Introduction to diagnostics for particle accelerators

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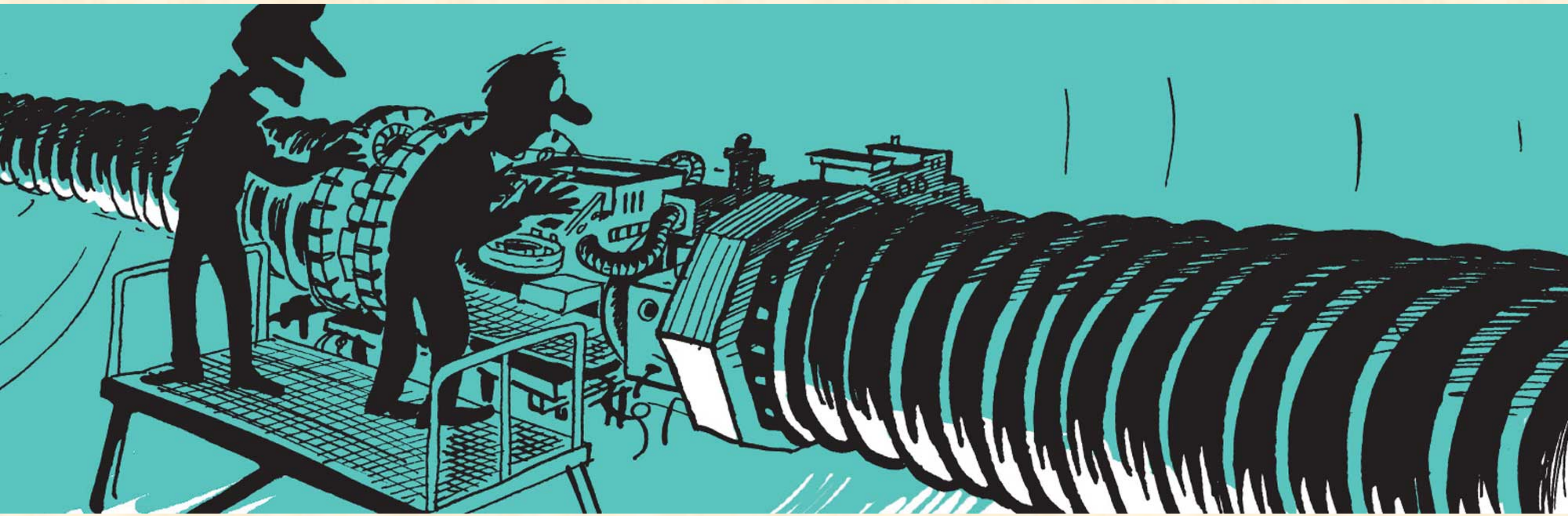
Content

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

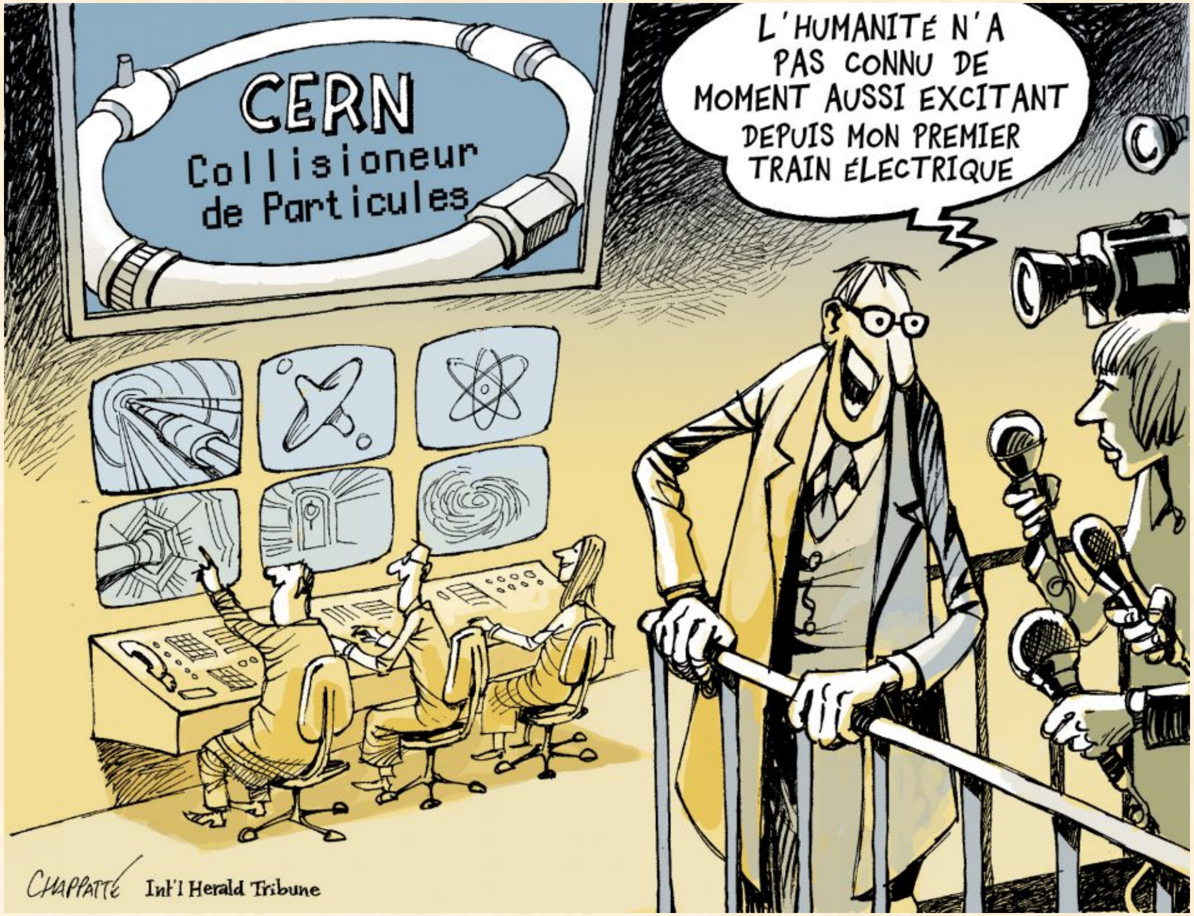
WHY USE DIAGNOSTICS ON AN ACCELERATOR?

How can we know what happens inside the accelerator?



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

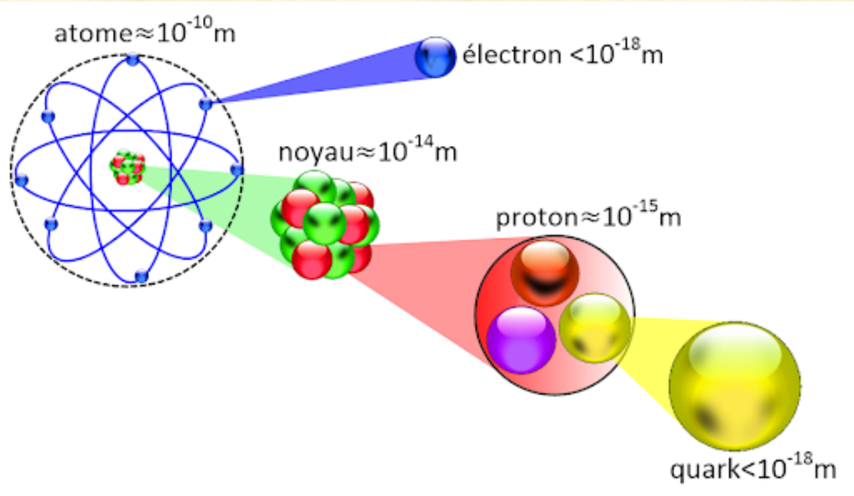
How can we know what happens inside the accelerator?



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

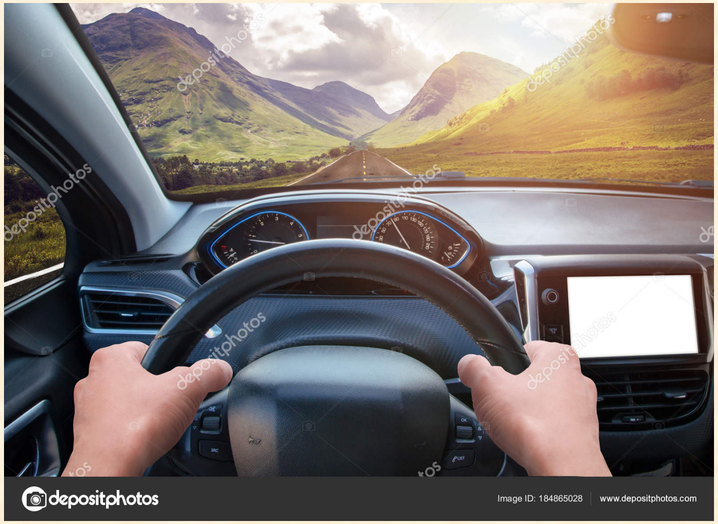
Looking inside the accelerator

- Particles are too small to be seen
- They are smaller than visible photons
- Orders of magnitude:
  - Visible photon:
    ~500 nanometre ($5x10^{-7}$m)
  - Proton:
    ~0,8 femtometre ($8x10^{-16}$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?

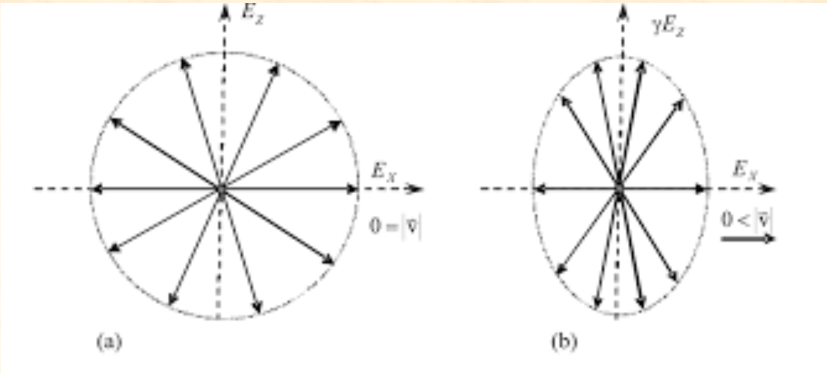
- To tune an accelerator one needs:
  - To know what's happening
  - To know the effects of the settings applied
- Tuning an accelerator without diagnostics would be like driving a car with closed eyes.



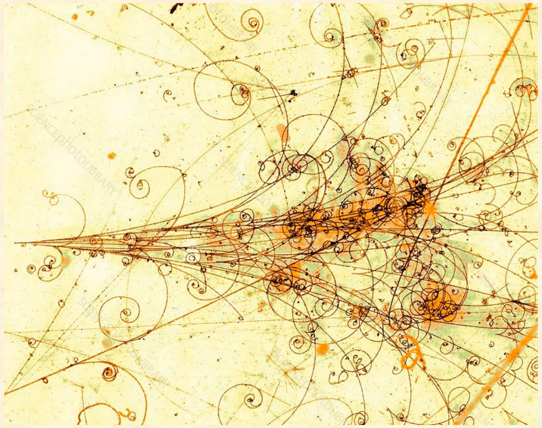
HOW DO DIAGNOSTICS ON ACCELERATOR WORK?

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

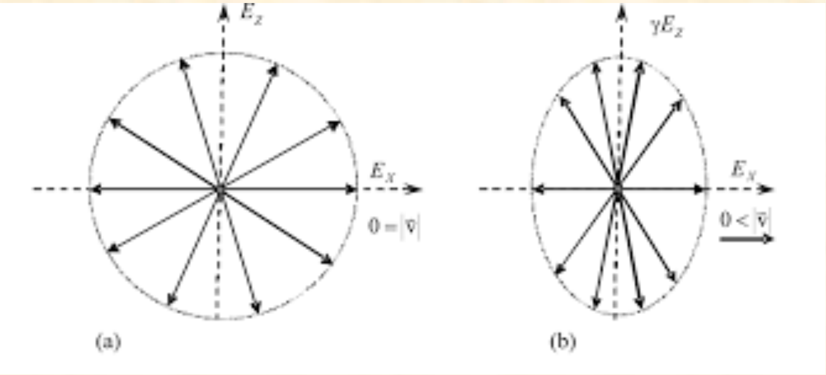


Source: https://www.quora.com/How-did-Feynman-explain-that-magnetic-fields-are-created-by-moving-charges-due-to-length-contraction



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

Radiation emitted by charged particles

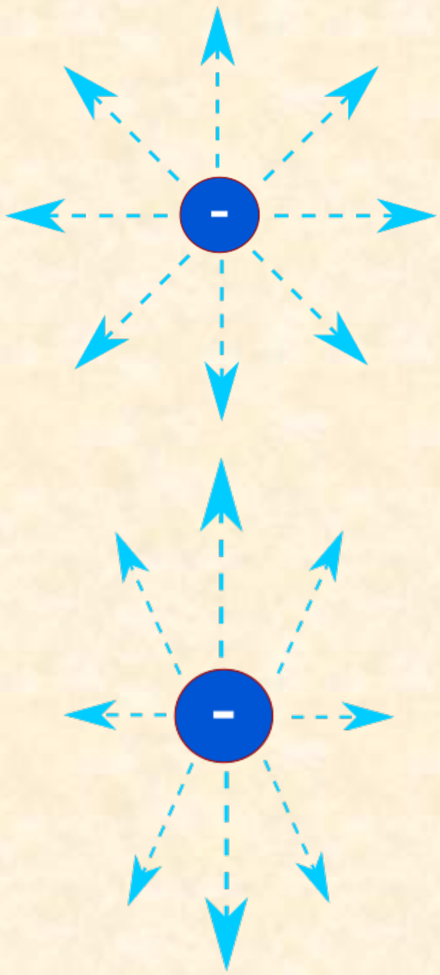


Source: https://www.quora.com/How-did-Feynman-explain-that-magnetic-fields-are-created-by-moving-charges-due-to-length-contraction

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

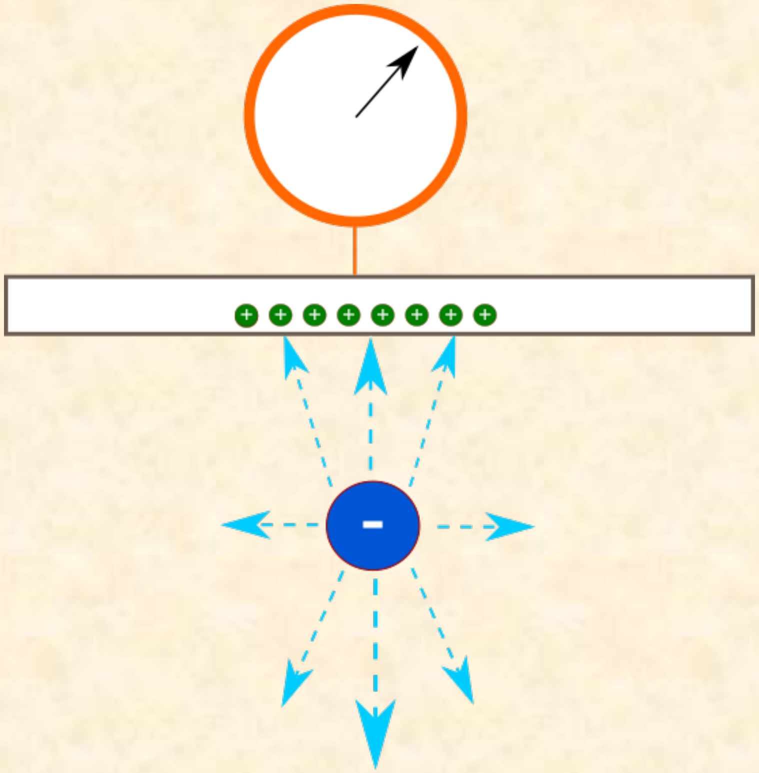
Radiation emitted by charged particles

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



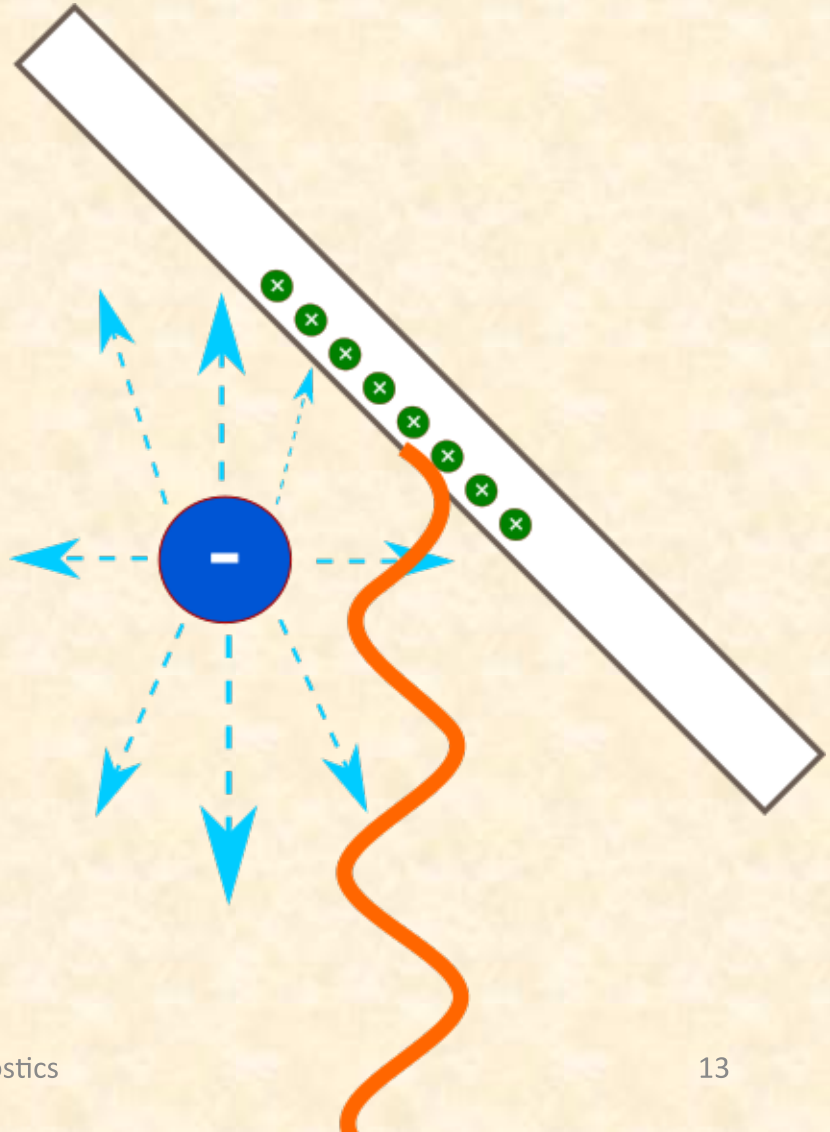
Radiation emitted by charged particles

- Field lines of a charged particle propagetaing 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.



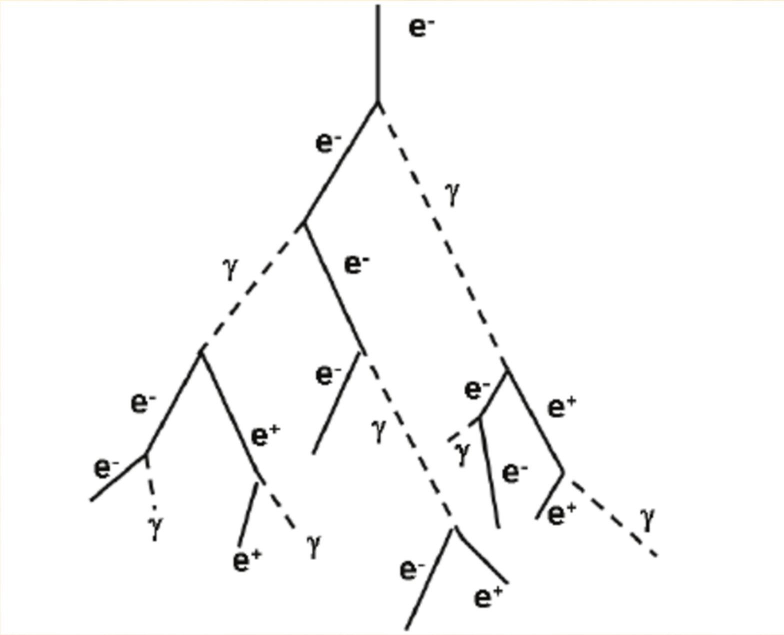
Radiation emitted by charged particles

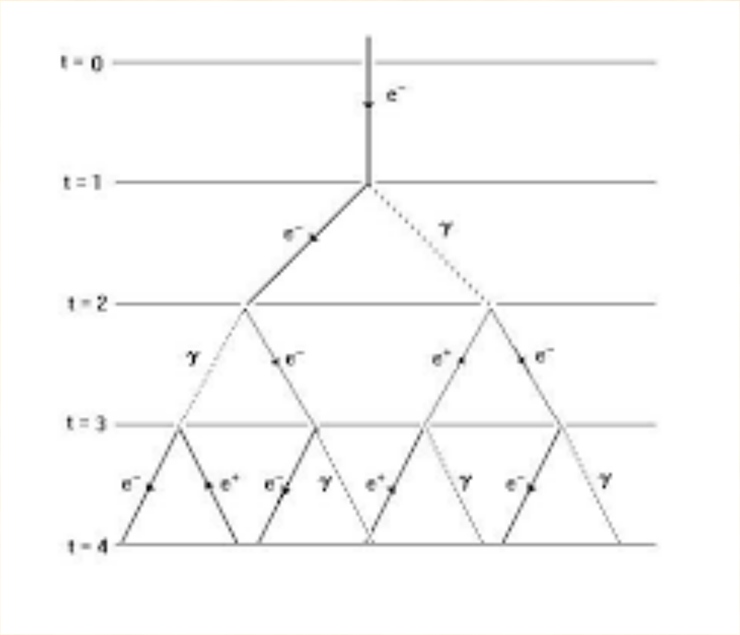
- If a particle crosses a conductor, radiation is emitted due to the change in permittivity as the particle reaches the surface of that conductor.



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.

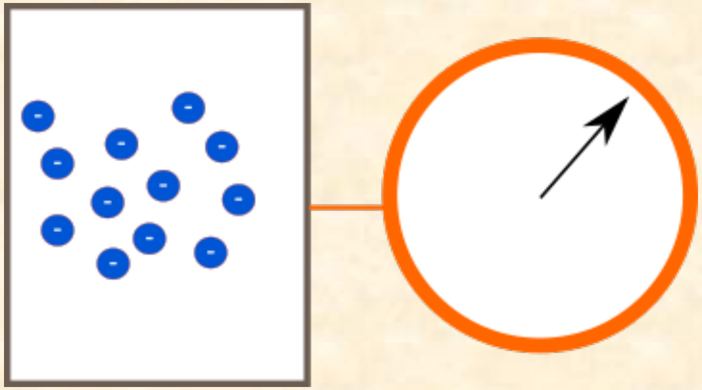




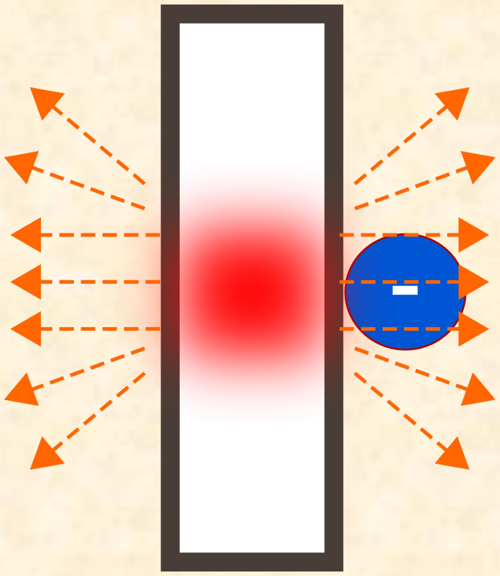
Source: https://www.researchgate.net/figure/Schematic-diagram-of-an-electron-initiated-electromagnetic-shower-This-multiplication_fig1_221911282

Source: http://www-hep.uta.edu/hep_notes/general/general_0001.pdf

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.



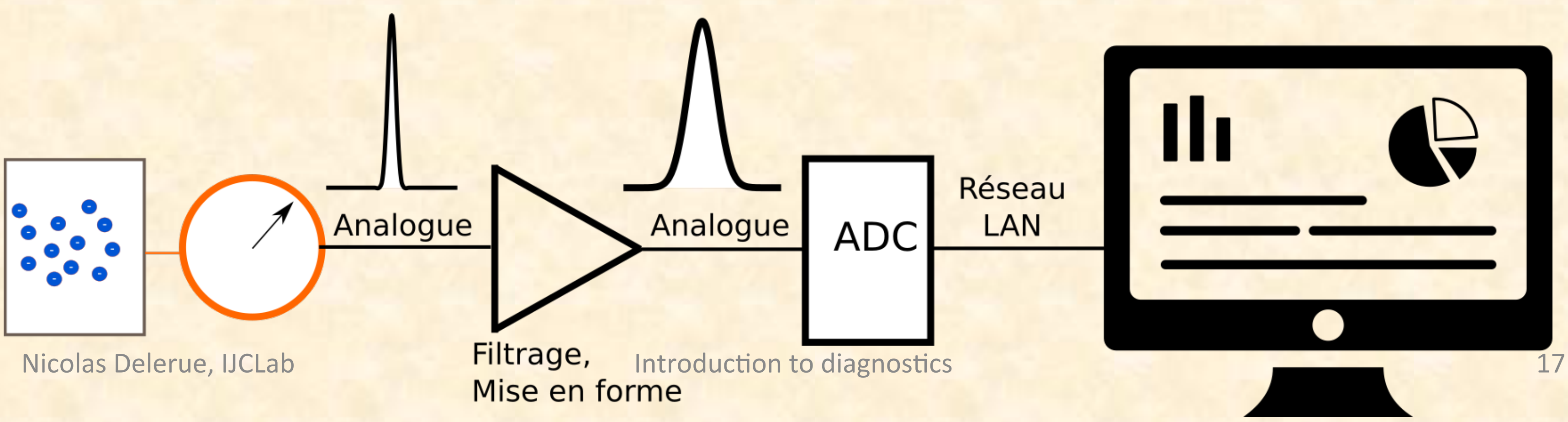
Shaping the signal

- Nowadays almost all signals from the accelerators are digitised.

Source: https://cds.cern.ch/

Shaping the signal

- To go from the equipement where it is produced to the 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.

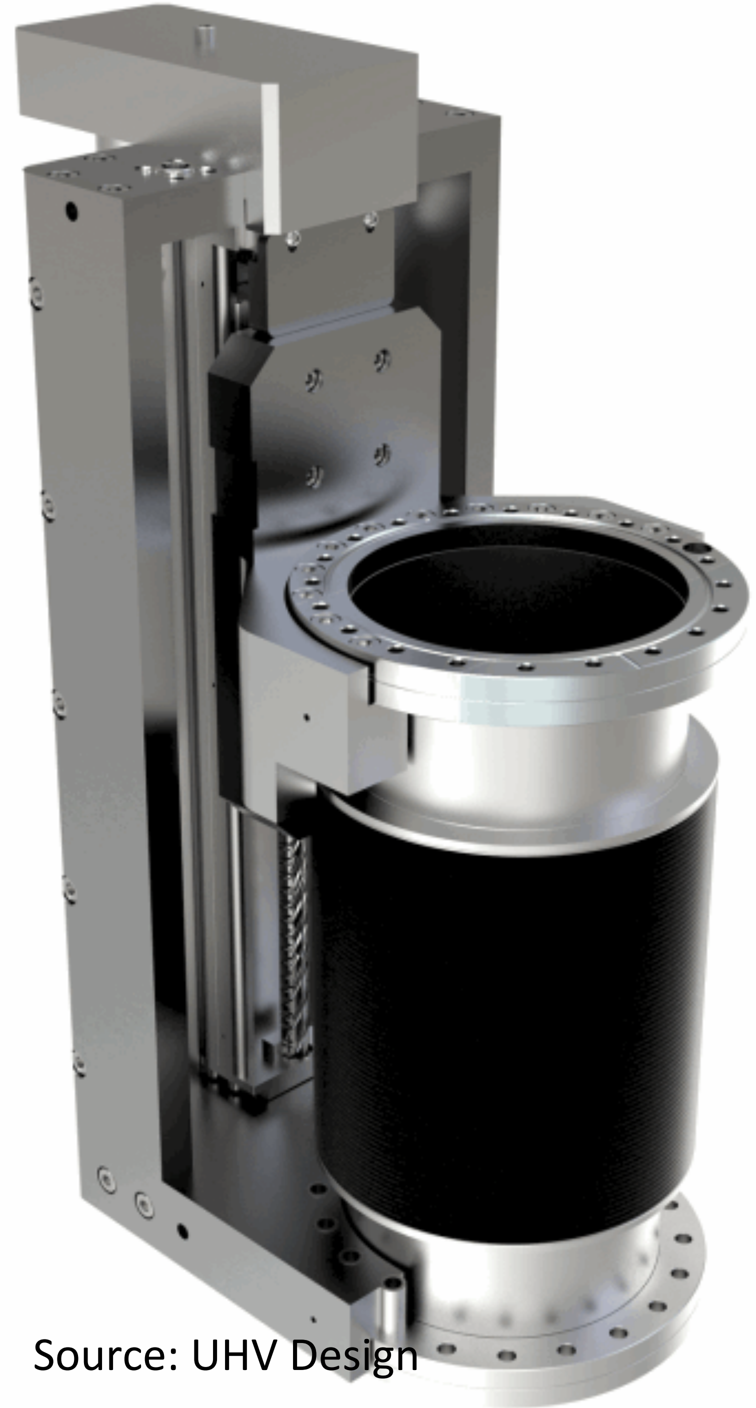


Indirect measurements

- 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

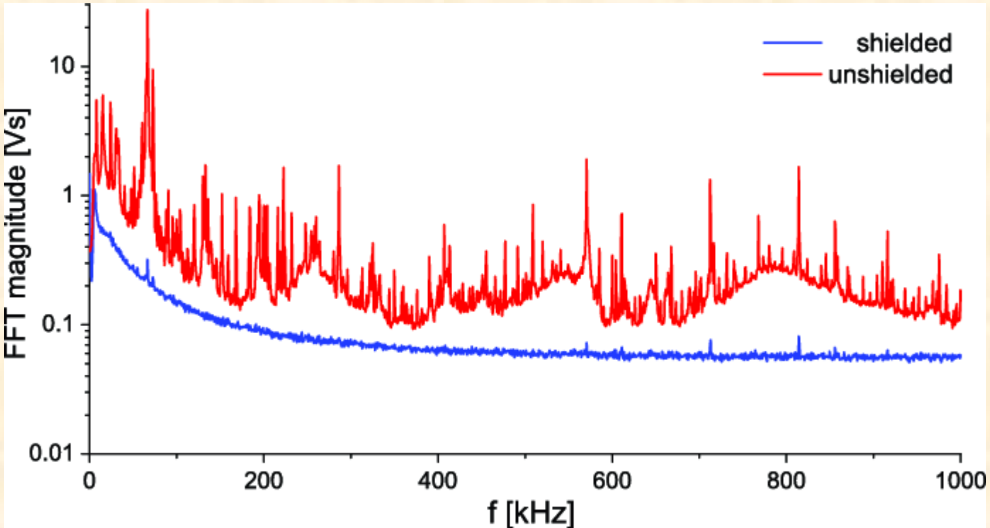
- Diagnostics used in accelerator must be compatible with Ultra High Vacuum.
- This requires special manipulators for anything that needs to be moved inside the beam pipe.



Source: UHV Design

Electromagnetic noise and grounding

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



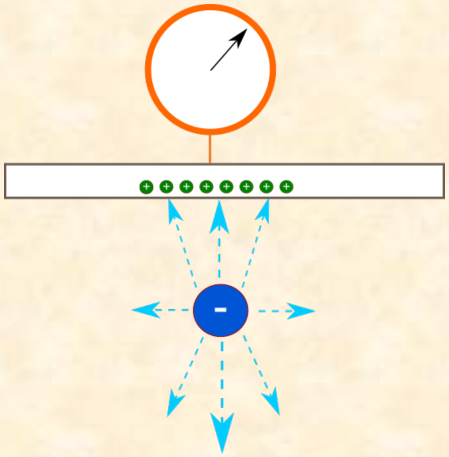
Linear or circular?

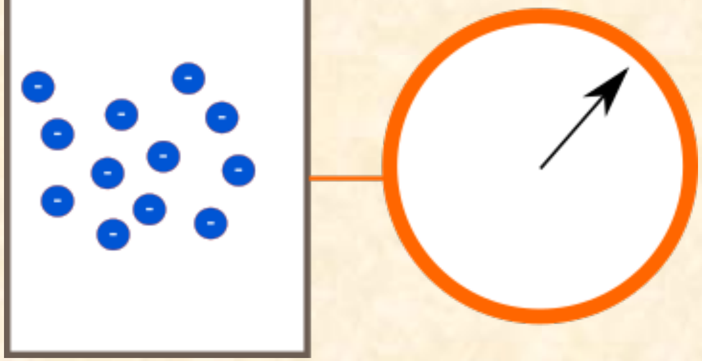
- The type of accelerator will affect the type of detectors you can use.
- Intercepting detectors should mostly be used on linear accelerators. In circular accelerator they prevent the beam from circulating.
- In circular accelerators, the large number of turn allows the detection of weaker signals or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

WHICH MEASUREMENTS CAN BE DONE WITH BEAM DIAGNOSTICS?

Charge measurement

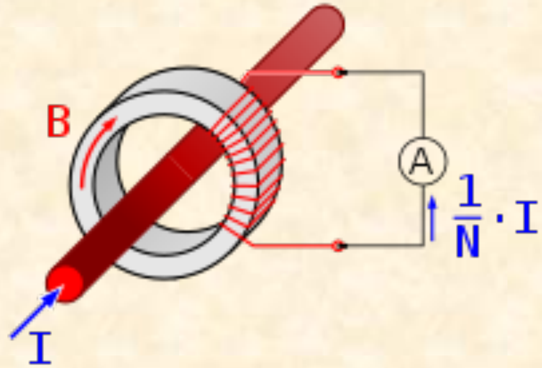
- Charge can be measured two ways:
  - By measuring the current flowing in the beam pipe => current transformer
  - By measuring the current deposited in a block of matter => Faraday cup





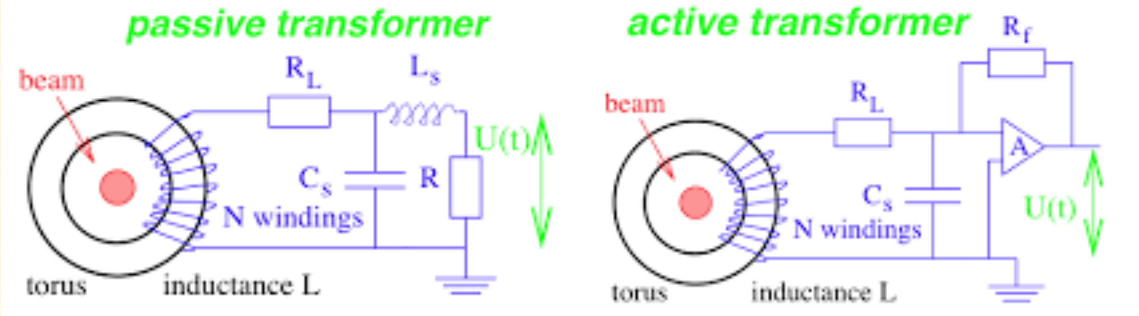
Current transformer

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



Source: https://www.bergoz.com/

AC Current transformer



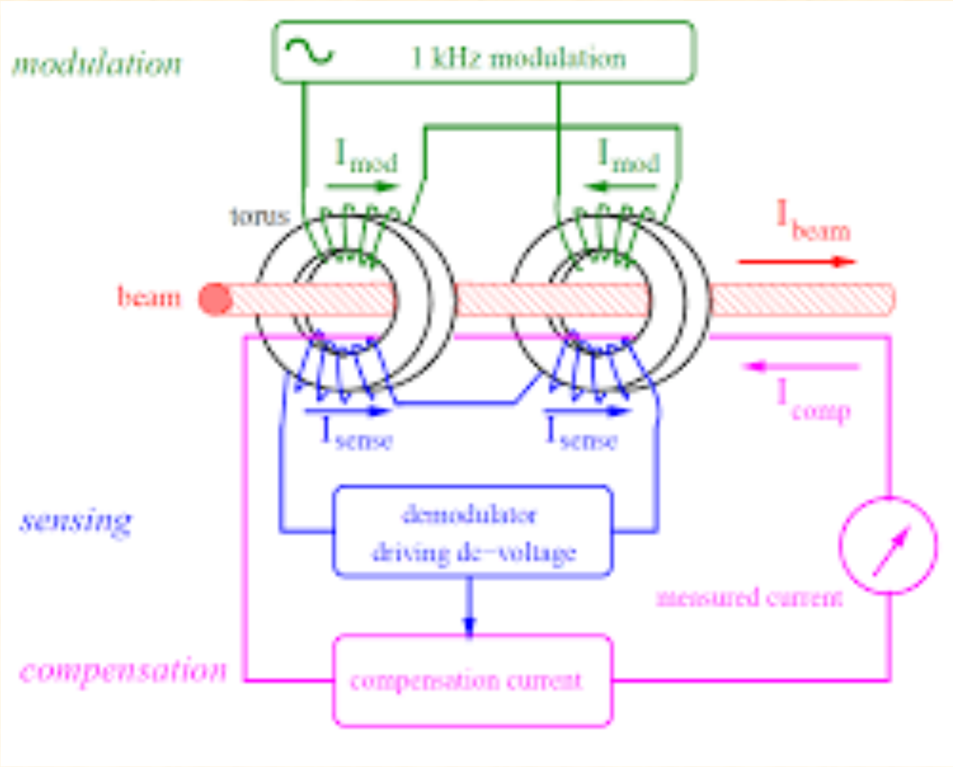
Source: Peter Forck, JUAS

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

Source: https://www.bergoz.com/

DC Current transformer

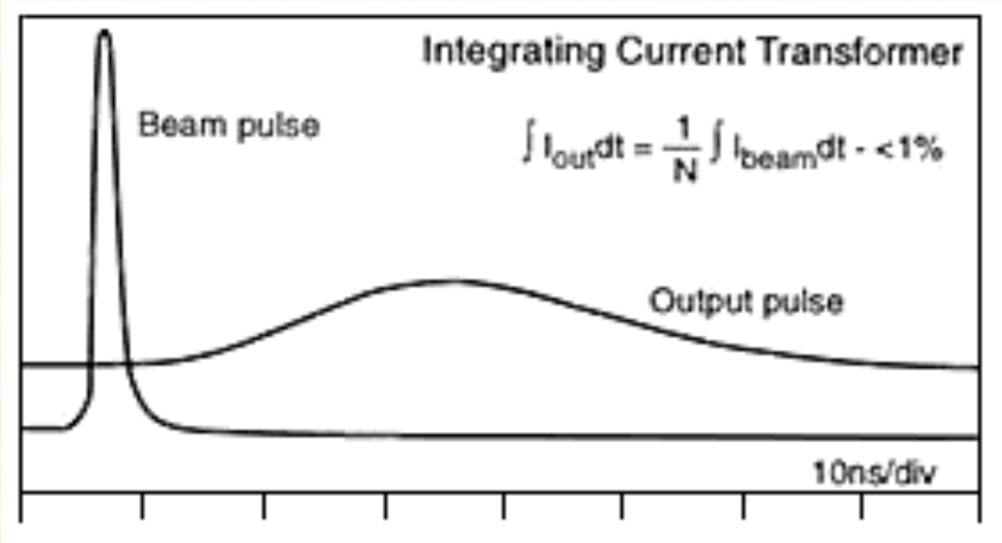
- If the beam is almost continuous a more complex DCCT will be used.
- Here the current measured is the current required to cancel the signal in the two toroids.



Source: Peter Forck, JUAS

Integrating Current transformer

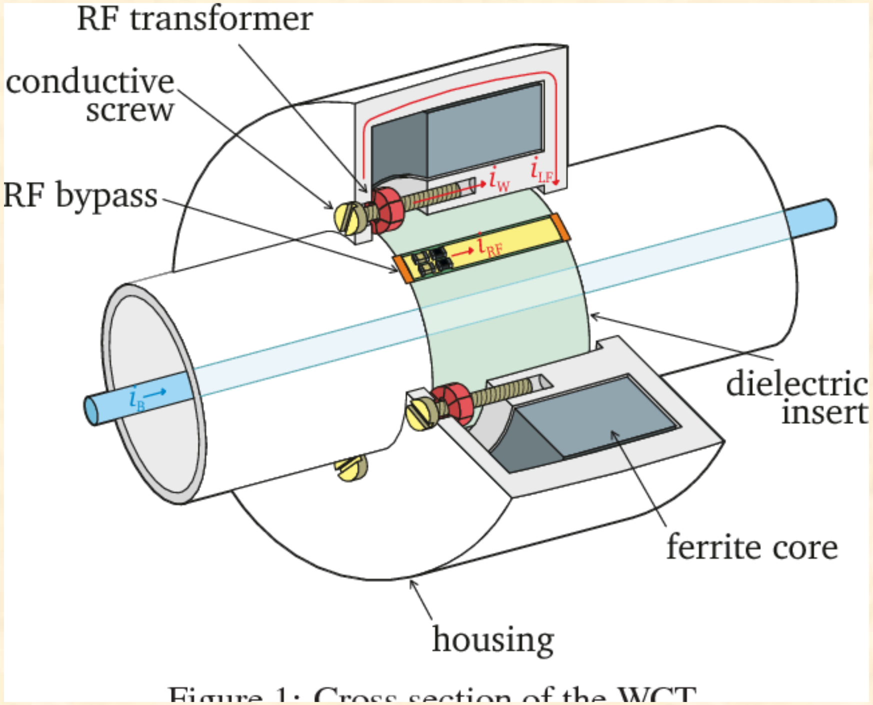
- If the beam pulsed are very short (picoseconds), it can't be recorded as is by the electronic.
- An integrating current transformer (ICT) with large capacitance will be used to smooth the pulse.



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.



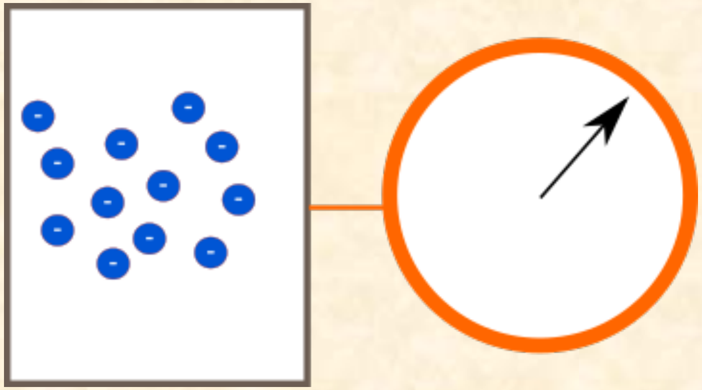
Source: CERN

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.
- 100MeV/(12.57MeV/cm) ~ 8cm
- The Faraday cup must be at least 8 cm.
- A margin of at least 50% must be added => ~12cm
- Beware that some secondary particles (neutrons, …) may travel further than that.
- 1GeV => 120cm
- Graphite: 100MeV/(3.56MeV/cm) ~26cm +50% => 39cm.

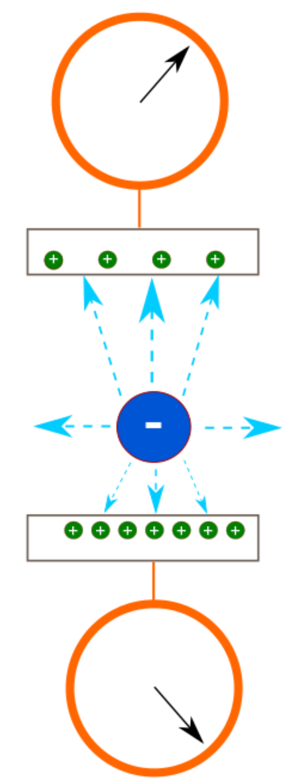
Current transformers vs Faraday cup

- 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

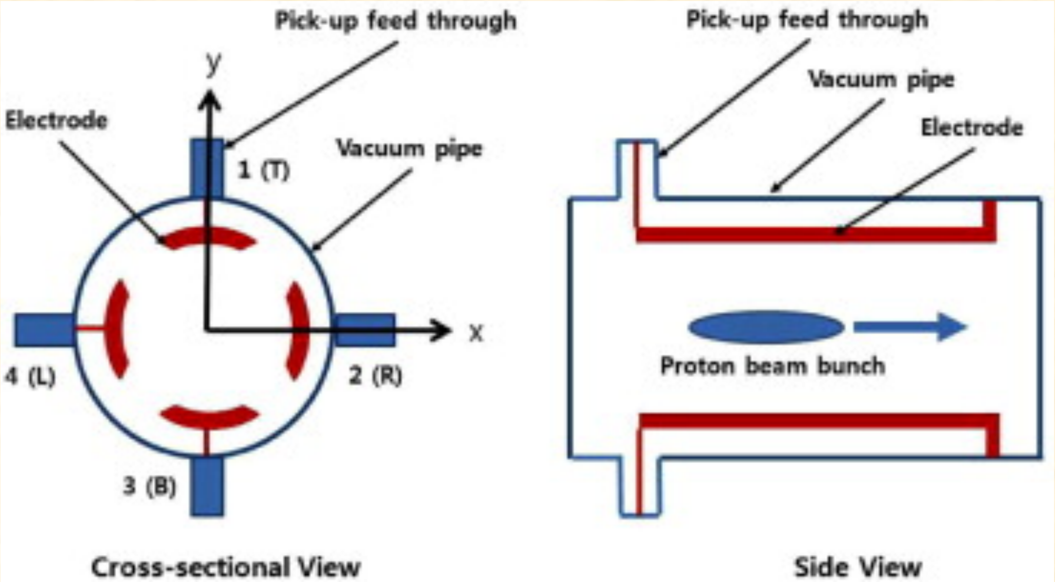
Beam position measurement

- 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)

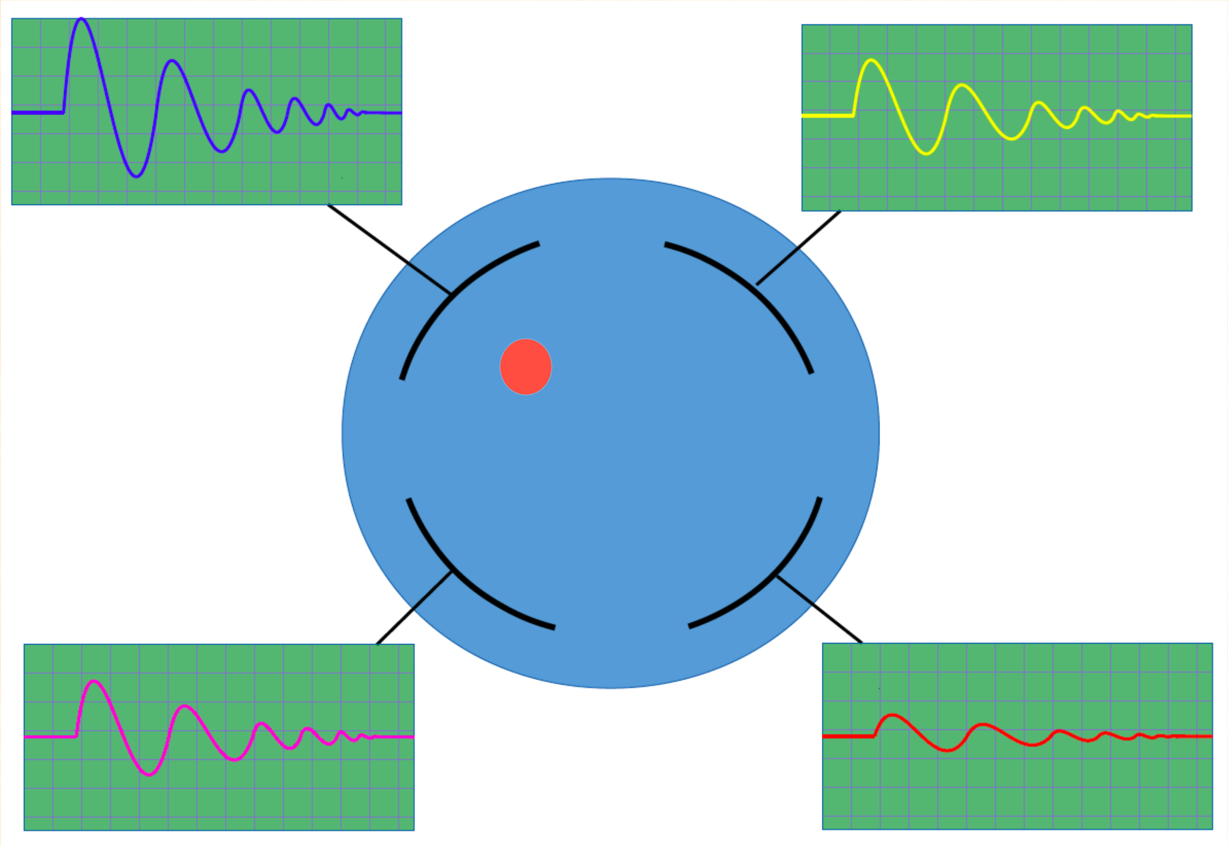


Beam position monitors (BPM)

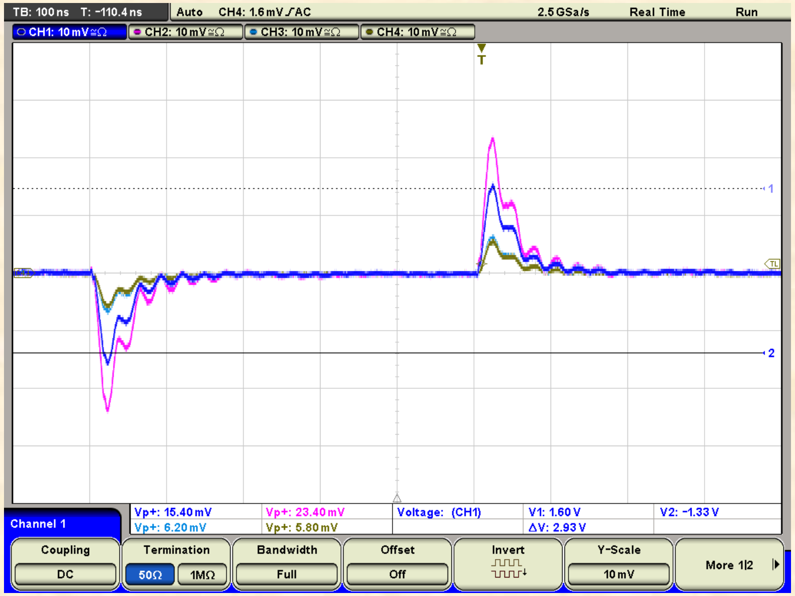
- To get the position one need to compare the signal of the electrodes two by two.
- The difference in signal between two opposite electrodes give the position on that axis.
- The sum of the signal on the 4 electrodes is proportional to the charge.

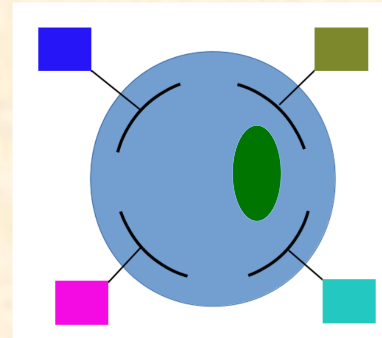


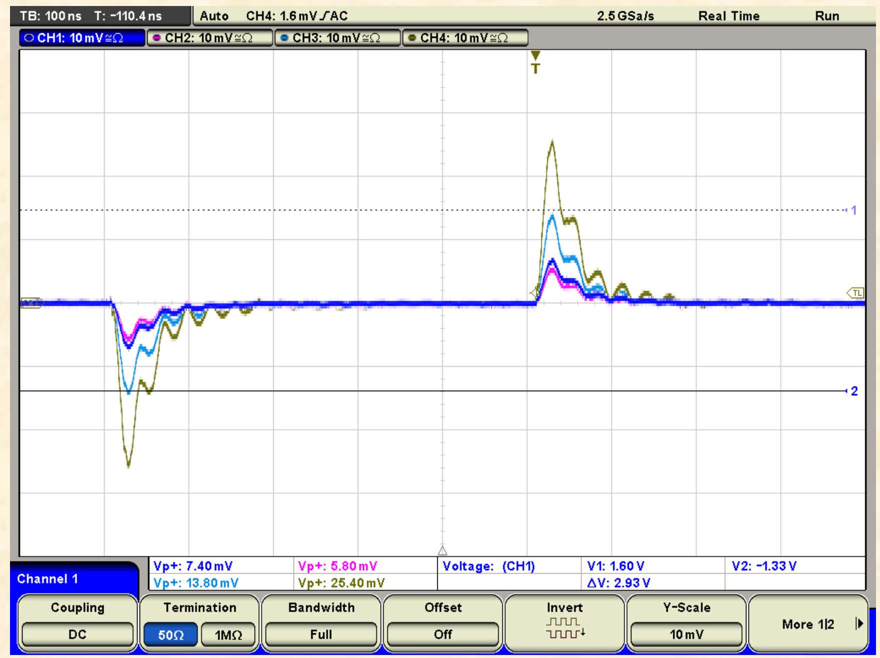
Signal on the electrodes

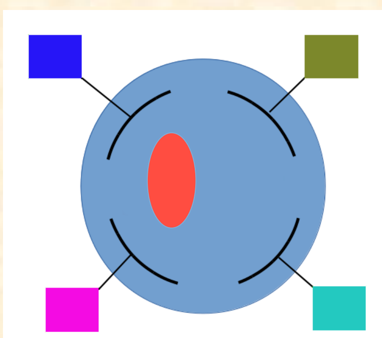


Example of measurements



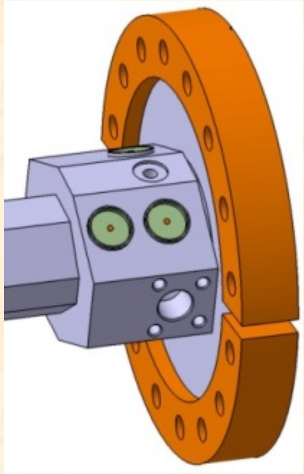


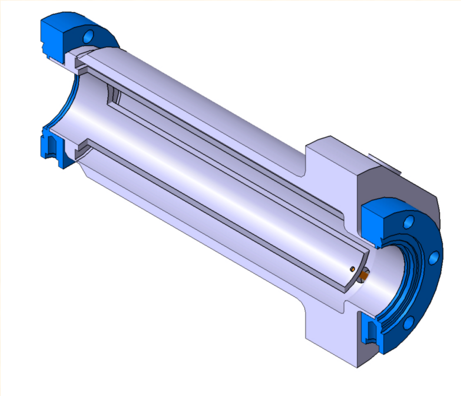


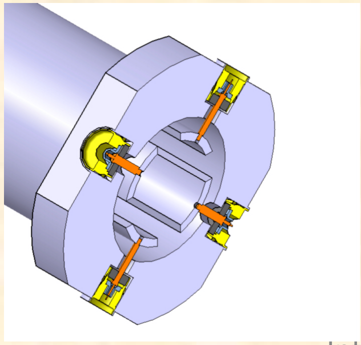


Beam position monitors (BPM)

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

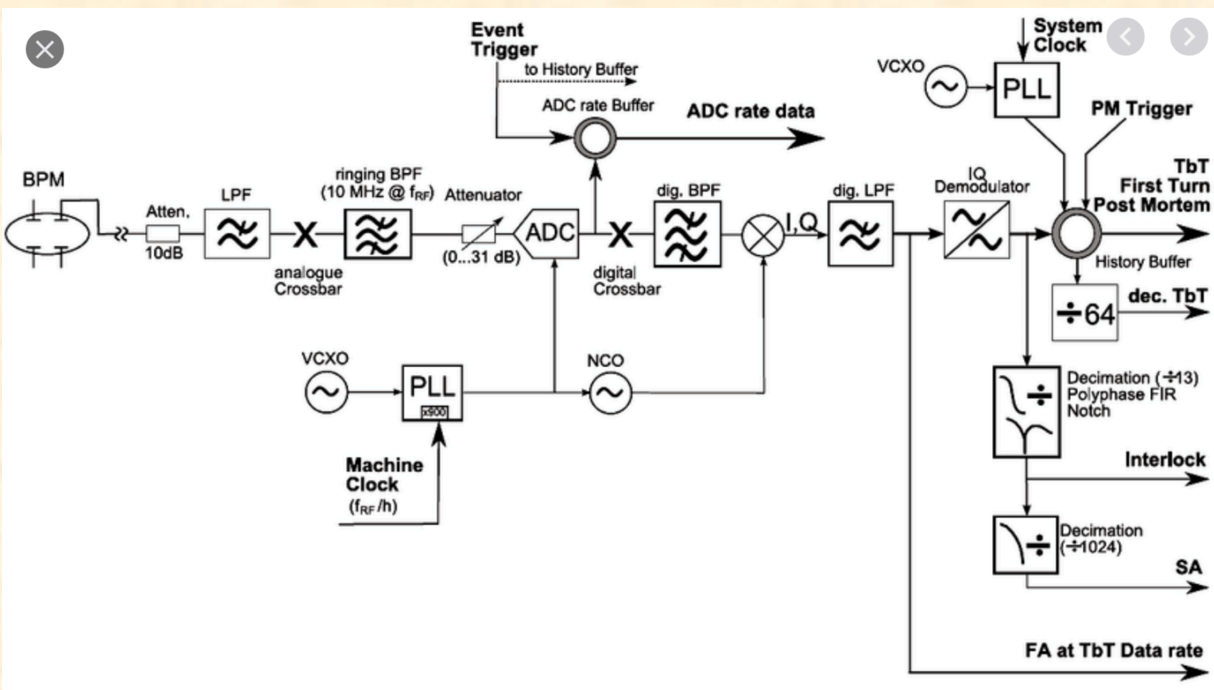






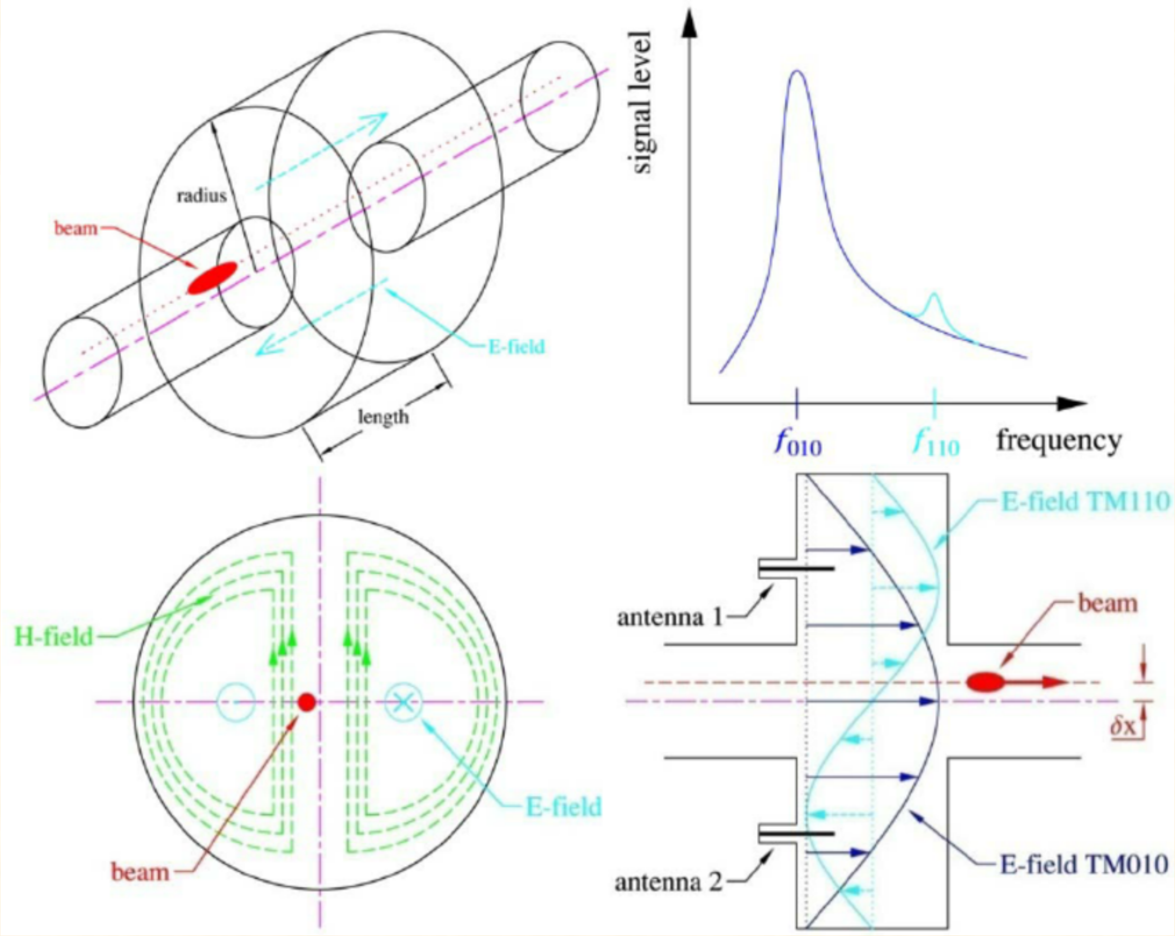
BPM electronics

- 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

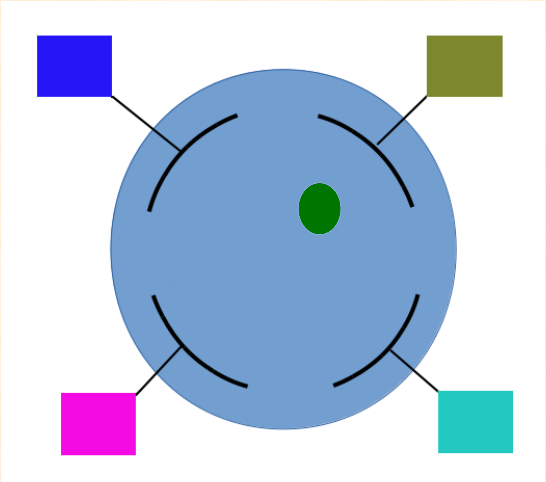
- Instead of electrodes of BPM can use a pillbox cavity.



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.

$$\iint_{(S)} \vec{E} \cdot \mathrm{d}\vec{S} = \frac{Q_{int}}{\varepsilon_0}$$



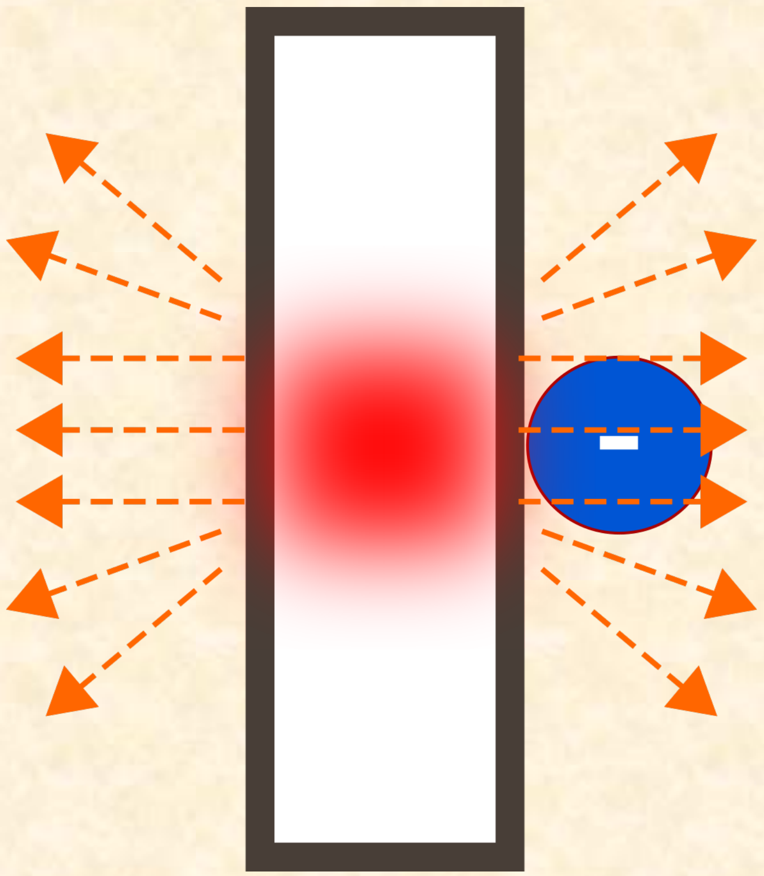
Beam profile measurement

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

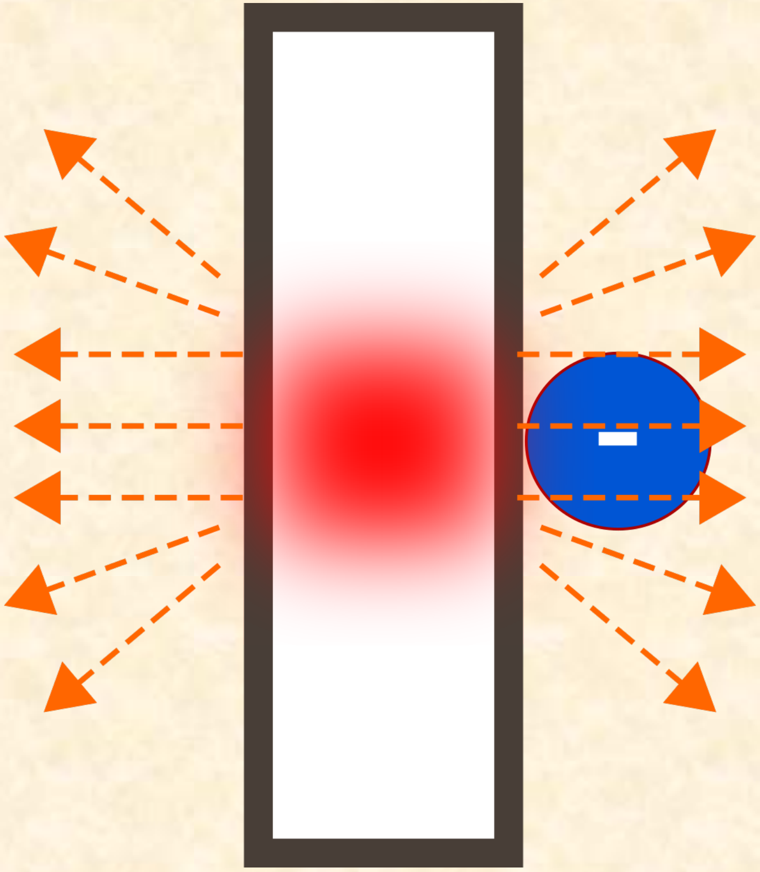
Beam profile measurement using luminescent screens

- 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.



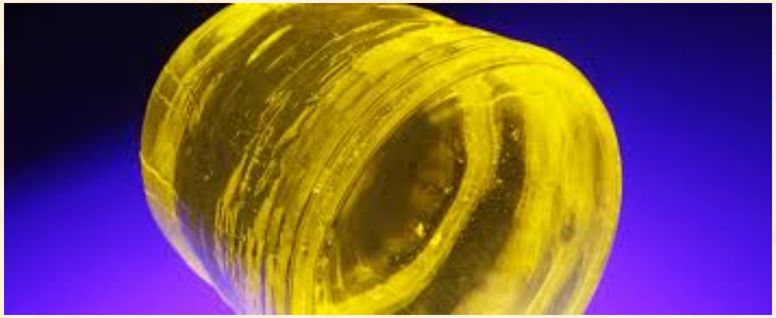
Beam profile measurement using luminescent screens

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

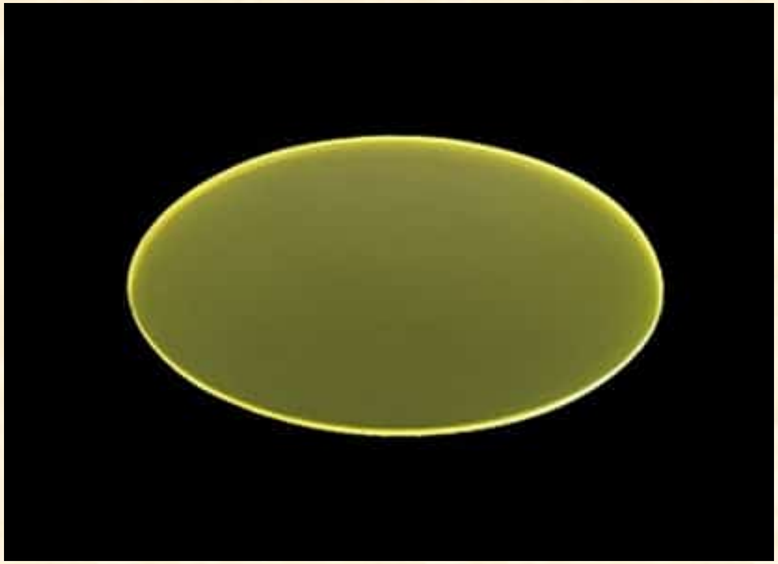


YAG:Ce

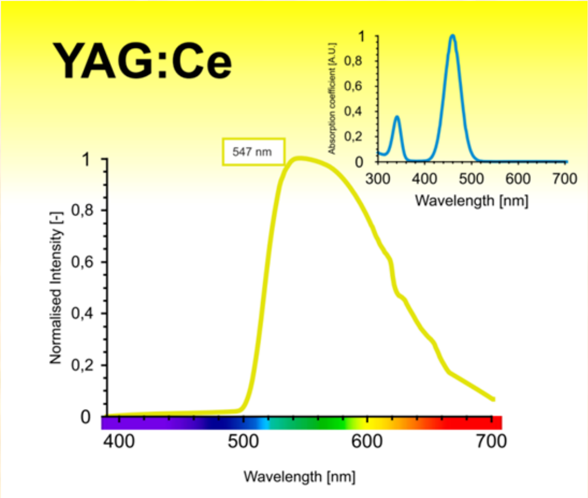
- Yttrium aluminum garnet activated by cerium is a fast scintillator with excellent mechanical and chemical resistance.
- Yield: $3x10^3$ ph/MeV
- Density : 4.57 g/cm^3
- Minimum d'ionisation:
  2 MeV cm^2/g
  => 9.2MeV/cm



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

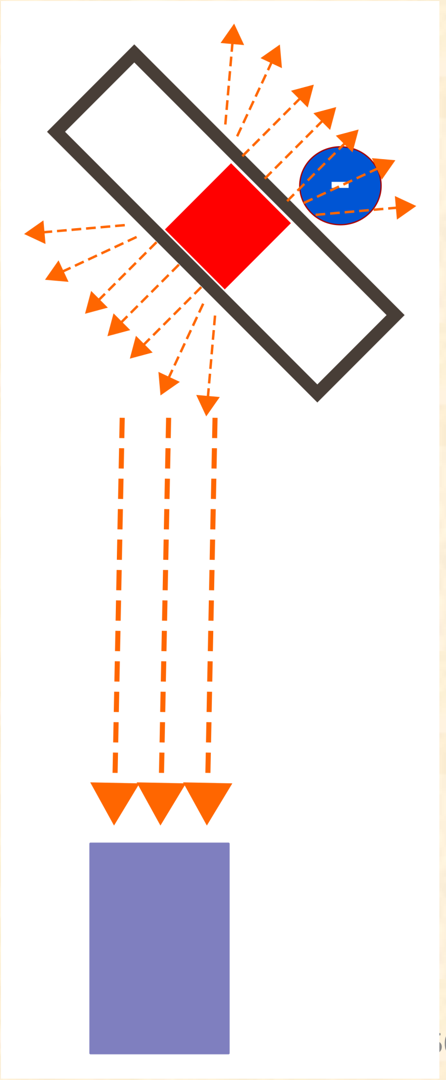
EMVA Quantum Efficiency (typical)	46.0 %
Dark Noise (typical)	11.2 e⁻
Saturation Capacity (typical)	14.0 ke⁻
Dynamic Range (typical)	62.1 dB
Signal-to-Noise Ratio (typical)	41.6 dB

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

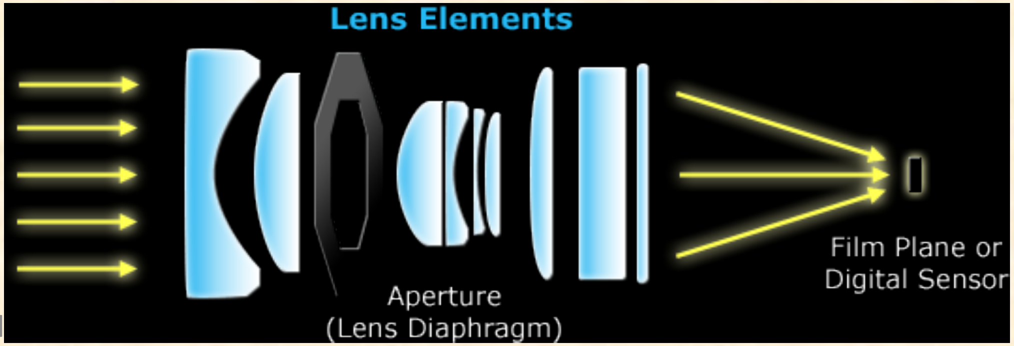
Beam profile measurement using luminescent screens

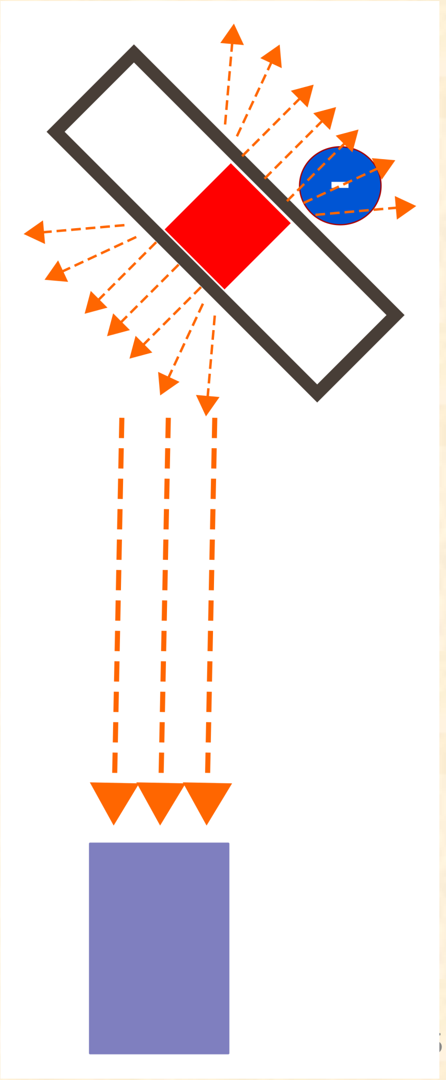
- Beware: don't put a camera directly in the particle beam.
- Typically the screen is tilted at 45º and the camera looks at it from from the side.
- In other configurations the screen is at 90º and a mirror reflects the light toward the camera.



Beam profile measurement using luminescent screens: optical function

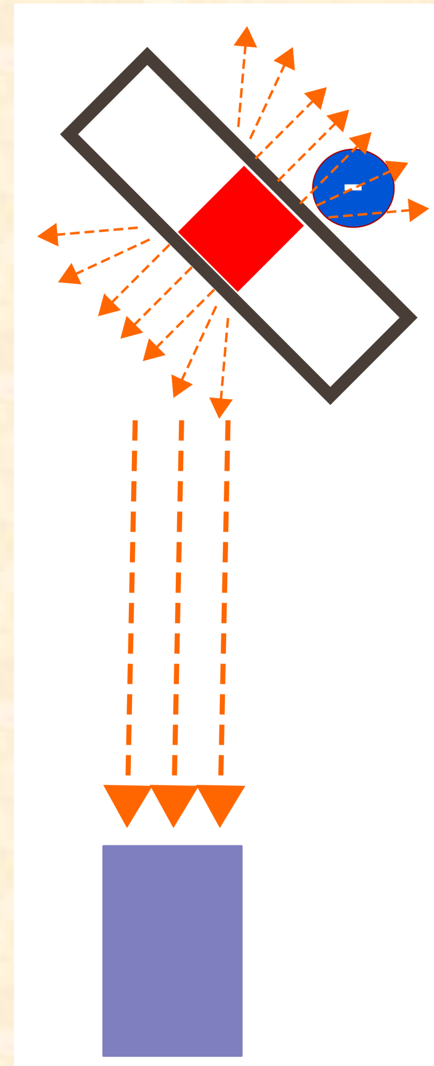
- Optics must be installed between the screen and the camera.
- Can be simple lenses or more advanced zoom lenses (including consumer lenses).

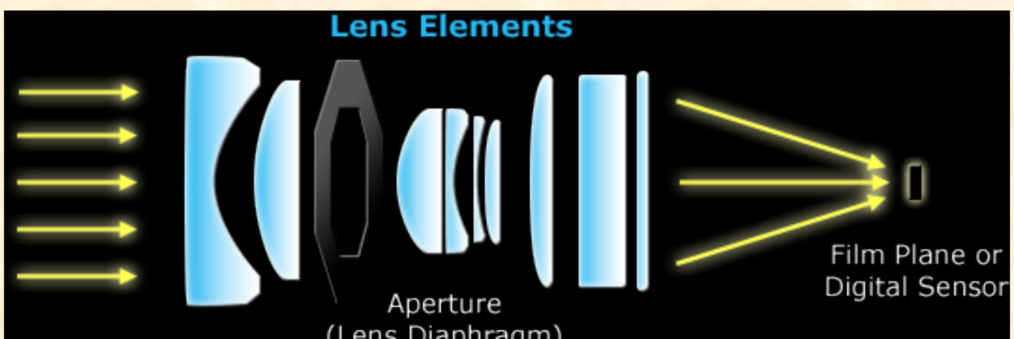




Beam profile measurement using luminescent screens: optical function

- Field of view (fov): size of the object (screen) to be imaged.
- Working distance (WD): distance to the screen.
- We have the relation:
  focal length x FOV = sensor size x WD



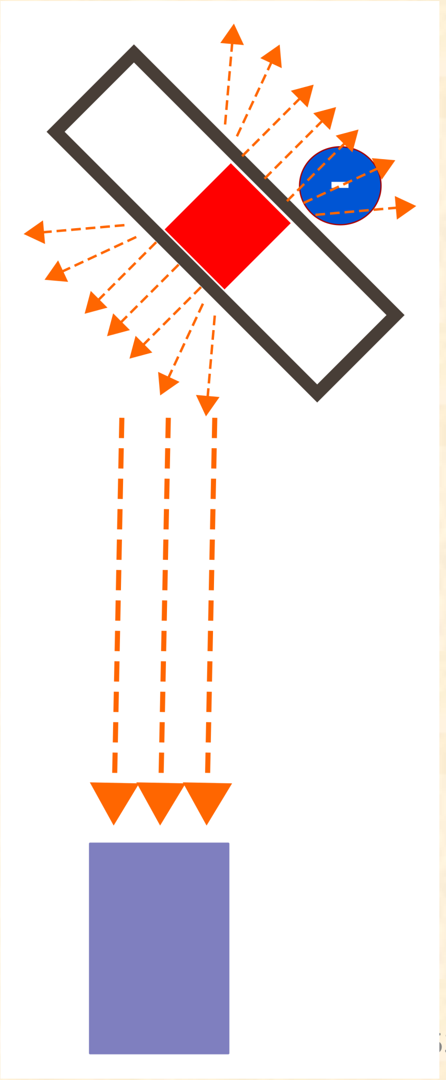


Source: https://www.cambridgeincolour.com/

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:
  Focal length = (sensor size x WD)/FOV
  => 5mm x 1m/25mm = 200mm



Beam profile measurement using luminescent screens: optical function

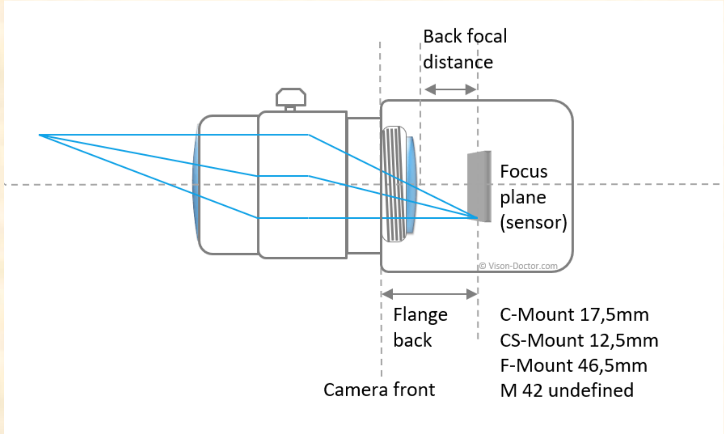
Lens mount:

- 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.

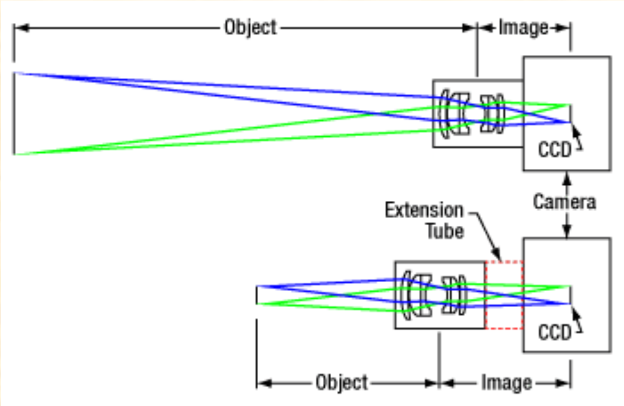
Beam profile measurement using luminescent screens: optical function

Focal length correction when using adapter:

- Focal length scales with back focal length.
- C=>Cs: 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.



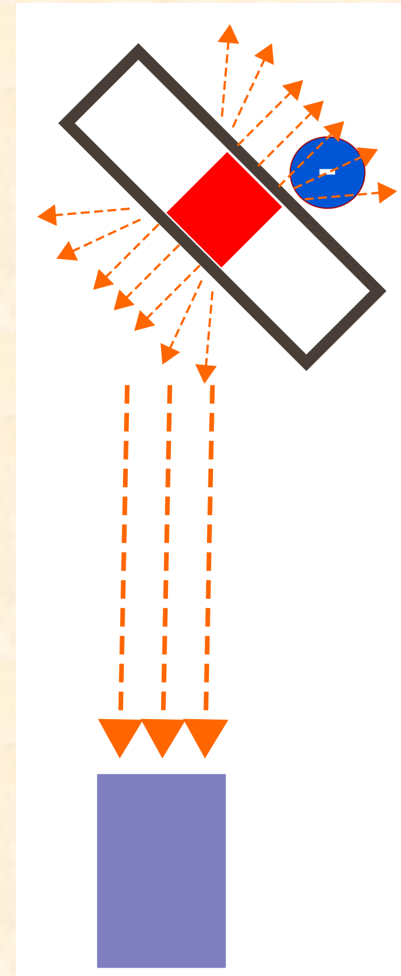
Source: https://www.vision-doctor.com/



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

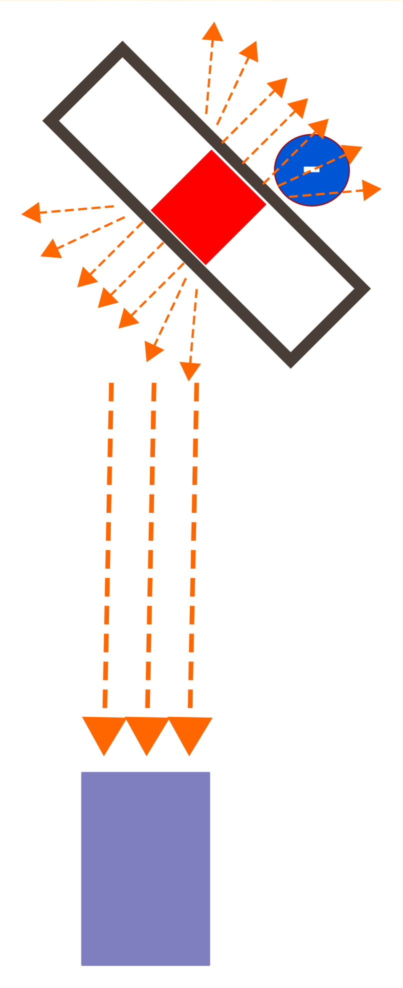
Beam profile measurement using luminescent screens

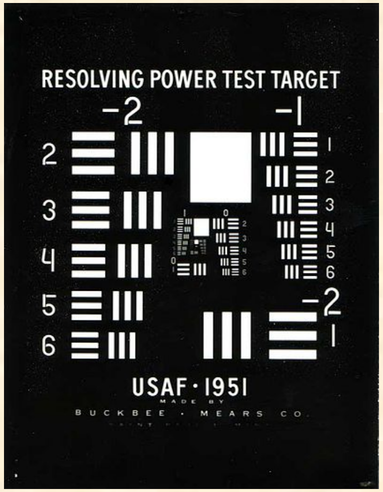
- The screen can't be left permanently in the beam.
- UHV compatible actuators must be used.
- Also, remember to trigger the camera at the right time otherwise you won't see the beam.



Beam profile measurement using luminescent screens

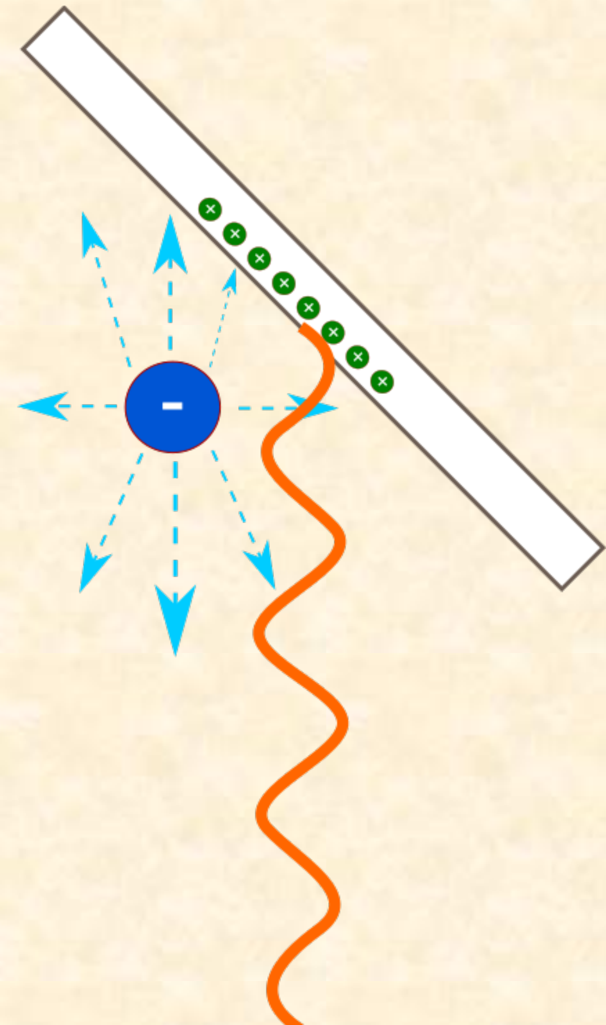
- The optical function (camera + lens) must be calibrated.
- Ideally the system must have a built-in target to recalibrate the system from time to time.





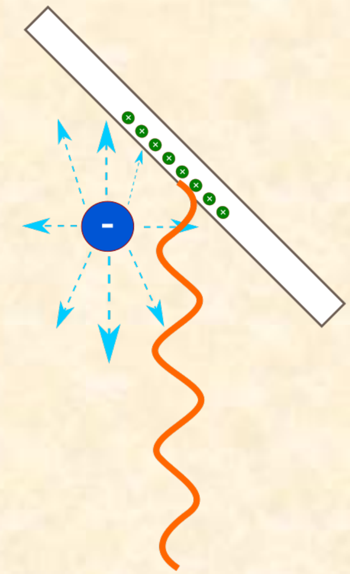
Beam profile measurement using transition radiation screens

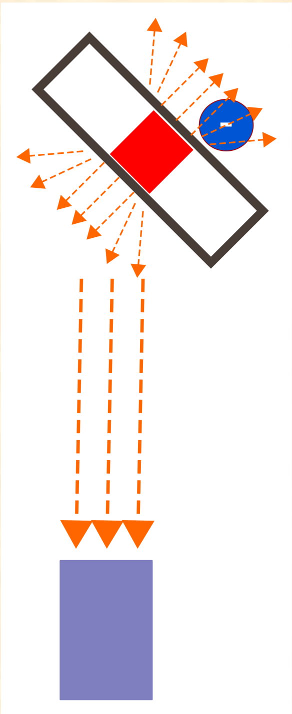
- When charged particles travel across a surface some of the virtual photons surrounding them may become real.
  => Transition radiation.
- By orienting the screen at 45º the radiation may be observed with a camera.



Beam profile measurement
Transition radiation vs luminescence

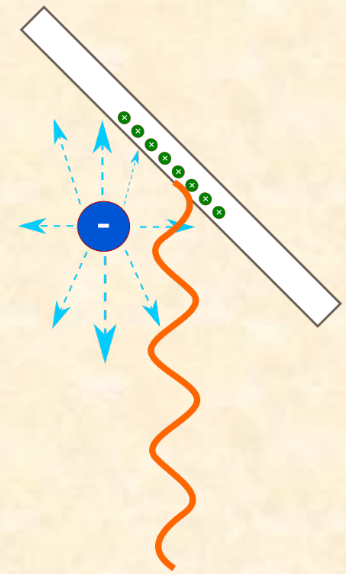
- Location:
  - Lumin. happens in the volume of the screen
  - TR happens at the surface.
- Directionality:
  - Lumin. is emitted over 4pi
  - TR is emitted in a 1/gamma cone
- Intensity:
  - Lumin. depends on screen thickness
  - TR is 1% of the number of electrons (usually much weaker)
- Spectrum
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

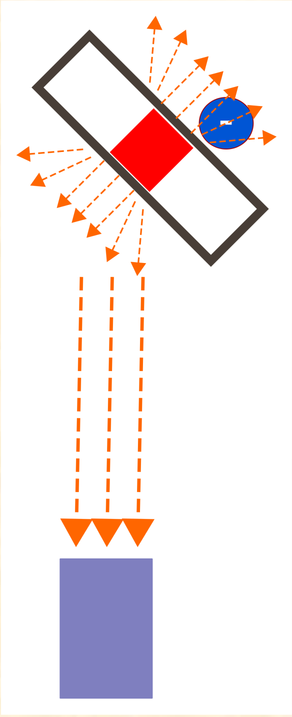


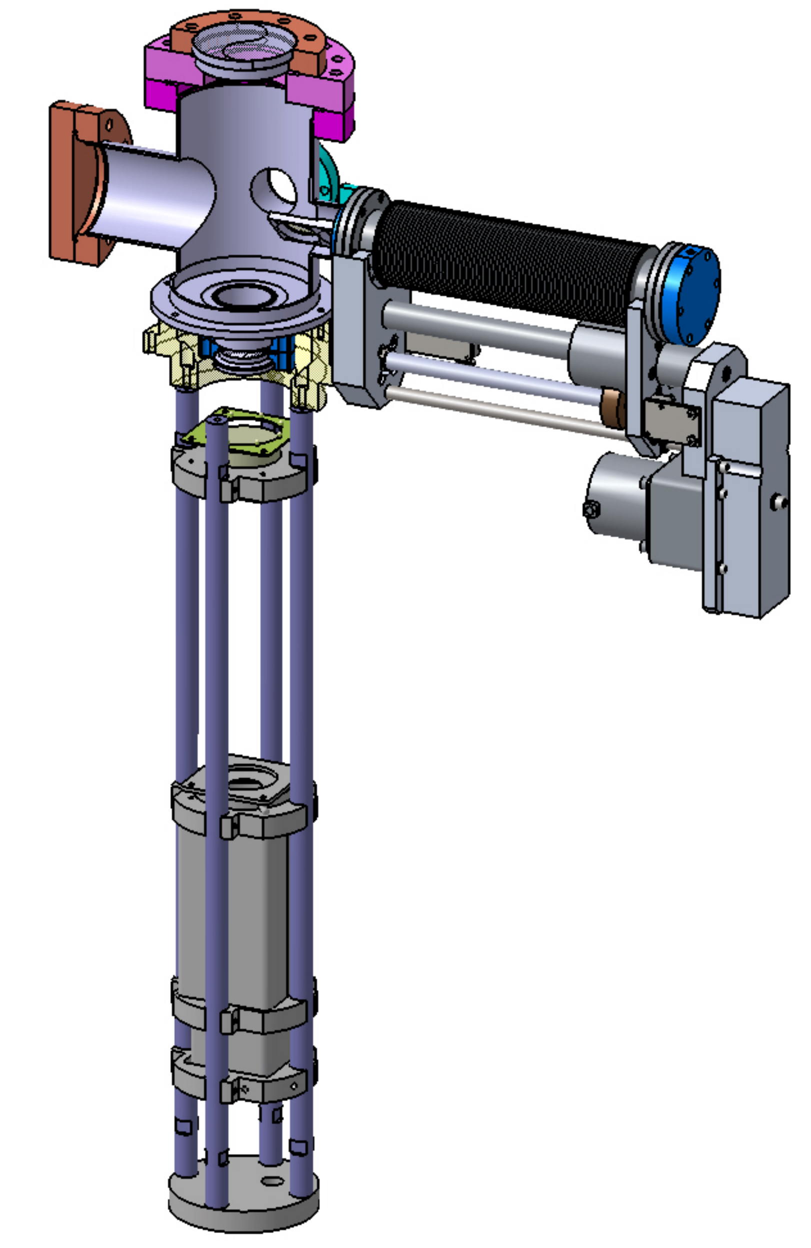


Beam profile measurement
Transition radiation vs luminescence

- 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 ~5mrad. All reach the lens.
- Lumin. :
  - 100MeV => minimum ionising
  - 0.92MeV of energy deposited.
  - 2.7 x 10^3 photons emitted over 4pi.
  - Lens surface: 1962.5mm^2
  - 1m sphere = 4.2m2
  - 1962.5mm^2 / 4.2m2 ~4%
  - 1265 photons per electrons captured by the lens.
  - 1.265 10^{12} photons captured in total.





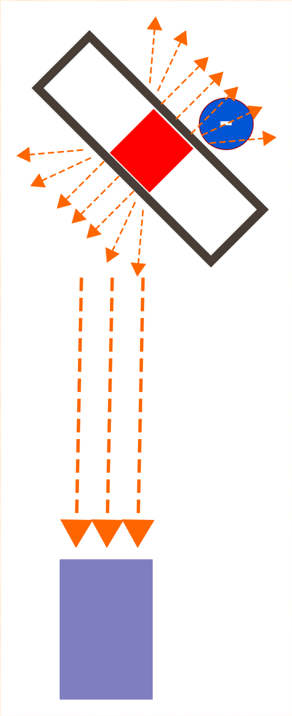


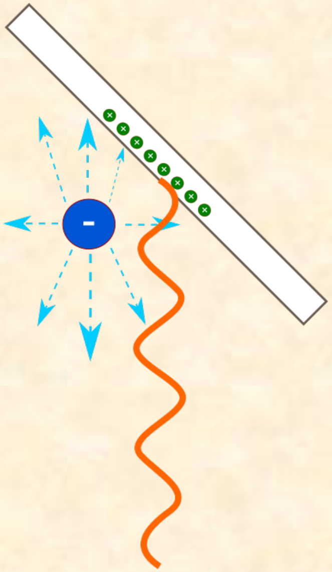
Beam profile measurement using luminescent screens

- The ThomX diagnostics stations.

Beam profile measurement
Transition radiation vs luminescence
Quizz

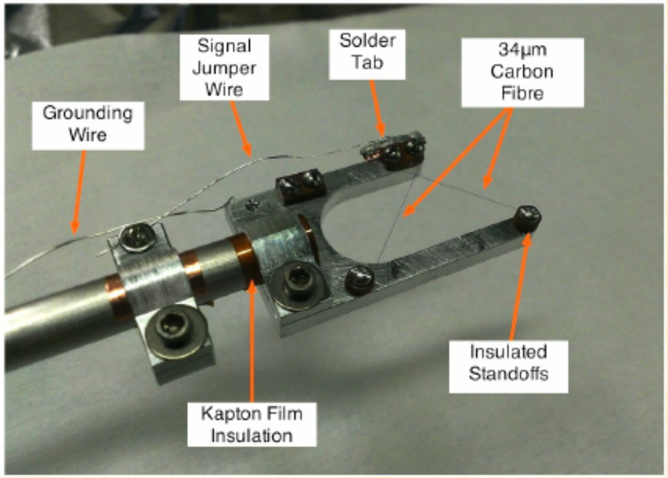
- Same calculation for a 10^9 electrons beam with 250 MeV energy a 0.2mm thick YAG:Ce screen
- Let's assume a 20 mm wide screen with thickness 0.2 mm and a $3x10^9$ electrons beam at 250 MeV.
- Lens at 2m, aperture size 40mm diameter.
- Between the lens and the camera there are two mirrors with 90% reflectivity and there is a vacuum viewport with 95% reflectivity.

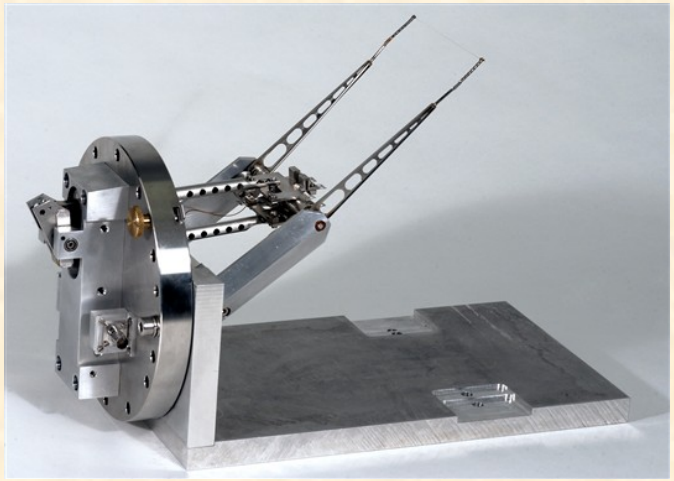




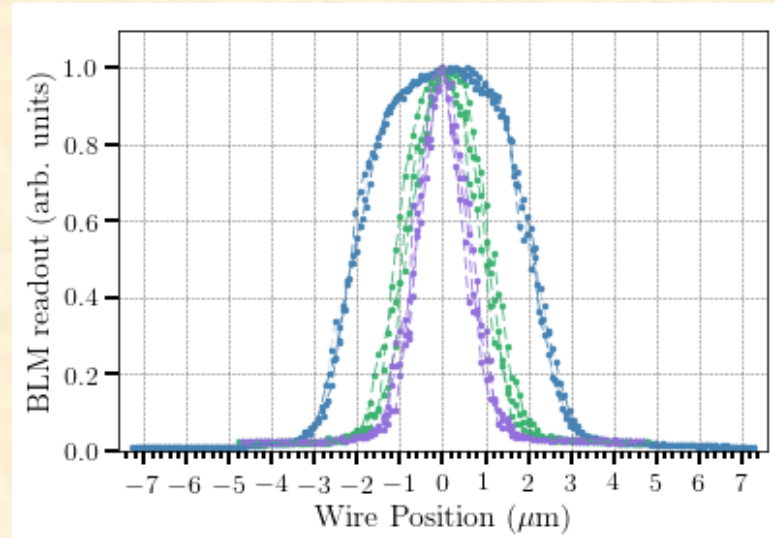
Beam profile measurement
Wire scanners

- 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

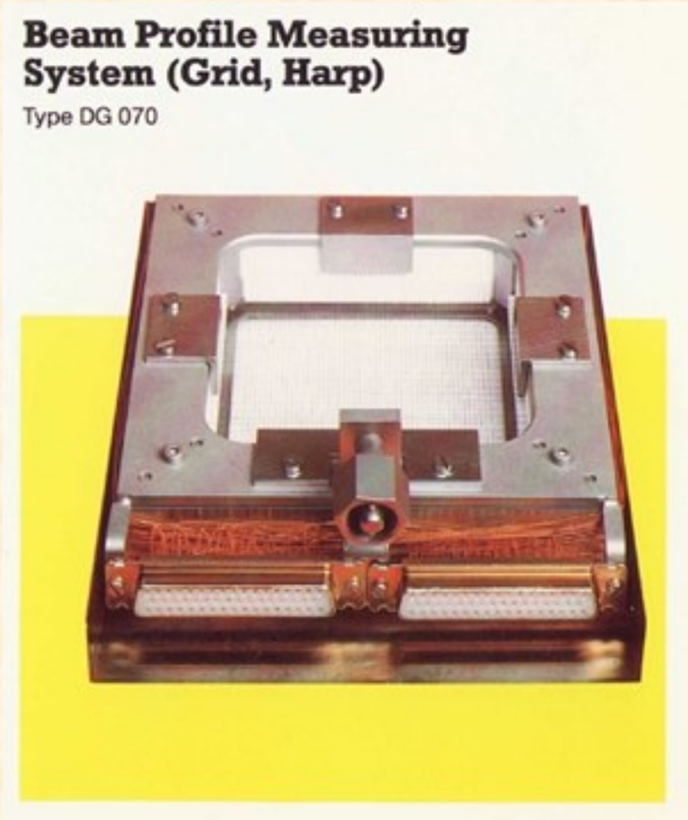


- Example of wire scanner measurements

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

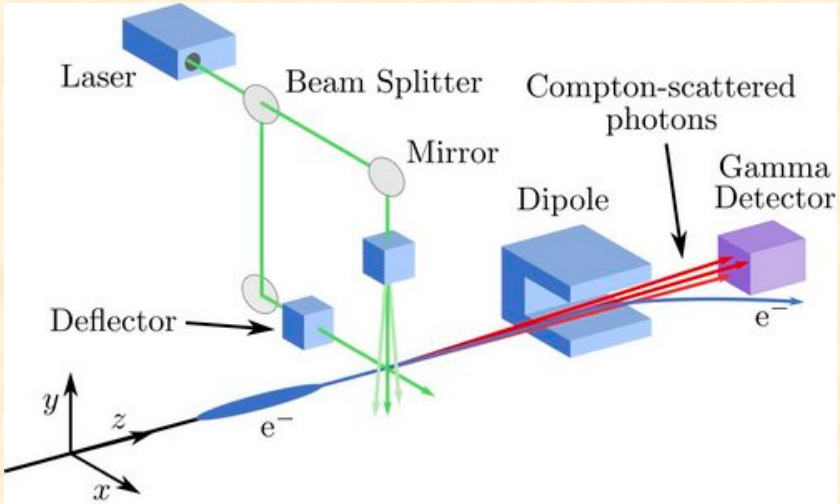
Beam profile measurement
Wire scanners: harps

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



Beam profile measurement
Laser-wire

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



Control system: TANGO and EPICS

- As beam diagnostics and accelerators in general use a large variety of devices, it is necessary to unify the control systems for the operator (and the developers).
- Several control system architectures exist.
- Two of the most commons are TANGO and EPICS.
- See talk on TANGO.

Real cases of diagnostics: ThomX (see separate talk)

Thank you