Instabilities Part I: Introduction – multiparticle systems, macroparticle models and wake functions

Giovanni Rumolo and Kevin Li

Outline

We will look conceptually into **collective effects** and their **impact on beams**. We will first introduce **multiparticle systems** and investigate **multiparticle effects**. This will be important to effectively describe collective effects. We will then introduce the concept of **wake fields** as one very important collective effect.

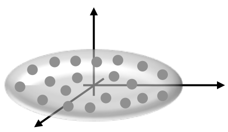
- Part 1: Introduction – multiparticle systems, macroparticle models and wake functions
  - Introduction to beam instabilities
  - Basic concepts
    - Particles and macroparticles – macroparticle distributions
    - Beam matching
    - Multiparticle effects – filamentation and decoherence

What are collective effects?

- We will study the dynamics of **charged particle beams** in a **particle accelerator environment**, taking into account the **beam self-induced electromagnetic fields**, i.e. not only the **impact of the machine onto the beam** but also the **impact of the beam onto the machine**.

What are collective effects?

- A charged particle beam is generally described as a **multiparticle system** via the **generalized coordinates** and **canonically conjugate momenta** of all of its particles – this makes up a distribution in the 6-dimensional beam phase space which can be described by a **particle distribution function**.
- Hence, we will study the **evolution of the beam phase space** (or particle distribution function)**:**



$$\frac{\partial}{\partial s}\boldsymbol{\psi}\left(x, x', y, y', z, \delta, s\right)$$

What are collective effects?

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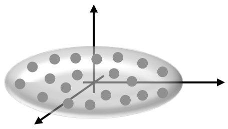
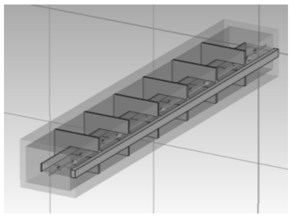
- Hence, we will study the **evolution of the beam phase space** (or particle distribution function)**:**
  - o Optics defined by the machine lattice provides the **external force fields** (magnets, electrostatic fields, RF fields), e.g. for guidance and focusing
  - o Collective effects add to this **distribution dependent force fields** (space charge, wake fields)





$$\frac{\partial}{\partial s}\psi\left(x,x',y,y',z,\delta,s\right)\propto f\left(F_{\text{extern}}+F_{\text{coll}}\left(\psi\right)\right)$$

What are collective effects?

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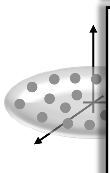
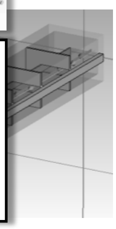


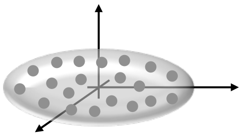


- For a **multiparticle system** this self-consistency equation becomes arbitrarily complex and practically **impossible to solve**
- Obtaining the **multiparticle dynamics** very often requires **computer simulation codes**

$$\frac{\partial}{\partial s}\psi\left(x,x',y,y',z,\delta,s\right)\propto f\left(F_{\text{extern}}+F_{\text{coll}}\left(\psi\right)\right)$$

What is a beam instability?

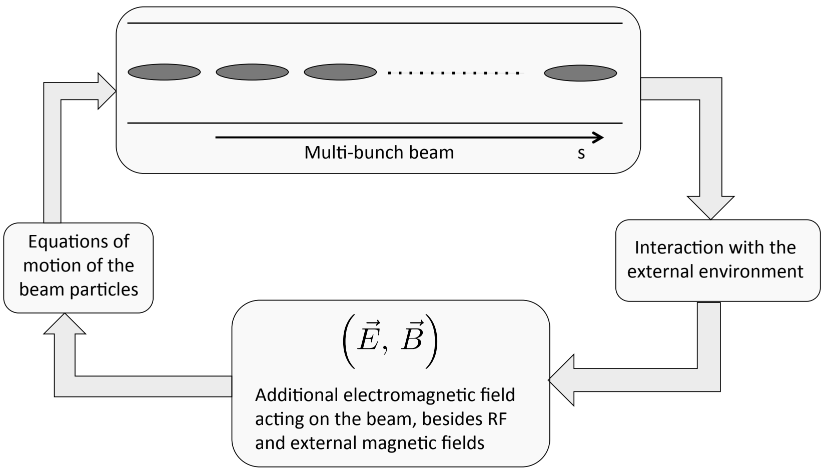
- A beam becomes unstable when a **moment of its distribution** exhibits an **exponential growth** (e.g. mean positions, standard deviations, etc.), resulting into beam loss or emittance growth!



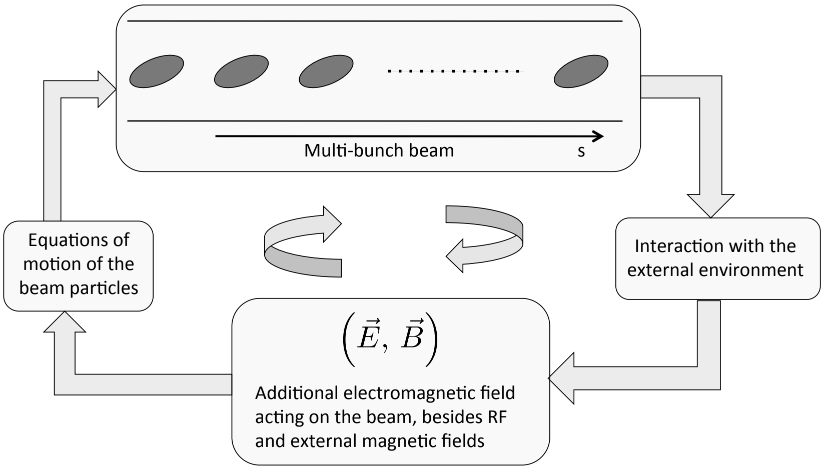
$$N = \int \psi\left(x, x', y, y', z, \delta\right)\, dx dx' dy dy' dz d\delta$$
$$\langle x \rangle = \frac{1}{N} \int x \cdot \psi\left(x, x', y, y', z, \delta\right)\, dx dx' dy dy' dz d\delta$$
$$\sigma_x^2 = \frac{1}{N} \int \left(x - \langle x \rangle\right)^2 \cdot \psi\left(x, x', y, y', z, \delta\right)\,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

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

The instability loop

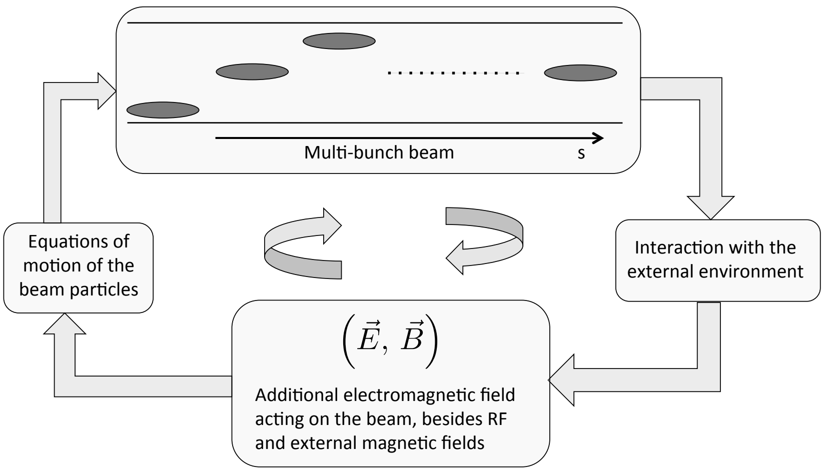


The instability loop



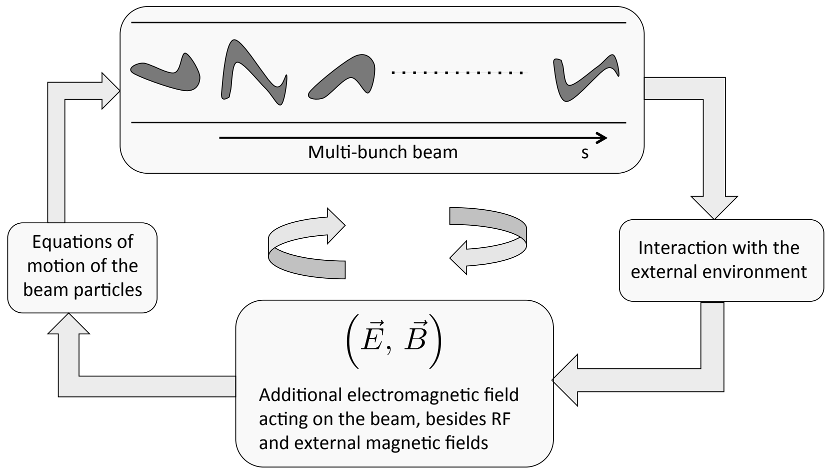
When the loop closes, either the beam will find a new stable equilibrium configuration …

The instability loop



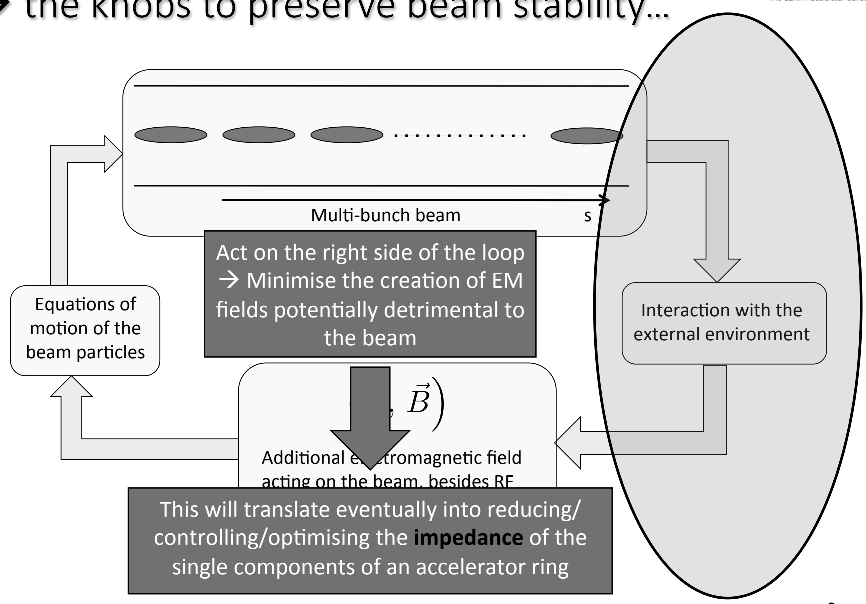
… or it might develop an instability along the bunch train …

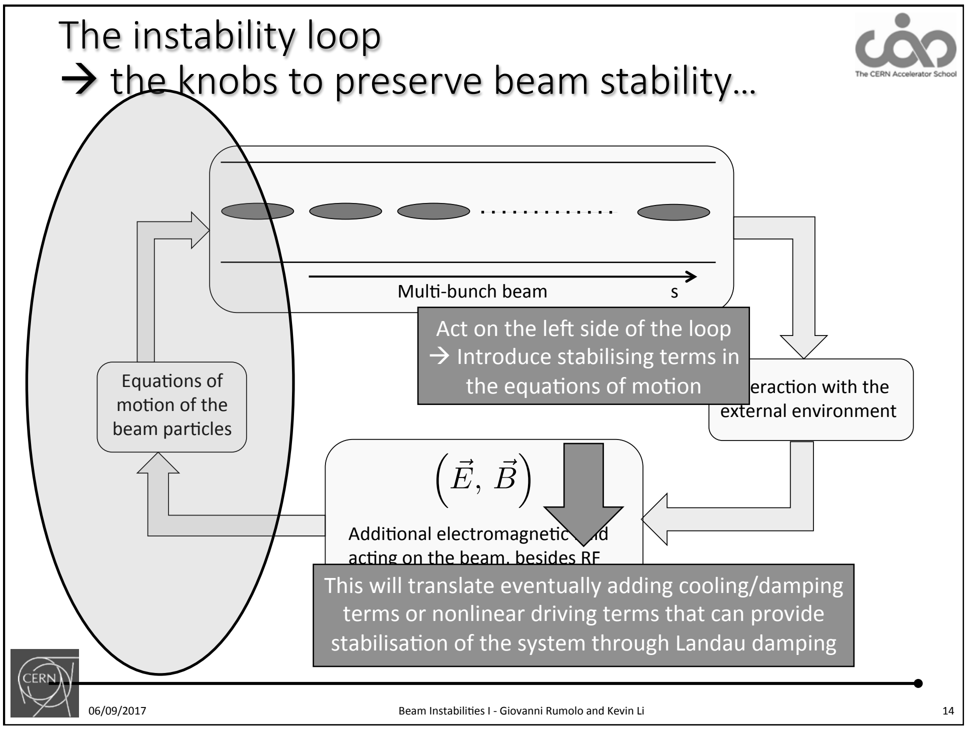
The instability loop



… or also an instability affecting different bunches independently of each other

The instability loop → the knobs to preserve beam stability…





The instability loop
→ the knobs to preserve beam stability…
The CERN Accelerator School
Multi-bunch beam
s
Act on the left side of the loop
→ Introduce stabilising terms in the equations of motion
eraction with the
external environment
Equations of motion of the beam particles
$\left(\vec{E}, \vec{B}\right)$
Additional electromagnetic
This will translate eventually adding cooling/damping terms or nonlinear driving terms that can provide stabilisation of the system through Landau damping
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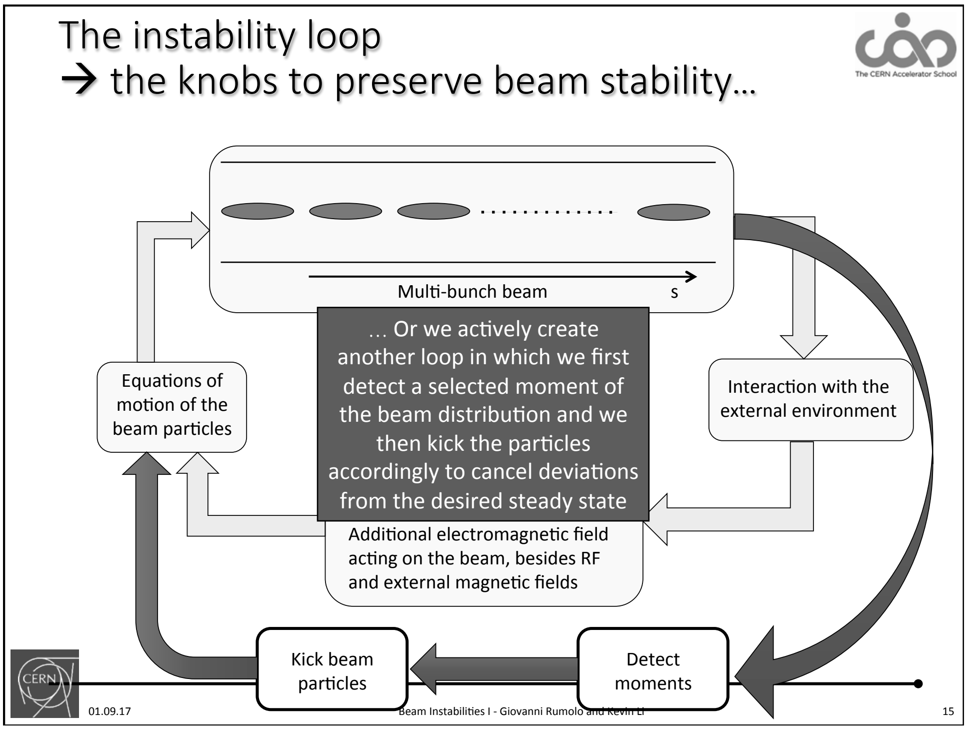

The instability loop
→ the knobs to preserve beam stability…
The CERN Accelerator School
Multi-bunch beam
s
… Or we actively create another loop in which we first detect a selected moment of the beam distribution and we then kick the particles accordingly to cancel deviations from the desired steady state
Equations of motion of the beam particles
Interaction with the external environment
Additional electromagnetic field acting on the beam, besides RF and external magnetic fields
Kick beam particles
Detect moments
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Formal description of a beam instability

- Formally, instead of investigating the full system of equations for a multiparticle system, we typically instead describe the latter by a **single particle distribution function**:

$$\boldsymbol{\psi} = \boldsymbol{\psi}(x, x', y, y', z, \delta, s)$$

where

$$d\boldsymbol{N}(s) = \boldsymbol{\psi}(x, x', y, y', z, \delta, s)\, dx dx' dy dy' dz d\delta$$

- The accelerator environment constitutes a **Hamiltonian system** for which:

$$\frac{\partial x}{\partial s} = \frac{\partial H}{\partial x'}\,, \quad \frac{\partial x'}{\partial s} = -\frac{\partial H}{\partial x}\,, \quad \frac{d}{ds}\boldsymbol{\psi} = 0$$

Vlasov equation

- It follows for the evolution of this **particle distribution function**:

$$\begin{aligned} \frac{d}{ds}\boldsymbol{\psi} &= \frac{\partial \boldsymbol{\psi}}{\partial x}\frac{\partial x}{\partial s} + \frac{\partial \boldsymbol{\psi}}{\partial x}\frac{\partial x'}{\partial s} + \frac{\partial}{\partial s}\boldsymbol{\psi} \\ &= \underbrace{\frac{\partial \boldsymbol{\psi}}{\partial x}\frac{\partial H}{\partial x'} - \frac{\partial \boldsymbol{\psi}}{\partial x}\frac{\partial H}{\partial x}}_{[\boldsymbol{\psi}, H]} + \frac{\partial}{\partial s}\boldsymbol{\psi} = 0 \end{aligned}$$

Poisson bracket

Formal description of a beam instability

- The evolution of a **multiparticle system** is given by the evolution of its **particle distribution function**

$$\frac{\partial}{\partial s}\boldsymbol{\psi} = [\boldsymbol{H}, \boldsymbol{\psi}]$$

- With the Hamiltonian composed of **an external** and **a collective part**, and the particle distribution function decomposed into **an unperturbed part** and **a small perturbation** one can write

$$\frac{\partial}{\partial s}\boldsymbol{\psi} = [\boldsymbol{H_0} + \boldsymbol{H_1}, \boldsymbol{\psi_0} + \boldsymbol{\psi_1}]$$

- This becomes to **first order**

$$\frac{\partial}{\partial s}\boldsymbol{\psi_1} = \underbrace{[\boldsymbol{H_0}, \boldsymbol{\psi_1}] + [\boldsymbol{H_1}(\boldsymbol{\psi_0} + \boldsymbol{\psi_1}), \boldsymbol{\psi_0}]}_{\text{Linearization in } \boldsymbol{\psi_1}:\quad \dots \propto \boxed{\hat{\boldsymbol{\Lambda}}\boldsymbol{\psi_1} = -i\frac{\Omega}{\beta c}\boldsymbol{\psi_1}}}$$

$$\Longrightarrow \; \boldsymbol{\psi_1}(s) = \exp\left(-i\frac{\Omega}{\beta c}s\right)\boldsymbol{\psi_1}(0)$$

We are looking for the EV of the evolution
→ **becomes an EV problem**!

Formal description of a beam instability

- The evolution of a **multiparticle system** is given by the evolution of its **particle distribution function**

$$\frac{\partial}{\partial s}\psi = [\boldsymbol{H}, \psi]$$

We call these distinct eigenvalues ψ_1 **a bunch or a beam mode**.

The mode and thus for example also an instability is fully characterized by a single number:

the complex tune shift Ω

$$\text{Linearization in } \boldsymbol{\psi_1}: \quad \ldots \propto \boxed{\hat{\boldsymbol{\Lambda}}\boldsymbol{\psi_1} = -i\frac{\Omega}{\beta c}\boldsymbol{\psi_1}}$$

$$\Longrightarrow \boldsymbol{\psi_1}(s) = \exp\left(-i\frac{\boxed{\Omega}}{\beta c}s\right)\boldsymbol{\psi_1}(0)$$

We are looking for the EV of the evolution
→ **becomes an EV problem**!

Formal description of a beam instability

- The evolution of a **multiparticle system** is given by the evolution of its **particle distribution function**

$$\frac{\partial}{\partial s}\psi = [\boldsymbol{H}, \psi]$$

Remark:

- The stationary distribution $\boldsymbol{\psi_0}$ is the distribution where

$$\frac{\partial}{\partial s}\boldsymbol{\psi_0} = [\boldsymbol{H_0}, \boldsymbol{\psi_0}] = 0$$

- In particular, a distribution is always stationary if

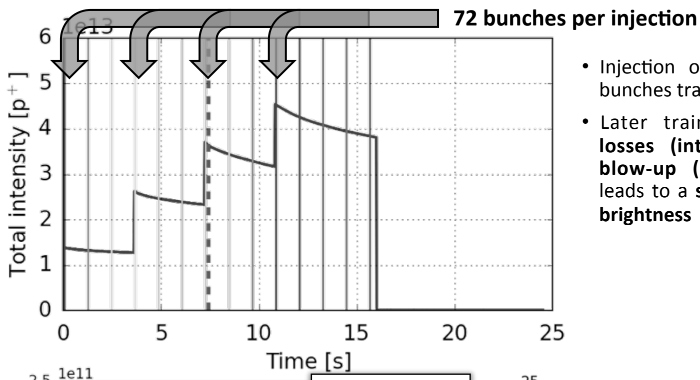
$$\boldsymbol{\psi_0} = \boldsymbol{\psi_0}(\boldsymbol{H_0}), \quad \text{as} \quad [\boldsymbol{H_0}, \boldsymbol{\psi_0}(\boldsymbol{H_0})] = 0$$

Solving for or finding the stationary solution for a given H_0 (which in fact represents the machine ‚potential') will be later referred to as **matching**.

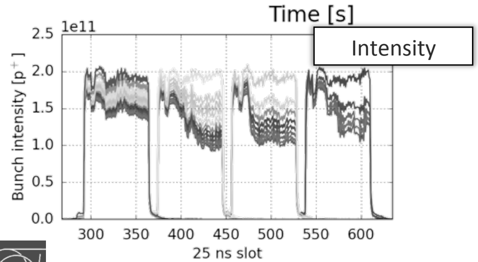
Why worry about beam instabilities?

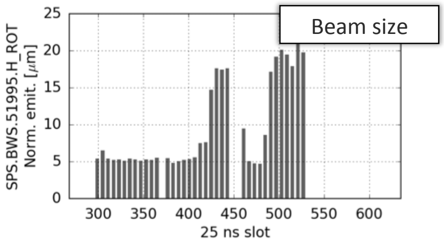
- Why study beam instabilities?
  - The onset of a beam instability usually determines the maximum beam intensity that a machine can store/accelerate (performance limitation)
  - Understanding the type of instability limiting the performance, and its underlying mechanism, is essential because it:
    - Allows identifying the source and possible measures to mitigate/suppress the effect
    - Allows dimensioning an active feedback system to prevent the instability

Coupled bunch instability in the SPS

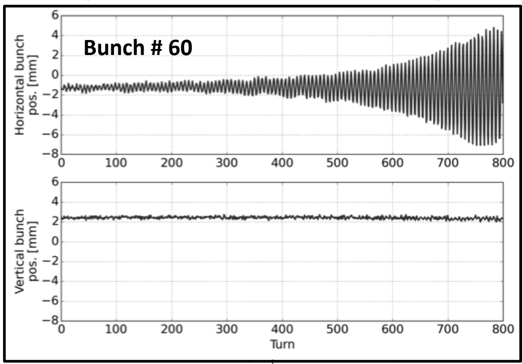


- Injection of 4 batches of 72 bunches trains into the SPS
- Later trains feature **strong losses (intensity)** and **large blow-up (emittance)** – this leads to a **strong loss of beam brightness**

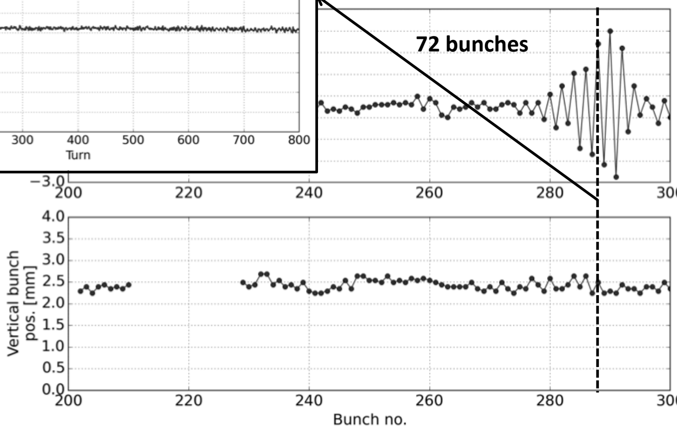




Coupled bunch instability in the SPS



- Injection of 4 batches of 72 bunch trains into the SPS
- A closer look into one train exhibits **strong coherent coupled bunch oscillations**



Coupled bunch instability in the SPS

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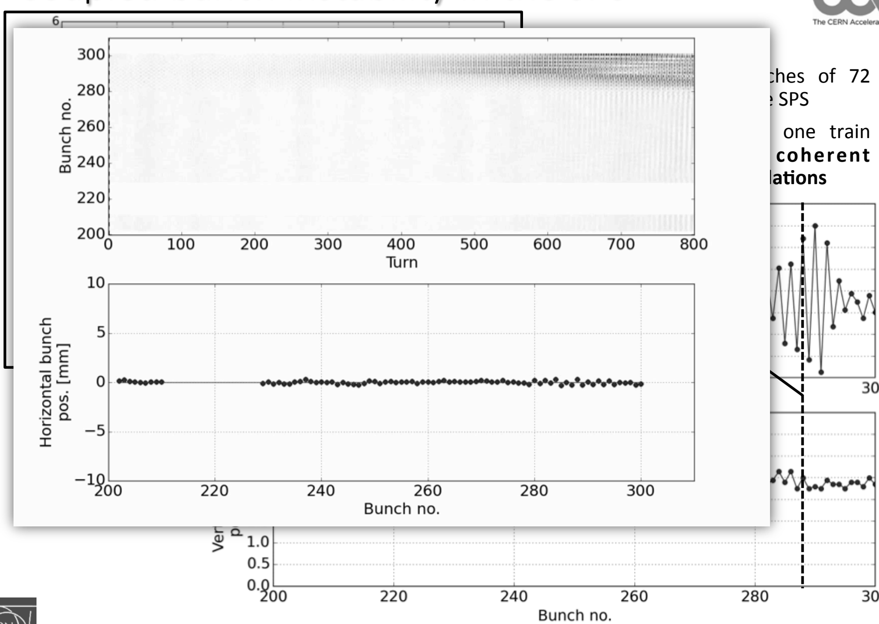
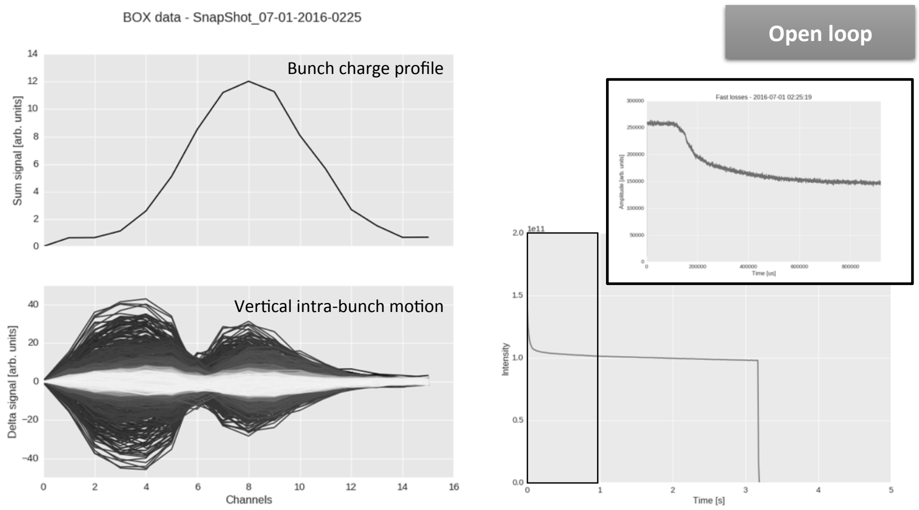
one train
coherent
lations



Single bunch instability in the SPS

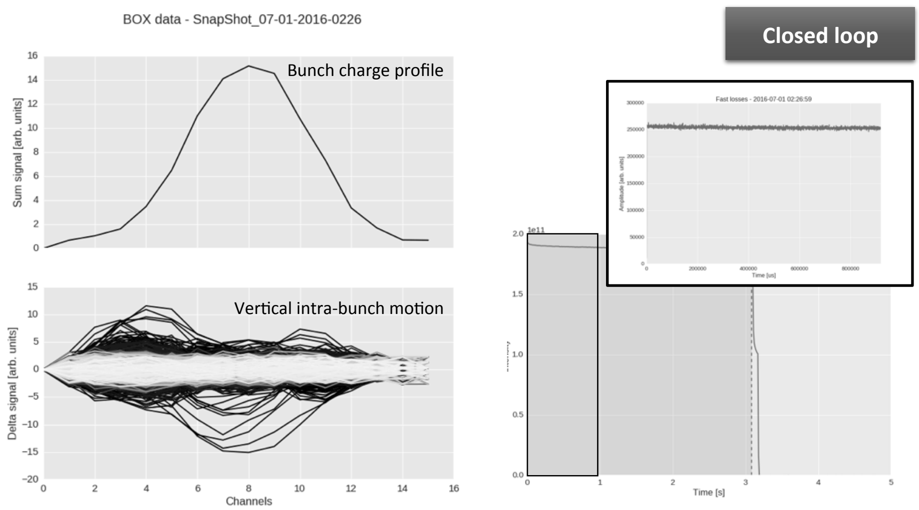
Open loop



- Loss of more than 30% of the bunch intensity due to a **slow transverse mode coupling instability (TMCI)**.

Single bunch instability in the SPS

Closed loop



- Loss of more than 30% of the bunch intensity due to a **slow transverse mode coupling instability (TMCI)** → can be mitigated by a **wideband feedback system**.

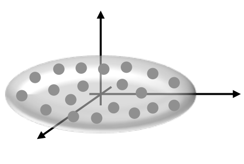
Signpost

- We have seen the difference between **external forces** and **self-induced forces** which lead to **collective effects**.
- We have seen schematically how these collective effects can induce **coherent beam instabilities and some knobs to avoid them**.
- We have seen **examples of beam instabilities** and have understood how they can lead to serious **performance limitations**.

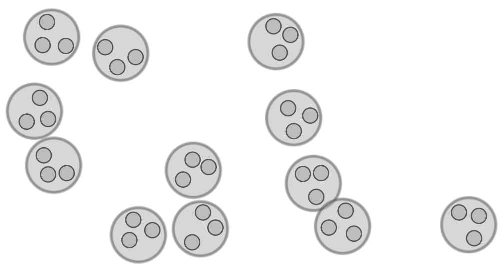
- Part 1: Introduction – multiparticle systems, macroparticle models and wake functions
  - Introduction to beam instabilities
  - Basic concepts
    - Particles and macroparticles – macroparticle distributions
    - Beam matching
    - Multiparticle effects – filamentation and decoherence

The particle description

- As seen earlier, and especially for the analytical treatment, we can represent a charged particle beam via a **particle distribution function**.
- In computer simulations, a charged particle beam is still represented as a multiparticle system. However, to be **compatible with computational resources**, we need to rely on **macroparticle models**.
- A **macroparticle** is a numerical **representation** of a **cluster of neighbouring physical particles**.
- Thus, instead of solving the system for the **N (~10^{11})** physical particles one can significantly **reduce the number of degrees of freedom** to **N_{MP} (~10^6)**. At the same time one must be aware that this **increases of the granularity** of the system which gives rise to numerical noise.



$$\Psi\left(x, x', y, y', z, \delta\right)$$



Macroparticle representation of the beam

- Macroparticle models permit a **seamless mapping** of realistic systems into a **computational environment** – they are fairly easy to implement

Beam:

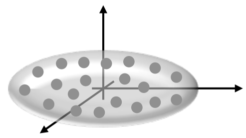
$$\begin{pmatrix} x_i \\ x'_i \end{pmatrix} \quad \begin{pmatrix} q_i \\ m_i \end{pmatrix}, \quad i = 1, \ldots, N$$

Macroparticlenumber

$$\begin{pmatrix} y_i \\ y'_i \end{pmatrix}$$

Canonically conjugate coordinates and momenta

$$\begin{pmatrix} z_i \\ \delta_i \end{pmatrix}$$



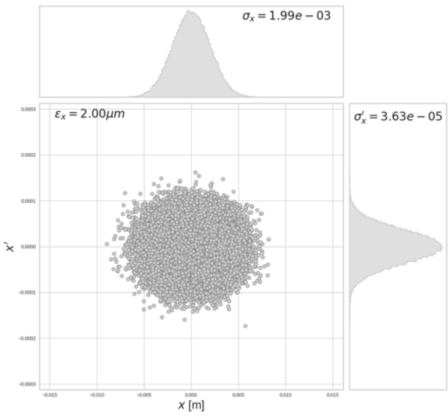
$$\Psi\left(x, x', y, y', z, \delta\right)$$

```
In [6]: df = pd.DataFrame(bunch.get_coords_n_momenta_dict())
        df
```

Out[6]:

	dp	x	xp	y	yp	z
0	0.001590	0.000566	-2.285393e-05	-0.001980	4.283152e-06	0.353427
1	0.001978	0.000370	1.954404e-05	-0.000359	5.543904e-05	0.159670
2	0.003492	-0.000829	-2.773707e-05	0.000291	6.627340e-05	-0.251489
3	0.002195	-0.001668	-2.317633e-05	0.001878	-1.870926e-05	-0.038597
4	0.000572	0.000990	5.493907e-05	0.000152	-1.951051e-05	0.492968
5	-0.000418	0.001088	4.778027e-05	0.003320	-7.716856e-06	0.415582
6	-0.000114	-0.000194	1.065400e-05	0.001798	-4.984276e-07	-0.349064
7	0.001100	-0.001257	-6.873217e-05	-0.002374	5.657645e-06	-0.023157
8	0.002706	0.005351	-1.867898e-07	-0.000765	3.012523e-05	-0.291095
9	0.003508	0.000499	1.865768e-05	-0.001032	-5.363820e-05	0.211726
10	-0.001711	-0.003168	4.372560e-05	-0.001933	-2.151020e-05	-0.145358
11	-0.002150	-0.000565	-1.853825e-05	-0.003895	-6.192450e-06	0.072499
12	0.002059	0.003453	-3.808703e-05	0.000118	3.179588e-05	-0.001816
13	0.002709	0.000241	-3.457535e-05	0.000474	5.057865e-05	-0.005464
14	-0.001593	0.000711	-1.667091e-05	-0.002523	-3.804168e-05	-0.089881
15	-0.000830	-0.000393	-7.473946e-05	-0.003633	[illegible]	[illegible]
16	-0.001743	-0.003034	[illegible]	[illegible]	[illegible]	[illegible]
17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Macroparticle representation of the beam

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2	0.003492	-0.000829	-2.773707e-05	0.000291	[illegible]
3	0.002195	-0.001668	-2.317633e-05	0.001878	[illegible]

- Initial conditions of the beam/particles

Profile	Size	Matching
Gaussian	Emittance	Optics
Parabolic		
Flat		
…		

- We use **random number generators** to obtain **random distributions of coordinates and momenta**
- Example transverse Gaussian beam in the SPS with normalized emittance of 2 um (0.35 eVs longitudinal)

$$\varepsilon_\perp = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$
$$= \beta\gamma\sigma_x\sigma_{x'}$$

$$\varepsilon_\parallel = 4\pi\sigma_z\sigma_\delta\frac{p_0}{e}$$

Signpost

- We have learned about the **particle description** of a beam.
- We have seen **macroparticles** and **macroparticle models**.
- We have seen how **macroparticle models** are **mapped and represented in a computational environment**.

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Beam matching

- As seen earlier, given a particle distribution function and a machine (described by a Hamiltonian H) the stationary solution is given by:

$$\frac{\partial}{\partial s}\boldsymbol{\psi} = [\boldsymbol{H}, \boldsymbol{\psi}] = 0$$

and can be constructed via matching:

- In real life, an injected beam ought to be **matched to the machine** for best performance.
- Given a **particle distribution function** and a **machine optics** locally described by a Hamiltonian we ensure matching by targeting for:

Beam Matching **Machine**

$\psi \rightarrow$ $\psi = \psi(H)$ $\leftarrow H$

Matching examples

We take the example of Gaussian distribution functions

$$\psi(H) = \exp\left(\frac{H}{H_0}\right)$$

- Betatron motion

$$H = \frac{1}{2}x'^2 + \left(\frac{Q_x}{R}\right)^2 x^2$$

$$H_0 = \sigma_{x'}^2 = \left(\frac{Q_x}{R}\right)^2 \sigma_x^2 \implies \boxed{\frac{\sigma_x}{\sigma_{x'}} = \frac{R}{Q_x} = \beta_x}$$

- Synchrotron motion - linear

$$H(z,\delta) = -\frac{1}{2}\eta\beta c\,\delta^2 + \frac{eVh}{4\pi R^2 p_0} z^2$$

$$H_0 = \eta\beta c\,\sigma_\delta^2 = \frac{eVh}{2\pi R^2 p_0}\sigma_z^2 \implies \boxed{\frac{\sigma_z}{\sigma_\delta} = R\eta\sqrt{\frac{2\pi\beta^2 E_0}{eV\eta h}} = \frac{R\eta}{Q_s}\sigma_\delta = \beta_z}$$

Matching examples

We take the example of Gaussian distribution functions

$$\psi(H) = \exp\left(\frac{H}{H_0}\right)$$

In reality the synchrotron motion is described by the Hamiltonian:

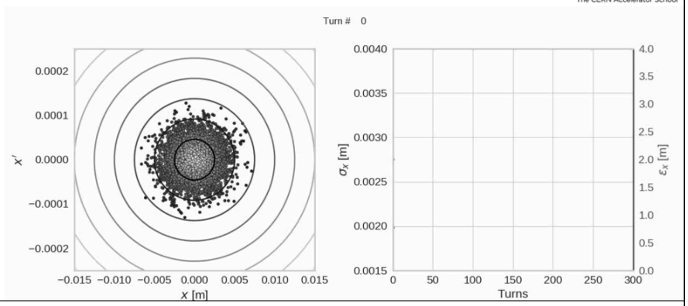
$$H(z,\delta) = -\frac{1}{2}\eta\beta c\,\delta^2 + \frac{eV}{2\pi h p_0}\left(\cos\left(\frac{hz}{R}\right) - \cos\left(\frac{hz_c}{R}\right) + \frac{\Delta E}{eV}\left(\frac{hz}{R} - \frac{hz_c}{R}\right)\right)$$

This leads to **nonlinear equations** and the matching procedure becomes more involved.

Matching illustration – matched beams

- Betatron motion
  - **linear**

$$\frac{\sigma_x}{\sigma_{x'}} = \beta_x$$

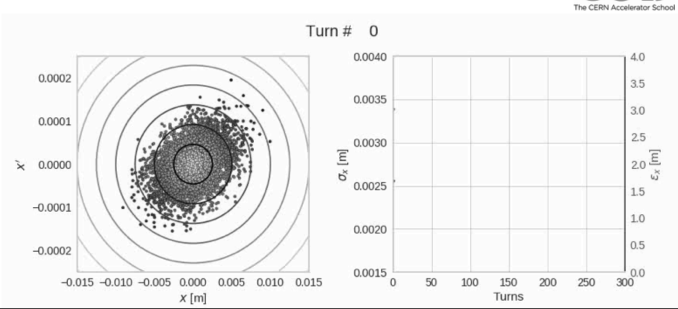


Matched beams **maintain their beam moments** and their shape in phase space

Matching illustration – mismatched beams

- Betatron motion
  - **linear**

$$\frac{\sigma_x}{\sigma_{x'}} = \beta_x$$

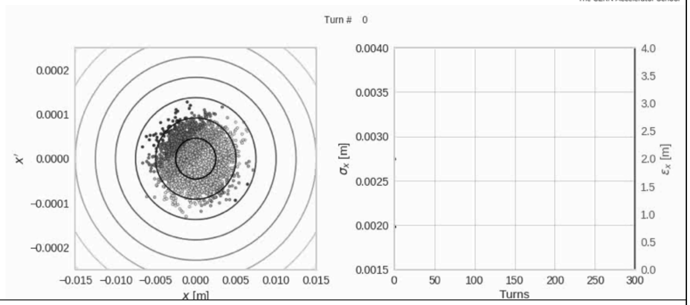


Mismatched beams show **oscillations in their beam moments** and may **change their shape due to filamentation**

Matching illustration – linear vs. nonlinear

- Betatron motion – **linear**

$$\frac{\sigma_x}{\sigma_{x'}} = \beta_x$$



Nonlinearities lead to **detuning with amplitude**. This is visible as the **characteristic spiraling** of larger amplitude particles.

Signpost

- We have learned about the **meaning of matching** a beam to the machine optics.
- We have seen how to **formally match a beam** to a given description of a machine.
- We have seen **examples of matched and mismatched beams** and have seen the difference between **linear and non-linear motion**.

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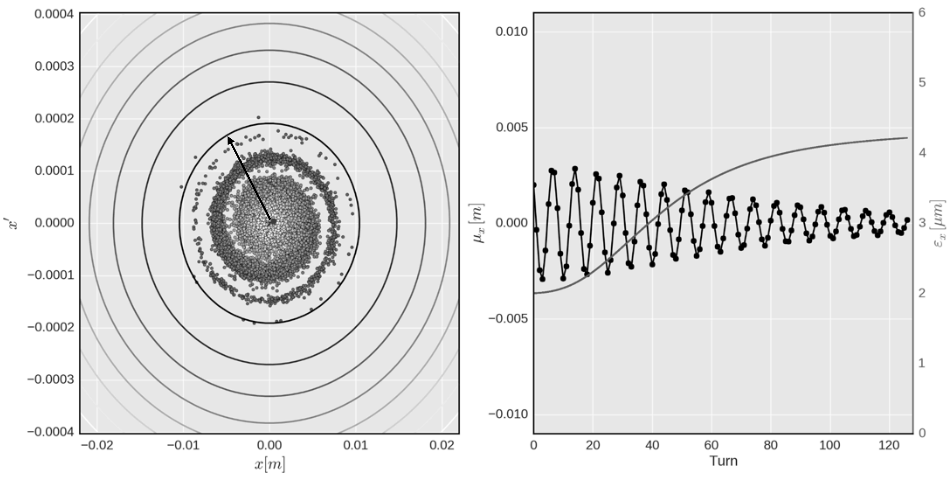
Sources and impact of transverse nonlinearities

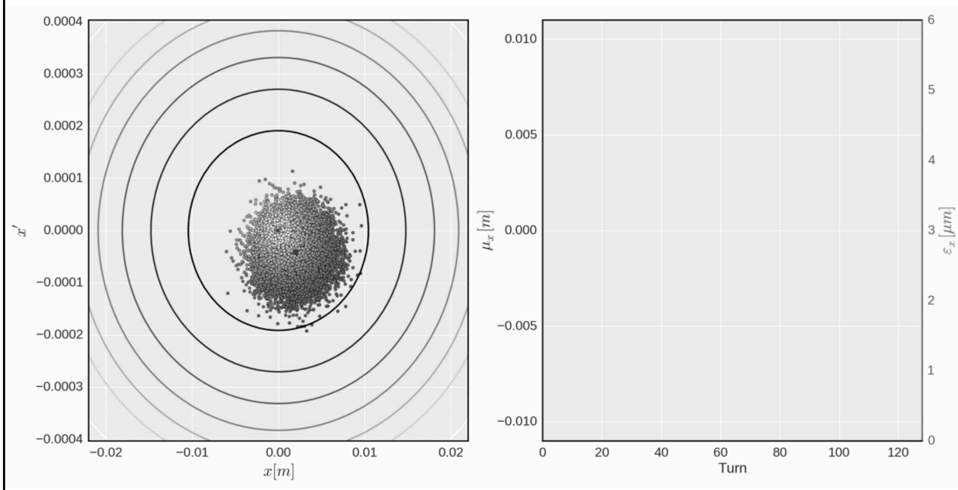
- We have learned or we may know from operational experience that there are a set of **crucial machine parameters to influence beam stability** – among them **chromaticity and amplitude detuning**
- Chromaticity
  - Controlled with sextupoles – provides **chromatic shift** of bunch spectrum wrt. impedance
  - Changes interaction of beam with impedance
  - Damping or excitation of **headtail modes**
- Amplitude detuning
  - Controlled with octupoles – provides (incoherent) **tune spread**
  - Leads to absorption of coherent power into the incoherent spectrum → **Landau damping**
-

model – fortunately, this is pretty simple!

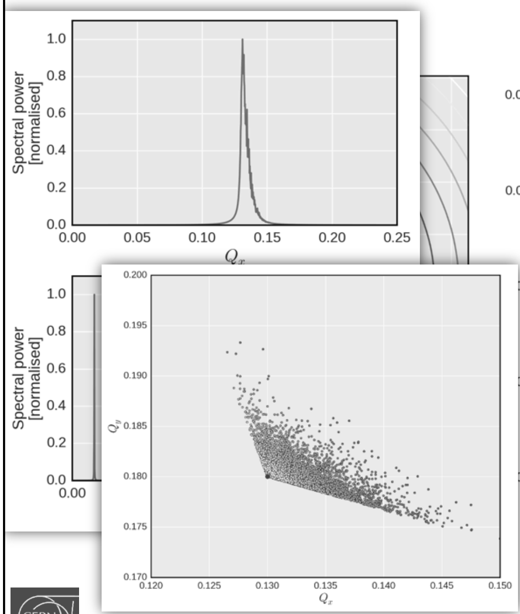
Filamentation and decoherence

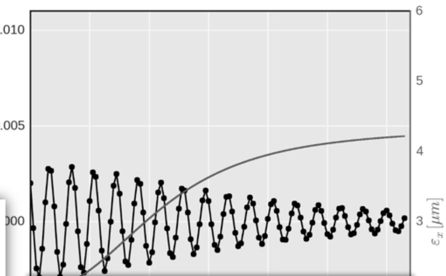


Example: filamentation as result of detuning



Example: filamentation as result of detuning





- Taking an **FFT of the centroid motion** (black curve) **reveals the tune** – interestingly there **is a spread**
- In the simulation we have access to the trajectory of **each individual macroparticle** – we can equally perform an **FFT of every macroparticle** and plot the horizontal vs. vertical tune to obtain the **tune footprint**

Signpost

- Source for transverse nonlinearities are **chromaticity** and **detuning with amplitude** from octupoles, for example.
- Transverse nonlinearities can lead to **decoherence** and **emittance blow-up**.
- The effects seen so far are **chacteristics for multiparticle systems** but are **not collective effects**.

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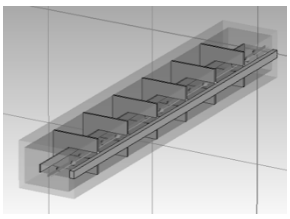
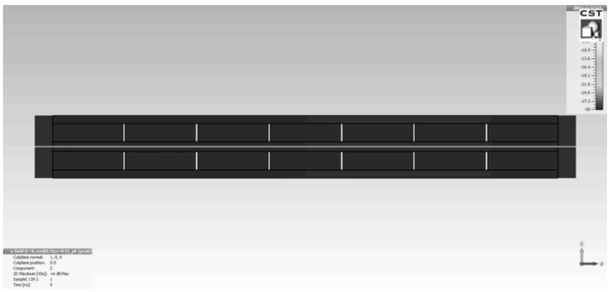
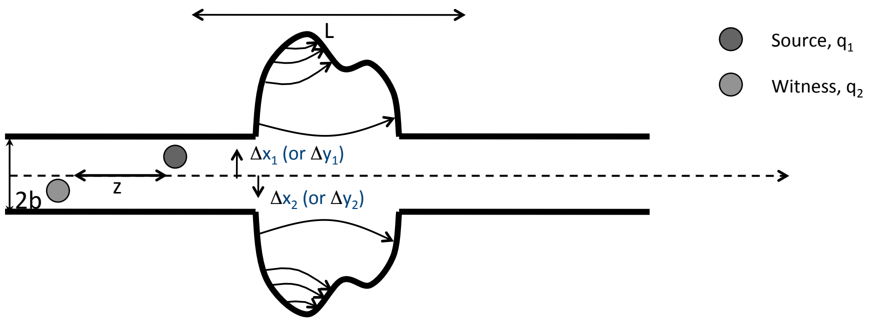
Wakefields as sources of collective effects





- The **wake function** is the **electromagnetic response** of an object to a charge pulse. It is an intrinsic property of any such object.
- The wake function **couples two charge distributions** as a function of the distance between them.
- The response depends on the boundary conditions and can occur e.g. due to **finite conductivity** (resistive wall) or more or less sudden **changes in the geometry** (e.g. resonator) of a structure.

Wake functions in general



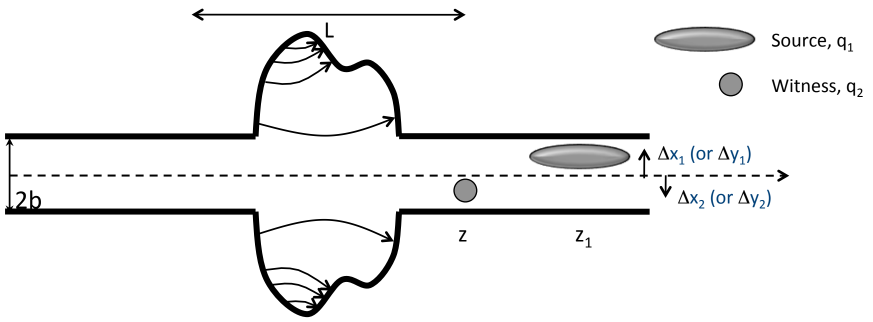
Definition as the **integrated force** associated to a change in energy:

- In general, for two point-like particles, we have

$$\Delta E_2 = \int F(x_1, x_2, z, s)\, ds = -q_1 q_2\, \boldsymbol{w(x_1, x_2, z)}$$

w is typically expanded in the transverse offsets of source and witness particles. This yields the different types of wake fields (dipole, quadrupole, coupling wakes)

Wake potential for a distribution of particles



Definition as the **integrated force** associated to a change in energy:

- For an extended particle distribution this becomes

$$\Delta E_2(z) \propto \int \boxed{\lambda_1(x_1, z_1)}\, \boldsymbol{w(x_1, x_2, z - z_1)}\, dx_1 dz_1$$

Forces become dependent on the **particle distribution function**

Wake fields – impact on the equations of motion

$$\Delta E_2(z) \propto \int \lambda_1(x_1, z_1)\, \boldsymbol{w(x_1, x_2, z - z_1)}\, dx_1 dz_1$$

- We include the impact of wake field into the standard Hamiltonian for linear betatron (or synchrotron motion):

$$H = \frac{1}{2}x' + \frac{1}{2}\left(\frac{Q_x}{R}\right)^2 x^2 + \frac{e^2}{\beta^2 EC}\int \lambda_1(x_1, z_1)\, w(x_1, x, z - z_1)\, dx_1 dz_1 dx$$

- The equations of motion become:

$$x'' + \left(\frac{Q_x}{R}\right)^2 x + \frac{e^2}{\beta^2 EC}\int \boxed{\lambda_1(x_1, z_1)\, w(x_1, x, z - z_1)}\, dx_1 dz_1 = 0$$

The presence of wake fields adds an **additional excitation** which depends on

1. The moments of the beam distribution
2. The shape and the order of the wake function

How are wakes and impedances computed?

- **Analytical or semi-analytical** approach, when geometry is simple (or simplified)
  - Solve Maxwell's equations with the correct source terms, geometries and boundary conditions up to an advanced stage (e.g. resistive wall for axisymmetric chambers)
  - Find closed expressions or execute the last steps numerically to derive wakes and impedances
- **Numerical approach**
  - Different codes have been developed over the years to solve numerically Maxwell's equations in arbitrarily complicated structures
  - Examples are CST Studio Suite (Particle Studio, Microwave Studio), ABCI, GdFidL, HFSS, ECHO2(3)D. Exhaustive list can be found from the program of the ICFA mini-Workshop on "Electromagnetic wake fields and impedances in particle accelerators", Erice, Sicily, 23-28 April, 2014
- **Bench measurements** based on transmission/reflection measurements with stretched wires
  - Seldom used independently to assess impedances, usefulness mainly lies in that they can be used for validating 3D EM models for simulations

Signpost

- We have learned about the concept of **particles**, **distributions** and **macroparticles** as well as some **peculiarities of multiparticle dynamics** in accelerators, decoherence, filamentation.
- We have learned about the basic **concept of wake fields** and how these can be characterized as a **collective effect** in that they depend on the particle distribution.
- We now have a basic understanding of multiparticle systems and wakefields and are now ready to look at the **impact of these** in the longitudinal and transverse planes.

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End part 1