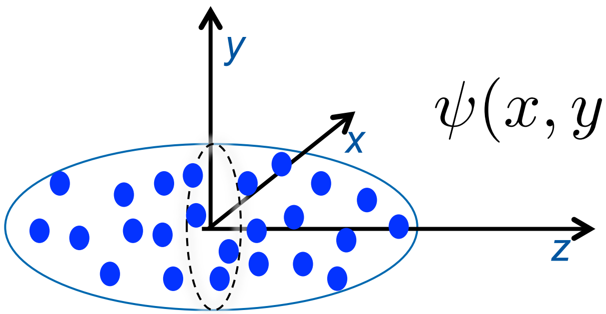
Introduction to collective effects

- Collective effects start playing a role when the beam density is very high
  - They are also referred to as "high current", "high intensity", "high brightness" effects and exhibit a threshold behaviour
  - They result into a measurable response of the beam to the collective interaction, which can be **detrimental and lead to beam degradation and loss**

→ **Transverse collective effects**
  - Due to self-induced EM fields
  - Coherent:
    - The beam centroid is affected, resulting in betatron tune shift and possibly in exponential growth (single or multi-bunch instabilities, strong head-tail) → Coherent beam instability
    - Can be seen with standard Beam Position Monitors
  - Incoherent:
    - Beam centroid not affected
    - Result into emittance growth but also halo/tail formation and slow particle loss (poor beam lifetime)

Introduction to collective effects

- How do we recognize a coherent beam instability?
  - A beam becomes unstable when a moment of its distribution exhibits an exponential growth (e.g. mean positions <x>, <y>, <z>, standard deviations σ_x, σ_y, σ_z, etc.) – resulting into beam loss or quality degradation!



$$\psi(x, y, z, x', y', \delta)$$

$$N = \int_{-\infty}^{\infty} \psi(x, y, z, x', y', \delta) dx dx' dy dy' dz d\delta$$

$$\langle x \rangle = \frac{1}{N} \int_{-\infty}^{\infty} x \psi(x, y, z, x', y', \delta) dx dx' dy dy' dz d\delta$$

$$\sigma_x^2 = \frac{1}{N} \int_{-\infty}^{\infty} (x - \langle x \rangle)^2 \psi(x, y, z, x', y', \delta) dx dx' dy dy' dz d\delta$$

And similar definitions for $\langle y \rangle, \ \sigma_y, \ \langle z \rangle, \ \sigma_z$

Introduction to collective effects

- An example of transverse coherent beam instability
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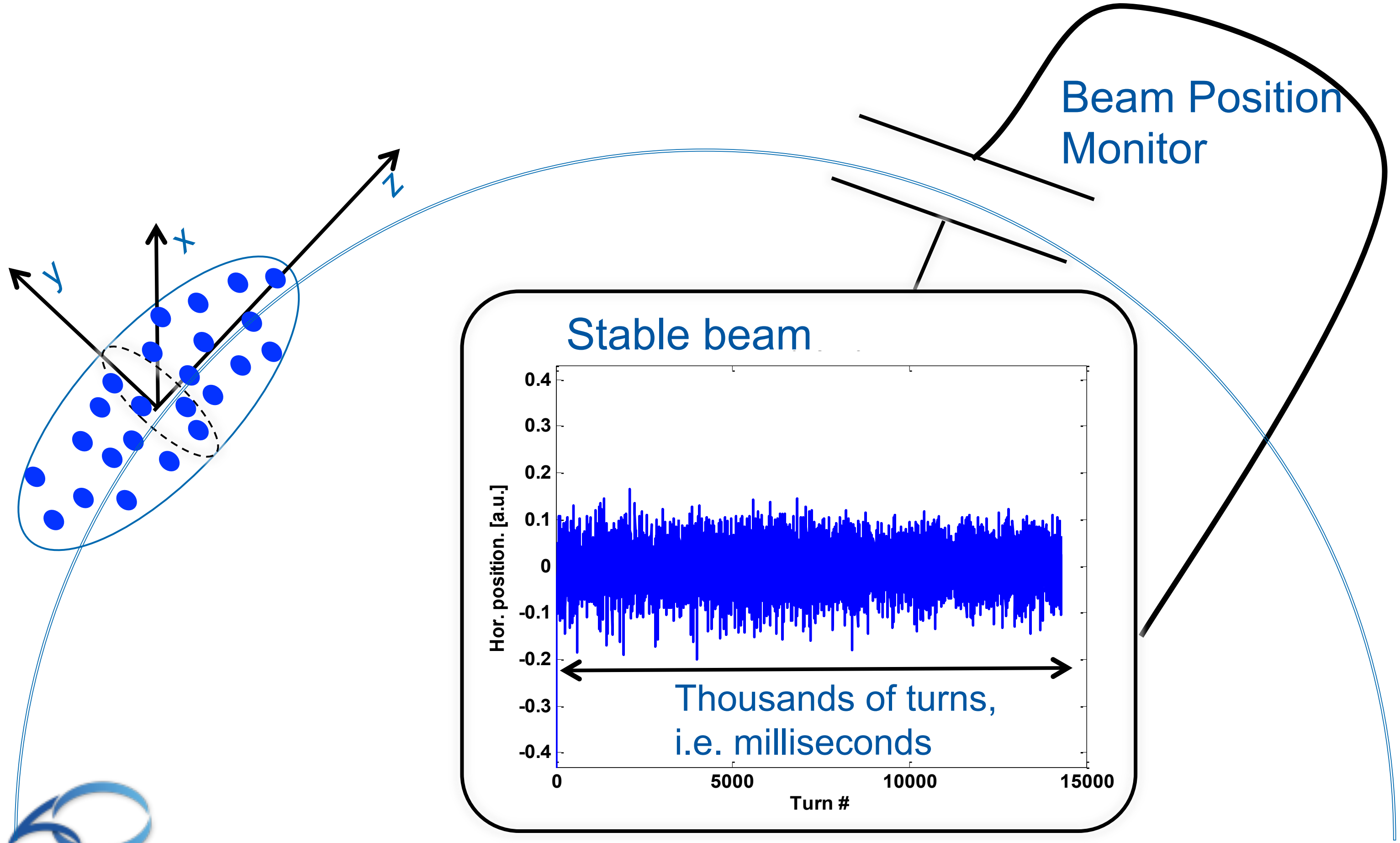

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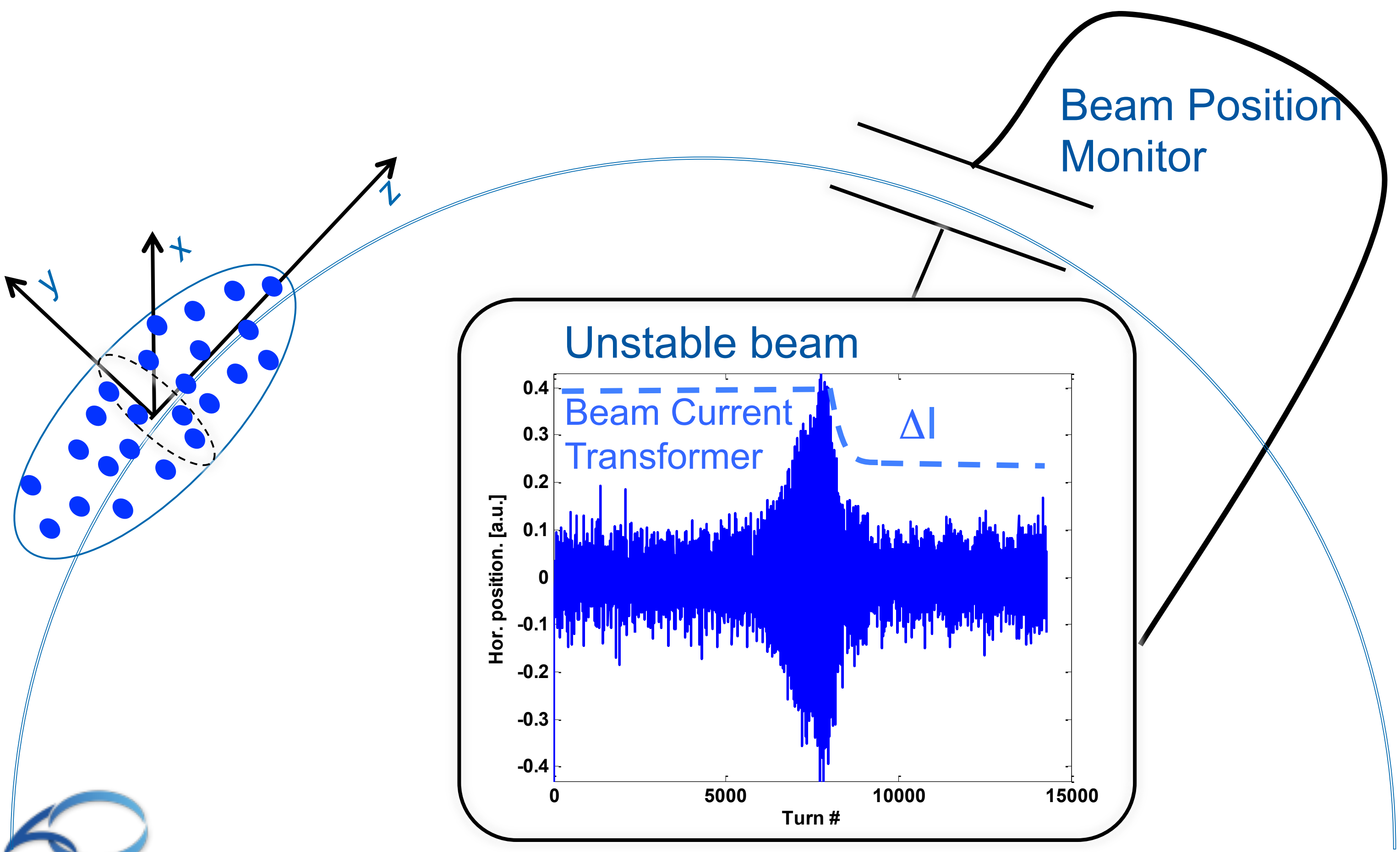

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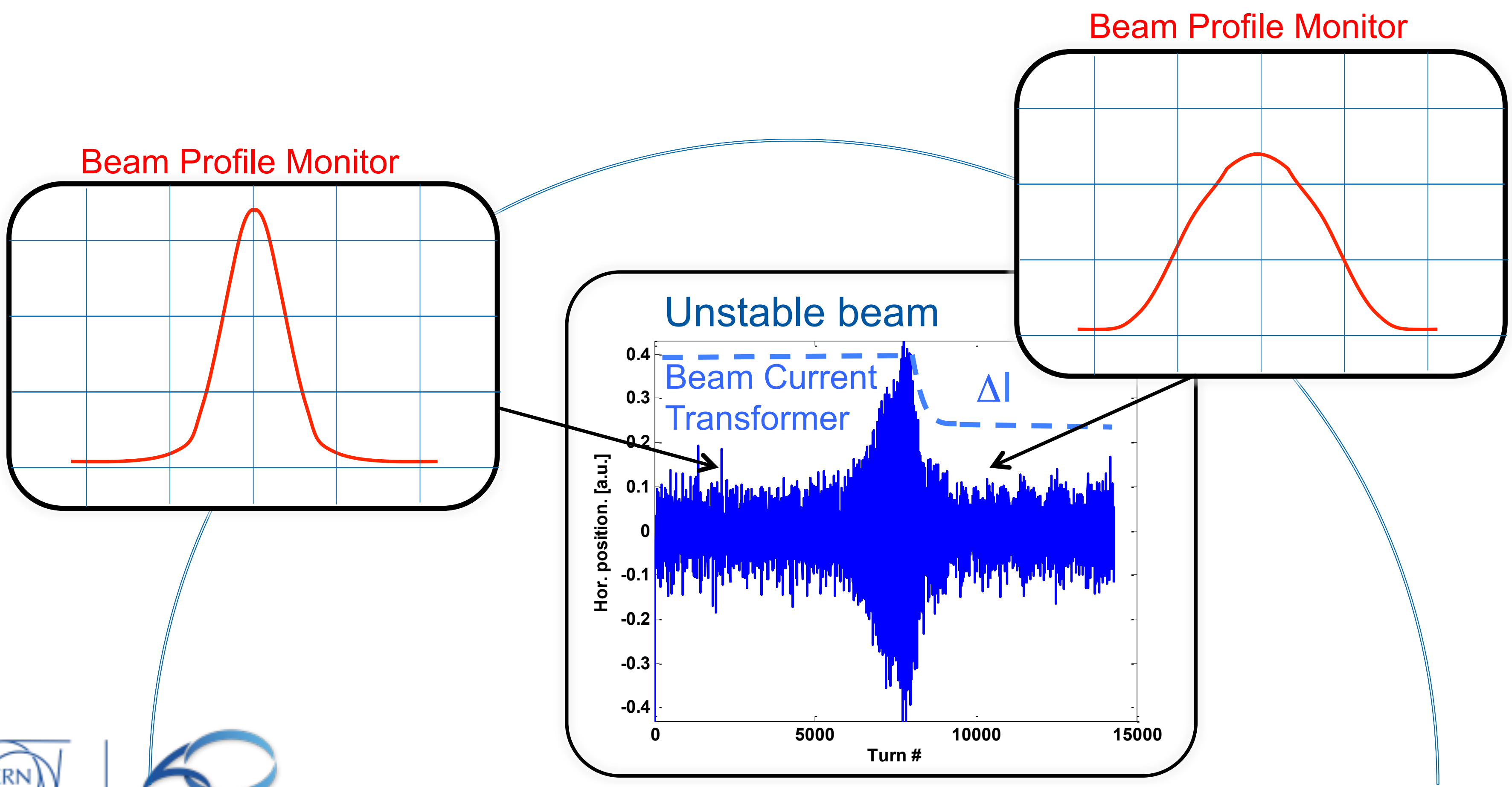

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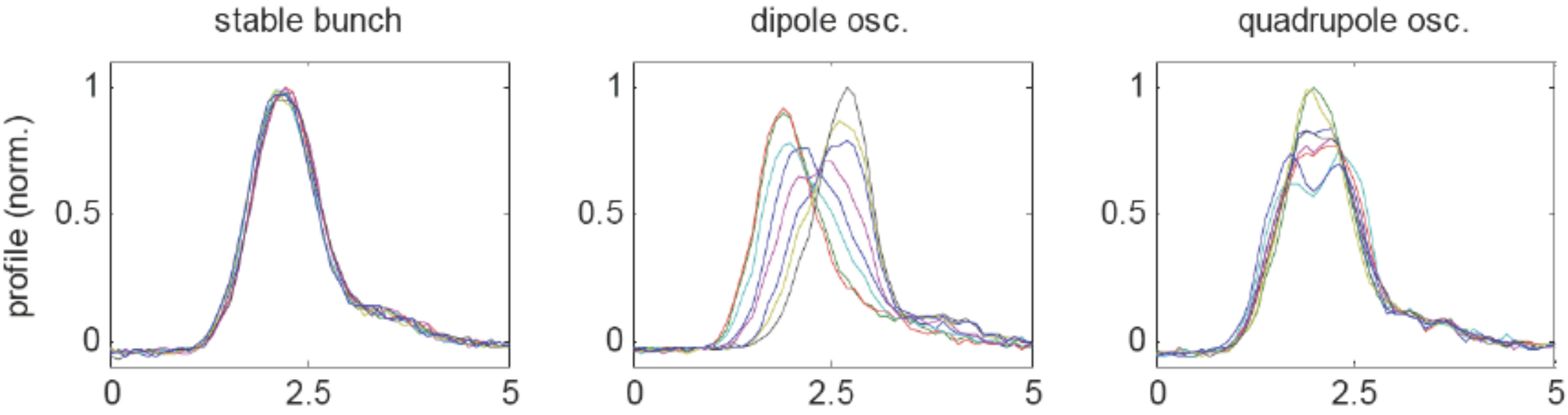
- **Longitudinal collective effects**
  - Due to self-induced EM fields
  - Longitudinal space charge, energy loss, potential well distortion (synchronous phase shift, bunch lengthening)
  - Instabilities (negative mass instability, single or coupled bunch instabilities, microwave instability)

Introduction to collective effects

- Example of longitudinal coherent motion
  - The beam profile, measured at a Wall Current Monitor, shows a bunch oscillating in its buckets (plot 2) or executing quadrupole oscillations (plot 3)

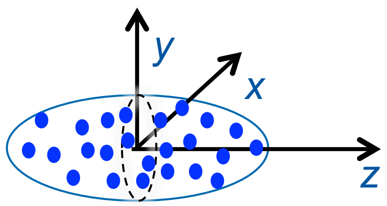
Observations in the CERN SPS in 2007

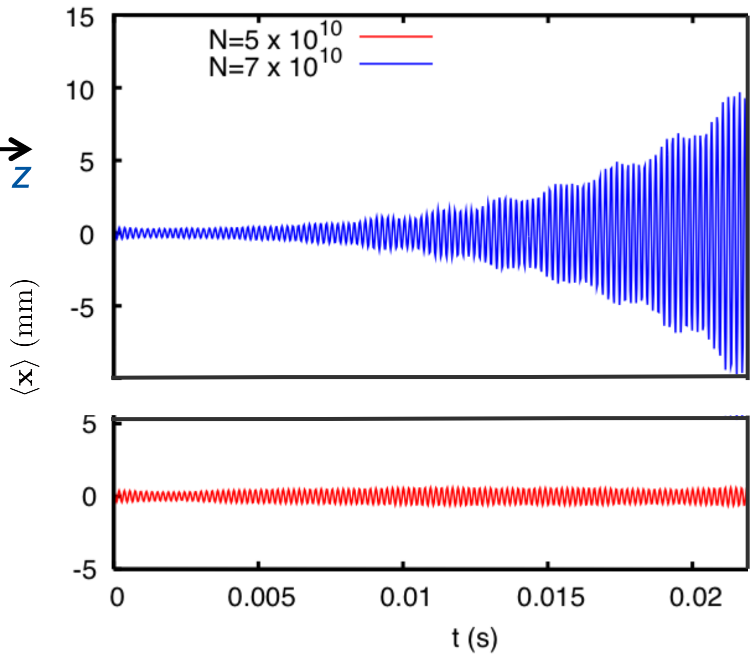


Introduction to collective effects

Why it is important to study beam coherent motion

- The beam coherent motion becomes unstable for a certain beam intensity, which is the maximum that a machine can store/accelerate (performance limitation)





Typical situation

- A beam centroid instability appears when the intensity is raised above a certain **threshold**
- The **threshold** can be optimized by an accurate choice of the machine settings

Introduction to collective effects

Why it is important to study beam coherent motion

- The beam coherent motion becomes unstable for a certain beam intensity, which is the maximum that a machine can store/accelerate (performance limitation)
- Understanding the type of instability limiting the performance, and its underlying mechanism, is essential because it:
  - Allows identification of the source and the possible measures to mitigate/suppress the effect
  - Allows specification of an active feedback system to prevent the instability

Introduction to collective effects

Types of coherent instabilities

⇒ Beam instabilities occur in both linear and circular machines
- Longitudinal phase plane (z,δ)
- Transverse phase plane (x,y,x',y')

⇒ Beam instabilities can affect the beam on different scales
- Cross-talk between bunches
  - → The unstable motion of subsequent bunches is coupled
  - → The instability is consequence of another mechanism that builds up along the bunch train
- Single bunch effect
- Coasting beam instabilities

Introduction to collective effects

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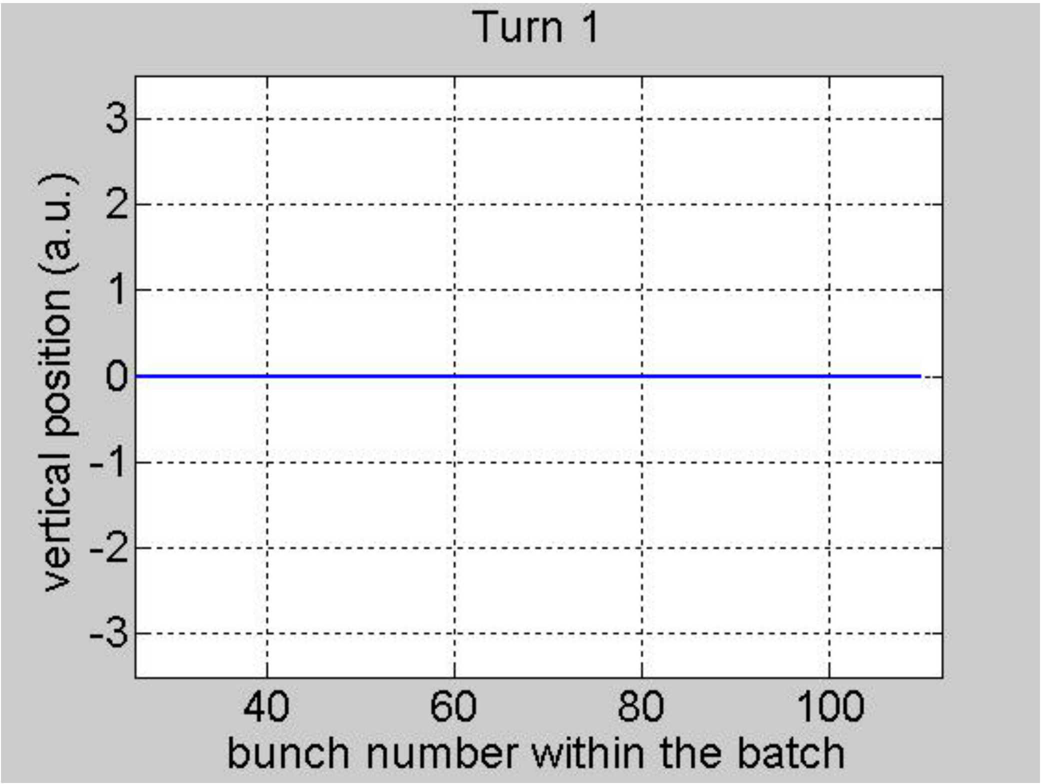

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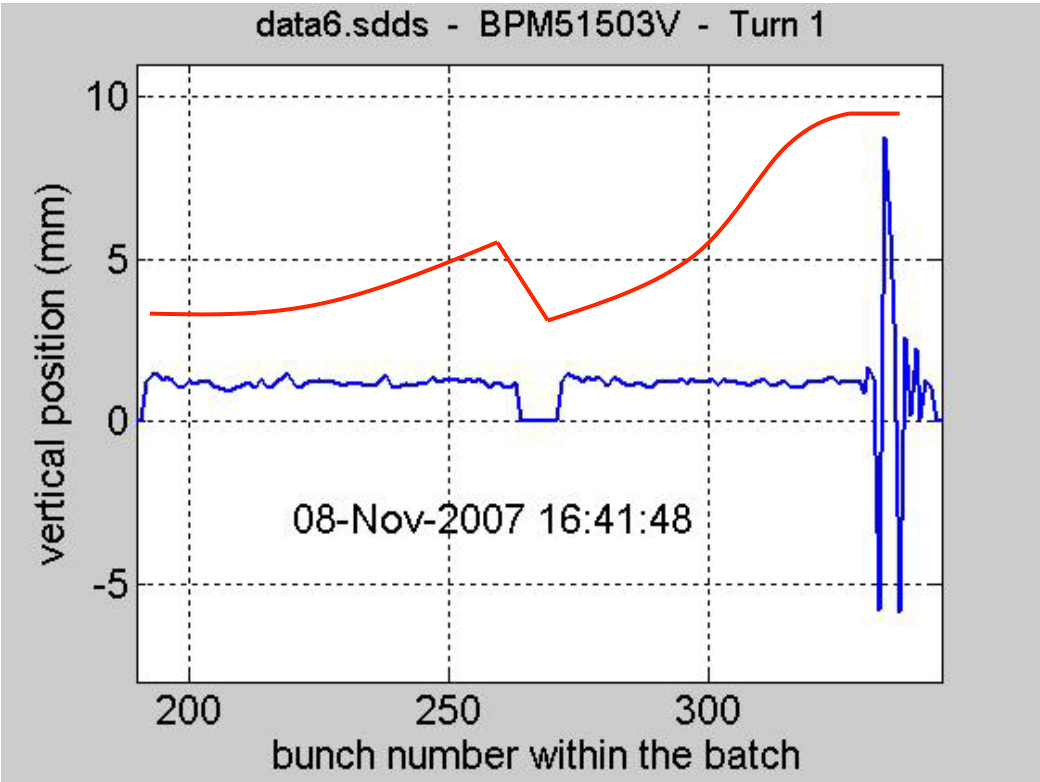

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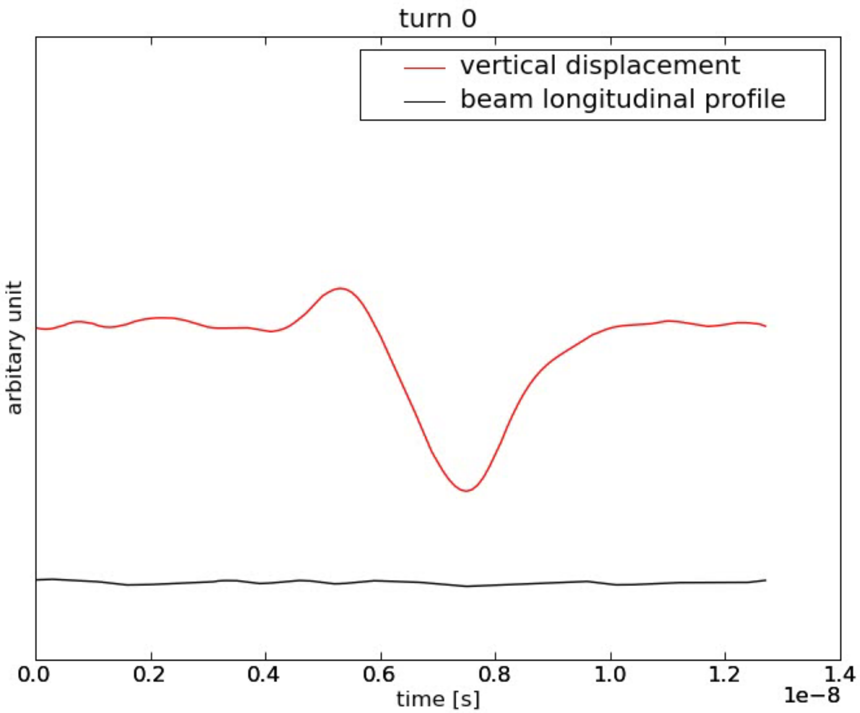

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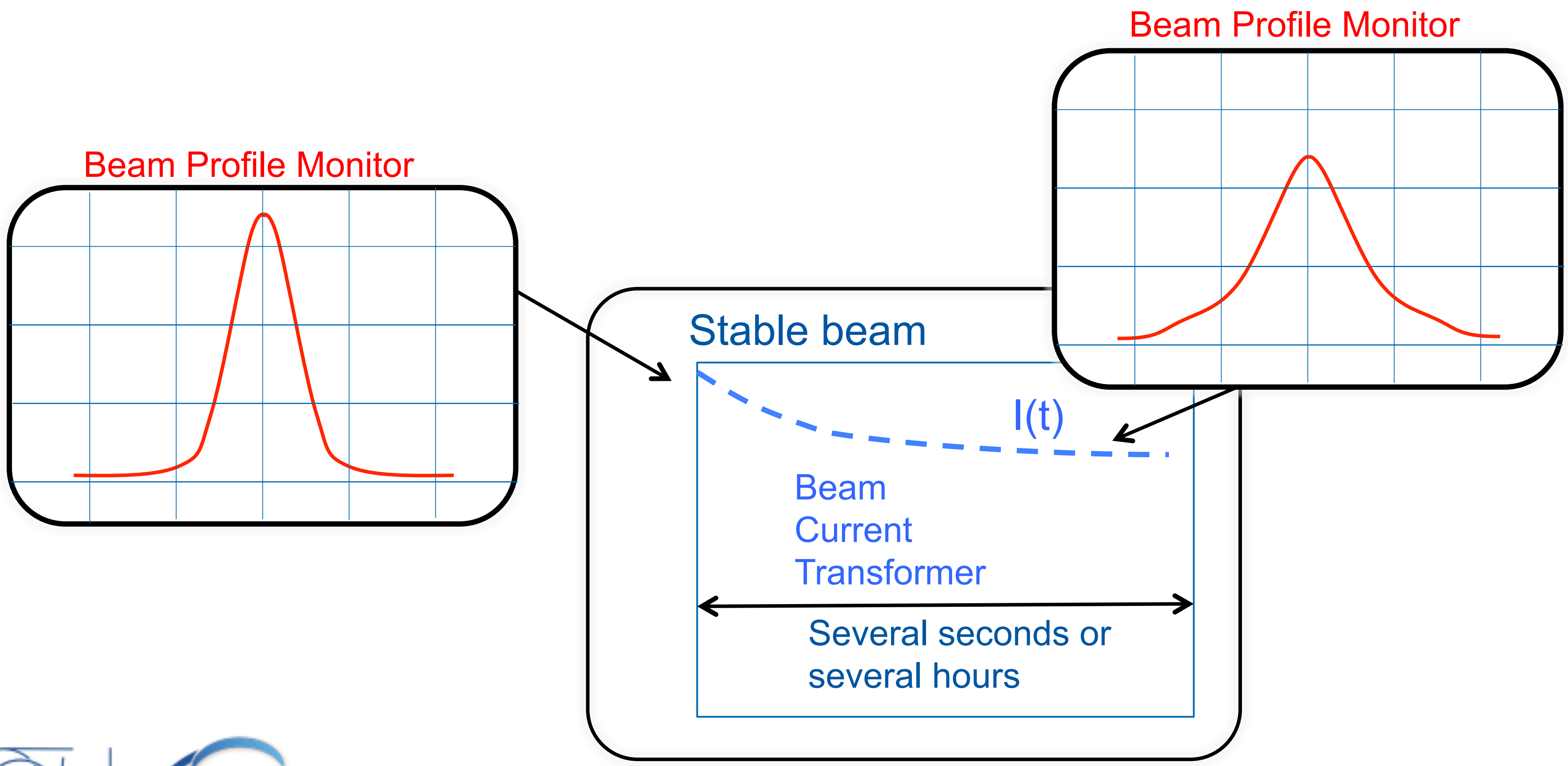
- **Collisional effects (transverse and longitudinal)**
  - Due to scattering events (collisions) between individual particles
    - Short range encounters causing large angle deviations (single events, modeled as Touschek effect)
    - Long range encounters causing small angle deviations (cumulative effect, modeled as Intra Beam Scattering)
  - Tend to depopulate the denser beam core and degrade emittance (i.e. volume occupied by the beam in the phase space) and lifetime, similar to what is caused by incoherent collective effects, like direct space charge.

Introduction to collective effects

- Transverse incoherent effects or collisional effects
  - A beam exhibits slow losses (on the time scale of the cycle or store) and emittance growth visible from a beam profile measurement device, possibly associated to development of halo or tails



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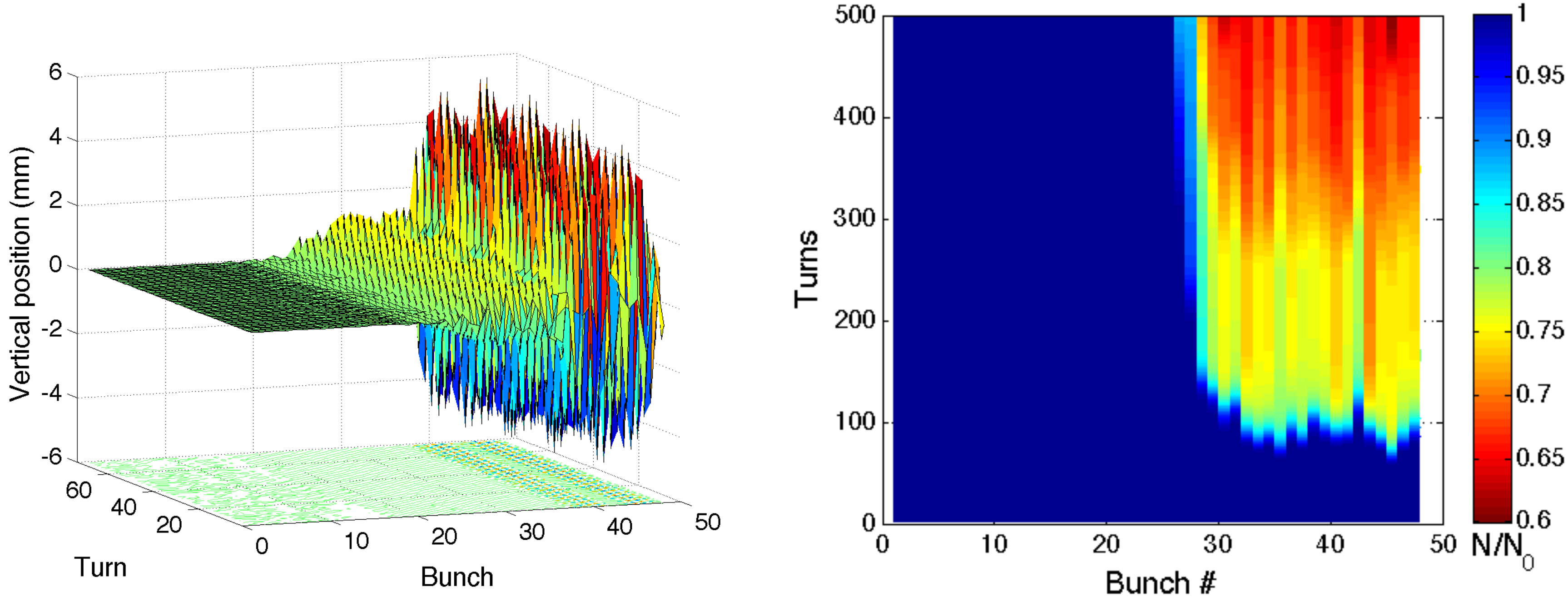
- **Two-stream effects (transverse and longitudinal)**
  - Due to the interaction with another set of charged particles (e.g. electron cloud)
  - Can cause coherent motion as well as incoherent emittance growth and losses, as previously described

Introduction to collective effects

- Electron cloud instability
  - A coherent instability is visible for the last bunches of a train (BPM signal and beam losses), because an electron cloud has formed along the train and can only make these bunches unstable

48b injection test in LHC (26/08/11)

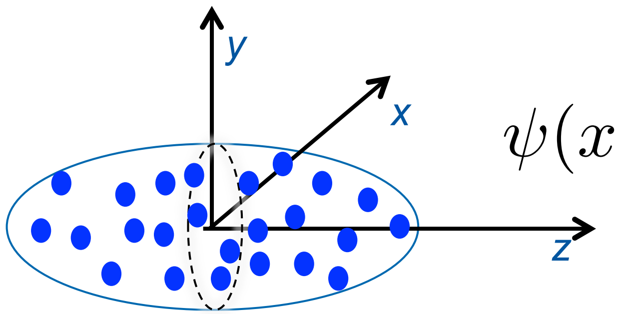


Introduction to collective effects

- Modeling of collective effects due to self-induced EM fields
  - Single particle motion under the overall effect of externally applied fields (RF, magnets) and those created by the beam itself with the proper boundary conditions.

→ **Single particle dynamics not sufficient, need to describe a system of many particles**

- ✓ **Theory:** kinetic models based on distribution functions (Vlasov-Maxwell)



$$\psi(x, y, z, x', y', \delta, t)$$

$$\frac{d\psi}{dt} = 0 \quad \longleftrightarrow \quad \begin{cases} \vec{E} = \vec{E}_{\mathrm{ext}} + \vec{E}(\psi) \\ \vec{B} = \vec{B}_{\mathrm{ext}} + \vec{B}(\psi) \end{cases}$$

in Maxwell's equations

Introduction to collective effects

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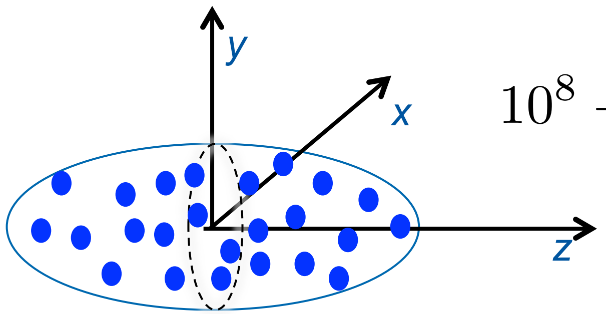
→ **Single particle dynamics not sufficient, need to describe a system of many particles**

- ✓ **Theory:** kinetic models based on distribution functions (Vlasov-Maxwell)
- ✓ **Simulation:** solve numerically the equations of motion of a set of macroparticles and use the EM fields of the macroparticle distribution



$$10^8 - 10^{11} \text{ particles} \longrightarrow 10^4 - 10^6 \text{ macroparticles}$$

$$\frac{d\vec{p}_{\rm mp}}{dt} = q\left(\vec{E} + \vec{v}_{\rm mp} \times \vec{B}\right)$$

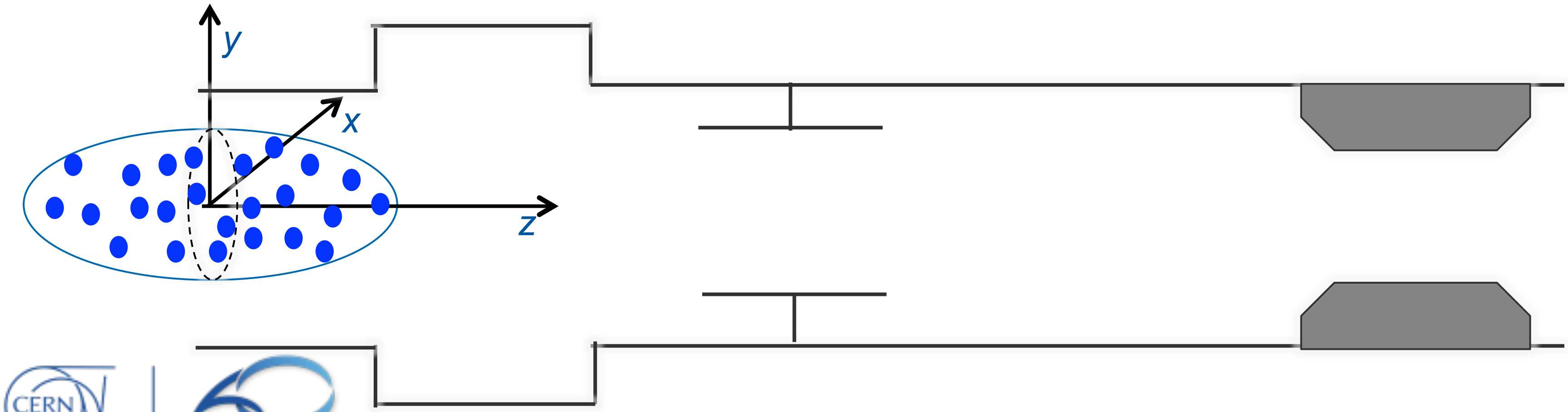
$$\begin{cases} \vec{E} = \vec{E}_{\rm ext} + \vec{E}(\psi_{\rm mp}) \\ \vec{B} = \vec{B}_{\rm ext} + \vec{B}(\psi_{\rm mp}) \end{cases}$$

Introduction to collective effects

- Modeling of collective effects due to self-induced EM fields
  - Single particle motion under the overall effect of externally applied fields (RF, magnets) and those created by the beam itself with the proper boundary conditions.

→ **Single particle dynamics not sufficient, need to describe a system of many particles**

- ✓ **Theory:** kinetic models based on distribution functions (Vlasov-Maxwell)
- ✓ **Simulation:** solve numerically the equations of motion of a set of macroparticles and use the EM fields of the macroparticle distribution
- ❑ **Direct space charge** refers to the EM fields created by the beam as if it was moving in open space,
- ❑ **Impedances** are used to describe EM interaction of beam with boundaries

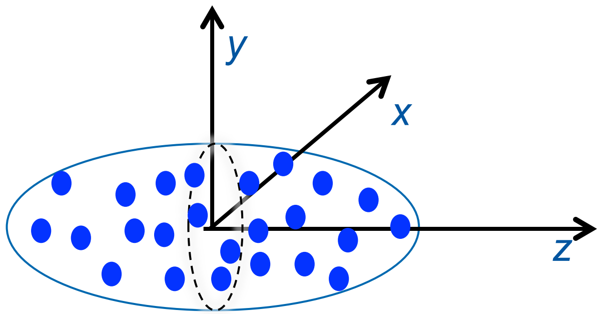


Introduction to collective effects

- Modeling of collective effects due to self-induced EM fields + Coulomb collisions
  - Single particle motion under the overall effect of externally applied fields (RF, magnets) and those created by the beam itself with the proper boundary conditions.

→ **Single particle dynamics not sufficient, need to describe a system of many particles**
  - ✓ **Theory:** kinetic models based on distribution functions (Vlasov-Maxwell)
  - ✓ **Simulation:** solve numerically the equations of motion of a set of macroparticles

  - **Probability of close encounters can be included through the appropriate models**



$$\frac{d\psi}{dt} = \left(\frac{\partial \psi}{\partial t}\right)_{\text{coll}} \quad \longleftrightarrow \quad \begin{cases} \vec{E} = \vec{E}_{\text{ext}} + \vec{E}(\psi) \\ \vec{B} = \vec{B}_{\text{ext}} + \vec{B}(\psi) \end{cases}$$

Vlasov-Fokker-Planck formalism

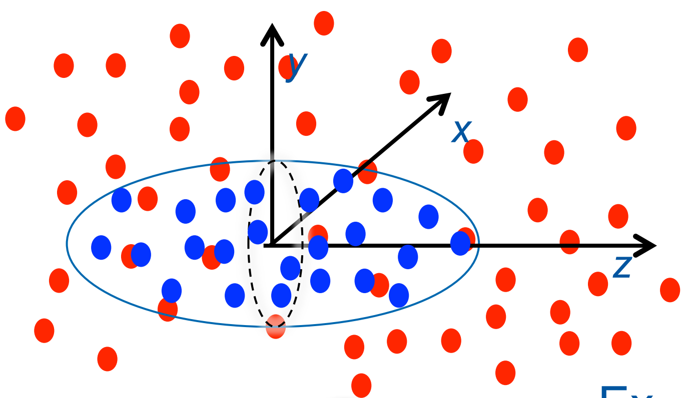
Introduction to collective effects

- Modeling of collective effects due to EM fields from another charge distribution
  - Single particle motion under the overall effect of externally applied fields (RF, magnets) and those created by the second "beam".

  → **Single particle dynamics not sufficient, need to describe evolution (and sometimes generation) of the other system of particles to derive its EM fields**
    - ✓ **Theory:** simplified models to include the effect of the second "beam"
    - ✓ **Simulation:** describe numerically the second "beam" and calculate its fields as driving terms in the equations of motion of the set of macroparticles representing the beam

$$\frac{d\vec{p}_{\mathrm{mp1,mp2}}}{dt} = q\left(\vec{E} + \vec{v}_{\mathrm{mp1,mp2}} \times \vec{B}\right)$$

$$\begin{cases} \vec{E} = \vec{E}_{\mathrm{ext}} + \vec{E}(\psi_{\mathrm{mp1}}, \psi_{\mathrm{mp2}}) \\ \vec{B} = \vec{B}_{\mathrm{ext}} + \vec{B}(\psi_{\mathrm{mp1}}, \psi_{\mathrm{mp2}}) \end{cases}$$



Ex. Beam going through an **electron cloud**

Introduction to collective effects

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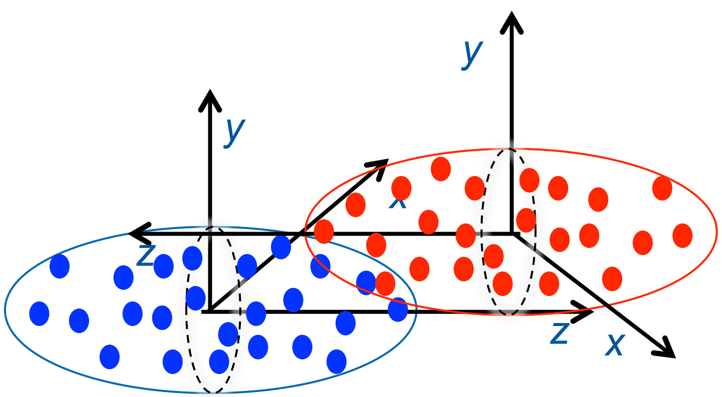

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Ex. Beam-beam effects in colliders

Outline of the course

1. Introductory concepts
2. Space charge
3. Wake fields and impedance
4. Instabilities – 2-particle model
5. Instabilities – kinetic theory
6. Two stream effects

+ Numerical methods
+ Experimental examples
+ Mitigation techniques

Additional topics interleaved within the above list

Outline

1. Introductory concepts
   - Collective effects
   - Transverse single particle dynamics including systems of many non-interacting particles
   - Longitudinal single particle dynamics including systems of many non-interacting particles
2. Space charge
   - Direct space charge (transverse)
   - Indirect space charge (transverse)
   - Longitudinal space charge

Outline

3. Wake fields and impedance
   - Wake fields and wake function
   - Definition of beam coupling impedance
   - Examples – resonators and resistive wall
   - Energy loss
   - Impedance model of a machine
4. Instabilities – few-particle model
   - Equations of motion
   - Longitudinal plane: Robinson instability
   - Transverse plane: rigid bunch instability, strong head-tail instability, head-tail instability

Outline

5. Instabilities – kinetic theory
    - Introduction to Vlasov equation and perturbation approach
    - Vlasov equation in the longitudinal plane
    - Vlasov equation in the transverse plane
    - Oscillation modes, shift with intensity, instability
6. Two stream effects
    - Electron cloud build up
    - Electron cloud induced beam instability
    - Ion trapping and fast ion instability

Outline

- Numerical methods
  - Basic models for macroparticle simulations: approaches, approximations, assumptions
  - Beam tracking with collective effects (PyHEADTAIL)
- Experimental examples
  - Real life instabilities, observations, implications
  - Beam-based measurements to determine impedances
  - Electron cloud and fast ion observations in machines
- Mitigation techniques
  - Impedance reduction, electron cloud suppression
  - Beam parameters, machine settings, Landau damping
  - Feedback systems