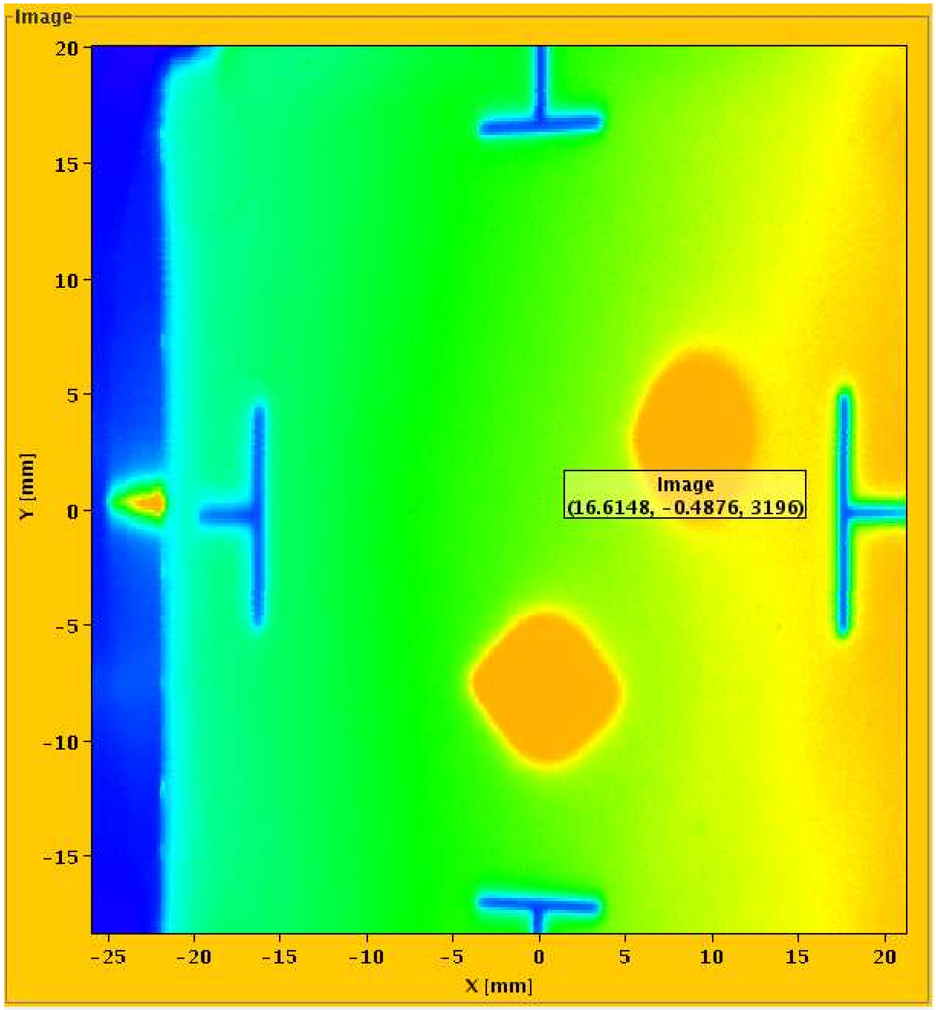
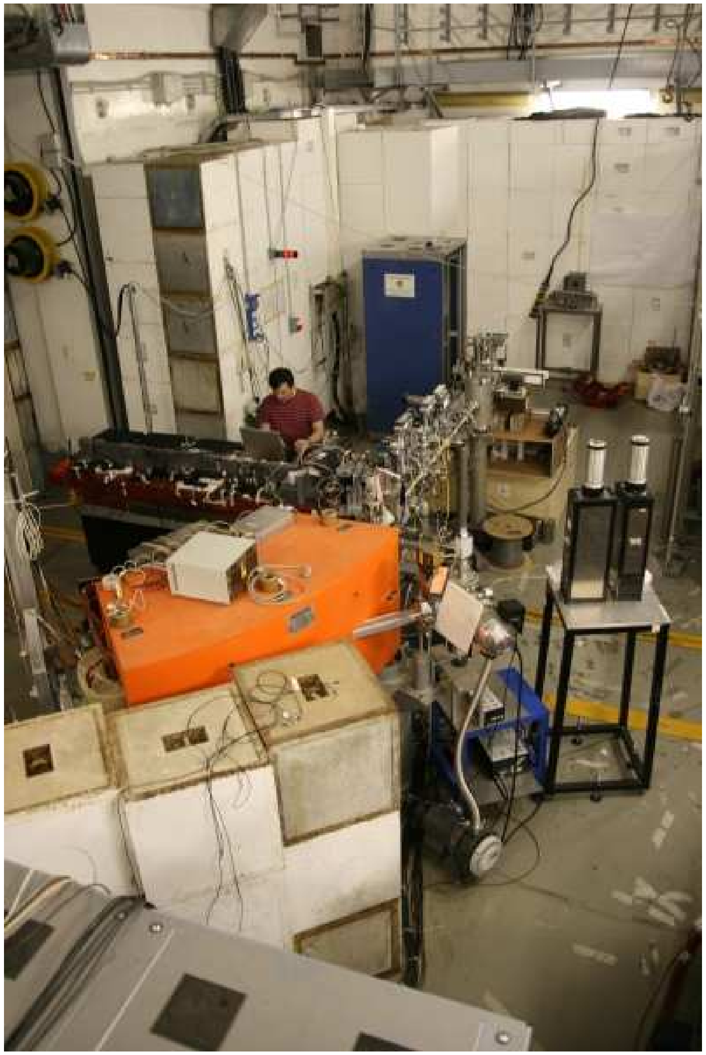
9. Diagnostics (1)



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

Problem set 6

Where are we?



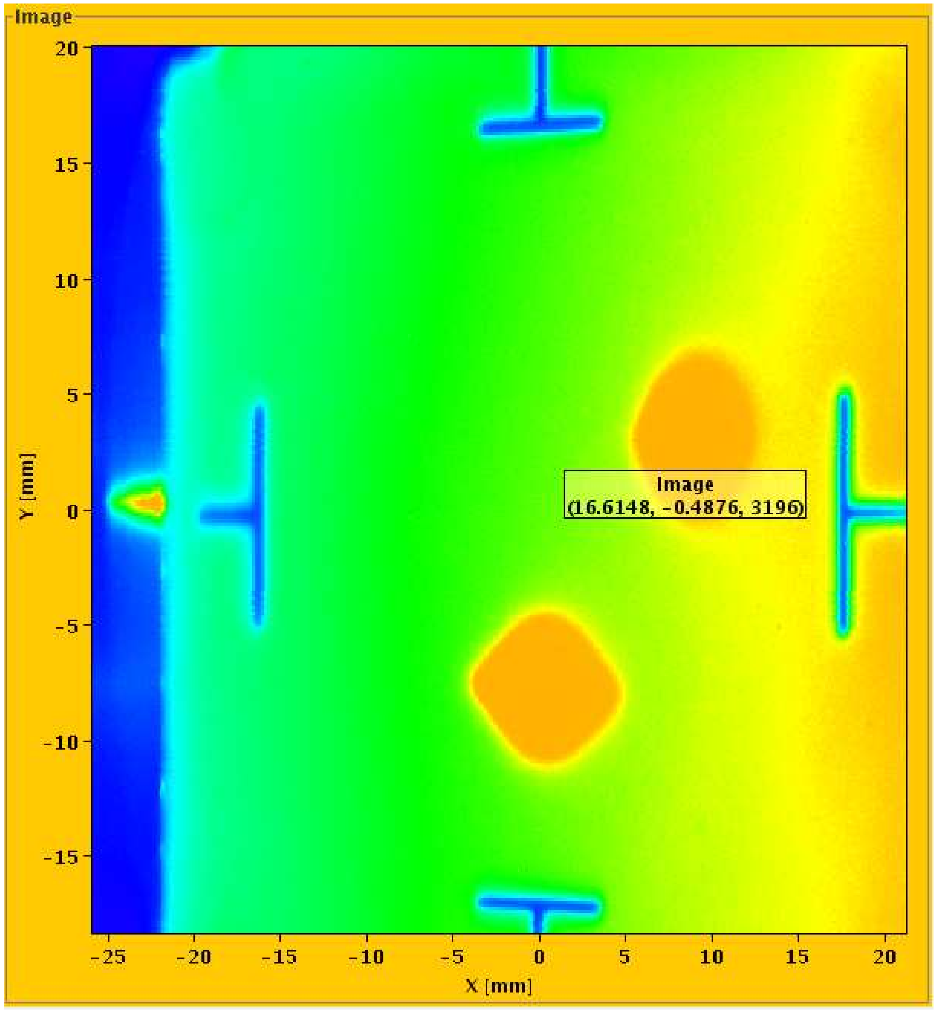
- Last week you learned what is the dynamic inside a beam.
- Today and Monday you will learn how to monitor what happens in an accelerator.
- Next week you will learn about the applications of particle accelerators.

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

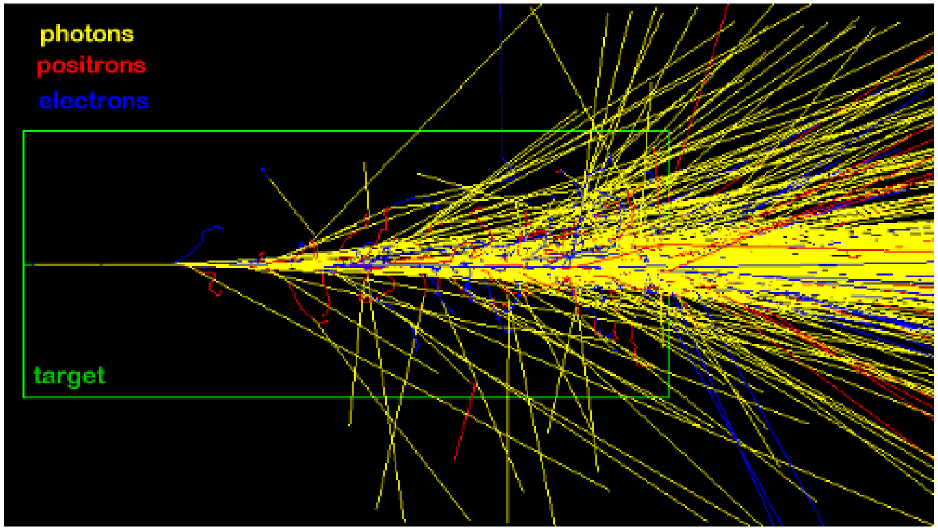


Properties of a charged beam

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

Particles interact with matter (1)

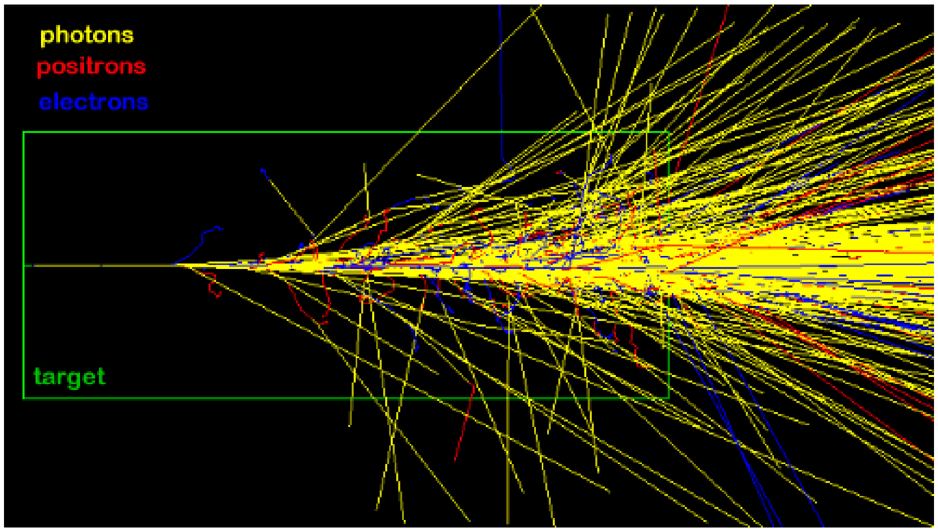
Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

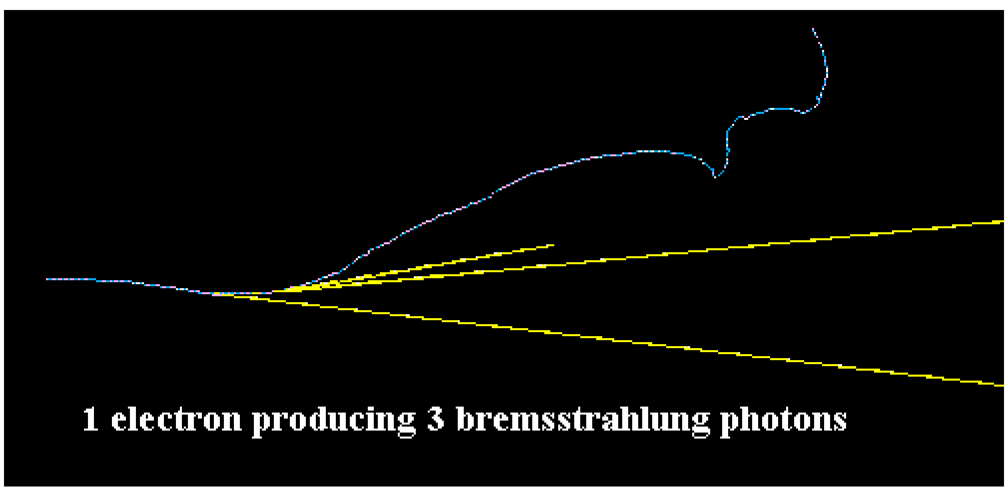


- High energy particles interact with matter in several ways.
- If you took the B1 paper you will have studied this more in details and you may learn more in the C4 next year.

Particles interact with matter (2)

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

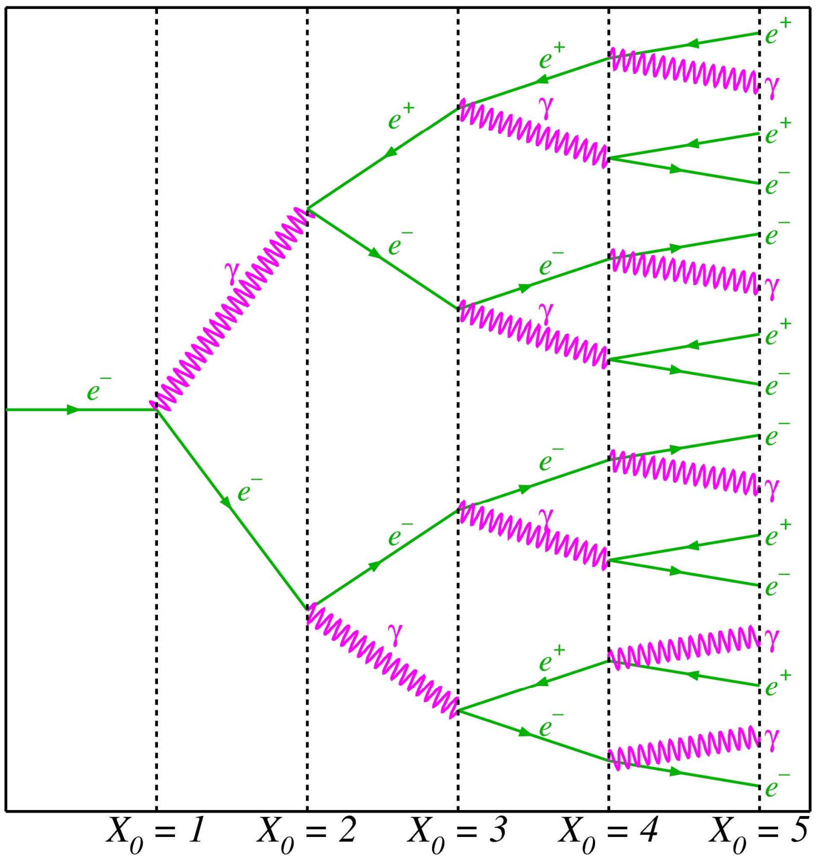




- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produced when such scattering occur will carry a significant energy and scatter themselves.

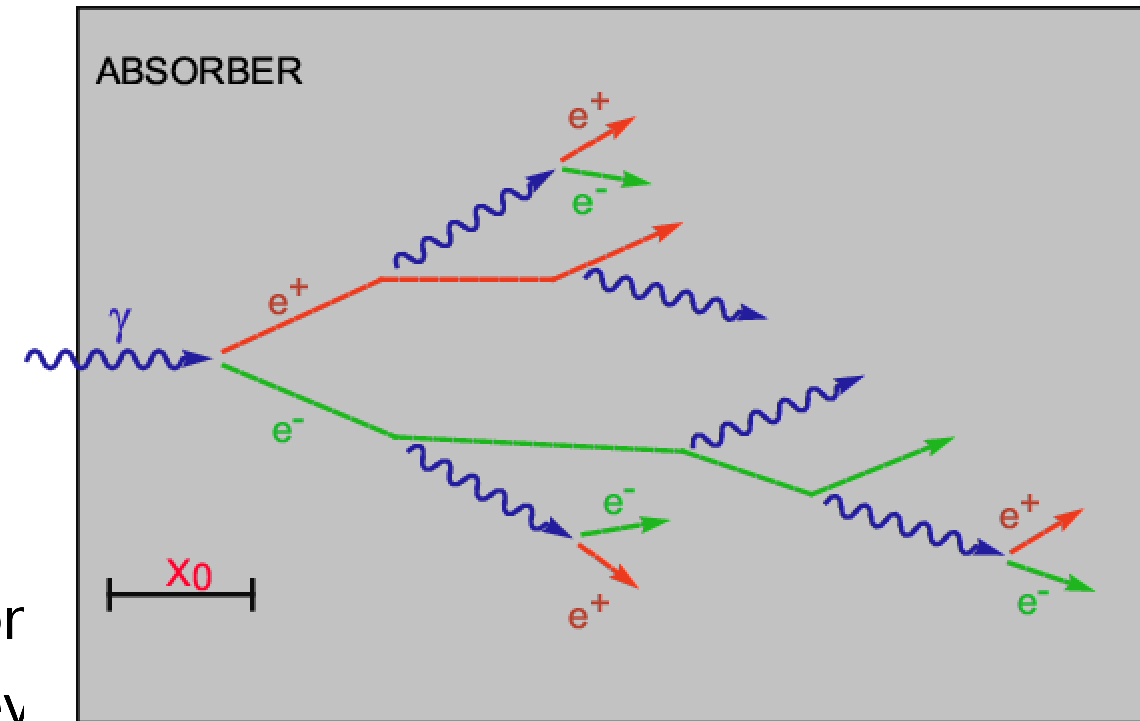
Example: Electron shower (1)

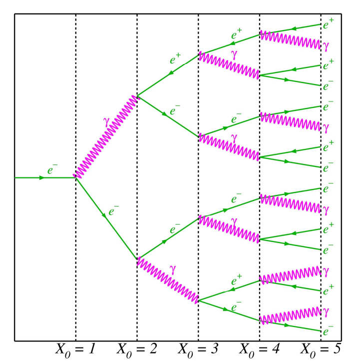
- The distance after which an electron or a photon interacts is called the “radiation length”
- Radiation length vary from material to material and can be found in tables.
- X_0(Pb)= 0.56cm
  X_0(Ta)= 0.41cm
  X_0(Cu)= 1.44cm
  X_0(Fe)= 1.76cm
  X_0(C graphite)= 19.32cm



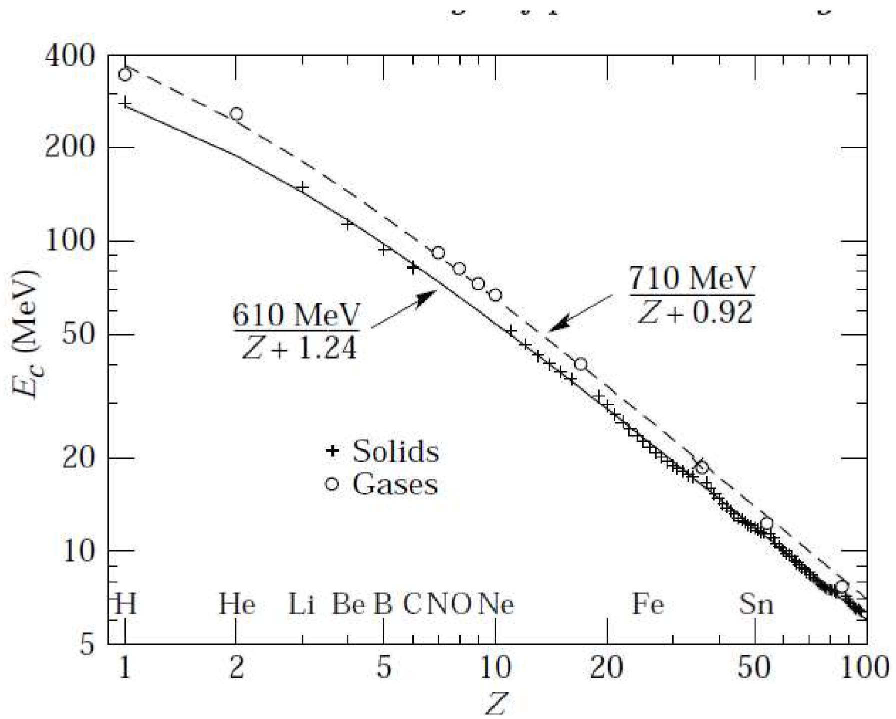
Example: Electron shower (2)

- Particles loose 1/e of their energy after each radiation length.
- The reality is a bit more complex but statistically this picture is true...
- Heavy particles such as protor will loose some energy as they travel in matter and suddenly stop when their energy slow enough.





Example: Electron showers (3)



- 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).

Image source: Particle Data Group

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

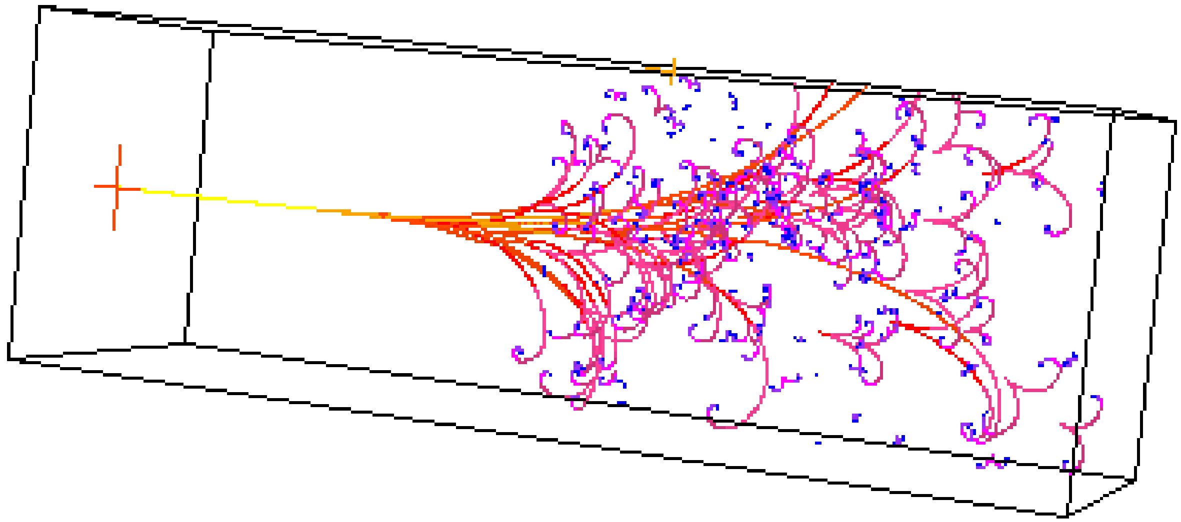
b) 10*10

c) 2^{10}

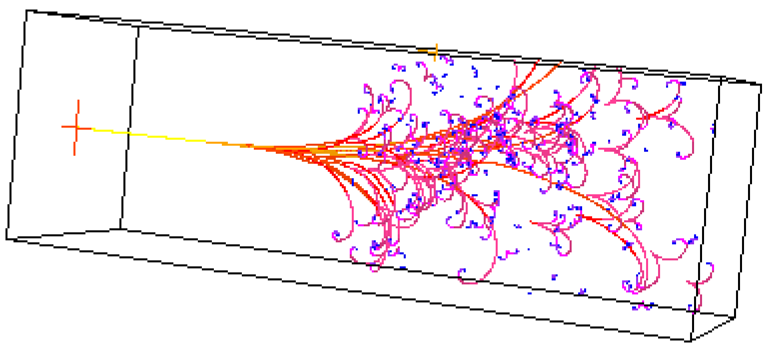
d) 1 (the original electron)

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)

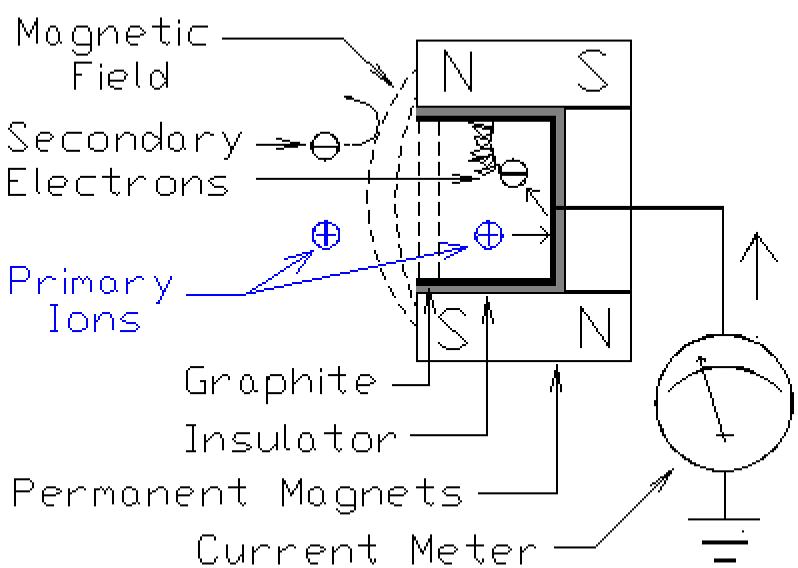


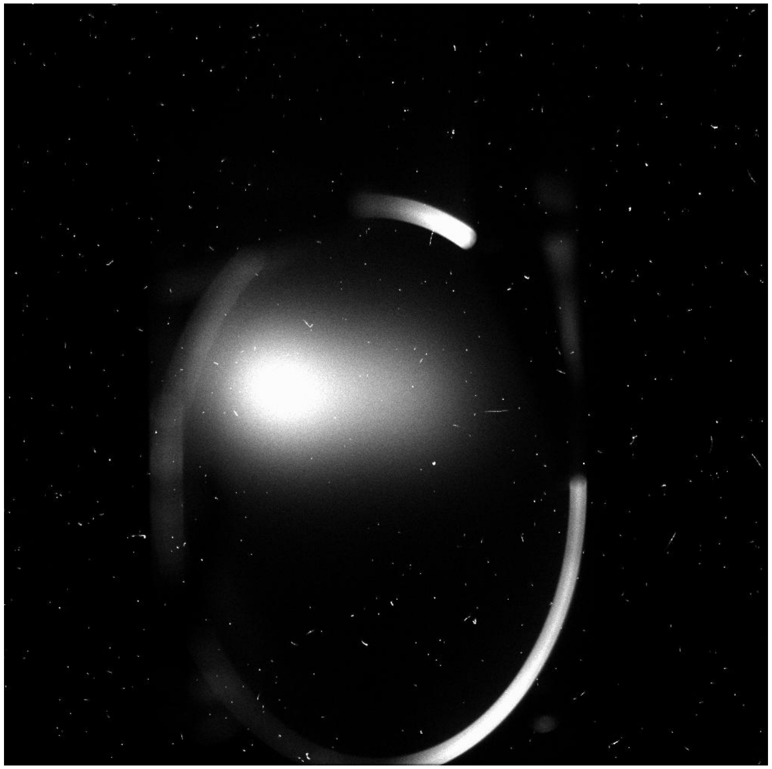
Image source: Pelletron.com

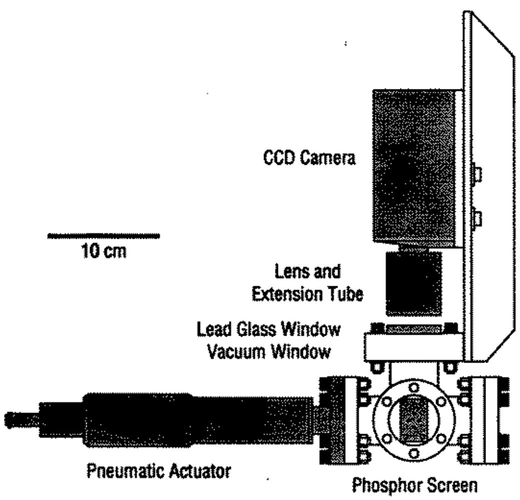
- Two properties can be measured:
  - Beam total energy
  - Beam total charge
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large:
  More than 1m at Diamond for a 3 GeV electron beam.

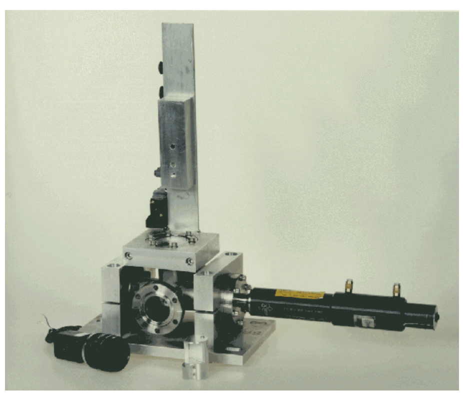
Screen (1)

- 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)

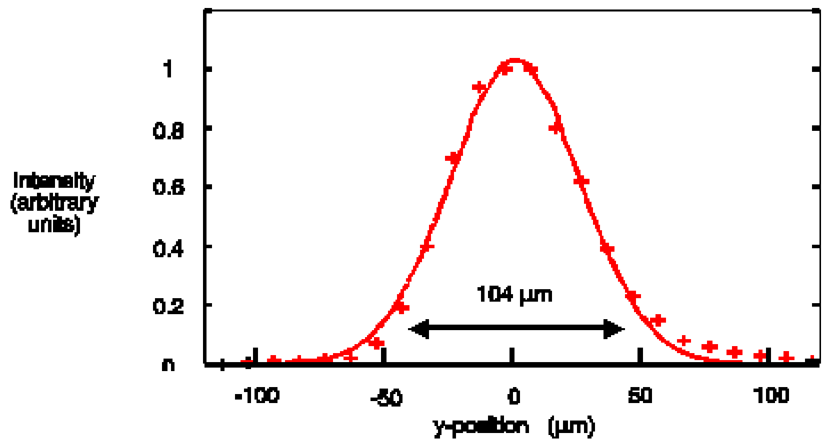


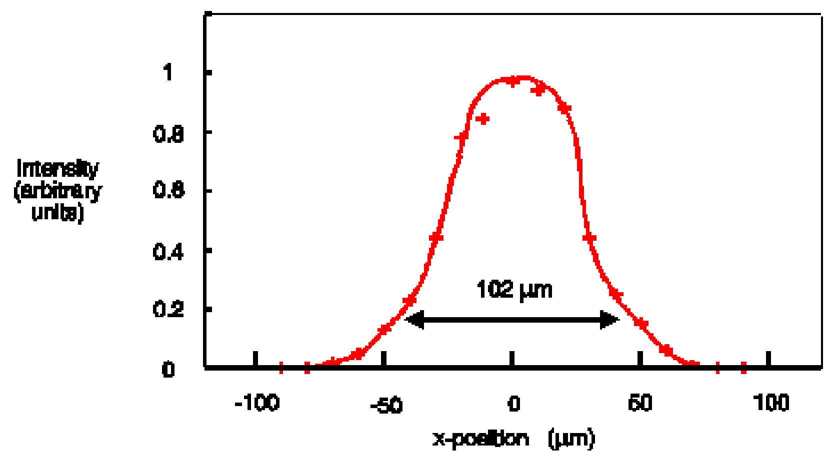




- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at 45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

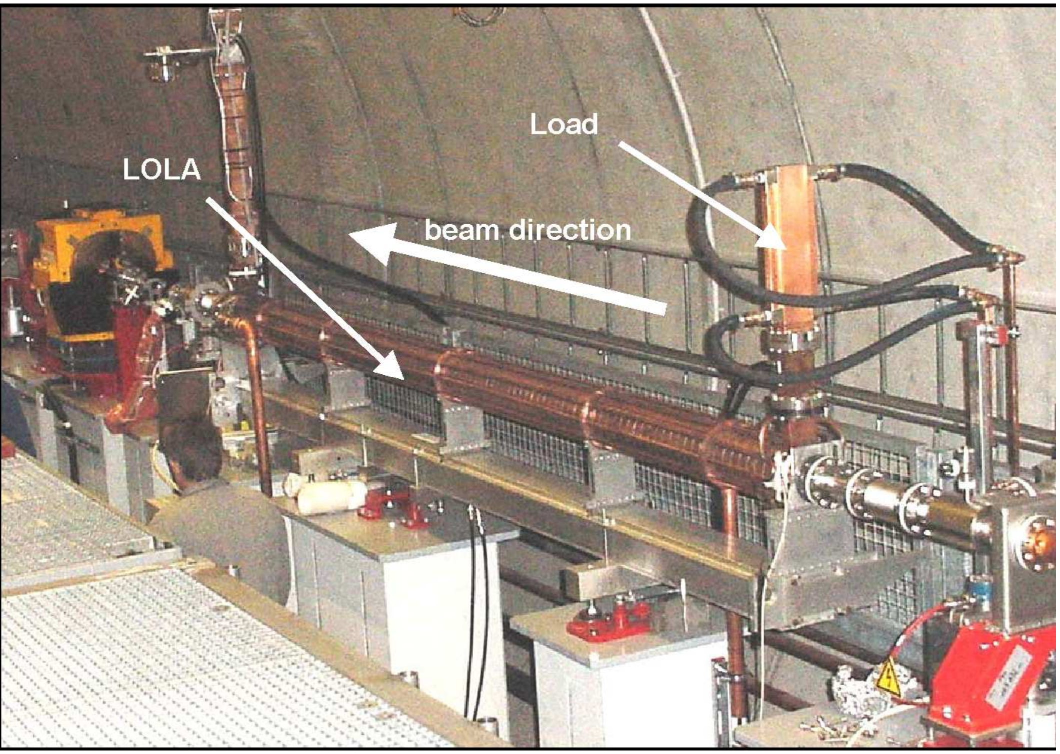
Wire-scanner



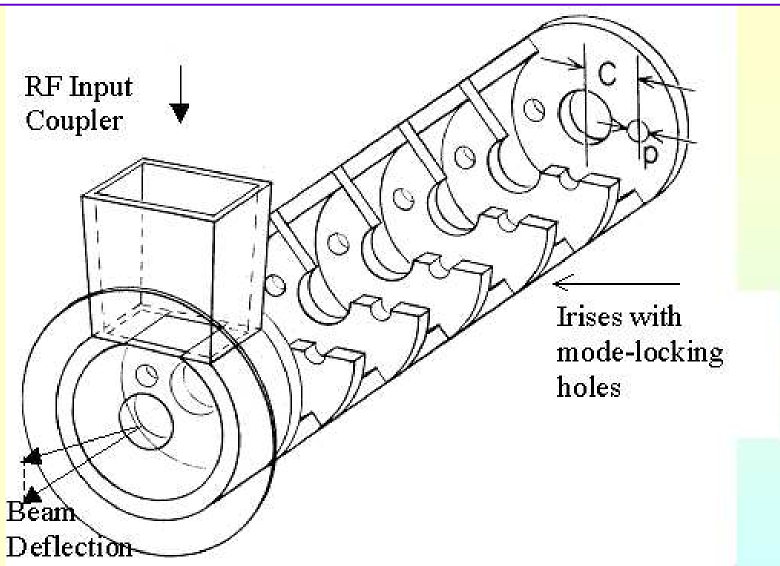


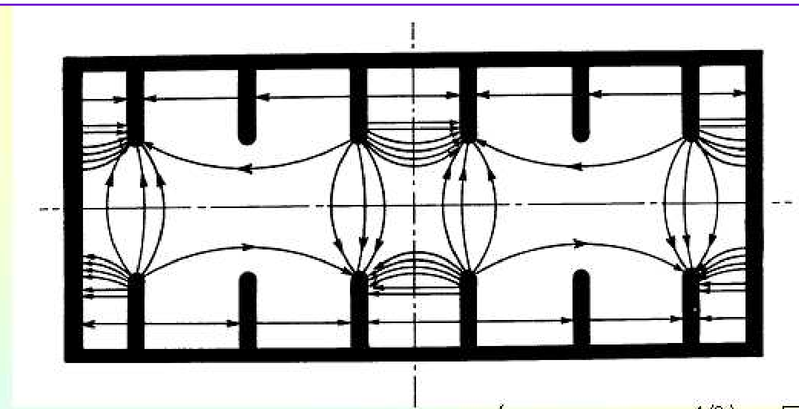
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
- However, a too strong beam current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

Longitudinal properties



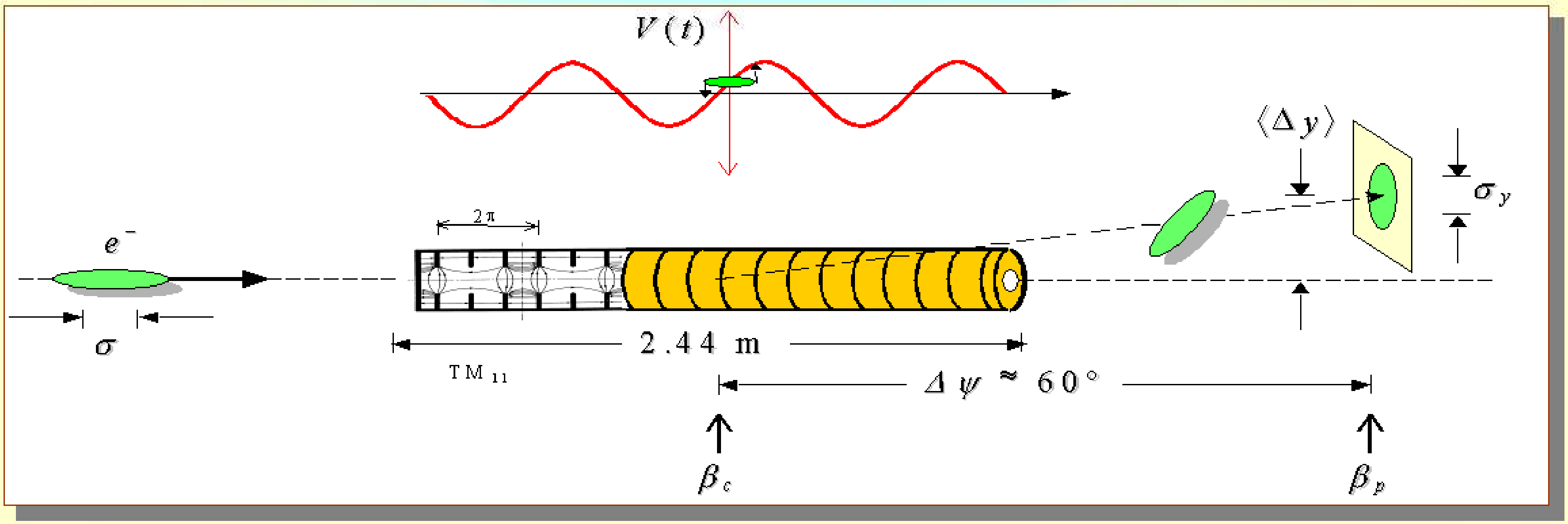
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



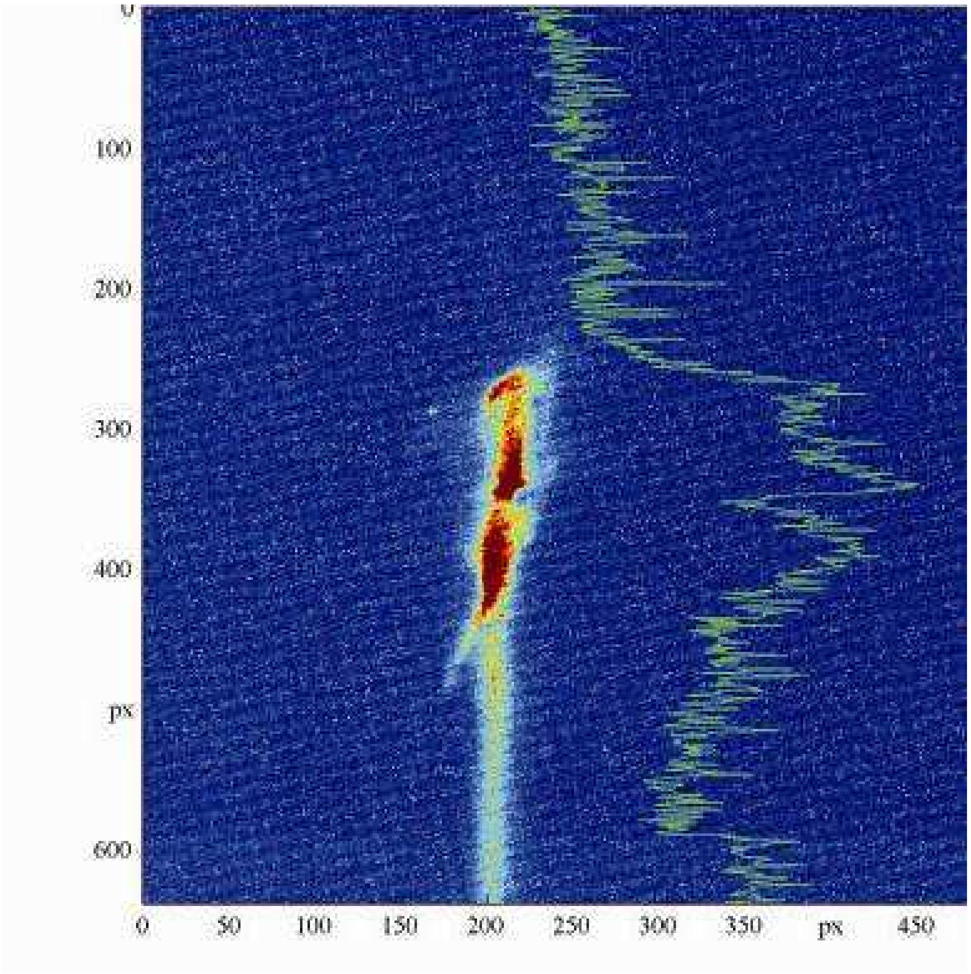


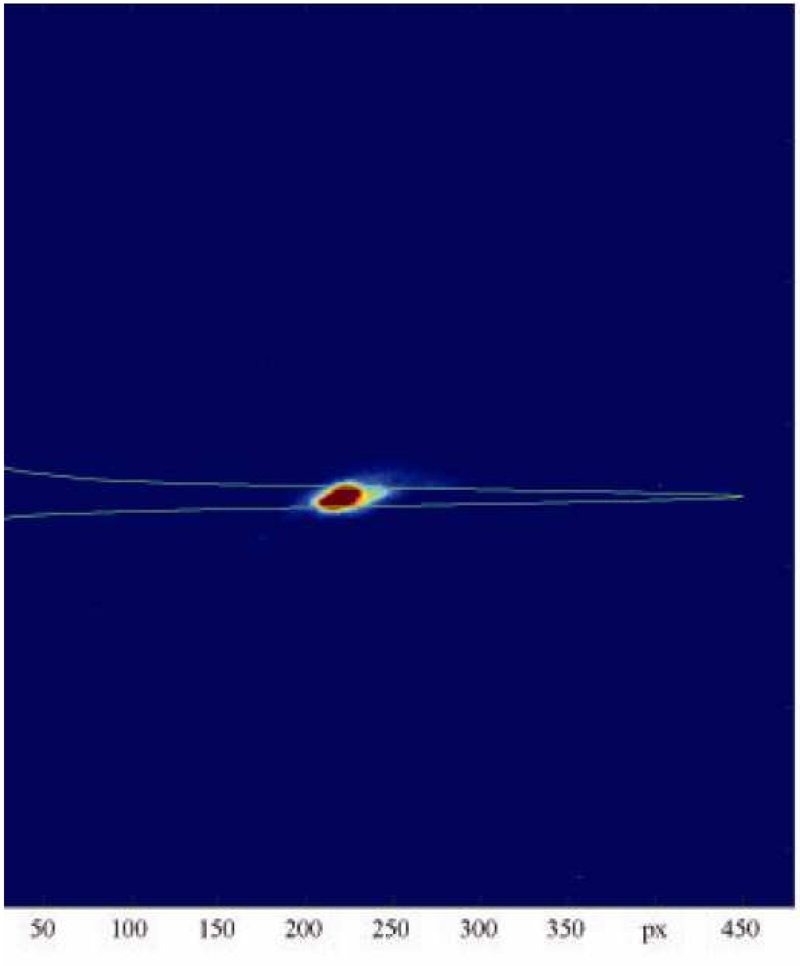
$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L\sqrt{P_0}$$

$$bunchlenght, \sigma_z \approx \frac{\lambda_{\mathrm{rf}}}{2\pi}\frac{E_s}{|eV_0 \sin\Delta\psi \cos\varphi|}\sqrt{\frac{\left(\sigma_y^2-\sigma_{y_0}^2\right)}{\beta_d\beta_s}}$$

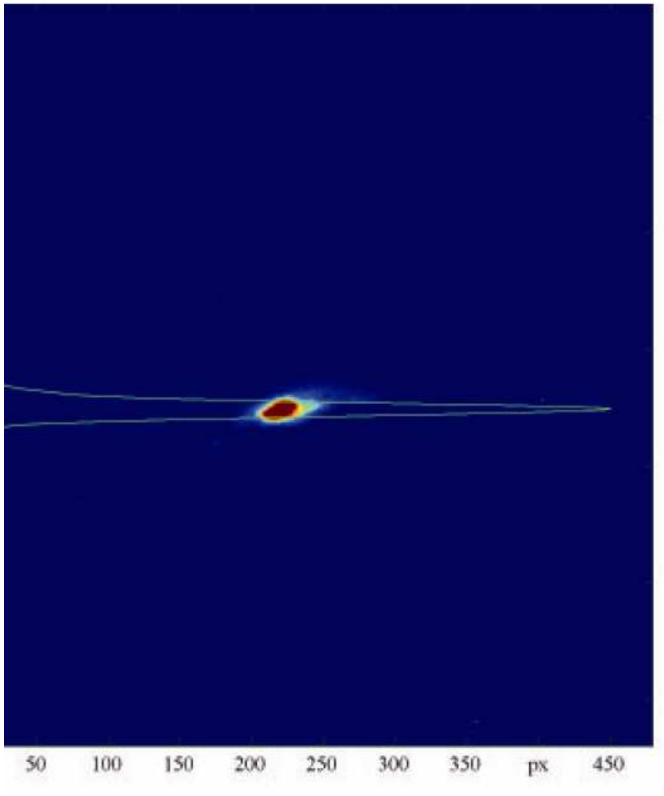


RF deflector off and on





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

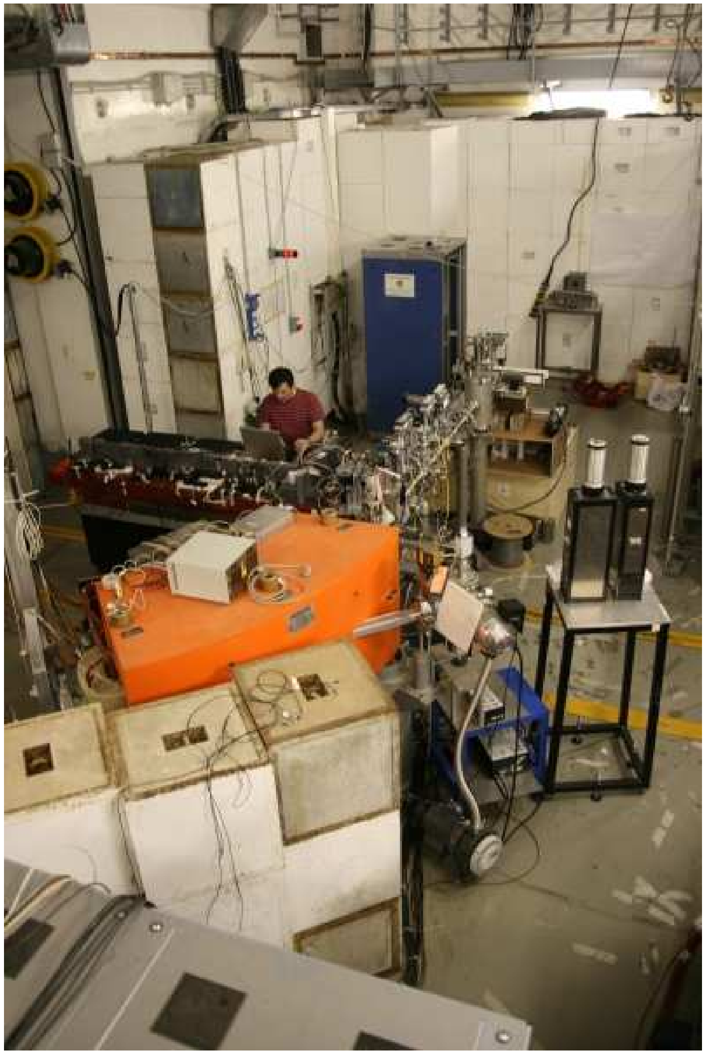
$$\Delta x = \sqrt{\beta_1\beta_2}\sin\Delta\psi \cdot \Delta\theta$$

- And a resulting beam size

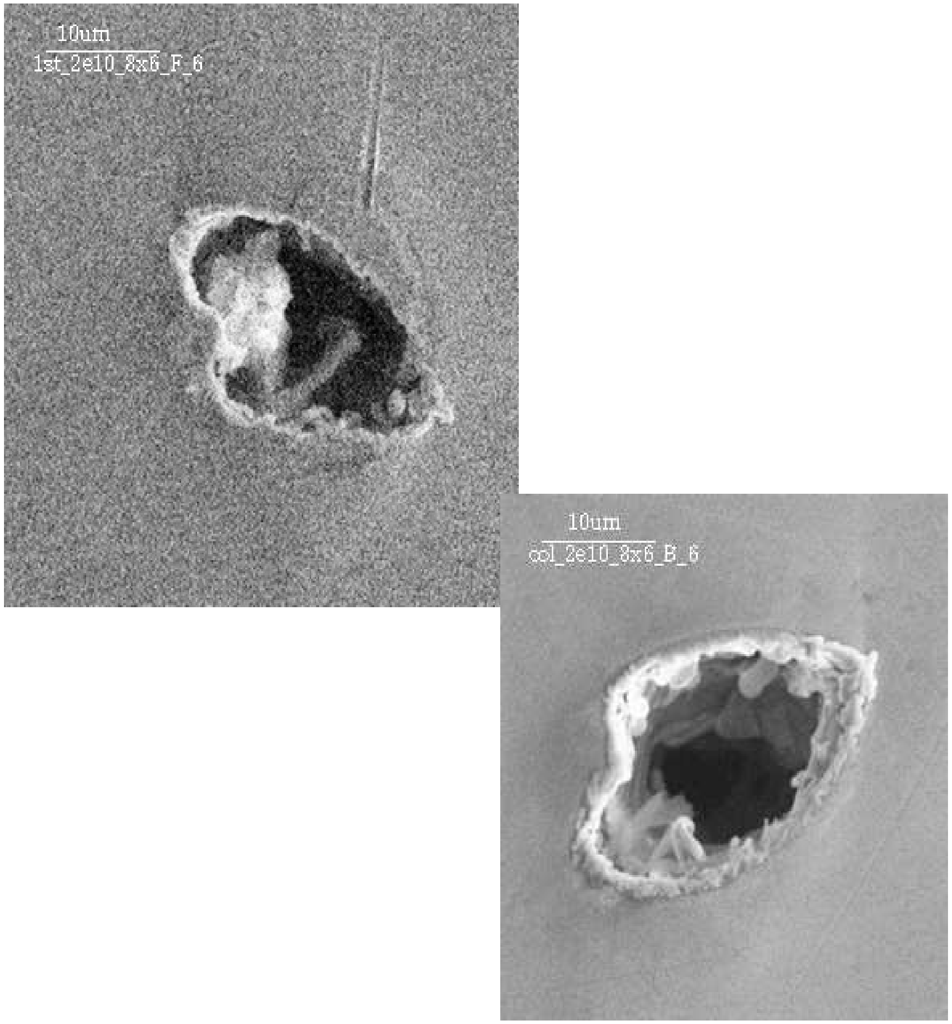
$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda\gamma m_e}\sin\Delta\psi\cos\varphi\right)^2}$$

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.

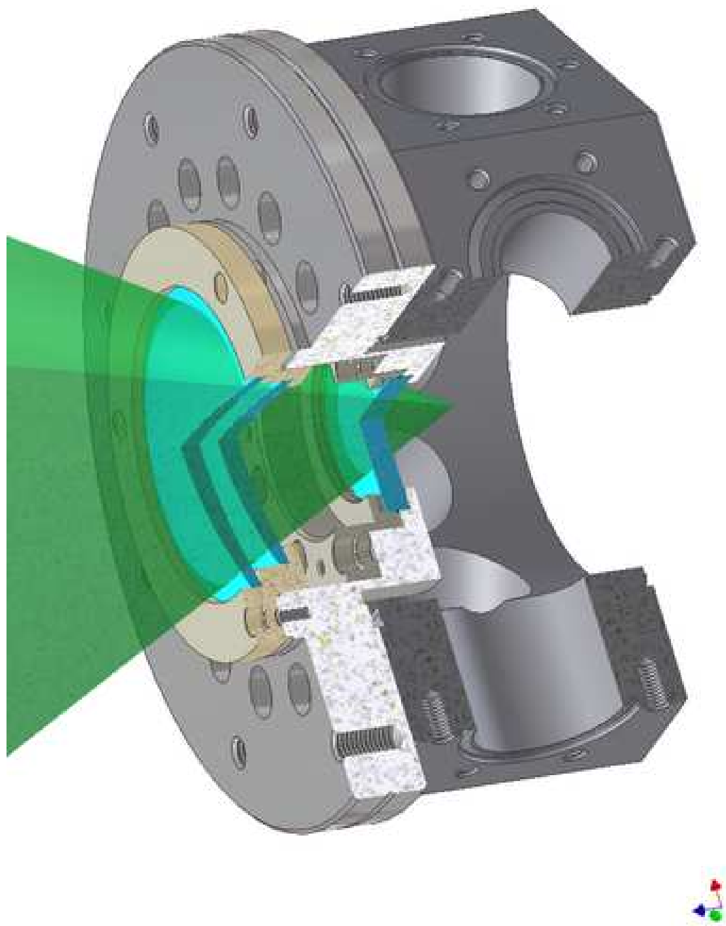


Limitation of these monitors



- 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



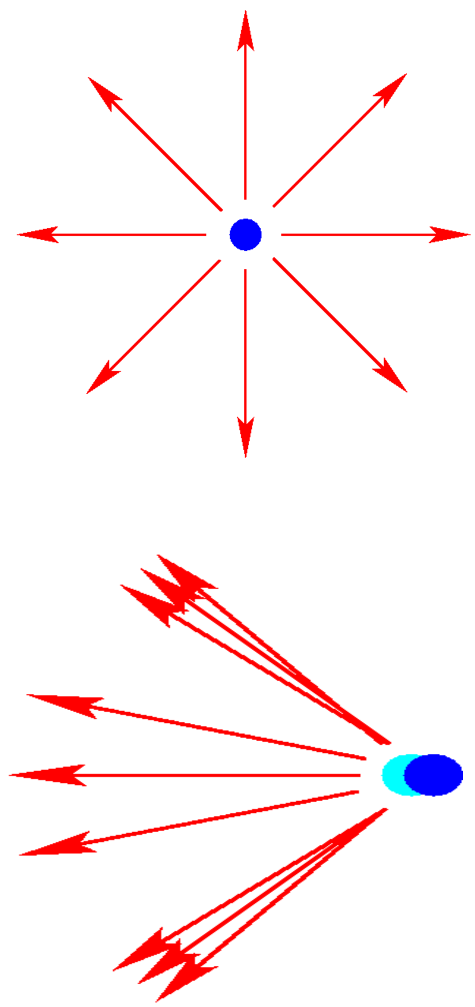
- To mitigate the problem of broken wires in wire-scanners it is possible to replace the wire by a laser.
- This technique called “laser-wire” also allow to reach better resolutions.
- High power lasers (or long integration times) are needed.
- Some of this work is done in Oxford.

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

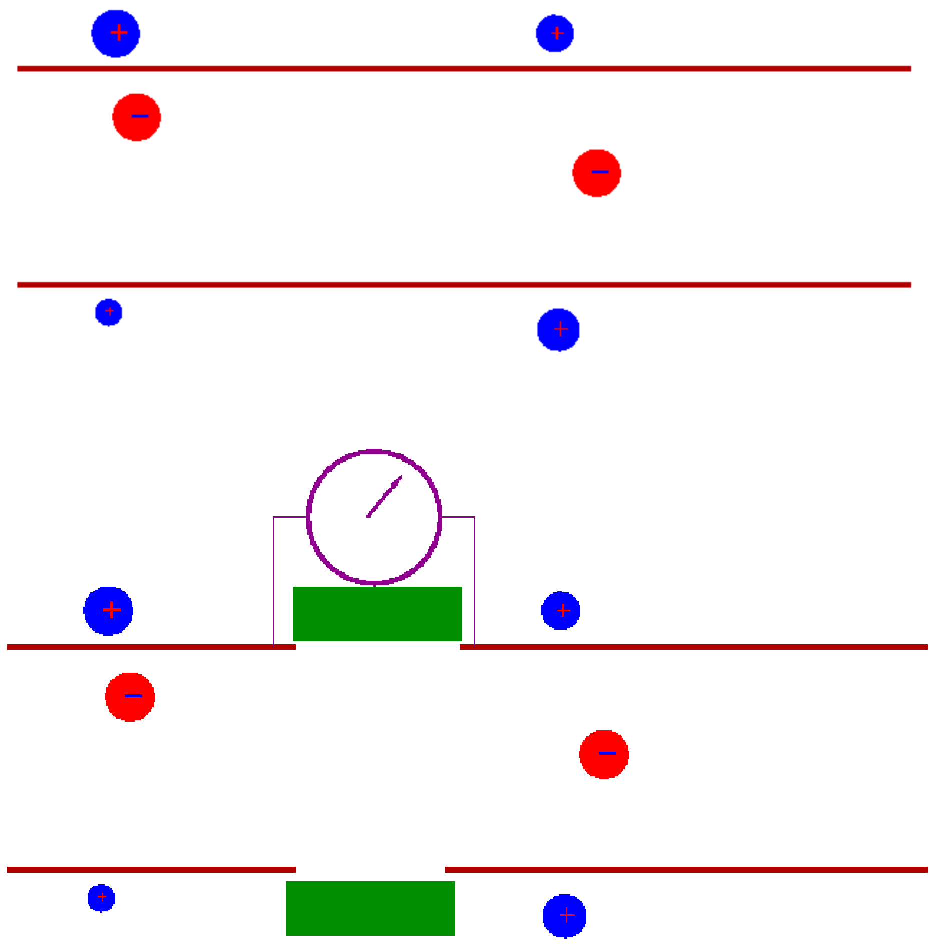
- We have seen that it is possible to build monitors which use the interactions of particles with matter.
- These monitors tend to be destructive: they significantly damage the beam.
- These monitors tend to be simple but can be damaged by high energy high intensity beams.

Charged particle



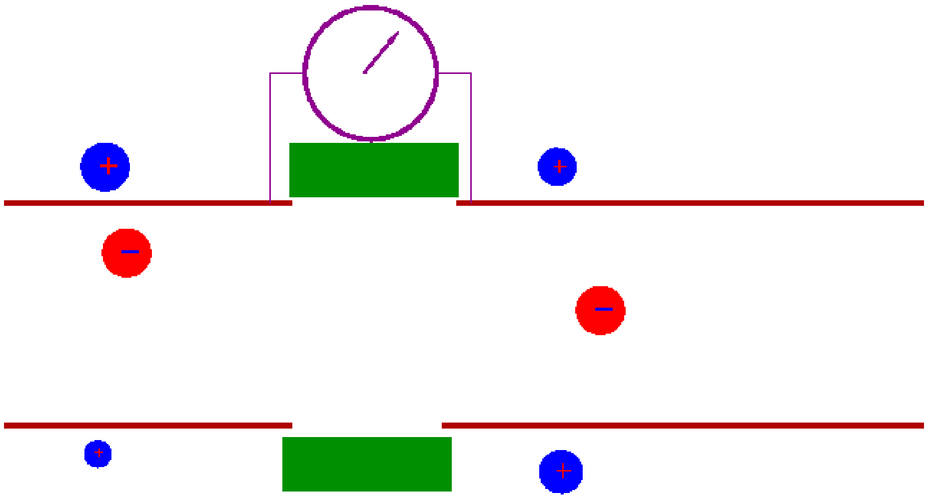
- Any charged particle "radiates"
- These electromagnetic radiations can be detected without disrupting the beam.
- One need to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

Beam current monitor



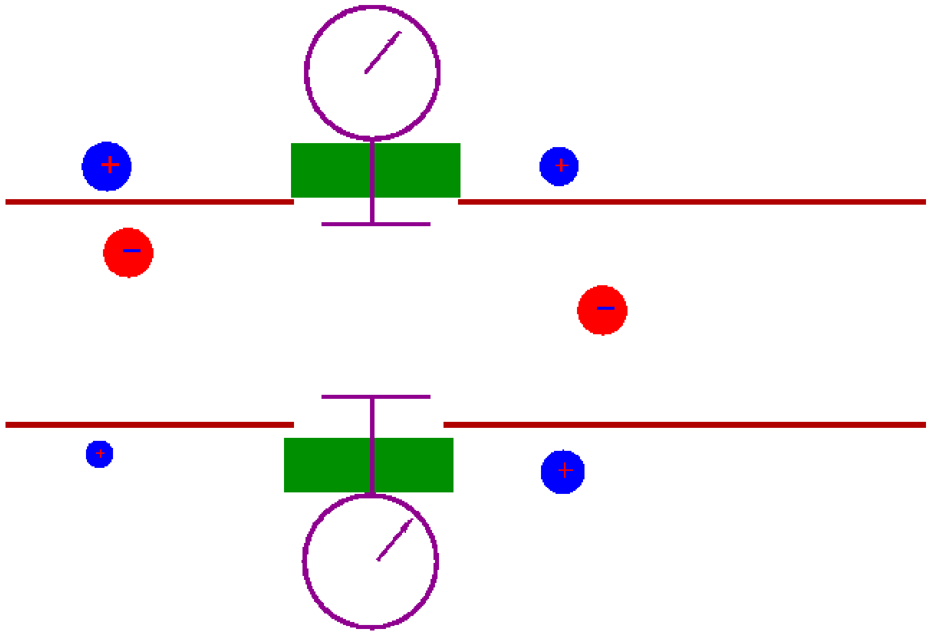
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

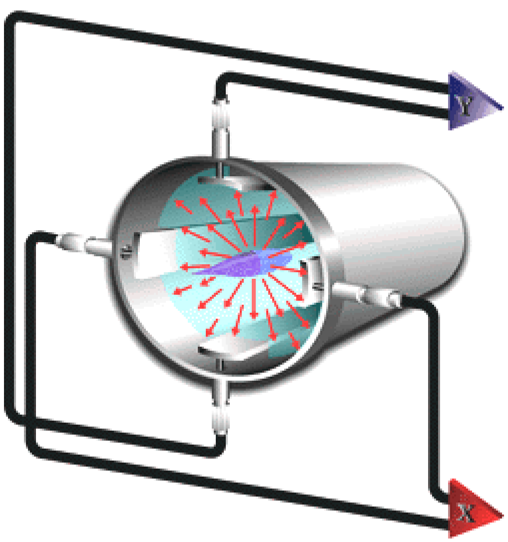
Beam current monitor vs Faraday cup



- 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

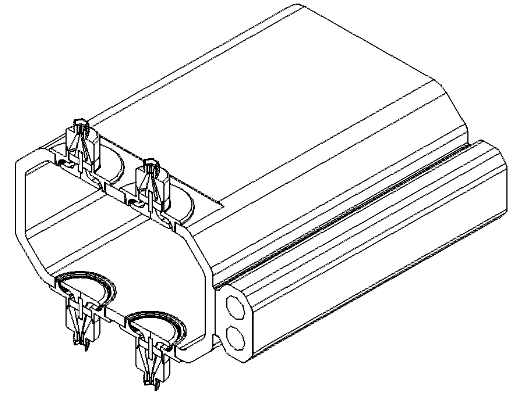


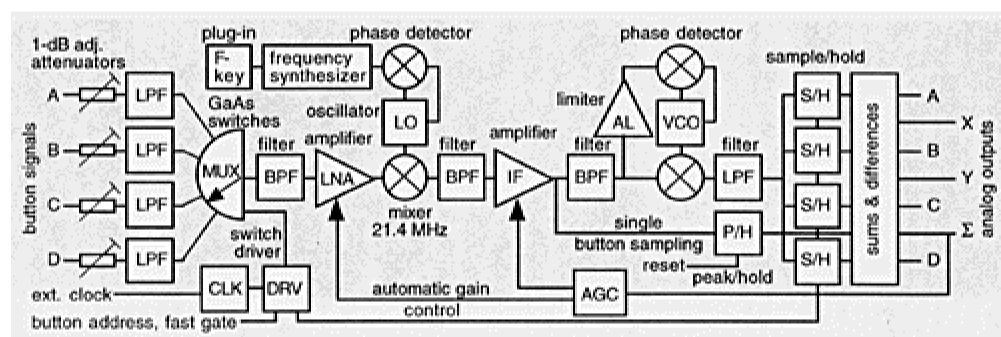


- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

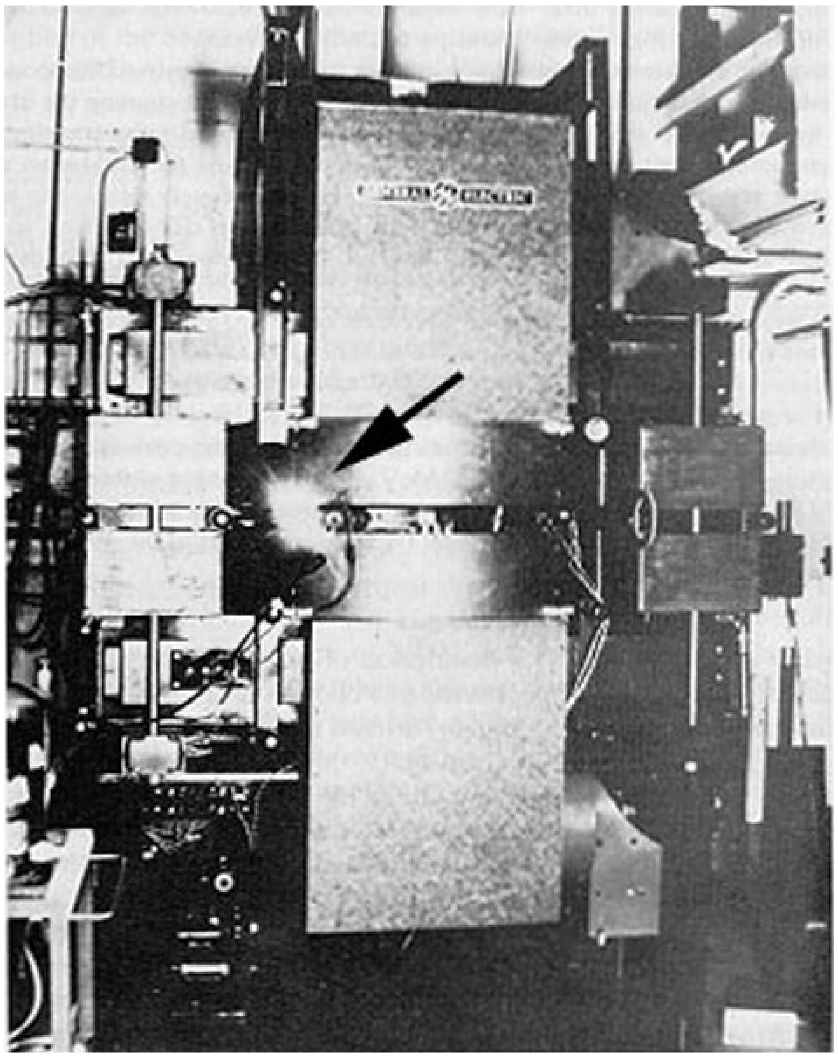
Beam Position Monitor (2)

- BPM are one of the most common diagnostic at an accelerator.
- They exist on many different configurations.
- At synchrotrons it is not possible to have electrodes in the horizontal plane so the electrodes have to be above or below the beam.
- Although the basic principle is simple, very advanced electronics are used to get he best possible precision.
- At Diamond there are 220 BPMs, about 1 every 4 meters in the ring!

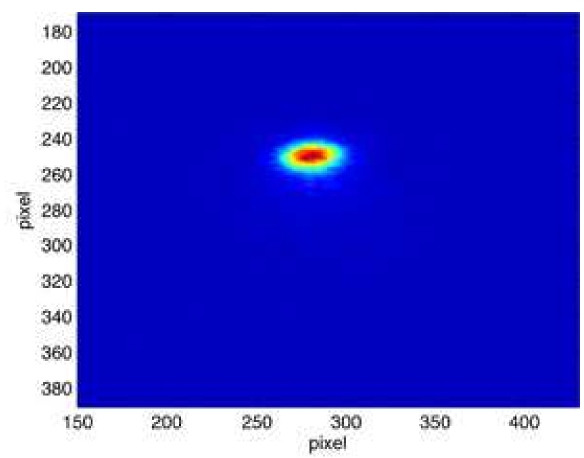




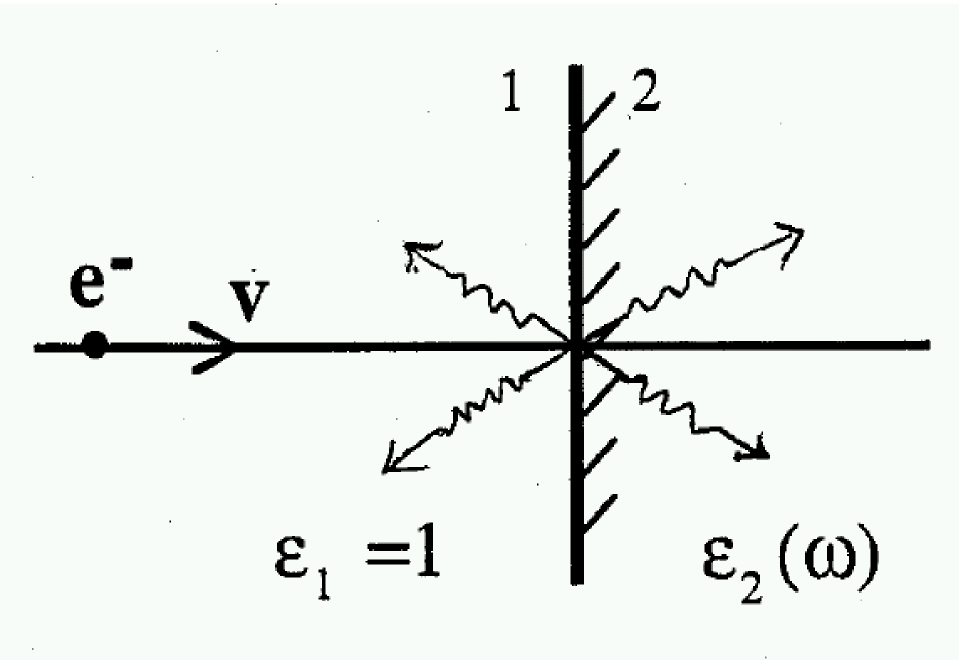
Synchrotron radiation

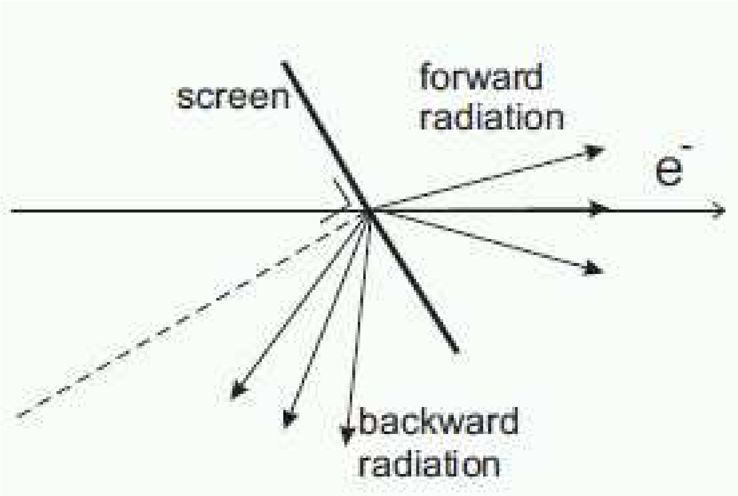


- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



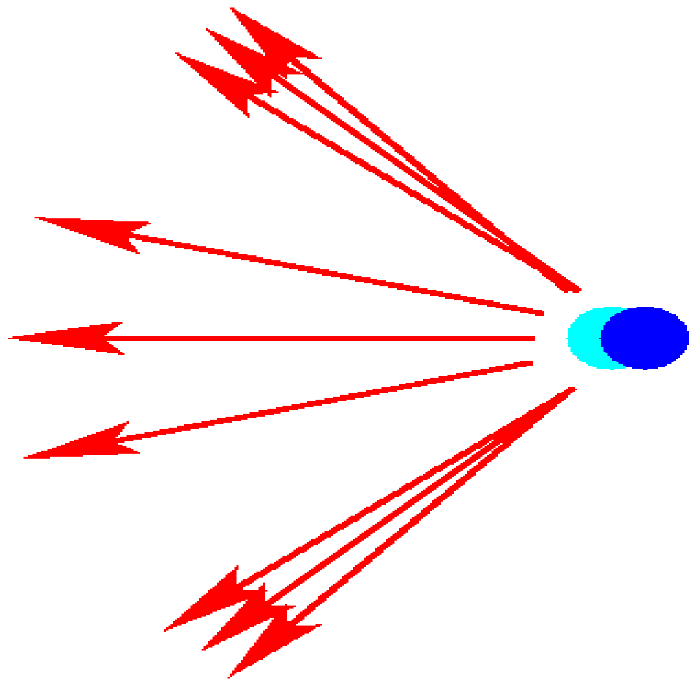
Optical Transition Radiation





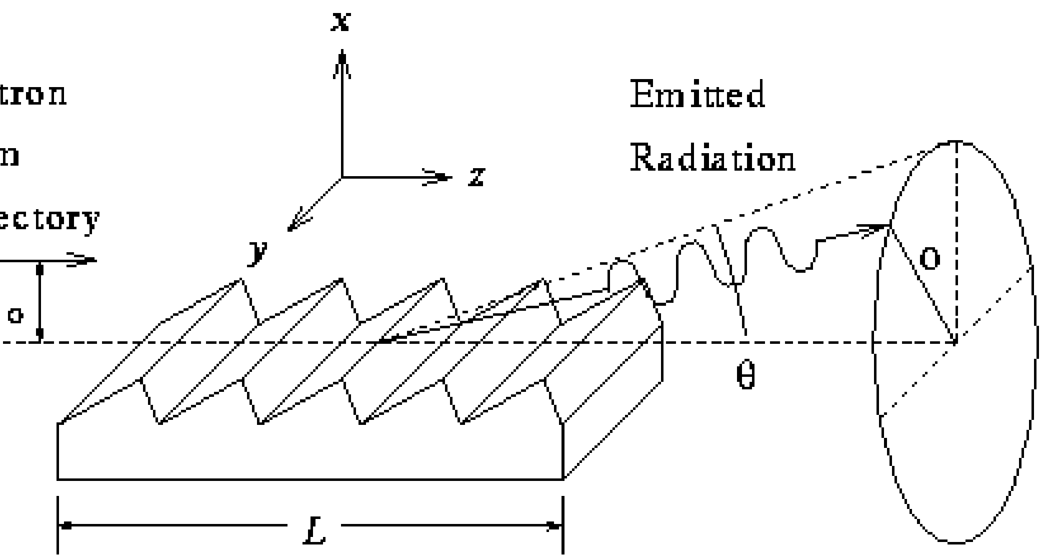
- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape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

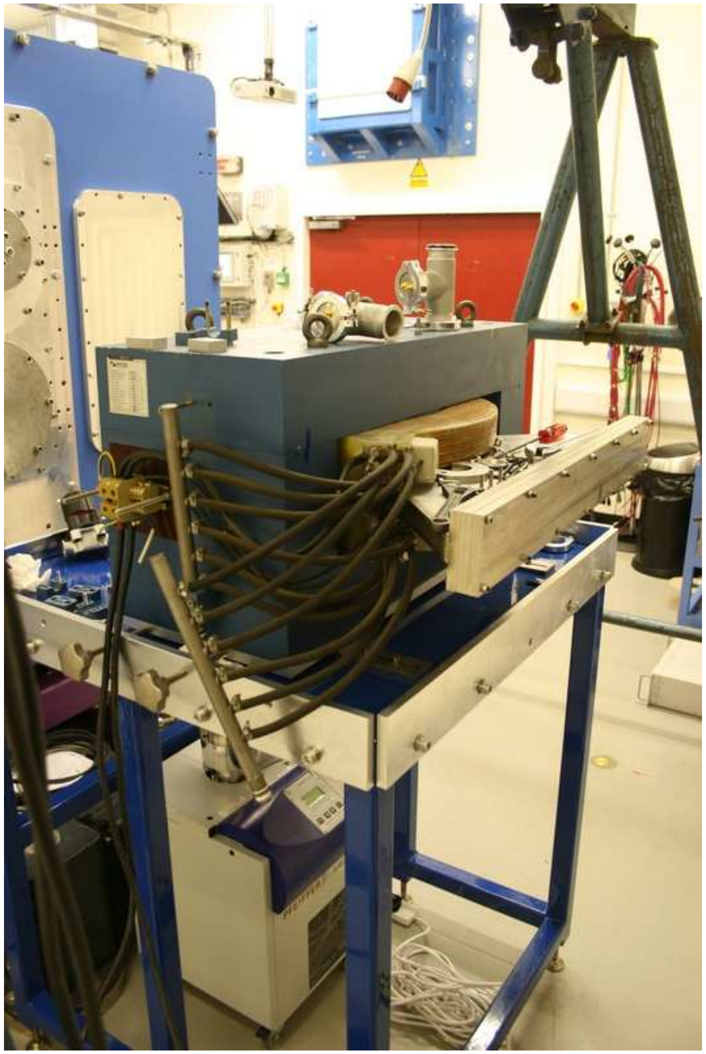
Longitudinal profiles



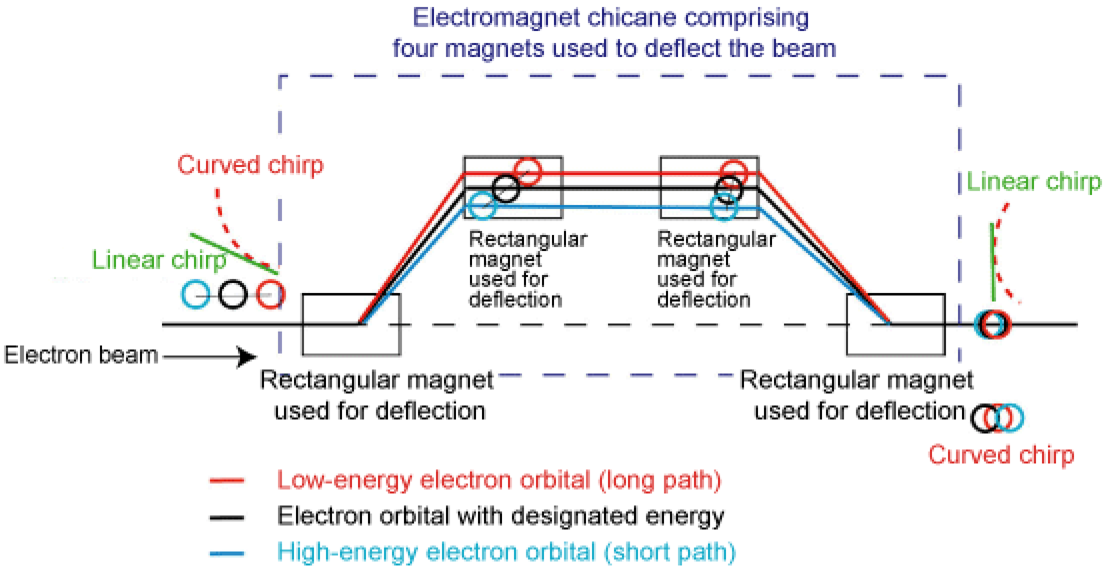
Principle of Smith-Purcell Radiation

- Longitudinal profiles of short beams are one of the most difficult measurement.
- 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.
- Several other bunch profile measurement methods rely also on the radiation emitted by the beam.

Energy measurements



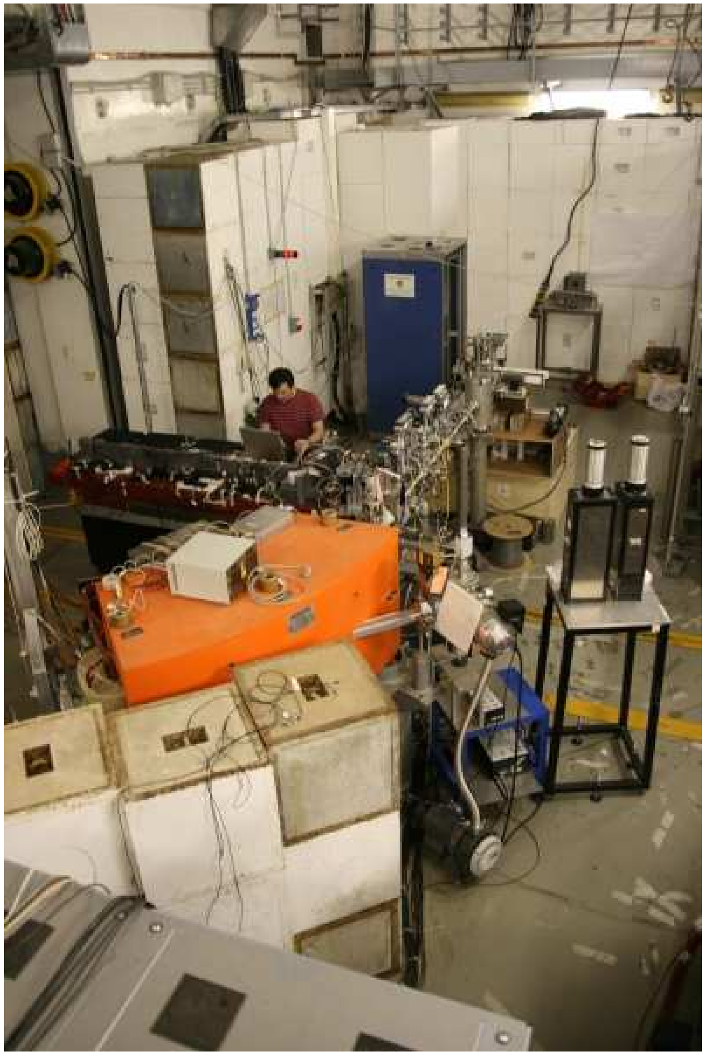
- To measure (or select) the energy of the particles a bending magnet is often the best solution.
- This can be done in an “energy chicane”.



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



- There are two ways of measuring the properties of a beam:
  - By forcing it to interact with matter
  - By looking at the EM radiation emitted.
- How to build the best diagnostic is then a matter of imagination!