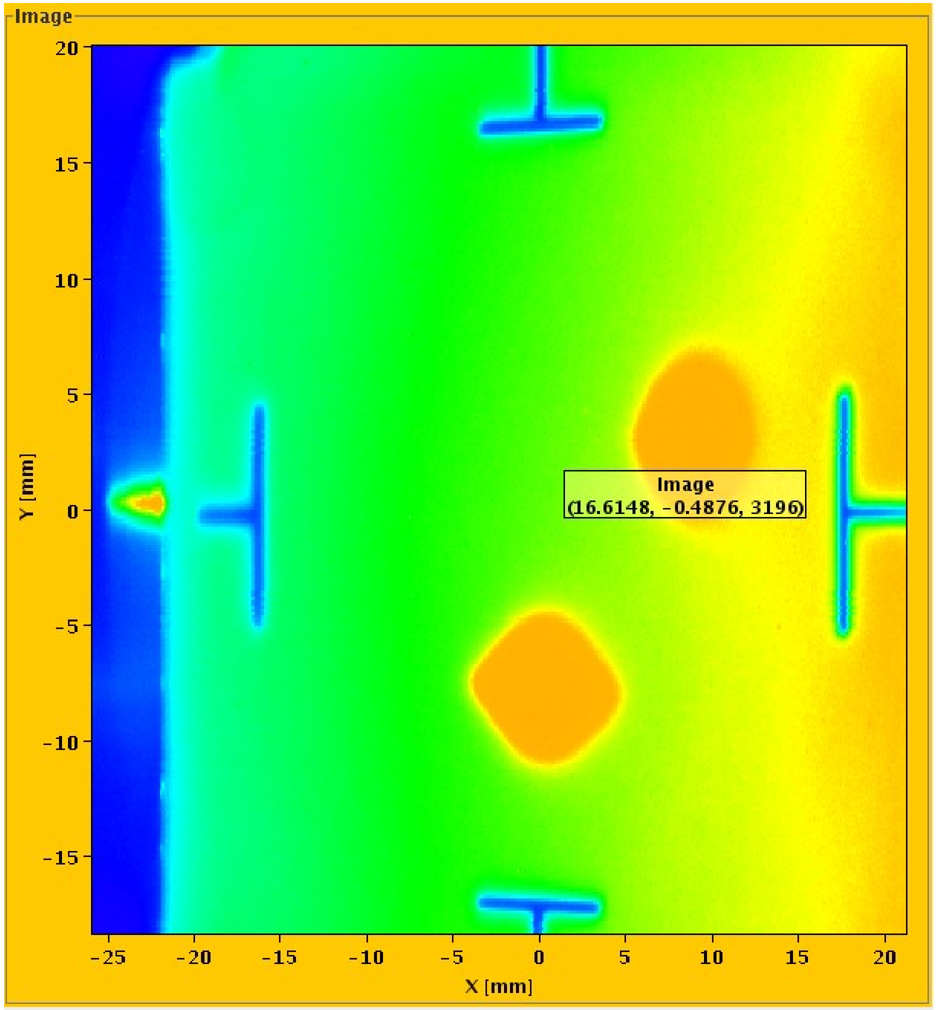
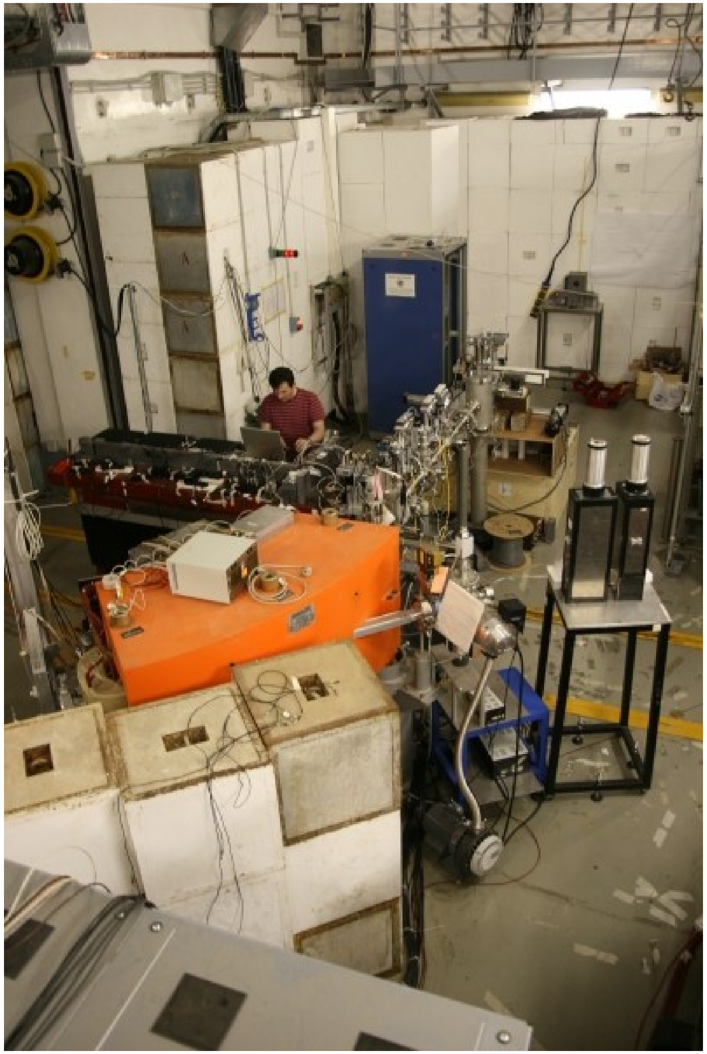
9. Diagnostics (1)



- Which diagnostics do we need?
- Particles interactions with matter
- Charged particles detection

Where are we?



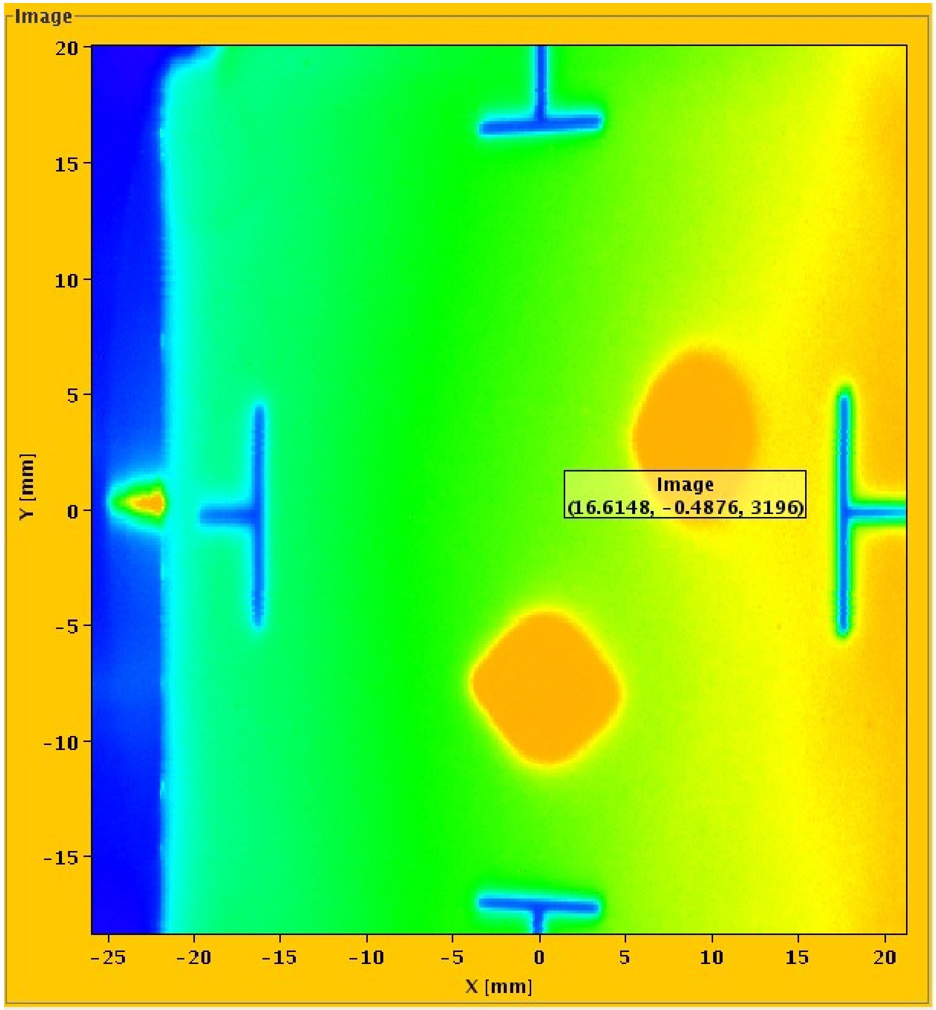
- Last week you learned what is the dynamic inside a beam.
- Today and tomorrow you will learn how to monitor what happens in an accelerator.
- At the end of the week you will learn about the applications of particle accelerators.

What do **<u>you</u>** want to know about the beam?

?

What do you want to know about the beam?

- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses

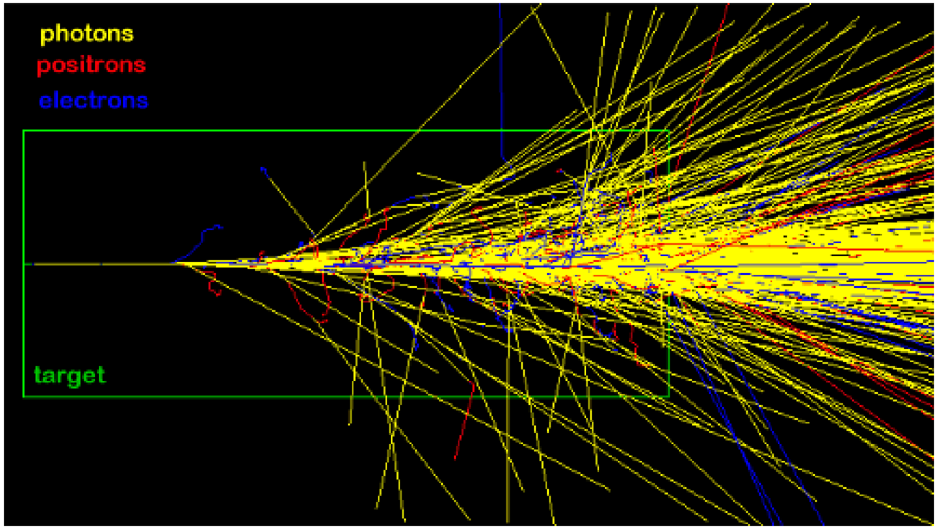


Properties of a charged beam

- Almost all accelerators accelerate
  charged particles which interact with matter.
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

Particles interact with matter (1)

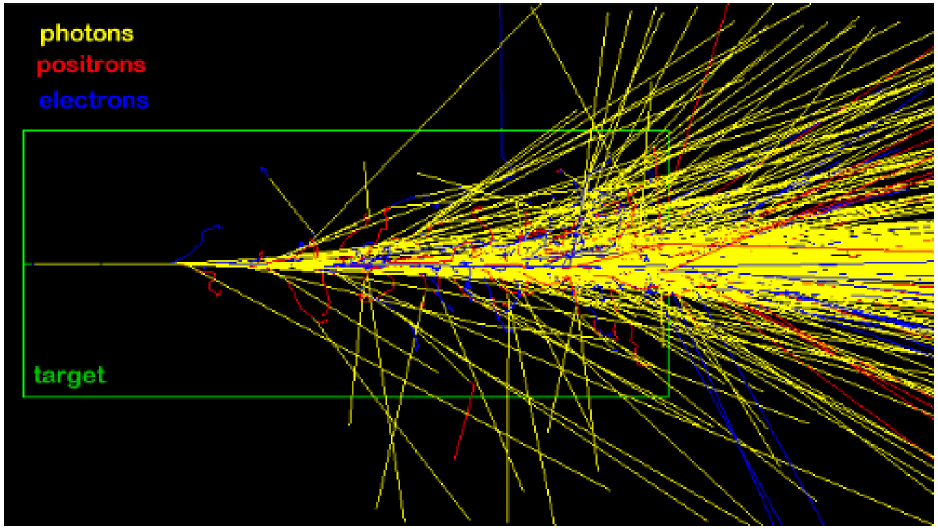
Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

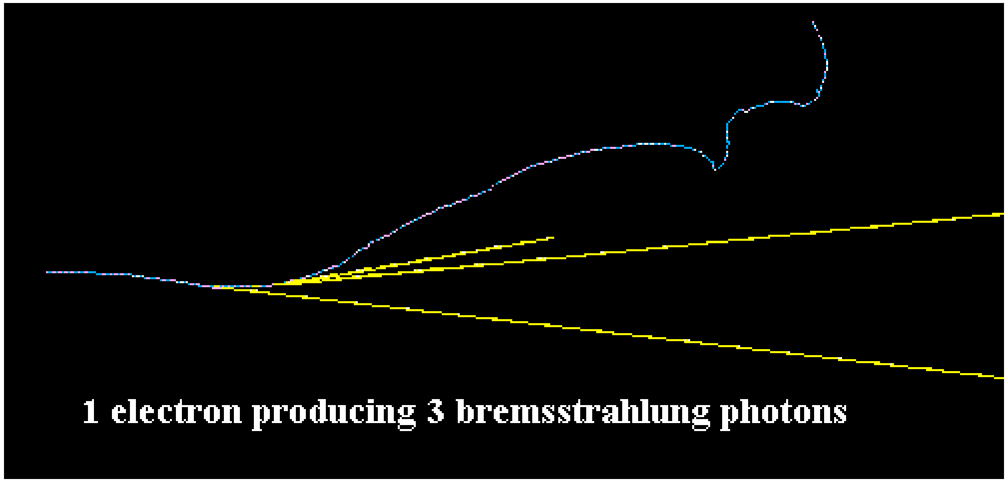


- High energy particles interact with matter in several ways.
- If you took the B1 paper you will have studied this more in details and you may learn more in the C4 next year.

Particles interact with matter (2)

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

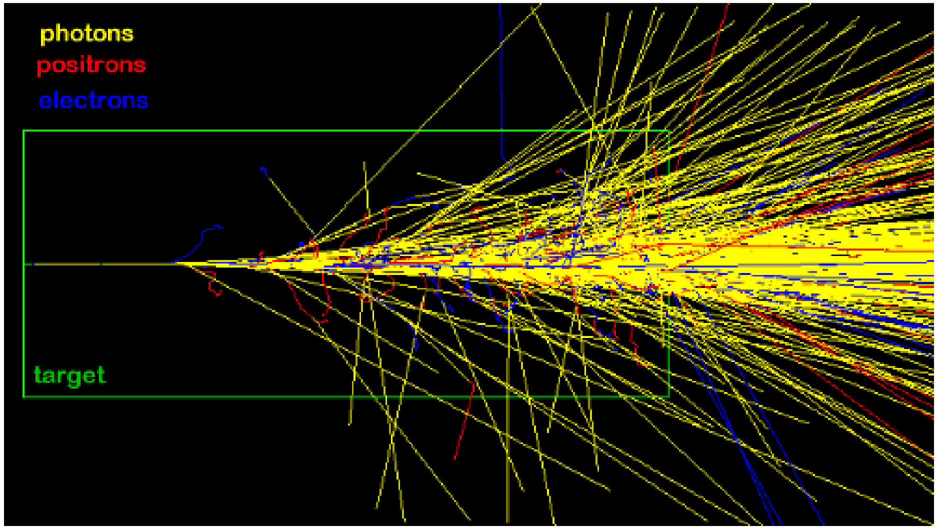


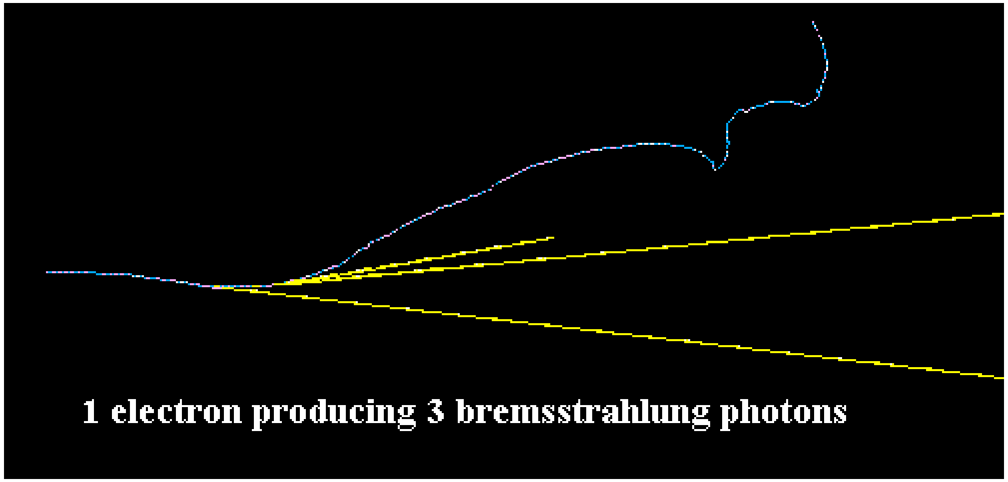


- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produces when such scattering occur will carry a significant energy and scatter themselves.

Particles interact with matter (3)

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.





- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produces when such scattering occur will carry a significant energy and scatter themselves.

Example: Electron shower (1)

- The distance after which an electron or a photon interacts is called the “radiation length”

- Radiation length vary from material to material and can be found in tables.

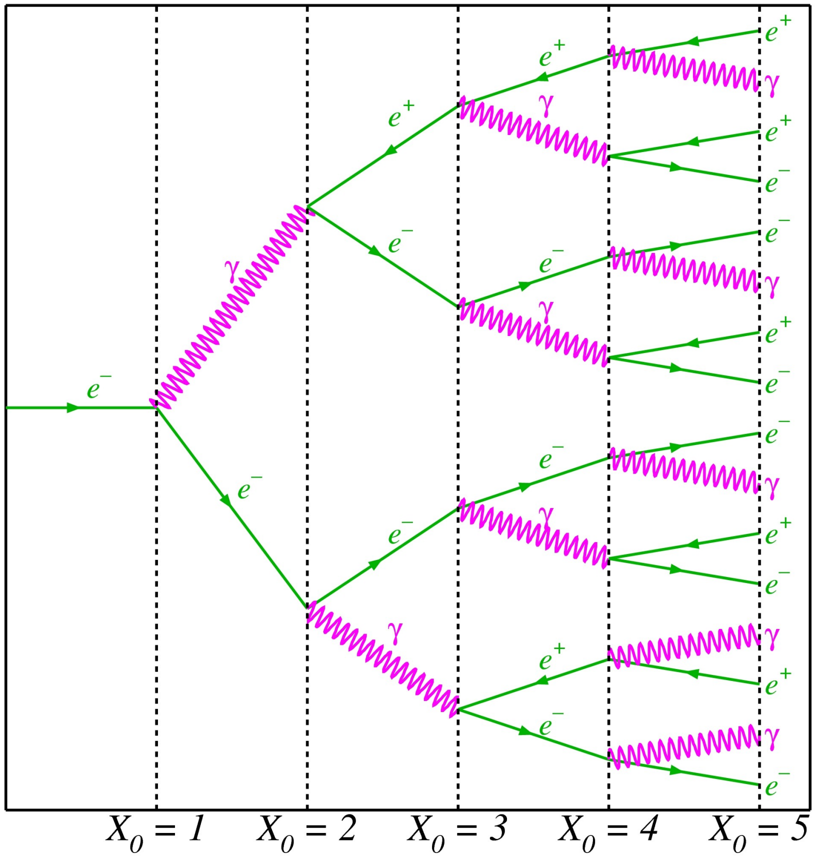
- X_0(Pb)= 0.56cm

  X_0(Ta)= 0.41cm

  X_0(Cu)= 1.44cm

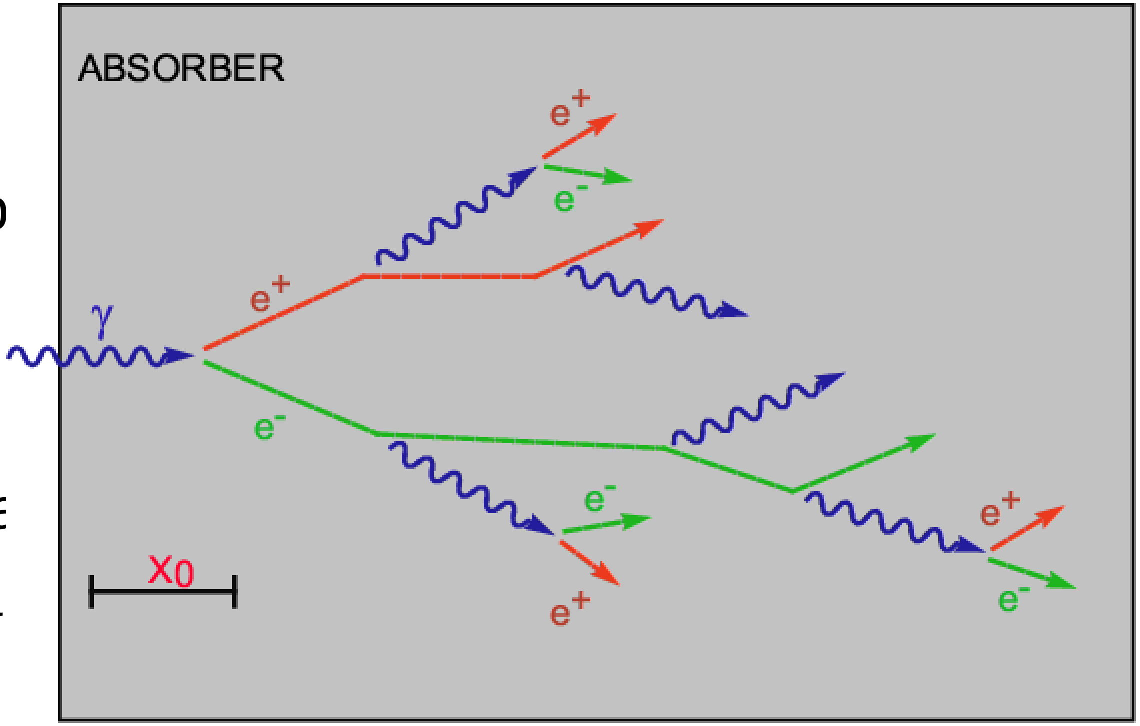
  X_0(Fe)= 1.76cm

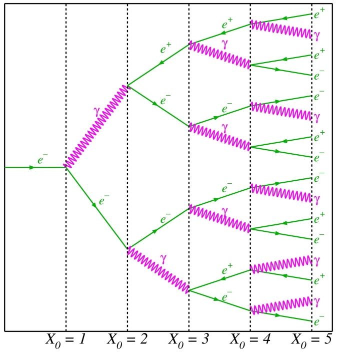
  X_0(C graphite)= 19.32cm



Example: Electron shower (2)

- Particles loose 1/e of their energy after each radiation length.
- The reality is a bit more comp but statistically this picture is true...
- The same is true for protons a other particles (with additiona complications).





Example: Electron showers (3)

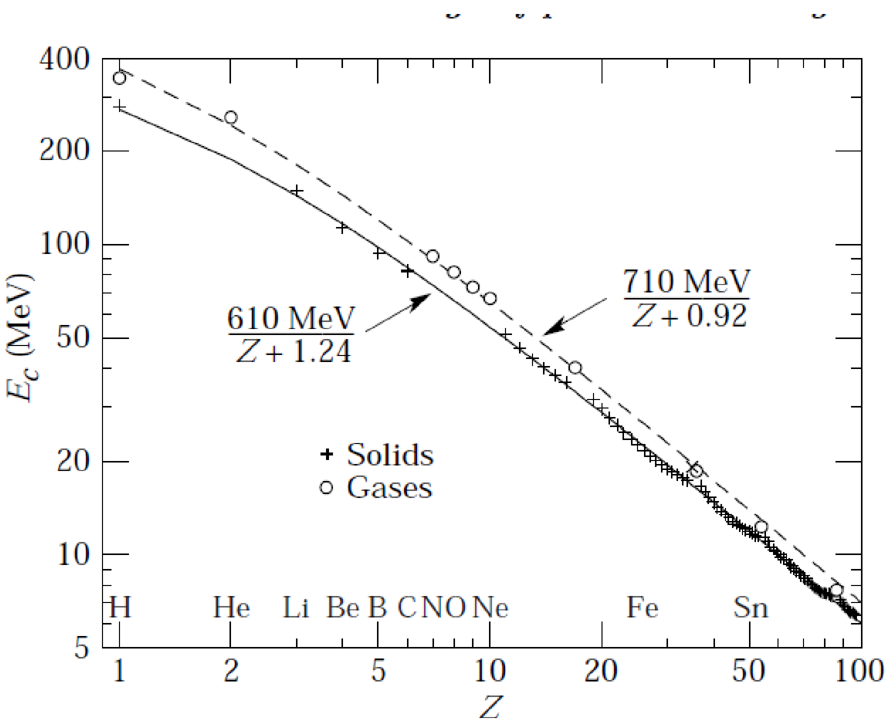


Image source: Particle Data Group

- After loosing enough energy the electrons are finally absorbed.
- The energy at which they are absorbed depends on the absorber (see Particle Data Group booklet for more details).

Quiz: shower depth

- A 1 GeV electron hits a 4.1cm thick plate of Tantalum.
- X_0(Ta)= 0.41cm
- How many particles will be present in the shower at the exit of the plate?

a) 10

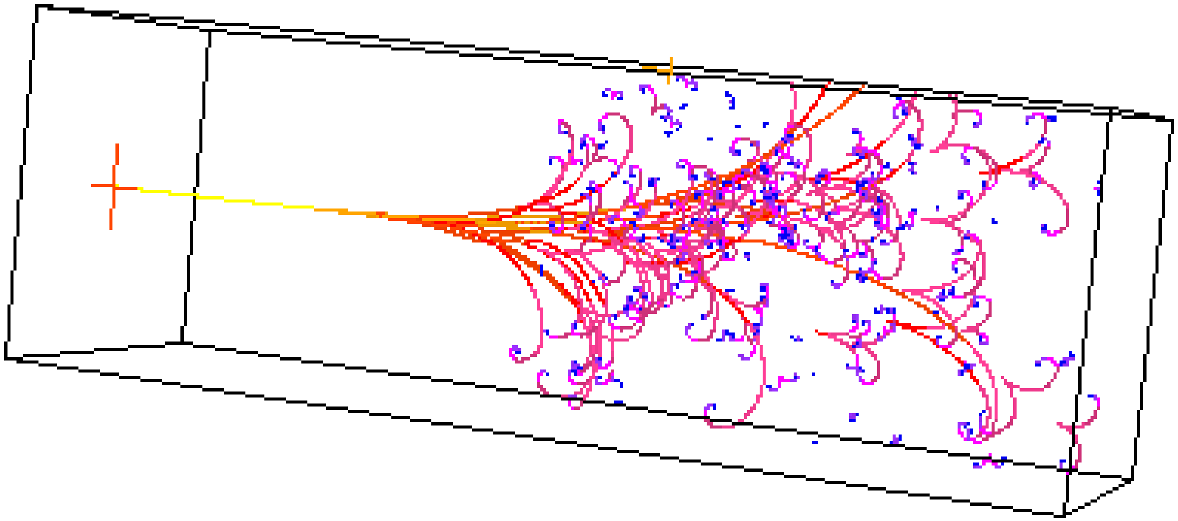
b) 10*10

c) 2^{10}

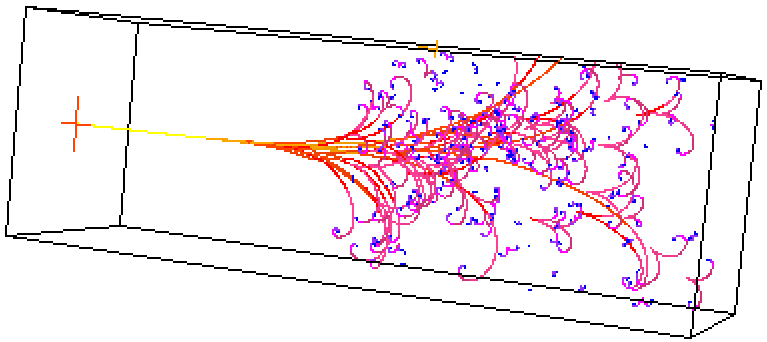
d) 1 (the original electron)

Answer: (c)

- The number of particles double after each radiation length.
- There are 4.1cm/0.41=10 radiation length
- So there will be 2^{10} particles after the plate.



Faraday cup (1)



- Let's send the beam on a piece of copper.
- What information can be measured after the beam has hit the copper?

Faraday cup (2)

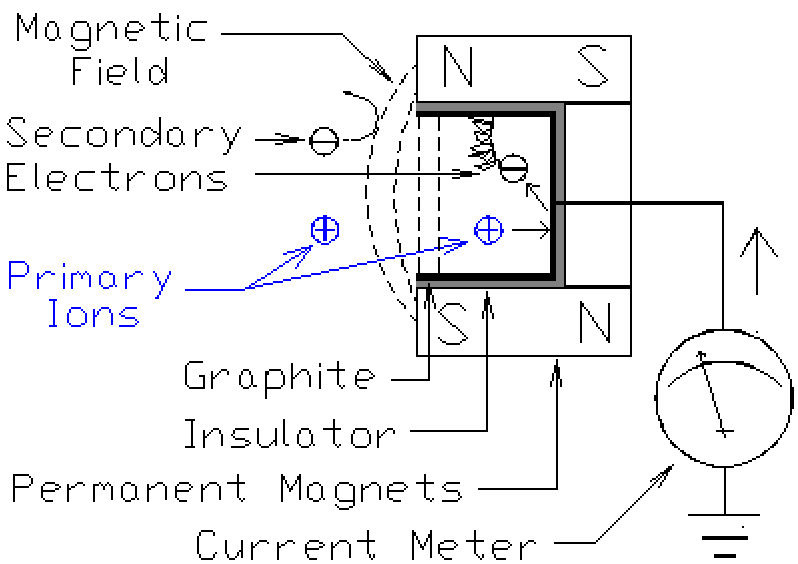


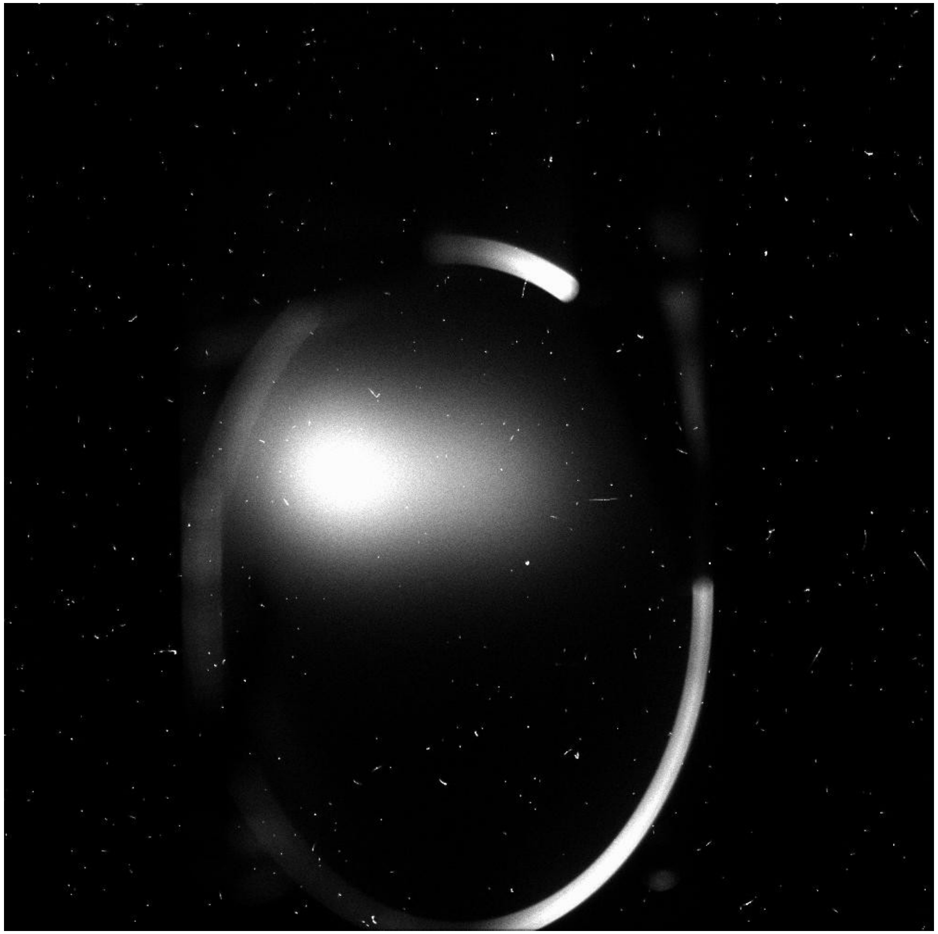
Image source: Pelletron.com

- Two properties can be measured:
  - Beam total energy
  - Beam total charge
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large: More than 1m at Diamond.

Screen (1)

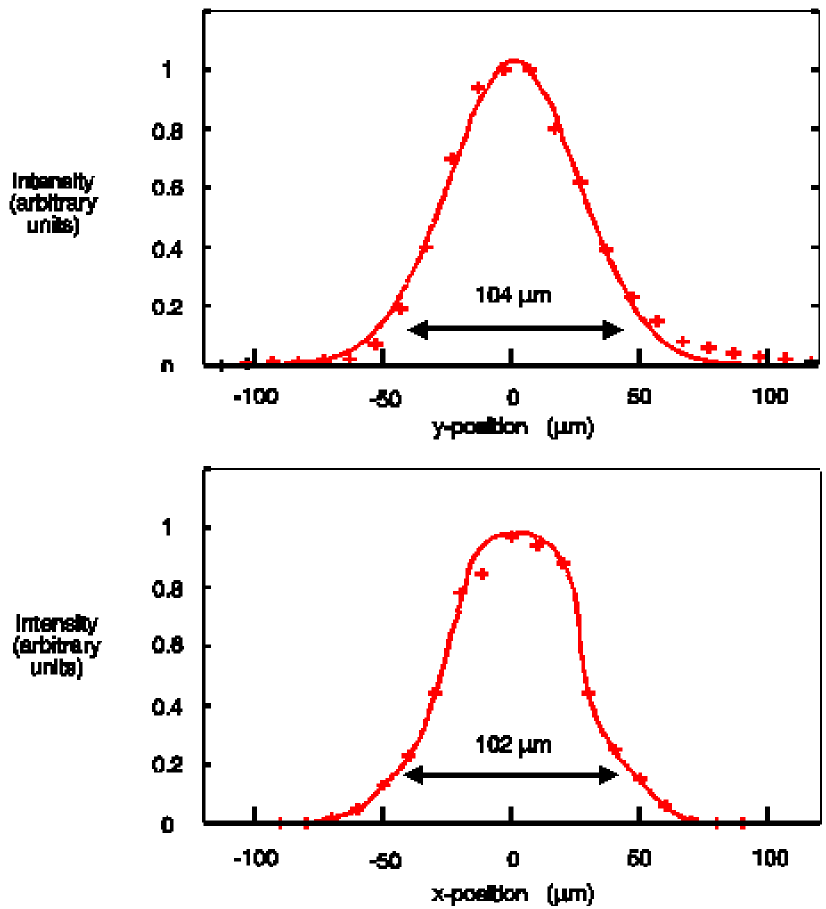
- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

Screen (2)



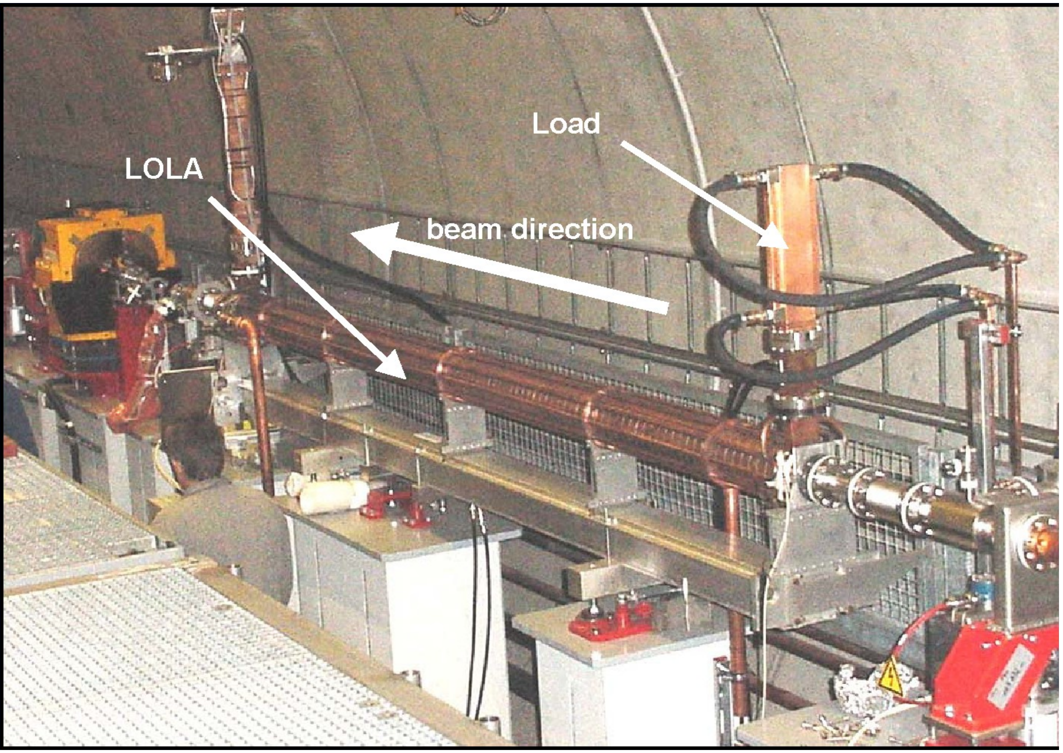
- It is not possible to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at 45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

Wire-scanner

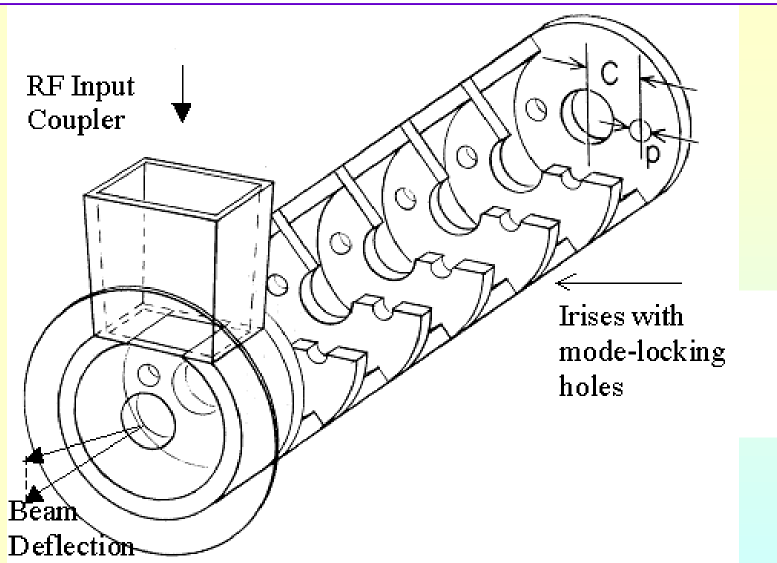


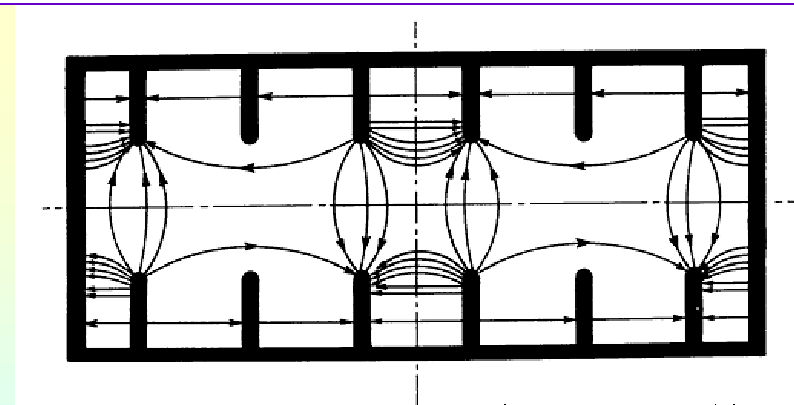
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.

Longitudinal properties



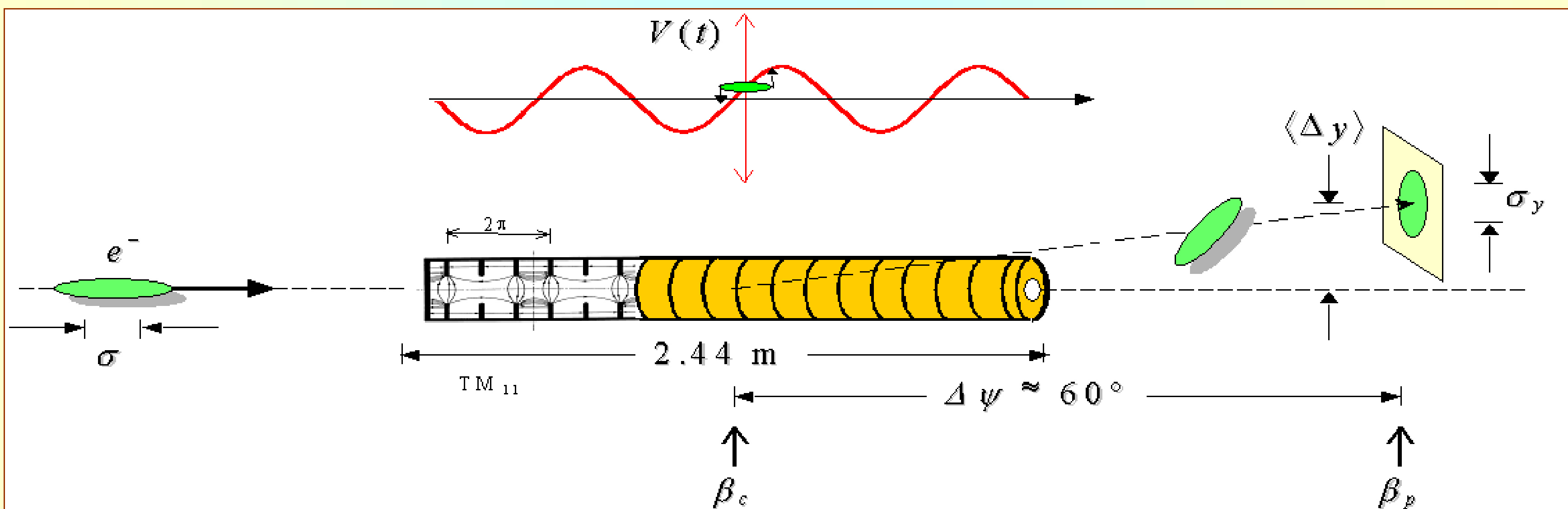
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



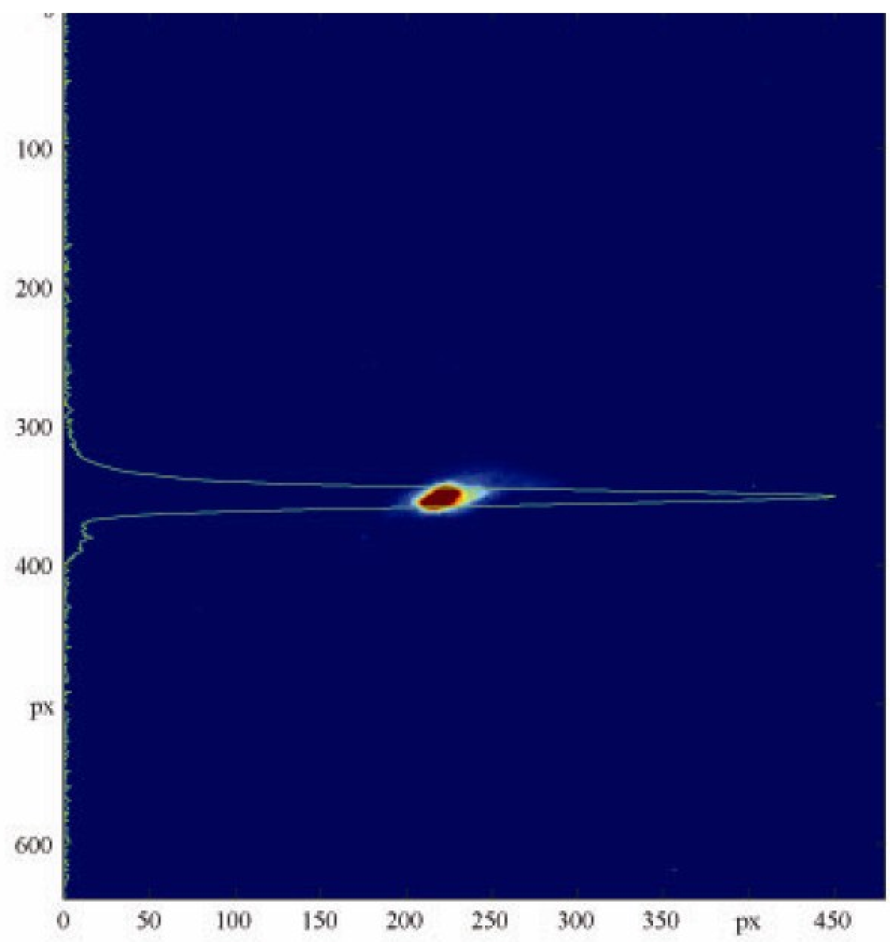


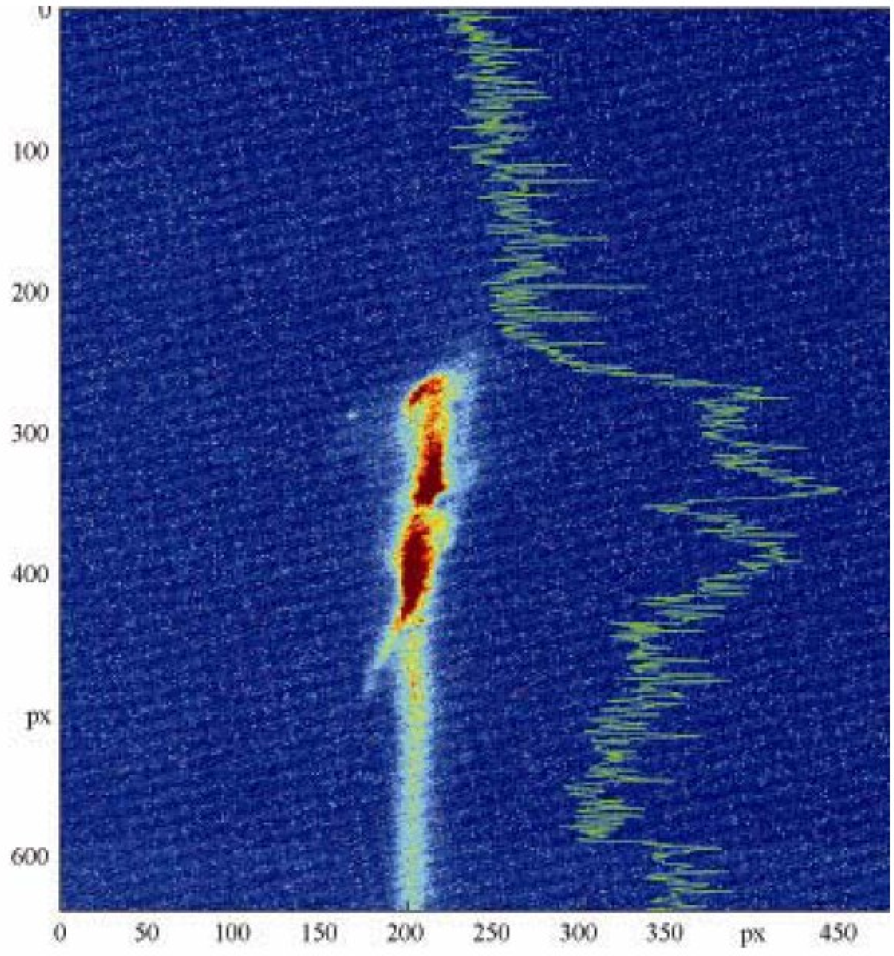
$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW^{1/2}}\right) L\sqrt{P_0}$$

$$bunchlenght, \sigma_z \approx \frac{\lambda_{rf}}{2\pi}\frac{E_s}{|eV_0 \sin\Delta\psi\cos\varphi|}\sqrt{\frac{\left(\sigma_y^2-\sigma_{y0}^2\right)}{\beta_d\beta_s}}$$

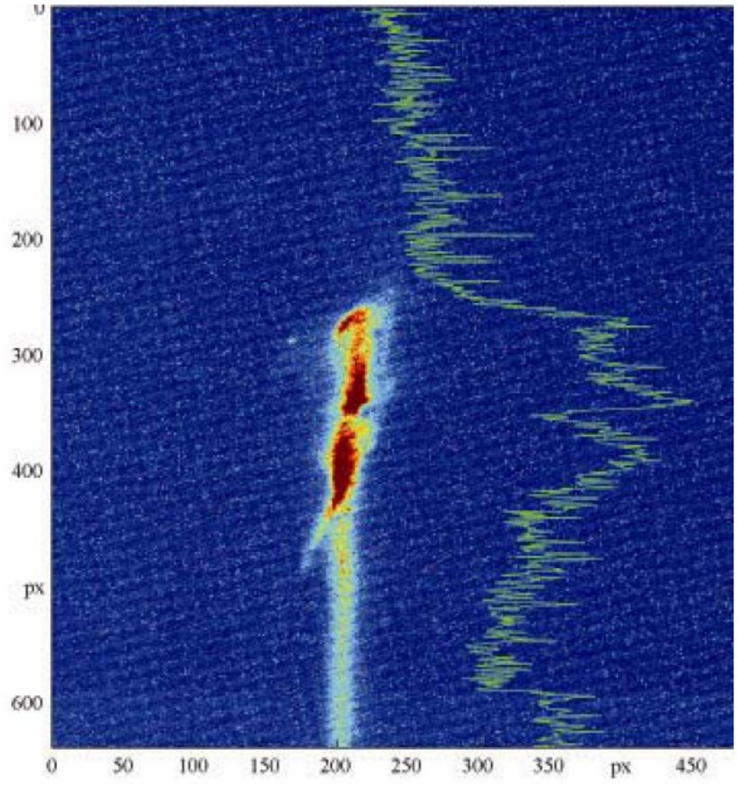


RF deflector off and on





Deflection calculations



- The transverse quick given by the cavity is

$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{pc}\left[\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right]$$

- This leads to an offset

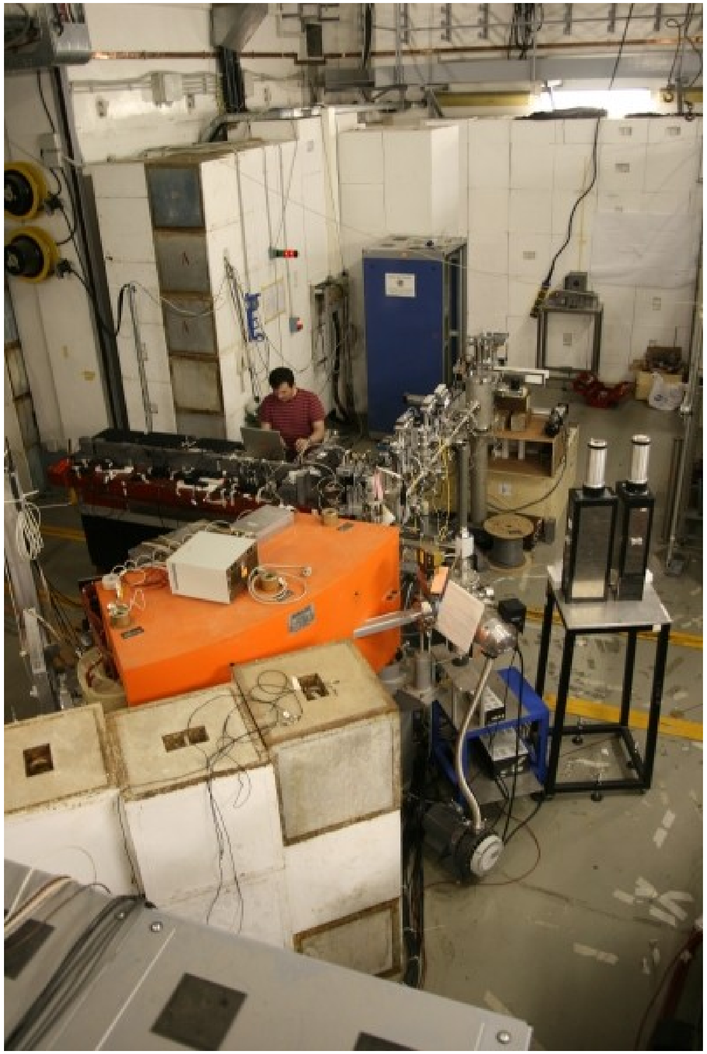
$$\Delta x = \sqrt{\beta_1\beta_2}\,\sin\Delta\psi\cdot\Delta\theta$$

- And a resulting beam size

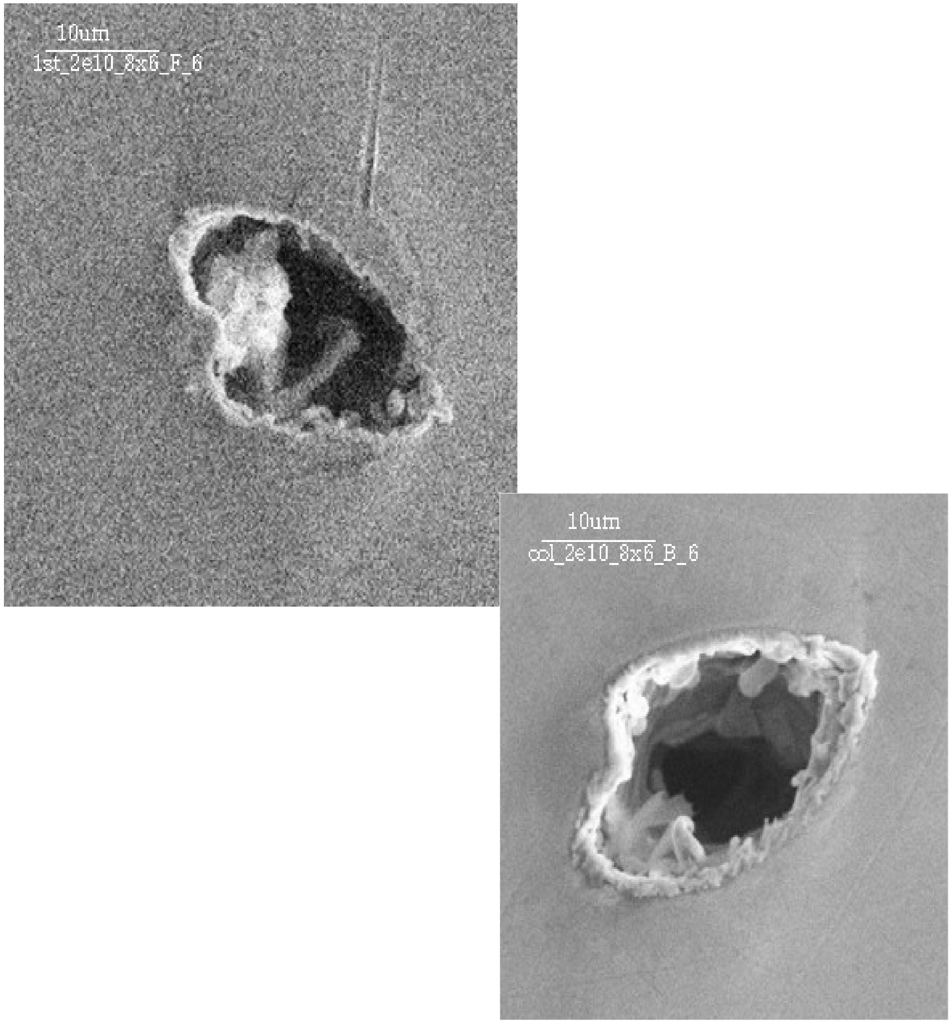
$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda\gamma m_e}\sin\Delta\psi\cos\varphi\right)^2}$$

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.

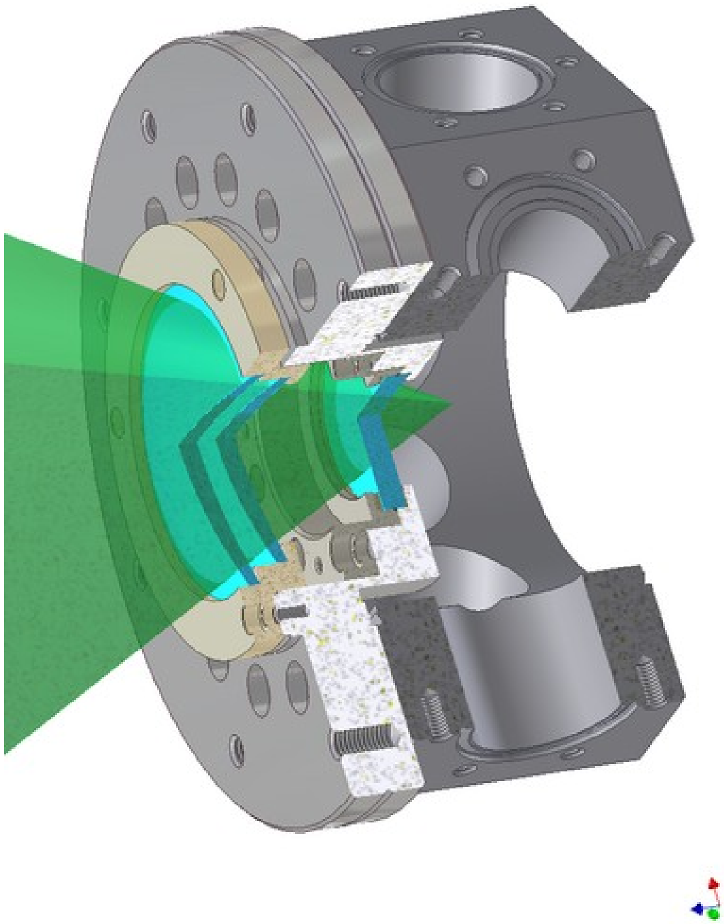


Limitation of these monitors



- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

Laser-wire



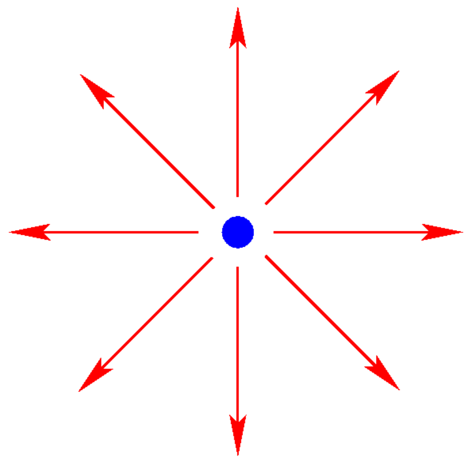
- To mitigate the problem of broken wires in wire-scanners it is possible to replace the wire by a laser.
- This technique called “laser-wire” also allow to reach better resolutions.
- High power lasers (or long integration times) are needed.
- Some of this work is done in Oxford.

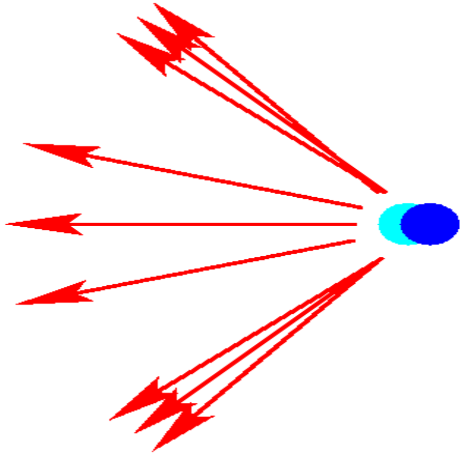
Summary
(particles interaction with matter)

	Interaction with matter
Charge	Faraday cup
Position	Screen
Size or shape (transv.)	Screen or wire-scanner/LW
Size or shape (longit)	RF cavity + screen
Energy	???
Losses	Scintillator

- We have seen that it is possible to build monitors which use the interactions of particles with matter.
- These monitors tend to be destructive: they significantly damage the beam.
- These monitors tend to be simple but can be damaged by high energy high intensity beams.

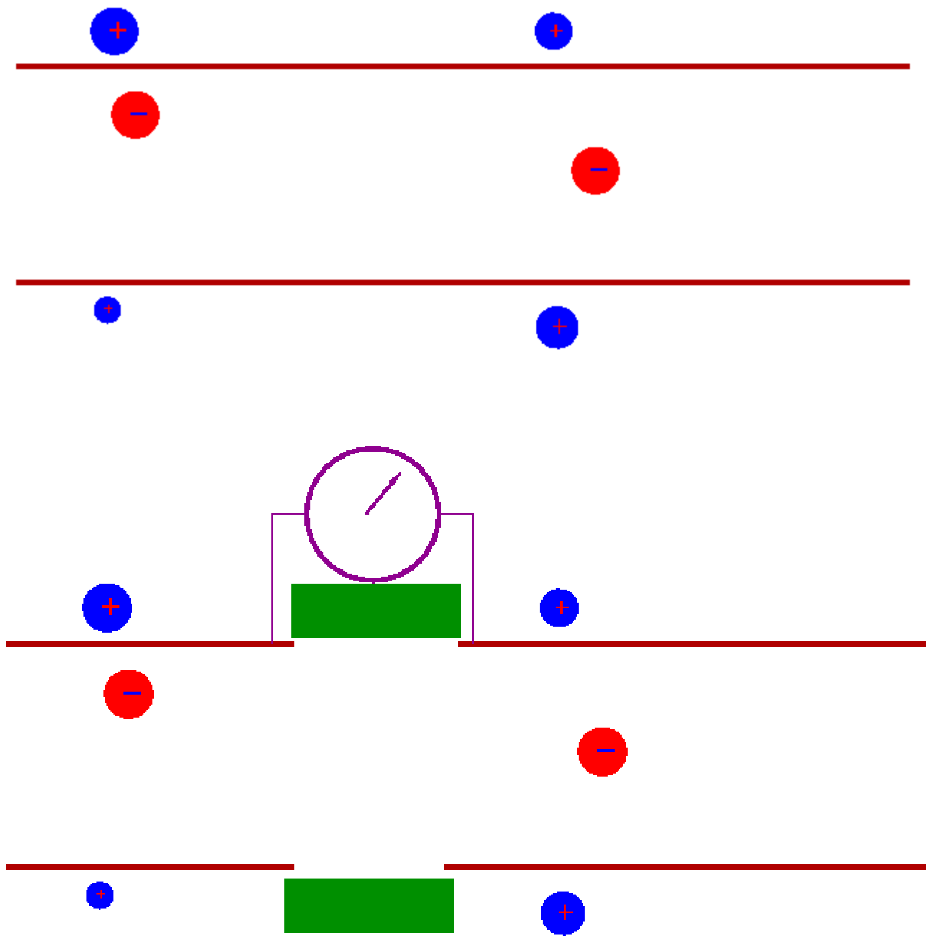
Charged particle





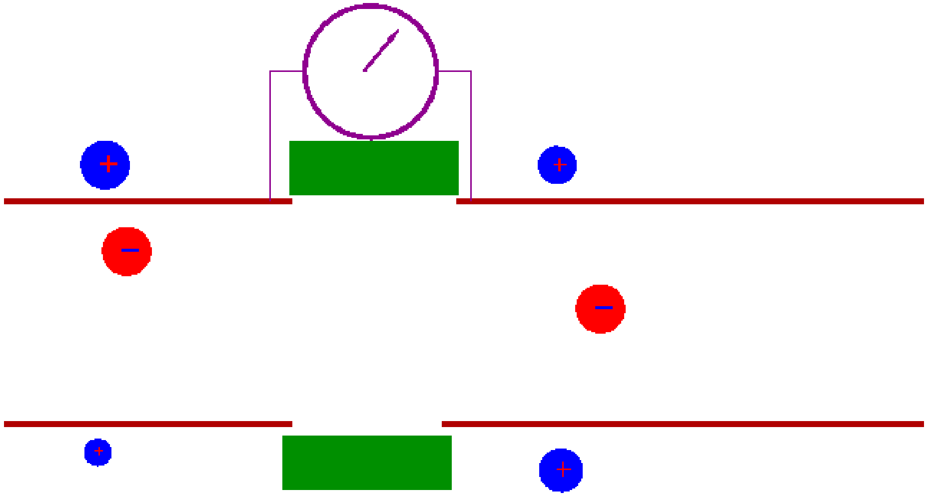
- Any charged particle "radiates"
- These electromagnetic radiations can be detected without disrupting the beam.
- One need to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

Beam current monitor



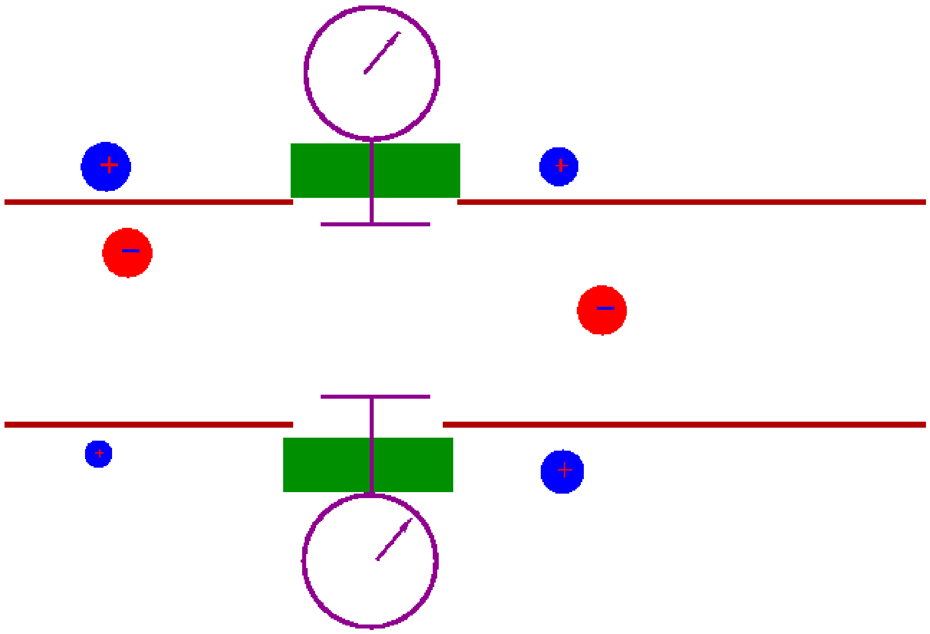
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

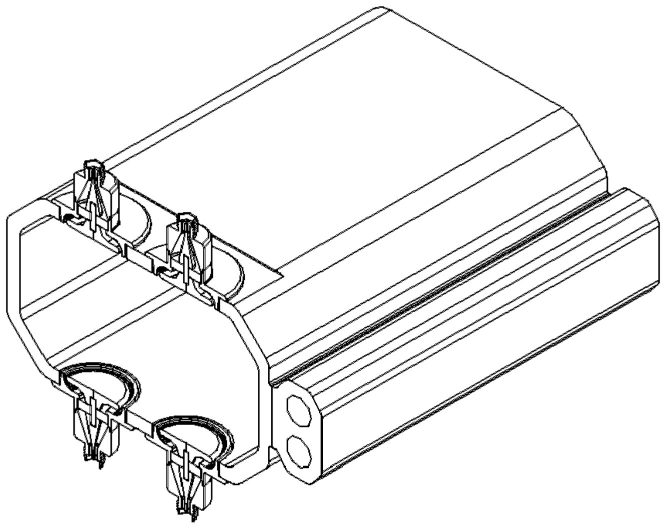
Beam current monitor vs Faraday cup



- Both devices have pros and cons.
- A Faraday cup destroys the beam but it gives a very accurate charge measurements
- A Beam current monitor does not affect the beam but must be calibrated.
- Both tend to be used at different locations.

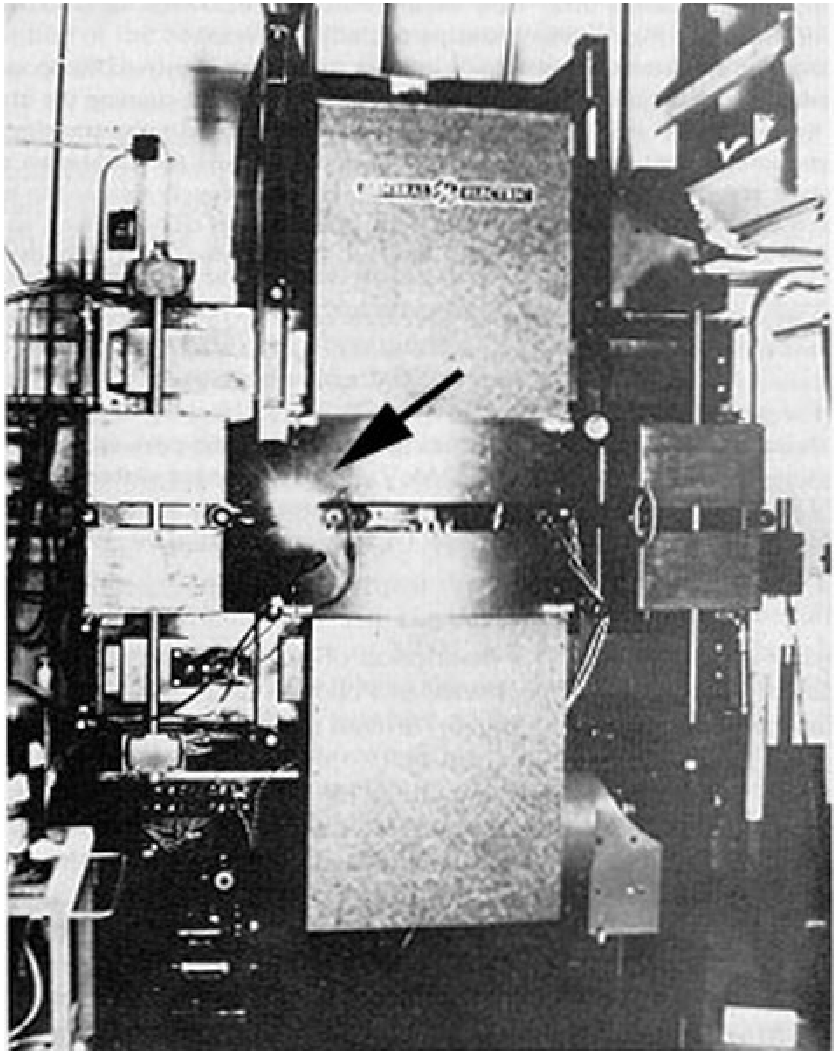
Beam position monitor





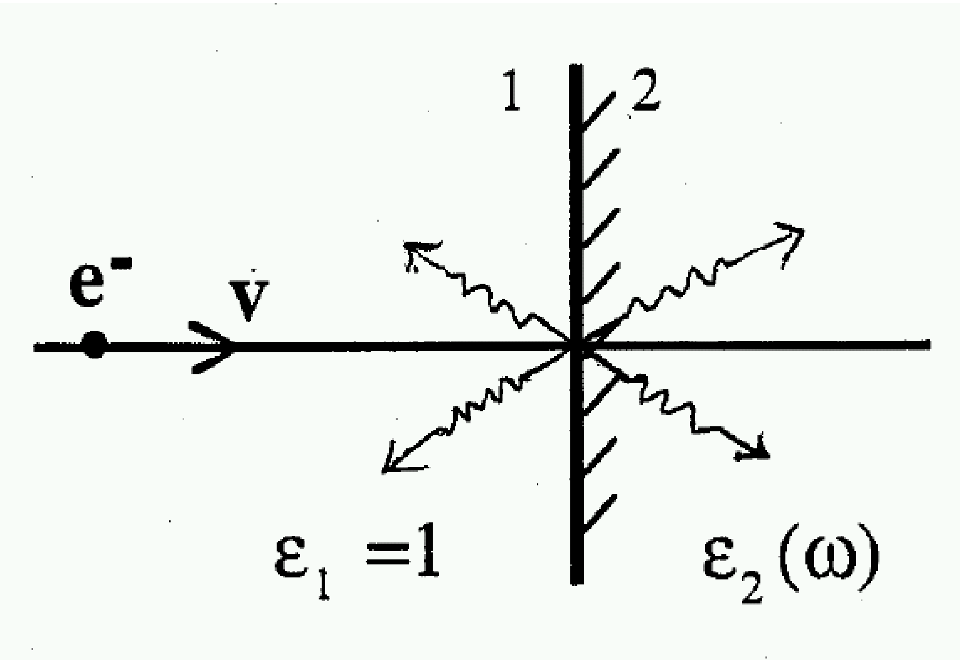
- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

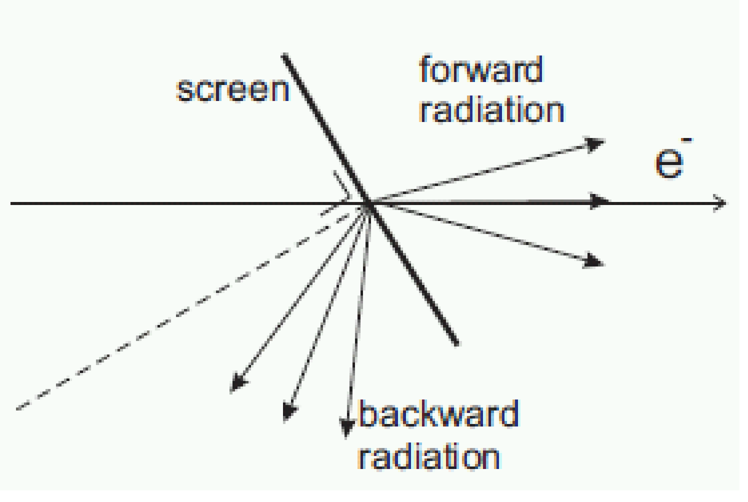
Synchrotron radiation



- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam shape.

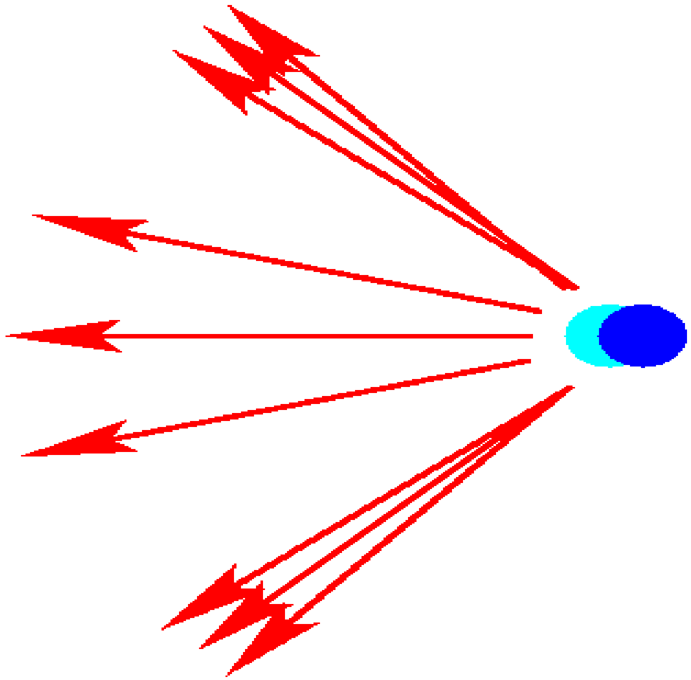
Optical Transition Radiation





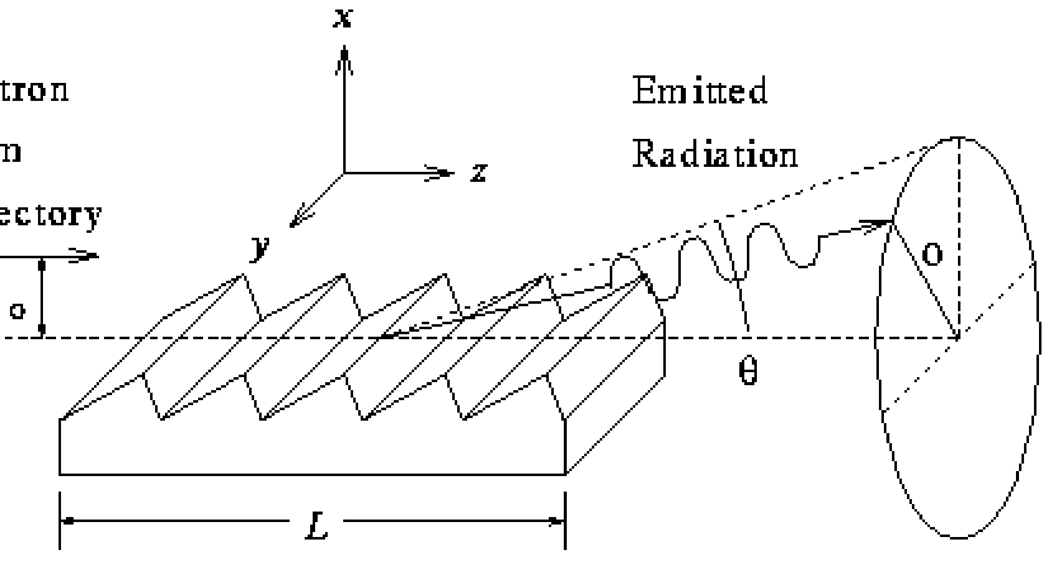
- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape (and possibly other things).

Optical Diffraction Radiation



- It is also possible to use a screen to reflect the wake created by the charged particles bunch.
- This technique is called ODR.
- It is even less disruptive than OTR.

Longitudinal profiles



Principle of Smith-Purcell Radiation

- Several methods can be used to measure the beam longitudinal profile.
- In the Smith-Purcell method a grating is used.
- The beam interacts coherently with the grating and emits radiation.
- The intensity and wavelength of this radiation depends on the longitudinal profile of the beam.

Energy measurements

Diagnostics overview

	Interaction with matter	**Charge**
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transv.)	Screen or wire-scanner/LW	Synchrotron rad. OTR/ODR
Size or shape (longit)	RF cavity + screen	Radiation detectors
Energy		Bending magnet
Losses	Scintillator	

Summary

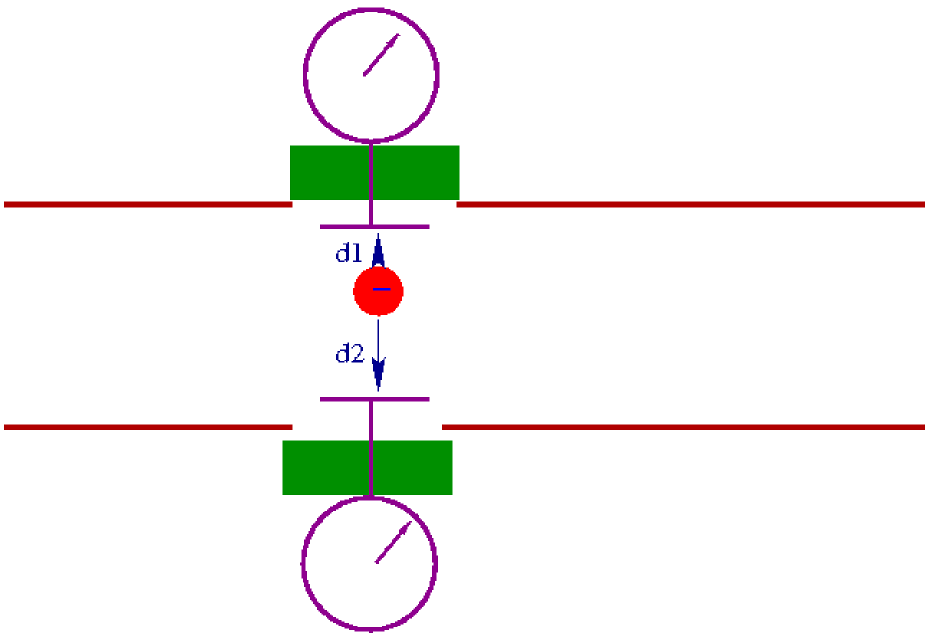
Still to add

- Transition radiations
- Screens
- Longitudinal profiles (LOLA, Smith Purcell,...)
- Crab cavities???
- Covered in (1): BPMs, WCM/ICT, Feedbacks? alignements and metrology
- Destructive /non-destructive

Problems

- Faraday cup depth
- Give data and ask wire scan?
- Interpret LHC image
- Current on WCM and BPM

Beam position monitor (2)



- Let's consider a charge at a distance d1 from one antenna and a distance d2 from the other.
- Let's use Gauss law:

$$\phi = \frac{Q}{\epsilon_0} = \oint E\, dA = E\, 4\pi r^2$$