Beam diagnostics

for particle accelerators

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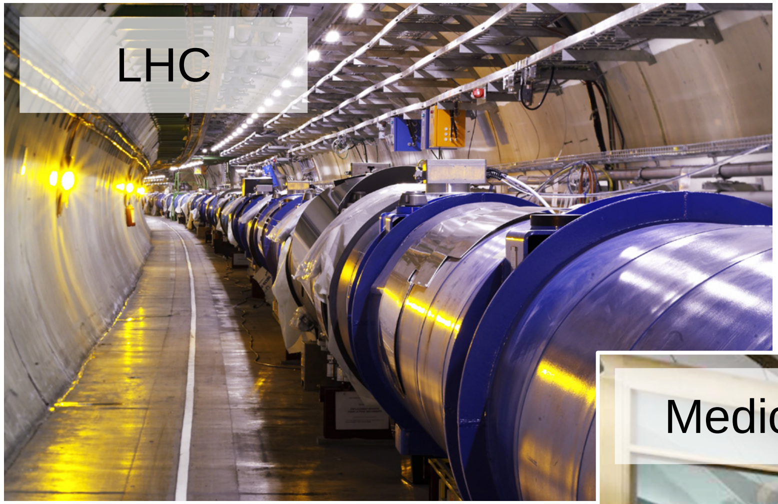
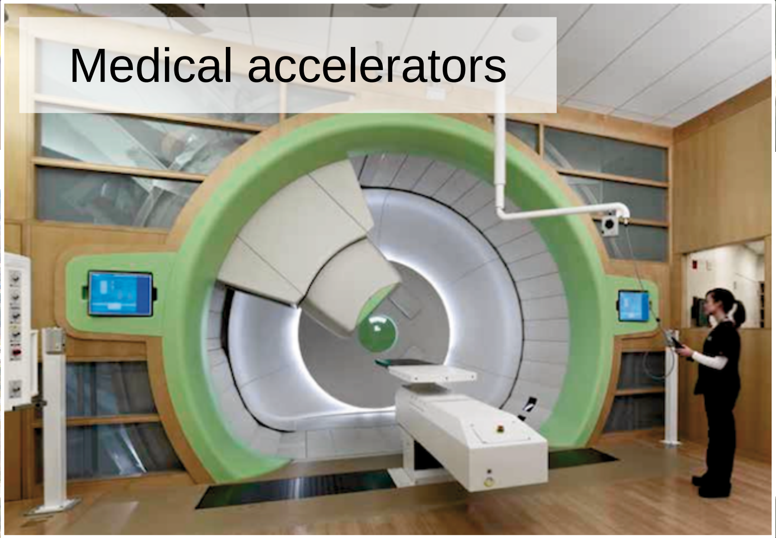
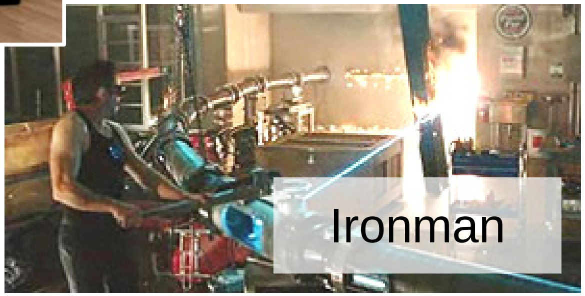
Outline

- Why?
  - Why do we need it?
- What?
  - What types of beam diagnostics?
- How?
  - Which methods do we use to diagnose the beam?
- Where?
  - Where do we place our diagnostics?

Why do we need beam diagnostics?

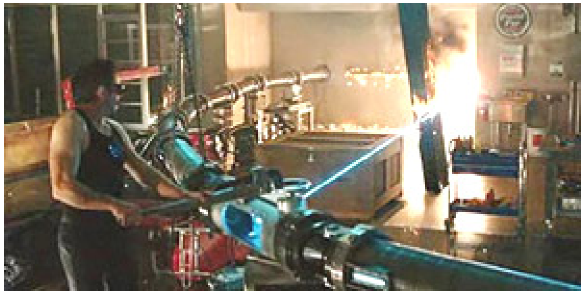






Why do we need beam diagnostics?

- Accelerators have a function:
  - Produce radiation, neutrons, etc
  - Produce exotic particles through beam-beam or beam-target collisions
  - Irradiate cancer tumors, food, etc
- We need to know that we do this in the desired way:
  - Optimizing:
    - Optimize radiated light (intensity, wavelength, geometric precision, stability....)
    - Maximize number of particles produced (luminosity)
  - SAFETY:
    - Protect people
    - Protect target
    - Protect machinery (protect the accelerator from itself)



Iron Man IS safety.

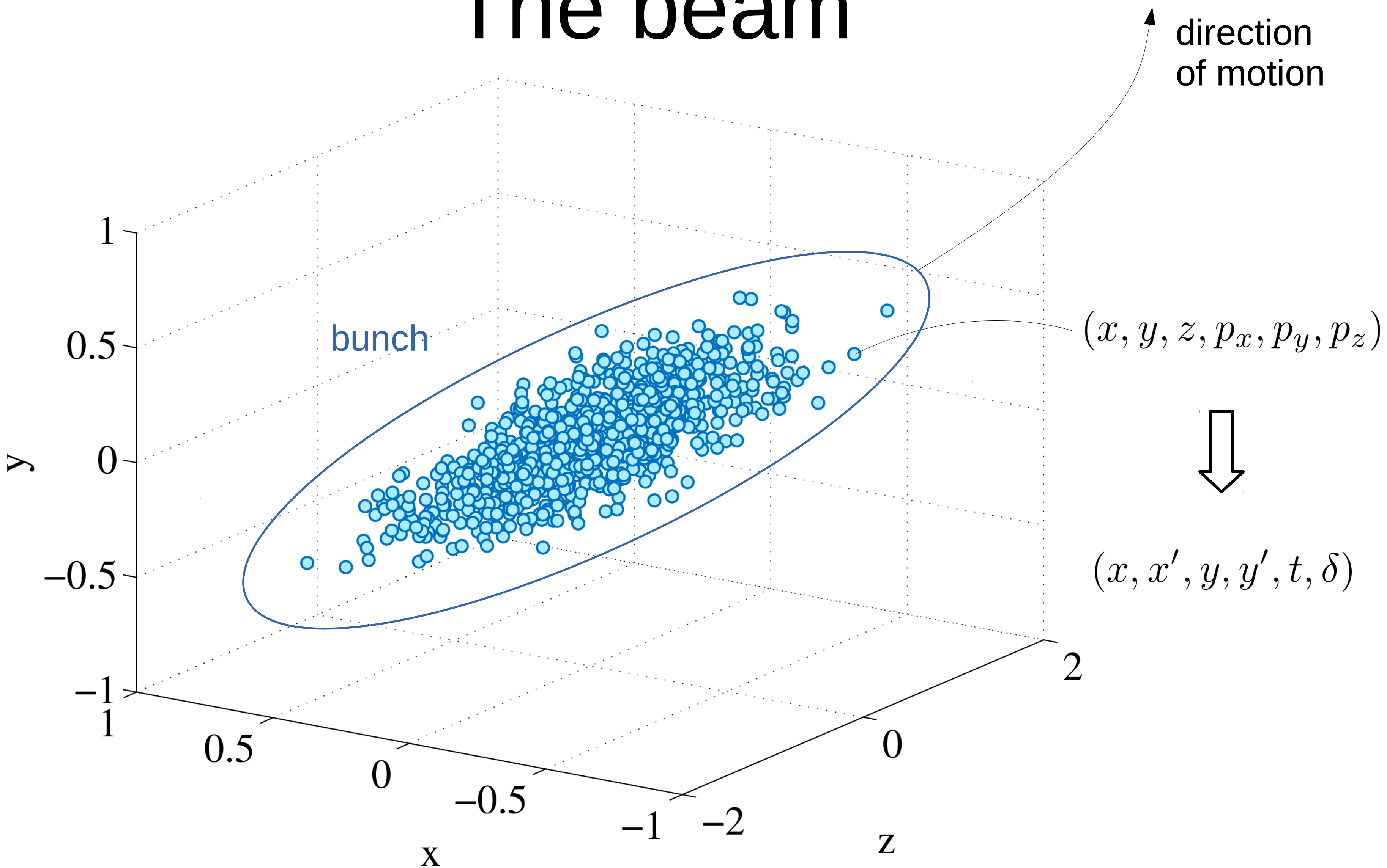
- The beam is small, sometimes dangerous and we cannot directly “see“ it.
  - We need detectors, equipment with the task to monitor all the properties of a particle beam that affects the operation of the accelerator.

Diagnostics or instrumentation?

- Sometimes we use ***instrumentation*** to refer to the detectors or instruments that measure or monitor beam properties while ***diagnostics*** is the method itself.
- Note that some parameters in accelerator physics is a property of the accelerator lattice (dispersion, chromaticity)
- Other are properties of the beam (energy, emittance, bunch length ?)
- Most of them are a combined effect of the whole machine and its operation.

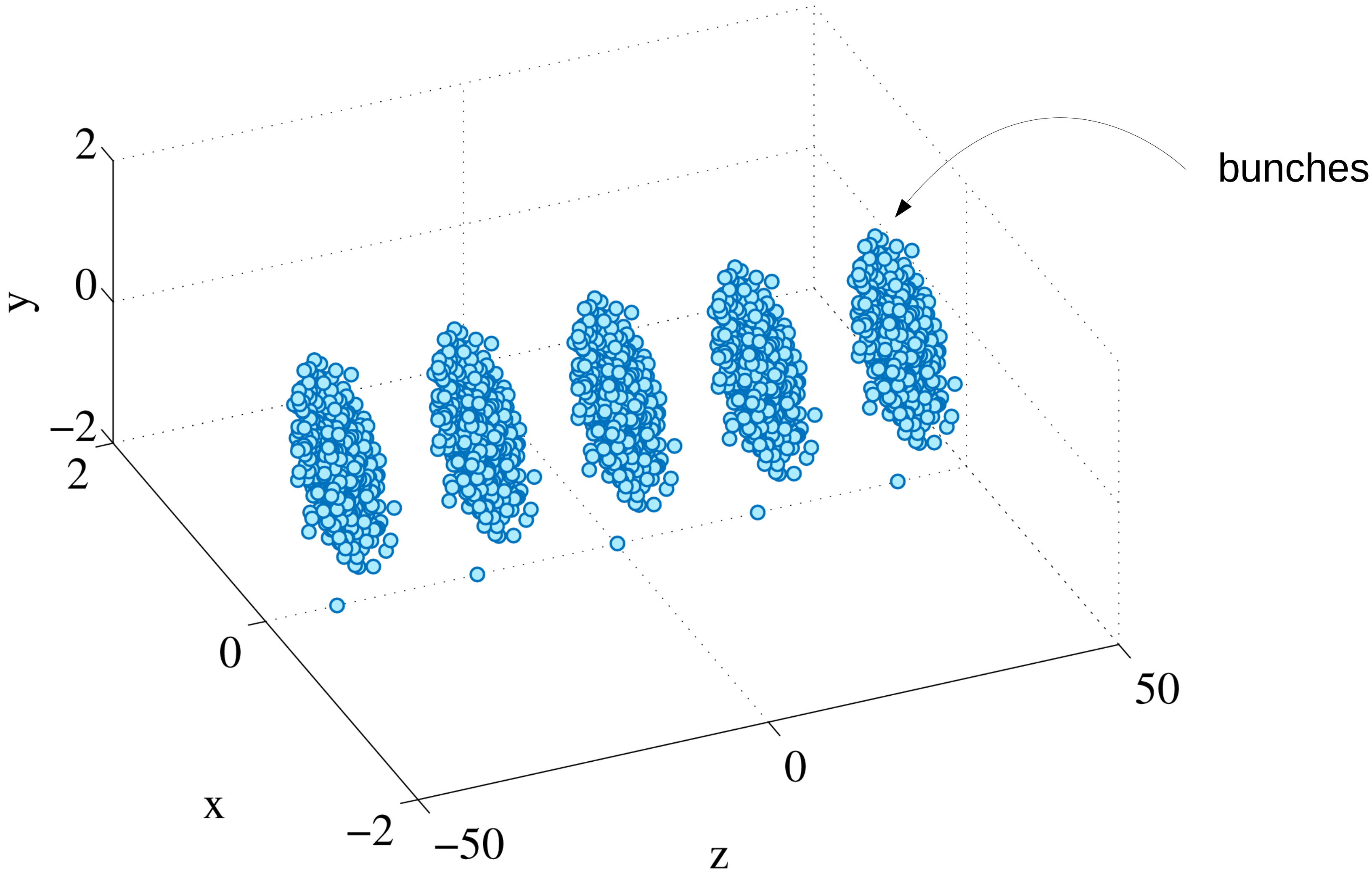
Which parameters and properties are we interested in?

The beam



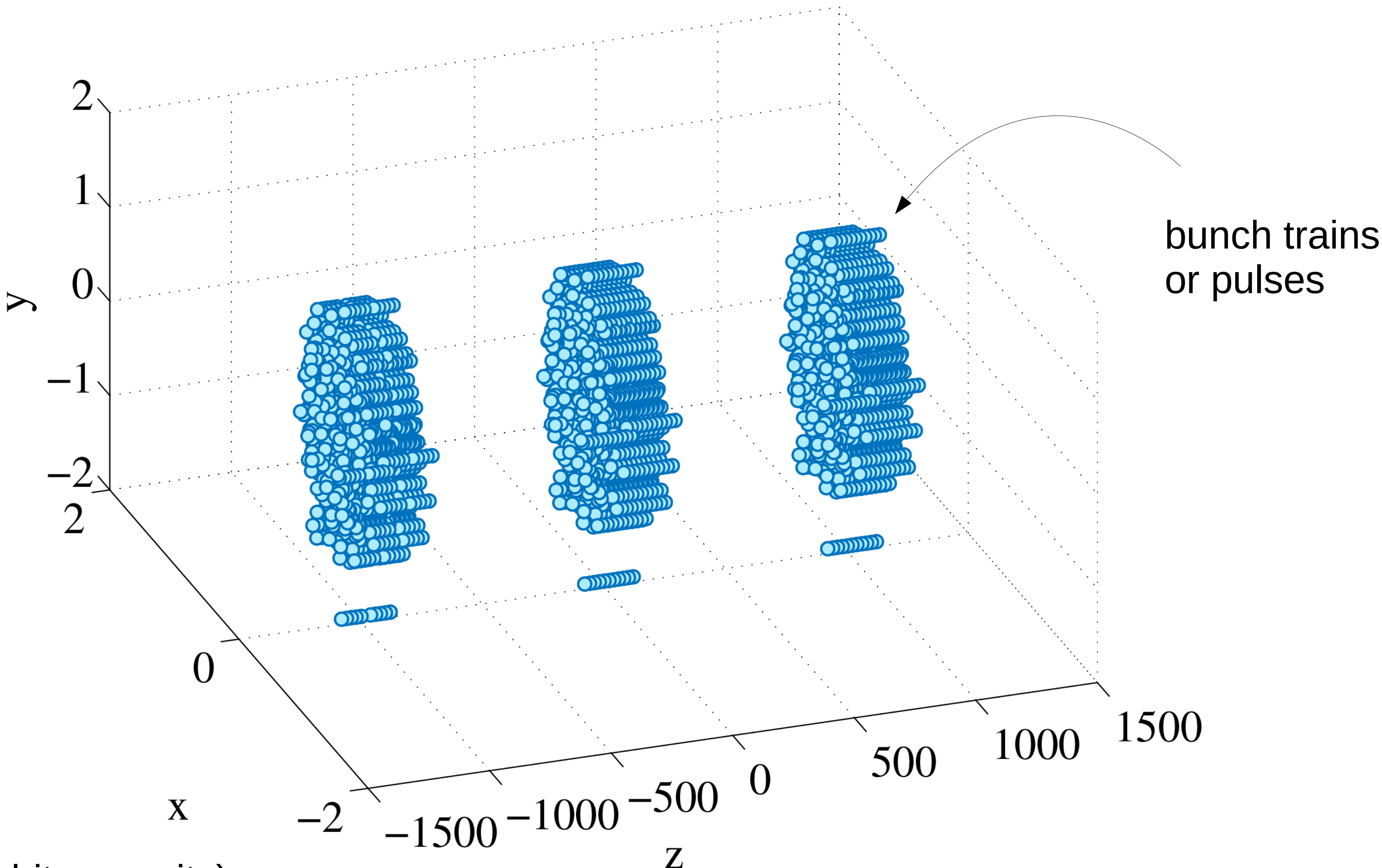
(Arbitrary units)

The beam, zooming out



(Arbitrary units)

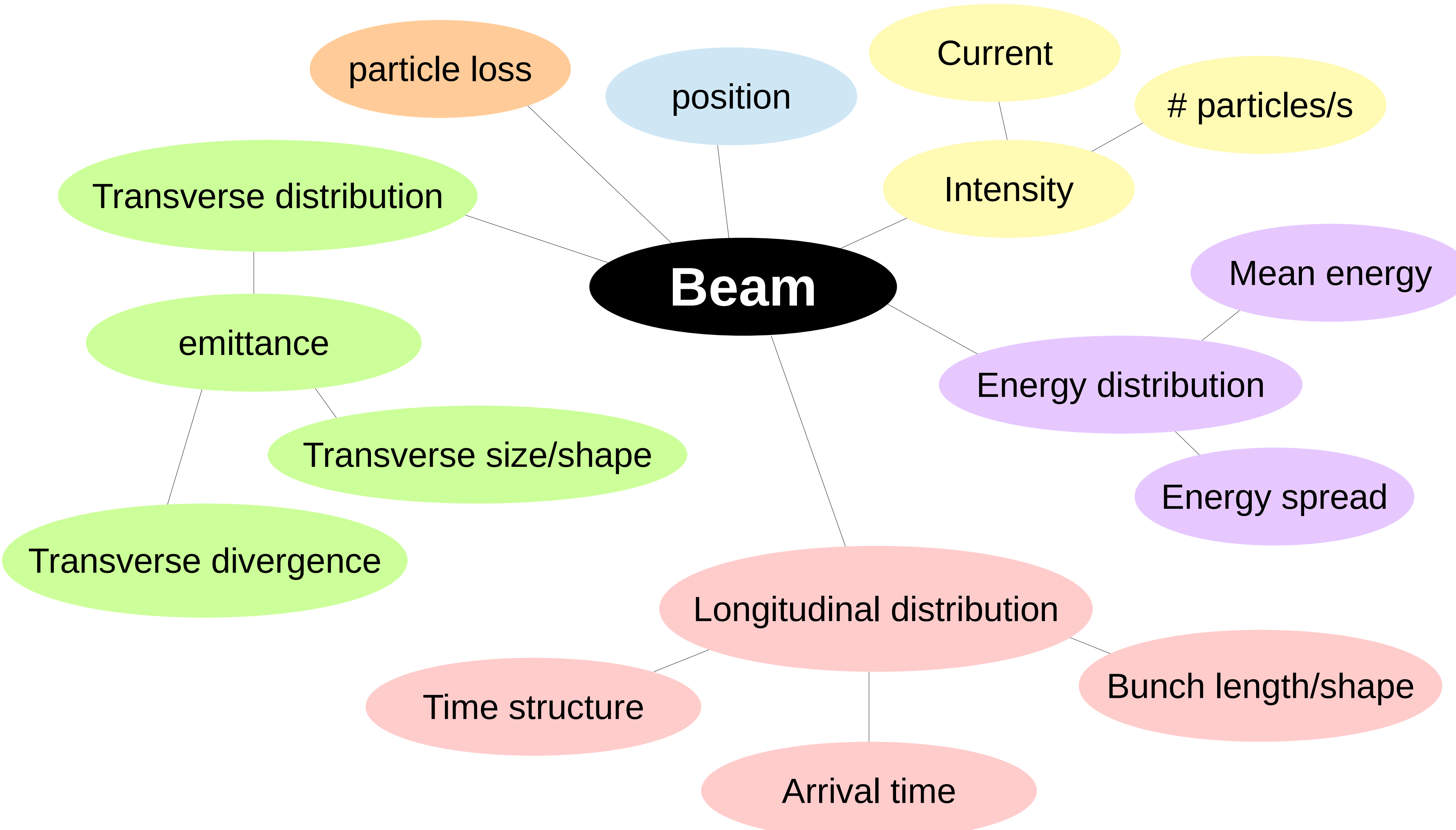
The beam, zooming out further



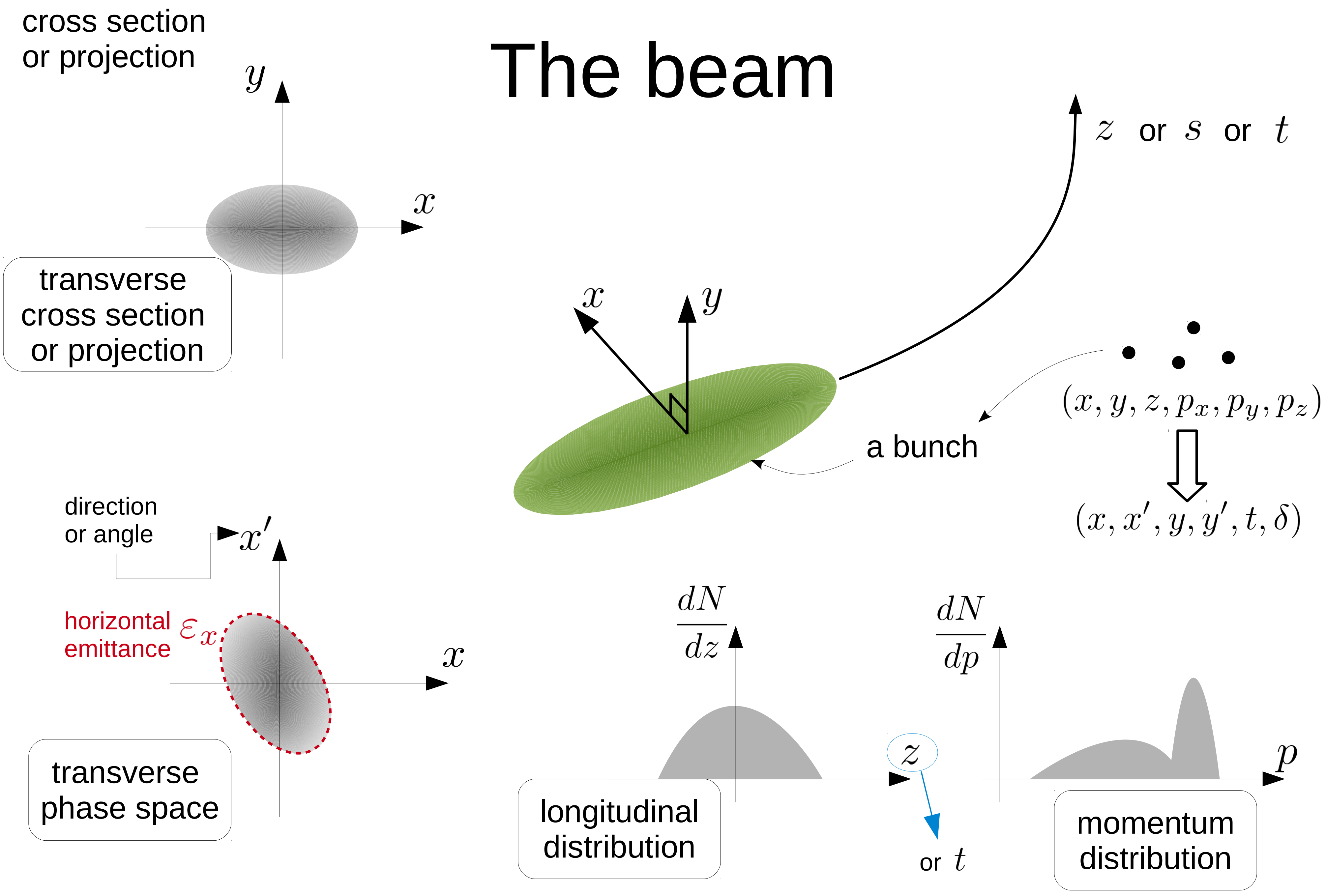
(Arbitrary units)

Let us think together....

Let us think together....



The beam

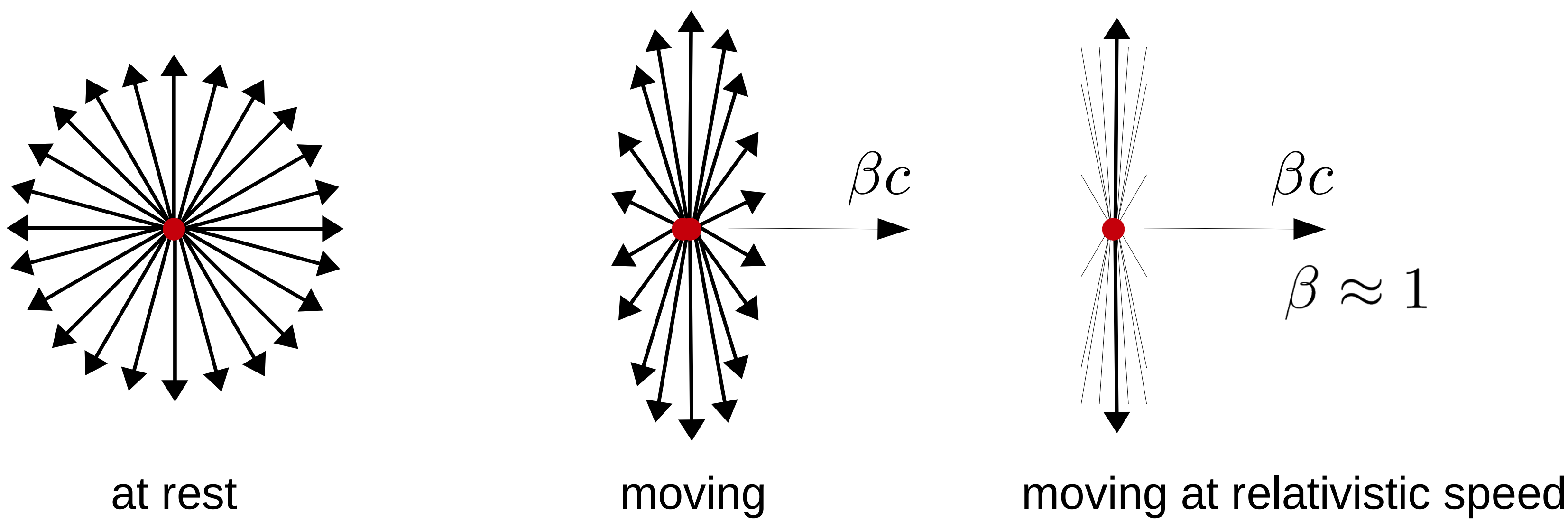


cross section
or projection
y
x
transverse
cross section
or projection
direction
or angle
x'
horizontal
emittance
ε_x
x
transverse
phase space
z or s or t
x
y
(x, y, z, p_x, p_y, p_z)
a bunch
$(x, x', y, y', t, \delta)$
$\frac{dN}{dz}$
$\frac{dN}{dp}$
z
or t
p
longitudinal
distribution
momentum
distribution

How can we “see” the beam?

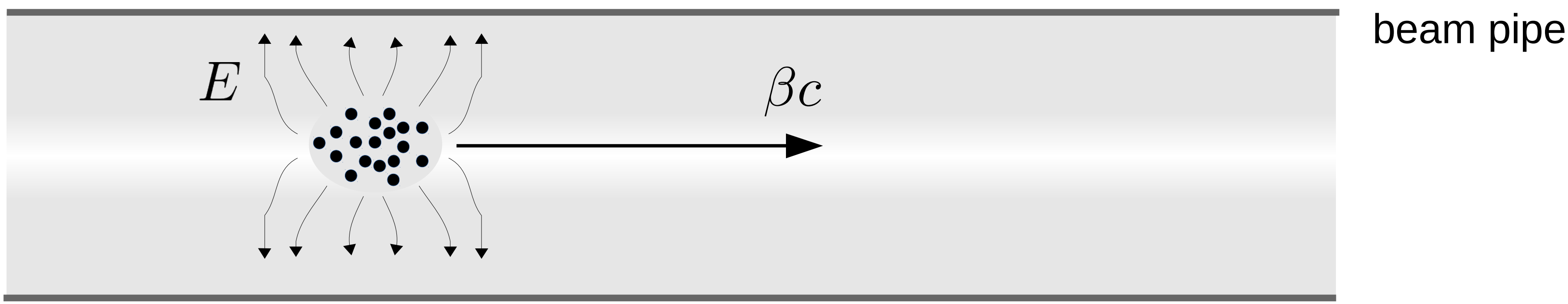
- We have to use the fundamental forces of nature.
- Always charged particles → surrounded by an electromagnetic field

Electric field around a point charge:



“Sensing” a particle beam

The beam pipe shields the surroundings from this field.



- We can sense this field in several different ways
  - Indirectly (placing something near or far from the beam)
  - Directly (placing something in the way of the beam)

How do we diagnose the beam?

- Vast variety of accelerators with different purposes and therefore different needs.
- Beam parameters vary greatly, so must the techniques to diagnose these parameters.
- A few central concepts:

parasitic	☐	☐	destructive
single-shot	☐	☐	multi-shot
continuous operation	☐	☐	dead time
integrated measurement	☐	☐	slice measurement → e.g. time resolved?
absolute	☐	☐	relative → cross-calibrate with other instrument?

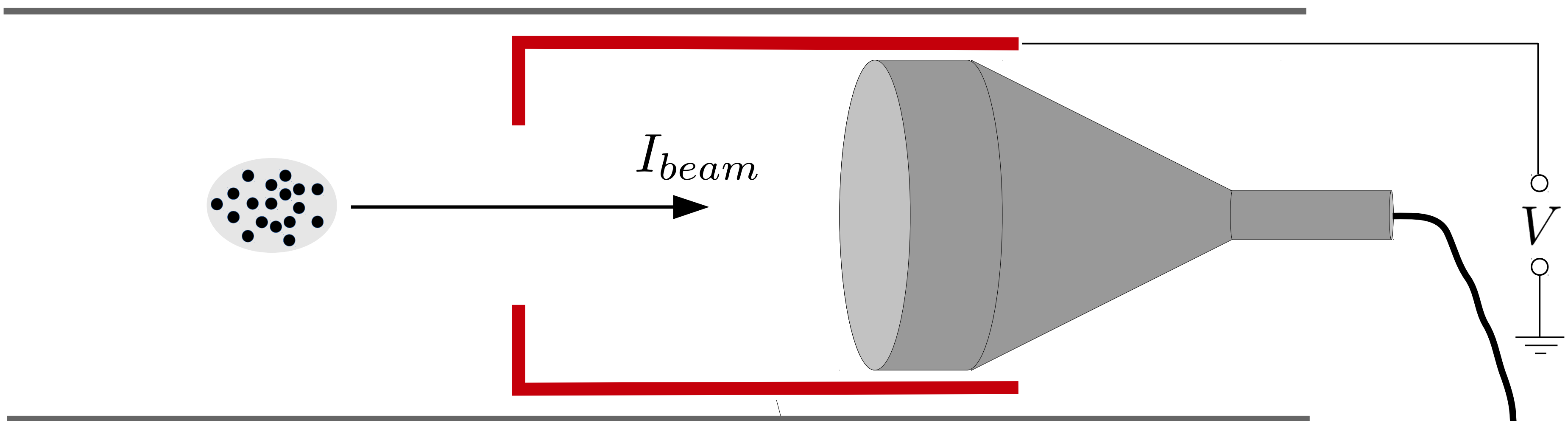
... and radiation hardness.

Beam current

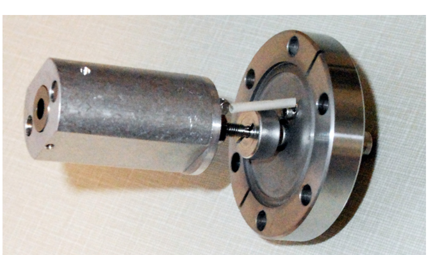
Faraday cup

destructive

The Faraday cup is a metallic body in which the beam particles are stopped. Every absorbed charge is sensed as an electric signal from the cup. Naturally, the cup must be long enough to stop all primary and secondary particles. It must be able to stand the thermal power that the beam induces.



A “bias voltage” V can force backscattered particles back into the cup

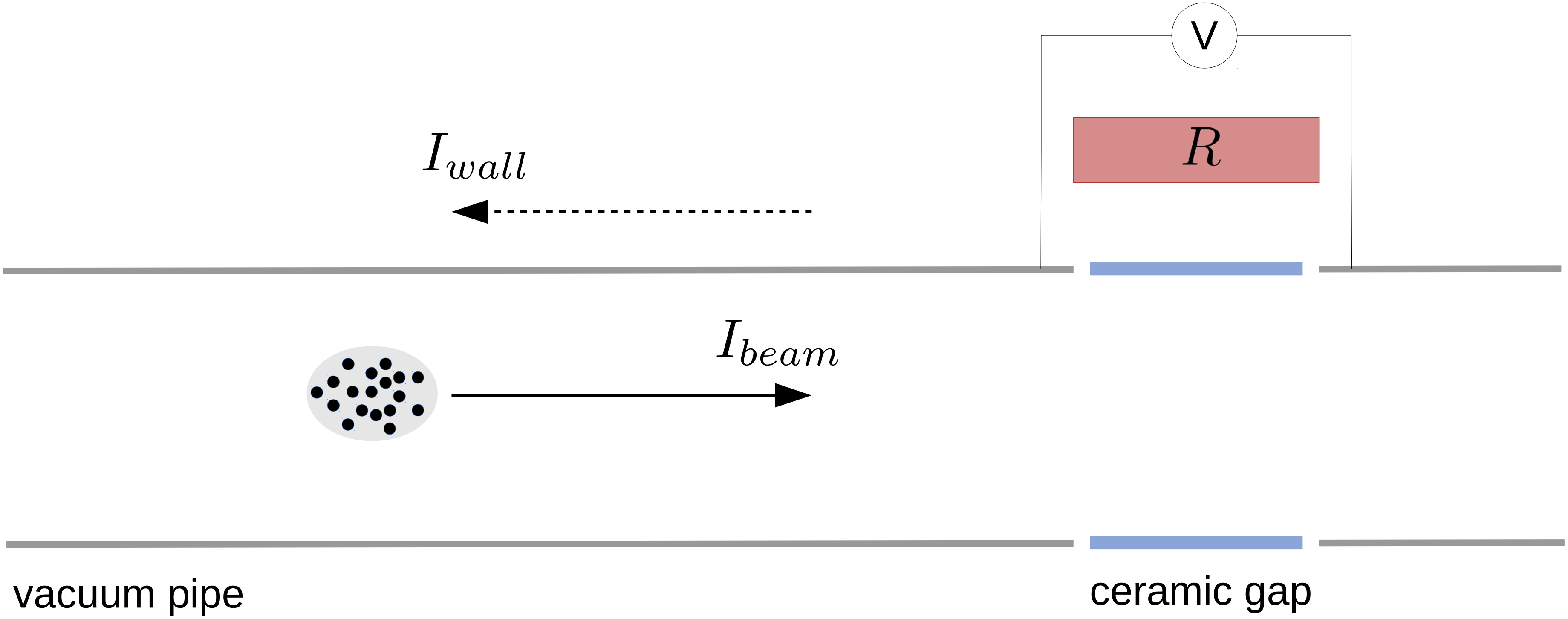


FC from
Beam Imaging Solutions

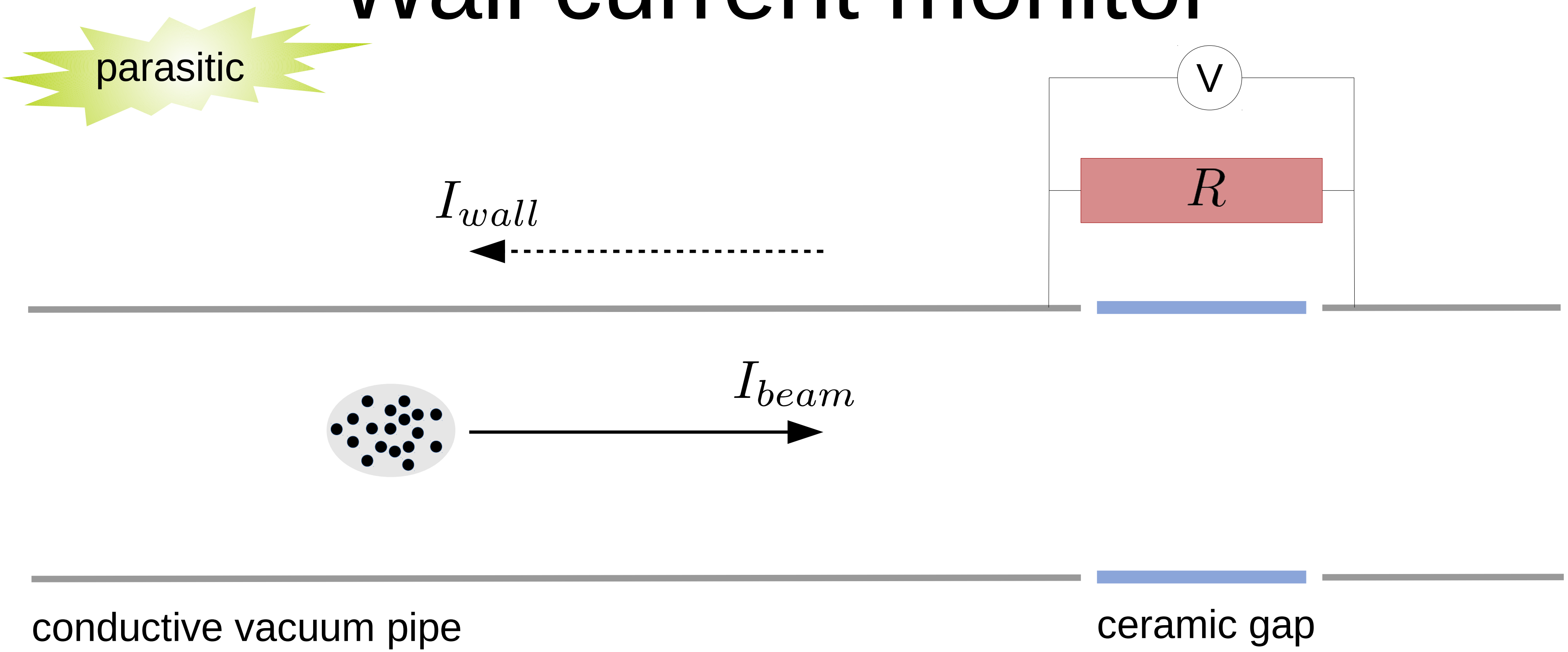
Wall Current Monitor

parasitic

The beam pipe shields the surroundings from this field.



Wall current monitor

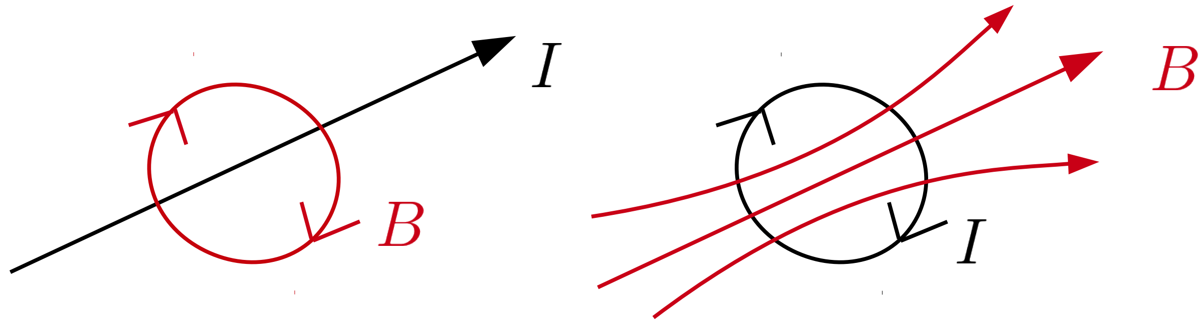


- We interrupt the conductive wall (beam pipe) by inserting a ceramic gap.
- The wall current will take any available path past this gap. In this case the wall current will propagate through the resistor.
- We then measure a voltage drop over the resistor.
- Normally works best at low frequencies, that is slow changes in the beam current.
- Careful consideration of all capacitances present is needed, together with the impedance added to the beam environment.

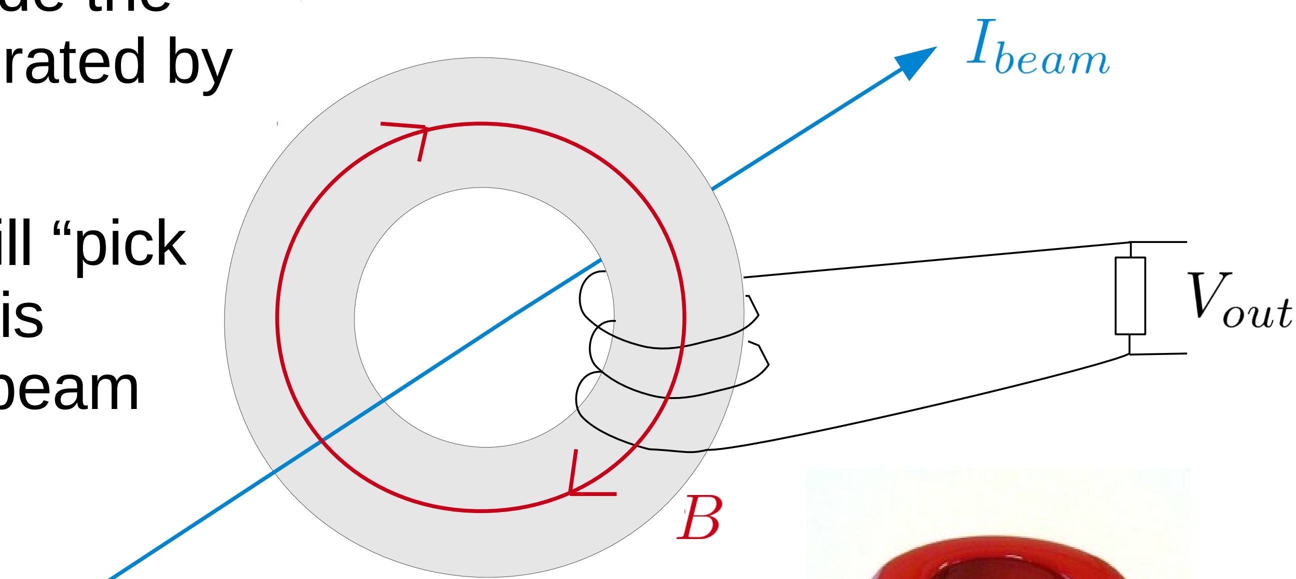
parasitic

Current transformer

- The “right hand rule”:



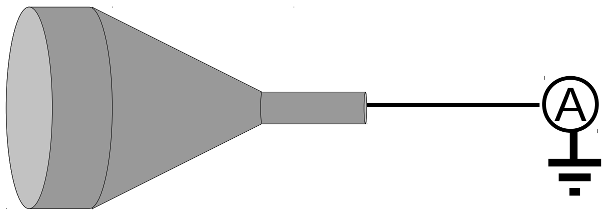
- Insert a torus to guide the magnetic field generated by the beam
- Current windings will “pick up” the field, which is proportional to the beam current.

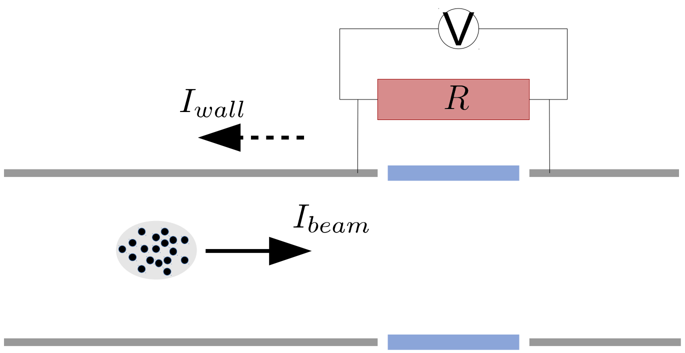


A real one, commercially available:

Beam current

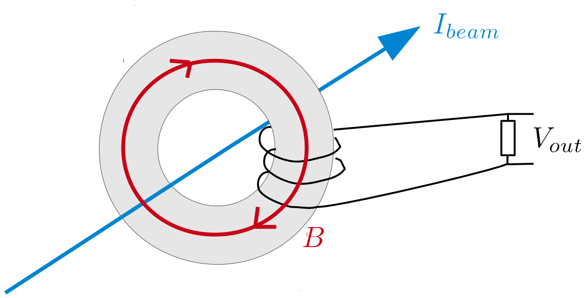
Faraday Cup





Wall Current Monitor

Beam Current Transformer



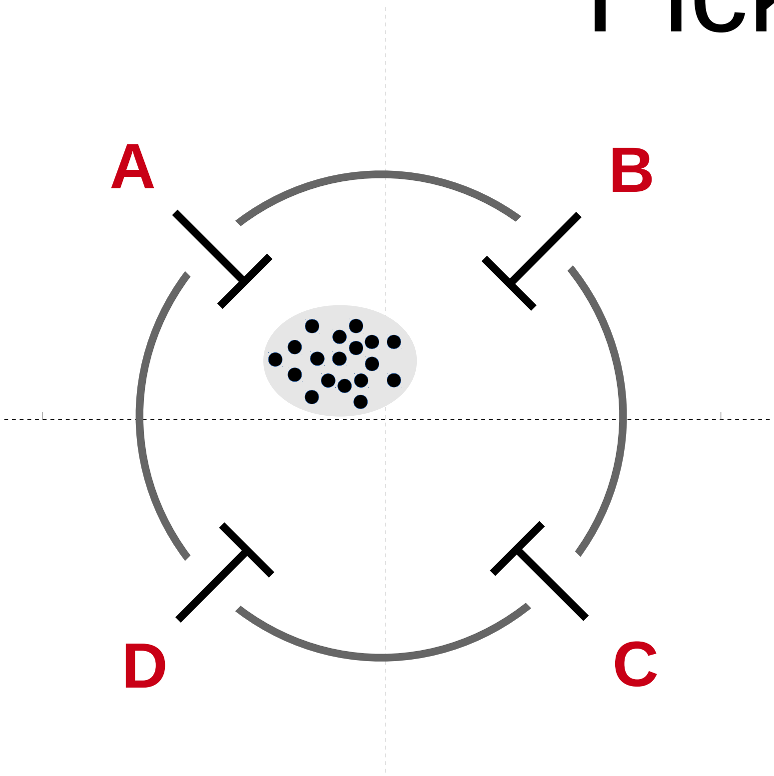
... and many more!

parasitic

Beam Position Monitors

- BPM -

Pick up



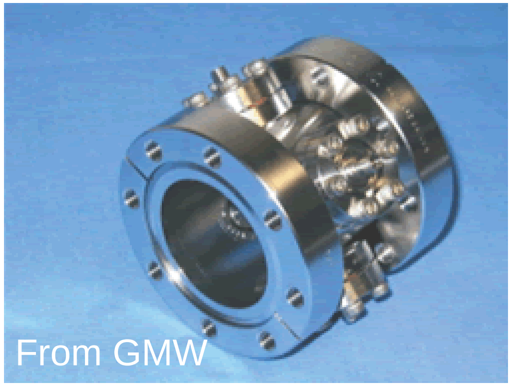
Horizontal position

$$x = k_x \frac{(A+D)-(B+C)}{A+B+C+D}$$

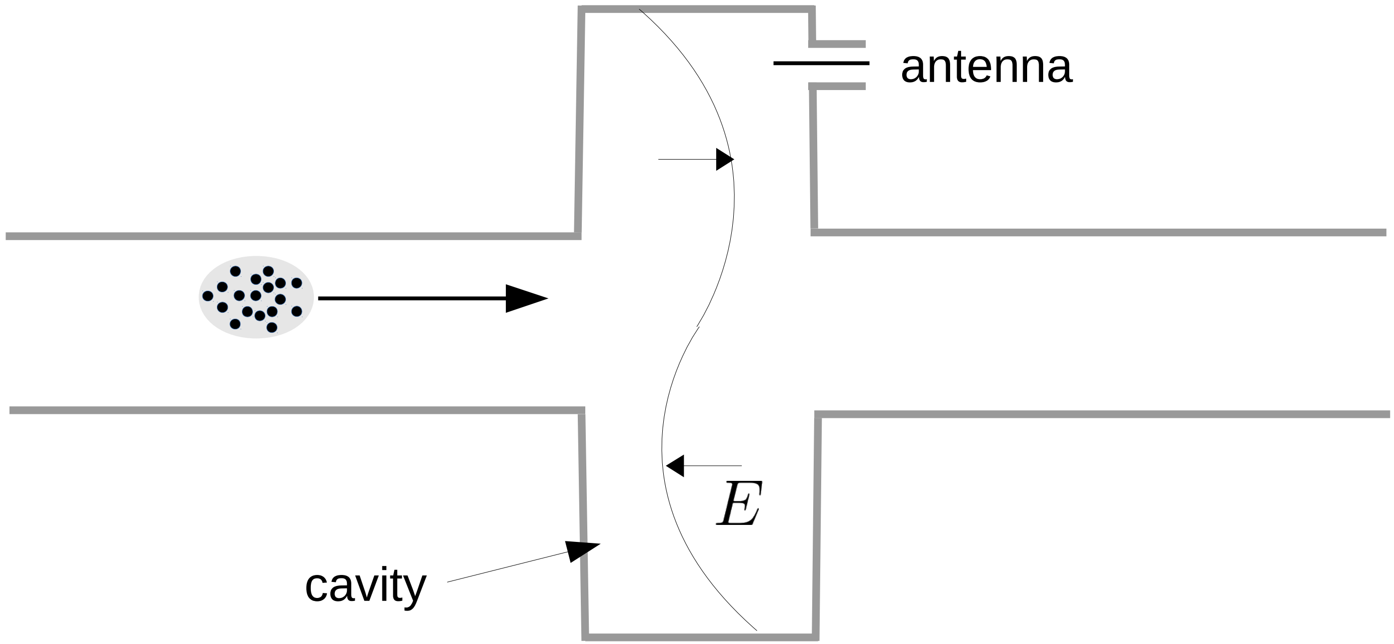
Vertical position

$$y = k_y \frac{(A+B)-(C+D)}{A+B+C+D}$$

- “Buttons” to pick up electric charges induces by the passing beam.
- Non-linear, requires very careful calibration.
- If properly calibrated, can be used for beam current measurements as well.
- Used when the bunch length ≈ bpm length, e.g. in synchrotron light sources

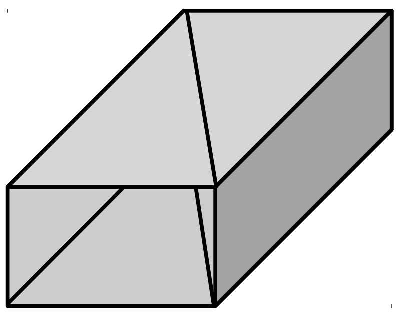


Cavity BPM



- When the bunch passes through the cavity it excites an electromagnetic field in the cavity.
- If the beam passes through exactly in the center there will be no field.
- The further away from the axis, the stronger the field.
- Very sensitive, but complex to make. Used mostly for electron linacs (short bunches).

Other BPM types

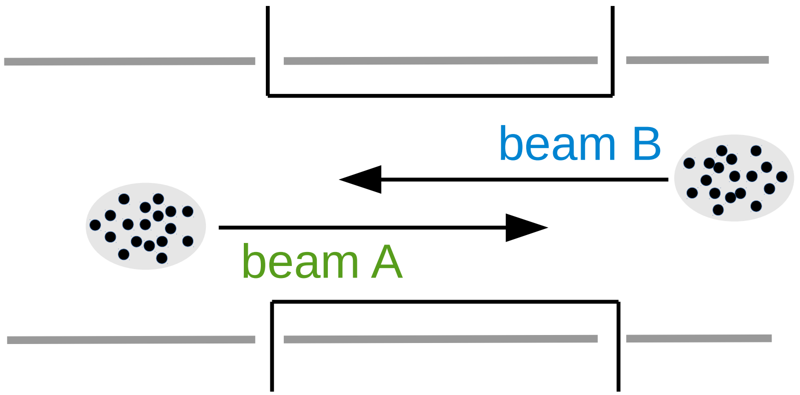


Shoe-box

Large plates as electrodes – useful for low currents.

Strip-line

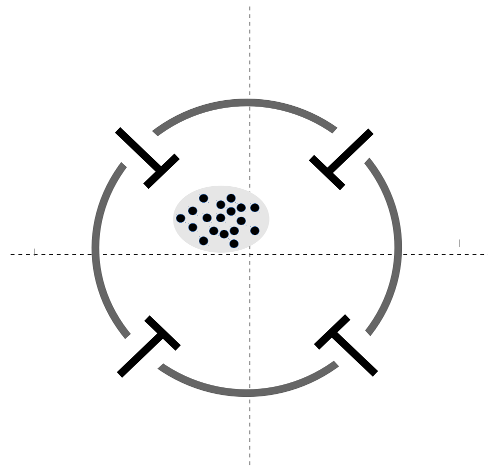
Used for very short bunches and for beams traveling in opposite direction



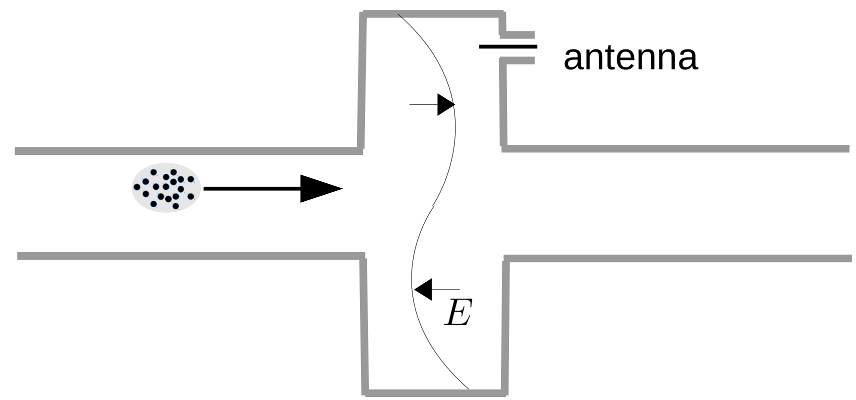
In common for all BPMs is the importance of signal handling and data acquisition electronics; bandwidth, impedance matching, amplifier and filter choice, etc.

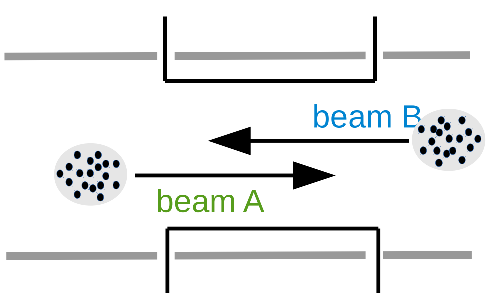
Beam Position Monitors

Button Pick-up



Cavity BPM

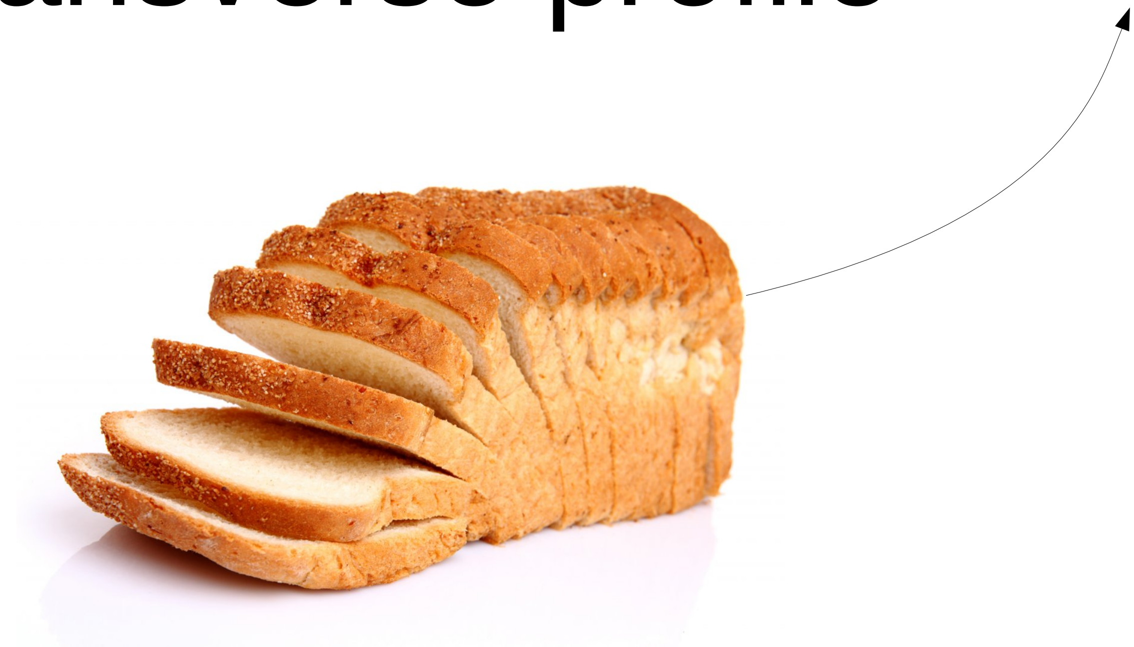




Stripline BPM

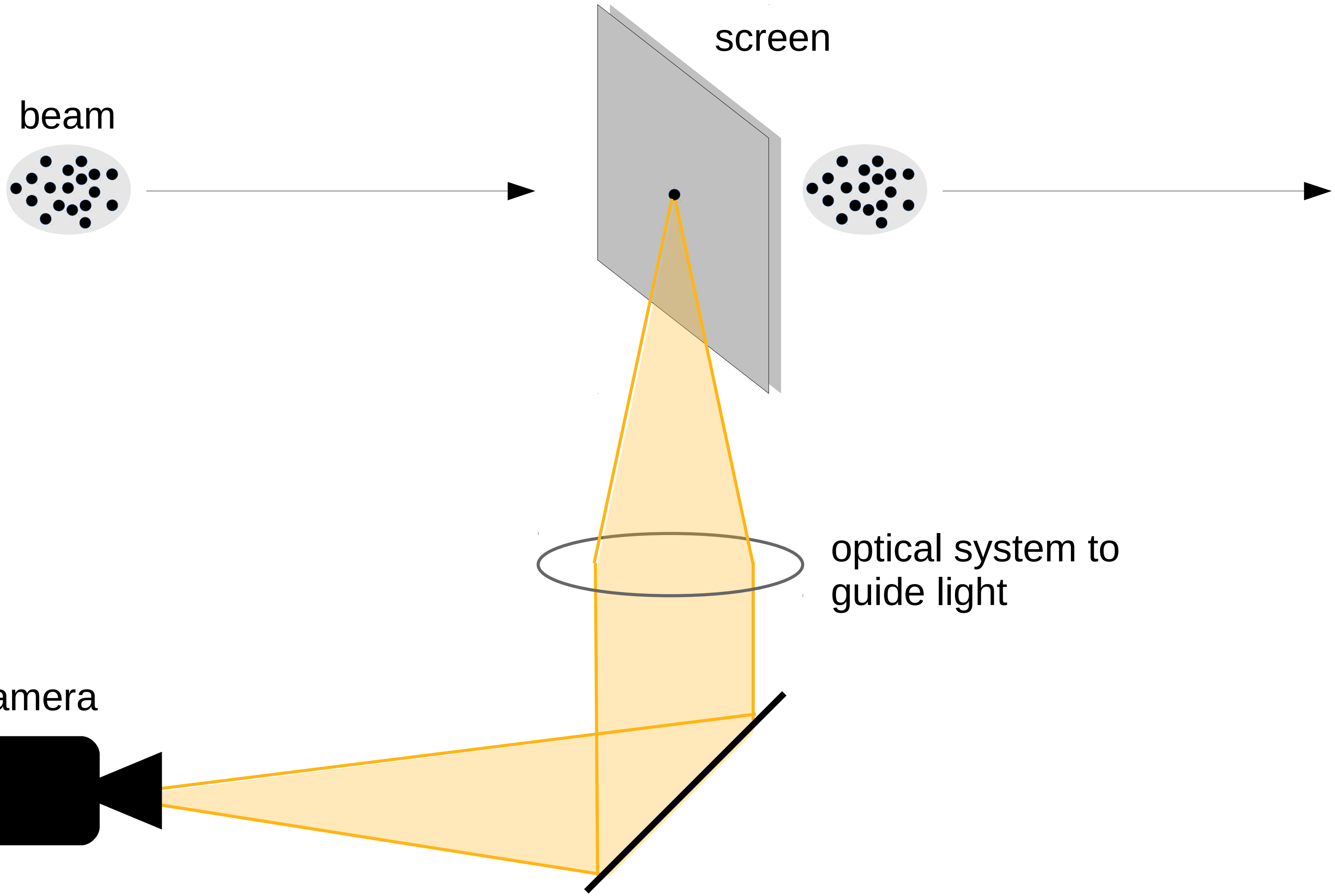
... and many more!

Transverse profile



Screen

perturbing

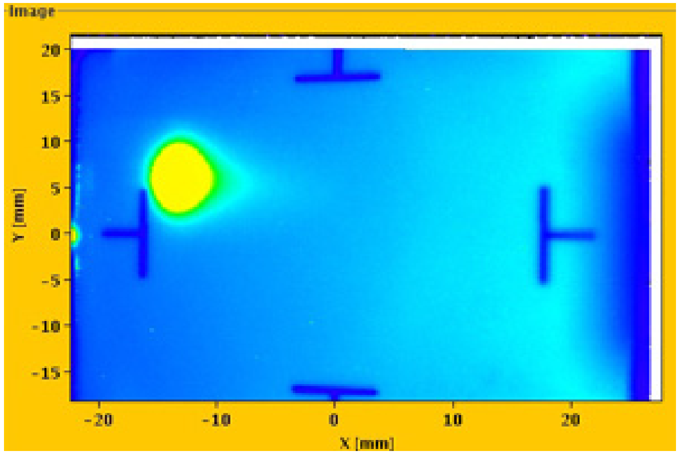

screen
beam
optical system to guide light
camera

Types of screens

- (Optical) Transition Radiation (OTR)
  - the beam polarizes the screen material
  - screen emits light when the polarization is “relaxed”
  - intensity increases with particle energy
  - almost instantaneous – can be used for fast measurements
- Scintillating screen:
  - atomic excitations
  - lots of light
  - slow process

OTR screen at LHC

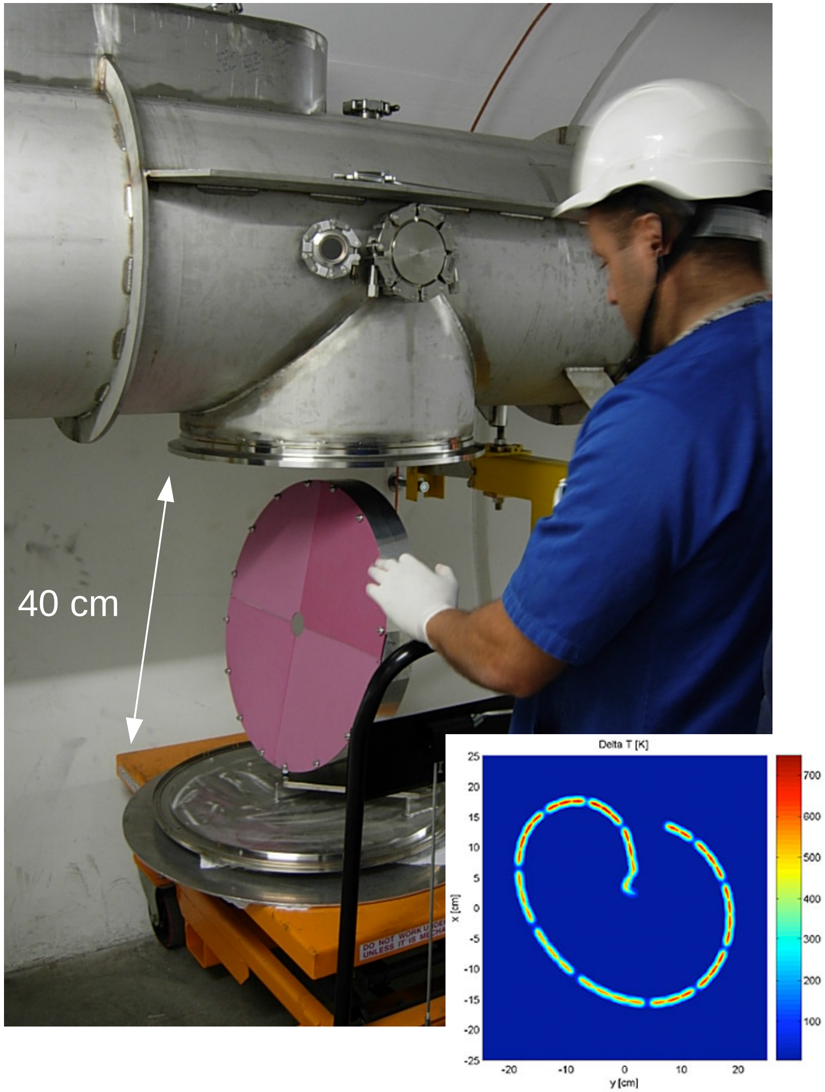
First beam in the LHC



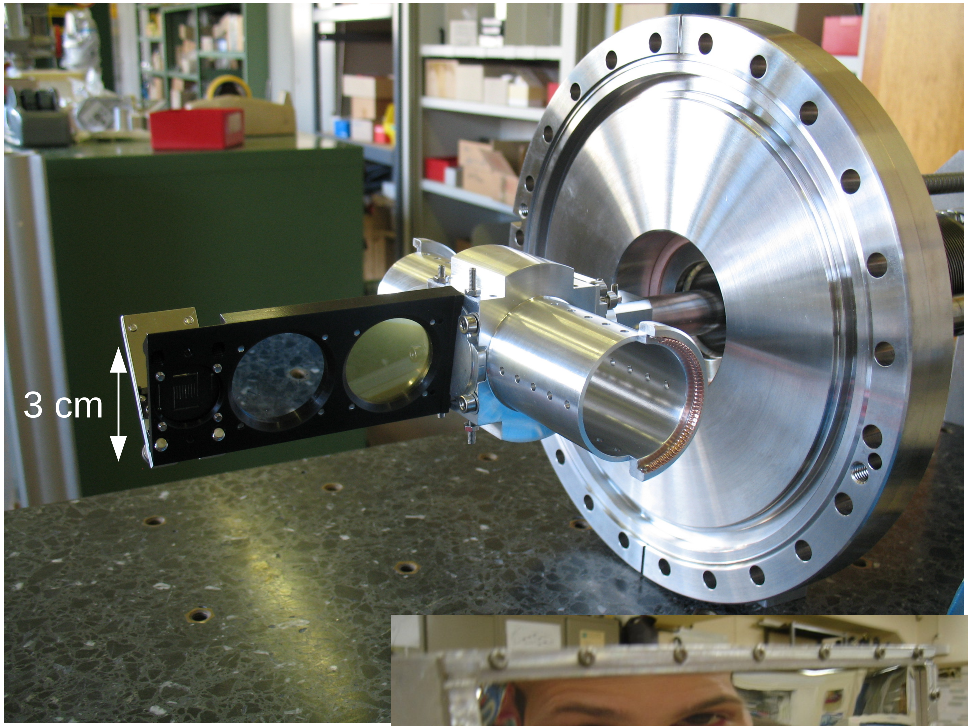
http://lhc-first-beam.web.cern.ch/lhc-first-beam/News/LHCsyncTest.html

Examples of screens

Scintillating screen in the LHC dump line



Screen for emittance measurement at CTF3

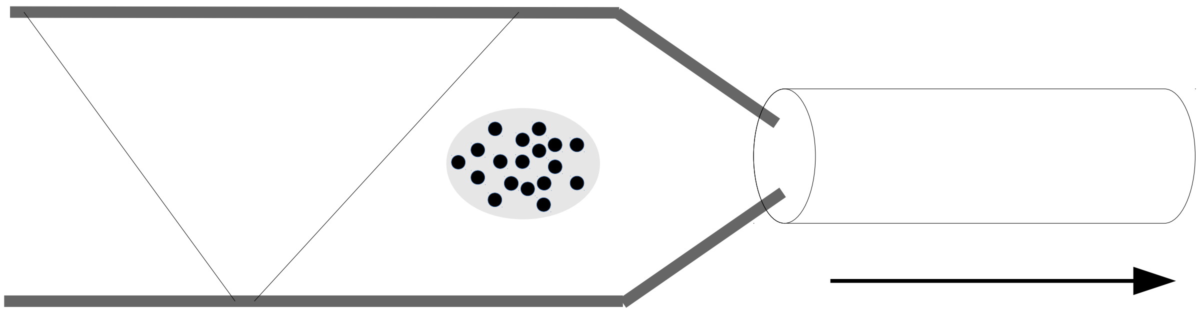


spectrometer
screen at CTF3

Wire scanner

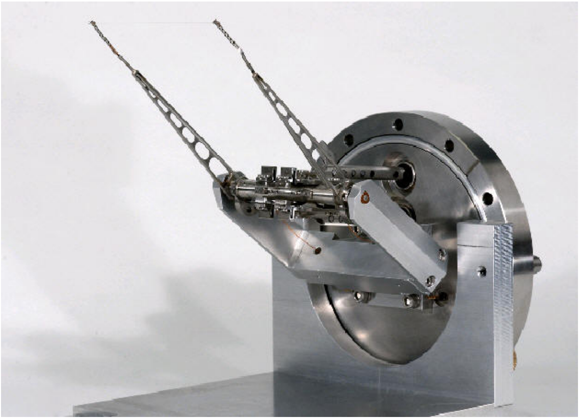
multi-shot

perturbing



- Scan a wire through the beam.
- Beam particles hit the wire and secondary particles are emitted.
- The secondary emission is detected as a current.
- Also possible to use a laser beam as a wire.

Rotating wire scanner; PS at CERN



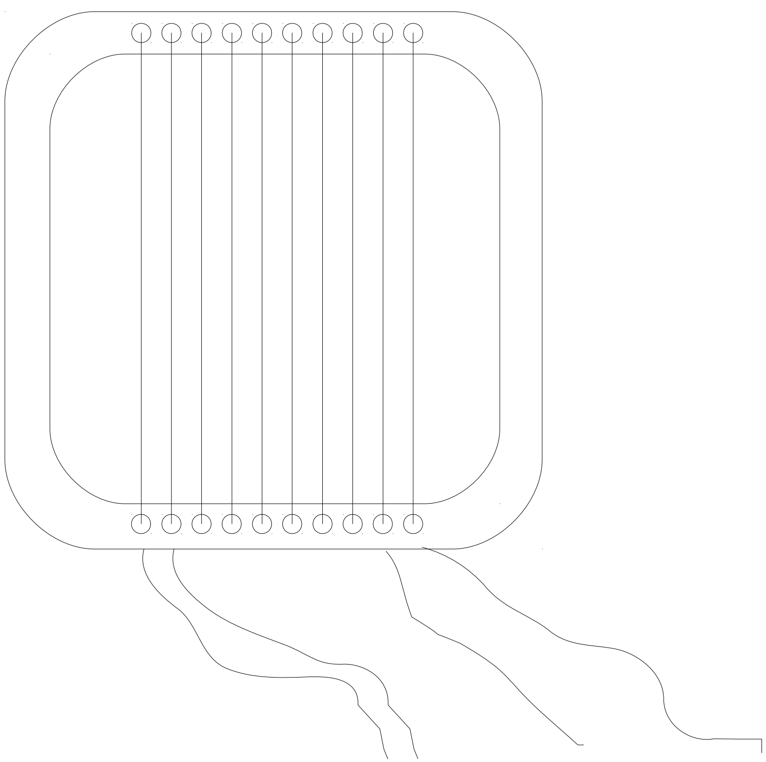
SEM grid

single-shot

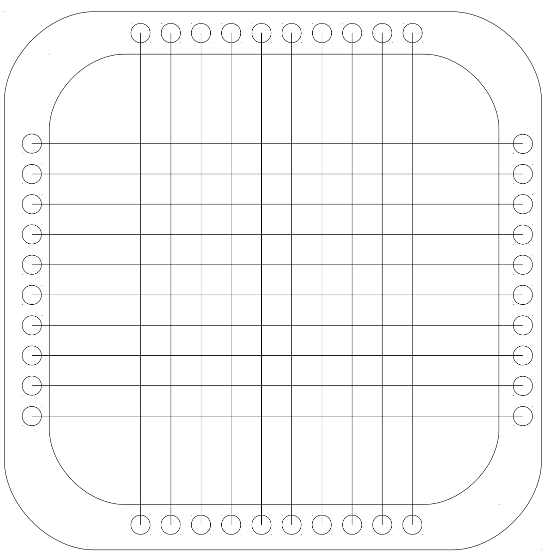
perturbing

- Instead of one moving wire, a grid of wires to detect secondary emission from beam particle hits: Secondary Emission Grids (SEM-grid) or Harp

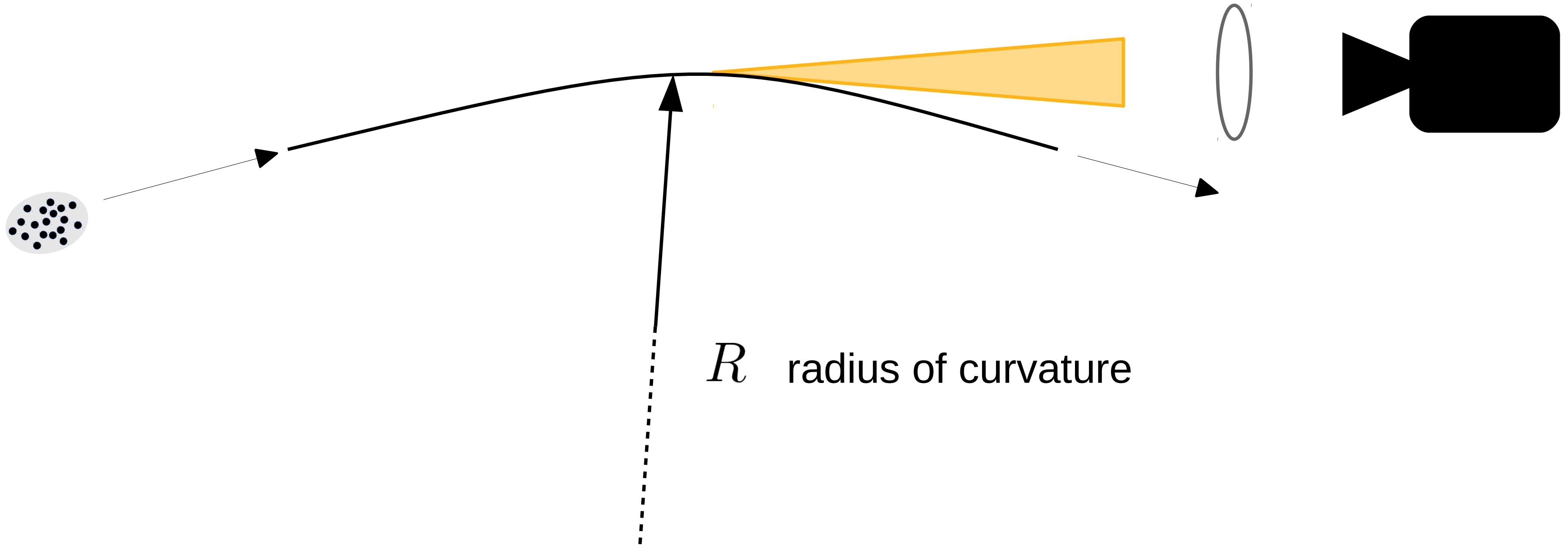
1D:



2D:



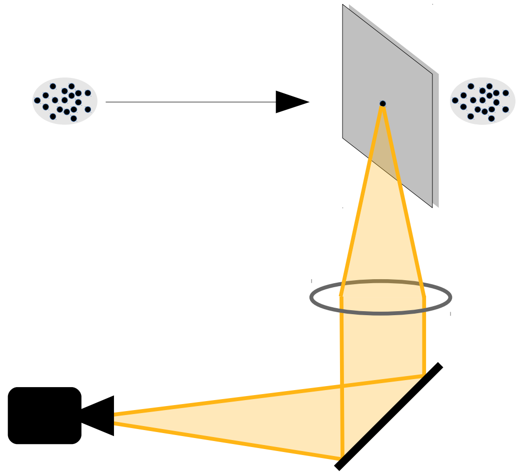
Synchrotron radiation monitor



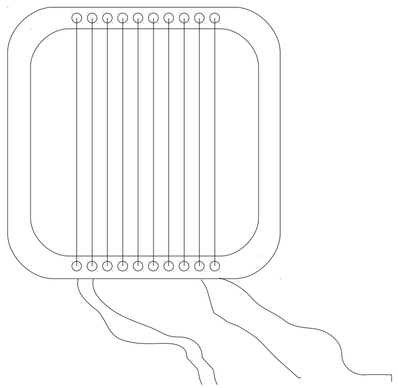
Note: Details of synchrotron radiation will be presented by Pedro Tavares on Friday.

Transverse Profile, recap

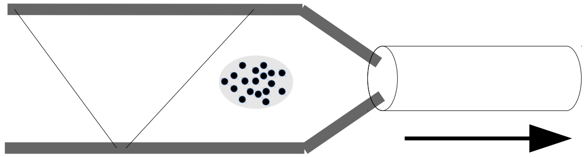
OTR screen /
Scintillating screen



SEM grid, Harp



Wire Scanner

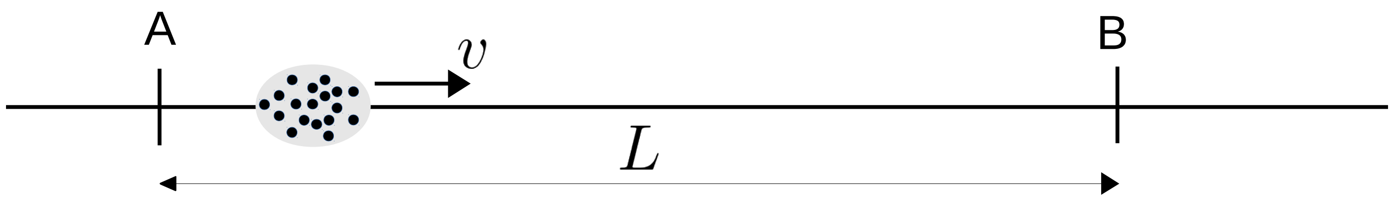


... and many more!

Beam energy and momentum

Time-of-flight TOF

parasitic

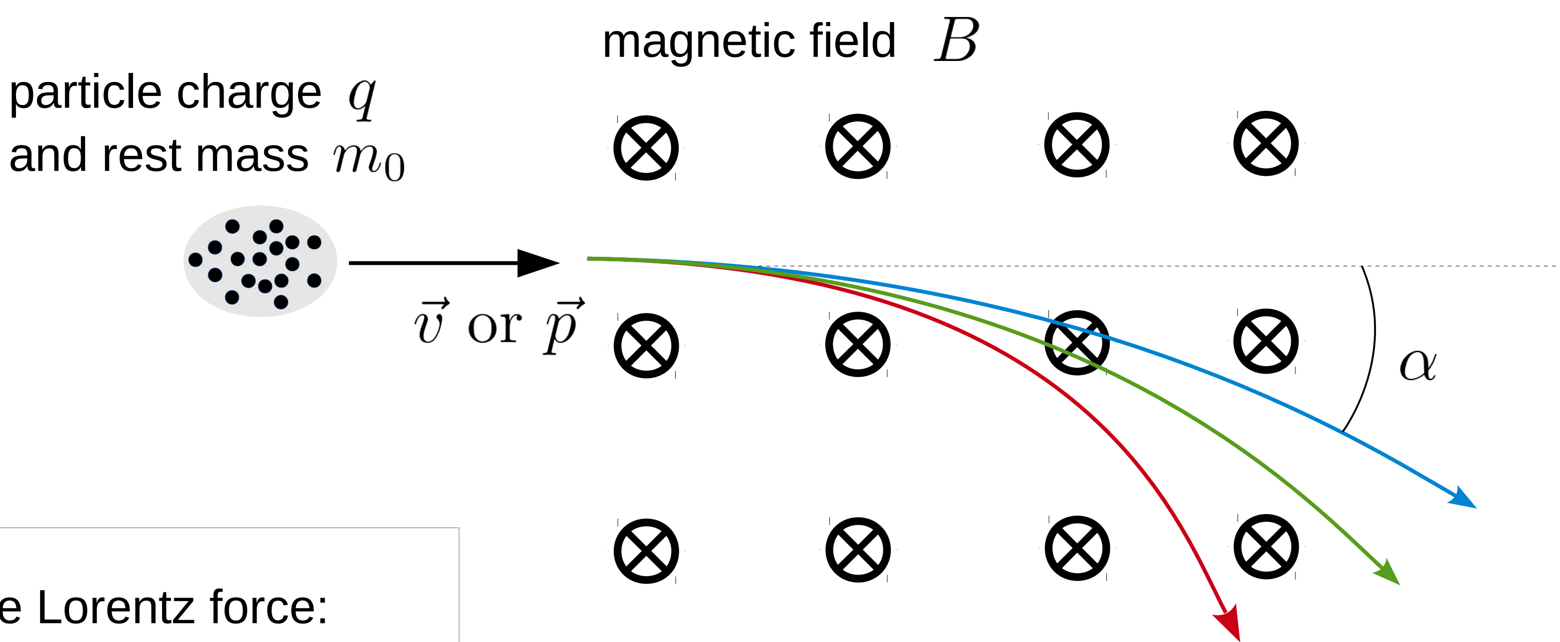


- Measure time of flight from A to B: $T_{tof} = t_B - t_A = L/v$
- Calculate kinetic energy: $E_k = \frac{mv^2}{2}$

Intuitive, BUT:

- For relativistic particles $v \longrightarrow c$ which means that the speed is the same even if the energy is different.
  - It becomes impossible to measure such short time differences.
- So, only used for heavy particles at low energy.

Spectrometer



The Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

Relativistic:

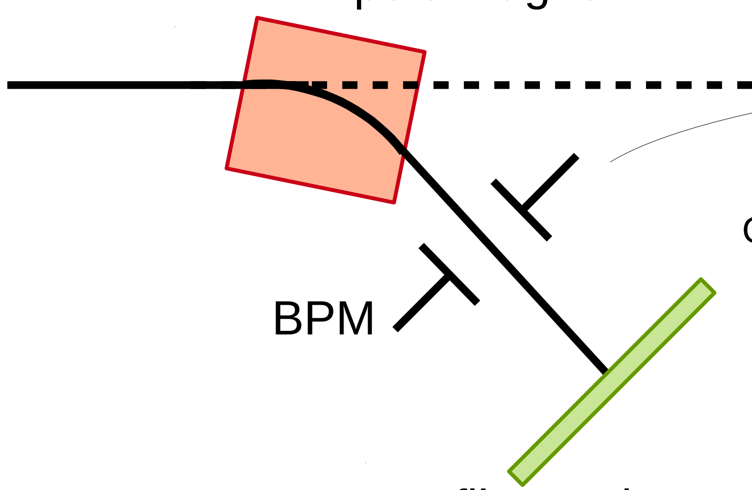
$$\gamma \frac{d\vec{p}}{dt} = \frac{q}{m_0} \vec{p} \times \vec{B}$$

The curvature of the path in a magnetic field depends on the particle momentum p.
Expressed in exit angle α:

$$p = \frac{q}{\alpha} \int B dl$$

destructive

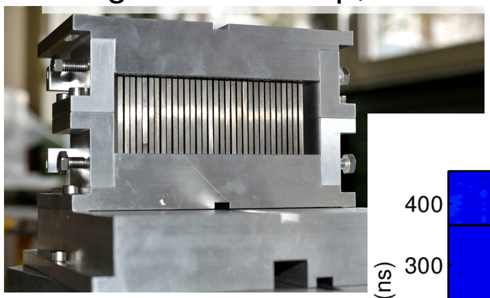
Spectrometer

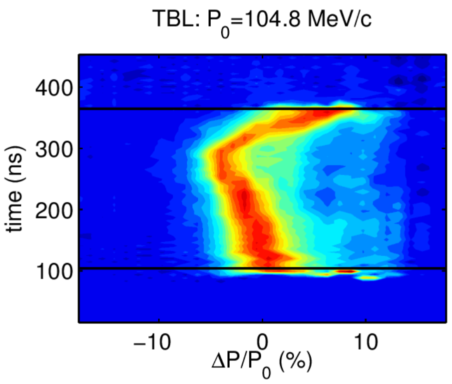


A BPM in the spectrometer line gives the central momentum of the beam accurately.

A profile monitor (screen, grid, multi-array Faraday cups ...) gives the momentum distribution of the beam.

Segmented dump, CTF3





Remember:

- The intrinsic beam size in the bending plane must be small compared to the beam size due to the momentum spread.
- The accuracy of the momentum measurement is determined by how well we know the integrated field of the magnet.

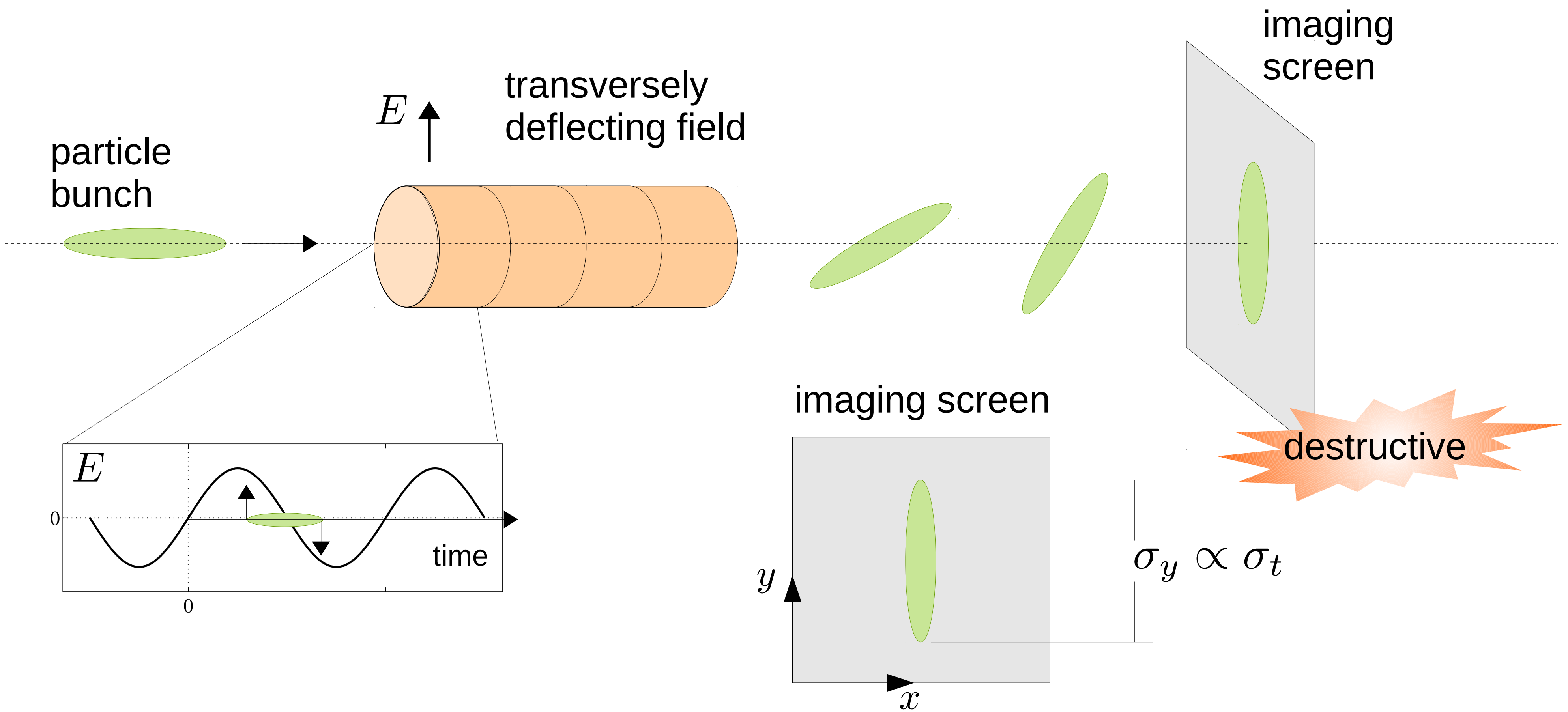
Longitudinal distribution & Bunch length

Longitudinal profile

- Particle bunches can vary from .... to ....
  - LHC: 0.27 ns → 8 cm
  - ESS (end): 3 ps → 1 mm
  - MAX IV: down to 31 fs → 10 μm
- Long bunches can be measured with a fast current transformer.
- Very short bunches need special tricks.

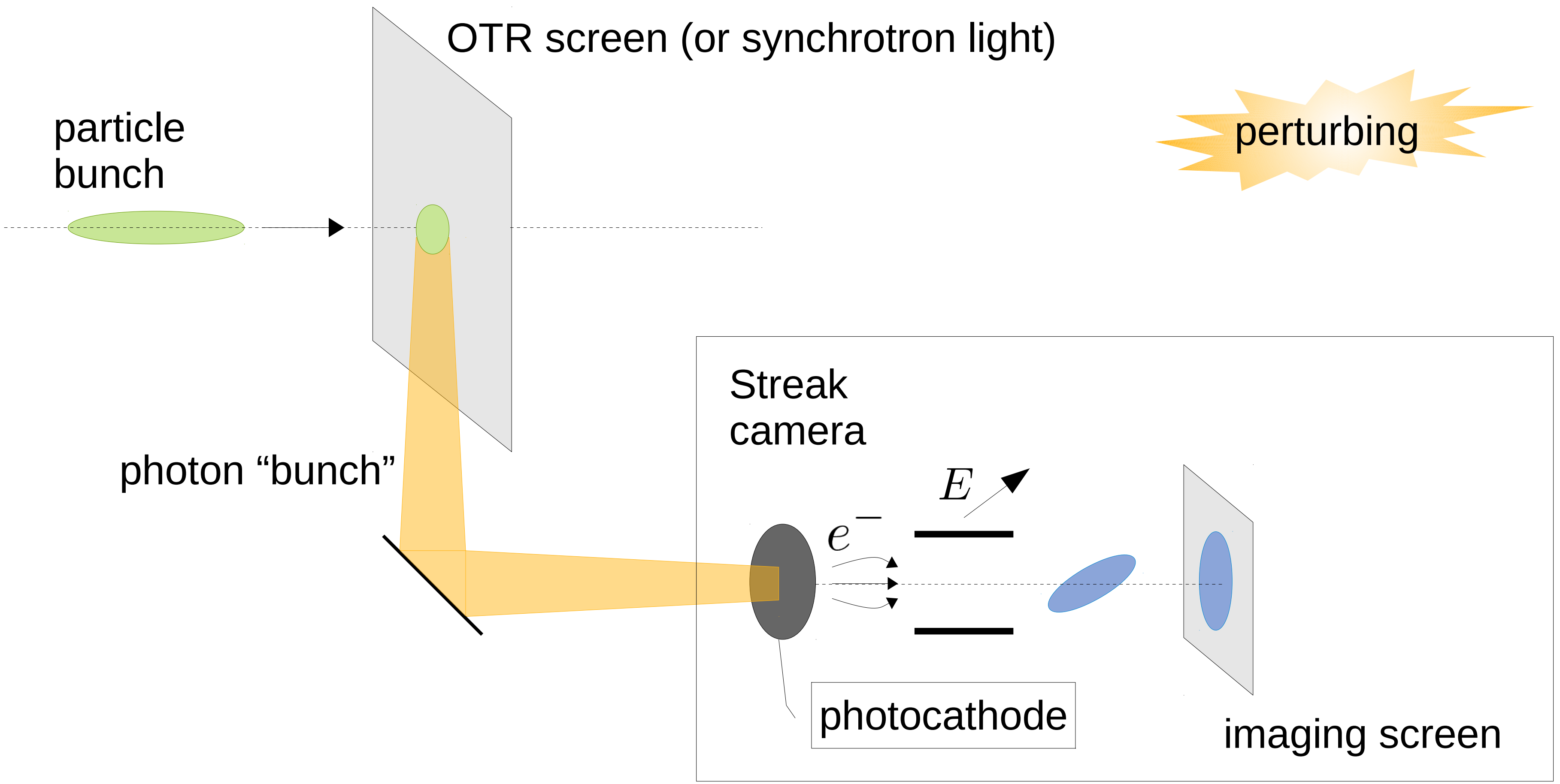
Bunch length: a) sweep particles

- A transversely deflecting cavity transfers the temporal density to vertical density on a screen.

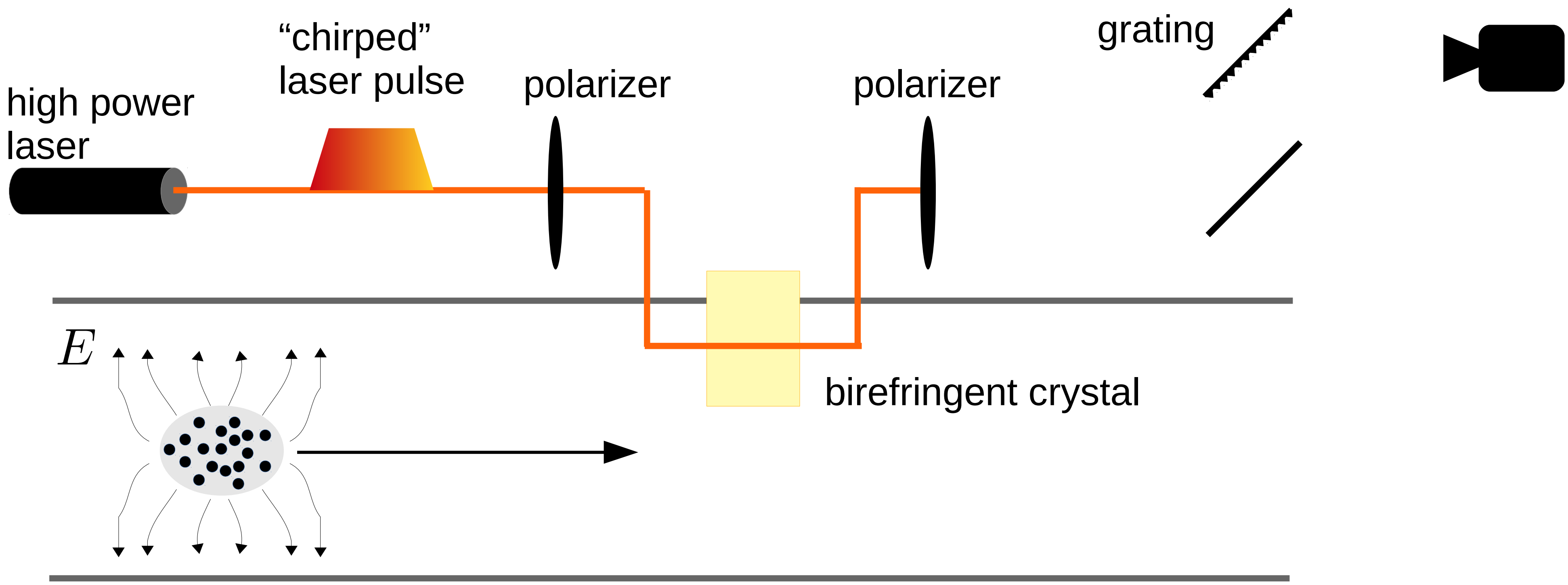


Bunch length: b) sweep light

- An OTR screen generates a light “bunch” or pulse corresponding to the particle bunch duration. The photon pulse is transformed to a new electron bunch at low energy, which is swept across a screen using a ramped field.

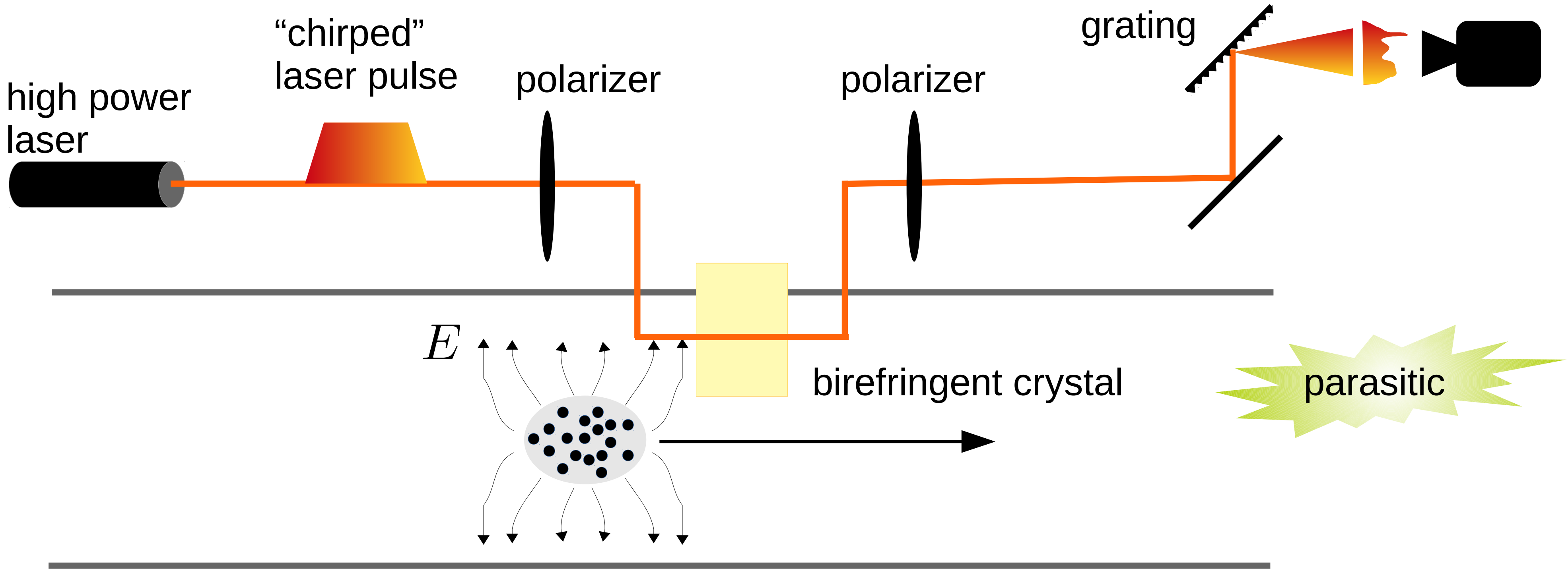


Electro-optical techniques



A short laser pulse is shone through a birefringent crystal. The laser light is initially blocked by two polarizing plates at 90 degrees.
A particle bunch approaches with its surrounding electric field strongly boosted to a transverse disk. The electric field polarizes the crystal and in that way, changes the refringence properties of the crystal.

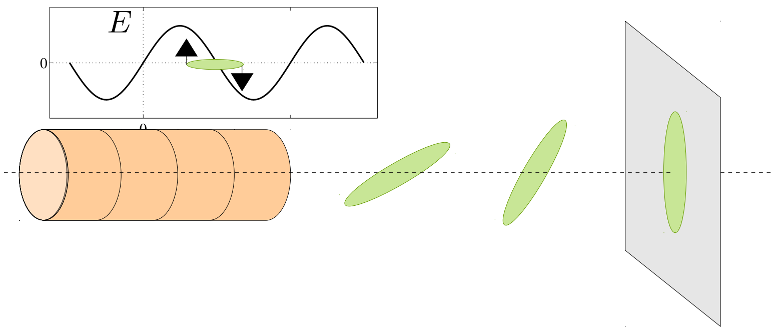
Electro-optical techniques



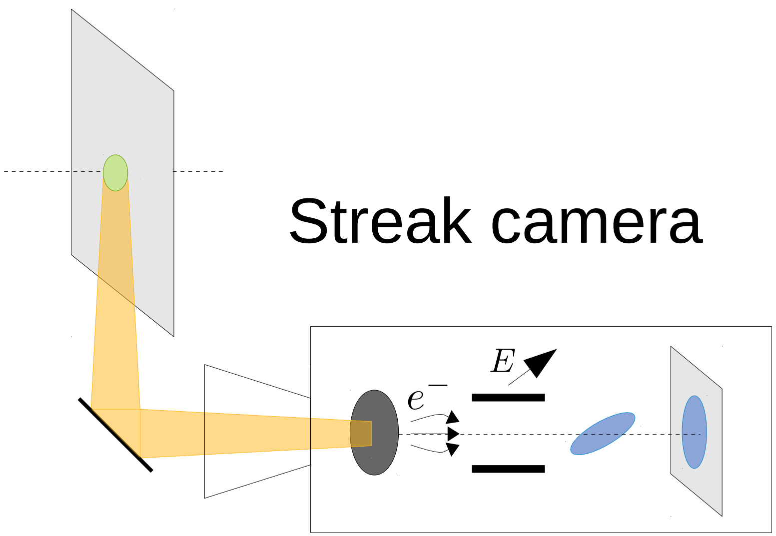
The laser light that is passing through the crystal changes polarization due to the presence of the electric field. Now the cancellation is no longer complete and some light is transmitted through the second polarizer plate. This light is directed to a grating, which splits the light up according to wavelength. A camera can then pick up the light intensity variations with wavelength. Remember: the time variable is encoded in the wavelength. Now the particle density is encoded in the light intensity.

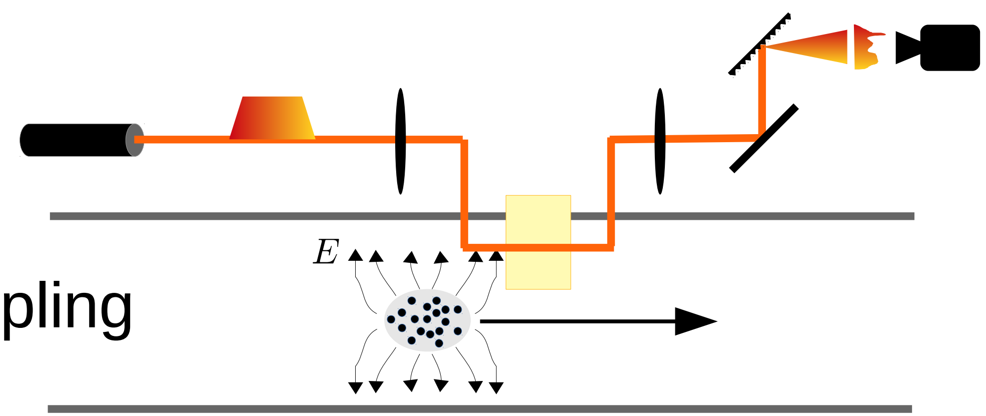
Longitudinal profile

Transversely deflecting cavity



Streak camera





Electro-optical sampling

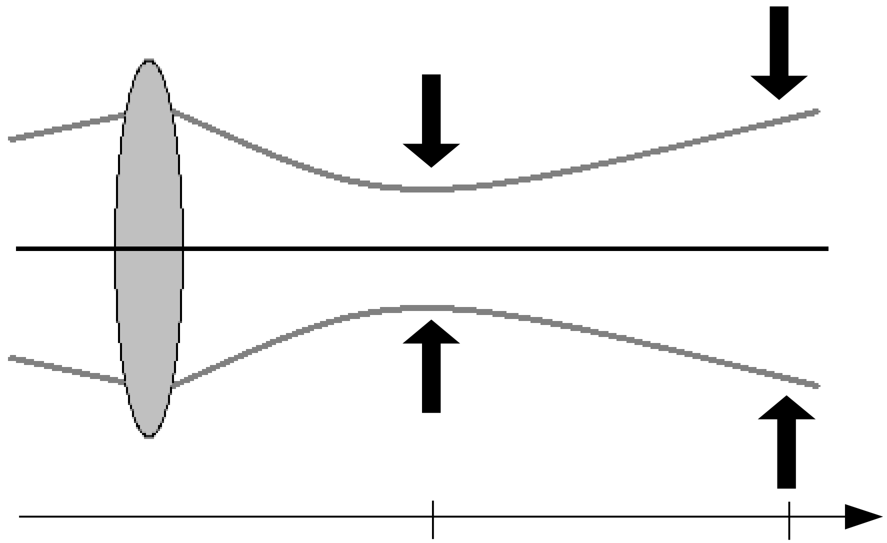
A diagnostic:

Emittance measurement

Emittance measurements

incoming beam

$\varepsilon, \alpha, \beta$

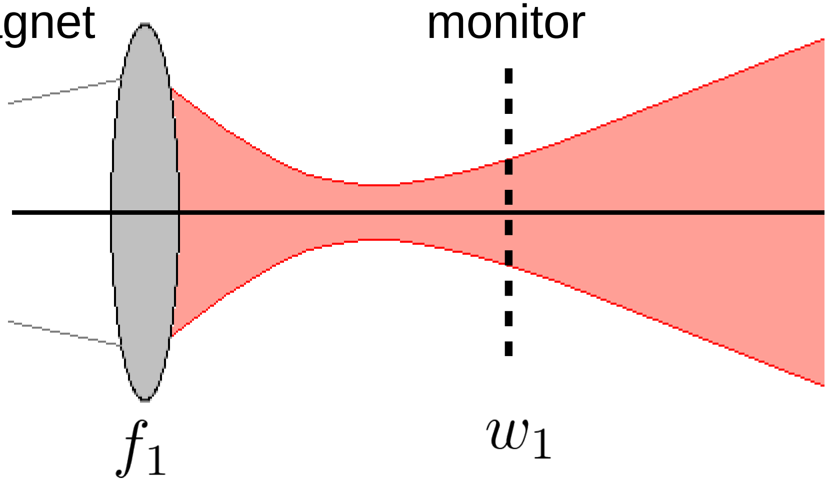


beam elsewhere
?

- Three parameters that define the beam (transversely):
  - width, divergence and coupling of the two.
- Three parameters to be measured, for example:
  - beam width at the waist.
  - beam width away from waist.
  - position of waist.

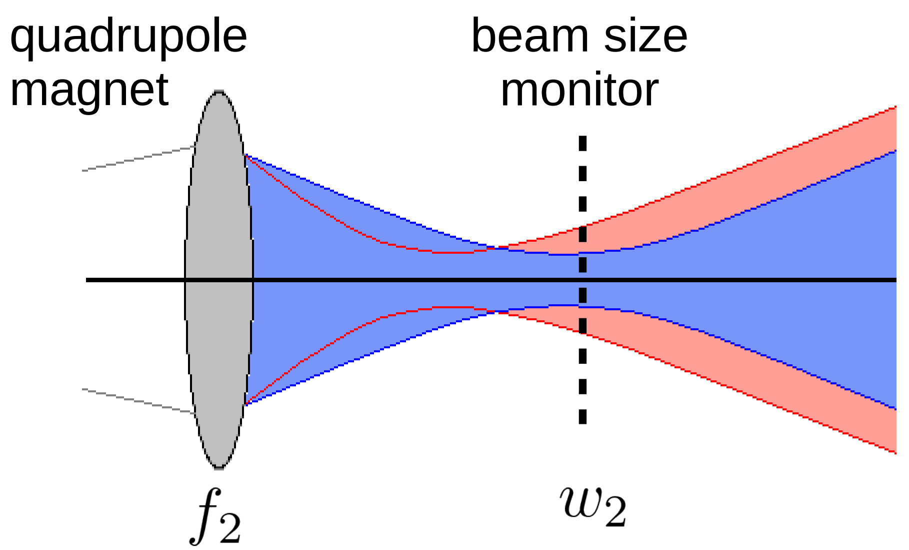
perturbing
(at least)

Quadrupole scan



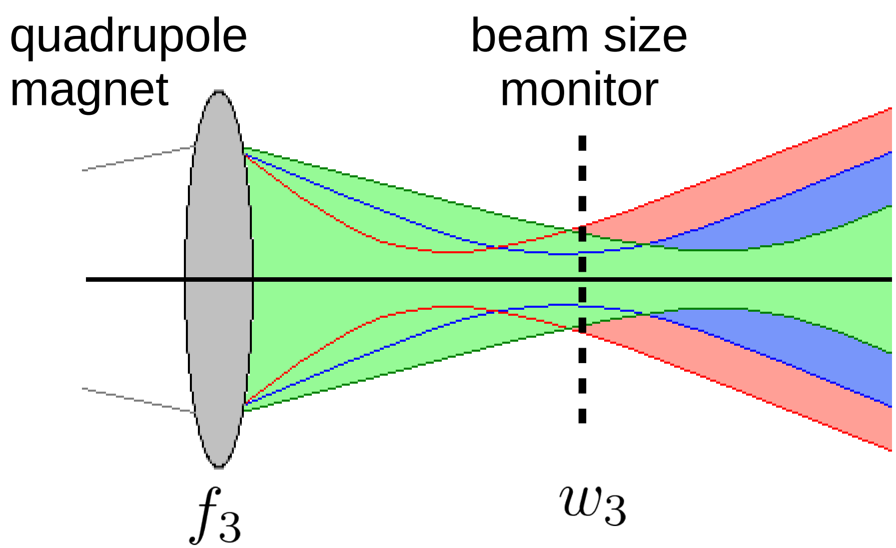
- Measure the beam size w_1 behind a quadrupole with setting f_1.

Quadrupole scan



- Measure the beam size w_1 behind a quadrupole with setting f_1.
- Change the quadrupole setting and measure the beam size again.

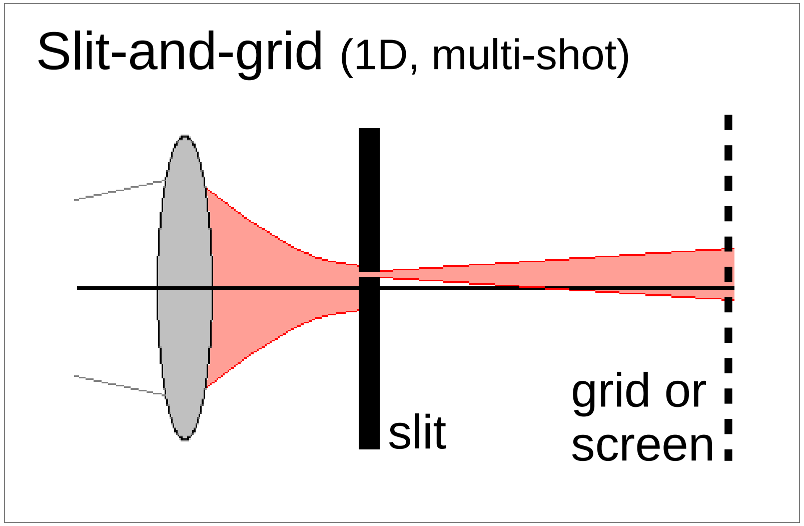
Quadrupole scan

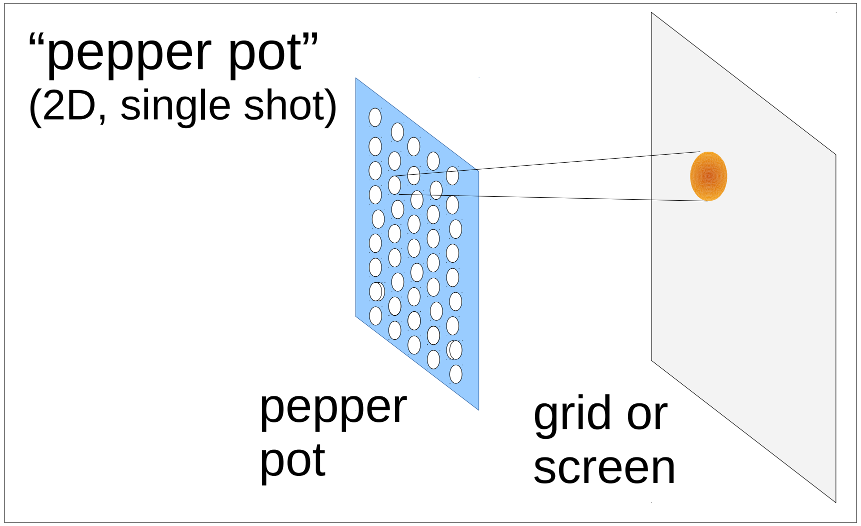


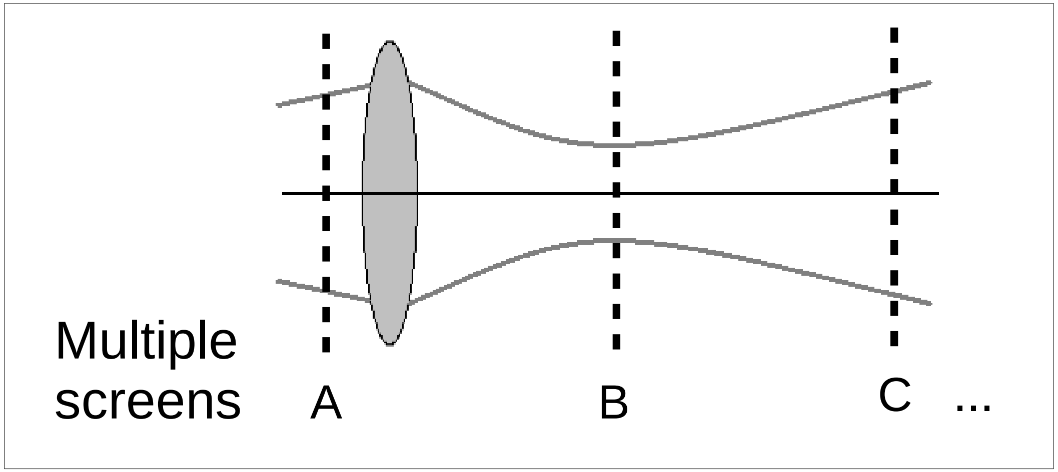
- Measure the beam size w_1 behind a quadrupole with setting f_1.
- Change the quadrupole setting and measure the beam size again.
- Repeat until you have at least three measurements. With the transfer matrix known you now have enough information to extract the incoming beam parameters.

Emittance measurements

There are other methods to determine the emittance:



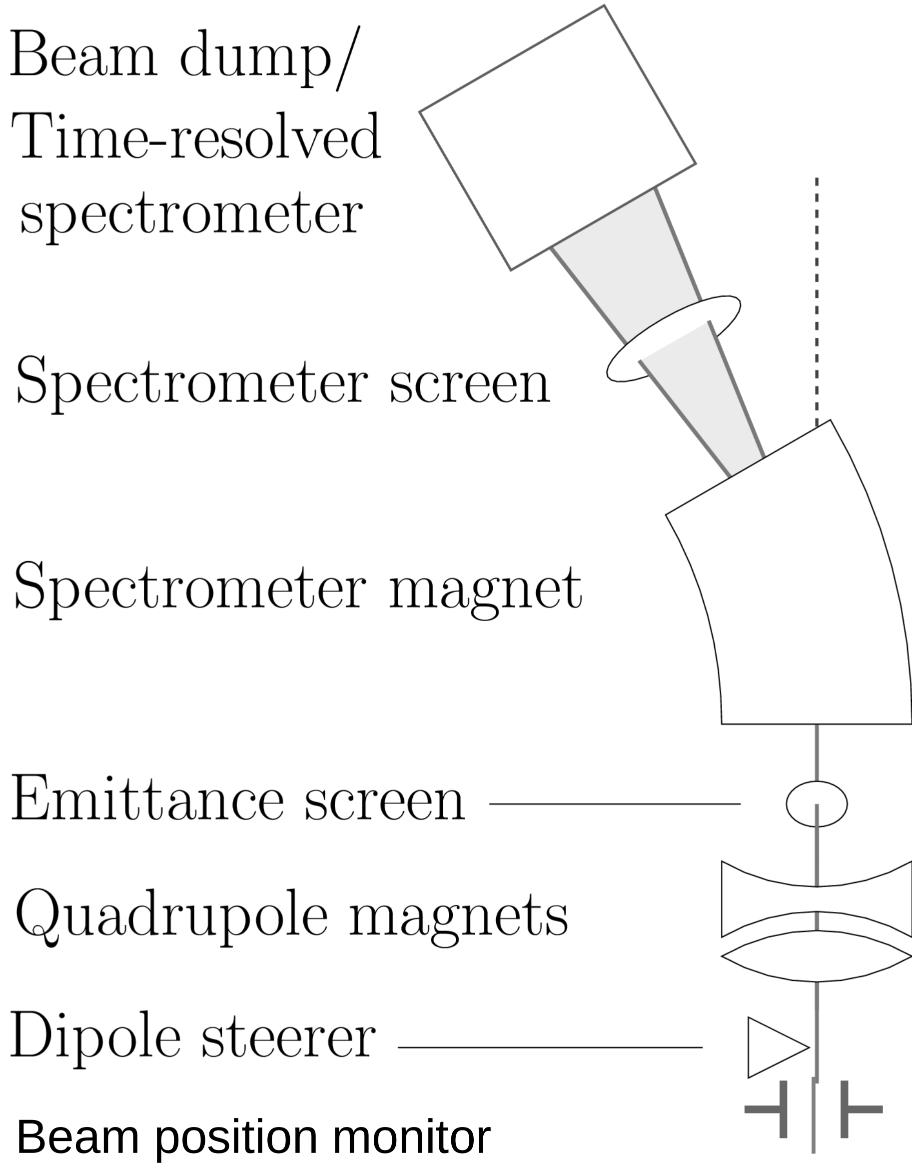




There are many more out there...

- Residual gas monitor (transverse profile)
- Optical diffraction radiation (transverse and longitudinal size)
- Synchrotron light monitor (transverse and longitudinal profile)
- Cherenkov radiation monitor (various)
- Feschenko monitor (bunch shape)
- Shintake monitor (nm scale beam size)
- Microchannel plate, MCP (transverse profile)
- Ionization chamber (beam loss)
- Solid-state Ion chamber, PIN photodiode (beam loss)
- Scintillation counters (beam loss)
- ...

Example: Diagnostics sector



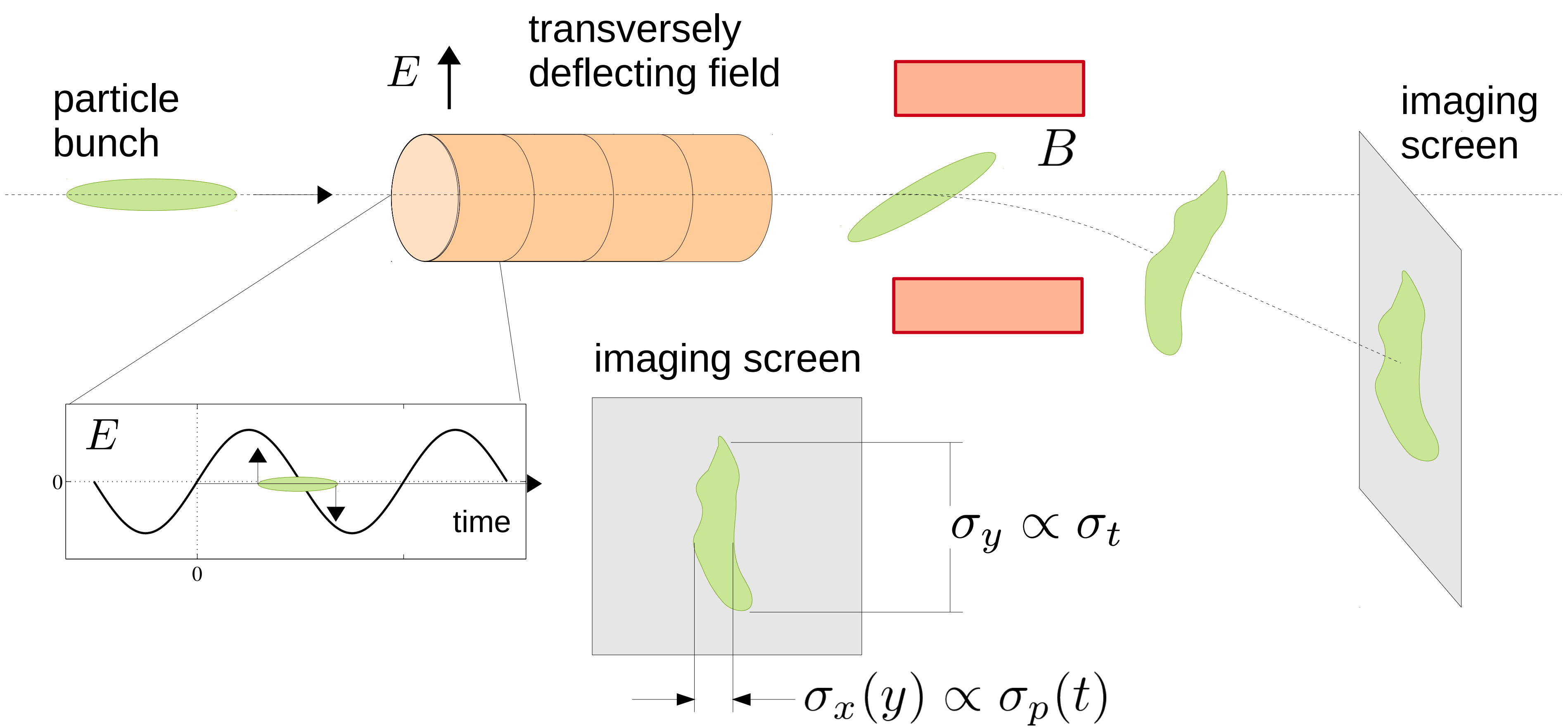
An accelerator sector where many parameters can be measured together:

- Beam position and current with a BPM
- Transverse emittance and Twiss parameters through a quadrupole scan and a screen
- High resolution (average) and Time-resolved momentum profile with a screen and a multi-array Faraday cup in a spectrometer line
- In addition, together with a streak camera the emittance screen can be used for bunch length measurements.

The layout is taken from the Compact LInear Collider Test Facility at CERN.

Combination measurements

- A transversely deflecting cavity + a spectrometer magnet
  - energy distribution and beam size variation within a bunch.



Measurement & Instrument Quality

Measurement & Instrument Quality

precision

resolution

trueness

accuracy

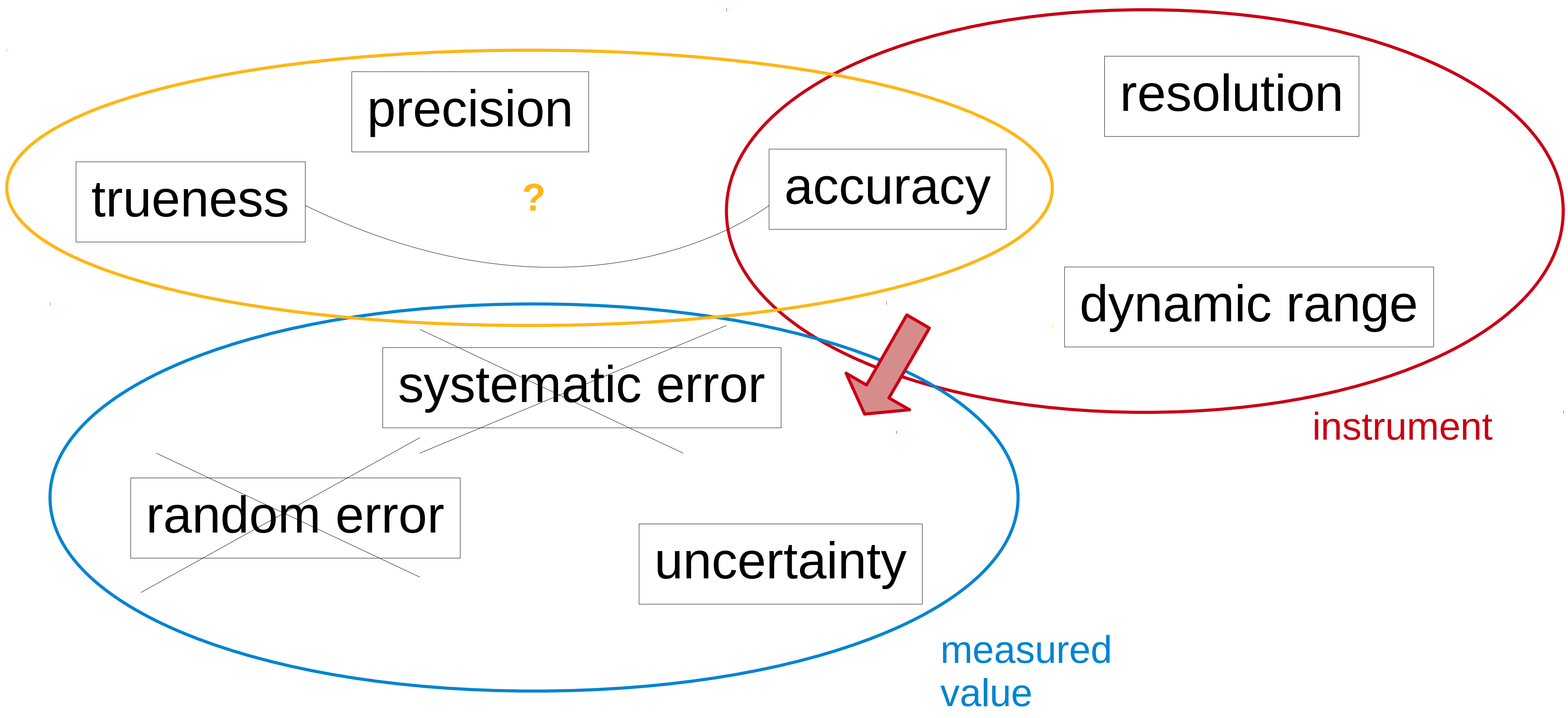
dynamic range

systematic error

random error

uncertainty

Measurement & Instrument Quality



It is preferable to talk about the *uncertainty* connected to a measurement value.
Errors should be corrected.

Measurement & Instrument Quality

resolution — the **fineness** to which an instrument can be read.

precision — the **fineness** to which an instrument can be read **repeatably and reliably**.

accuracy — the **correctness** of a measurement value. trueness

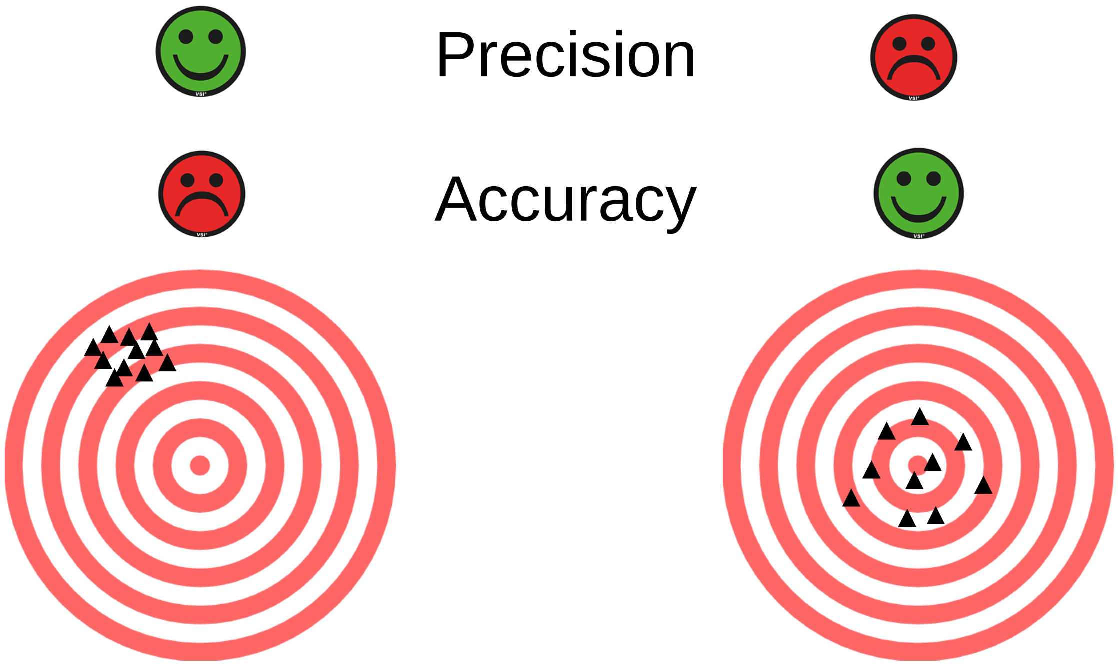
Source: http://www.tutelman.com/golf/measure/precision.php
Read more: https://en.wikipedia.org/wiki/Accuracy_and_precision

dynamic range — the **ratio** between the **largest and smallest** measurable values

Precision Vs. Accuracy

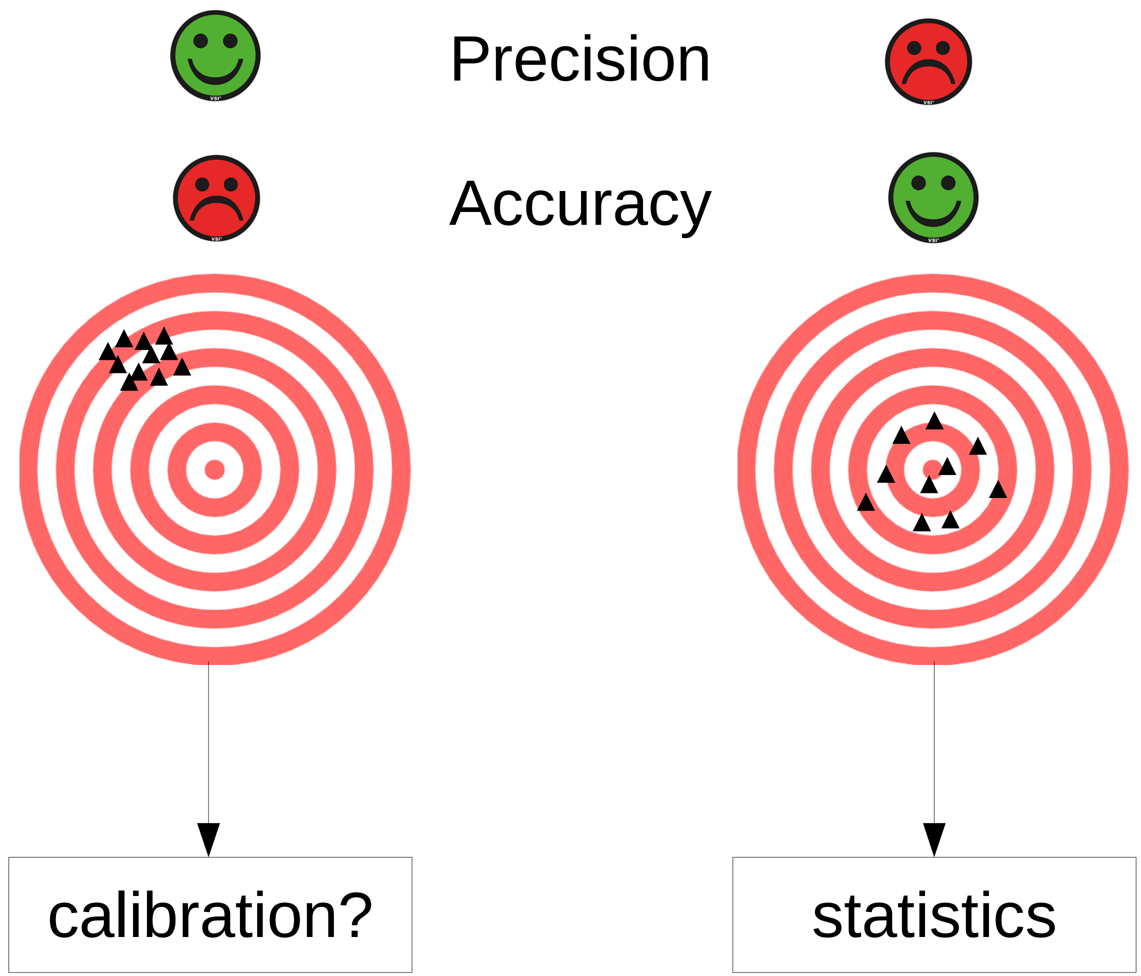
?	Precision	?
?	Accuracy	?

Precision Vs. Accuracy



How improve?

Precision Vs. Accuracy

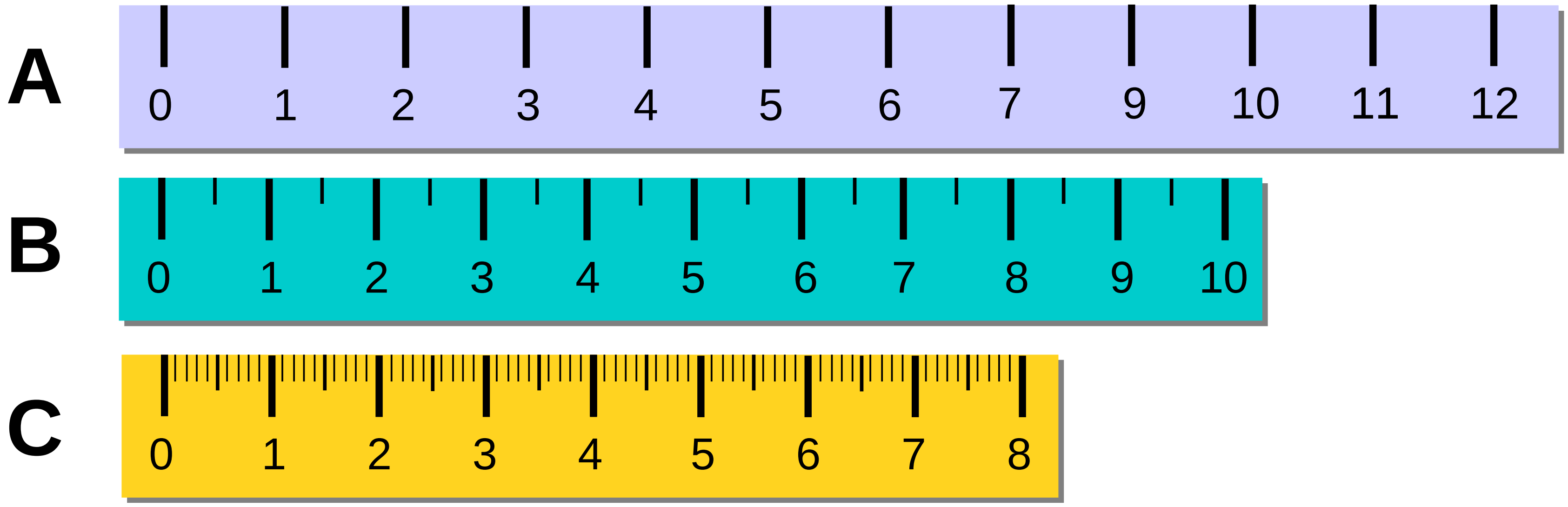


Instrument Performance

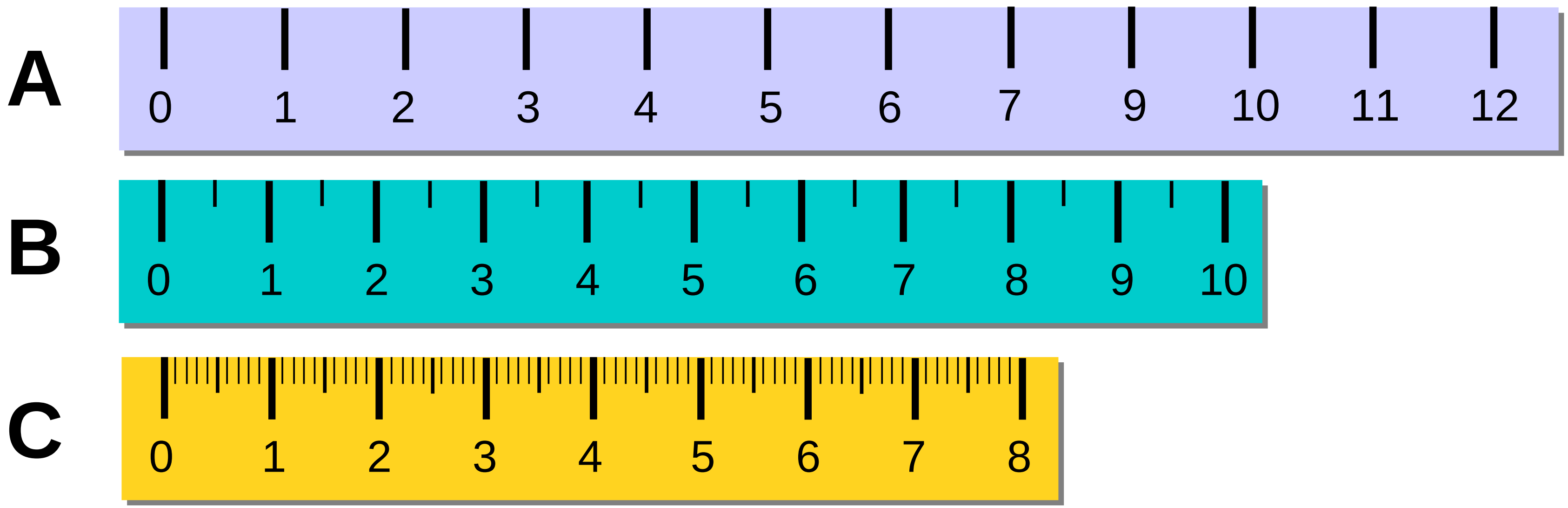
resolution

accuracy

dynamic range



Instrument Performance



Which ruler has the....

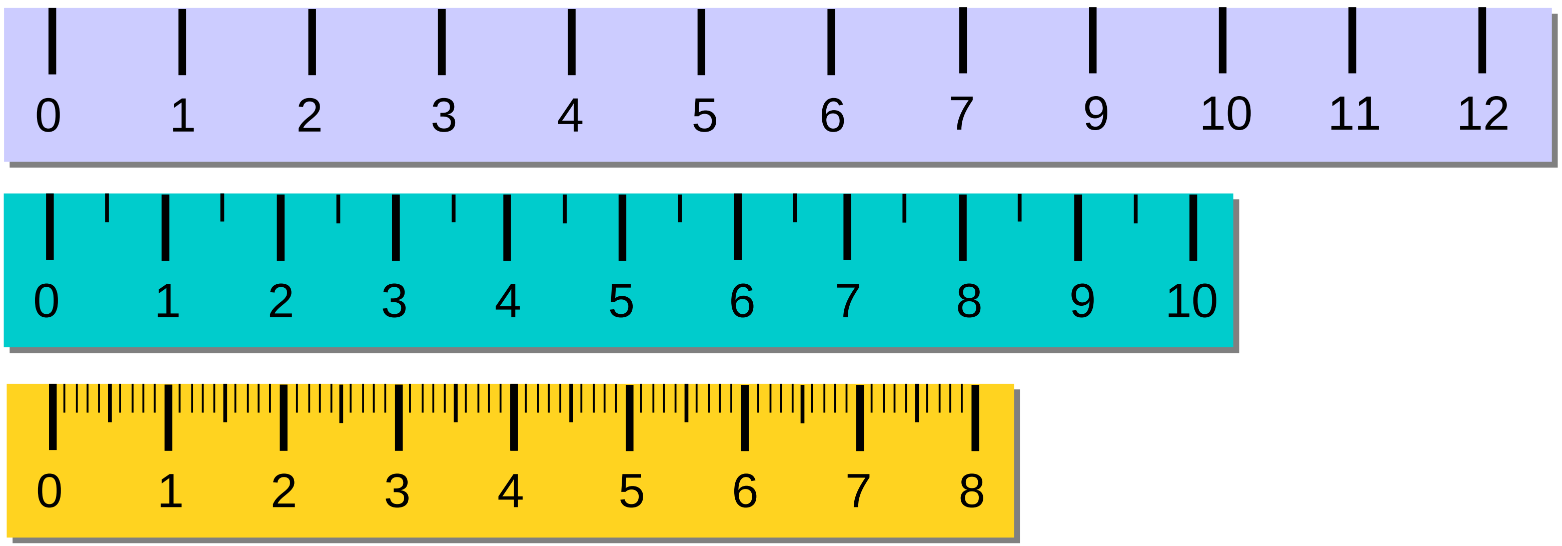
	A	B	C	neither
• ... highest *resolution*?	☐	☐	☐	☐
• ... highest *dynamic range*?	☐	☐	☐	☐
• ... highest *accuracy*?	☐	☐	☐	☐

Instrument Performance

A

B

C



Which ruler has the....

	A	B	C	neither
• ... highest *resolution*?	X			
• ... highest *dynamic range*?	X			
• ... highest *accuracy*?				X

Example: BPM

DEVELOPMENT OF NANOMETER RESOLUTION RF-BPMs

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Abstract:
The future e+e- linear colliders will use high resolution and high accuracy BPMs. A highest resolution of 10 nm is required for the beam-based alignment of magnetic elements in the final focus system. Very tight zero-point center accuracy, in the range of 1 to 10 μm, is required to align the accelerating structures in the main linac. The cavity type RF-BPM (Radio Frequency Beam Position Monitor) is one of the best candidates to meet those demands.

This paper describes a brief history of high resolution RF-BPM development, the beam test of C-band BPM at FFTB beam line, analytical models of resolution and accuracy in a simple pillbox-cavity BPM.

1. Introduction

Future linear colliders [1] will require high performance BPMs to control the beam trajectory with high precision in order to maintain a stable collision of required.

Among various type of BPMs, such as the electrostatic BPM using four button-pickups or the stripline type BPM, only the cavity RF-BPM has a potentiality to achieve the resolution of nm range and the center accuracy of μm level.

According to the accelerating structure alignment, there is another scheme, which is under development at NLC project. The wakefield power induced in the accelerating structure will provide direct information of the cavity displacement from the beam. The TM110 mode in the accelerating structure can be to detect the beam position. This idea is so called the structure BPM, which is planed to be used in the NLC design and its powerfulness was demonstrated with beam in ASSET test [4]. Since the basic mechanism in this scheme is exactly same as that in the cavity RF-BPM, we will focus our discussions into the cavity RF-BPM in this paper.

Summary

- Beam instrumentation (detector) and diagnostics (method) are necessary to
  - understand and control the accelerator
  - protect people and equipment
- Each machine has its requirements depending on
  - beam intensity
  - beam size,
  - beam energy and power
  - time structure
  - availability...

A few final words

An accelerator can never be better than the instruments measuring its performance!

- Beam instrumentation specialists get to combine their knowledge from many areas of physics:
  - particle and beam physics, detector physics and technology, electromagnetism, material science
  - electronics, mechanics, computing, numerical analysis, signal processing
  - ...and much more!
- So, it's a fun, challenging and important field to be in!

UPPSALA UNIVERSITET

“To think right is great,

but to measure right is greater”

Motto of the High Energy Physics Division at Uppsala University

Free adaptation of Uppsala University's motto:

“To think free is great, but to think right is greater”

(Thomas Thorild, 1794)

Literature

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    - CERN Yellow Report: CERN-2009-005
      - http://cdsweb.cern.ch/record/1071486/files/cern-2009-005.pdf
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    - CERN Yellow Report: CERN-2006-002
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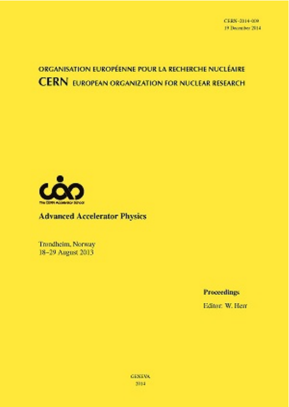
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Advanced Accelerator Physics

Trondheim, Norway
18–29 August 2013

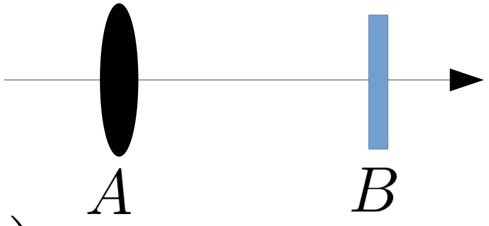
Proceedings
Editor: W. Herr

GENEVA
2014

Extra slides

Quadrupole scan

- Assume a section of an accelerator with a beam size monitor behind at least one quadrupole magnet. We assume that the transfer matrix R from the (first) quadrupole to the monitor is known.



- Remember that the sigma matrix is defined as

$$\bar{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} = \begin{pmatrix} \langle x^2 \rangle & \langle x x' \rangle \\ \langle x x' \rangle & \langle x'^2 \rangle \end{pmatrix}$$

$$w^2 = \sigma_{11} = \varepsilon\beta$$

- The sigma matrix is transported from A to B using R:

★ $\bar{\sigma}_B = R\bar{\sigma}_A R^T$ with $R = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}$

- Let's assume an incoming beam defined by the sigma matrix above and let w be the beam size on the screen. We can expand the matrix equation ★ ...

Quadrupole scan, cont. a)

- ... and express the beam size on the screen as

$$\bigstar \Longrightarrow w^2 = \sigma_{11} R_{11}^2 + \sigma_{12} 2 R_{11} R_{12} + \sigma_2 R_{12}^2$$

incoming beam (σ_{11}, σ_{12}, σ_2)

changes with quad setting (R_{11}^2, $R_{11}R_{12}$, R_{12}^2)

- For every quadrupole setting f_i, a new beam size w_i:

$$w_i^2 = \sigma_{11} R_{11}^2(f_i) + \sigma_{12} 2 R_{11}(f_i) R_{12}(f_i) + \sigma_2 R_{12}^2(f_i)$$

- We repeat the measurement and obtain a system of equations

$$\begin{pmatrix} w_1^2 \\ w_2^2 \\ \vdots \\ w_n^2 \end{pmatrix} = \begin{pmatrix} R_{11}^2(f_1) & R_{11}(f_1)R_{12}(f_1) & R_{22}^2(f_1) \\ R_{11}^2(f_2) & R_{11}(f_2)R_{12}(f_2) & R_{22}^2(f_2) \\ \vdots & \vdots & \vdots \\ R_{11}^2(f_n) & R_{11}(f_n)R_{12}(f_n) & R_{22}^2(f_n) \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix}$$

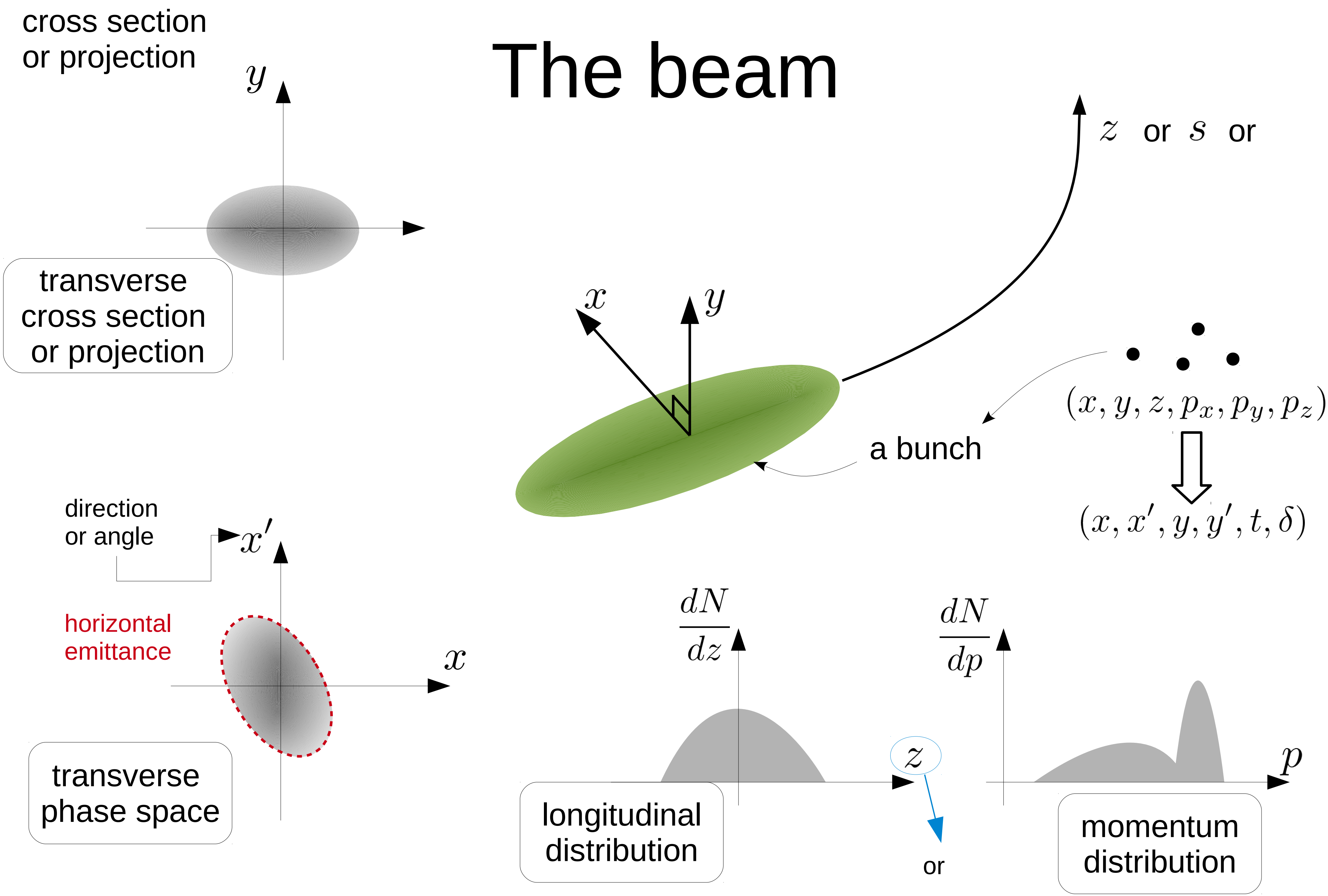
$\bar{u}$ M $\bar{v}$

Quadrupole scan, cont. b)

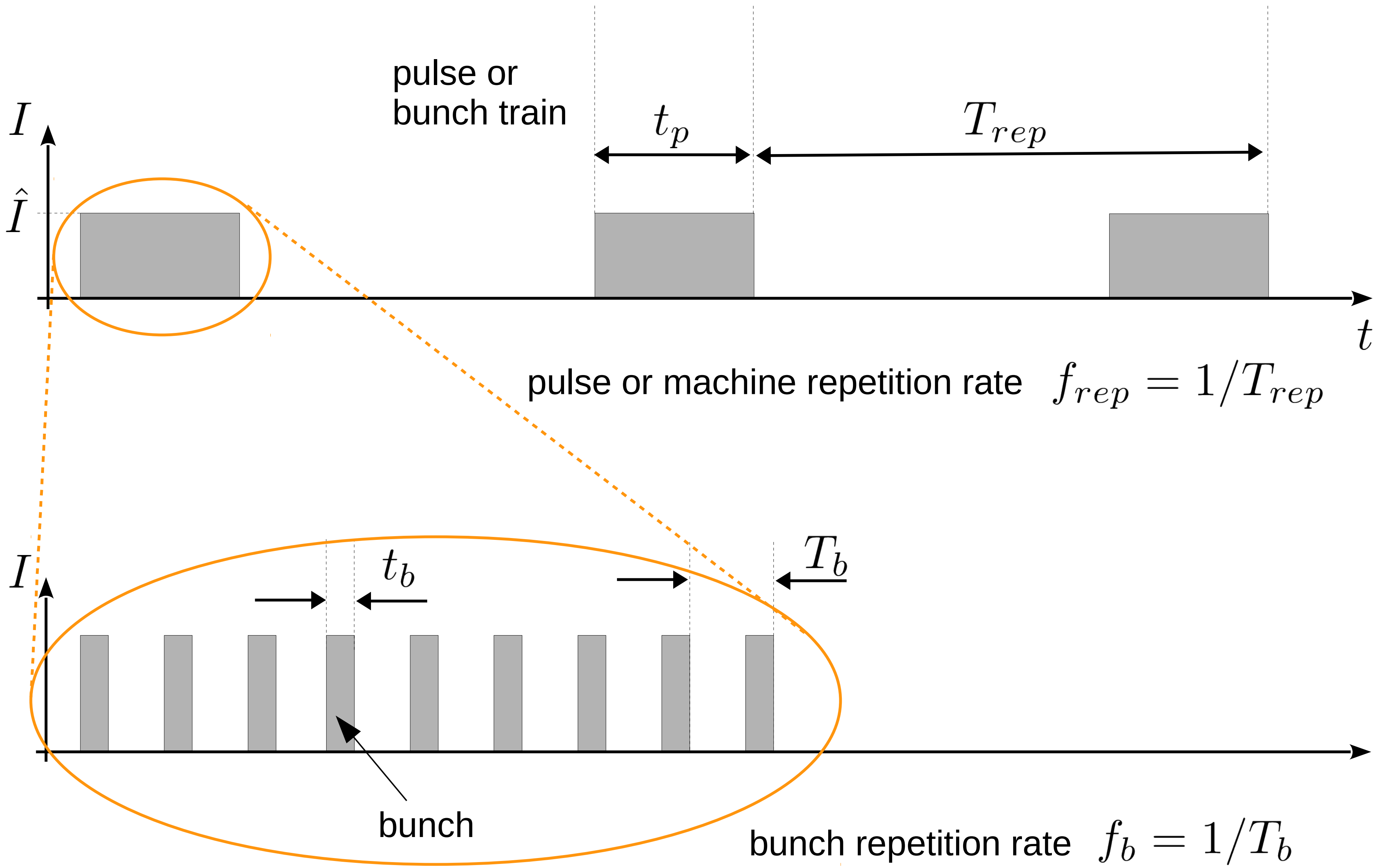
- We now have the matrix equation $\bar{u} = M\bar{v}$ which we want to solve fore $\bar{v}$.
- In the least-squares sense we have $\bar{v} = (M^T M)^{-1} M^T \bar{u}$
- Finally, we extract the Twiss parameters from $\bar{v} = \begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix}$:

$$\varepsilon = \sqrt{\det(\sigma)} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2} \qquad \beta = \sigma_{11}/\varepsilon \qquad \alpha = -\sigma_{12}/\varepsilon$$

The beam


cross section
or projection
y
transverse
cross section
or projection
z or s or
x
y
(x, y, z, p_x, p_y, p_z)
a bunch
$(x, x', y, y', t, \delta)$
direction
or angle
x'
horizontal
emittance
x
transverse
phase space
$\frac{dN}{dz}$
z
or
longitudinal
distribution
$\frac{dN}{dp}$
p
momentum
distribution

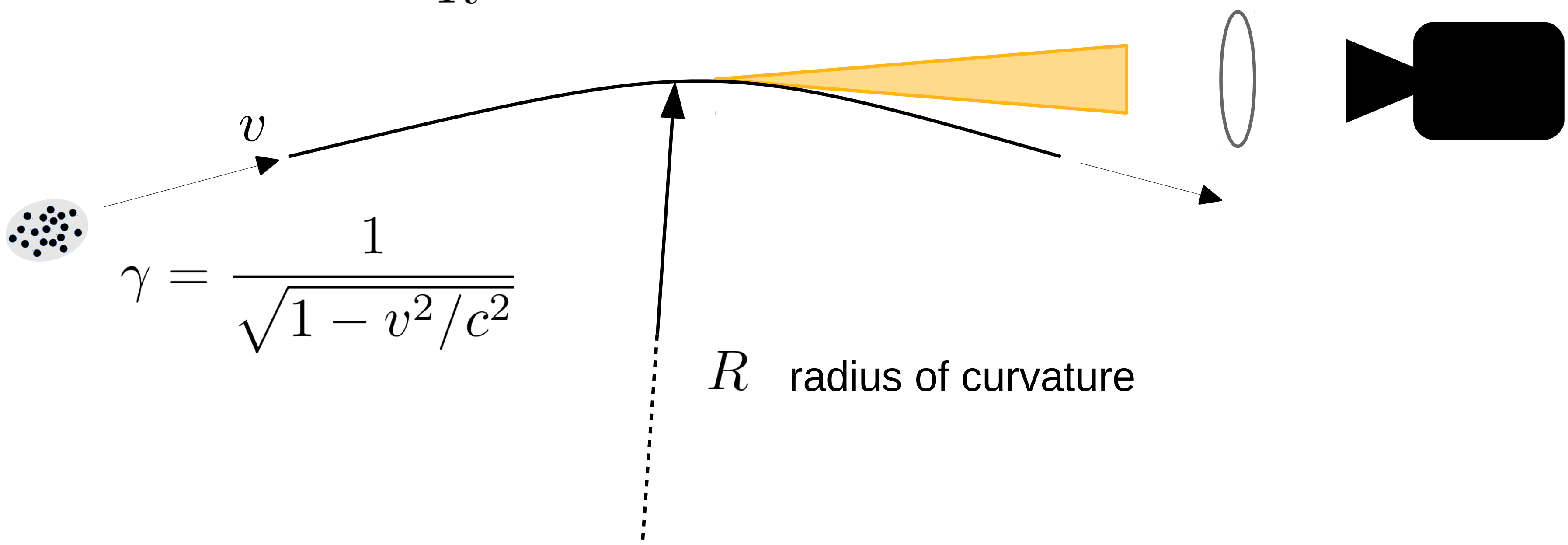
Beam structure



Synchrotron radiation

A charged particle will if accelerated emit energy in form of *synchrotron radiation* (described by classical electrodynamics). For relativistic particles it can be a substantial amount of energy if the acceleration is perpendicular to the direction of motion.

Radiated power: $P \propto \dfrac{\gamma^4}{R^2}$



$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

Note: Details of synchrotron radiation will be presented by Sverker Werin on Friday.