

Introduction to diagnostics for particle accelerators

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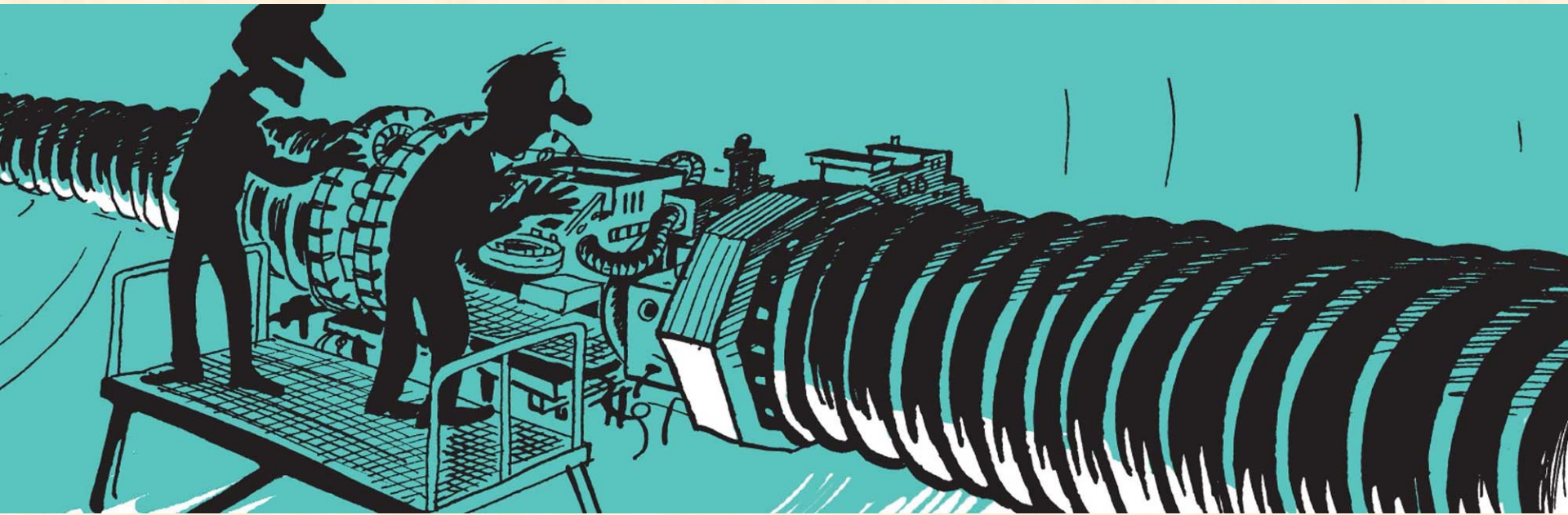


Content

- Why use diagnostics?
- How do they work?
- Which measurements?
- Examples of diagnostics
- Diagnostics in real life
- R&D diagnostics in France

WHY USE DIAGNOSTICS ON AN ACCELERATOR?

How can we know what happens inside the accelerator?



© Editions Dupuis https://bdi.dlpdomain.com/serie/visuel/BDA_15997/1.jpg

- Just by looking at the accelerator you can't know what is going on inside.

How can we know what happens inside the accelerator?

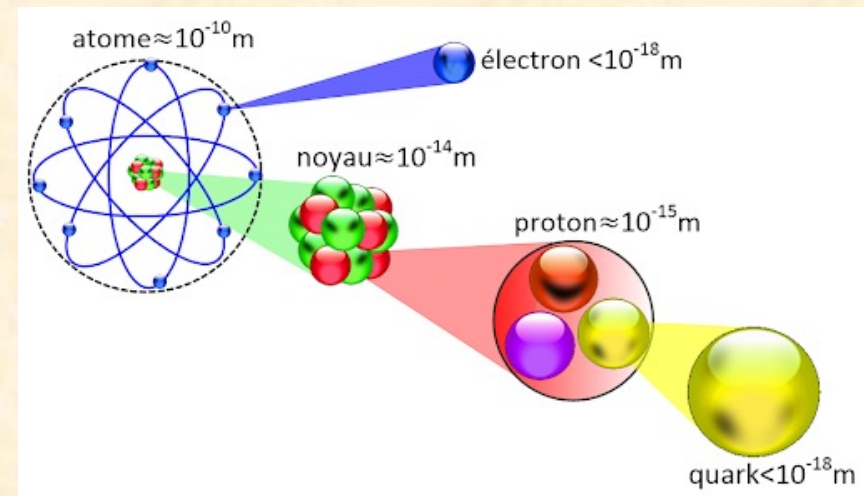


© Chapatte <https://www.chapatte.com/images/jour-historique-au-cern/>

- To know what happens inside the accelerator we need diagnostics.

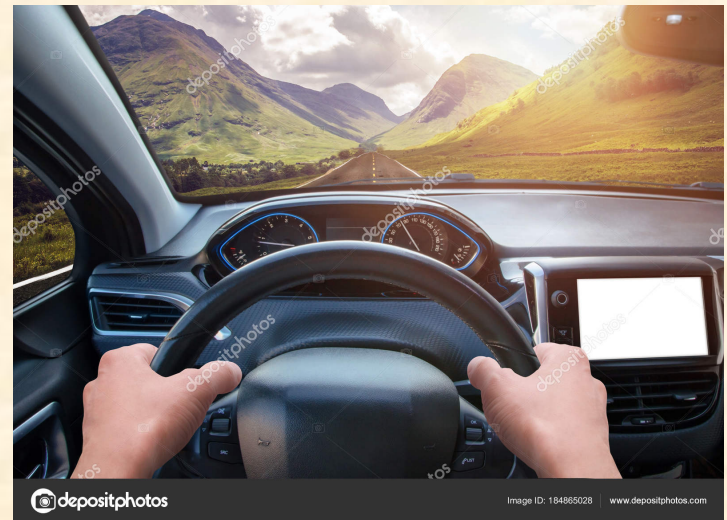
Looking inside the accelerator

- Particles are too small to be seen
- They are smaller than visible photons
- Orders of magnitude:
 - Visible photon:
 ~ 500 nanometre ($5 \times 10^{-7} \text{m}$)
 - Proton:
 $\sim 0,8$ femtometre ($8 \times 10^{-16} \text{m}$)
1 billion times less than a (visible) photon!
 - Electron:
 > 1 attometre (10^{-18}m)
1000 billion time less than a (visible) photon!
- We need to use tools to « see » what happens inside the accelerator.



Why look inside the accelerator?

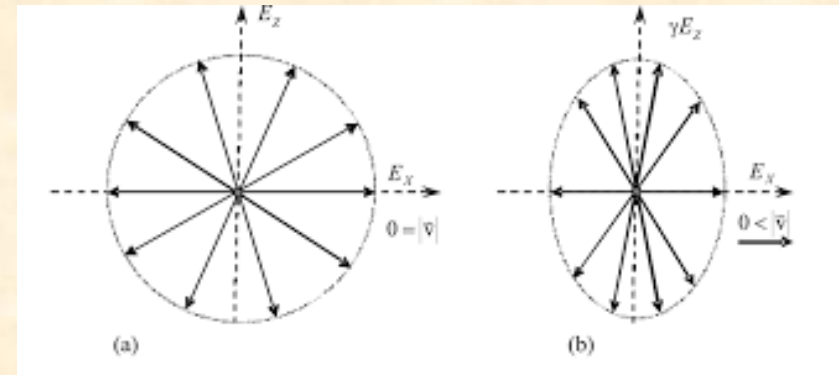
- To tune an accelerator one needs:
 - To know what's happening
 - To know the effects of the settings applied
- Tuning an accelerator without diagnostics would be like driving a car with closed eyes.



HOW DO DIAGNOSTICS ON ACCELERATOR WORK?

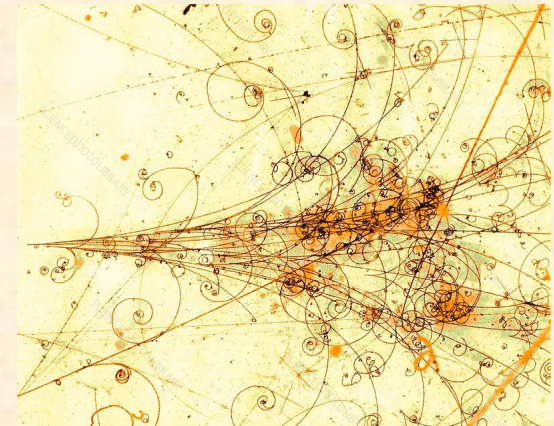
How to look inside the accelerator?

- Particles are too small to be seen.
- To see them it is necessary to use their physical properties:
 - Radiation emitted by particles
 - Interaction of the particles with matter



Source:

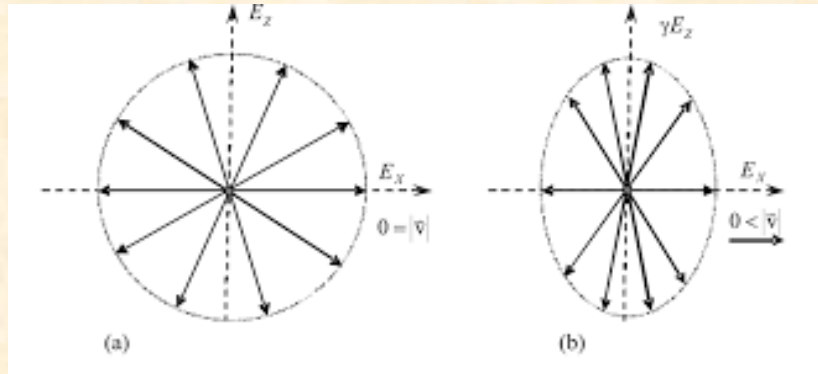
<https://www.quora.com/How-did-Feynman-explain-that-magnetic-fields-are-created-by-moving-charges-due-to-length-contraction>



Source:

<https://www.sciencephoto.com/media/106032/view/electromagnetic-particle-shower>

Radiation emitted by charged particles



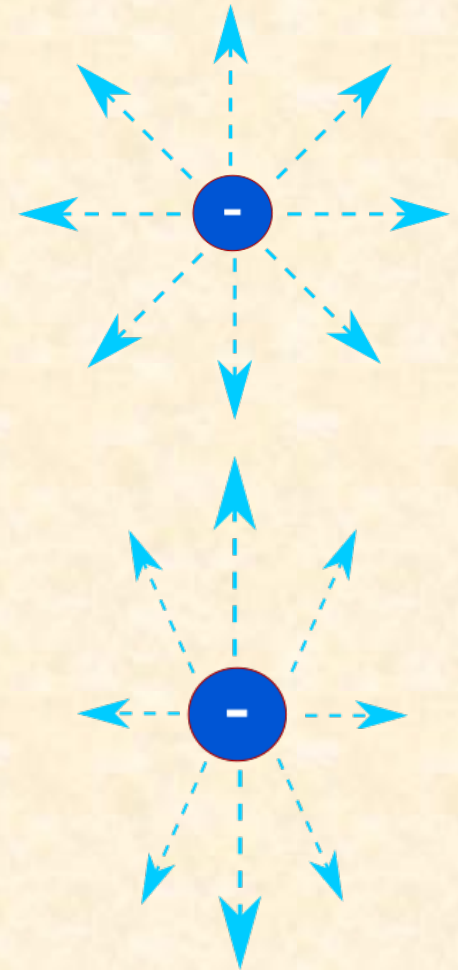
Source:

<https://www.quora.com/How-did-Feynman-explain-that-magnetic-fields-are-created-by-moving-charges-due-to-length-contraction>

- Particles accelerated in accelerators are charged.
- Electromagnetism laws indicate that when accelerated these particles will emit electromagnetic radiation (radio waves, visible light,...).

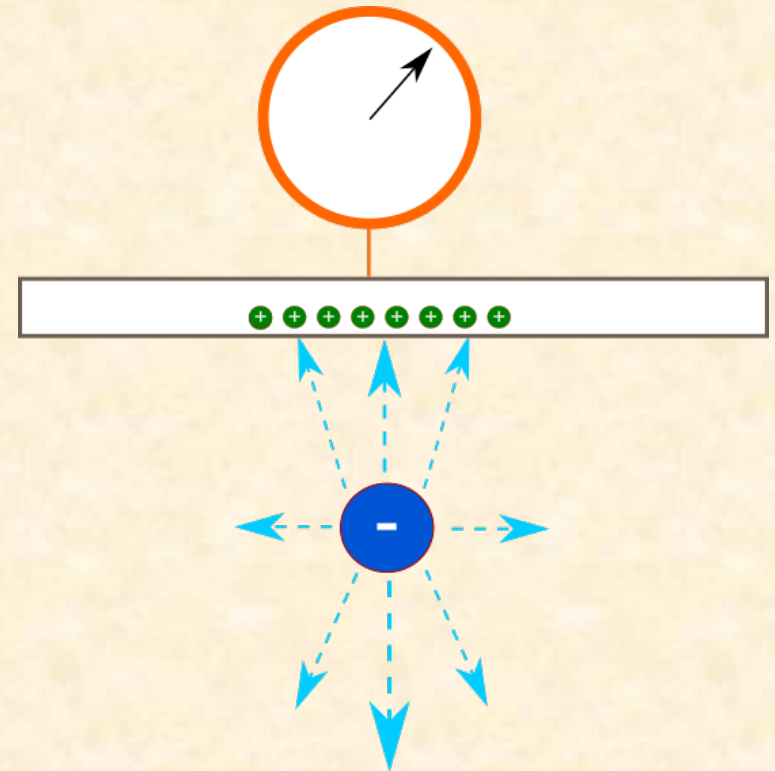
Radiation emitted by charged particles

- A charged particle is surrounded by electric field lines.
- When accelerated these fields lines will be compressed.



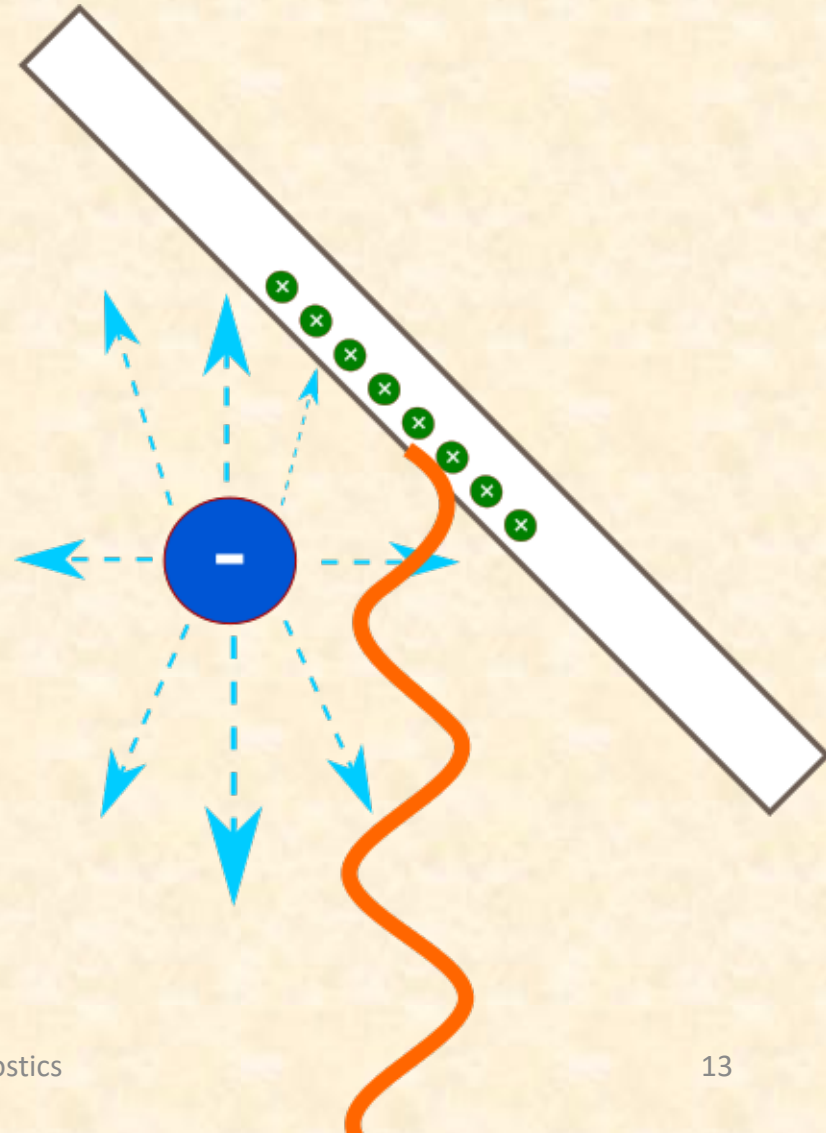
Radiation emitted by charged particles

- Field lines of a charged particle propagating near a conductor will induce a current in this conductor.
- This current can be measured.
- The intensity of this current will depend on the charge and the position of the particles.



Radiation emitted by charged particles

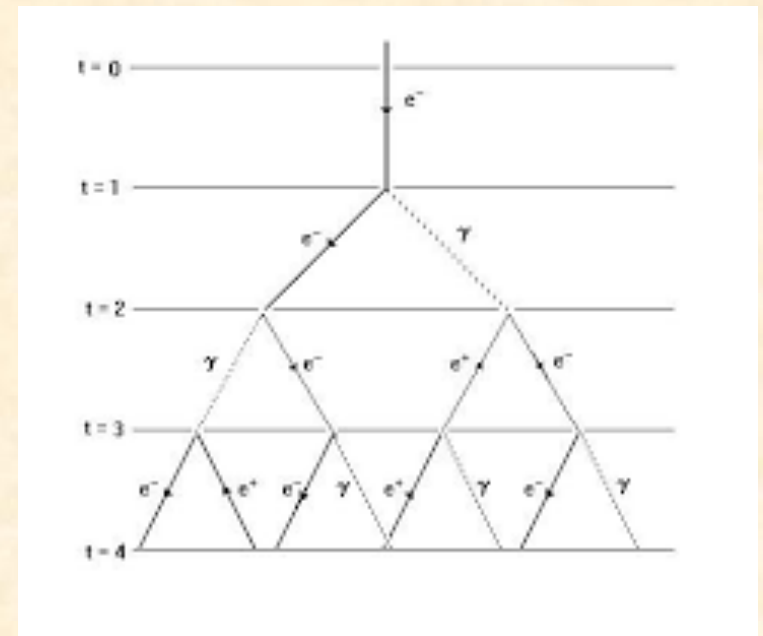
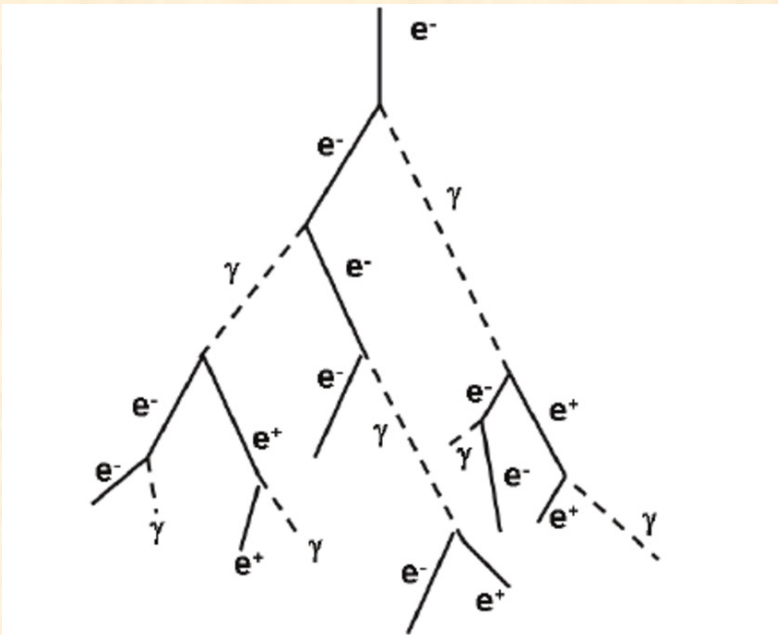
- If a particle crosses a conductor, radiation is emitted due to the change in permittivity as the particle reaches the surface of that conductor.



Interactions

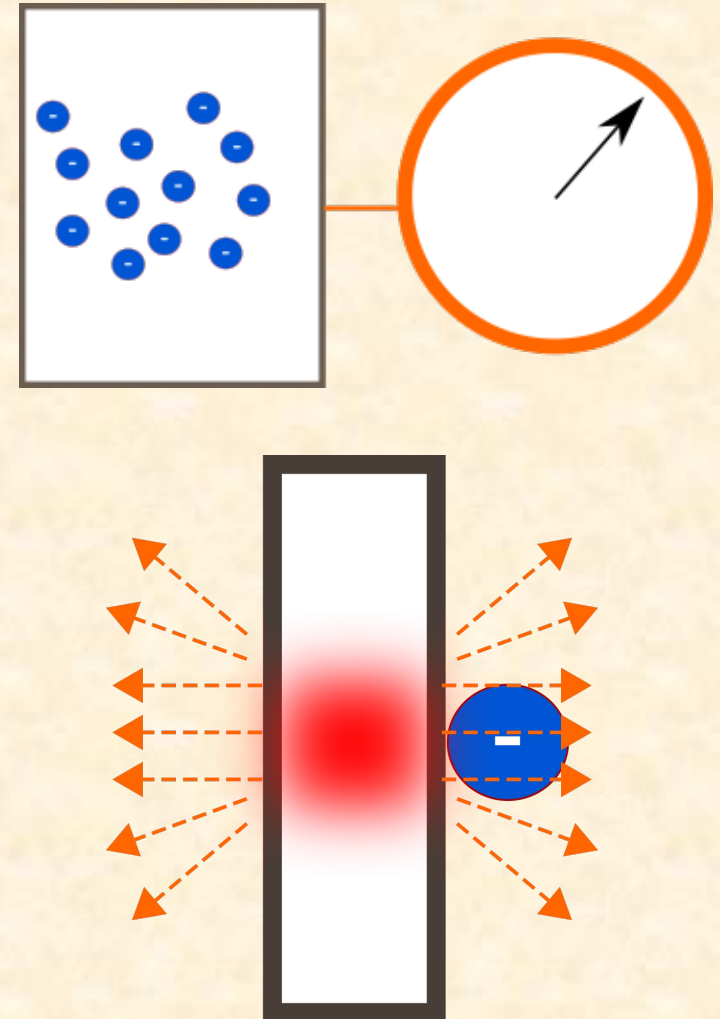
particles-matter

- When a particle interacts with matter it deposits energy as heat and as photons. These photons can lead to the formation of pairs of particles-antiparticles. This will lead to the formation of an electromagnetic shower.



Interactions particles-matter

- If the absorber (block of matter) is large enough to contain the full electromagnetic shower, the number of charges deposited is equal to the charge of the beam.
- By depositing energy in a fluorescent screen the particles will create light emission, allowing to visualise the beam's profile.



Shaping the signal

- Nowadays almost all signals from the accelerators are digitised.



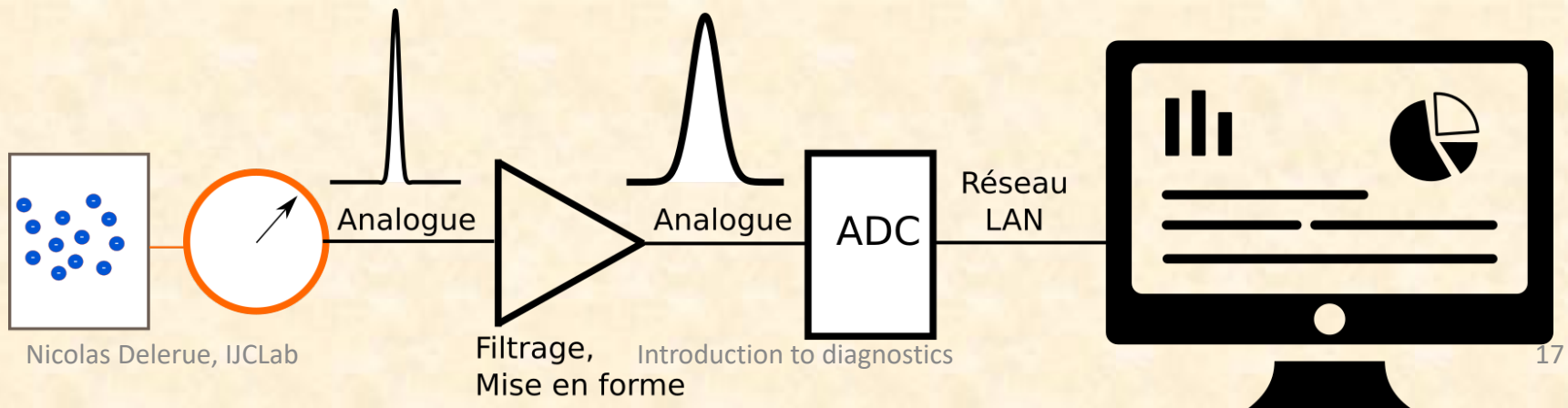
Nicolas Delerue, IJCLab



Introduction to diagnostics Source: <https://cds.cern.ch/>

Shaping the signal

- To go from the equipment where it is produced to the computer where it is digitised, it has to be shaped.
- In some accelerators the pulses have a duration of only a few picoseconds. The shaping must adjust that duration to the sampling frequency of the digitisers.



Indirect measurements

- Some quantities are not directly accessible.
- For example the emittance, the machine tune...
- For these quantities the value can be inferred from a combination of two or more measurements (eg: beam size at different location for the emittance).

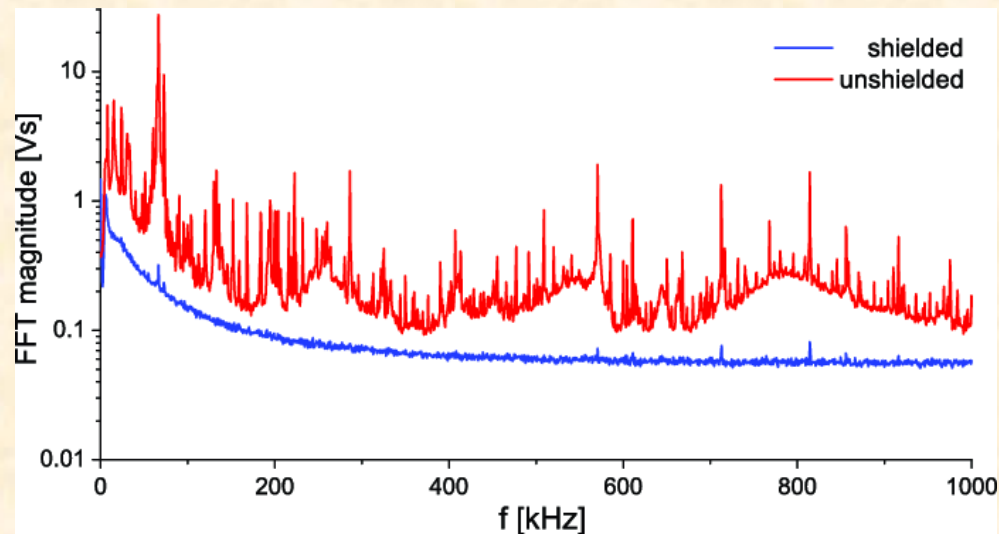
Ultra high vacuum

- Diagnostics used in accelerator must be compatible with Ultra High Vacuum.
- This requires special manipulators for anything that needs to be moved inside the beam pipe.



Electromagnetic noise and grounding

- In an accelerator there is a lot of electromagnetic noise.
- This can create fake signals or damage equipments.
- Countermeasures such as detectors grounding or shielding must be taken.
- Grounding of detectors is also necessary to prevent electrostatic discharges.



Linear or circular?

- The type of accelerator will affect the type of detectors you can use.
- Intercepting detectors should mostly be used on linear accelerators. In circular accelerator they prevent the beam from circulating.
- In circular accelerators, the large number of turn allows the detection of weaker signals or a better signal over noise ratio.

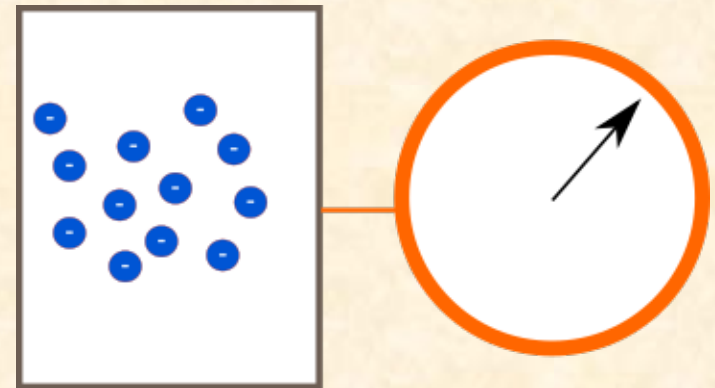
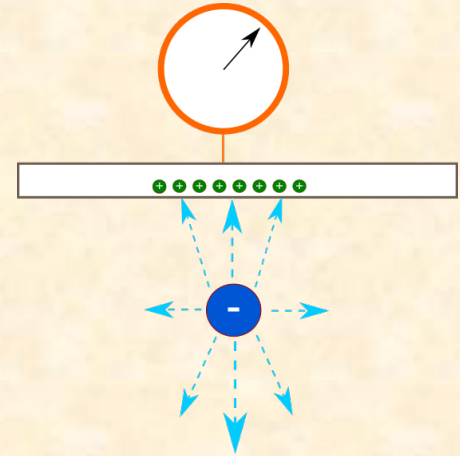
Leptons or hadrons?

- Electrons are 2000 lighter than protons
- Different penetration depth and activation

WHICH MEASUREMENTS CAN BE DONE WITH BEAM DIAGNOSTICS?

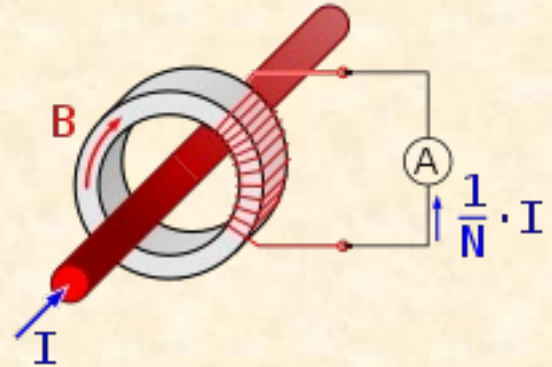
Charge measurement

- Charge can be measured two ways:
 - By measuring the current flowing in the beam pipe
=> current transformer
 - By measuring the charge deposited in a block of matter
=> Faraday cup

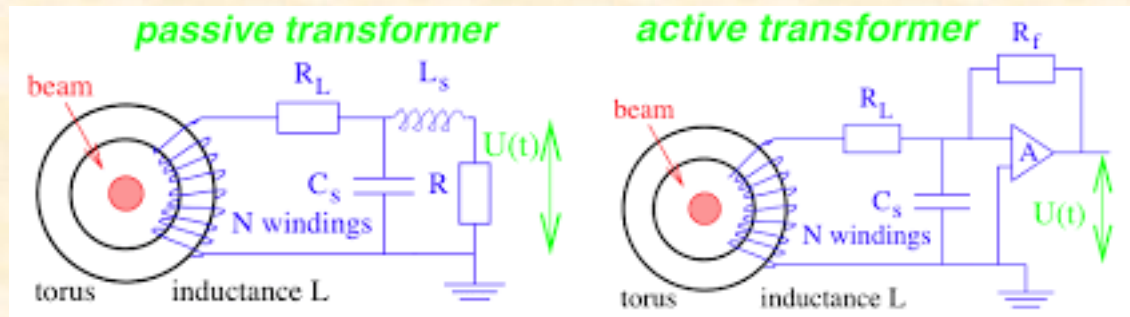


Current transformer

- Current transformer will measure the charge flowing through a toroid.
- Like a power transformer!
- Several flavours exist depending on the type of beams to be measured: AC, DC, short,...



AC Current transformer



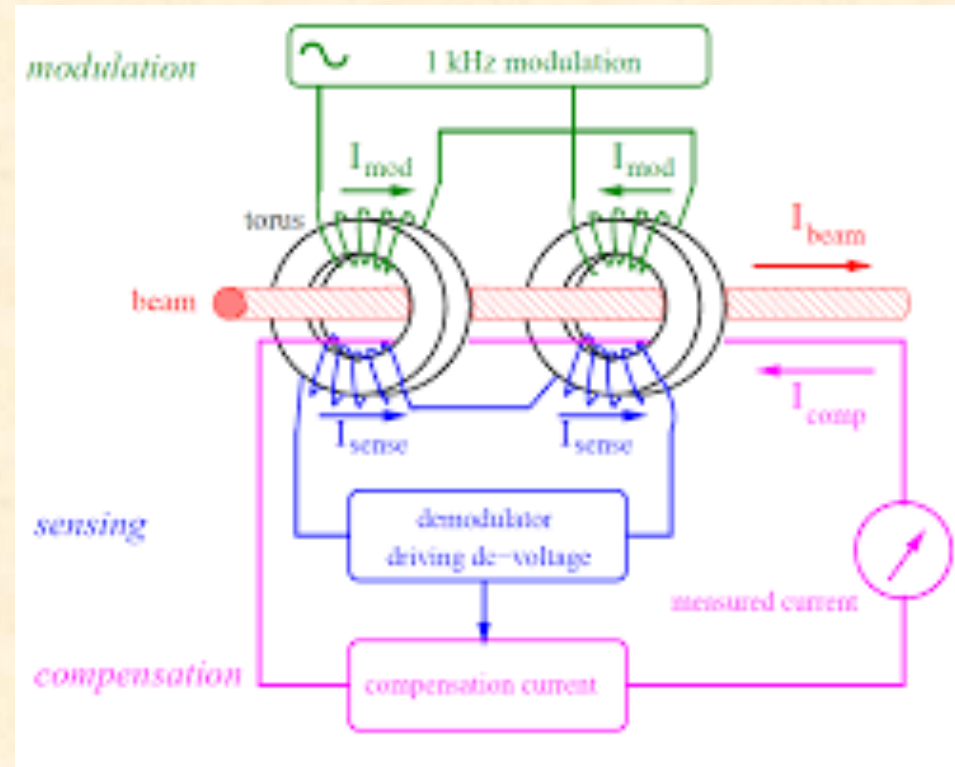
Source: Peter Forck, JUAS

- If the beam modulation are of the order of ns, then it will look like an AC current and an ACCT will be used.



DC Current transformer

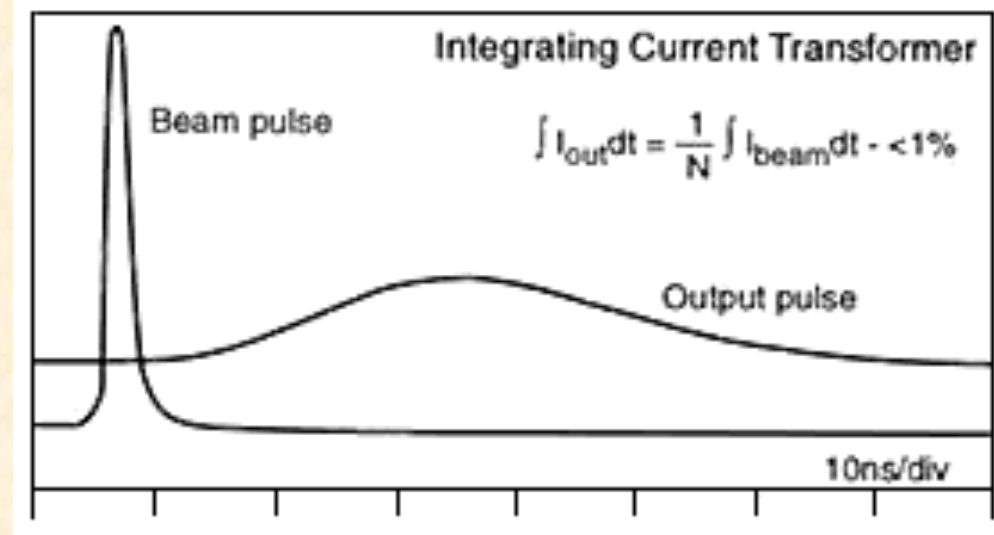
- If the beam is almost continuous a more complex DCCT will be used.
- Here the current measured is the current required to cancel the signal in the two toroids.



Source: Peter Forck, JUAS

Integrating Current transformer

- If the beam pulses are very short (picoseconds), it can't be recorded as is by the electronic.
- An integrating current transformer (ICT) with large capacitance will be used to smooth the pulse.



Source: Bergoz

Wall Current Monitors (WCT)

- For fast measurements a wall current monitor can be used.
- It consists of a dielectric insert in the beam pipe so that the current flowing in the beam pipe can be measured at one location.

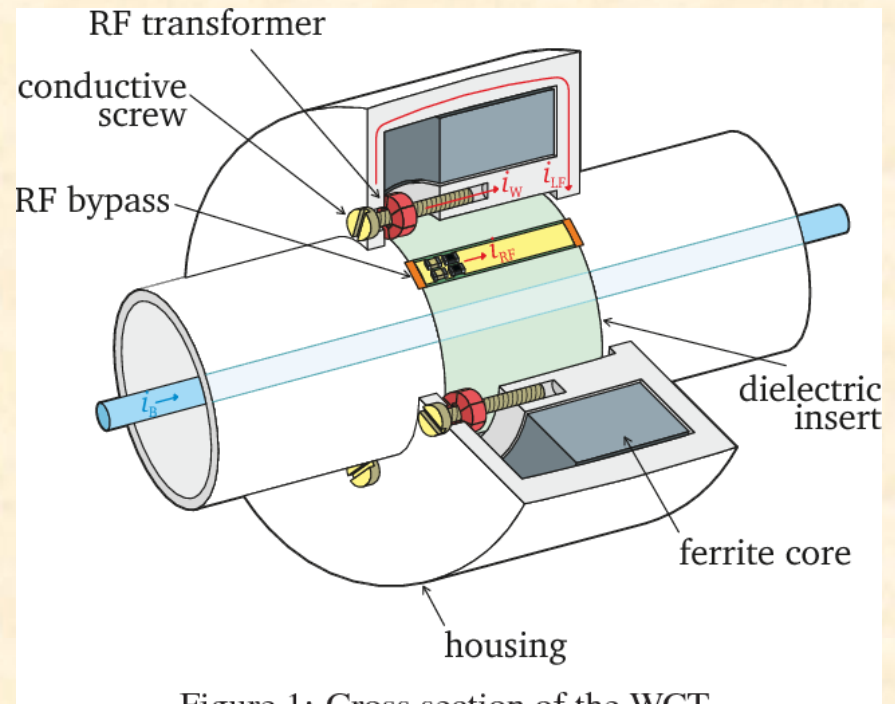


Figure 1: Cross section of the WCT

Source: CERN

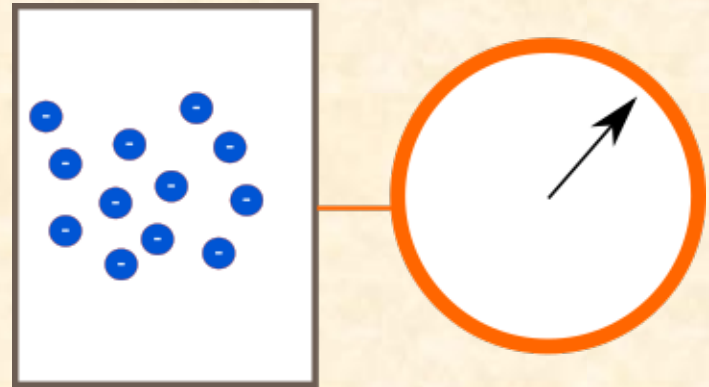
Quizz

Charge transformer

- Which quantity in Maxwell's equation is relevant for the performances of charge transformers?

Faraday cup

- Charges deposited in a block of matter will give the charge of the beam.
- At high energy a Faraday cup can be several metres long.
- To avoid backscattered particles the cup can be slightly biased.



Quizz

Faraday cup

- Estimate approximately the length of a Faraday cup made of Copper that must measure the charge of a 100MeV electron beam?
- How this length changes if the beam energy is 1GeV?
- How this length changes if the beam energy is 100MeV and the faraday cup is made of graphite?
- Reminder: the minimum ionization energy of copper is 12.57 MeV/cm and that of graphite is 3.85MeV/cm (see <https://pdg.lbl.gov/2020/AtomicNuclearProperties/index.html>)

Answer:

Faraday cup

- Electrons will deposit 12.57 MeV/cm.
- $100\text{MeV}/(12.57\text{MeV/cm}) \sim 8\text{cm}$
- The Faraday cup must be at least 8 cm.
- A margin of at least 50% must be added $\Rightarrow \sim 12\text{cm}$
- Beware that some secondary particles (neutrons,...) may travel further than that.
- $1\text{GeV} \Rightarrow 120\text{cm}$
- Graphite: $100\text{MeV}/(3.56\text{MeV/cm}) \sim 26\text{cm}$
 $+50\% \Rightarrow 39\text{cm}.$

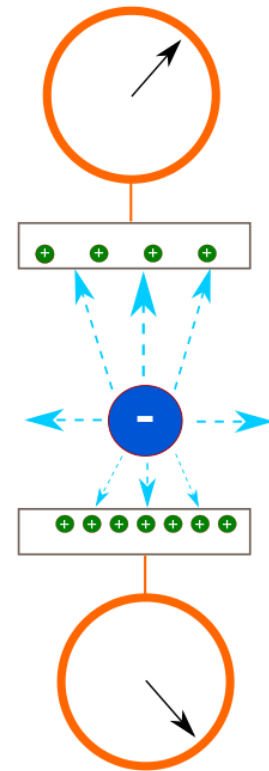
Current transformers vs Faraday cup

- Current transformers are non destructive measurements.
- Faraday cup is destructive.
- The reading of a Faraday cup is more direct than that of a current transformer.
- The size of a Faraday cup scales with the energy.

Beam position measurement

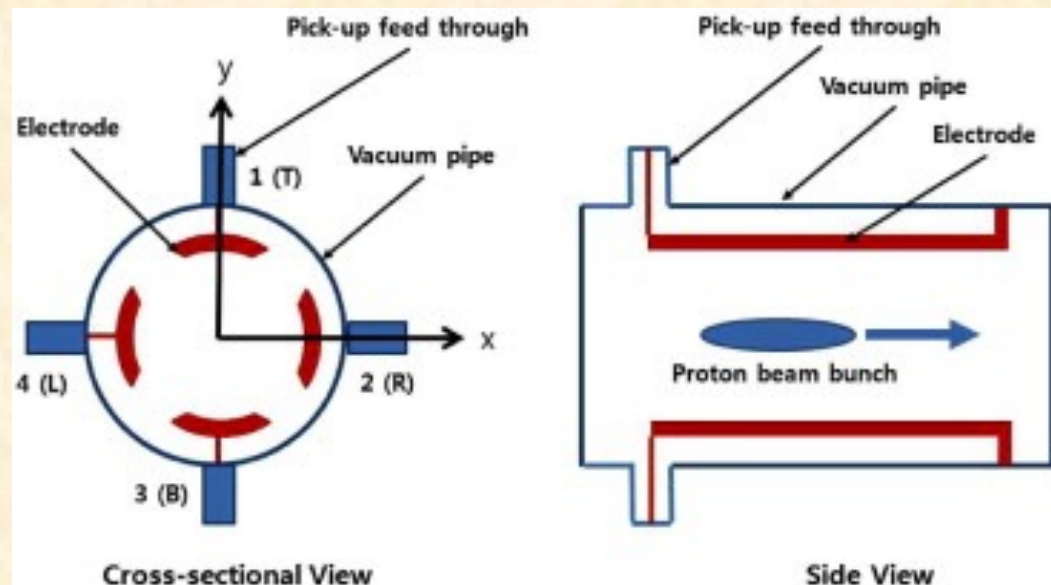
Beam position measurement

- Instead of measuring the total charge along one section of the beam pipe, one can measure it several electrode around the pipe.
- The charge on each electrode will then depend on the distance of the beam to that electrode.
=> Beam position monitors (BPM)

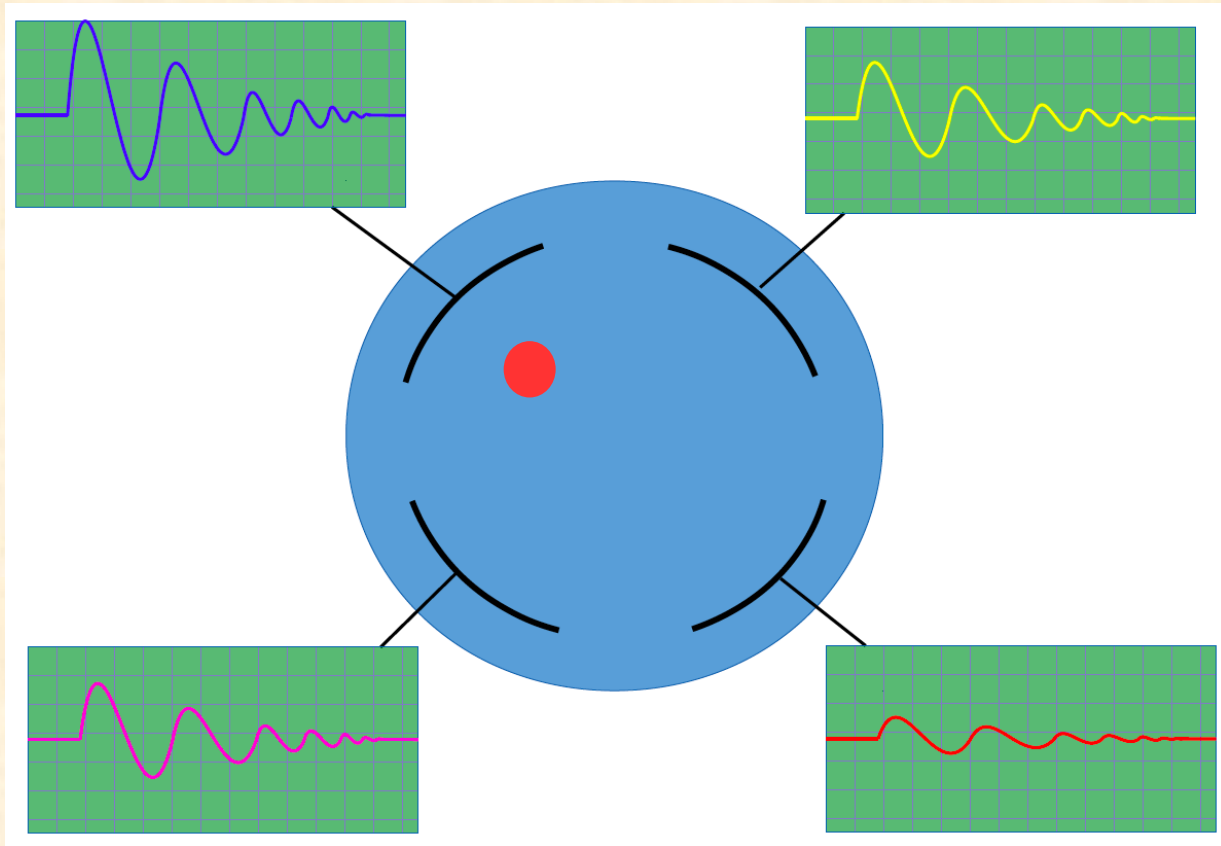


Beam position monitors (BPM)

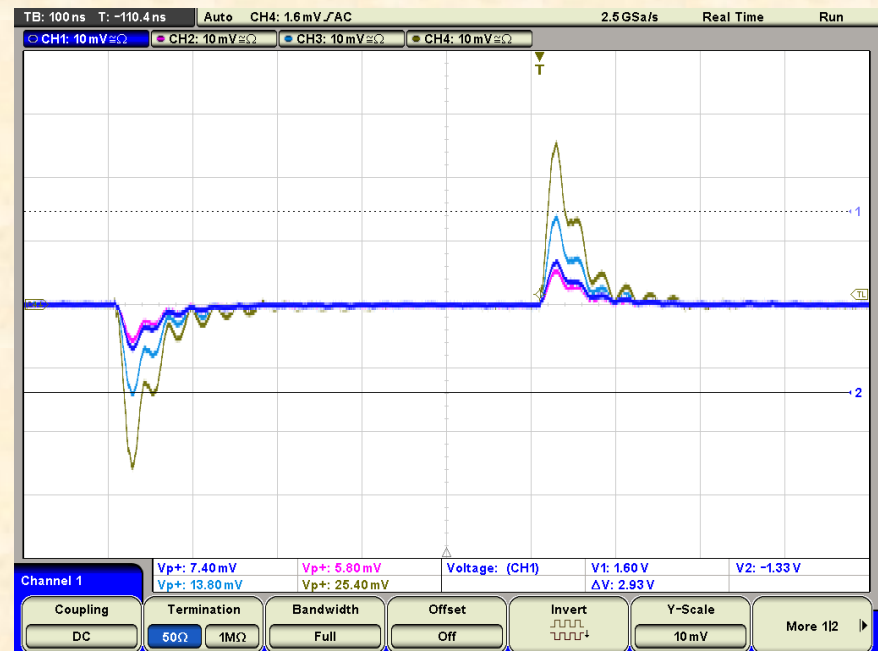
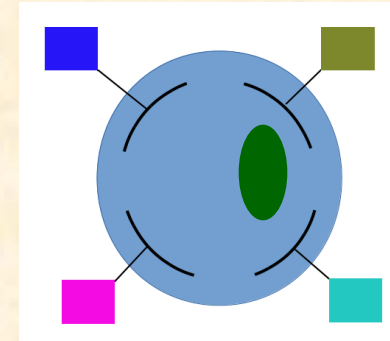
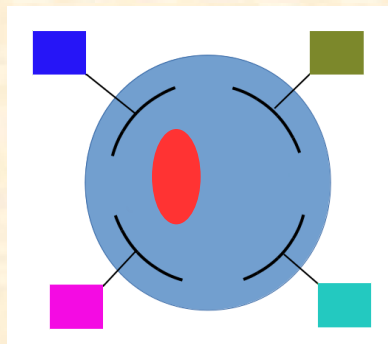
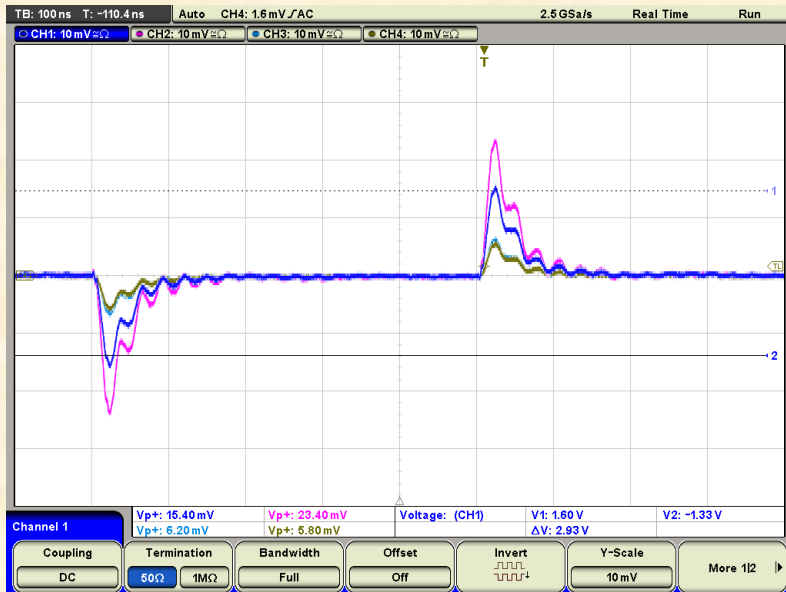
- To get the position one needs to compare the signal of the electrodes two by two.
- The difference in signal between two opposite electrodes gives the position on that axis.
- The sum of the signal on the 4 electrodes is proportional to the charge.



Signal on the electrodes

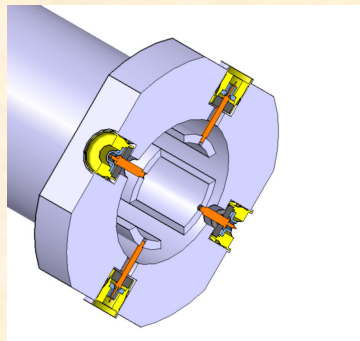
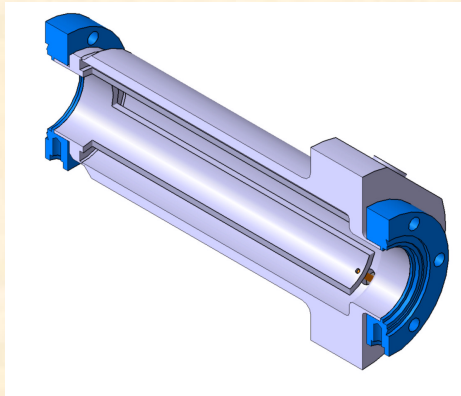
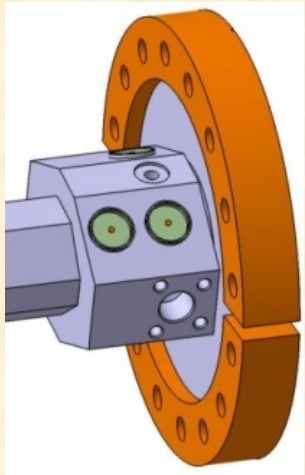


Example of measurements



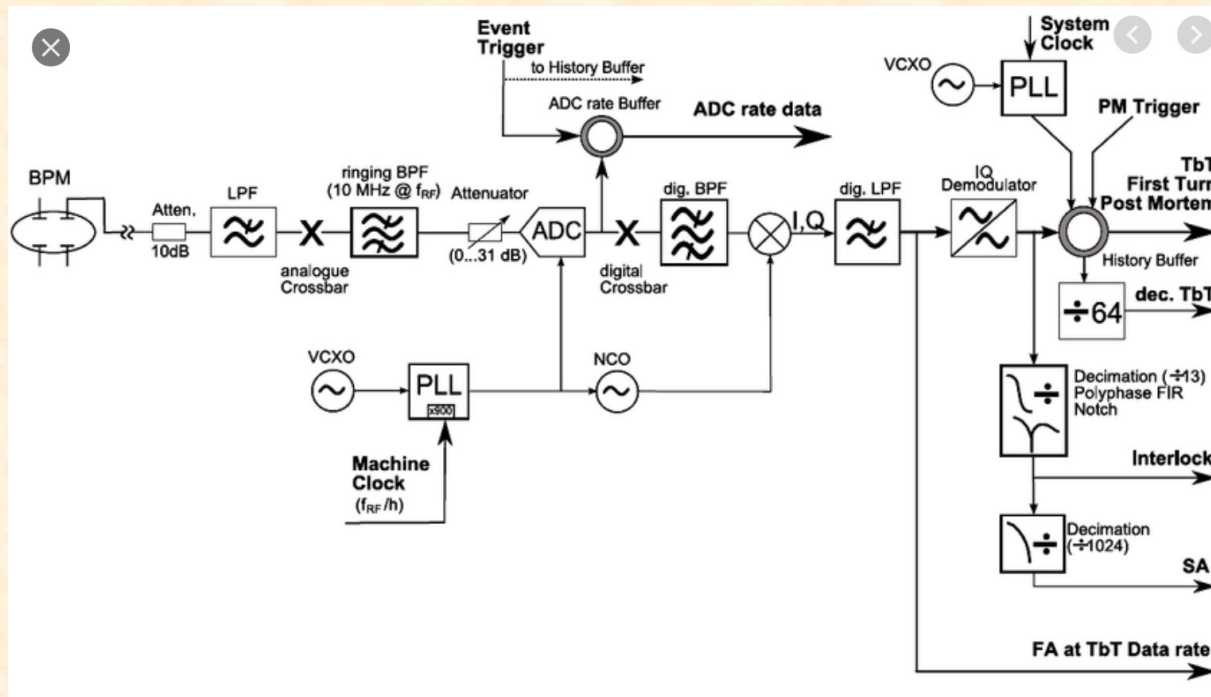
Beam position monitors (BPM)

- Beam position monitoring is very important in accelerators so beam position monitors exist in many different flavours.
- Accelerators can have one BPM every few meters.
- Button, electrodes,...



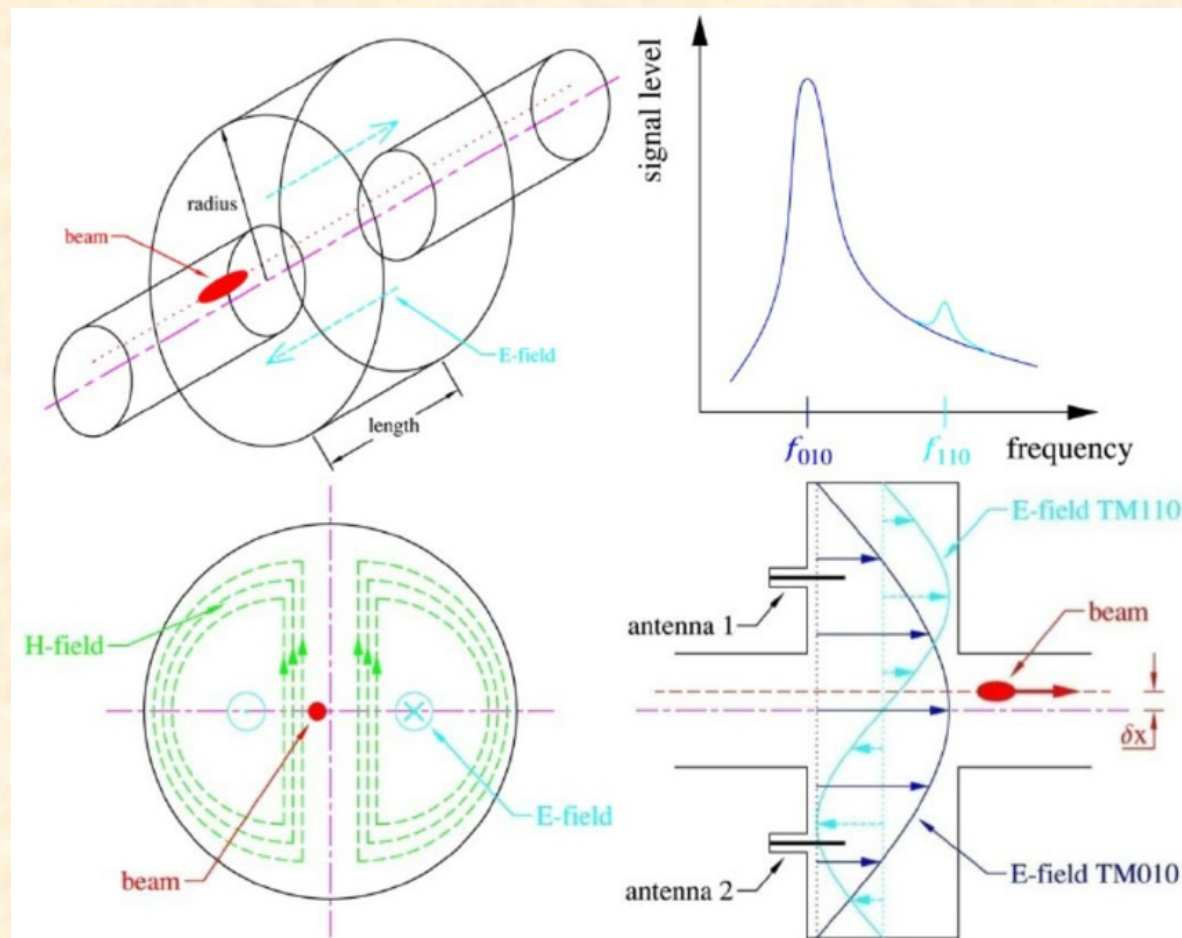
BPM electronics

- The accuracy of the measured position depends a lot on the quality of the electronics.
- Noise can affect position reading.
=> very complicated (expensive) electronics
- Active R&D on BPM electronics...



Cavity Beam position monitors

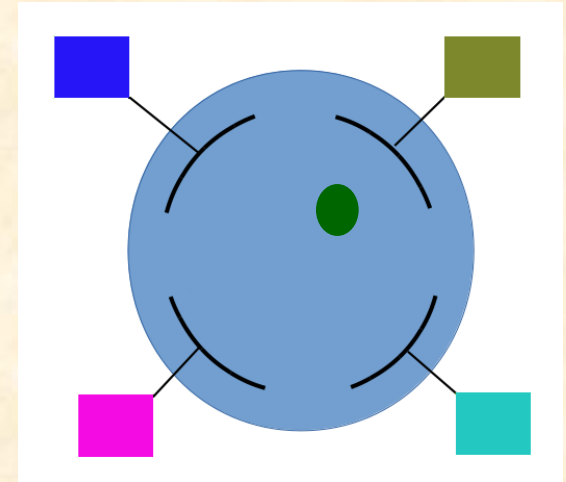
- Instead of electrodes of BPM can use a pillbox cavity.



Quizz: BPM

- Using Maxwell Gauss equation estimate the relative field between two opposite electrodes induced by a 1nC beam on 4 electrode located on a circle of diameter 10cm around the beam.
- a) When the beam is centred.
- B) When the beam is offset by 1cm toward an electrode.

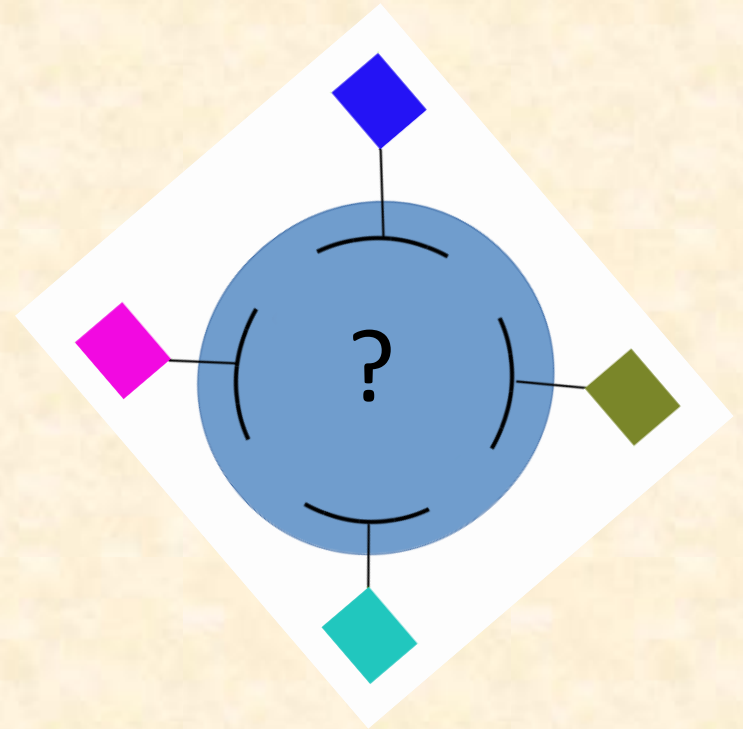
$$\iint_{(S)} \vec{E} \cdot d\vec{S} = \frac{Q_{int}}{\epsilon_0}$$



Quizz:

Lecture d'un BPM

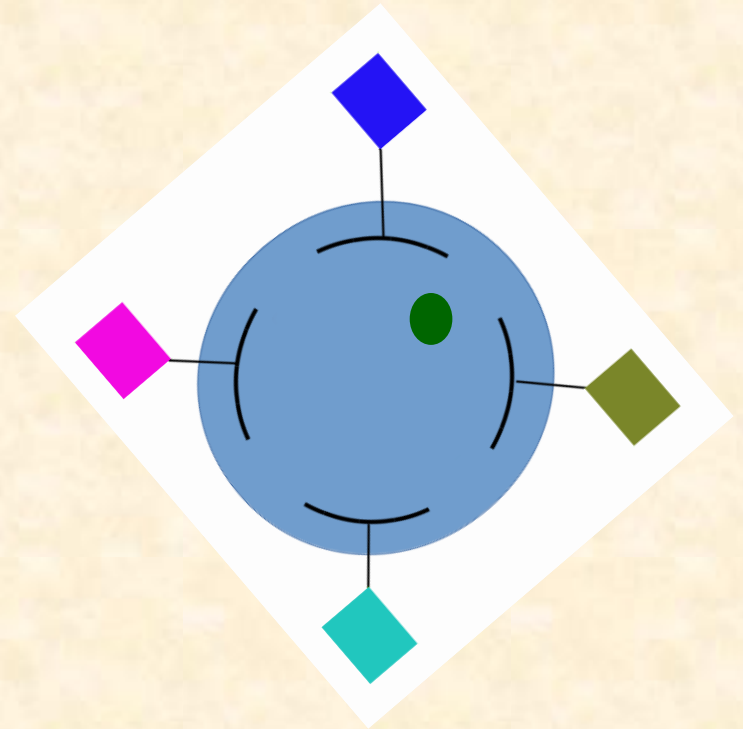
- Sur ce BPM, l'électrode du haut lit un signal de 4mV, celle de gauche un signal de 2,5mV, celle du bas un signal de 3mV et celle de droite un signal de 4,5mV.
- Dans quel partie du tube faisceau se trouve le faisceau?
 - a) En bas à gauche
 - b) En bas à droite
 - c) En haut à gauche
 - d) En haut à droite



Quizz:

Réponse: en haut à droite

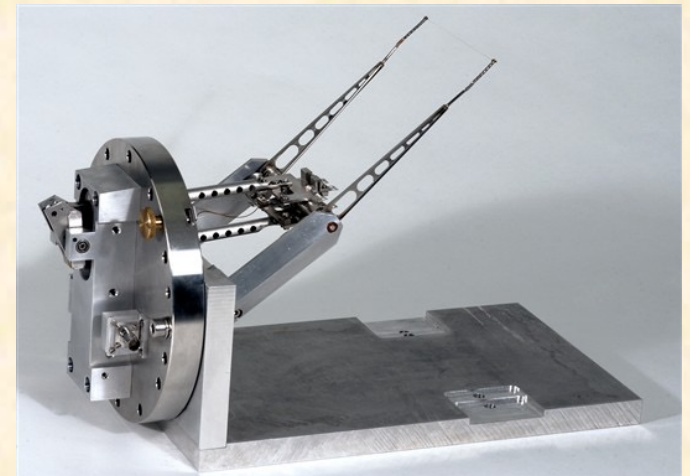
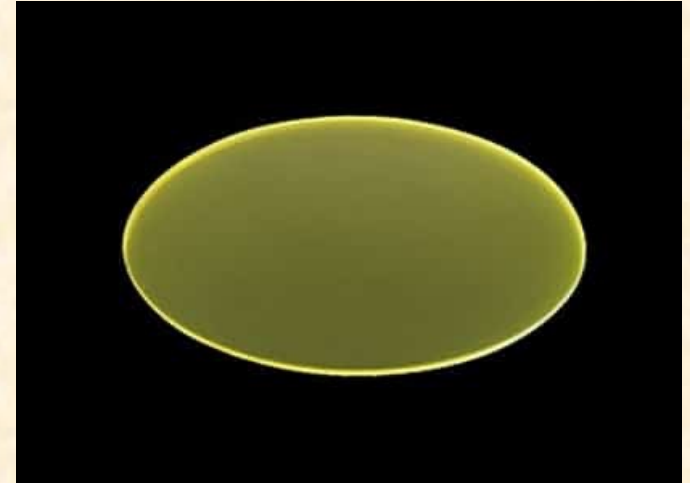
- Sur ce BPM, l'électrode du haut lit un signal de 4mV, celle de gauche un signal de 2,5mV, celle du bas un signal de 3mV et celle de droite un signal de 4,5mV.
- Électrodes verticales:
Haut > bas
- Électrodes horizontales:
Droite > Gauche
- Comme cela c'est très facile.
Quand le bruit de mesure s'en mêle cela devient plus difficile.



Beam profile measurement

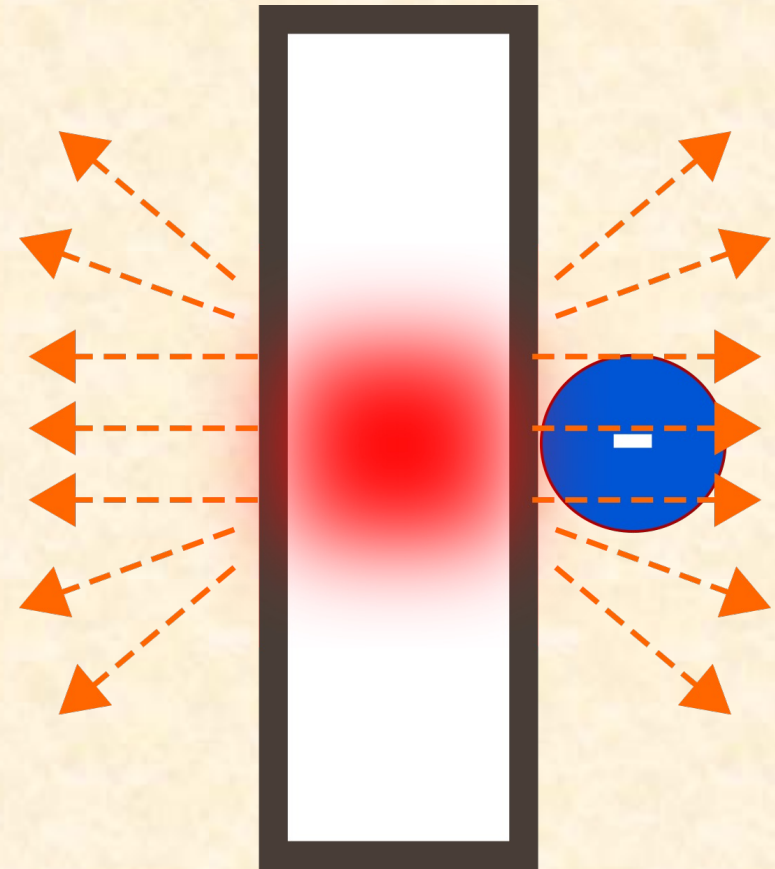
Beam profile measurement

- Knowing the shape of the beam is also very important.
- This can be done by several manners:
 - With a luminescent screen and a camera
 - With a transition radiation screen and a camera
 - With a moving wire
 - With several fixed wires
 - By looking at the fluorescence of a gas



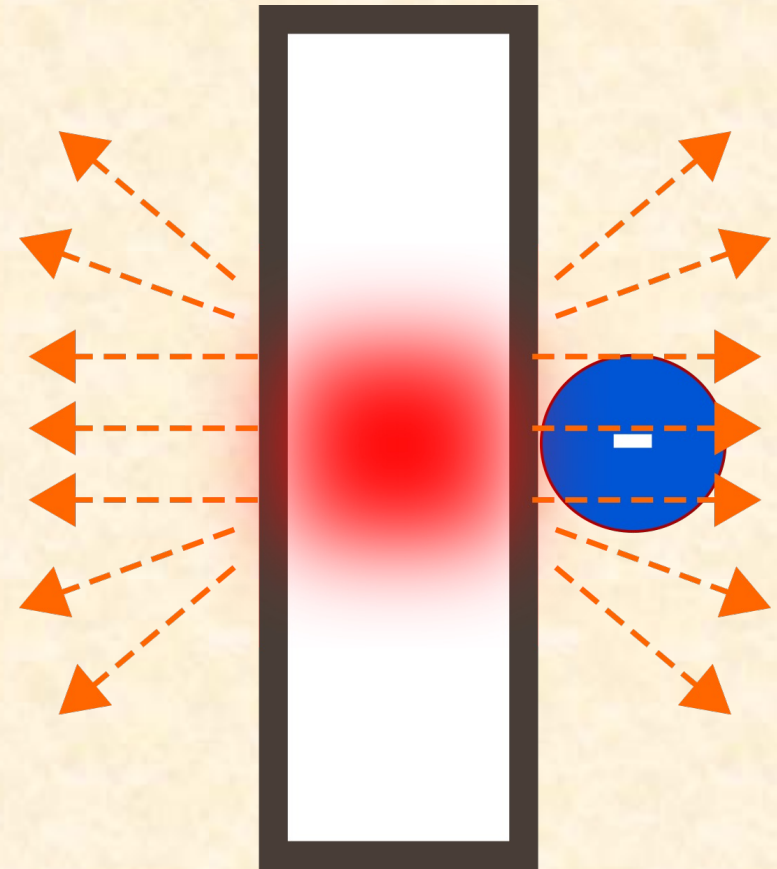
Beam profile measurement using luminescent screens

- A bunch of particles crossing a screen will deposit energy.
- If the material is chosen correctly most of the energy will excite atoms which will in turn emit light.
- This luminescent emission will give indication on the beam profile.
- This is a (partially) destructive measurement.



Beam profile measurement using luminescent screens

- Example of luminescent materials:
 - YAG:Ce (mostly used with electrons)
 - Al₂O₃ (mostly used with protons)
 - ...
- Many luminescent materials exist and some new ones are being studied continuously.

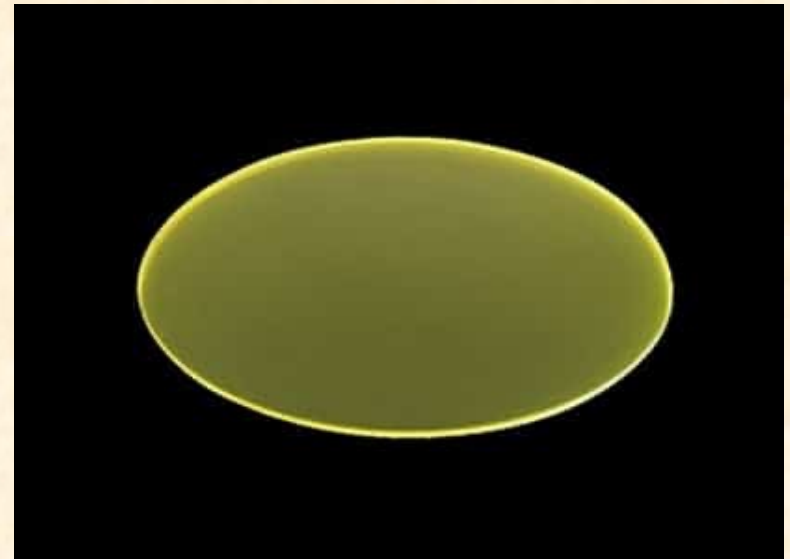
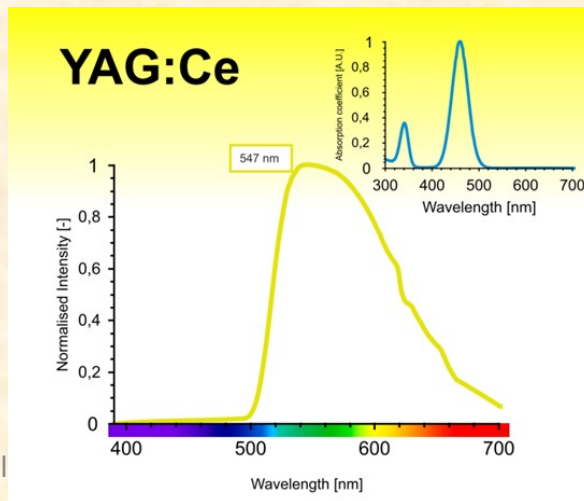


YAG:Ce

- Yttrium aluminum garnet activated by cerium is a fast scintillator with excellent mechanical and chemical resistance.
- Yield: 3×10^3 ph/MeV
- Density : 4.57 g/cm^3
- Minimum d'ionisation:
 $2 \text{ MeV cm}^2/\text{g}$
 $\Rightarrow 9.2 \text{ MeV/cm}$



Source: <https://www.crytur.cz/>



Source: <https://www.ost-photonics.com/>

Beam profile measurement using luminescent screens: camera

- A camera must monitor the screen.
- This must be a special camera that can be triggered with a low jitter, otherwise the beam will be missed.



Example of camera

- There are many camera on the market...
- Things to look for:
 - Triggering
 - Quantum efficiency
 - Gain
 - Pixel size
 - Readout
 - ...



EMVA Data

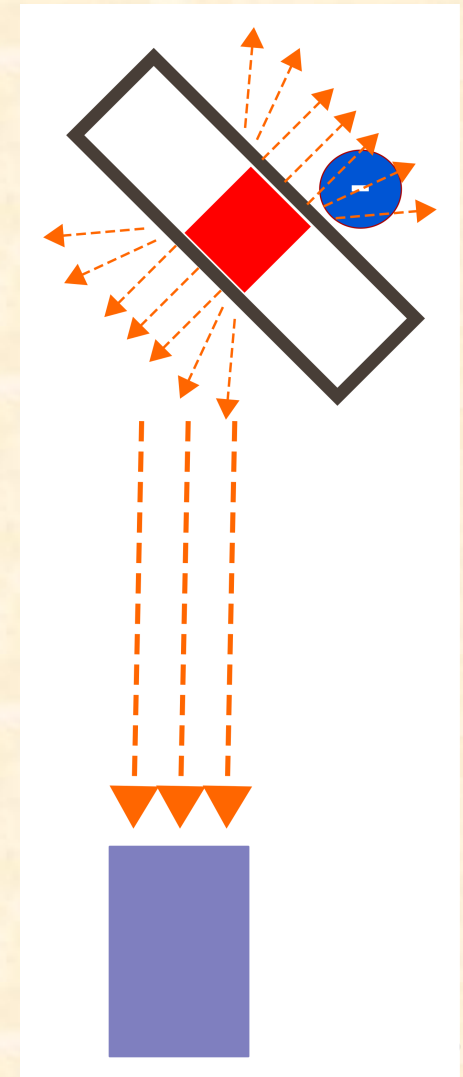
EMVA Quantum Efficiency (typical)	46.0 %
Dark Noise (typical)	11.2 e ⁻
Saturation Capacity (typical)	14.0 ke ⁻
Dynamic Range (typical)	62.1 dB
Signal-to-Noise Ratio (typical)	41.6 dB

Sensor

Sensor Vendor	Sony
Sensor	ICX424
Shutter	Global Shutter
Max. Image Circle	1/3"
Sensor Type	CCD
Sensor Size	4.9 mm x 3.7 mm
Resolution (HxV)	659 px x 494 px
Resolution	VGA
Pixel Size (H x V)	7.4 μm x 7.4 μm
Frame Rate	70 fps
Mono/Color	Mono

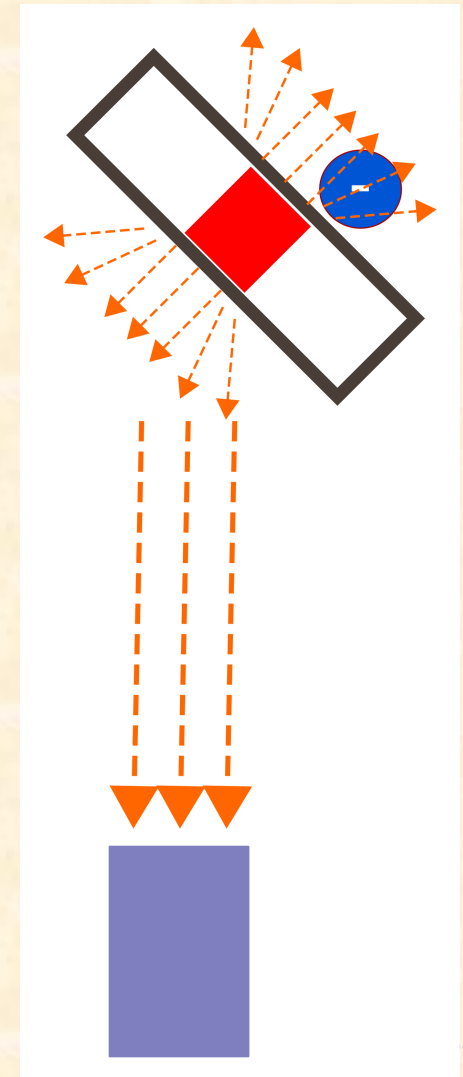
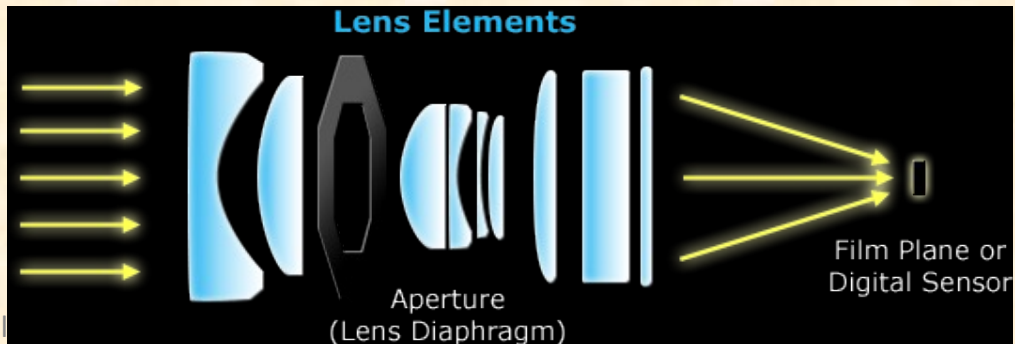
Beam profile measurement using luminescent screens

- Beware: don't put a camera directly in the particle beam.
- Typically the screen is tilted at 45° and the camera looks at it from the side.
- In other configurations the screen is at 90° and a mirror reflects the light toward the camera.



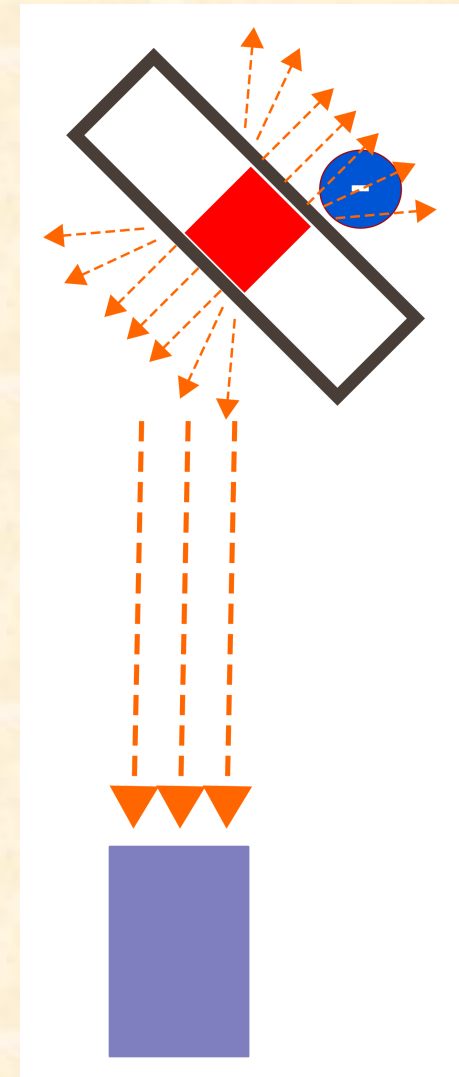
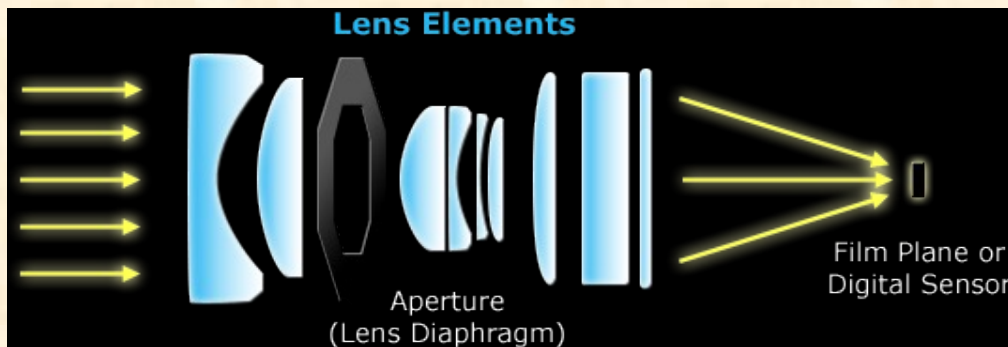
Beam profile measurement using luminescent screens: optical function

- Optics must be installed between the screen and the camera.
- Can be simple lenses or more advanced zoom lenses (including consumer lenses).



Beam profile measurement using luminescent screens: optical function

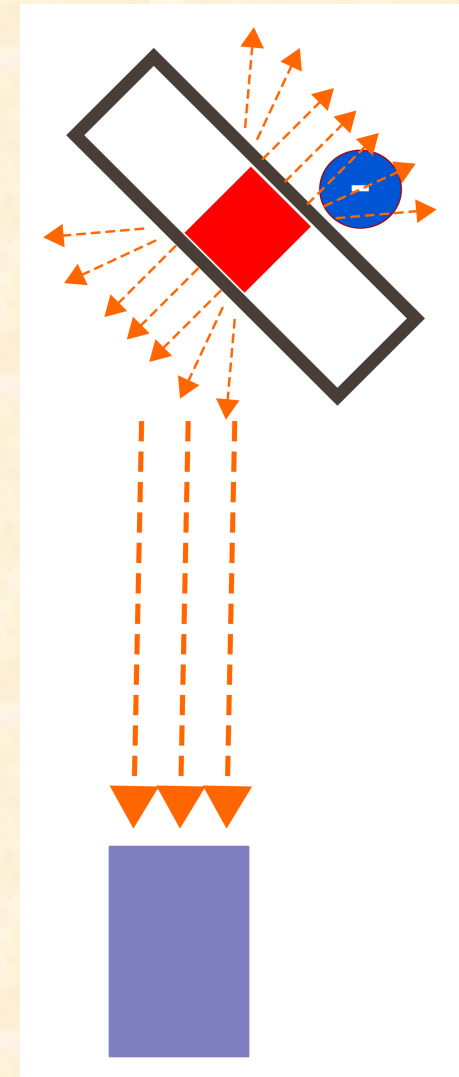
- Field of view (fov): size of the object (screen) to be imaged.
- Working distance (WD): distance to the screen.
- We have the relation:
$$\text{focal length} \times \text{FOV} = \text{sensor size} \times \text{WD}$$



Beam profile measurement using luminescent screens: optical function

Example

- Typical sensor size: 5mm x5mm
- Typical screen size 25mm diameter.
- The lens must give a factor 5 demagnification (sensor size/FOV).
- If the screen is 1m away from the lens, the focal length must be:
$$\text{Focal length} = (\text{sensor size} \times \text{WD}) / \text{FOV}$$
$$\Rightarrow 5\text{mm} \times 1\text{m} / 25\text{mm} = 200\text{mm}$$



Beam profile measurement using luminescent screens: optical function

Lens mount:

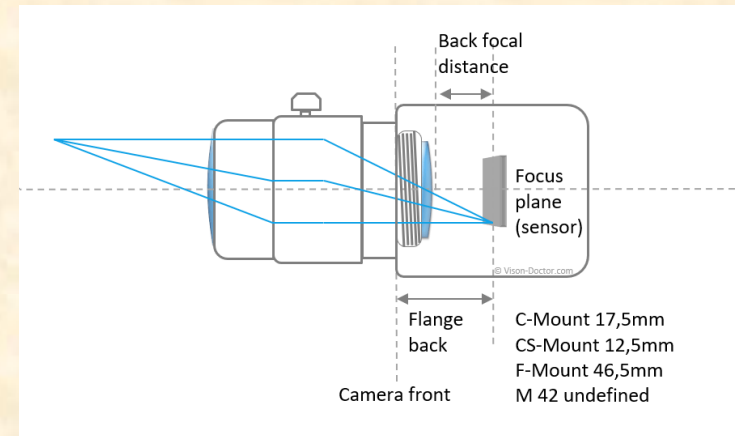
- Most scientific camera will have a c-mount.
- But beware there are also cs-mount and if you use consumer optics you may have Canon EOS,...
- This will change the back focal length of the length and hence you will have to apply a correction factor to the focal length.



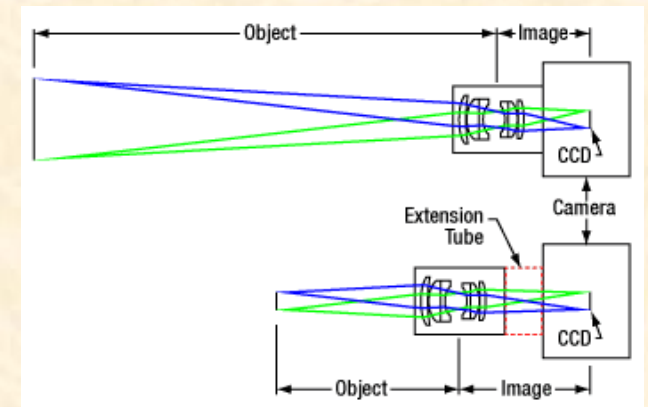
Beam profile measurement using luminescent screens: optical function

Focal length correction when
using adapter:

- Focal length scales with back focal length.
- $C \Rightarrow C_s$: Divide focal length by 1.4 (17.5mm/12.5mm)
- Beware, optical quality and operating distance may change also.
- You can also purchase specific adapters that fit between the lens and the CCD.



Source: <https://www.vision-doctor.com/>



Source: <https://www.thorlabs.com/>

Beam profile measurement using luminescent screens

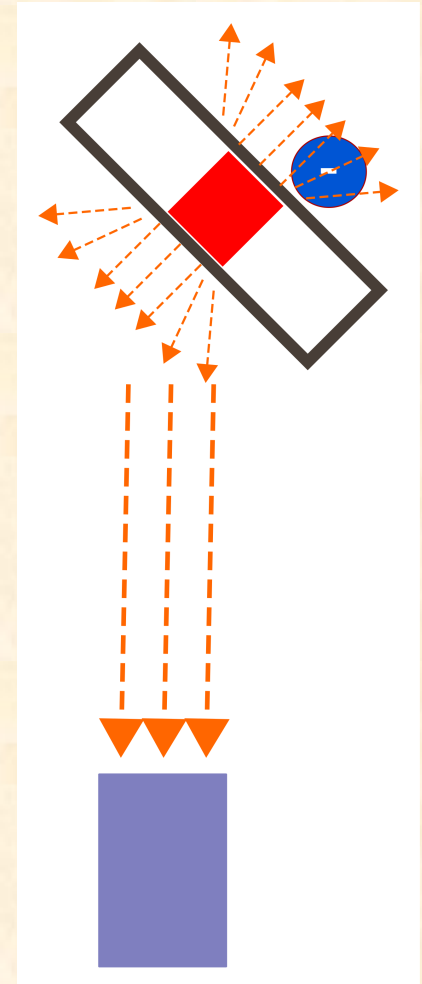


Nicolas Delerue, IJCLab

- The screen can't be left permanently in the beam.
- UHV compatible actuators must be used.
- Also, remember to trigger the camera at the right time otherwise you won't see the beam.

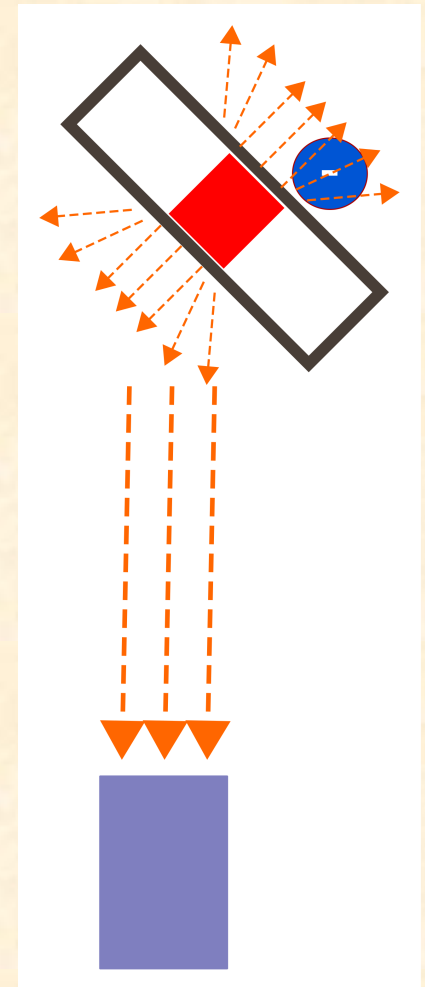


Introduction to diagnostics



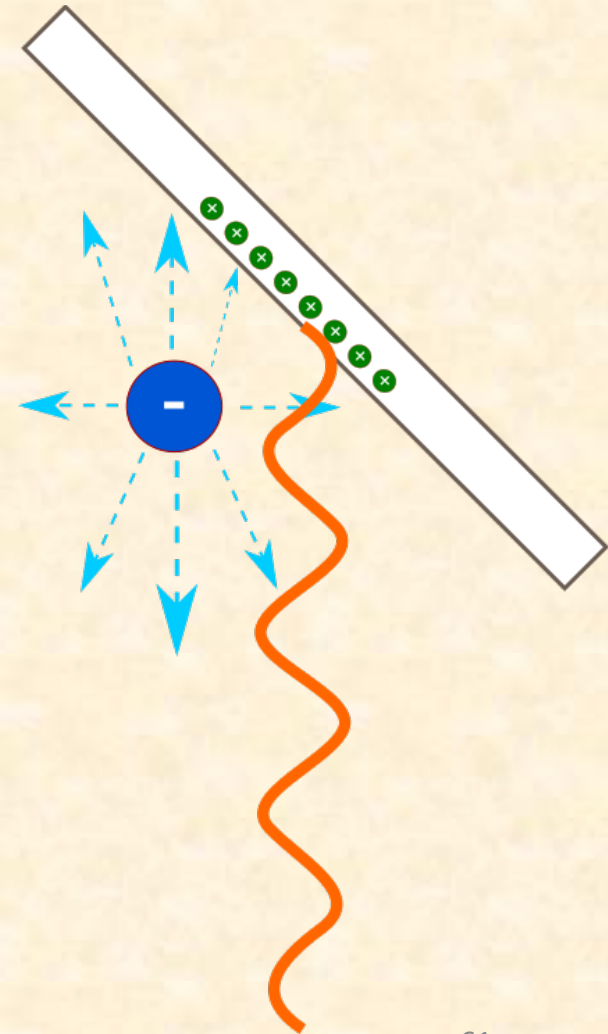
Beam profile measurement using luminescent screens

- The optical function (camera + lens) must be calibrated.
- Ideally the system must have a built-in target to recalibrate the system from time to time.



Beam profile measurement using transition radiation screens

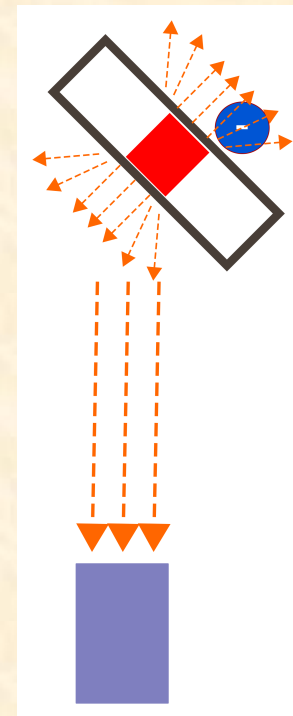
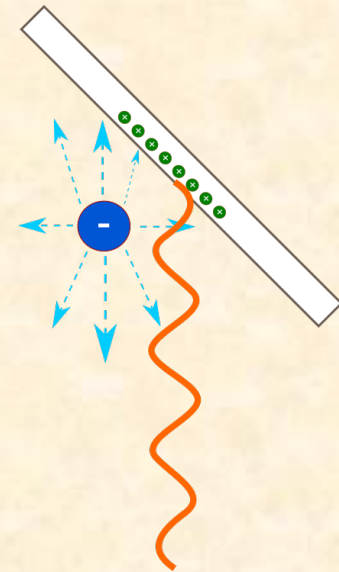
- When charged particles travel across a surface some of the virtual photons surrounding them may become real.
=> Transition radiation.
- By orienting the screen at 45° the radiation may be observed with a camera.



Beam profile measurement

Transition radiation vs luminescence

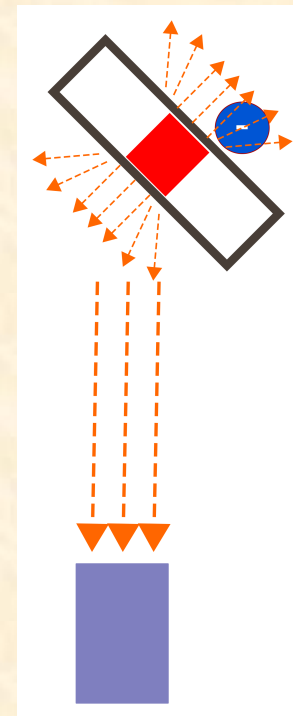
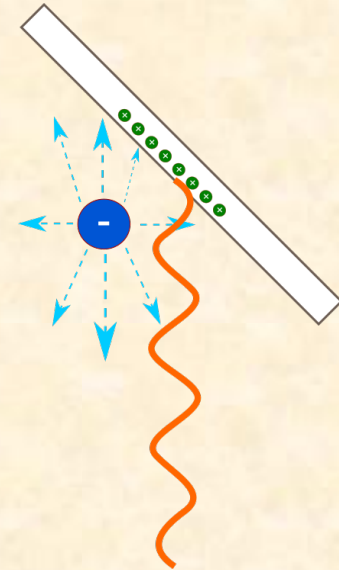
- Location:
 - Lumin. happens in the volume of the screen
 - TR happens at the surface.
- Directionality:
 - Lumin. is emitted over 4π
 - TR is emitted in a $1/\gamma$ cone
- Intensity:
 - Lumin. depends on screen thickness
 - TR is 1% of the number of electrons (usually much weaker)
- Spectrum
 - Lumin. peaked at some values
 - TR broad, decreasing at shorter wavelength.



Beam profile measurement

Transition radiation vs luminescence

- Let's assume a 25mm wide screen with thickness 1mm and a 10^9 electrons beam at 100 MeV ($\gamma=200$).
- Lens at 1m, aperture size 50mm diameter.
- TR: About 10^7 photons emitted in a $1/\gamma$ cone of $\sim 5\text{mrad}$. All reach the lens.
- Lumin. :
 - 100MeV => minimum ionising
 - 0.92MeV of energy deposited.
 - 2.7×10^3 photons/e- emitted over 4π .
 - Lens surface: 1962.5mm^2
 - 1m sphere = 4.2m^2
 - $1962.5\text{mm}^2 / 4.2\text{m}^2 \sim 4\%$
 - 1265 photons per electrons captured by the lens.
 - 1.265×10^{12} photons captured in total.

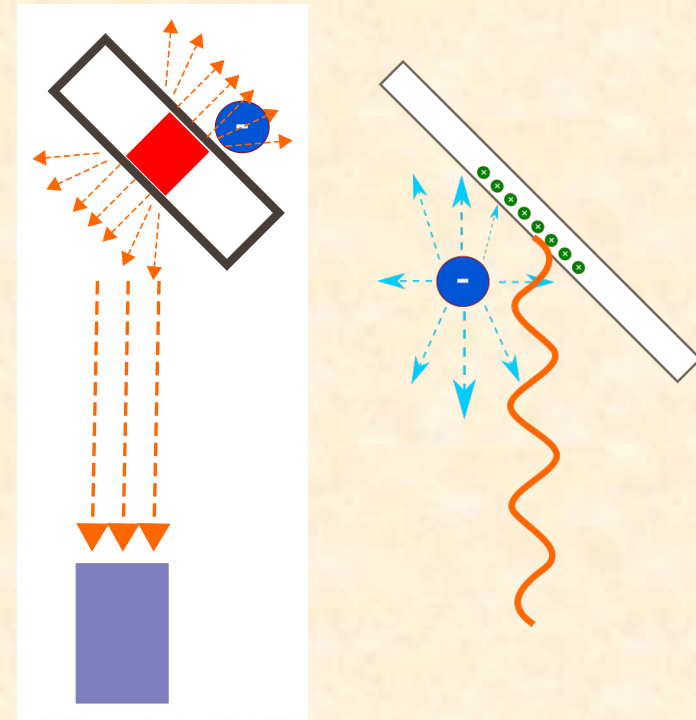


Beam profile measurement

Transition radiation vs luminescence

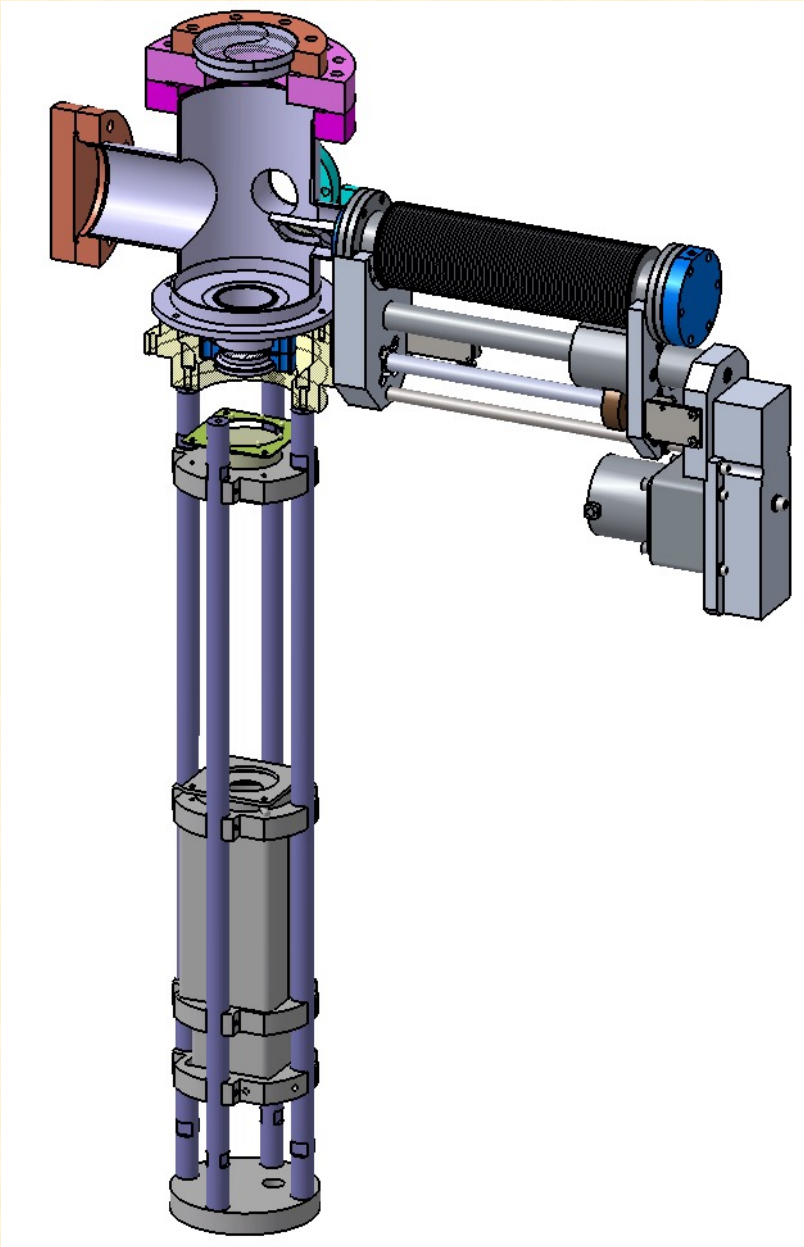
Quizz

- Same calculation for a 10^9 electrons beam with 250 MeV energy a 0.2mm thick YAG:Ce screen
- Let's assume a 20 mm wide screen with thickness 0.2 mm and a 3×10^9 electrons beam at 250 MeV.
- Lens at 2m, aperture size 40mm diameter.
- Between the lens and the camera there are two mirrors with 90% reflectivity and there is a vacuum viewport with 95% reflectivity.



Beam profile measurement using luminescent screens

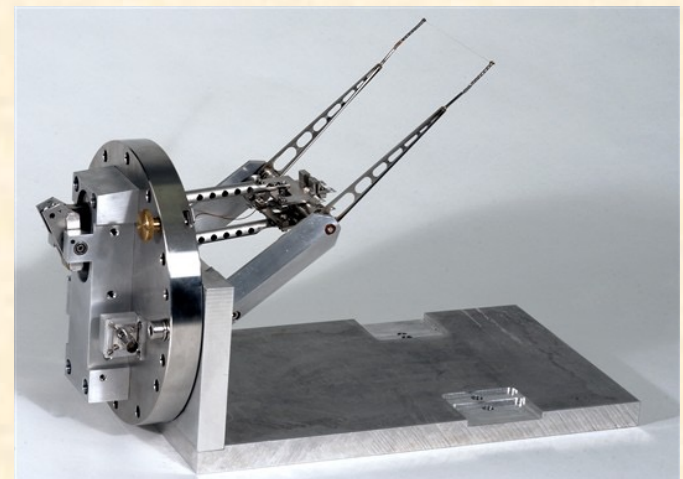
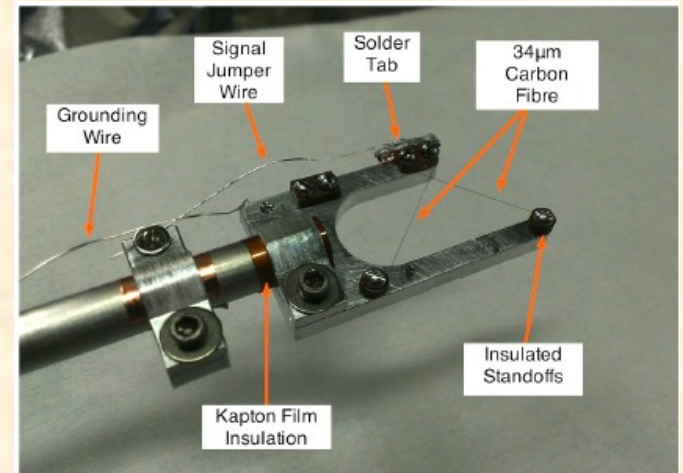
- The ThomX diagnostics stations.



Beam profile measurement

Wire scanners

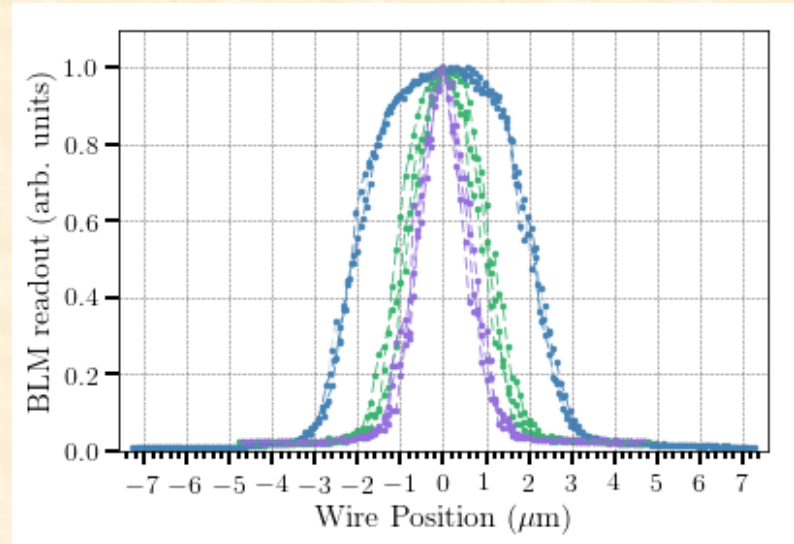
- Instead of using a screen one can use a moving wire across the beam.
- Working principle:
 - Either secondary particles are measured downstream,
 - Or the current induced on the wire is measured.
- Measurement is partially destructive but with a thin enough wire it can be used on a ring.
- Beware of not burning the wire with a too intense beam.



Beam profile measurement

Wire scanners

- Example of wire scanner measurements



Small pit marks seen near the end of the wire are further evidence for arcing.

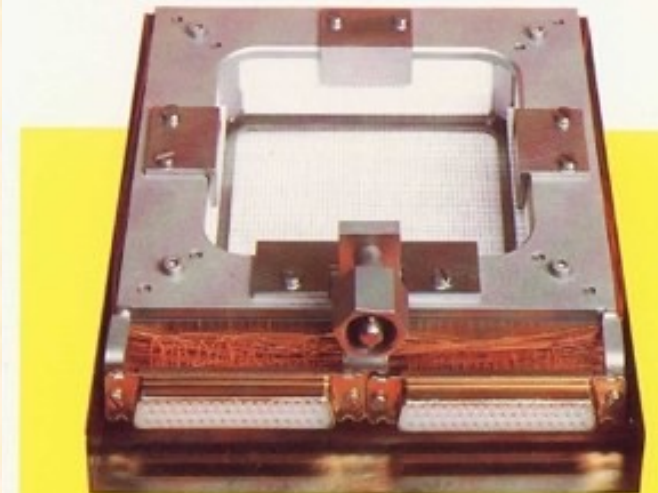
Beam profile measurement

Wire scanners: harps

- When the system reads charges, instead of a single wire, one can use a harp with several wires (including crossed wires).

**Beam Profile Measuring
System (Grid, Harp)**

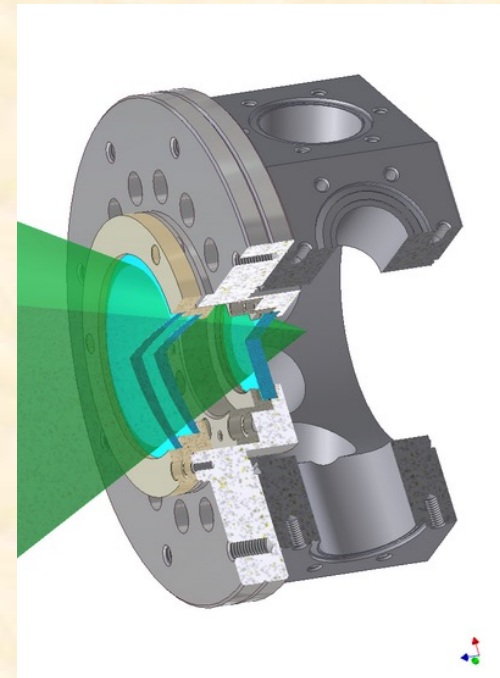
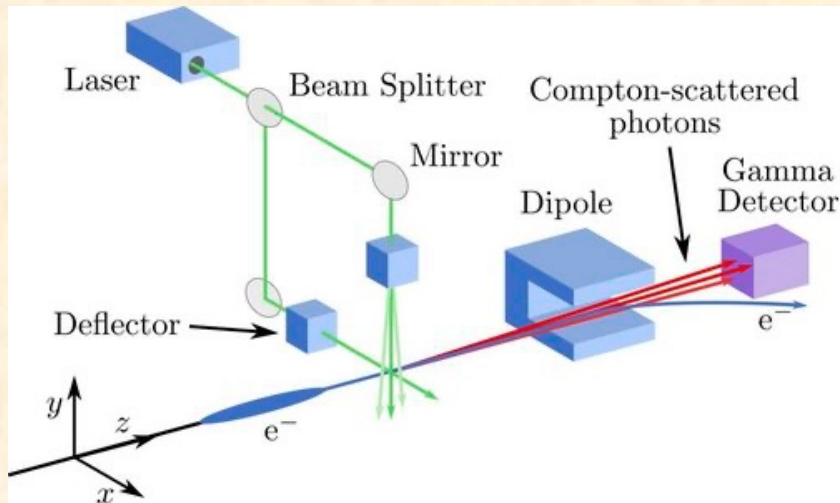
Type DG 070



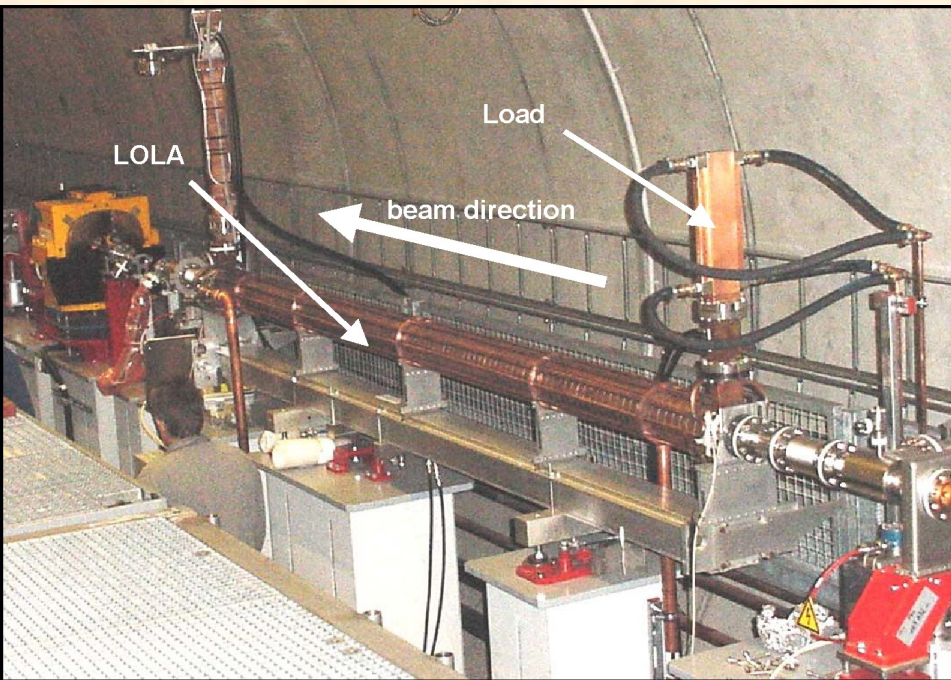
Beam profile measurement

Laser-wire

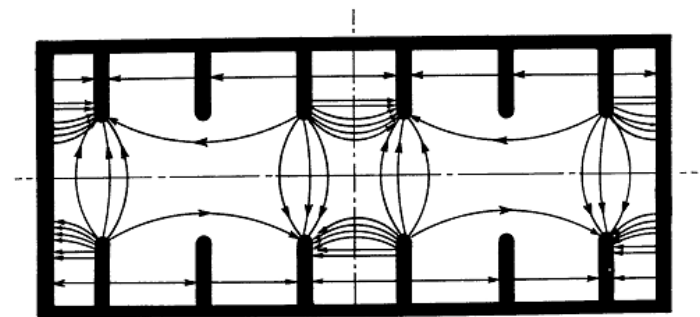
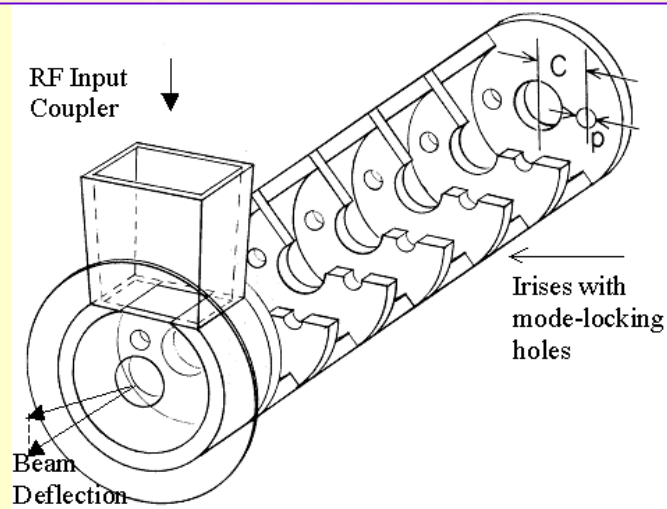
- The wire can also be replaced by a laser beam.
- Compton scattering with electrons
- Stripping with negative ions...



Longitudinal properties

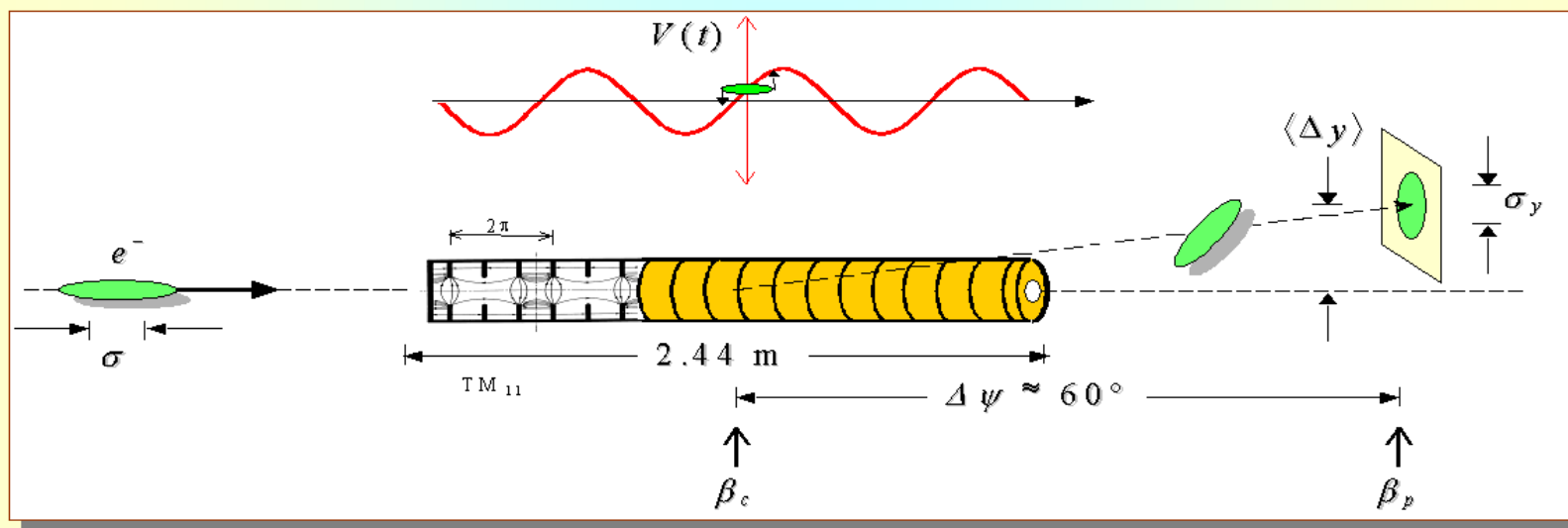


- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsions to the beam it is possible to make it rotate and observe its longitudinal profile.

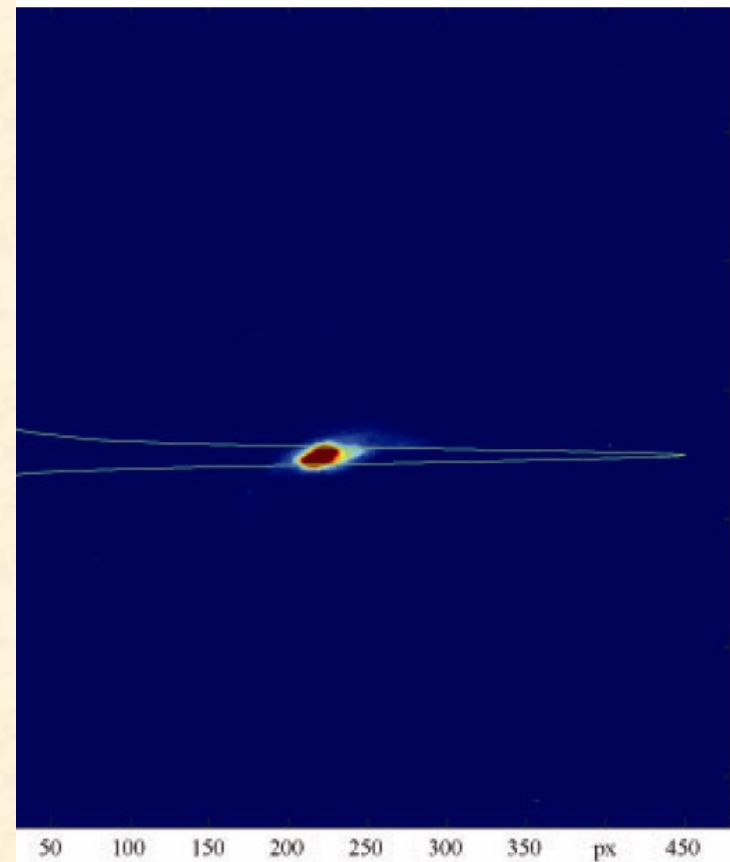
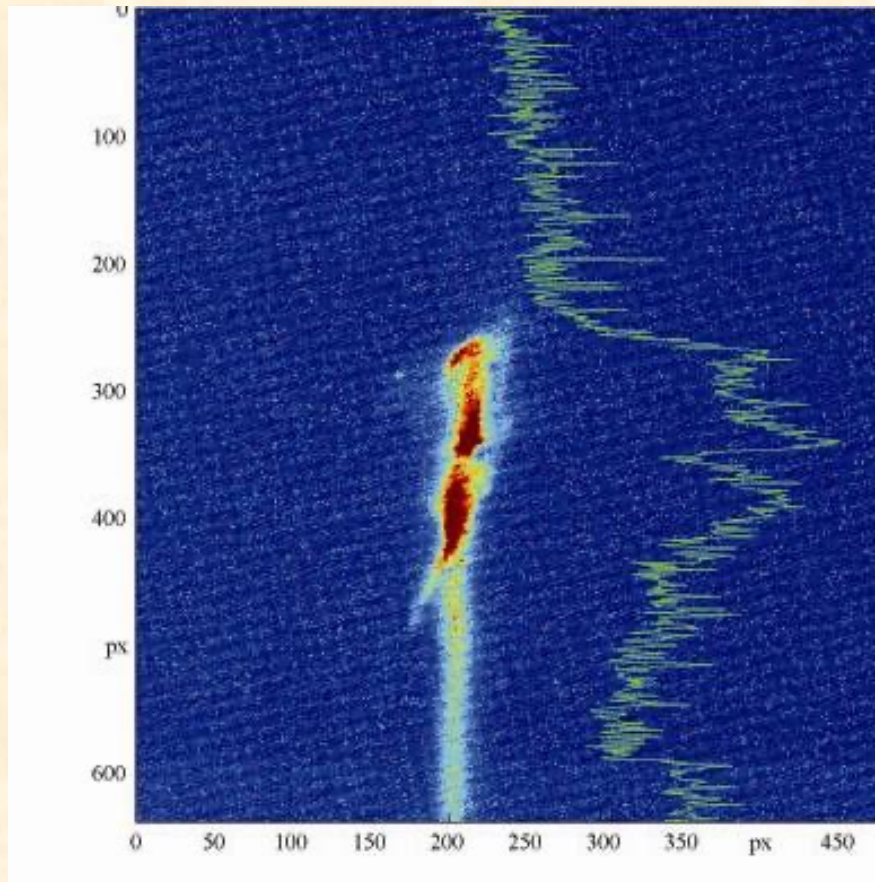


$$V_0 \approx (1.6 \text{ MV/m/MW}^{1/2}) L \sqrt{P_0}$$

$$\text{bunchlength, } \sigma_z \approx \frac{\lambda_{rf}}{2\pi} \frac{E_s}{|e V_0 \sin \Delta\psi \cos \phi|} \sqrt{\frac{(\sigma_y^2 - \sigma_{y0}^2)}{\beta_d \beta_s}}$$

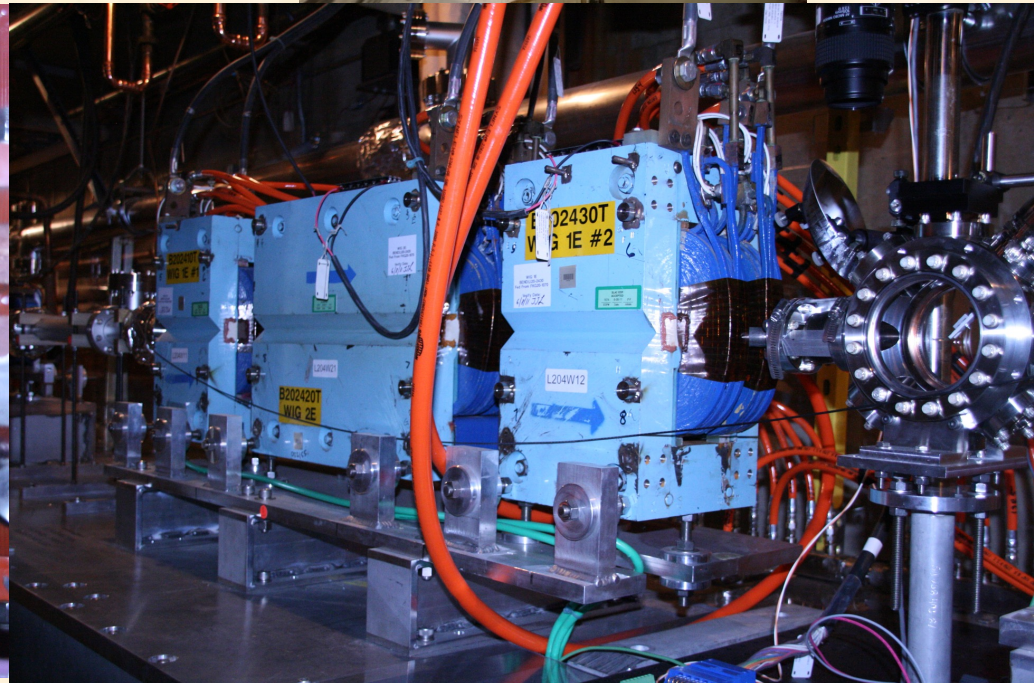
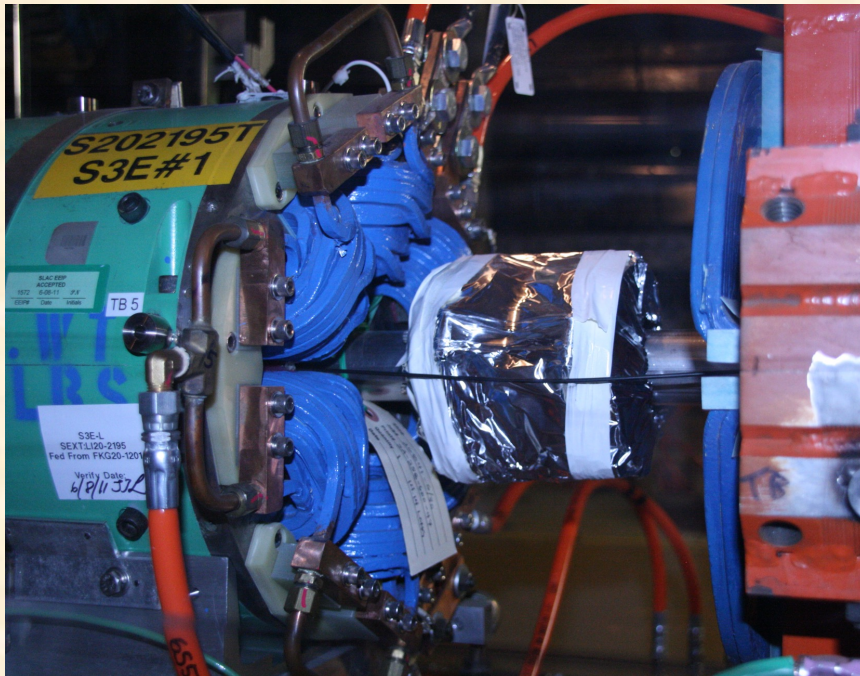
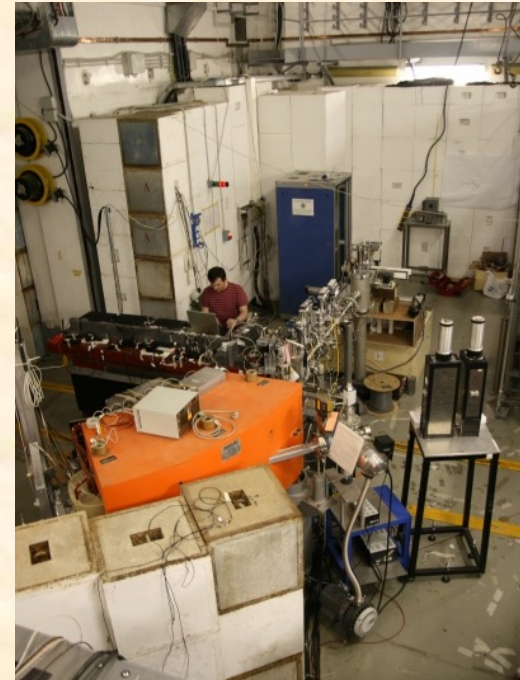


RF deflector off and on



Beam losses

- It is important to monitor the beam losses directly:
- Small beam losses may not be detected by other systems
- Beam losses are a source of radiation and activation
- Most beam losses indicate that there is a problem somewhere.
- In some accelerators on optical fibre is used to track the losses (by induced Cerenkov light).
- Beam loss monitoring is often compulsory to minimize health risks.



Real cases of diagnostics: ThomX (see separate talk)

Thank you