Introduction to particle accelerators III. Diagnostics and Applications

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Reminder

- During the first lecture we saw what are the basic building blocks of an accelerator:
  -particle sources using either thermionic effect, the photoelectric effect or plasma ionisation.
  - Accelerating structures using high frequency (RF) electromagnetic waves
  - Magnets to steer and focus the beam
- During the second lecture we saw:
  - that the beam quality is expressed by its emittance, its volume in 6D space
  - that interactions between particle of the beam or between the beam and the machine may reduce the beam quality.

Lectures overview

I. Basic principles and overview

II. Beam dynamics

III. Diagnostics and applications:

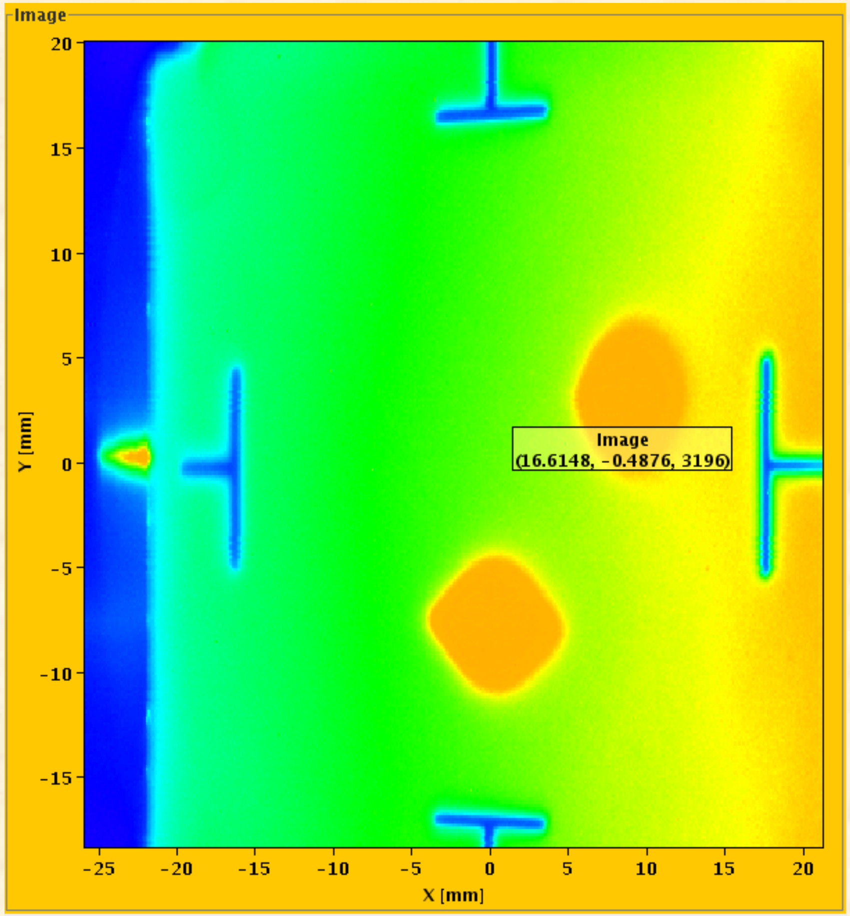
- How to “see” the beam?
    - + by destructing it
    - + by observing the radiation emitted
- What to do with an accelerator?
    - + look at old object
    - + read a book without opening it
    - + study chocolate
    - + ….

What do **we** want to know about the beam?

?

What do you want to know about the beam?

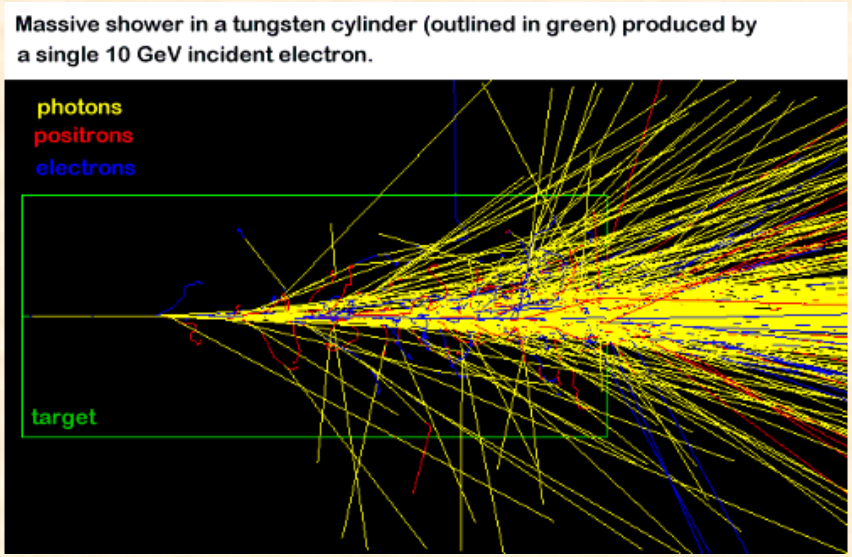
- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses

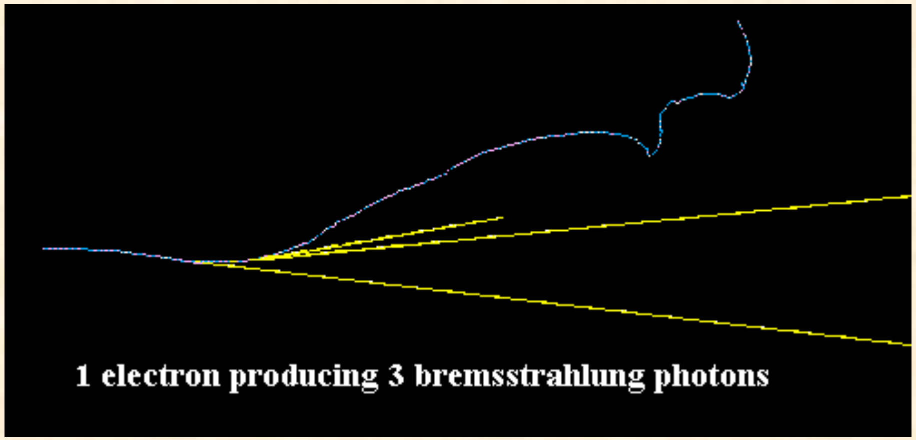


Properties of a charged beam

- 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

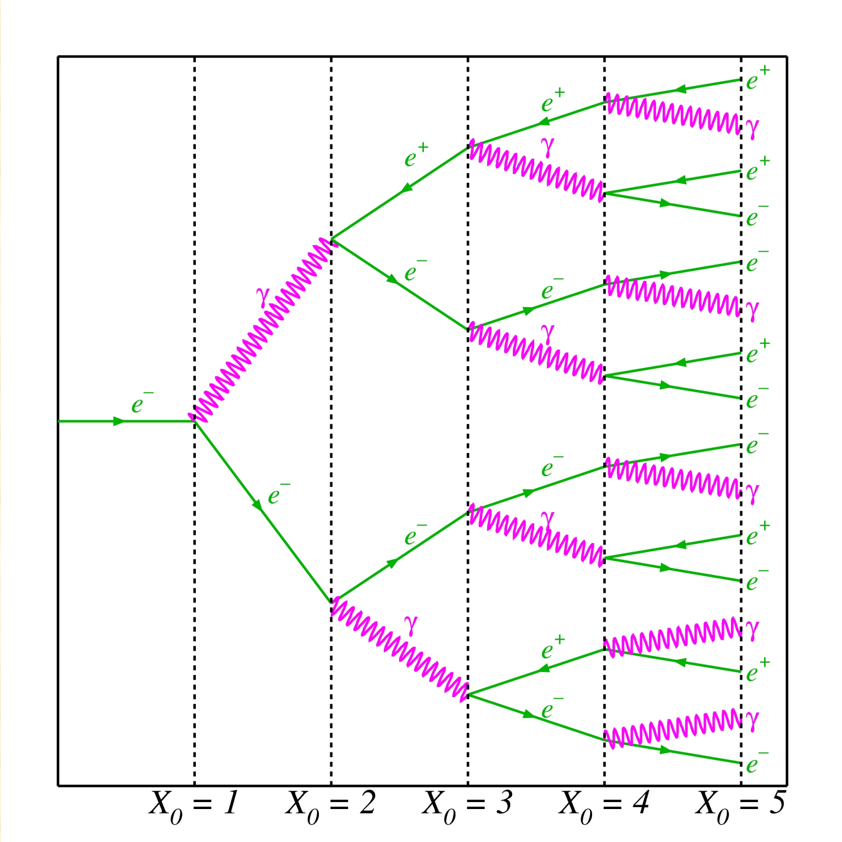




- High energy particles interact with matter in several ways.
- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produced when such scattering occur will carry a significant energy and scatter themselves.

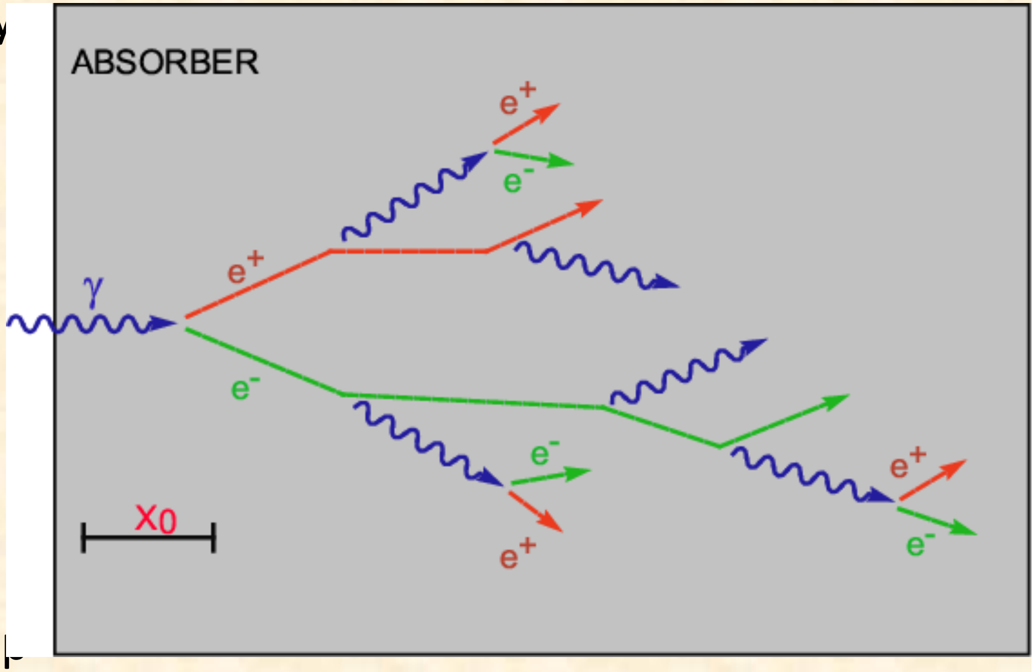
Example: Electron shower

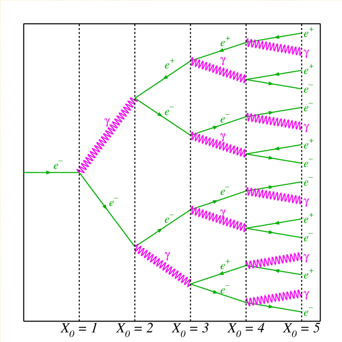
- The distance after which an electron or a photon interacts is called the "radiation length"
- Radiation length vary from material to material and can be found in tables.
- X_0(Pb)= 0.56cm
  X_0(Ta)= 0.41cm
  X_0(Cu)= 1.44cm
  X_0(Fe)= 1.76cm
  X_0(C graphite)= 19.32cm



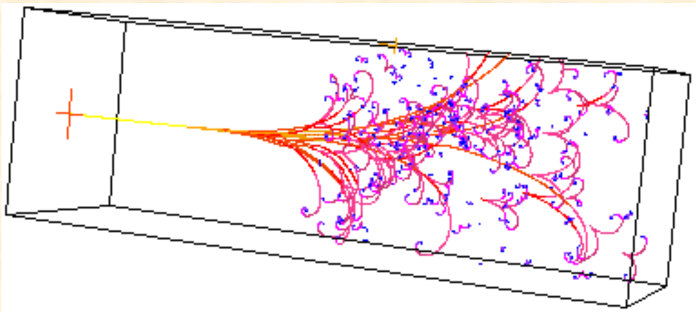
Particle absorption

- 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 protons will loose some energy as they travel in matter and suddenly stop when their energy slow enough.
- More details in the instrumentation lectures



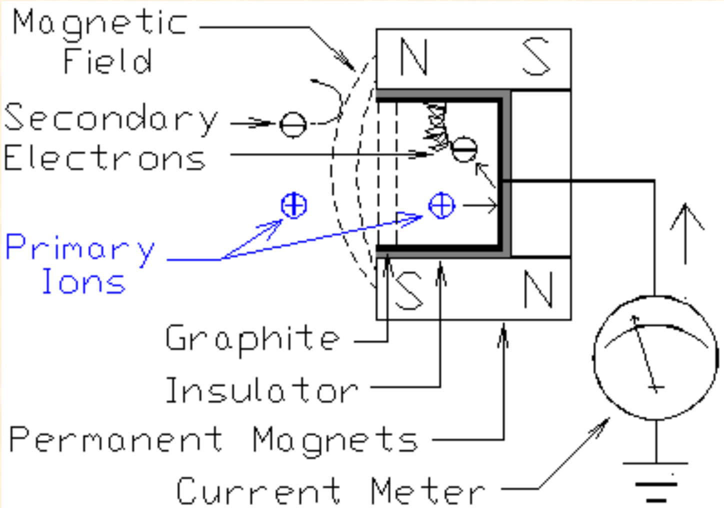


Faraday cup (1)



- 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)



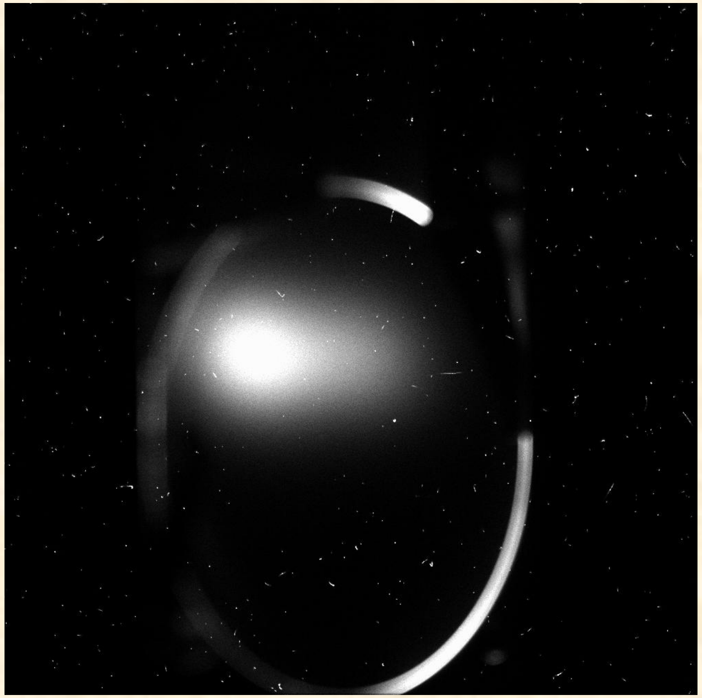
- Two properties can be measured:
  - Beam total energy
  - Beam total charge
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large:
  More than 1m at Diamond for a 3 GeV electron beam.

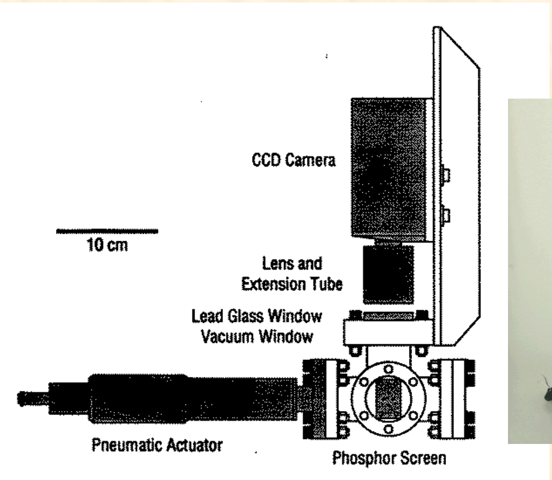
Image source: Pelletron.com

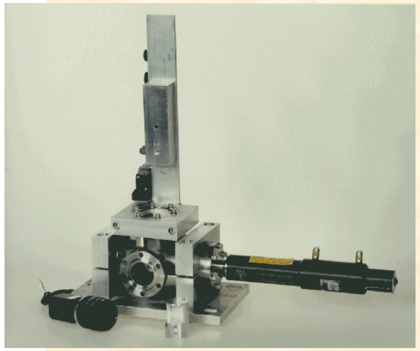
Screen (1)

- 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)

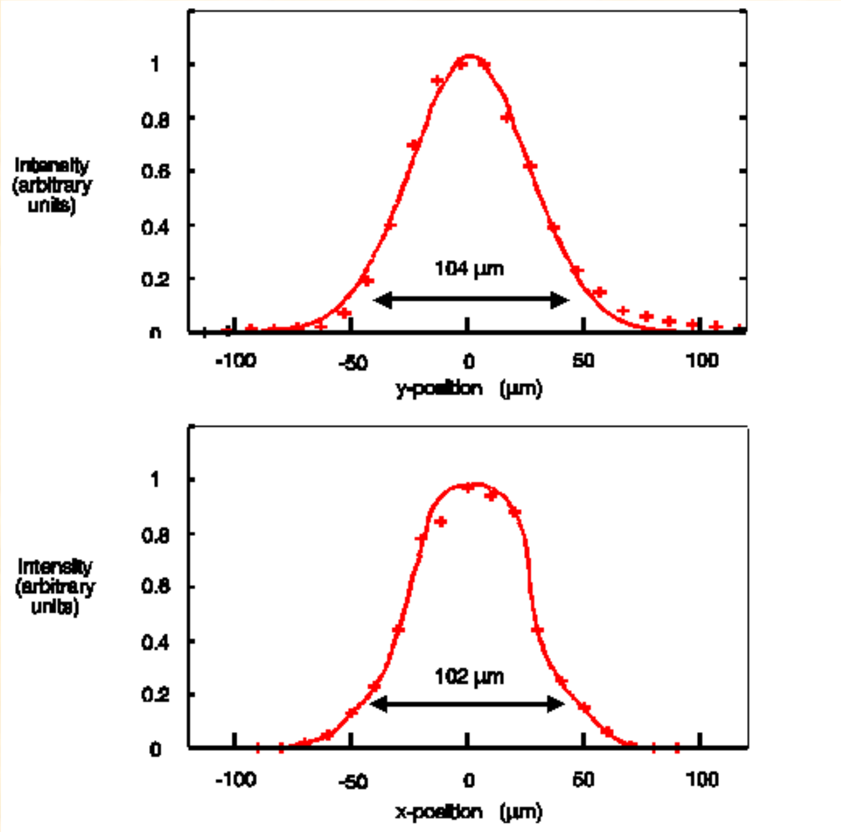






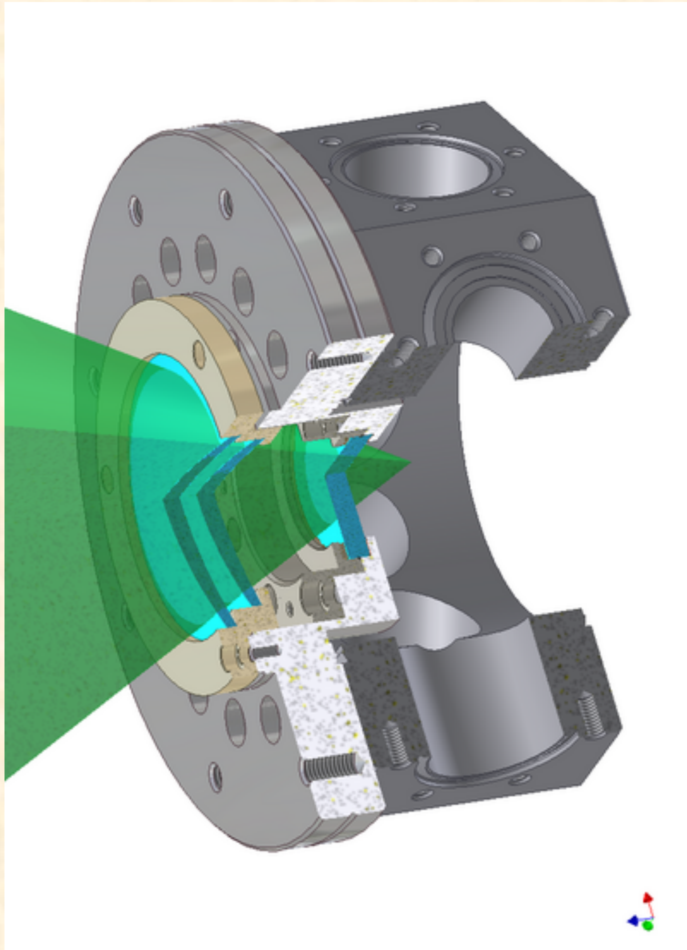
- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at
  45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

Wire-scanner



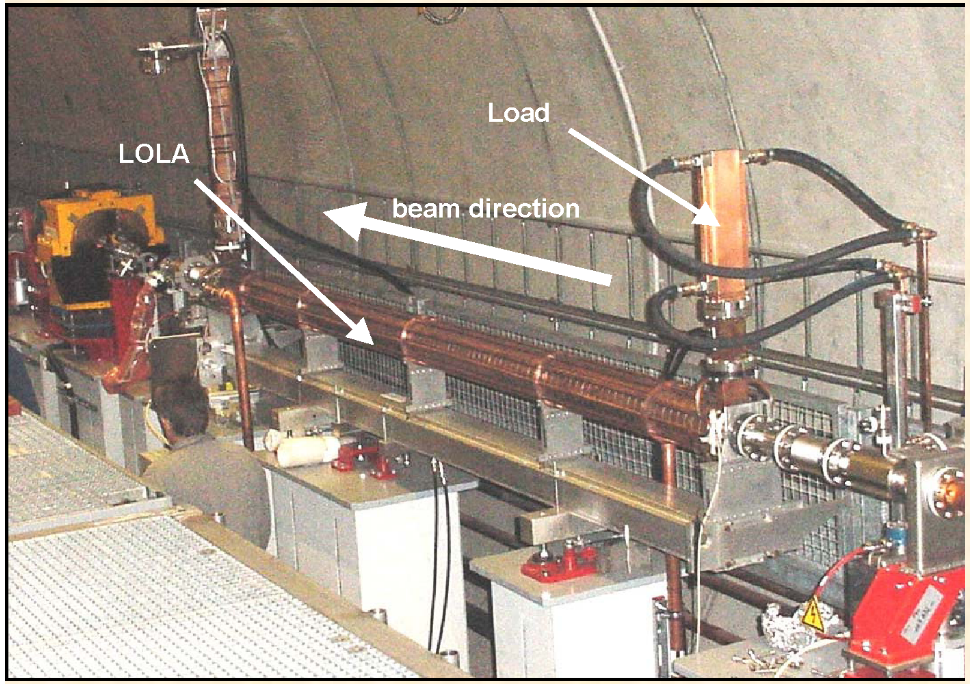
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
  => better resolution than with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

Laser-wire

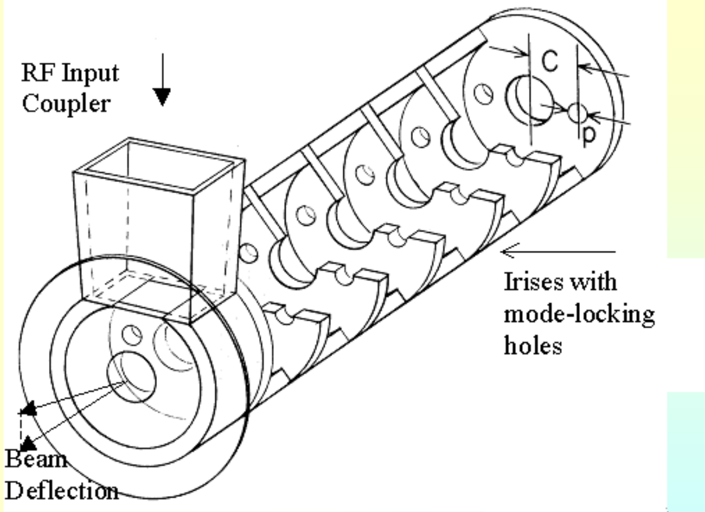


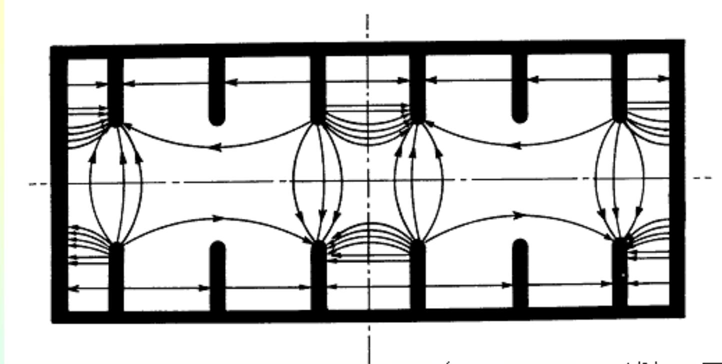
- To mitigate the problem of broken wires in wire-scanners it is possible to replace the wire by a laser.
- This technique called “laser-wire” also allow to reach better resolutions.
- High power lasers (or long integration times) are needed.

Longitudinal properties



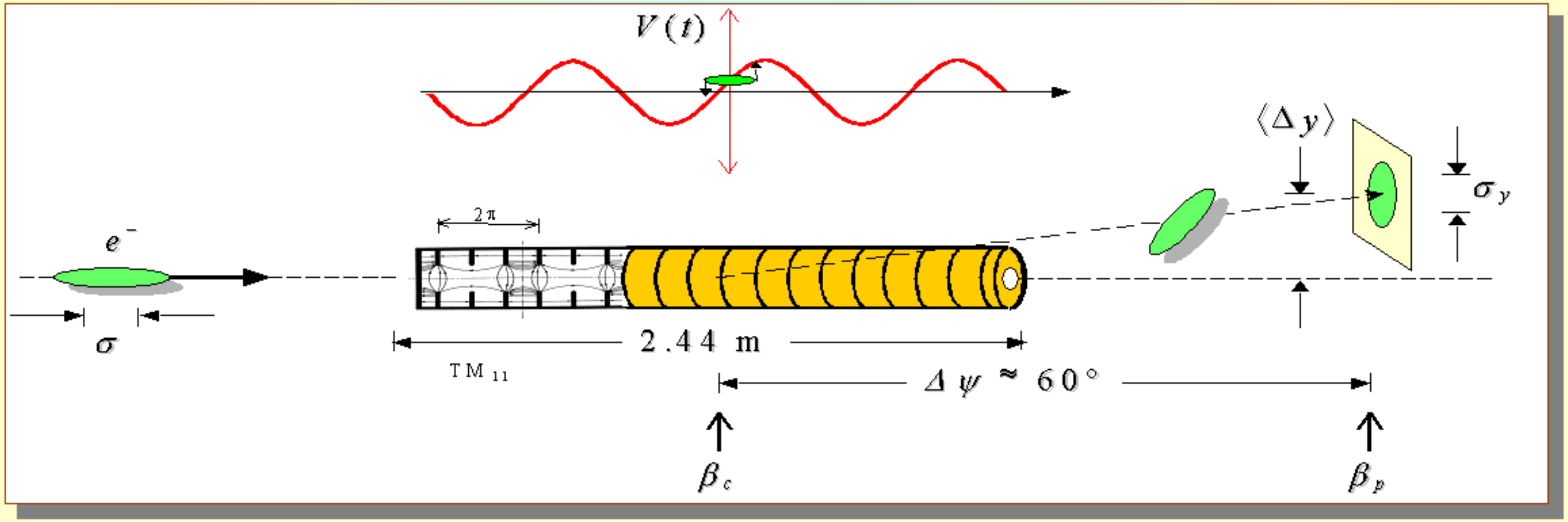
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



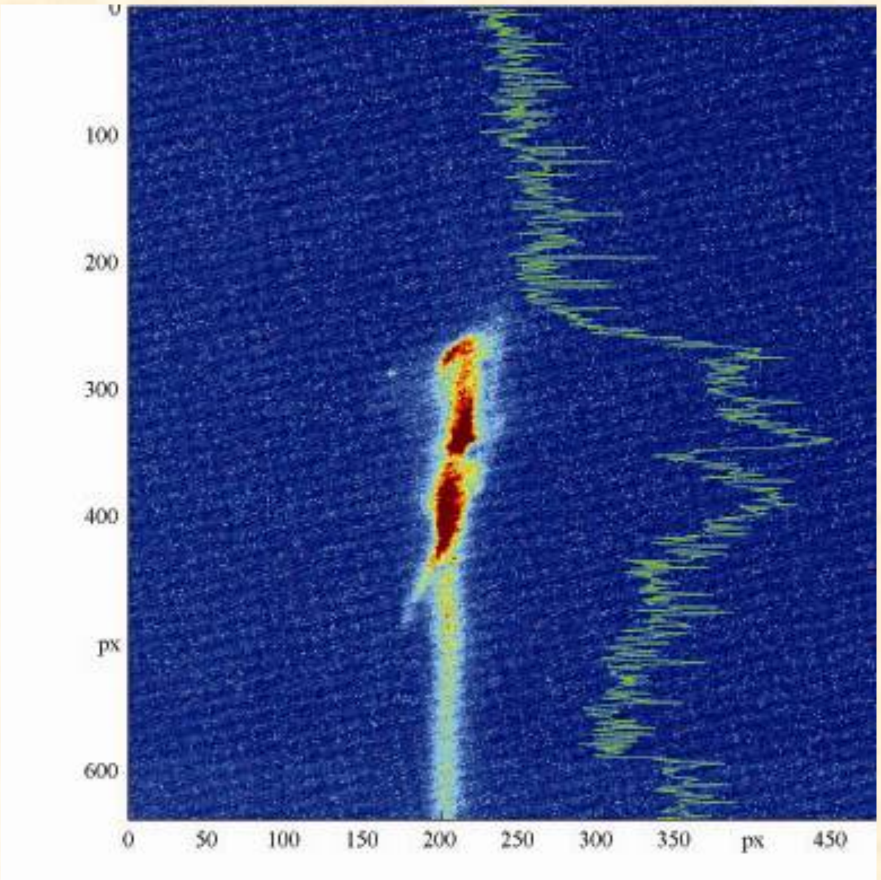


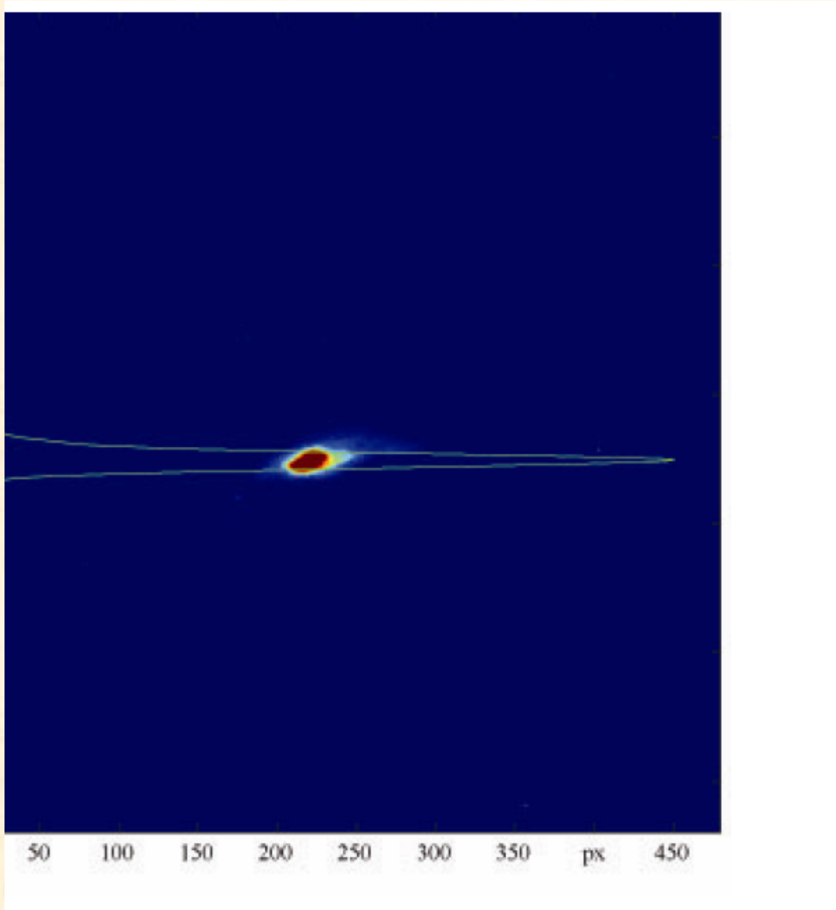
$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW^{1/2}}\right) L\sqrt{P_0}$$

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

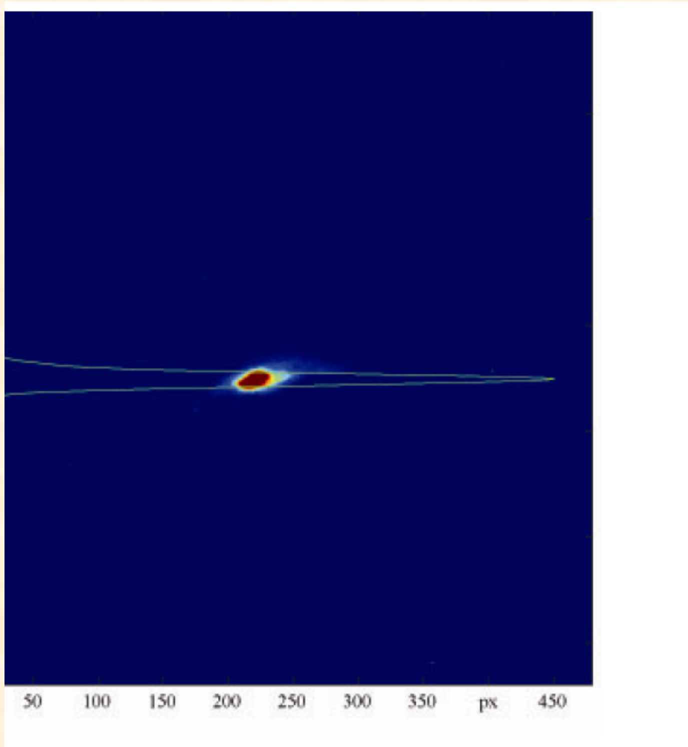


RF deflector off and on





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

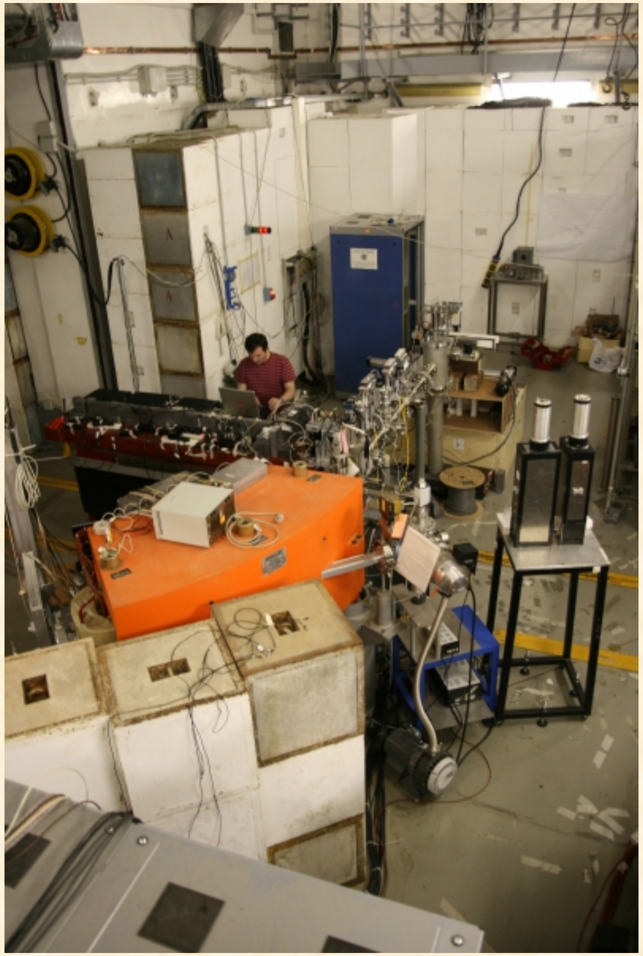
$$\Delta x = \sqrt{\beta_1\beta_2}\,\sin\Delta\psi \cdot \Delta\theta$$

- And a resulting beam size

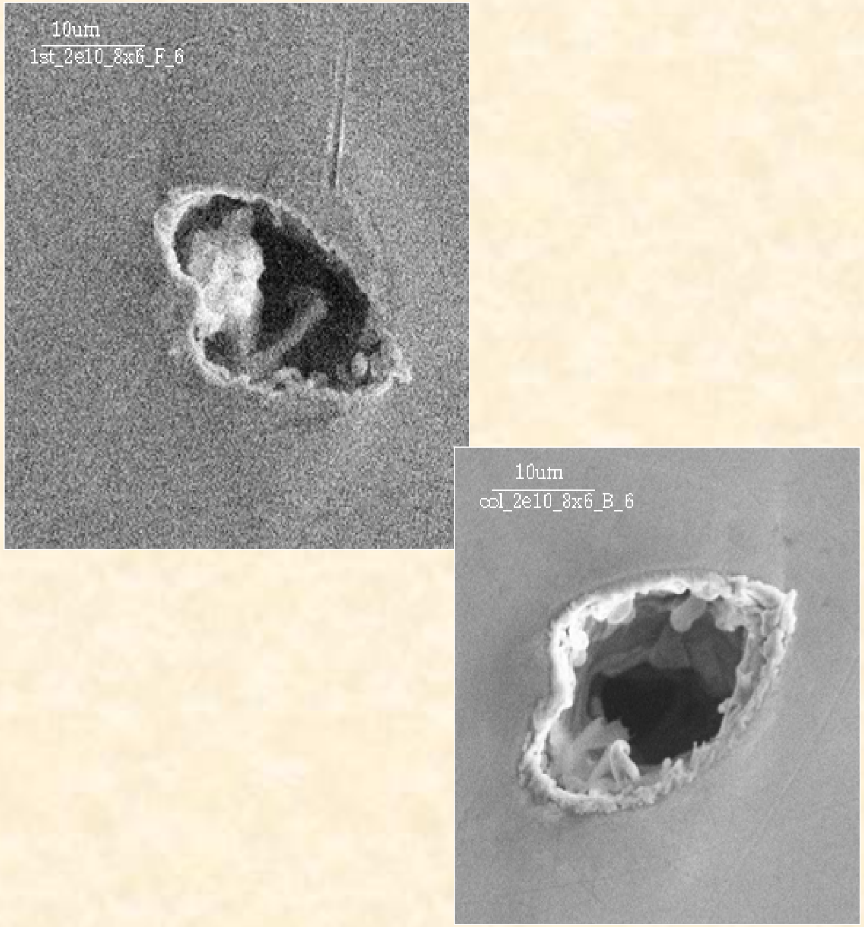
$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda\gamma m_e}\sin\Delta\psi\cos\varphi\right)^2}$$

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



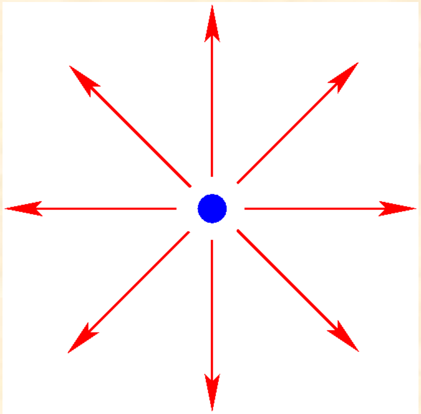
- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

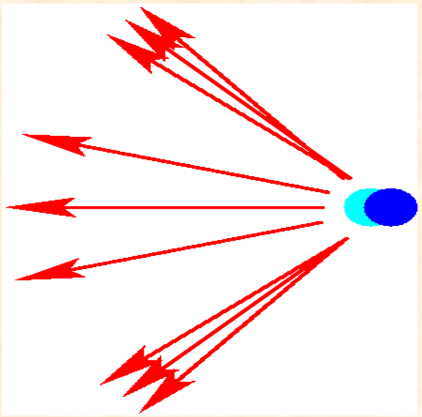
Summary (particles interaction with matter)

	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.

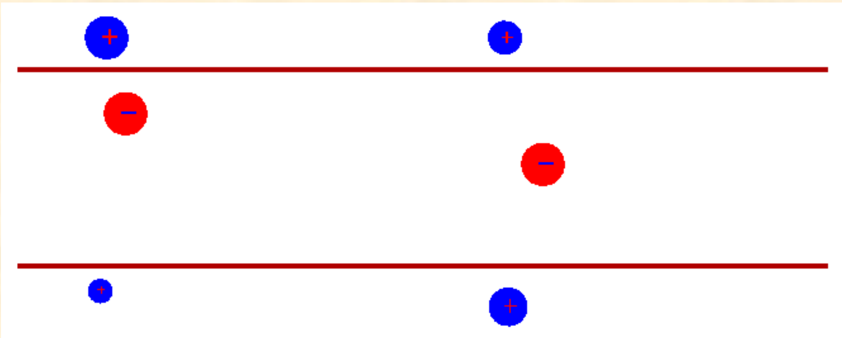
Charged particle

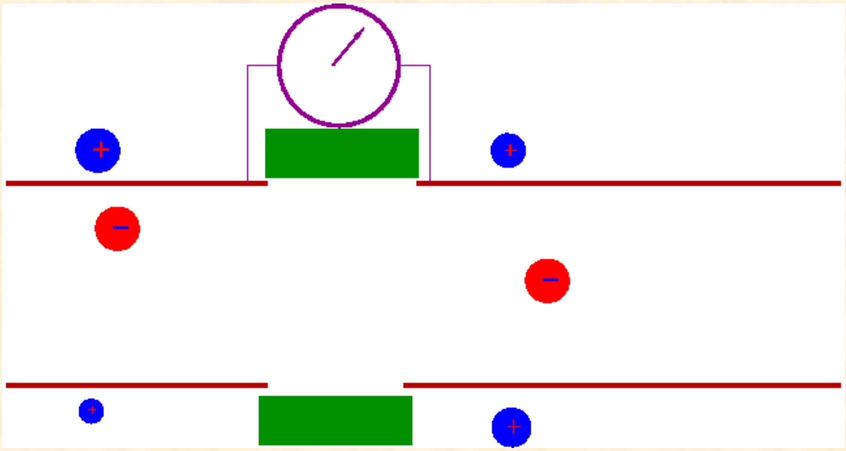




- Any charged particle "radiates"
- These electromagnetic radiations can be detected without disrupting the beam.
- One need to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

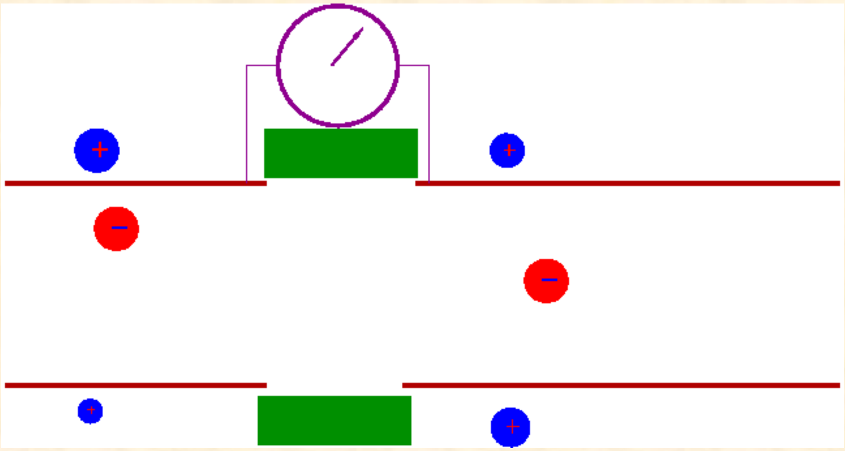
Beam current monitor





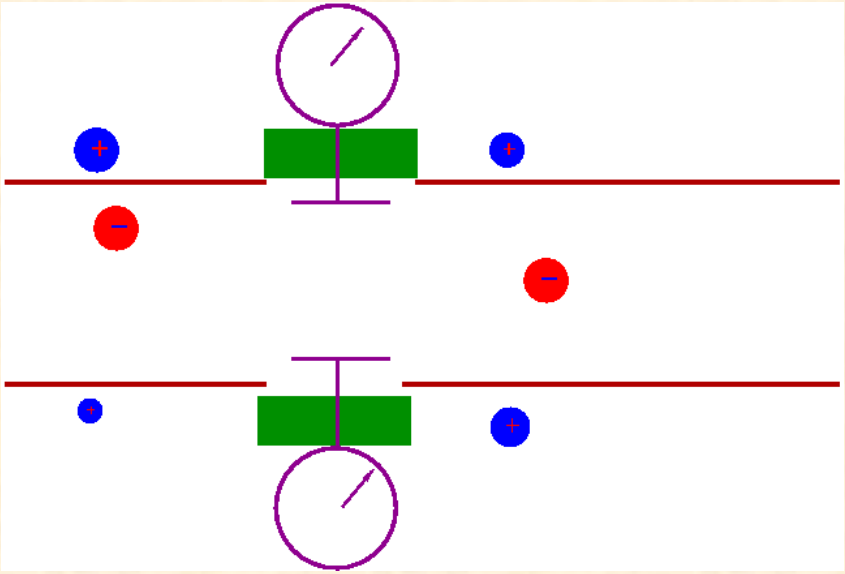
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

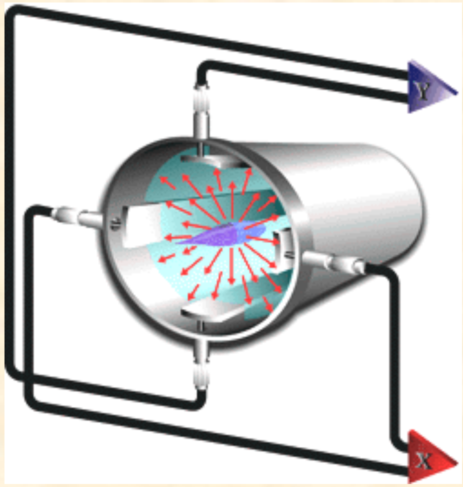
Beam current monitor vs Faraday cup



- 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 but at different locations along the accelerator.

Beam position monitor

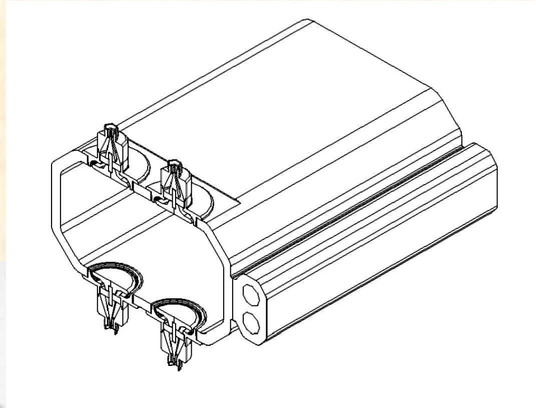


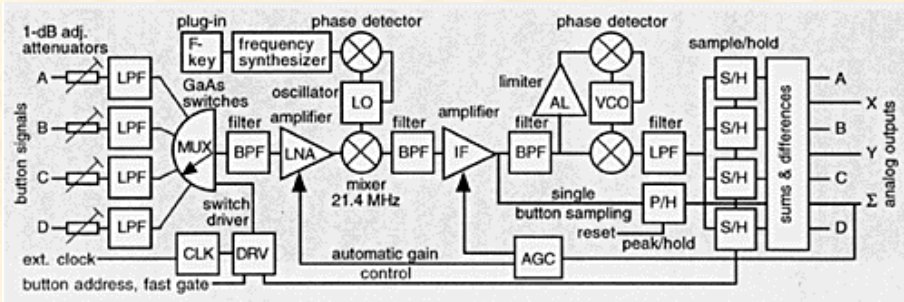


- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

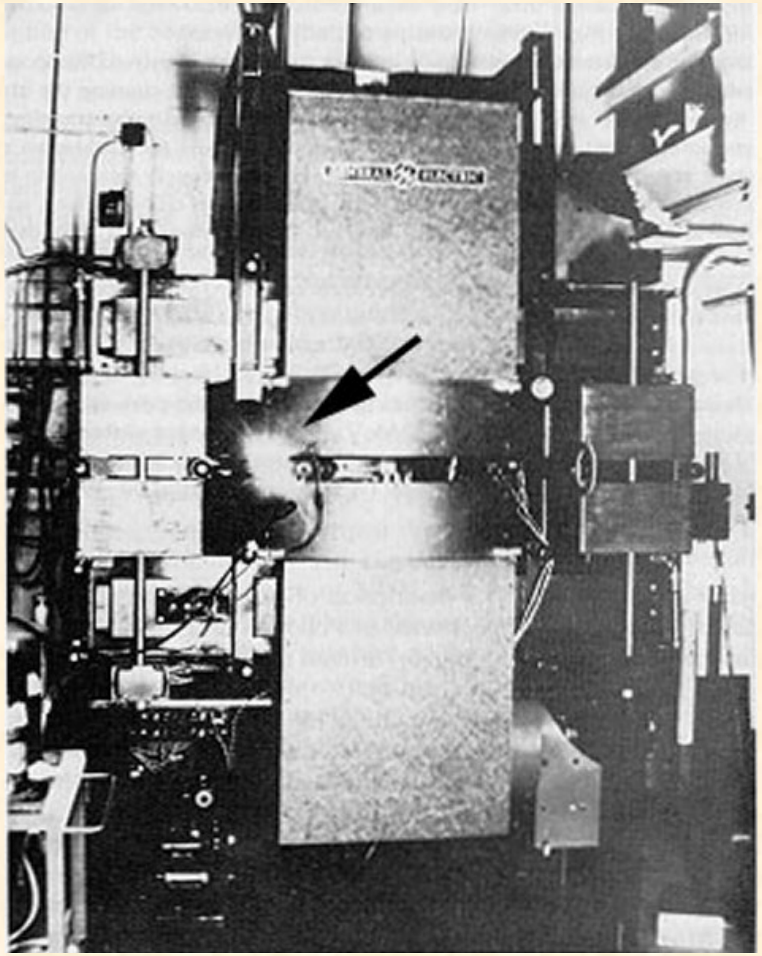
Beam Position Monitor (2)

- 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!

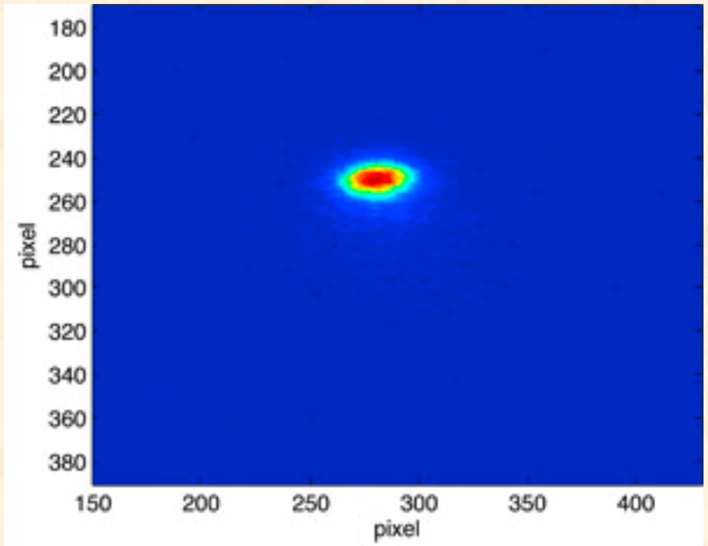




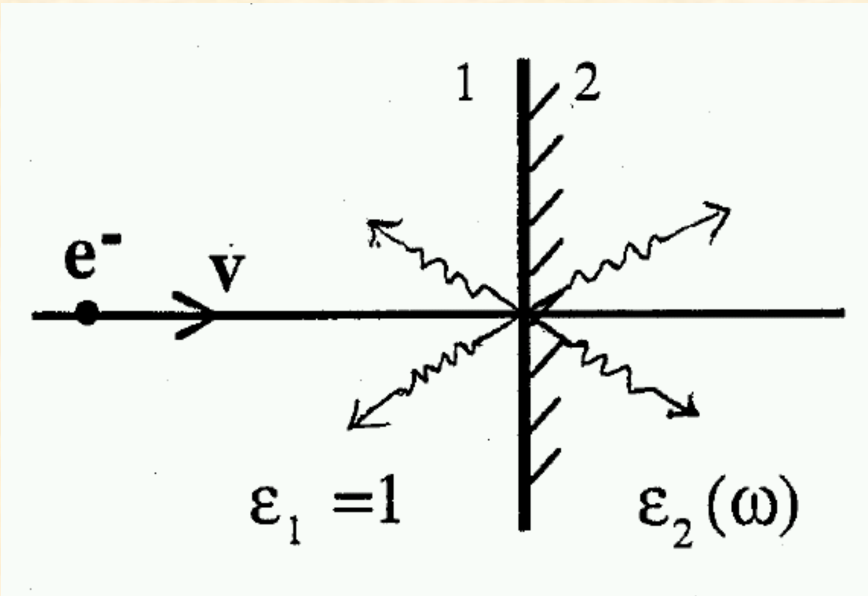
Synchrotron radiation

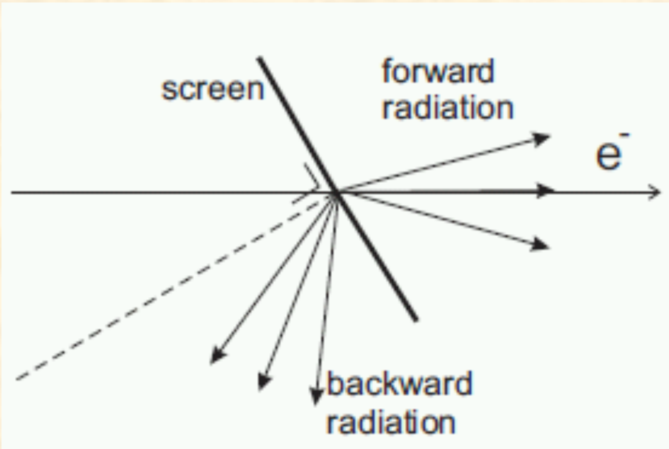


- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



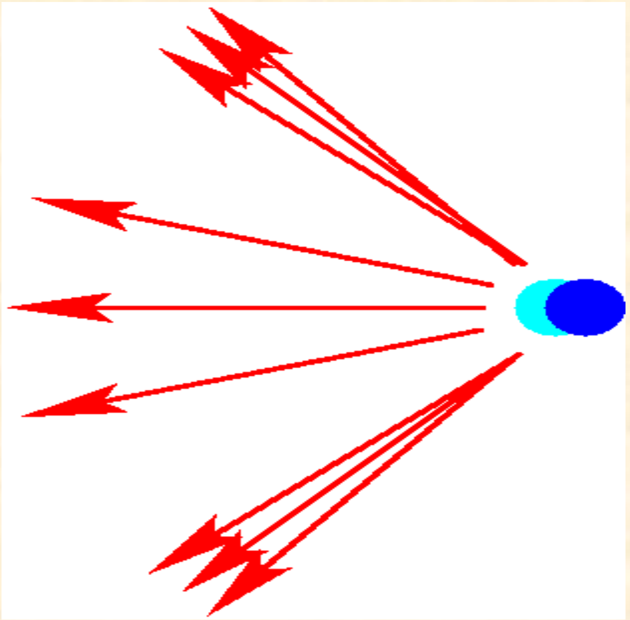
Optical Transition Radiation





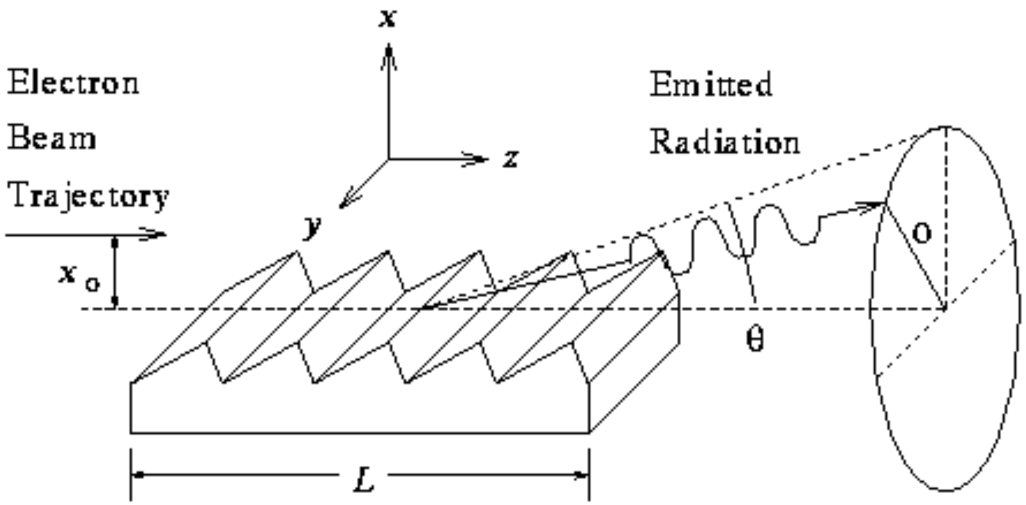
- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape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

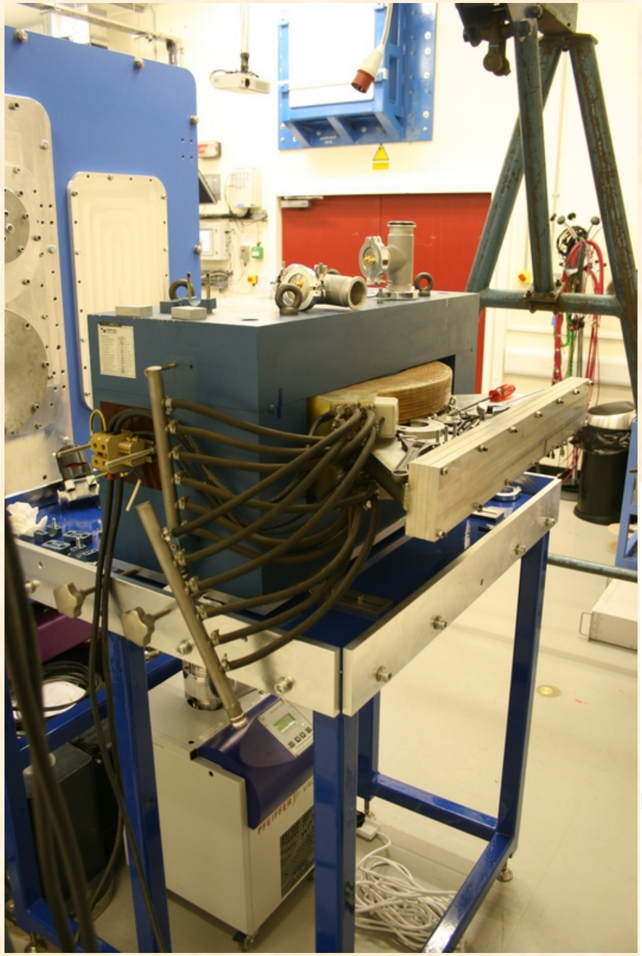
Longitudinal profiles



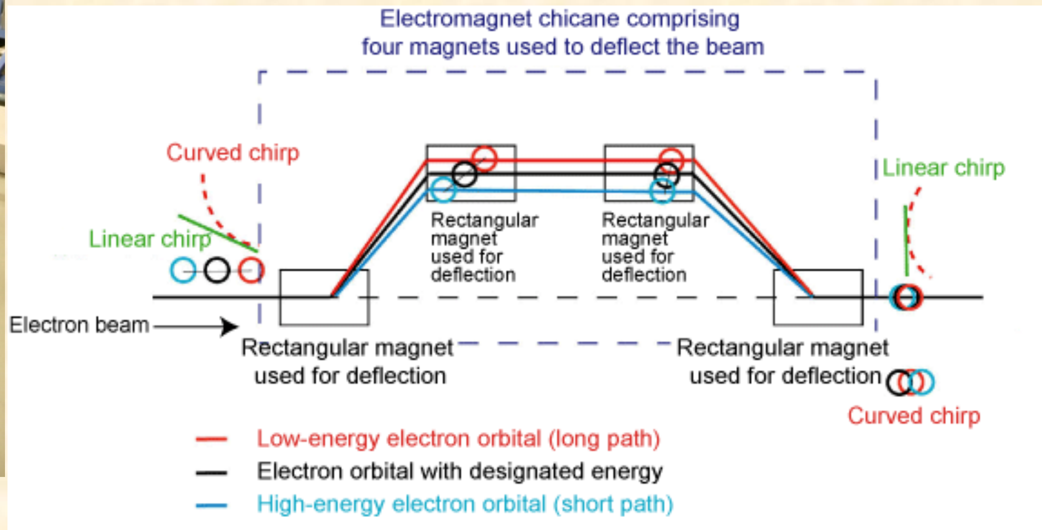
Principle of Smith-Purcell Radiation

- 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”.

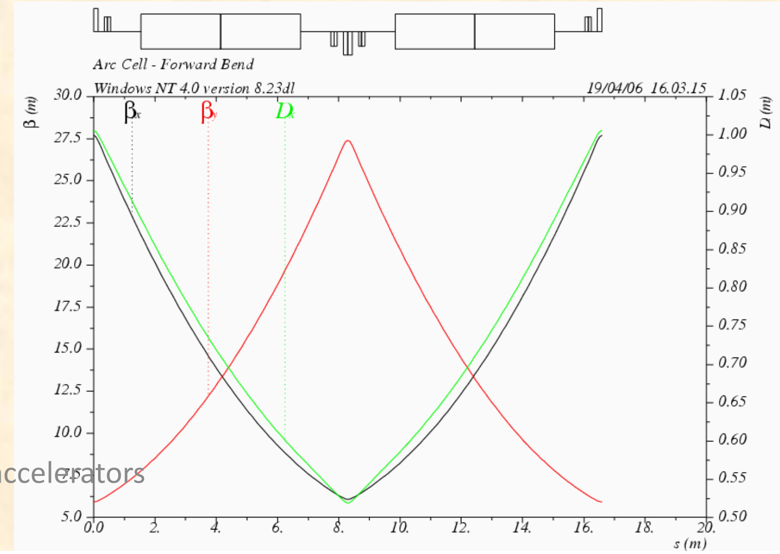


Diagnostics overview

	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	

Emittance measurement: Multi screen/wire method

- The emittance is not directly an observable.
- The beam size is an observable.
- By measuring the beam size at several locations it is possible to fit the best emittance.
- The beam size can be measured by using screens or wires (beam size measurements will be discussed next week during the diagnostics lecture).

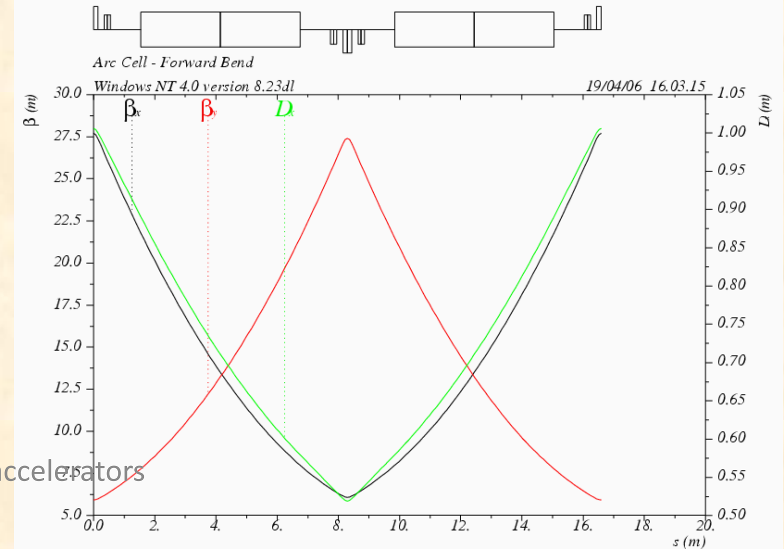


$$\sigma = \sqrt{\in(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$

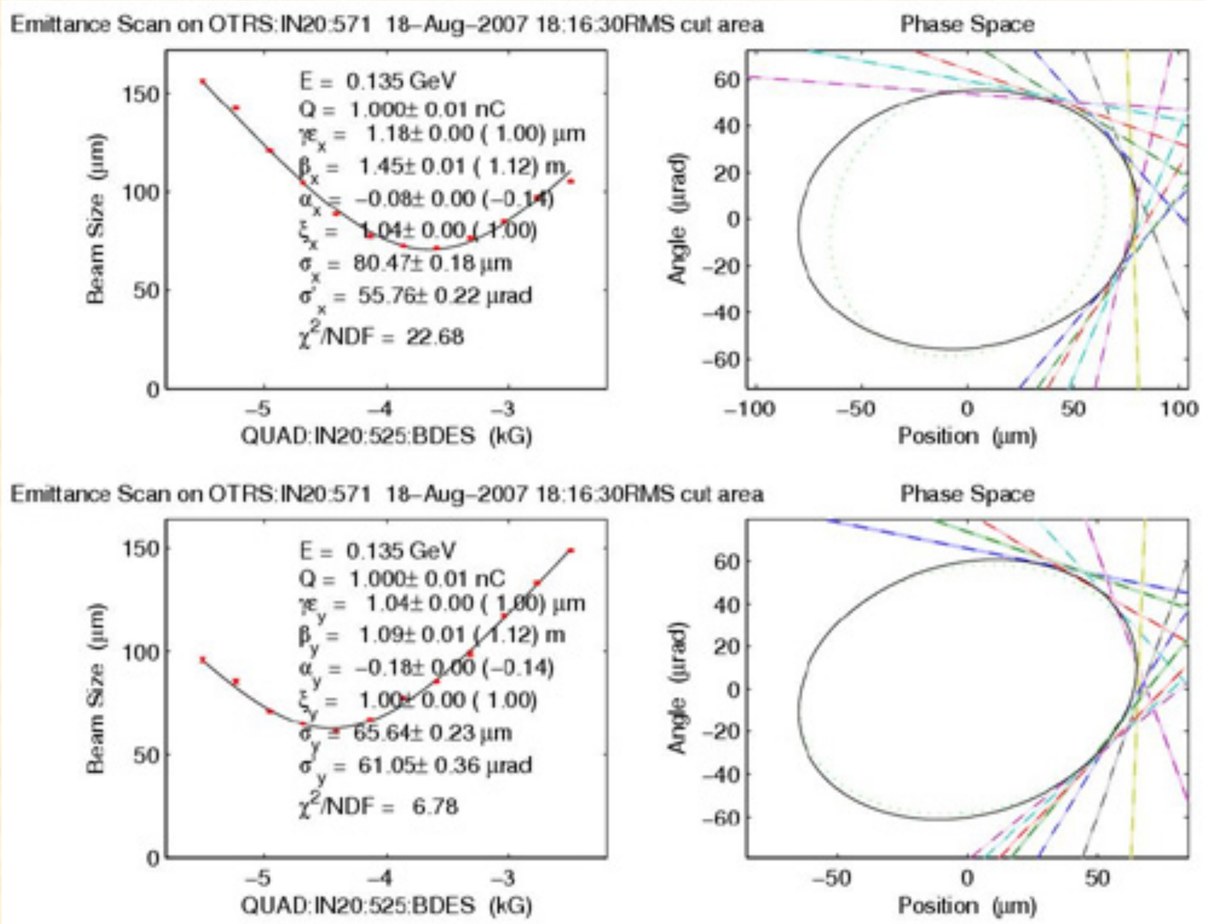
Quad scan

- The emittance can also be measured by changing the strength of a quadrupole and measuring the location at a fixed position.
- This modifies the beta function of the beam and once again this can be fitted to find the best emittance value.

$$\sigma = \sqrt{\in(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$



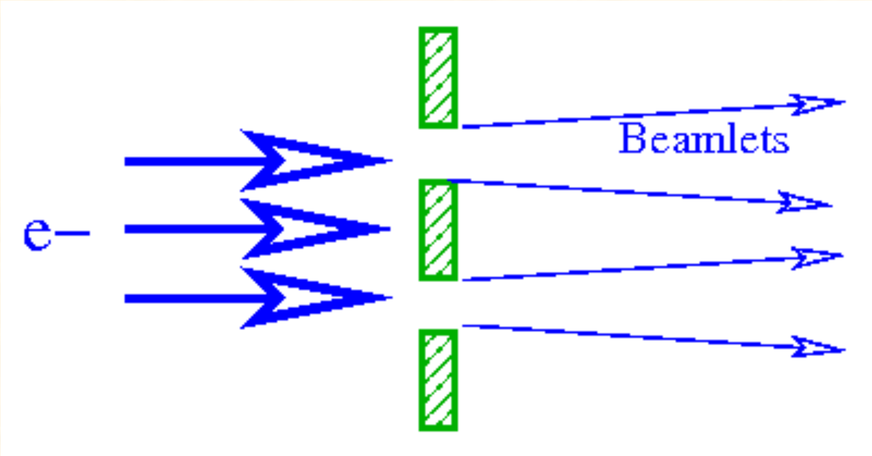
Quad scan emittance measurement

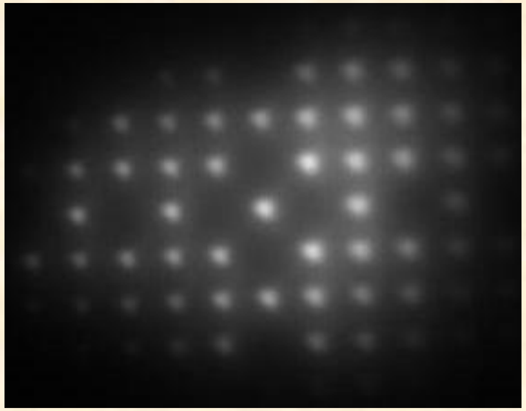


Source: LCLS

Pepper-pot (1)

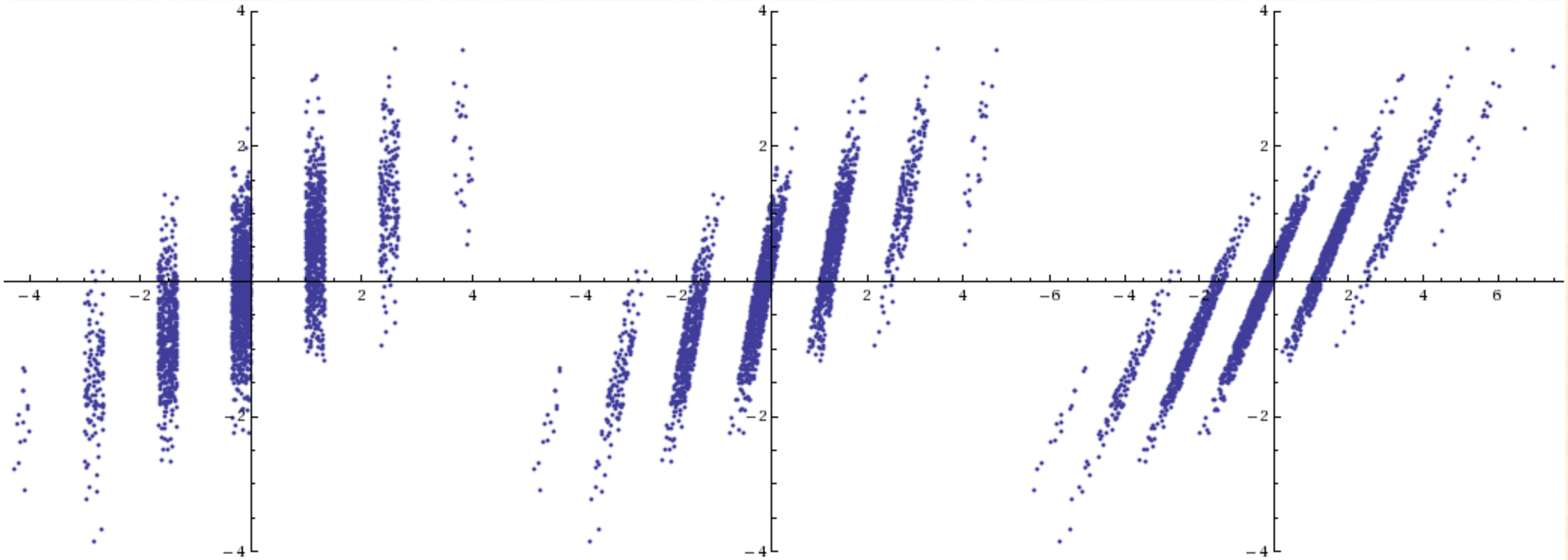
- A grid of dense material inserted in the beam path will split the beam in several beamlets.
- The transverse position at which these beamlets were created is know (it is the position of the grid).
- A measurement of the size of the beamlets downstream gives access to the beam divergence.
- The beam size plus the beam divergence can be combined to give the value of the emittance.





Pepper-pot measurement of the transverse emittance of a van de graaff

Pepper-pot (2)



- In the phase space, the effect of pepper-pot is shown above:
  - The beam is sampled at given x positions
  - After the pepper-pot, the beam drifts
- The measurement must be made close enough so that the beamlets do not overlap.
- The Pepper-pot method is a destructive single-shot technique (the beam is destroyed after the measurement but a single pulse is enough to make the measurement).
- It is used a low energy, for example for the study of particle gun properties.

Diagnostics summary

- The properties of a particle beam can be measured, either:
  - through its interactions with matter (destructive measurement)
  - or by detecting the radiation measurements (almost non perturbative measurement)
- The more accurate the measurement has to be the more precise/expensive the measuring equipment will be.

Quizz

- Particle accelerators are not used only for HEP, they have many other applications.
- In which kind of institutions are there the more particle accelerators in the world?
  (a) HEP lab
  (b) Other physical sciences labs (non HEP)
  (c) Museums
  (d) Hospitals

Answer (d)

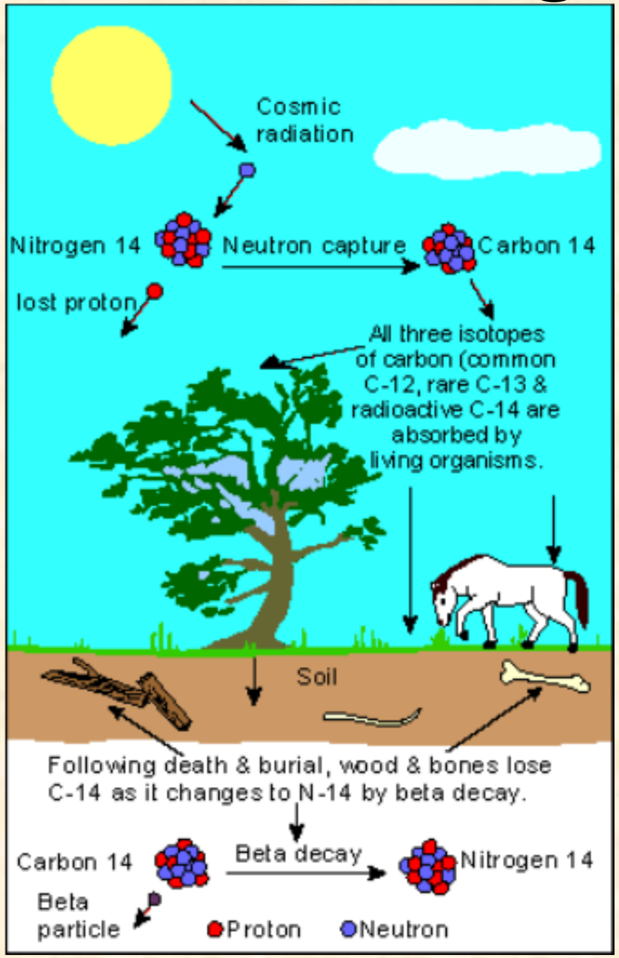
- HEP labs use the biggest particle accelerators in the world but there are only a few of them.
- Non HEP physical science labs use accelerators to produce X-rays. Every large country has 1 or 2 of such accelerators (SOLEIL and ESRF in France).
- Large museums like Le Louvres in Paris use particle accelerators to study cultural artefacts.
- Large hospitals use particle accelerators to treat cancer
  => a single hospital may have several accelerators!

HEP applications of accelerators

- Most of the physics we are studying this week relies on particle accelerators.
- The LHC is the largest of these accelerators.
- Tevatron is (was) the second largest
- Others include B-factories (KEKB, PEP-II), c-factories, heavy ions accelerators (BNL, GANIL, Darmstadt,…),…
- Between 10 and 50 machines in the world…
- To ensure maximum luminosity, a low emittance, a low beta function and a flat beam are necessary.

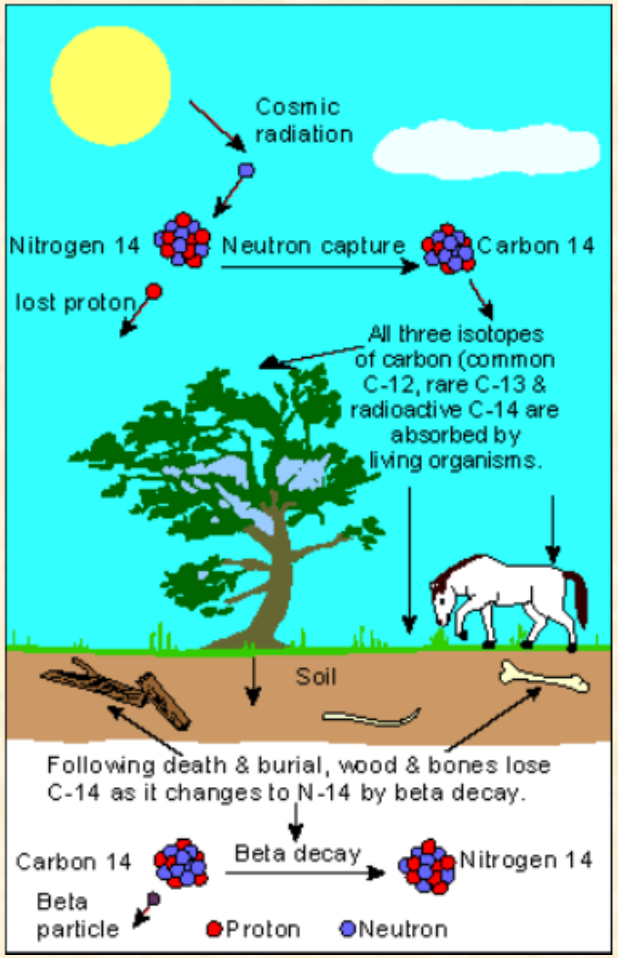
$$L = \frac{f N_1 N_2}{4\pi \epsilon_x \beta_y^* \frac{\xi_x}{\xi_y}}$$

Non HEP applications
Dating old artefacts



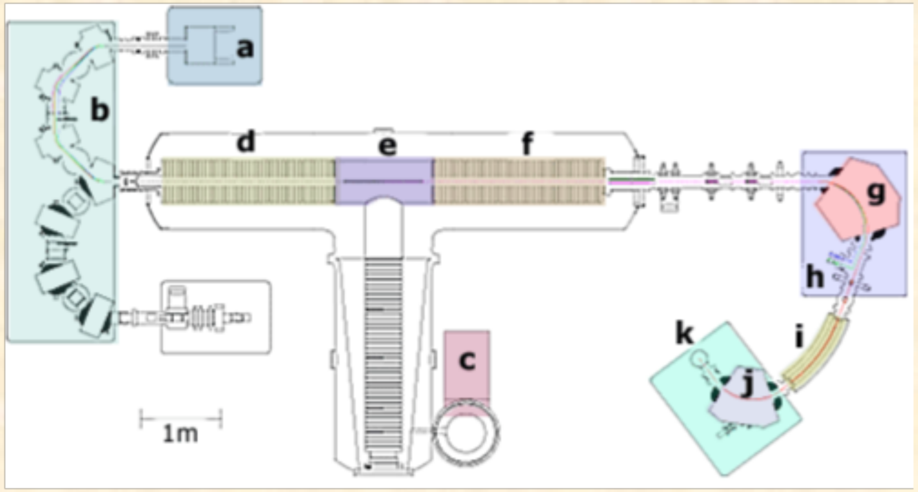
- Radiocarbon dating is allows to measure the age of ancient artefacts.
- The ratio C13 vs C14 can be measured by using an accelerator.
- This technique is called “Accelerator Mass spectroscopy”.

Accelerator Mass Spectroscopy (1)



- In an AMS device the C12, C13 and C14 beams need to be separated to allow an accurate counting.
- An energy of 10-15MV is sufficient.
- Beam stability is very important to ensure good accuracy.
- What type of source would you recommend?
- What type of accelerator?
  RF or electrostatic?
- Does the emittance matter?
- How would you count the charge of the ion beams with a good accuracy?

Accelerator Mass Spectroscopy (2)



- AMS machines use a sputtering ion source producing C- ions.
- A tandem Van de Graff is then used to accelerate the ions and strip then to C^{3+}.
- A DC accelerator offer a better stability than a RF accelerator.
- A Faraday cup is used to measure the beam charge.

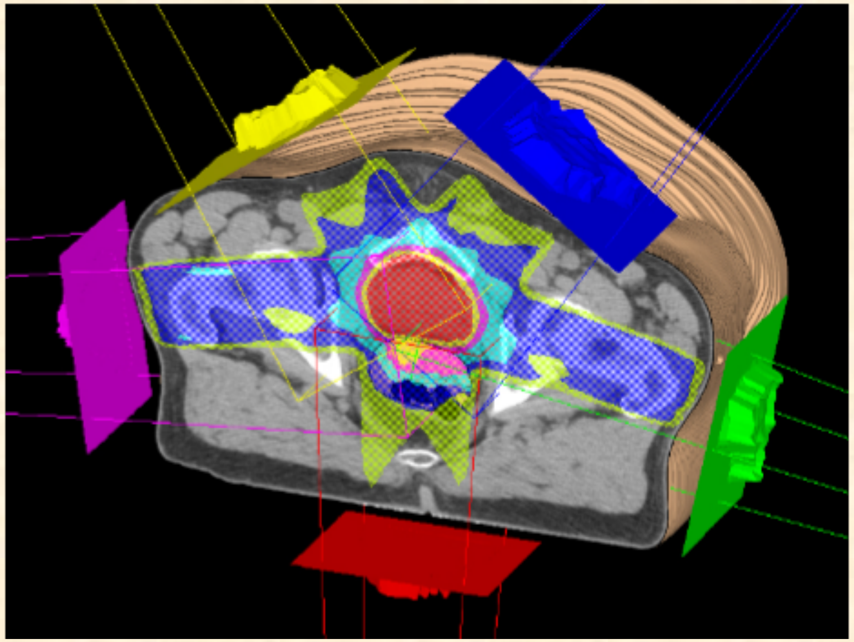
Example of AMS application Vinland map

- AMS was used to date ashes found in Newfoundland in a European-type settlement. These ashes were dated back to the XIth century.
- A viking map featuring Newfoundland was shown to be older than Columbus trip to America.
- AMS has contributed to establish that North America was visited by Vikings well before other European nations.

Dating old artefacts...

- There are many other accelerator based dating techniques which I do not have time to cover.
- Proton, Neutron and light sources can all be used to investigate some properties of old artefacts.
- Left:
  Roman Jug dated by ISIS.

Treating Cancer

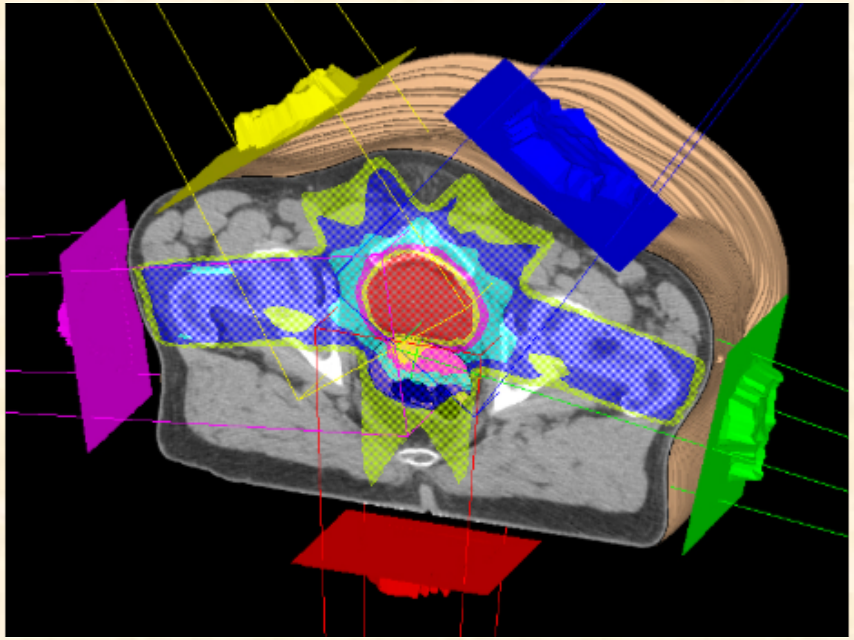


- Some type of cancer tumours are located at places difficult to reach by Surgery.
- X-rays can be used to kill such tumours.
- This is called Radiotherapy.
- Radiotherapy need 10-15 MeV electrons for a few seconds.
- The accelerator needs to be compact so that it fits in an hospital room and fields can be contained.
- What type of cathode do suggest to use? Thermionic or Photocathode?
- What type of accelerators do suggest to use?

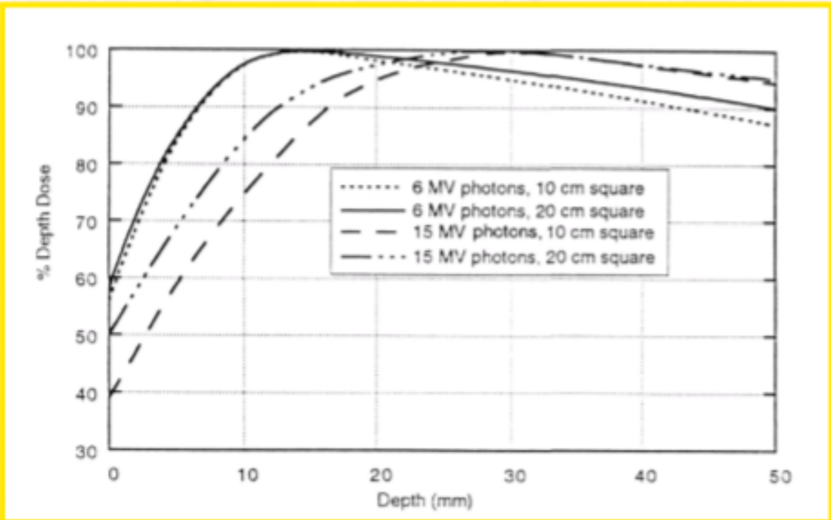
Medical linac

- Radiation therapy uses small 15MeV “linacs”.
- It is safer to produce a low current over several pulses rather than a high peak current over a few pulses, hence a thermionic gun is used (such gun are also more reliable and easier to maintain).
- To reach 15 MeV with a large electrostatic accelerator would require a large installation likely to frighten the patients.
- A short RF accelerator is used to reach the required energy.

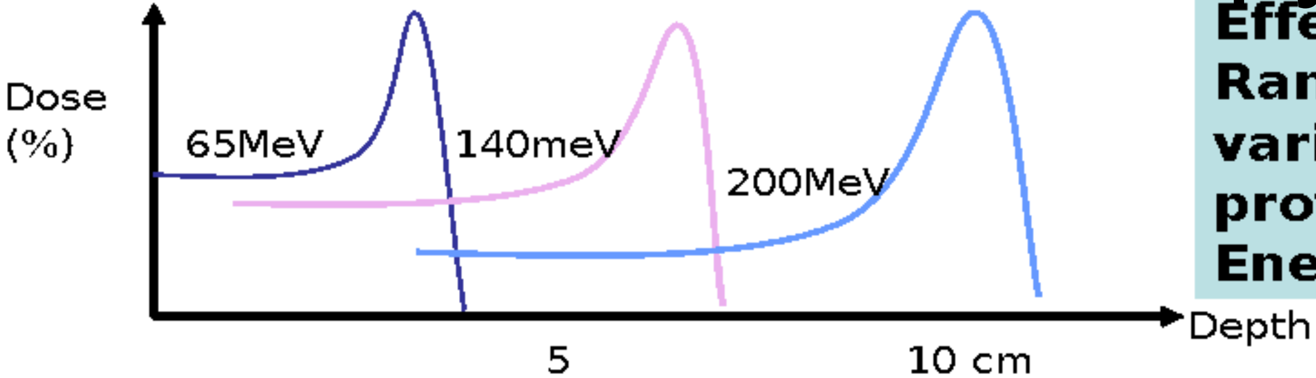
Radiotherapy



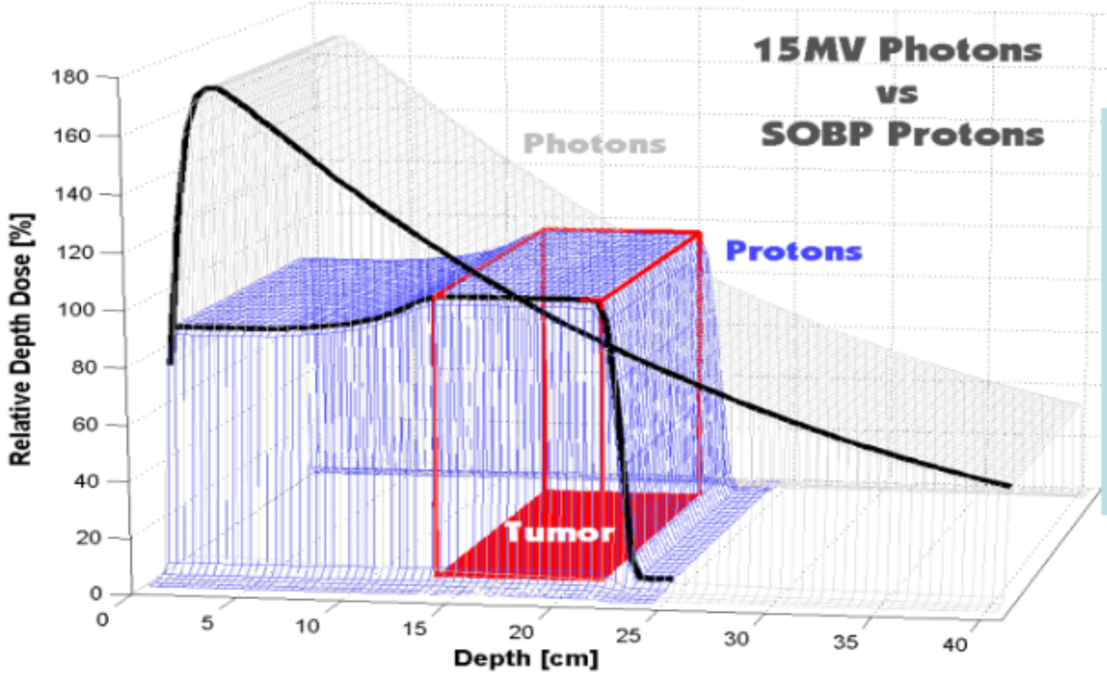
- X-rays are used to kill a tumour.
- To minimize the dose sent on healthy tissues several X-ray beams are sent in turn from different directions.
- However this technique is not ideal due to its impact on healthy tissues.



Proton and ion therapy



Effective Range varies with proton Energy



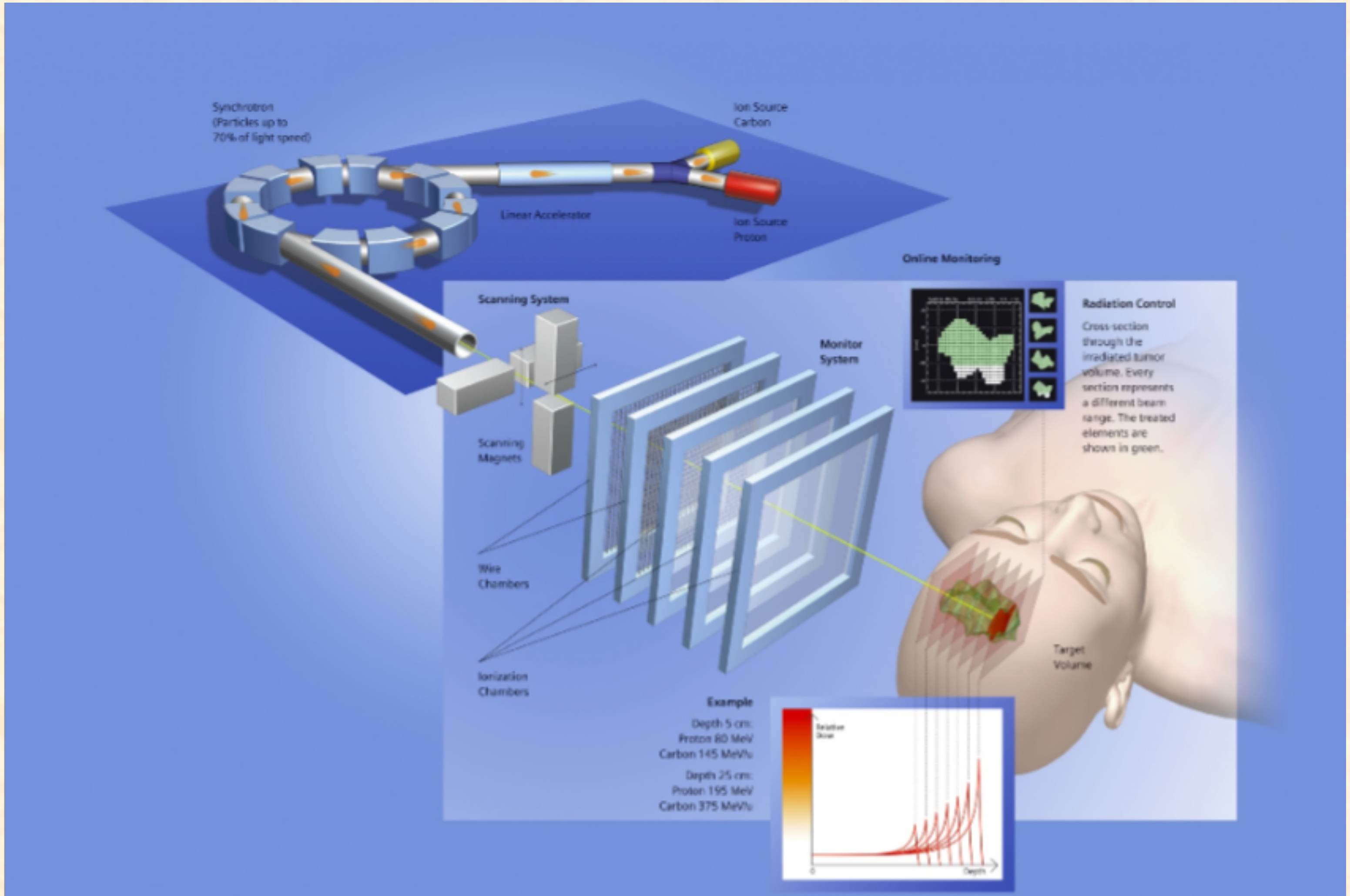
The 'spread out' Bragg Peak– plateau effect

[SOBP]

Source: Bleddyn Jones, JAI graduates lectures

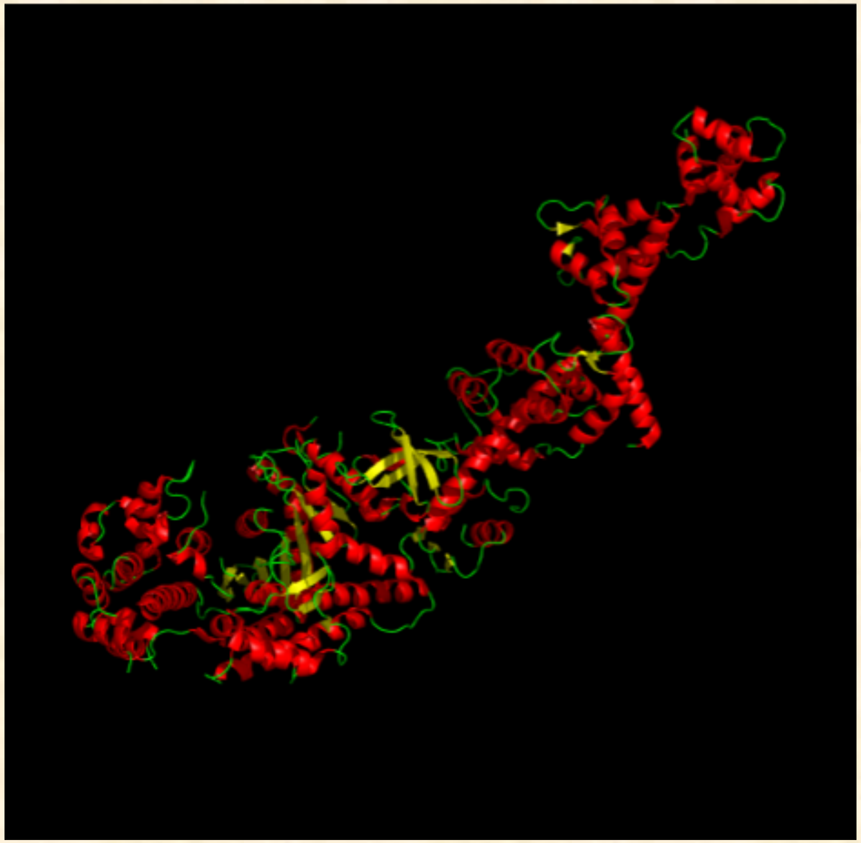
What gun and what machine shall we use for proton and ion therapy?

A possible solution...



Source: Bleddyn Jones, JAI graduates lectures

Pharmaceutical drugs

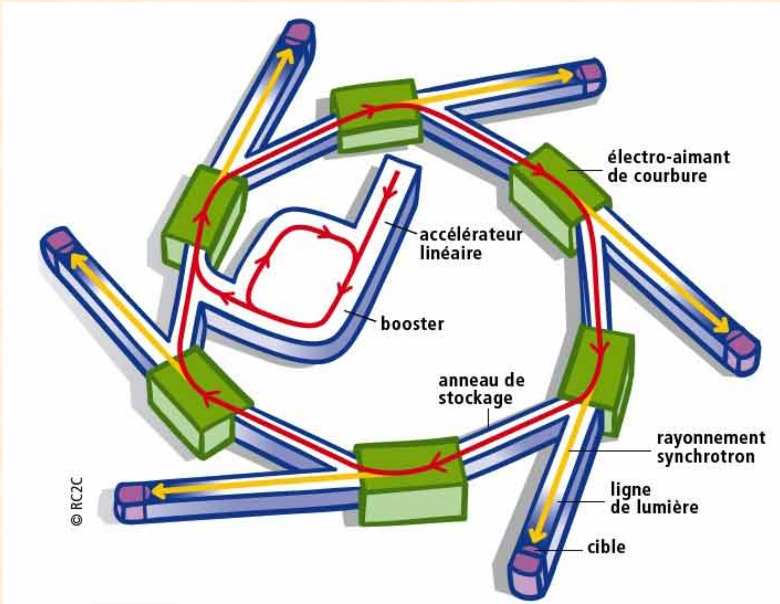


- To be efficient a drug need to target the correct molecule.
- This can only be achieved by studying the diffraction of intense on the molecule.
- What type of machine (gun, accelerator, ...) is best suited to deliver an intense stable beam of X-rays?

A source of intense X-rays

- Synchrotrons are best suited to deliver intense beams of X-rays.
- Although synchrotrons operate at ultra low emittance the gun can be thermionic as radiation damping reduces the transverse emittance.
- A RF accelerator is then used to accelerate the particles up to the ring energy. A booster may be used to reduce the length of the linac.

Source: Diamond



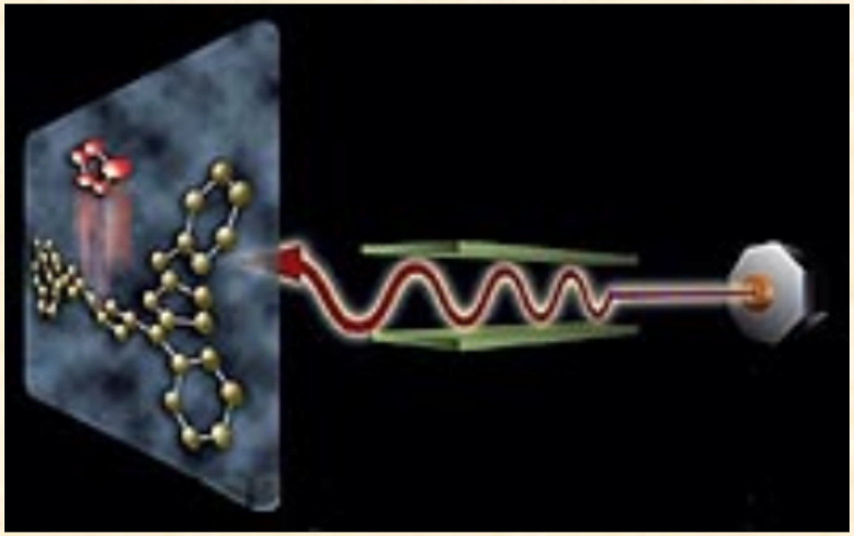
Source: SOLEIL

Applications of synchrotrons

- Light sources have a wide range of applications.
- A light source in England has been used to improve the quality of chocolate!
- Diamond is being used to study old manuscripts too precious to be opened!
- Protein imaging, drugs, material studies,...
- GMR (the phenomena that allows dense magnetic storage in your ipod) has been studied with light sources.

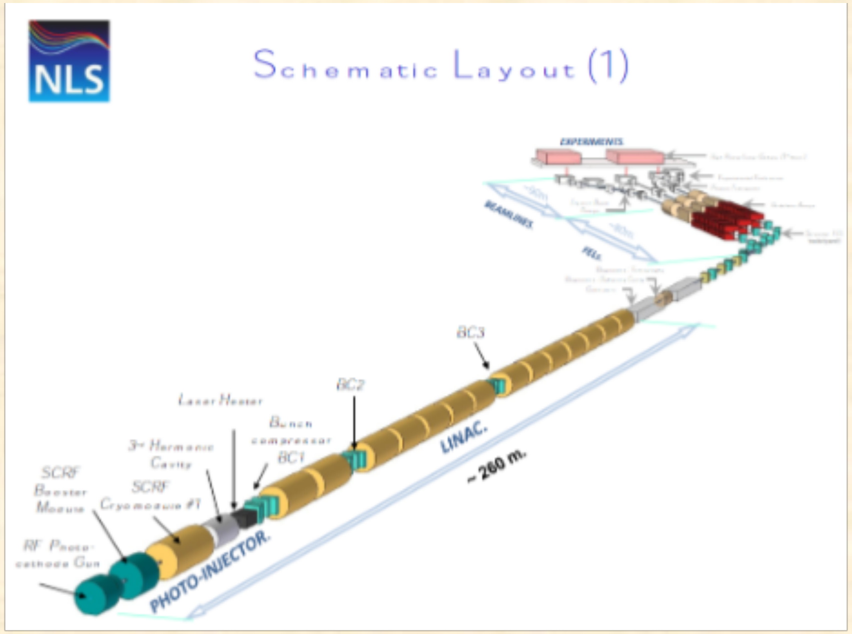
The next generation of light sources

- The drawback of using radiation damping to reach ultra-low emittance is that the beam is stretched longitudinally.
- This means that the X-ray pulse have a long (ps) duration.
- Some applications require fs long high brightness X-ray pulses...
- How can this be achieved?

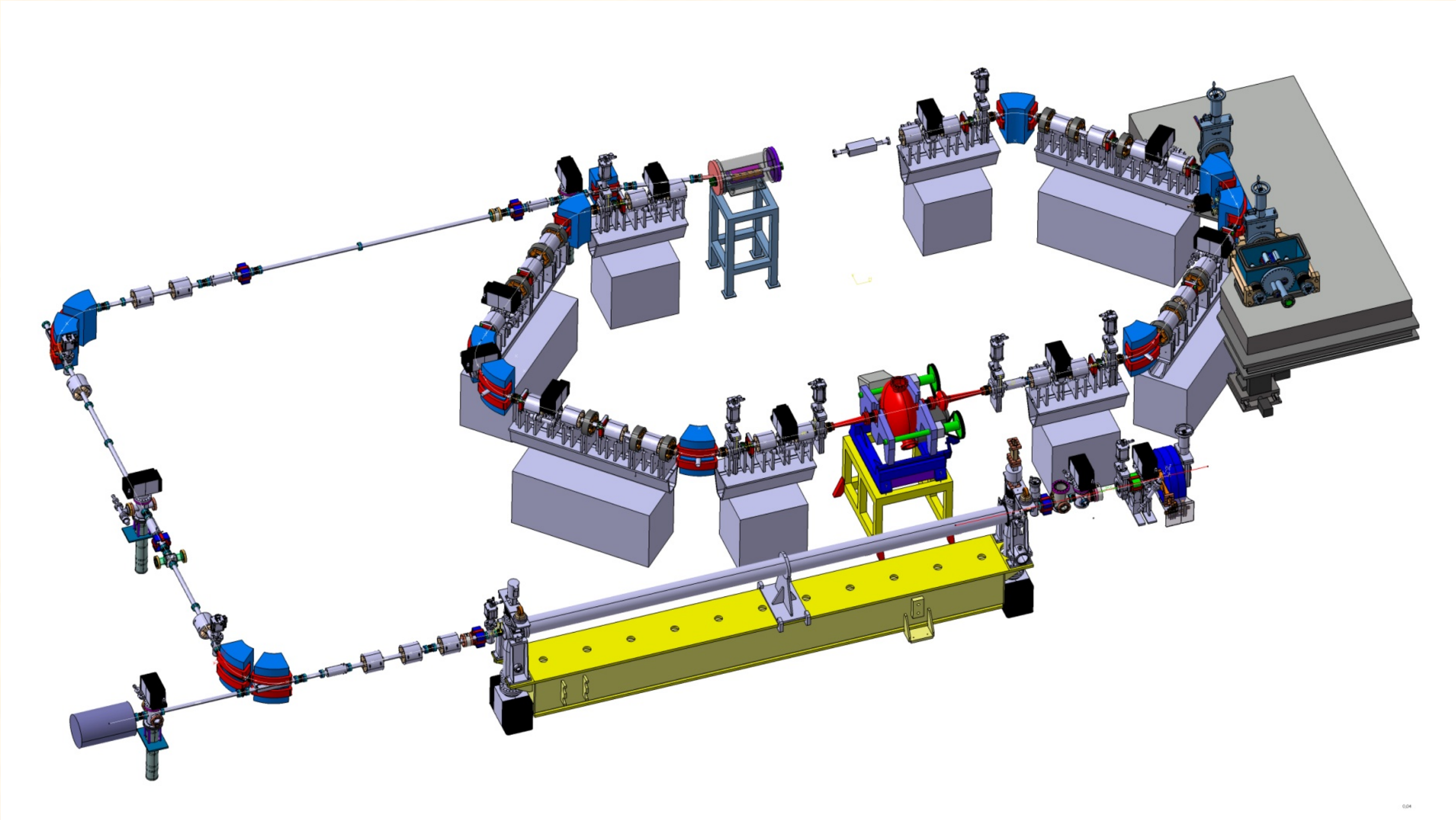


Next generation: Linac based Free electron lasers

- Only linac based accelerators can deliver ultra-short pulses.
- Hence the emittance must be ultra-low from the start.
- This requires a photo-cathode RF gun.
- With an ultra-low emittance it is possible to achieve lasing in the undulators (and thus an even higher light output)



Compact X-ray sources



Neutron crystallography

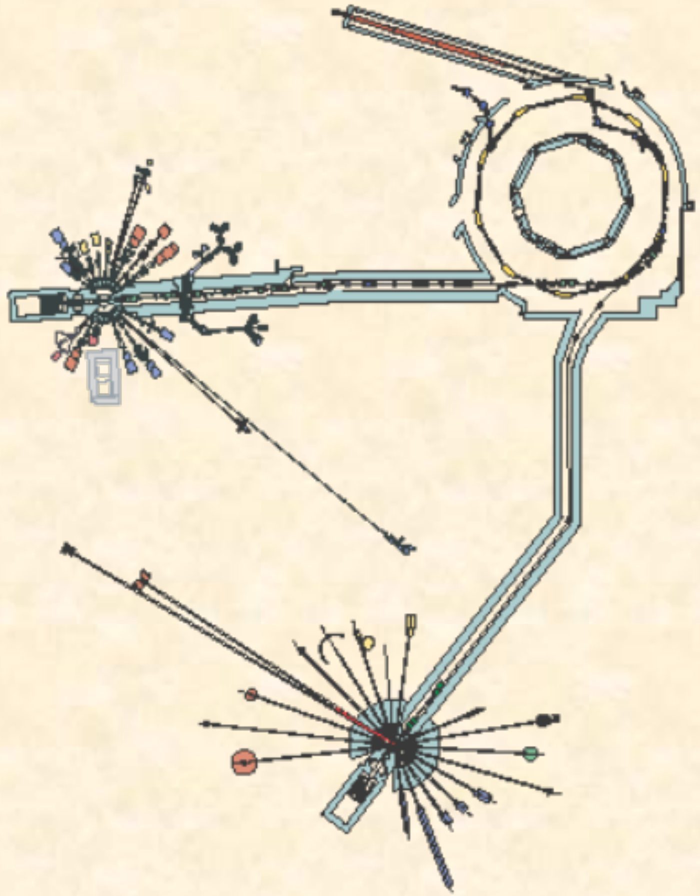
- X-ray crystallography can only be used on matter that is rather transparent to X-rays.
- Other objects such as this Roman vase or the materials used to build an aircraft need a probe that penetrate deeper in the material: Neutrons.
- How can we produce neutrons?

Neutrons sources

- It is not possible to directly accelerate neutrons.
- However neutrons are produced when a target is bombarded with protons.
- The ISIS neutron source requires 800 MeV protons.
- How to build this?

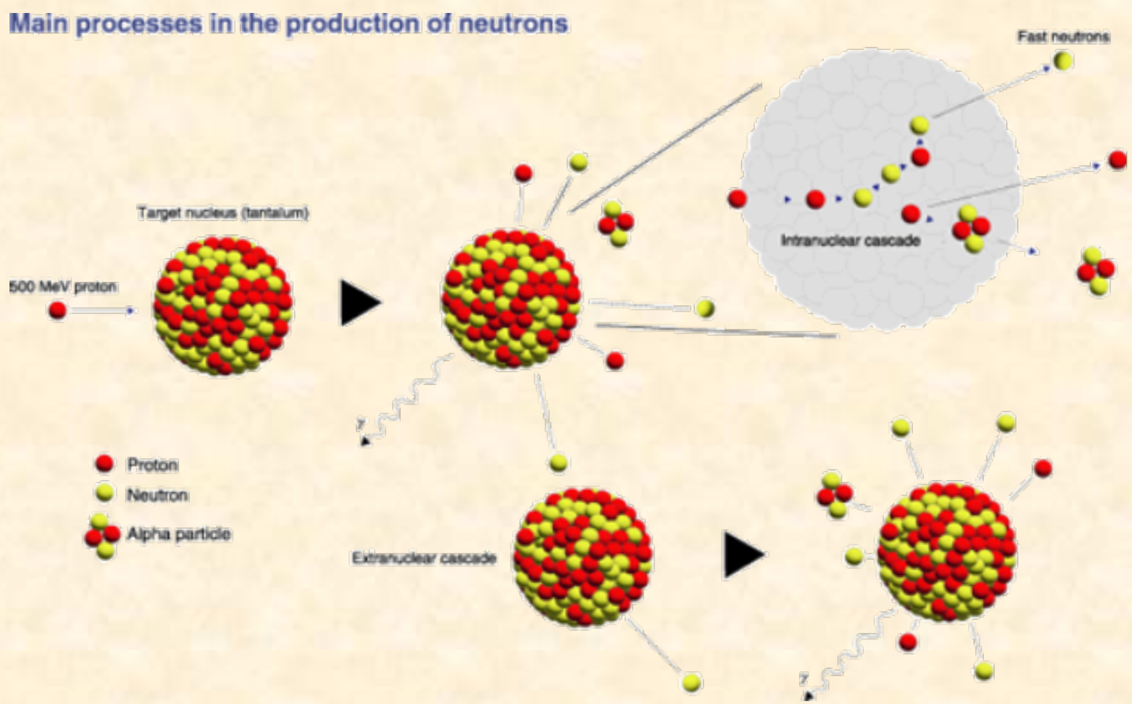
A neutron source: ISIS

- A proton synchrotron can be used to bring the protons to the right energy.
- Emittance is not a challenge at the target location but a low emittance beam helps minimizing the losses in the accelerator (and hence the activation).
- Note that it is easier to accelerate H- than H+.

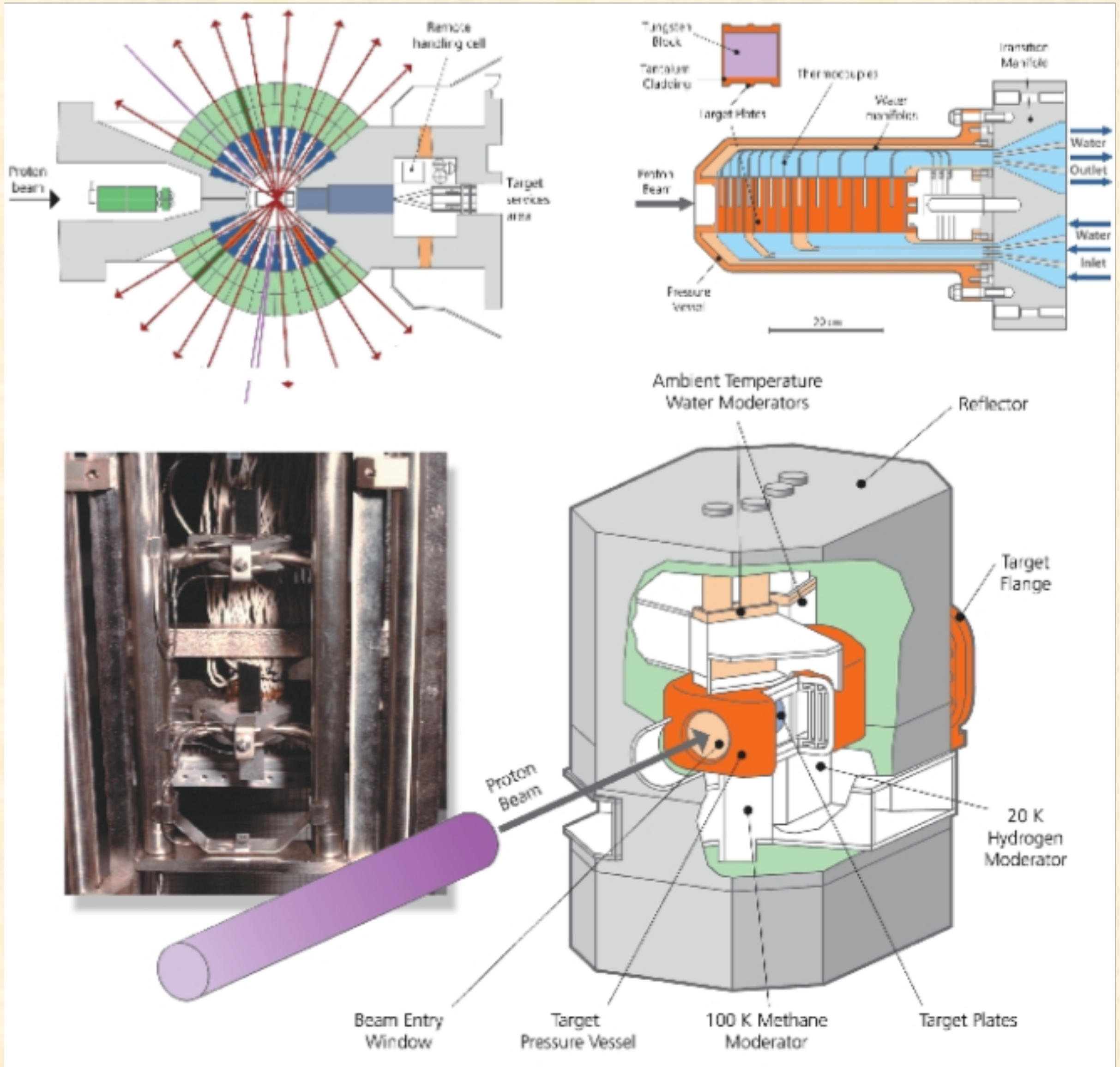


Spallation

- Spallation is a process in which fragments (protons, neutrons,...) are ejected from a target atom hit by a high energy proton.
- Such target is very challenging as most of the proton power is deposited in the target.

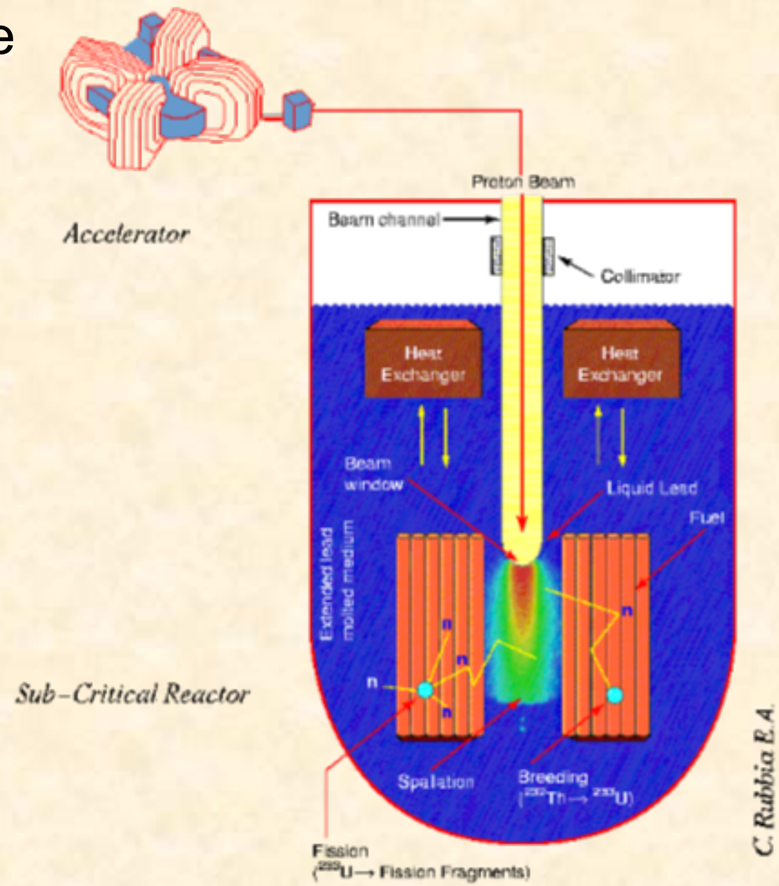


Spallation target

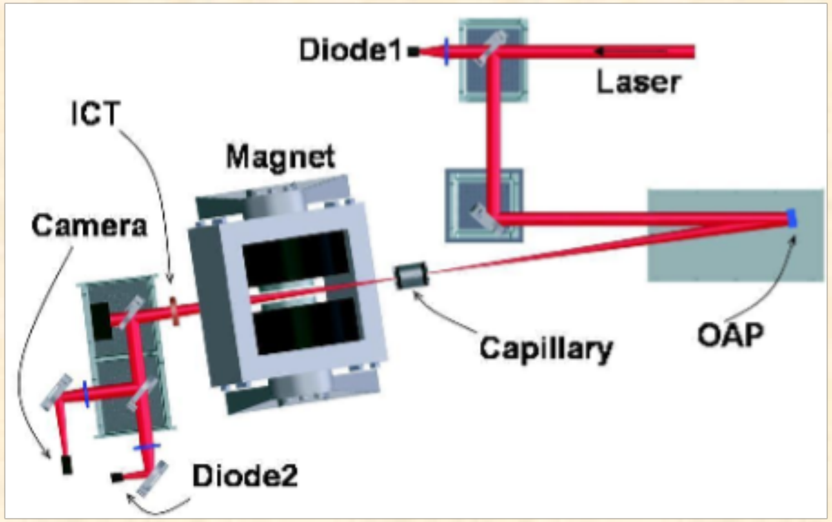


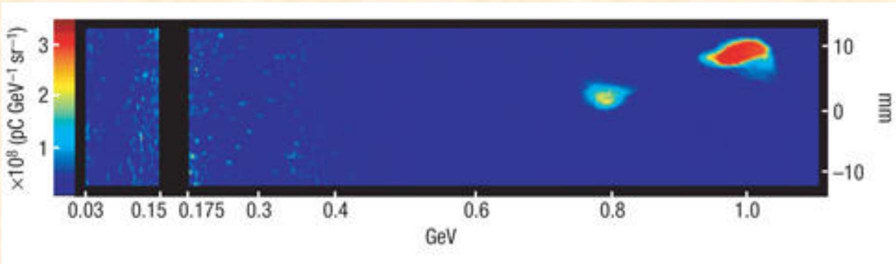
Accelerator Driven sub-critical reactor (ADSR)

- An intense source of protons could be used to produce an intense flux of neutrons.
- After moderation these neutrons would trigger nuclear reactions in some nuclear material.
- Advantage the reactor can operate in sub-critical mode (if the accelerator stops the nuclear reactions die automatically).
- The nuclear fuel could be made of isotopes that can not sustain a chain reaction (such as Thorium).
  => no risk of proliferation.



Ultra compact sources: Laser-driven plasma acceleration (1)

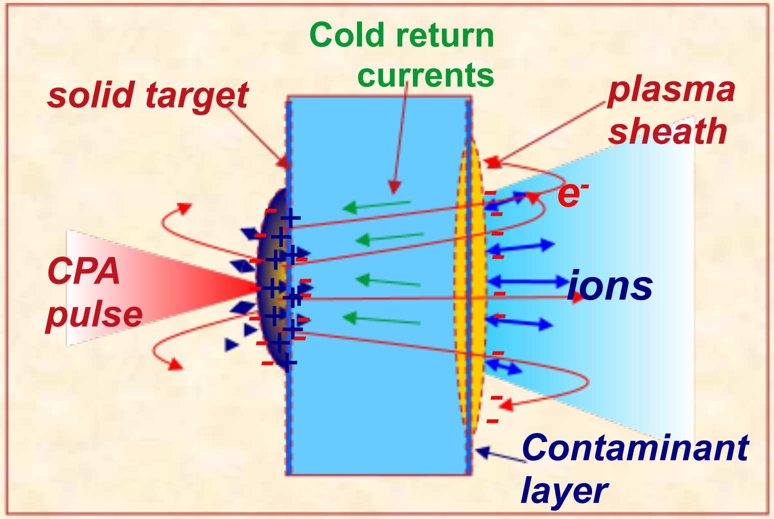




Leemans et al, doi:10.1038/nphys418

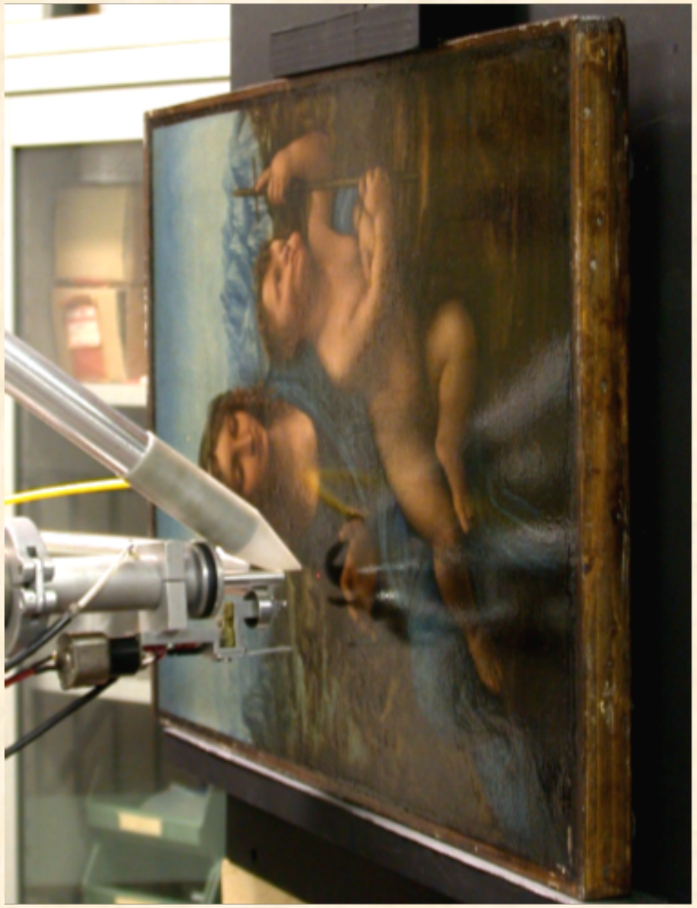
- An intense laser pulse shot in a plasma can accelerate electrons to very high energy: 1GeV over 33mm
- Such electron source could produce high energy low emittance electron beam over very short distances.
- This could be used to drive a compact FEL.

Ultra compact sources: Laser-driven plasma acceleration (2)



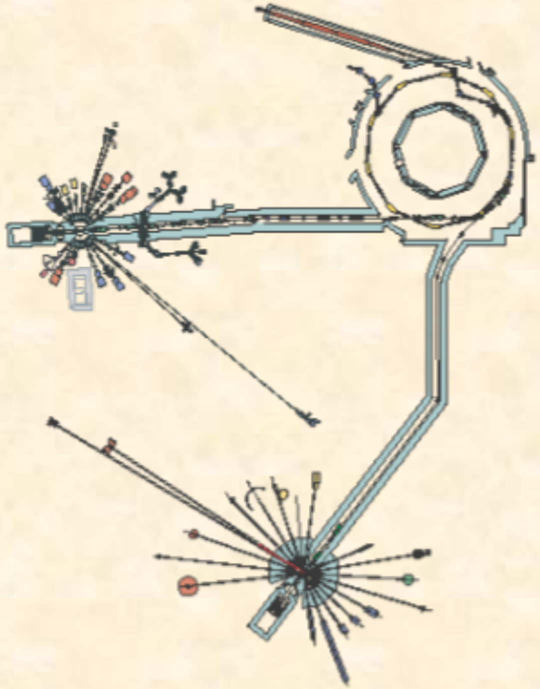
- If a similar laser is shot onto a target, medium energy ions can be produced.
- This could be used for ion therapy.

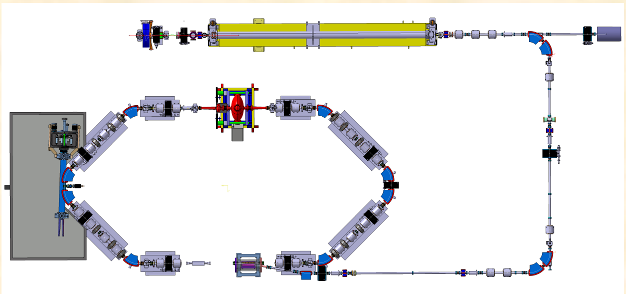
... and much more



- There are many more applications to accelerators.
- Although HEP is driving the progress other communities have now their types of accelerators.
- As new generations are built, new potentials and new possibilities are discovered.

Costs

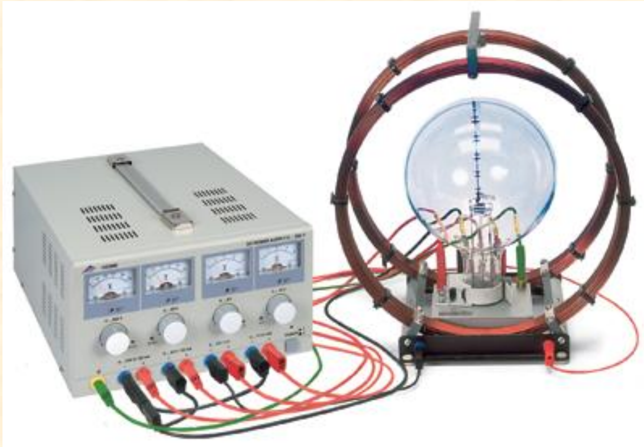


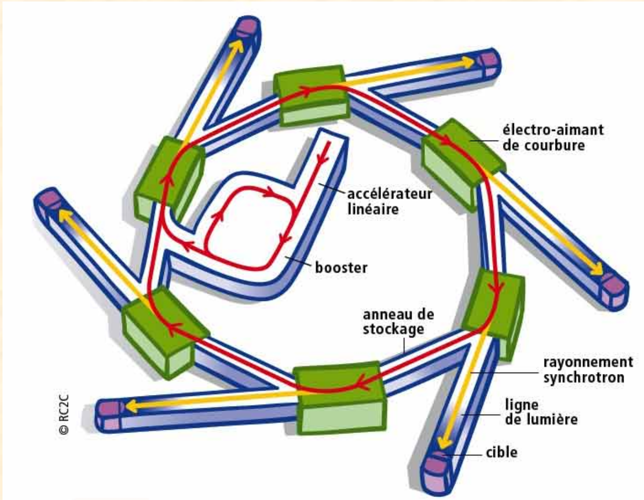


- Small accelerators can be operated by single institutions.
- Large accelerators need to be built as part of international collaborations.

Summary

- Particles accelerators use principles for several fields of physics to accelerate beams of particles.
- The more challenging the requirements of the users are, the more complex phenomena will appear:
  You can build a very crude accelerator in a University lab in a few days…
  but it took several years to build the LHC!
- Accelerators have a wide range of applications across many scientific fields reaching all the way to archaeology…





- ***If you have any questions on my lectures but are too shy to ask, feel free to ask me at the coffee break or during the afternoon tutorials.***

Recommended reading

- « Accelerators for pedestrians » CERN-AB-Note-2007-014
  Available for free online at http://cdsweb.cern.ch/record/1017689
- An introduction to particle accelerators, Edmund Wilson
- The physics of Particle accelerators, Klaus Wille

If you want to learn much more:

- Handbook of Accelerator Physics and Engineering,
  by Alex Chao and Maury Tigner ISBN-10: 9810235003
- Charged Particle Beams, by Stanley Humphries
  http://www.fieldp.com/cpb/cpb.html
- Principles of Charged Particle Acceleration by Stanley Humphries,
  http://www.fieldp.com/cpa/cpa.html