How to "see" the protons in the LHC? (or the electrons in the ILC) + What to do with a particle accelerator? (apart from particle physics)

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Lectures overview

I. How to produce protons for the LHC?

II. How to get protons in the LHC?

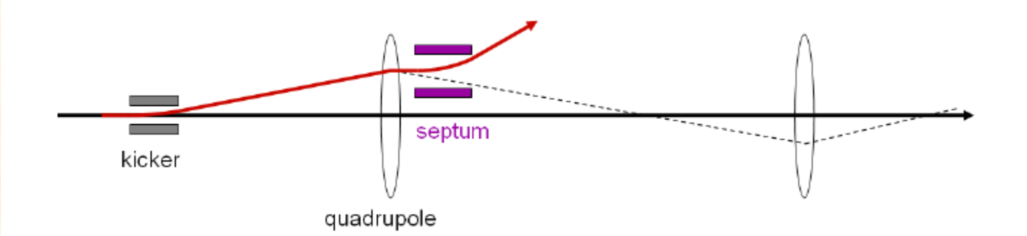
III. (a) Beam-beam effects

(b) How to "see" protons in the LHC?

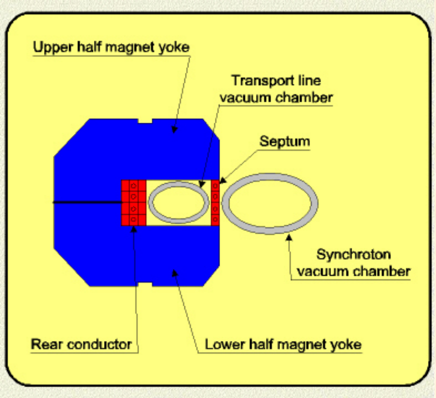
- Beam-matter interaction
- Radiation emitted by the beam

(c) What can you do with a particle accelerator (apart from hunting the Higgs)?

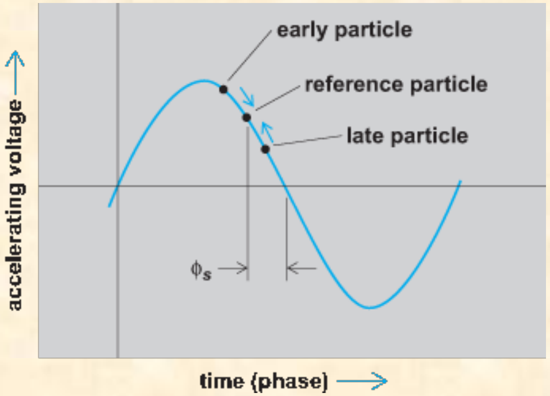
Answers to the questions asked



- Septum:
A septum is a kind of « half magnet ».
To inject/extract a beam you need both a septum and a kicker.

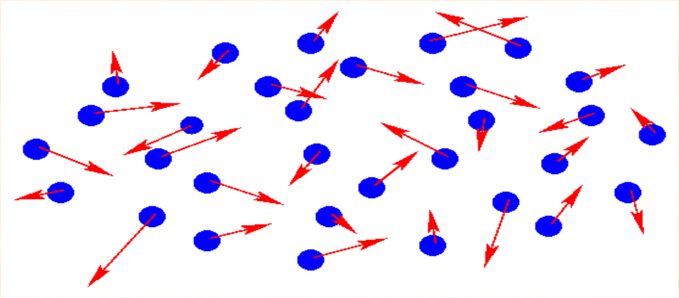


- Longitudinal and transverse focussing:
- The transverse size is determined by the quadrupole magnets. The longitudinal size is mostly determined by the RF frequency (more later today).

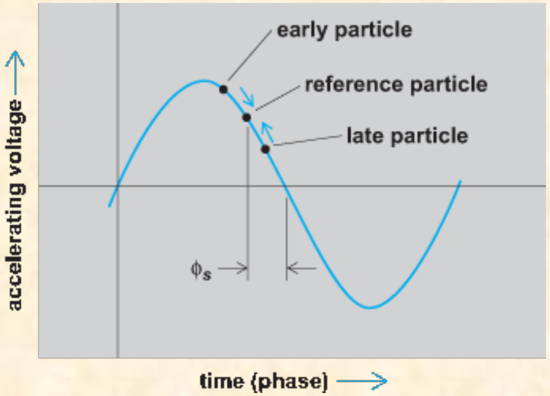


- Feel free to ask me at the breaks or to email me: delerue@lal.in2p3.fr

Where are we?



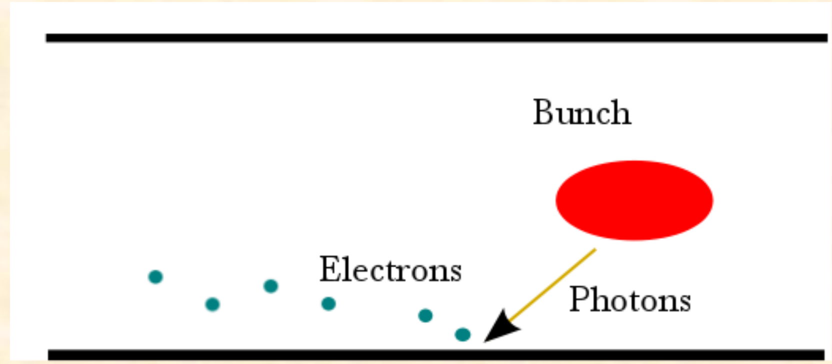
- We have seen how to produce particles.
- We also learnt how to accelerate them and how to control them.
- We are aware that some effects such as wakefield, electron cloud, scattering can limit the beam lifetime or performances…
- Today we will learn how to "look" at the beam in the accelerators and what to do with a particle accelerator.

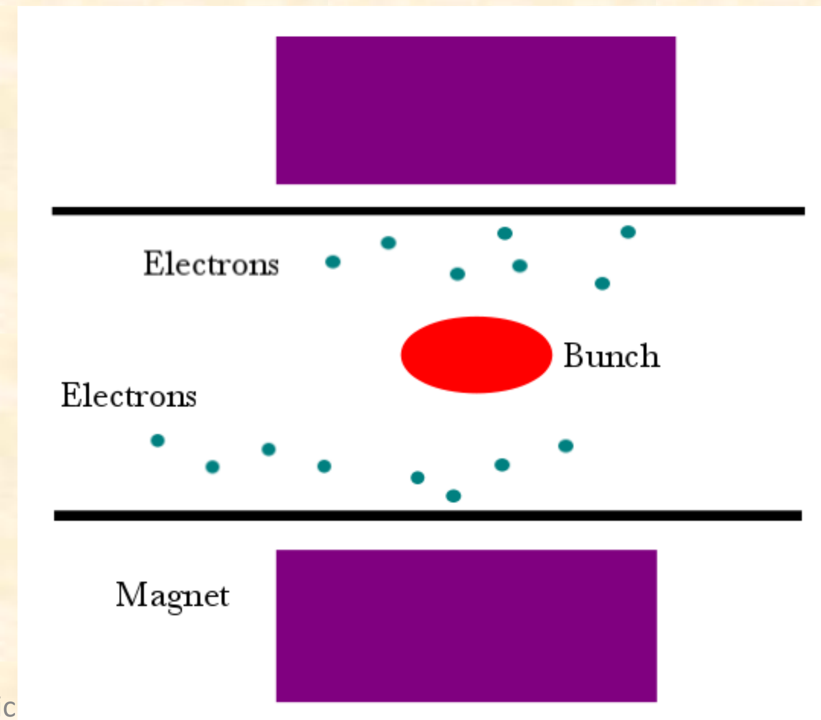


BEAM DYNAMICS (CONTINUED)

Electron cloud effect

- Radiation from a bunch can extract electrons (and ions) from the beam pipe and from residual gas in the vacuum.
- These electrons fall back and get re-absorbed with a certain time constant.
- However if the bunch frequency is too high these electrons (and ions) will accumulate in the beam pipe and shield the beam from the magnetic elements.
- Special coatings, beam pipe geometries and bunch repetition patterns can mitigate this problem to some extent.
- This is one of the main limitations to increasing the

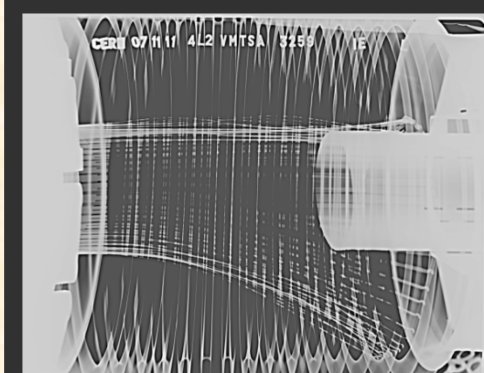




some issues in LHC 2011-12 operation

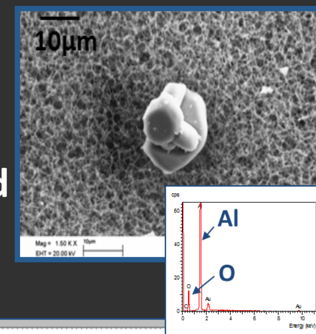
Beam induced heating

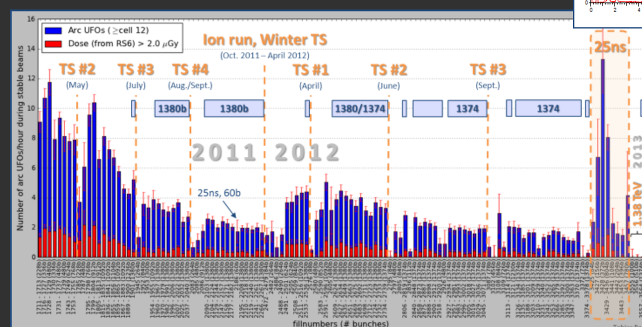
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

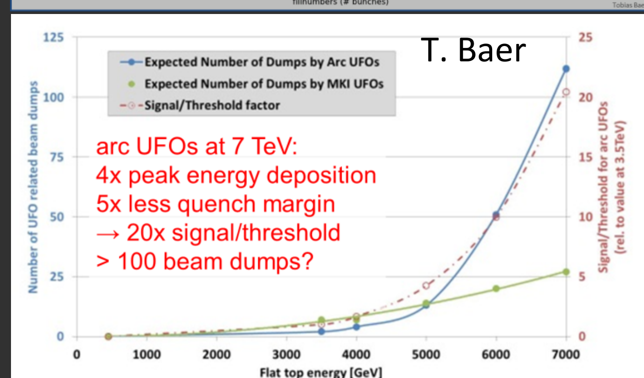


UFOs

- 20 dumps in 2012
- time scale 50-200 µs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

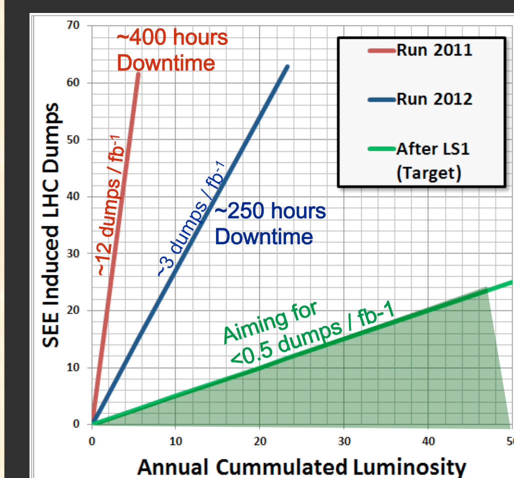






Radiation to electronics

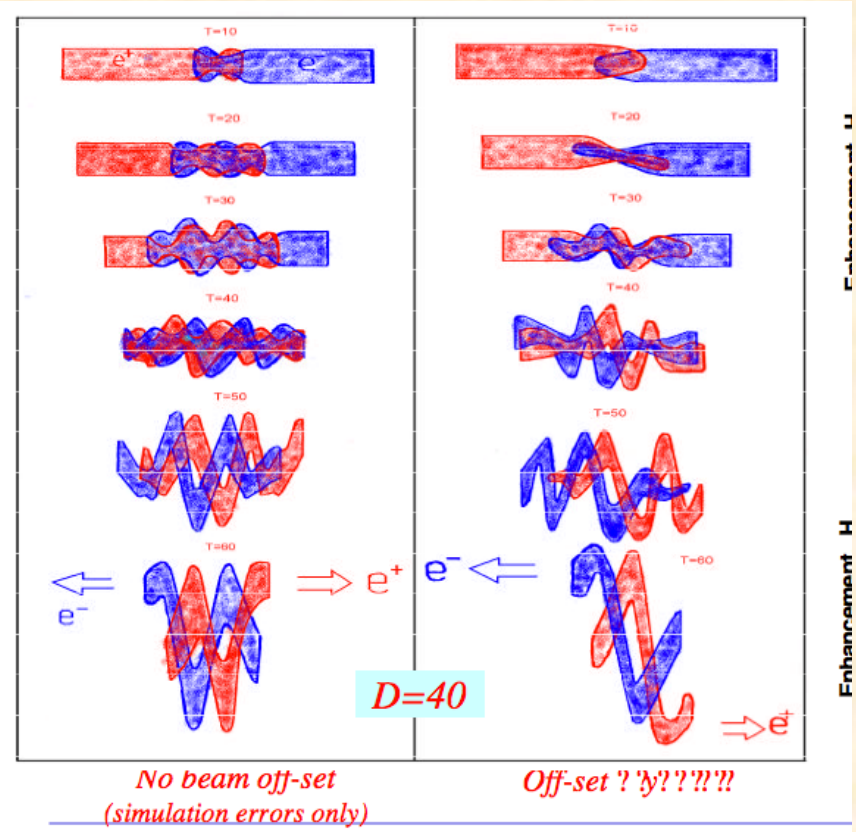
- concerted program of mitigation measures (shielding, relocation…)
- premature dump rate down from $12/fb^{-1}$ in 2011 to $3/fb^{-1}$ in 2012



Courtesy of F. Zimmerman

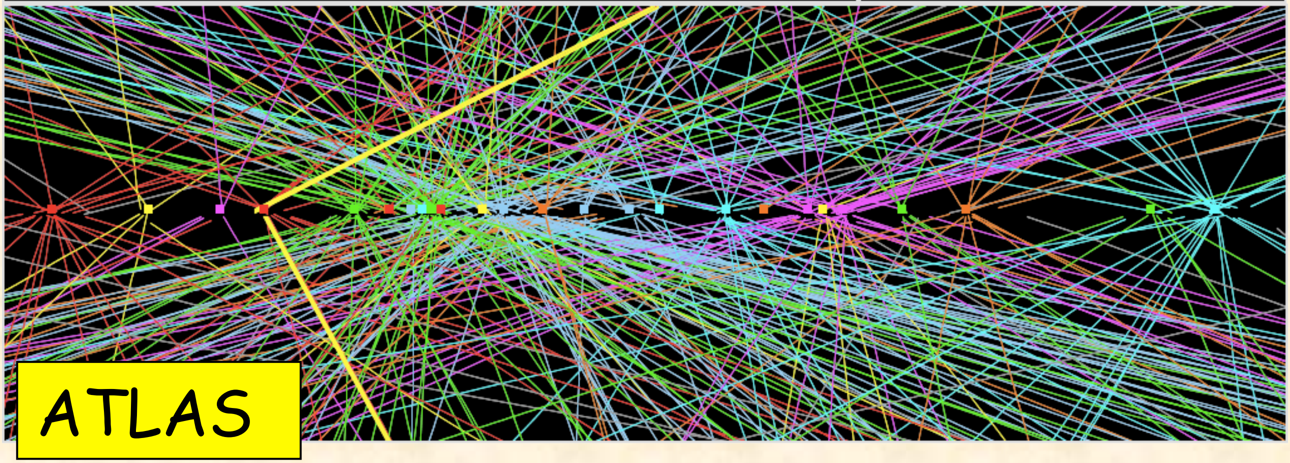
BEAM-BEAM EFFECTS

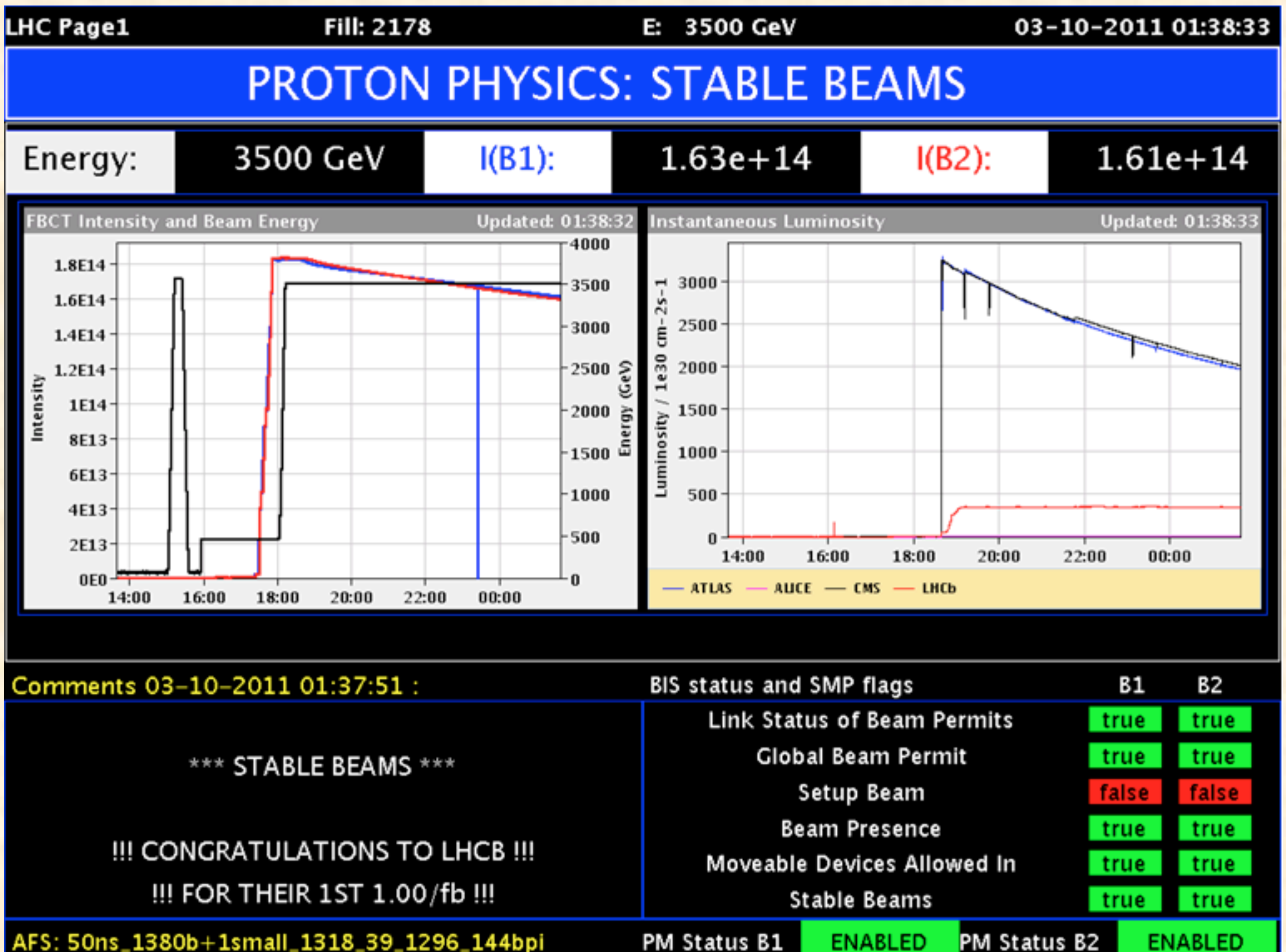
Beam beam effect



Courtesy of N. Solyak

- In a collider the two beams feel each other's electric field well before and well after colliding.
- Given that the particles come very close to each other, this lead to very intense forces.
- If the self focussing is too strong this can lead to a large emittance growth.
- If the two beam are not perfectly aligned this will also lead to large transverse deflection.
- This is a strong limitation on the size of the beams and therefore the luminosity, especially in a ring.



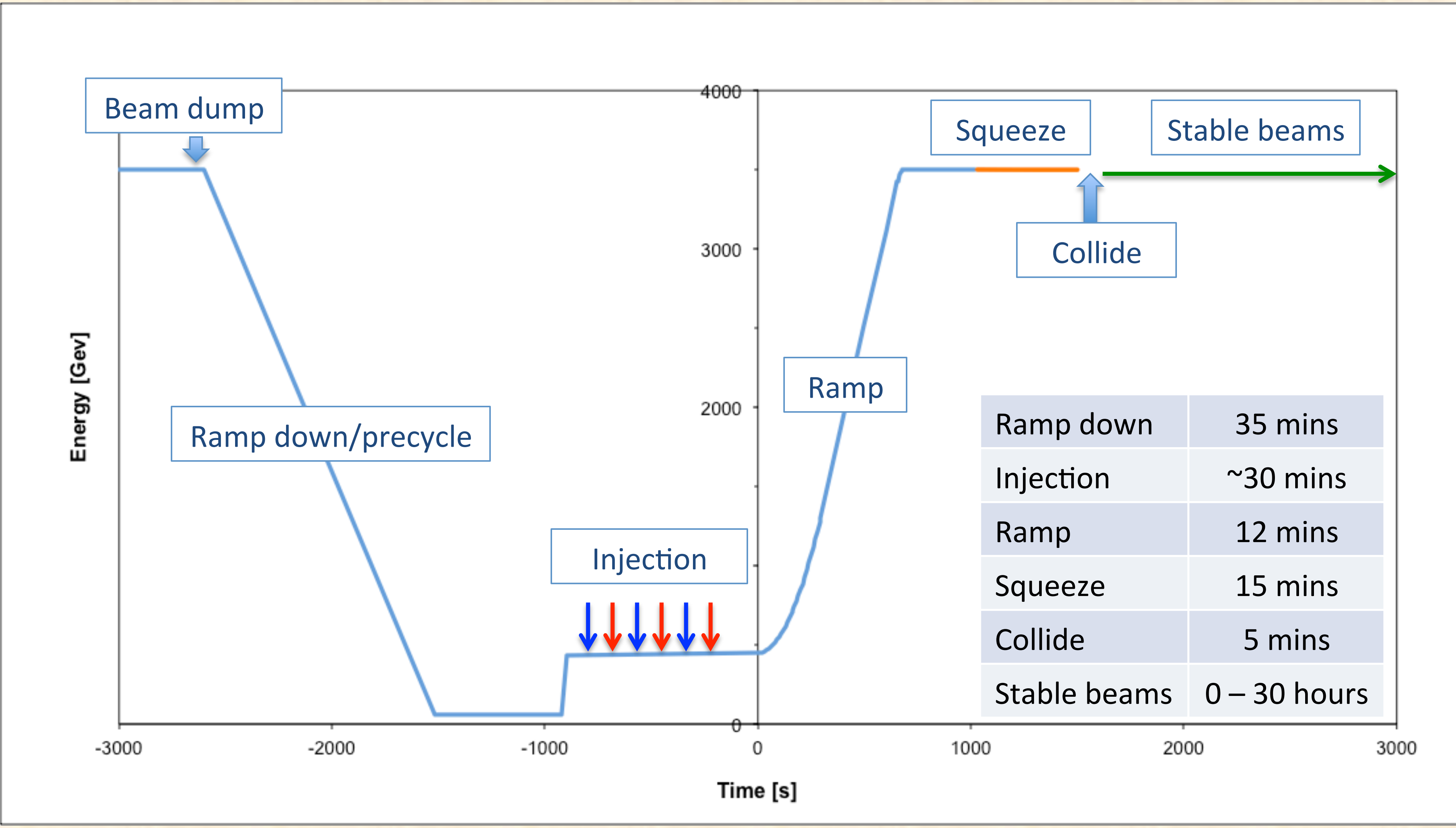


Luminosity issues

More luminosity,
=> more collisions per turn
=> pile-up.

Not everybody want more instantaneous luminosity. Eg: LHCb

Operational cycle at LHC



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

Turn around 2 to 3 hours on a good day

M. Lamont, IPAC'13

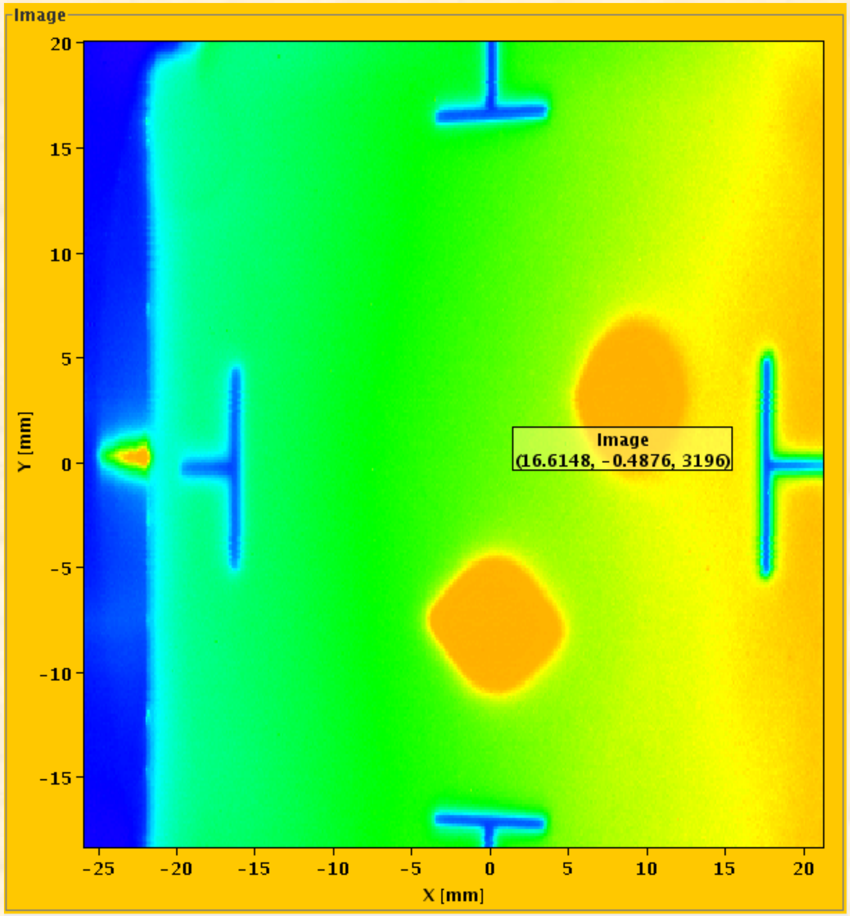
DIAGNOSTICS

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

?

What do you want to know about the beam?

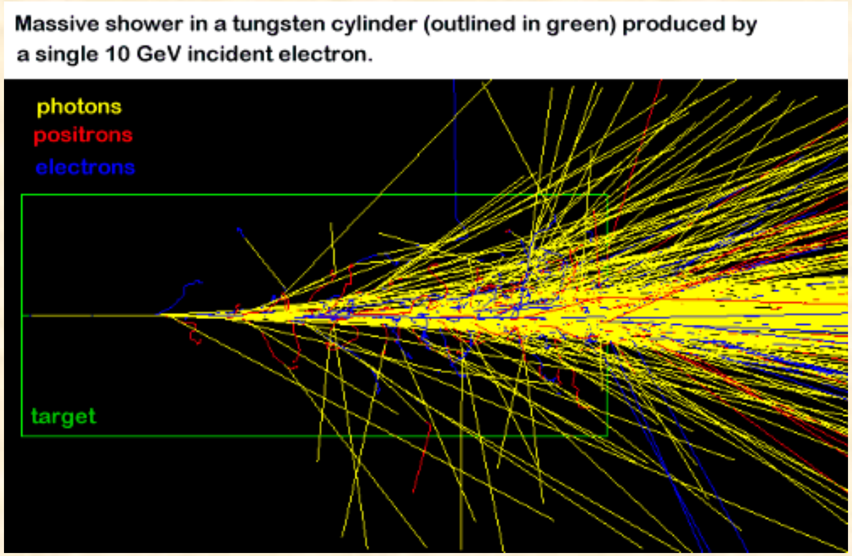
- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses

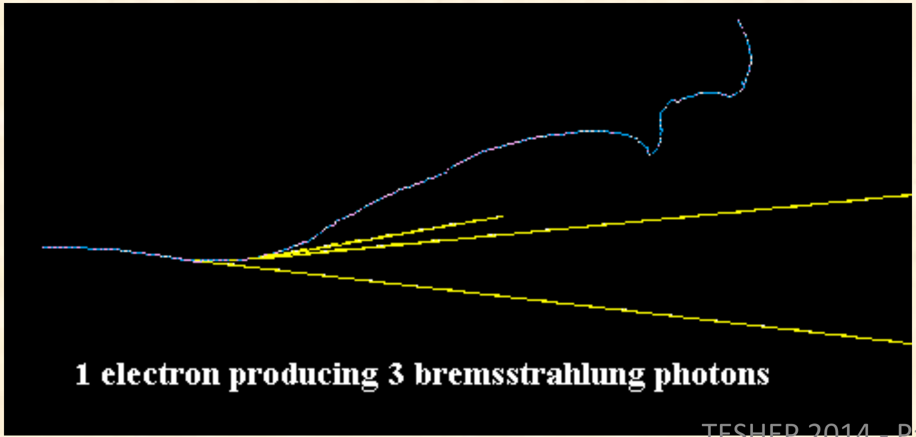


Beam properties measurements

- Almost all accelerators accelerate ***charged particles***
- There are mainly 2 types of beam diagnostics:
  - Diagnostics that use the interaction of the beam with matter (see Alexandre's lecture).
  - Diagnostics that use radiations emitted by the beam to measure its properties (see your favorite EM course).
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

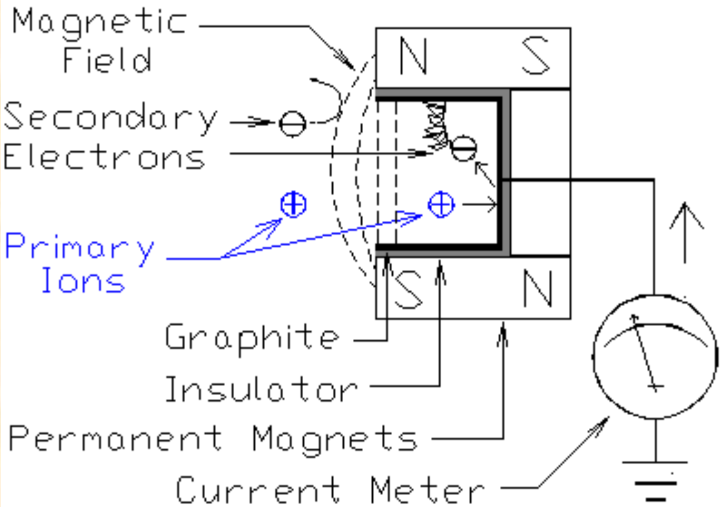
Particles interactions with matter





- 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.

Faraday cup



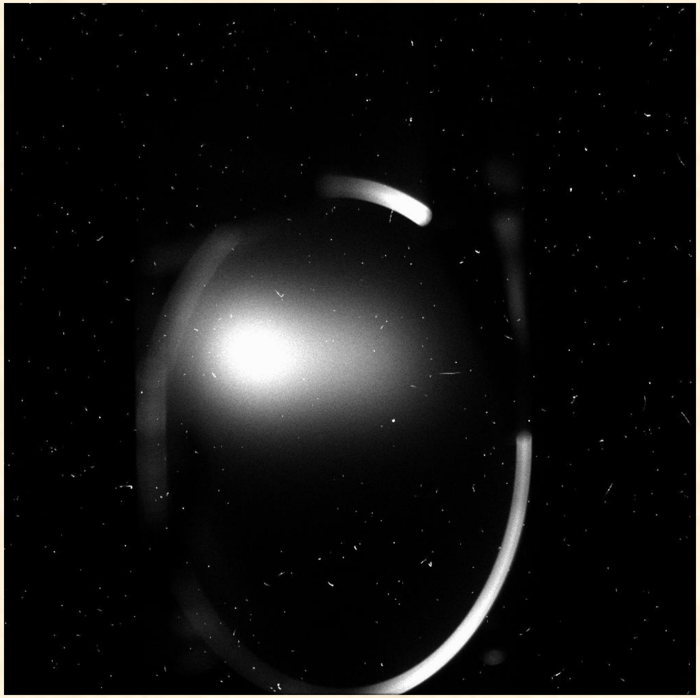
- Let's send the beam on a piece of copper.
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large:
  More than 1m at SOLEIL for a
  3 GeV electron beam.

Image source: Pelletron.com

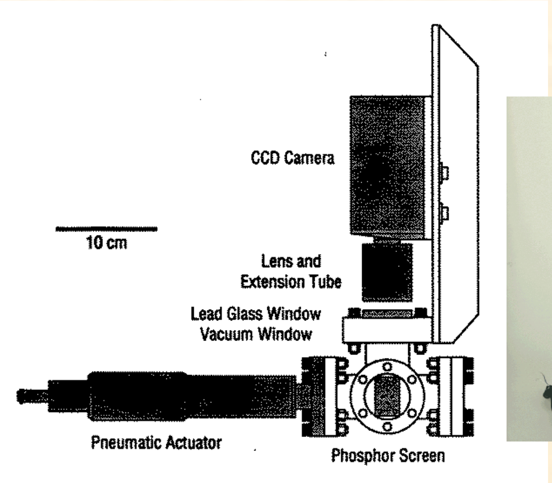
Screen (1)

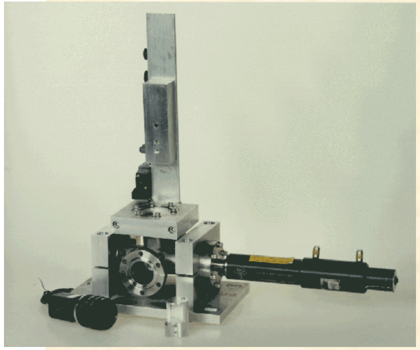
- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

Screen (2)

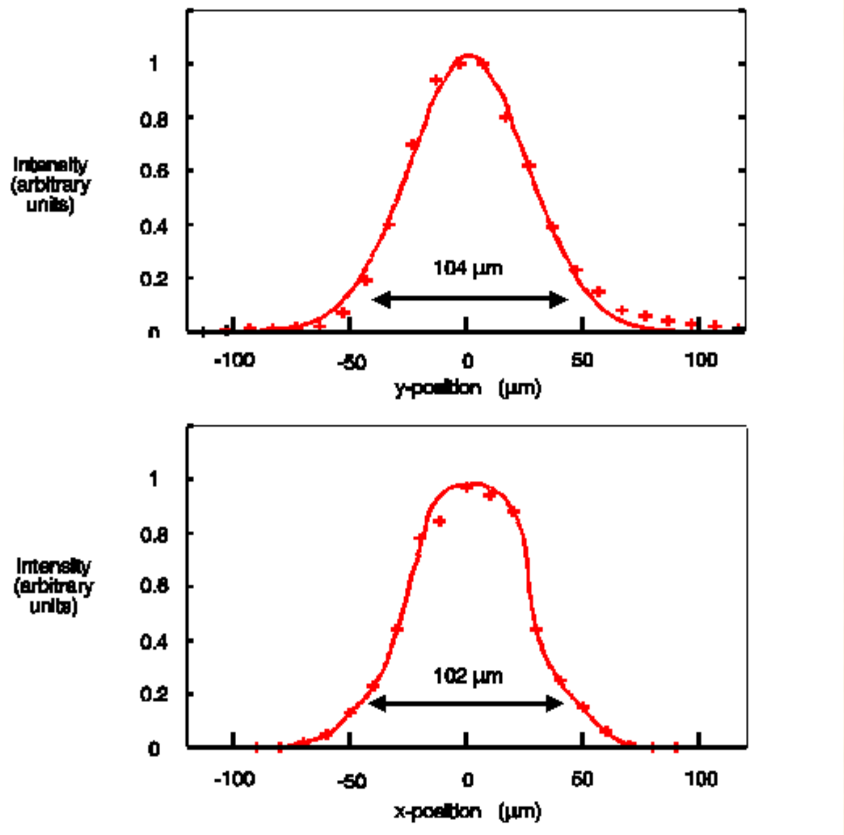


- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at 45 degrees.
- On this screen you can see the beam shape.



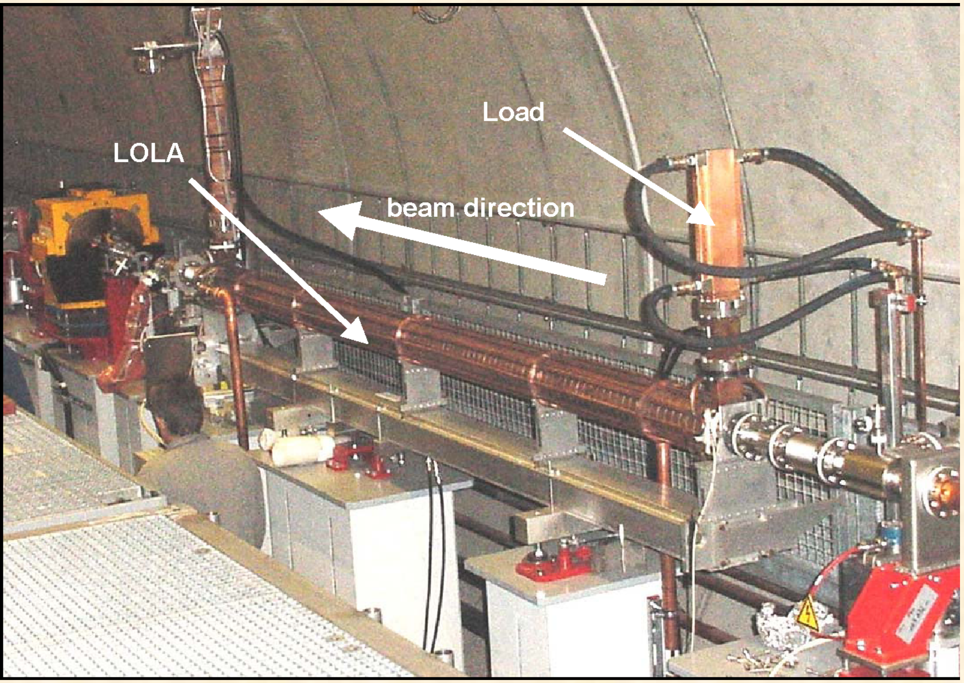


Wire-scanner

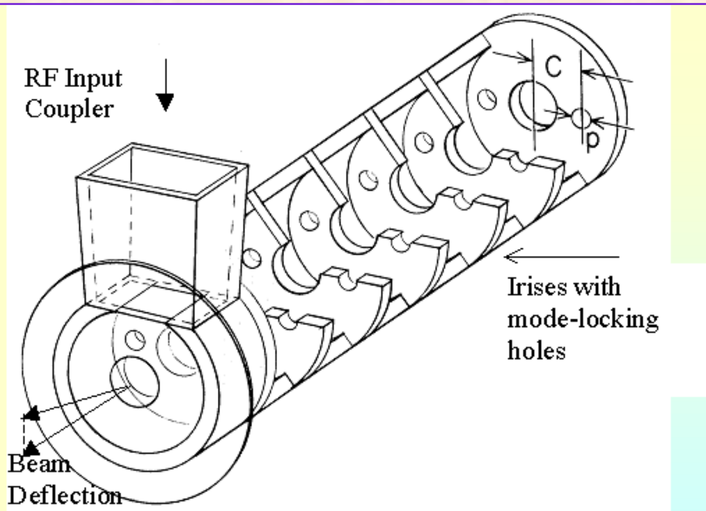


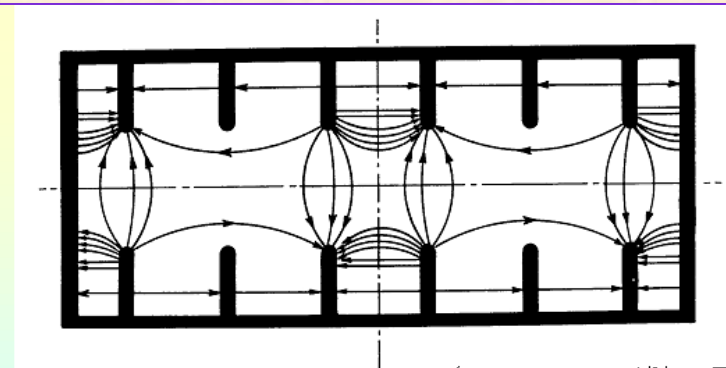
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
  => better resolution than with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

Longitudinal properties



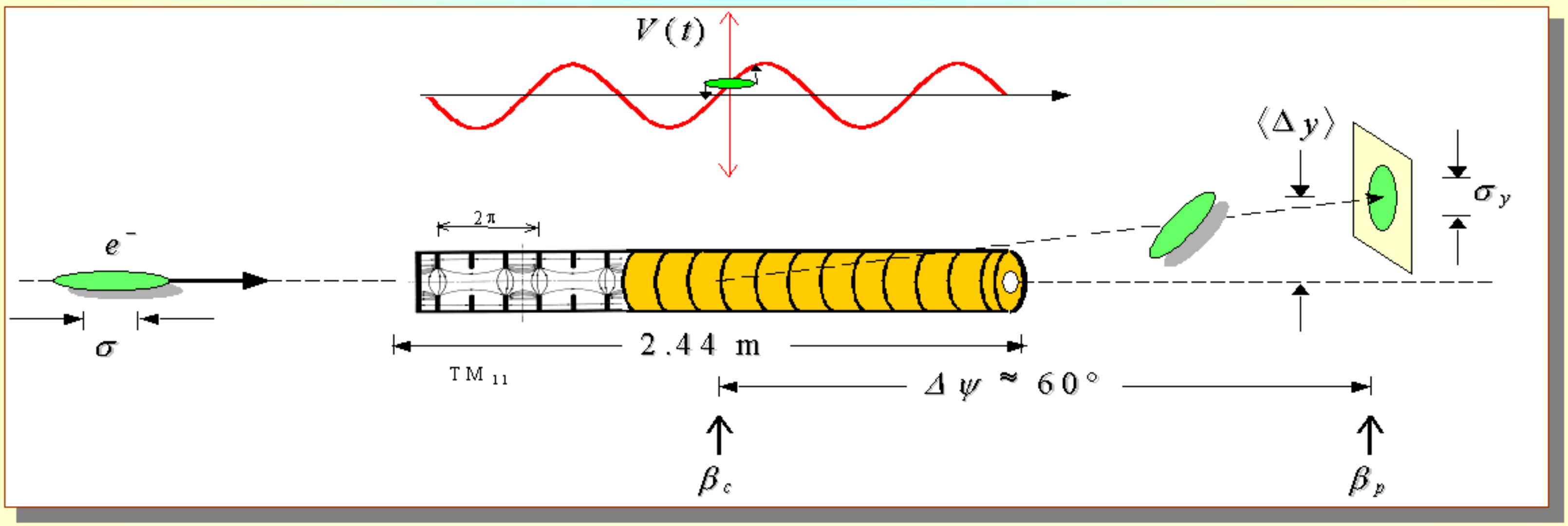
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



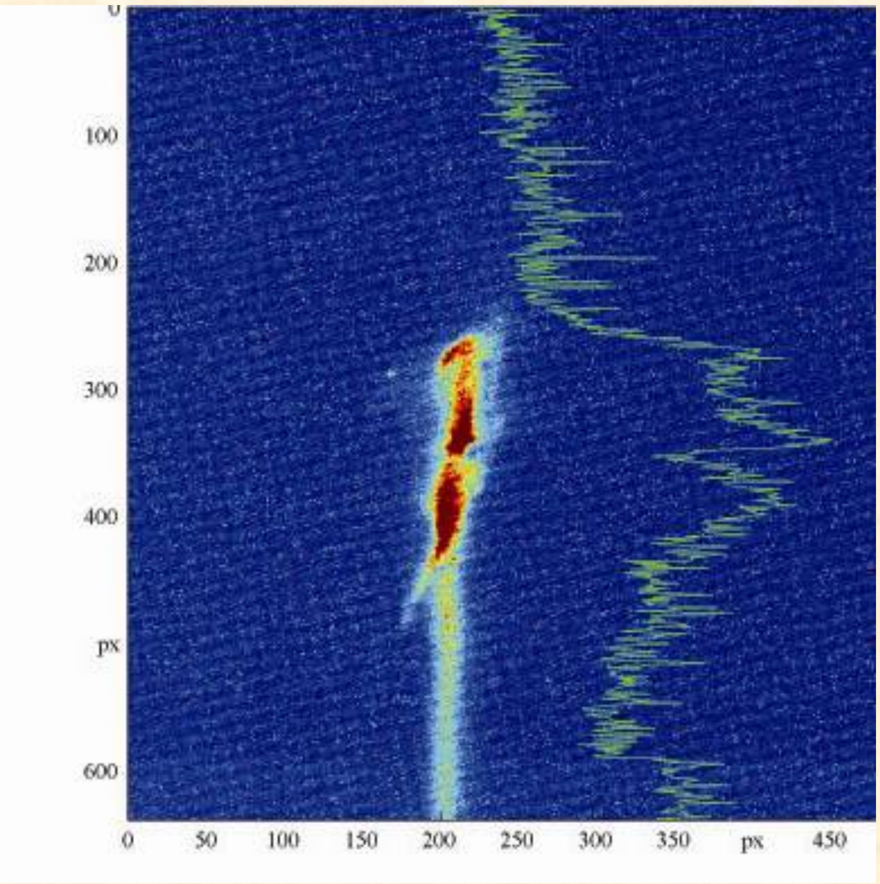


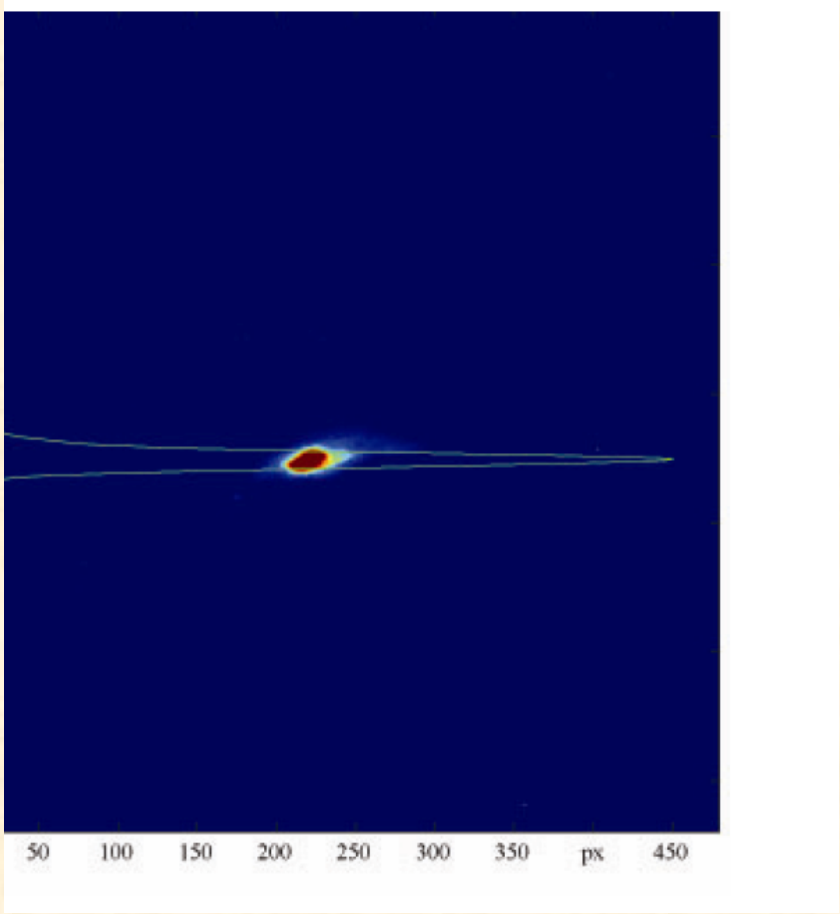
$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW^{1/2}}\right) L \sqrt{P_0}$$

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

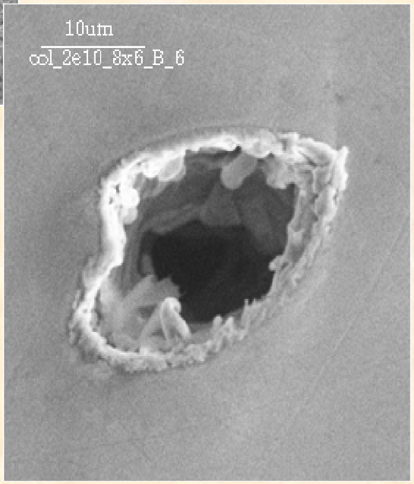


RF deflector off and on





Limitation of these monitors



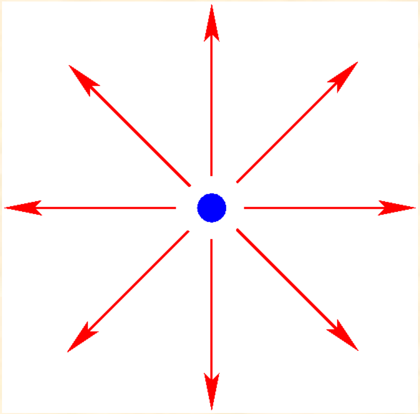
- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

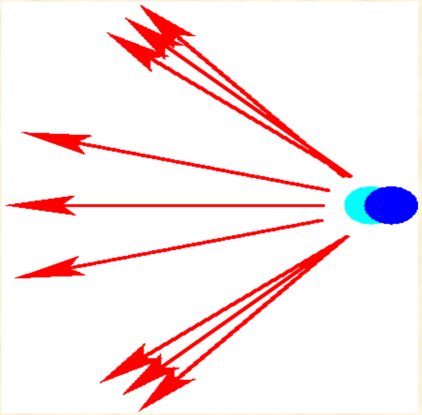
Summary (particles interaction with matter)

	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/modify the beam.
- These monitors tend to be simple but can be damaged by high energy and/or high intensity beams.

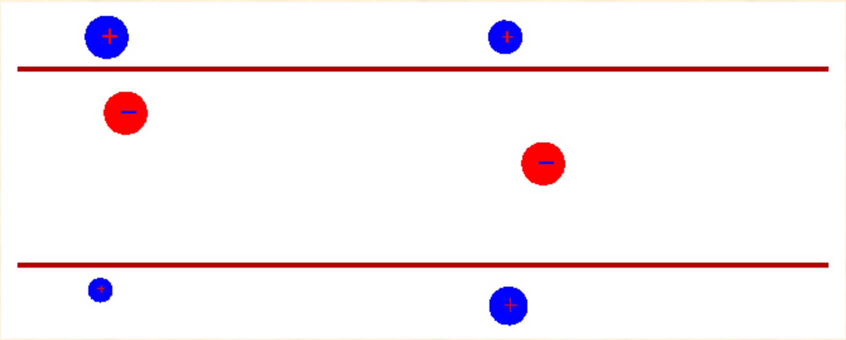
Charged particle

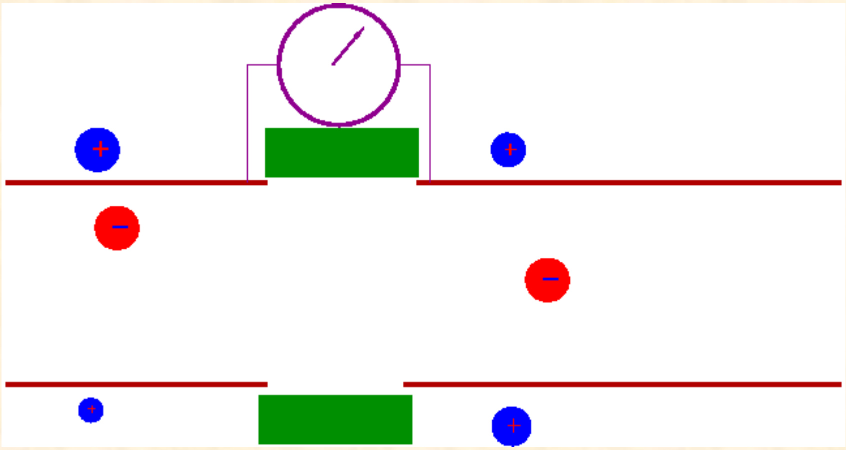




- Any charged particle “radiates”
- These electromagnetic radiations can be detected without disrupting the beam.
- One needs to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

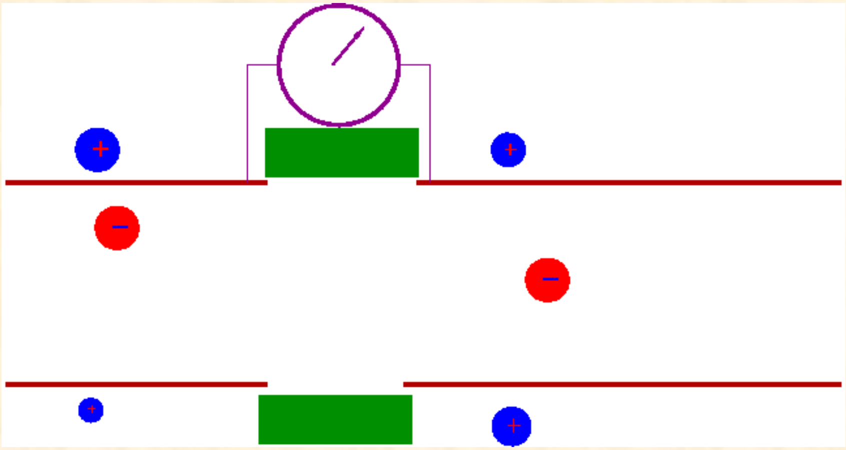
Beam current monitor





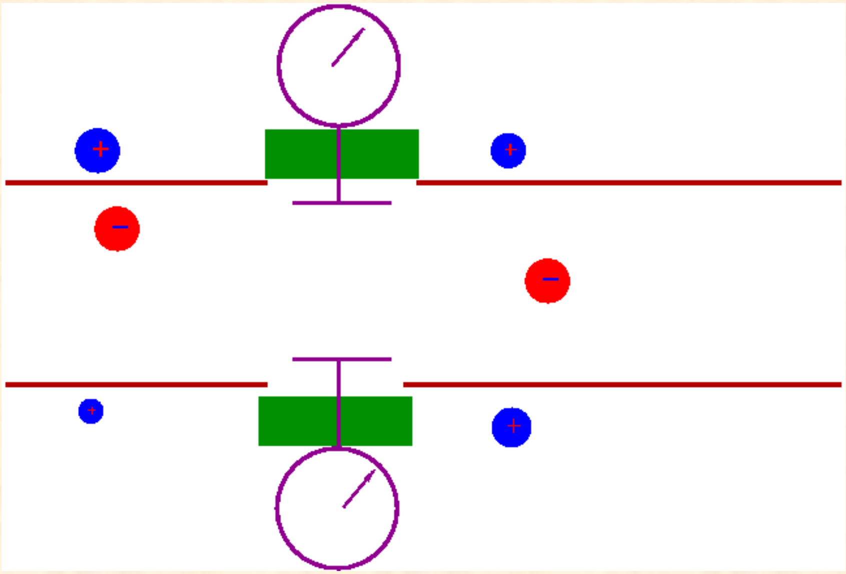
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

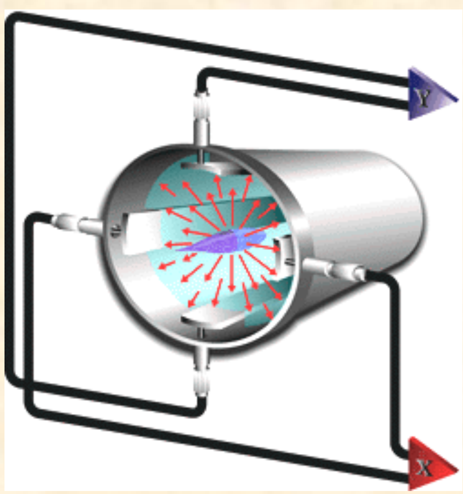
Beam current monitor vs Faraday cup



- 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.

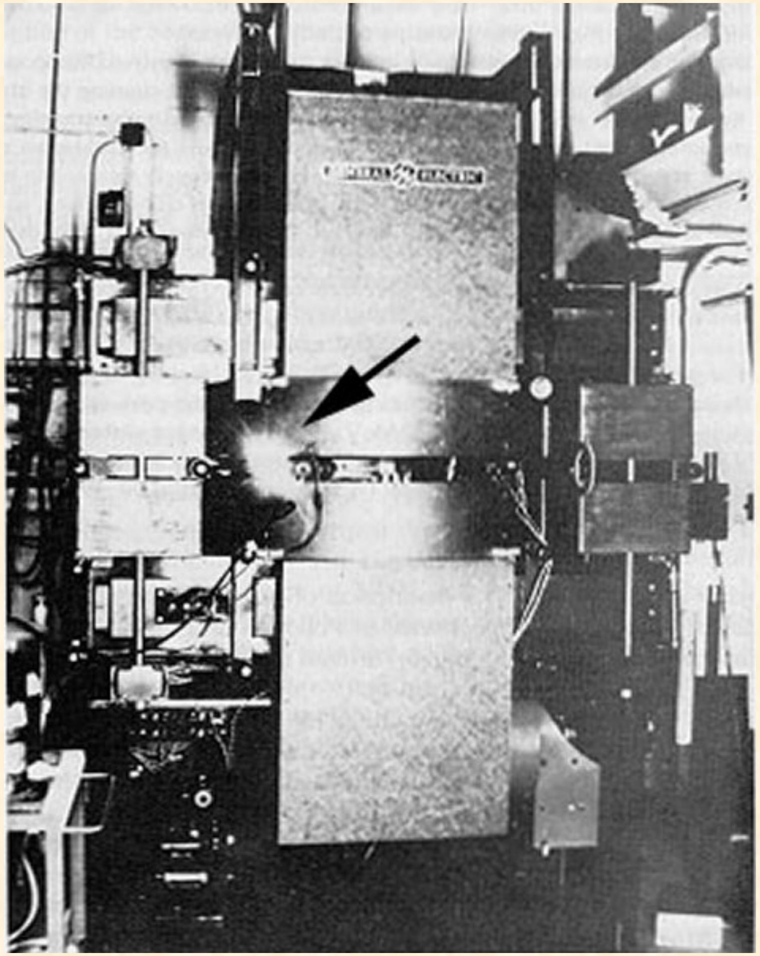
Beam position monitor



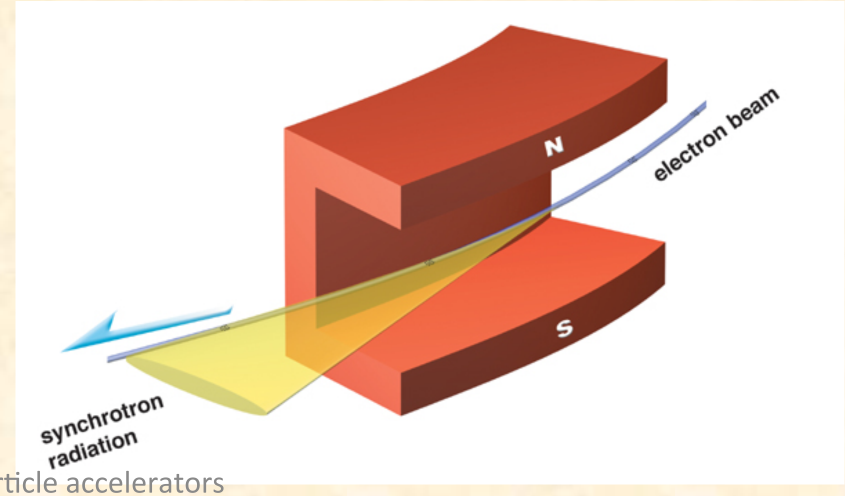


- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

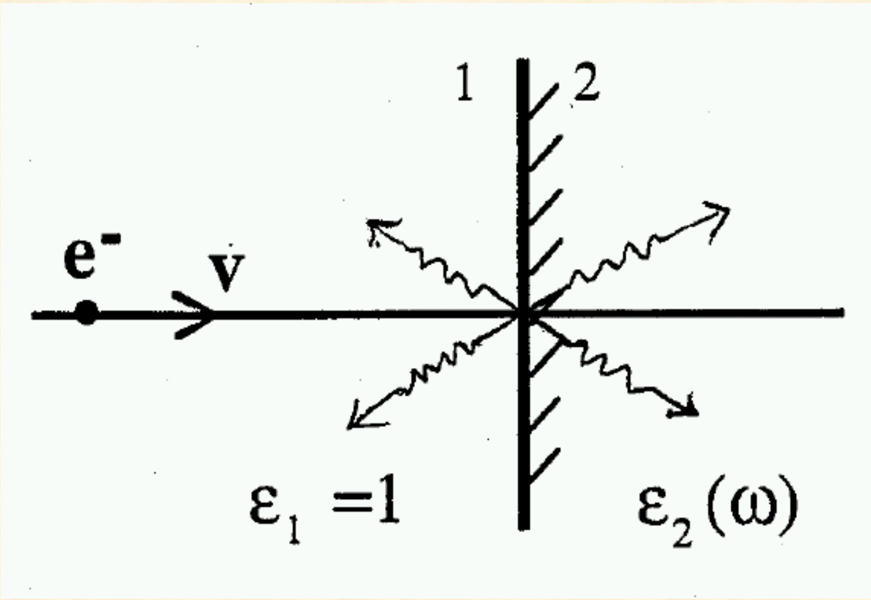
Synchrotron radiation

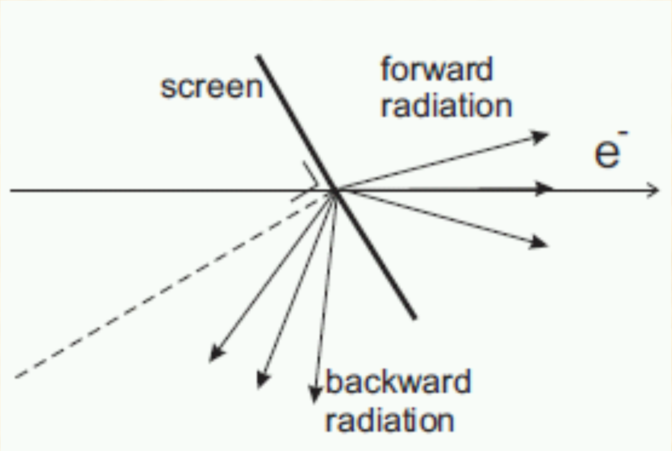


- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



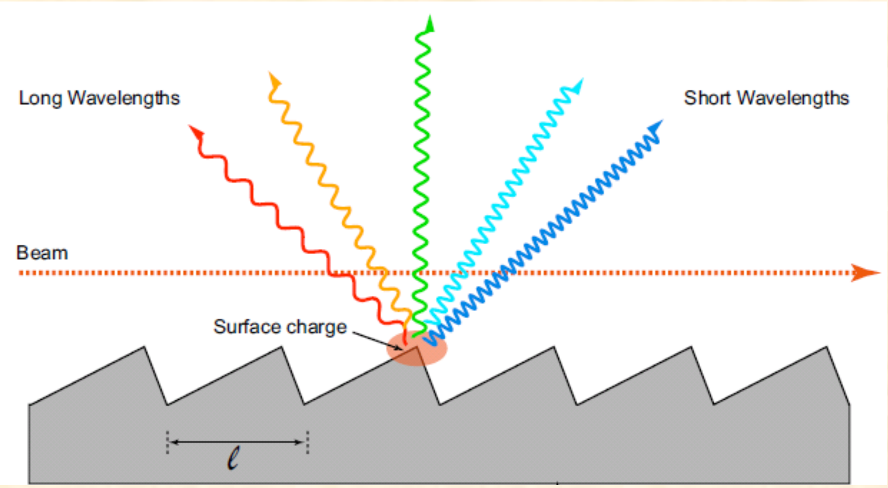
Optical Transition Radiation





- 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).
- As this is a surface effect, very thin (non disruptive) screens can be used.

Longitudinal profiles



- Longitudinal profiles of short beams are one of the most difficult measurement.
- Several techniques use radiation induced by the beam.
- In the Smith-Purcell method a grating is used and the beam interacts coherently with the grating and emits radiation.
- Most longitudinal profile measurement techniques actually measure the Fourier transform of the beam
  => reconstruction needed!

$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega)=\left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e+N_e(N_e-1)|F(\omega)|^2]$$

Energy measurements

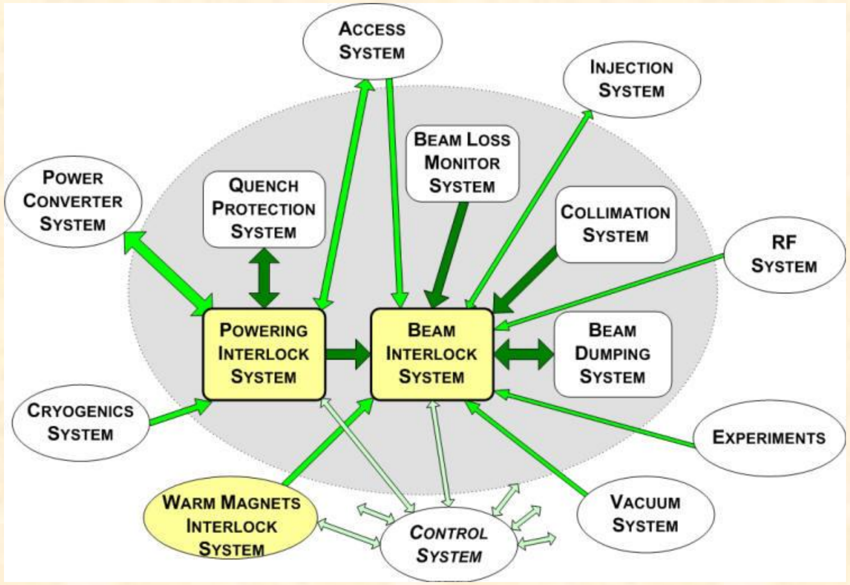
- To measure (or select) the energy of the particles a bending magnet is often the best solution.
- This can be done in an “energy chicane”.

Diagnostics overview

	Interaction with matter	Radiation
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transverse)	Screen or wire-scanner	Synchrotron radiation or optical transition radiation
Size or shape (longitudinal)	RF cavity + screen	Radiation detectors (eg: Smith-Purcell)
Energy		Bending magnet
Losses	Scintillator	

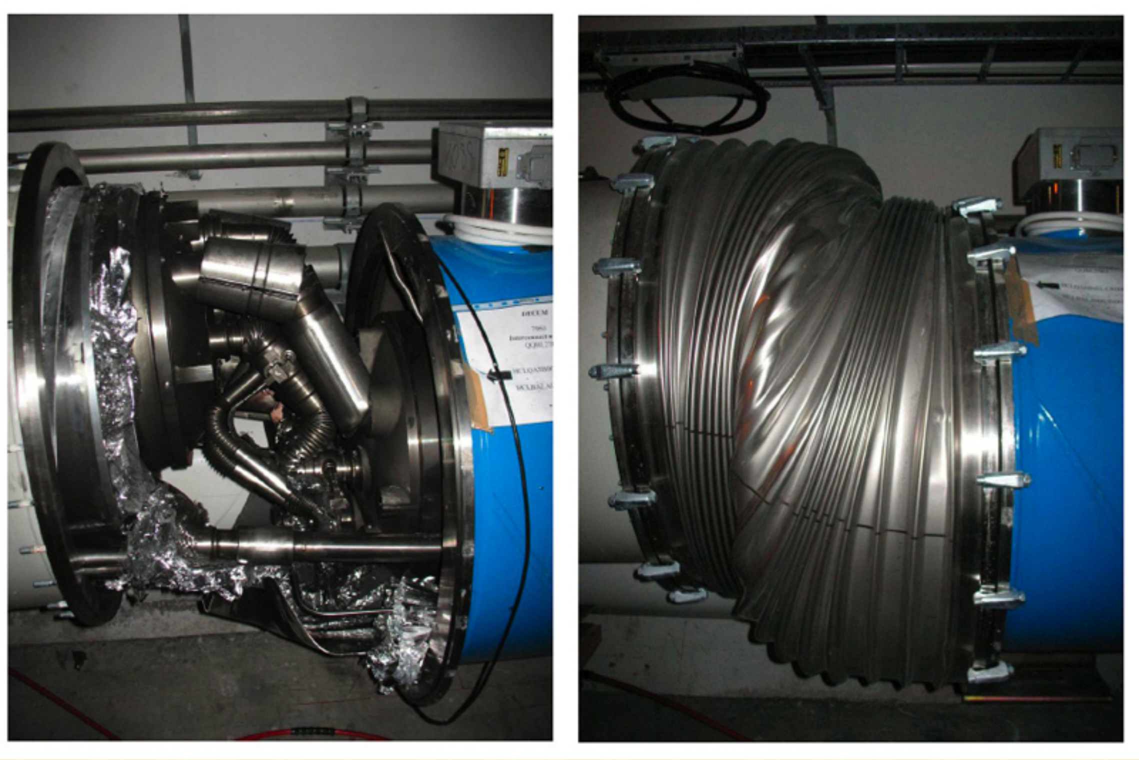
Machine protection system

- The LHC beams carry the same amount of energy than a jumbo plane at take-off => risk of serious damages!
- A complex "machine protection system" is used to monitor the machine at all time and prevent injection or dump the beam if a fault is detected.
- A system of flags and permits is used to prevent any situation that might led to significant damages => in case of doubt it is safer not to inject/keep the beam!



Quench

- Unfortunately a large quench occurred in September 2008.
- This was due to the resistance of a bus bar (connector) being a few nano-ohms too high.



Diagnostics summary

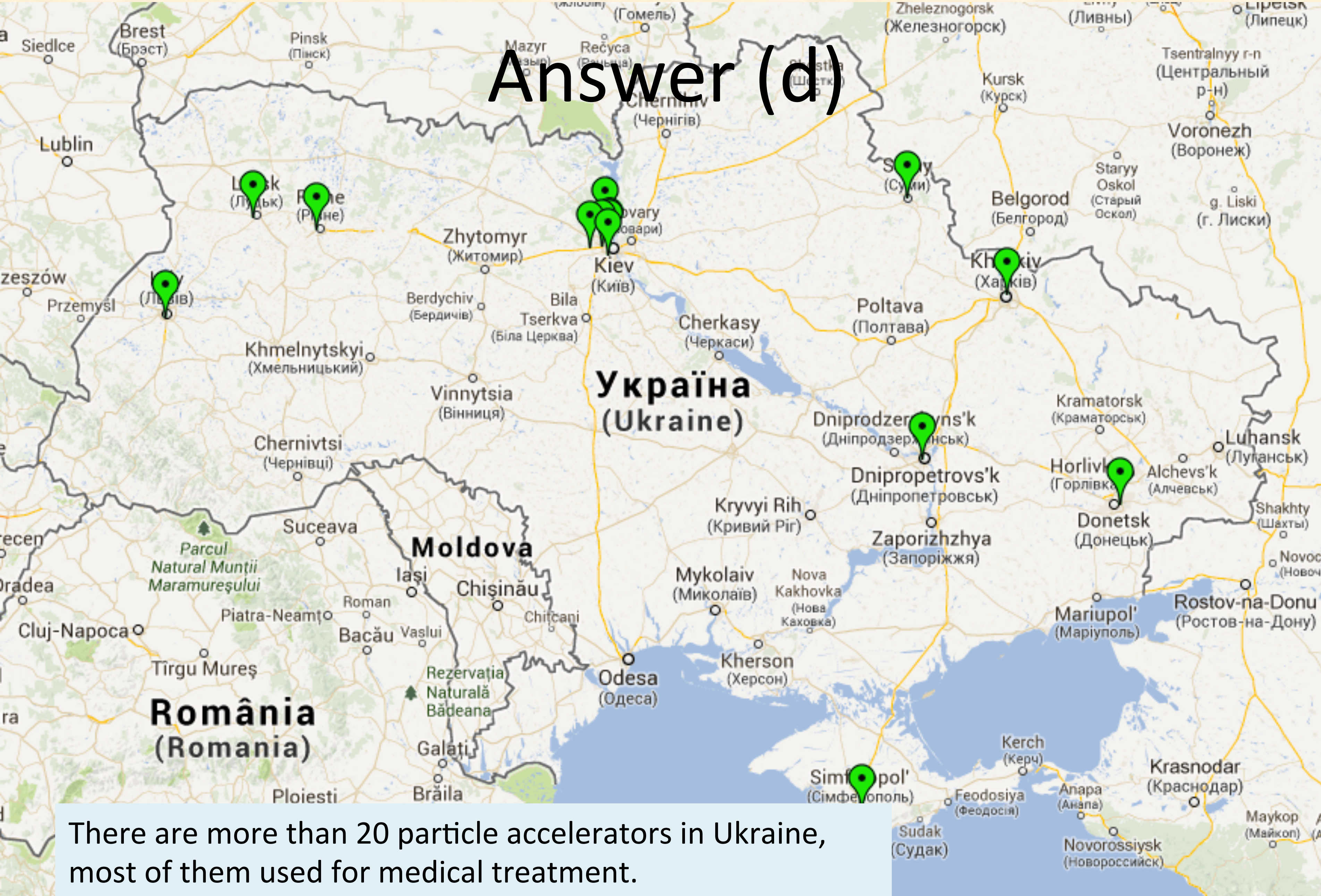
- The properties of a particle beam can be measured, either:
  - through its interactions with matter (destructive measurement)
  - or by detecting the radiation measurements (almost non perturbative measurement)
- The more accurate the measurement has to be the more precise/expensive the measuring equipment will be.
- At the LHC the diagnostics are the "eyes" of the system and some are part of the machine protection.

APPLICATIONS

Quizz

- In how many Ukrainian cities is there a particle accelerator?
- (a) 1-2
- (b) Between 3 and 5
- (c) Between 6 and 8
- (d) More than 8

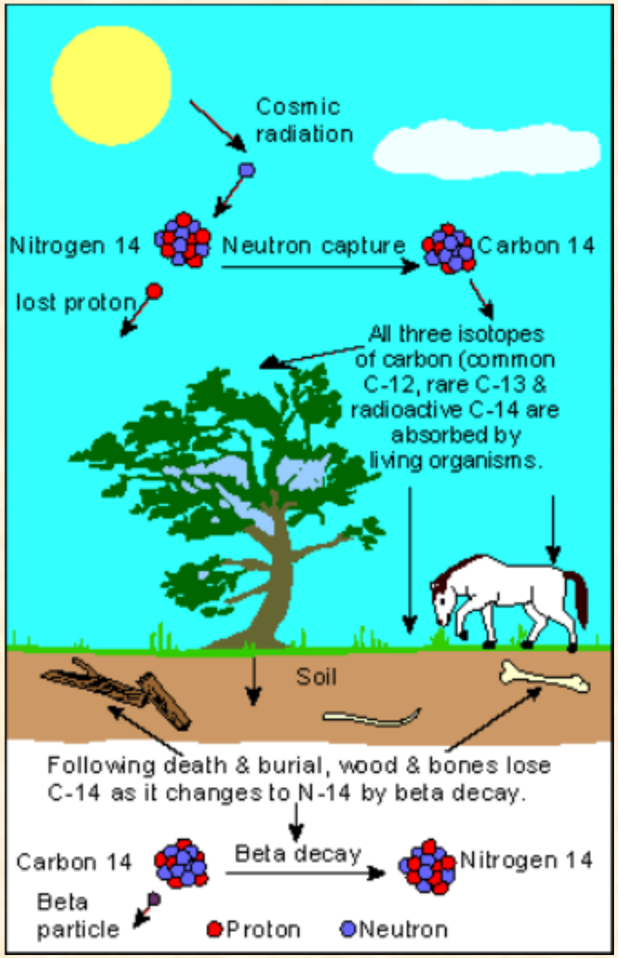
Answer (d)



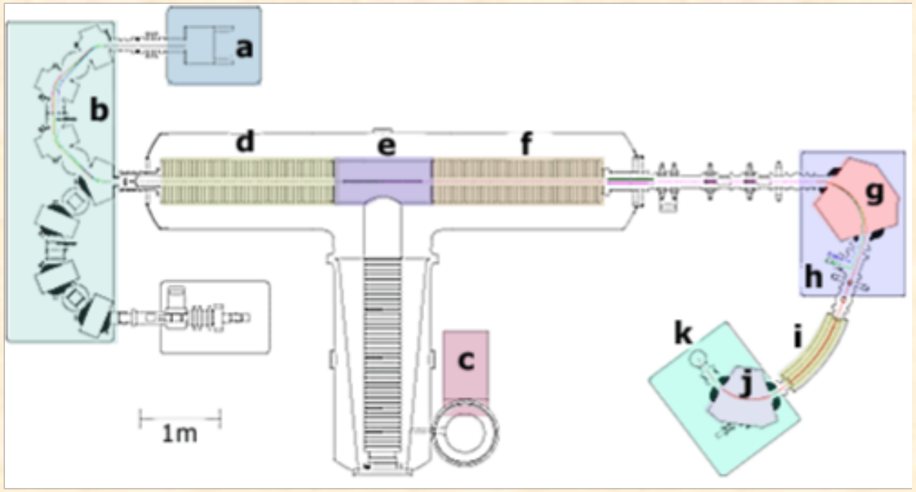
There are more than 20 particle accelerators in Ukraine, most of them used for medical treatment.

http://nicolas.delerue.free.fr/accelerateurs/accelerators_ua.php

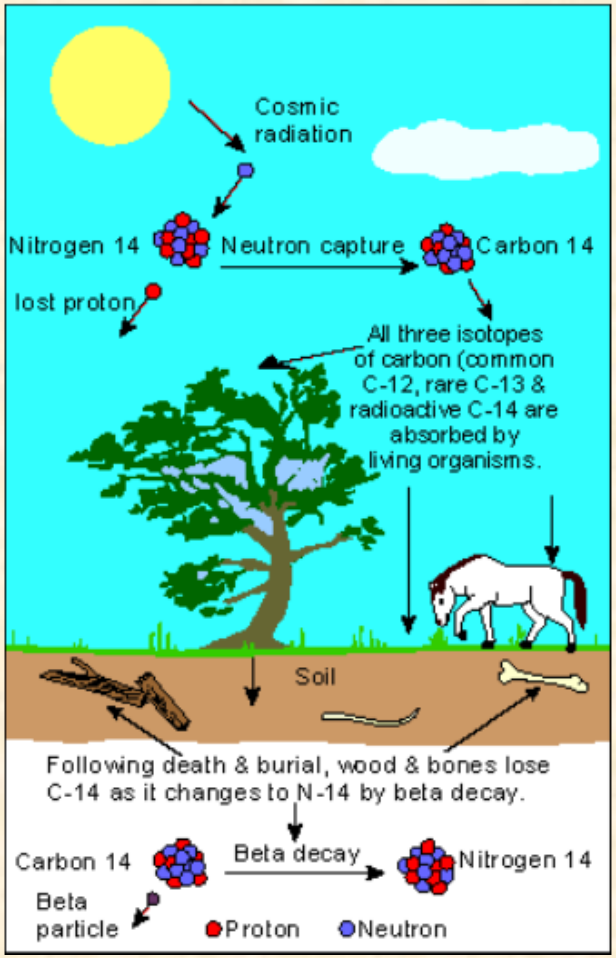
Non HEP applications
Dating old artefacts



- 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".

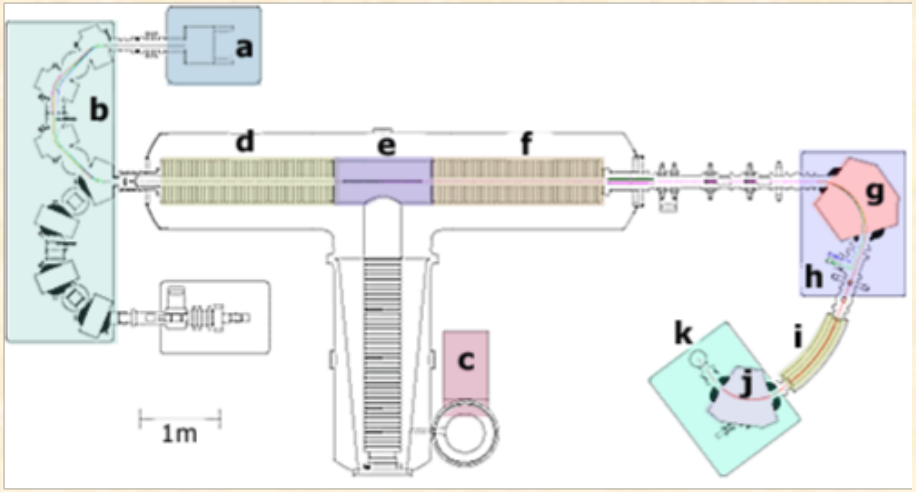


Accelerator Mass Spectroscopy (1)



- 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)

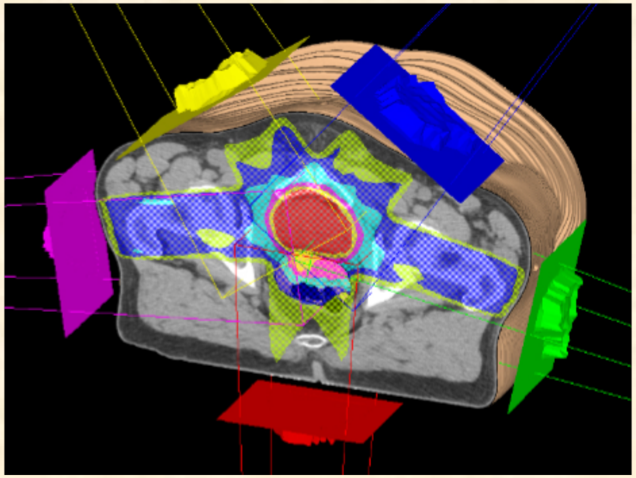


- AMS machines use a sputtering ion source producing C- ions.
- A tandem Van de Graff is then used to accelerate the ions and strip then to C^{3+}.
- A DC accelerator offer a better stability than a RF accelerator.
- A Faraday cup is used to measure the beam charge.

Example of AMS application Vinland map

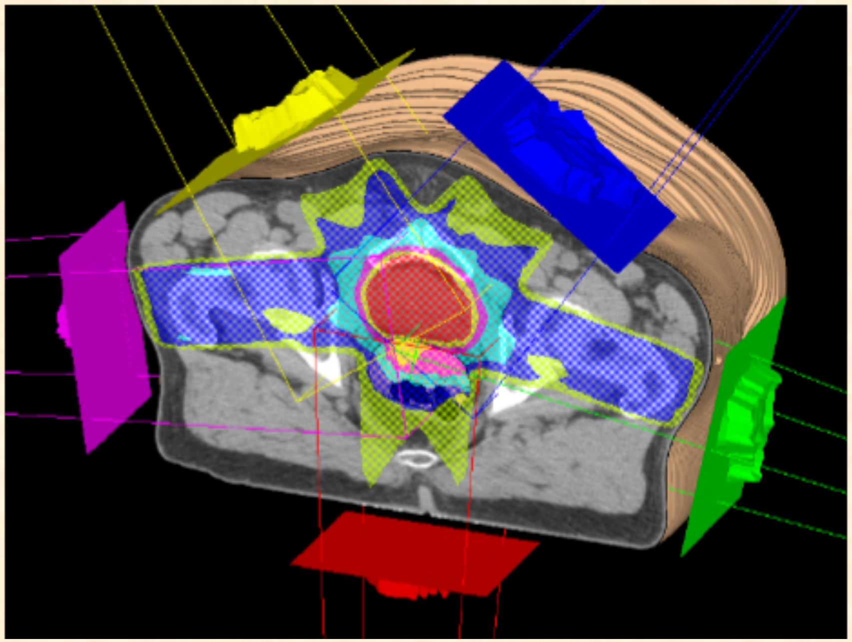
- AMS was used to date ashes found in Newfoundland in a European-type settlement. These ashes were dated back to the XIth century.
- A viking map featuring Newfoundland was shown to be older than Columbus trip to America.
- AMS has contributed to establish that North America was visited by Vikings well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

Treating Cancer



- Some type of cancer tumors are located at places difficult to reach by Surgery.
  => X-rays
- Radiotherapy need 10-15 MeV electrons for a few seconds.
- 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).
- A short RF accelerator is used to reach the required energy.

Treating Cancer

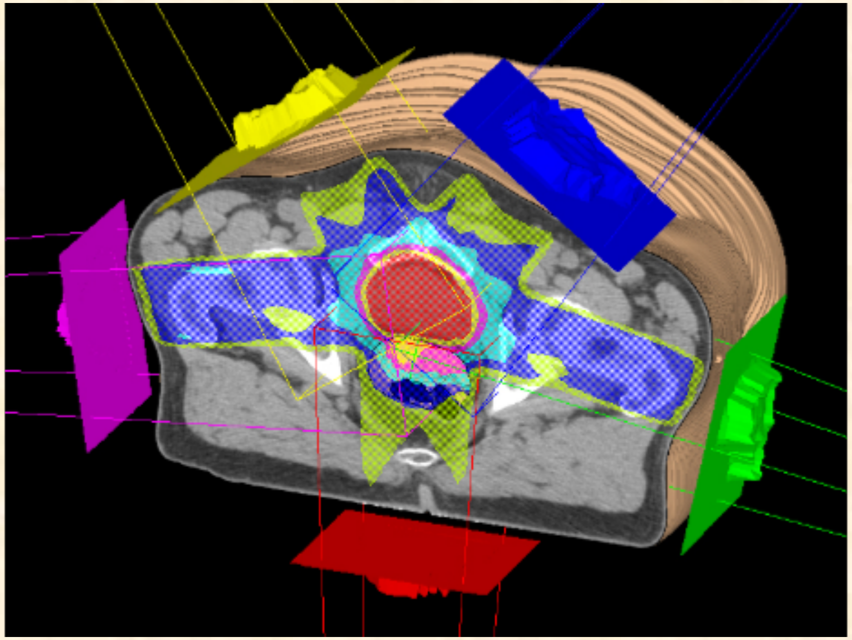


- Some type of cancer tumors are located at places difficult to reach by Surgery.
- X-rays can be used to kill such tumors.
- This is called Radiotherapy.
- Radiotherapy need 10-15 MeV electrons for a few seconds.
- The accelerator needs to be compact so that it fits in an hospital room and fields can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

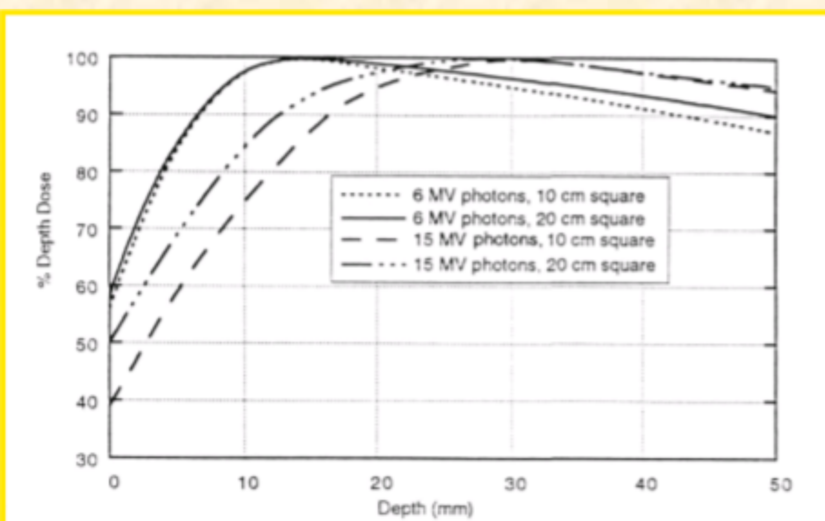
Medical linac

- 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.

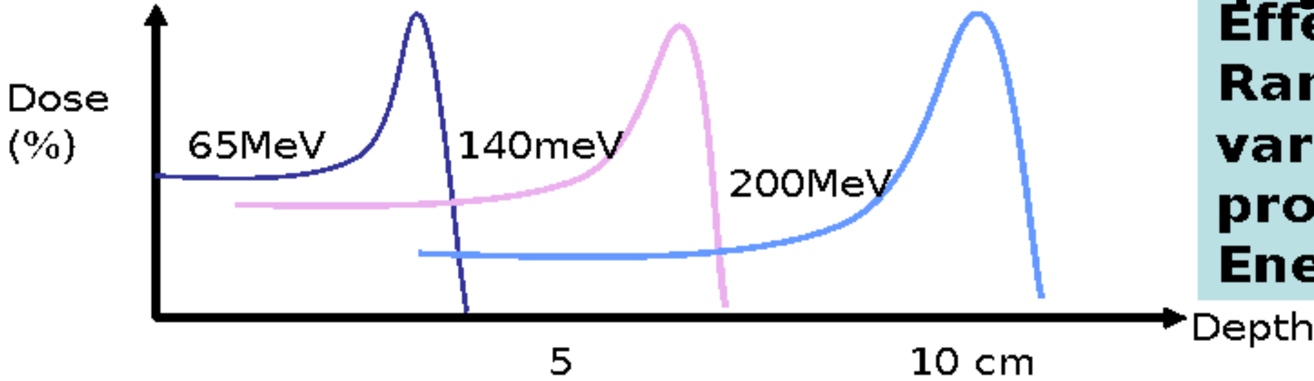
Radiotherapy



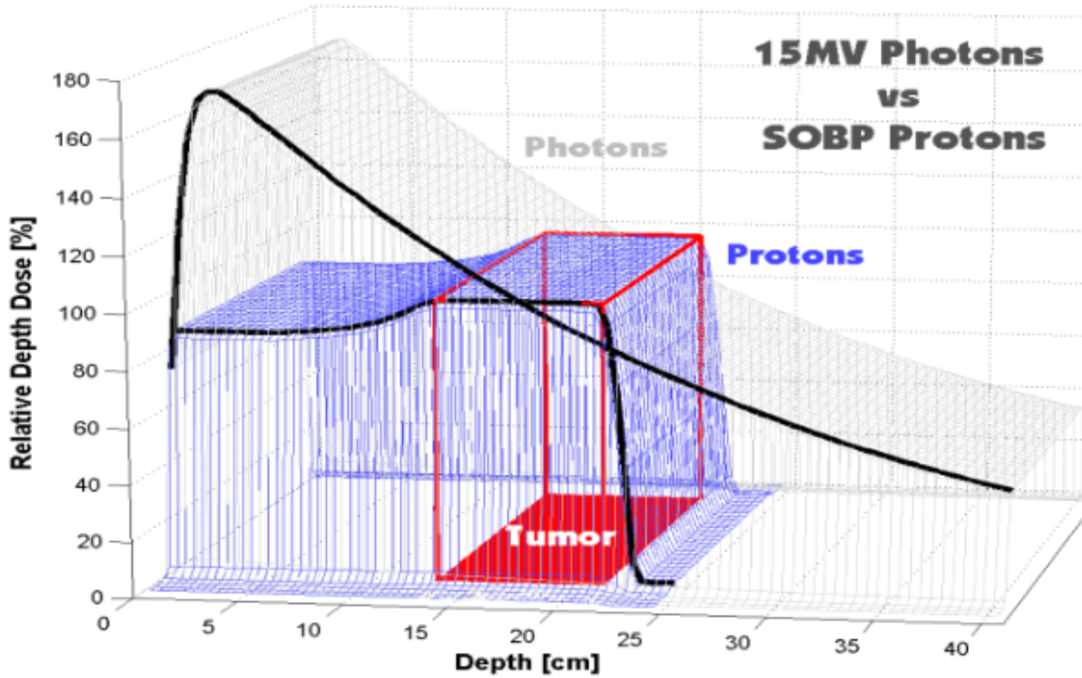
- X-rays are used to kill a tumour.
- To minimize the dose sent on healthy tissues several X-ray beams are sent in turn from different directions.
- However this technique is not ideal due to its impact on healthy tissues.



Proton and ion therapy



Effective Range varies with proton Energy



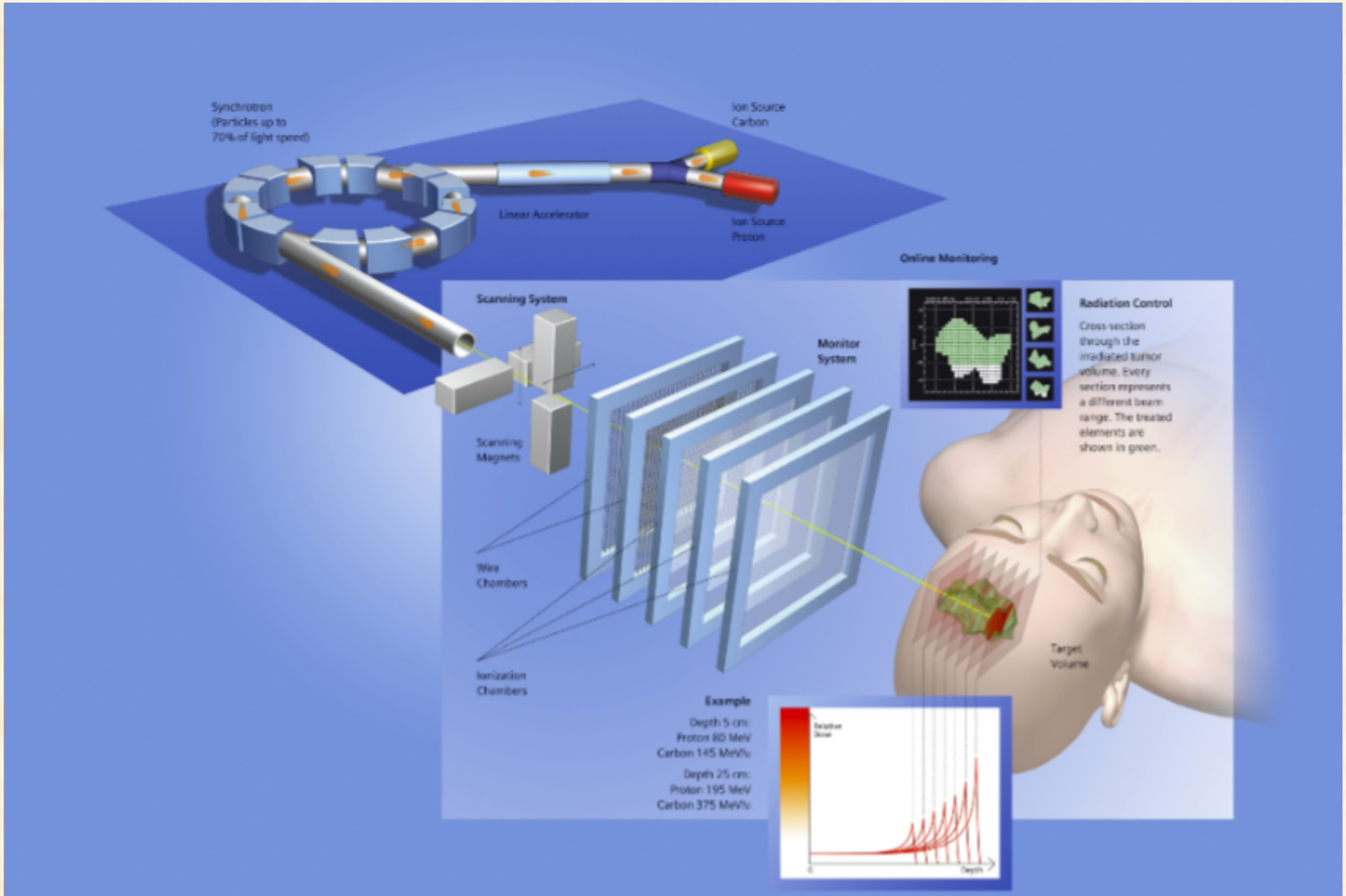
The‘spread out’ Bragg Peak– plateau effect

[SOBP]

Source: Bleddyn Jones, JAI graduates lectures

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

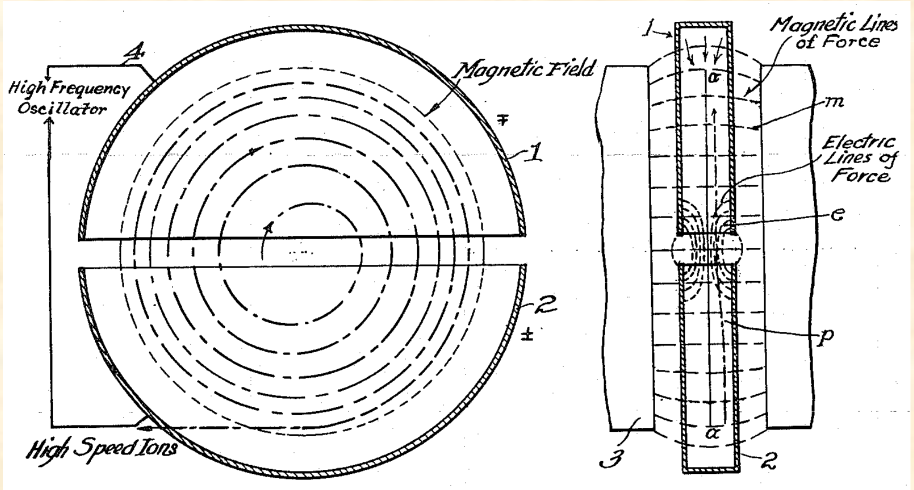
A possible solution...

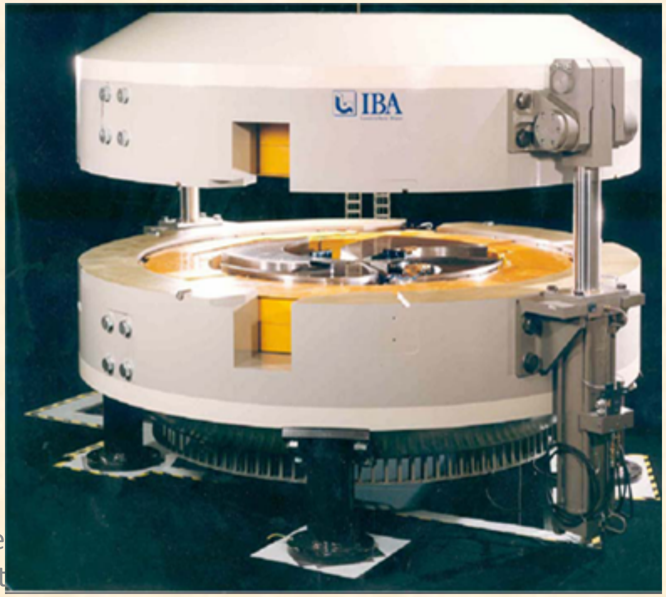


Source: Bleddyn Jones, JAI graduates lectures

Medical cyclotron

- Cyclotron are well suited to accelerate ions.
- Several hospitals or universities are equipped with cyclotrons to produce radioactive isotopes used as markers in drugs.
- Such cyclotron is a commercial product.

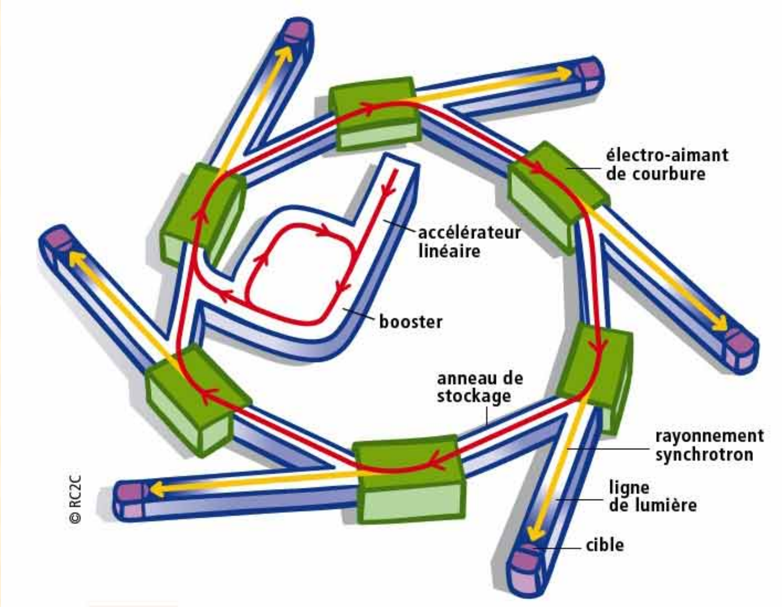




A source of intense X-rays

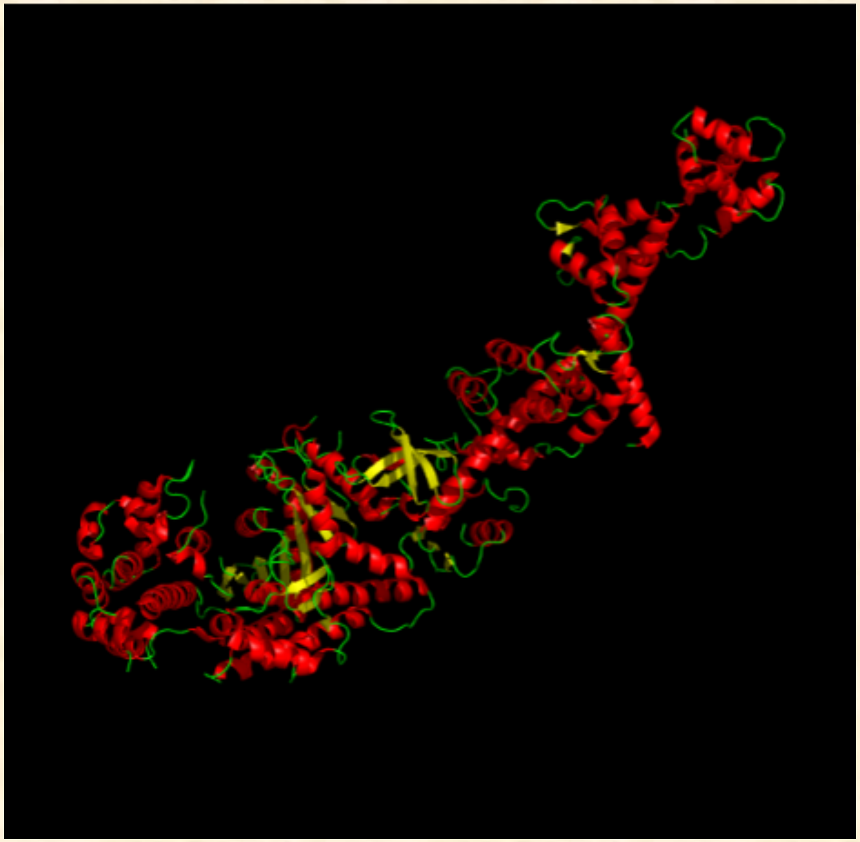
- Synchrotrons are best suited to deliver intense beams of X-rays.
- Although synchrotrons operate at ultra low emittance the gun can be thermionic as radiation damping reduces the transverse emittance.
- A RF accelerator is then used to accelerate the particles up to the ring energy. A booster may be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

Source: Diamond



Source: SOLEIL

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.
- Synchrotron are very well suited for this.

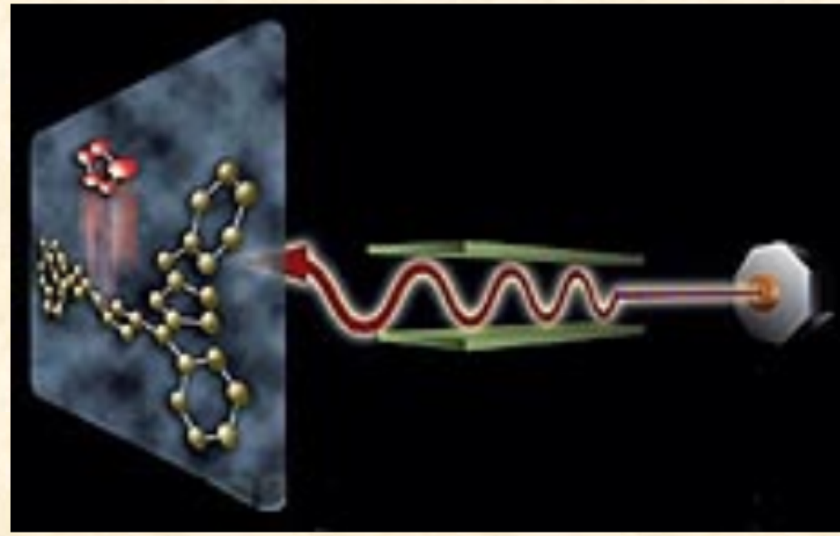
Applications of synchrotrons

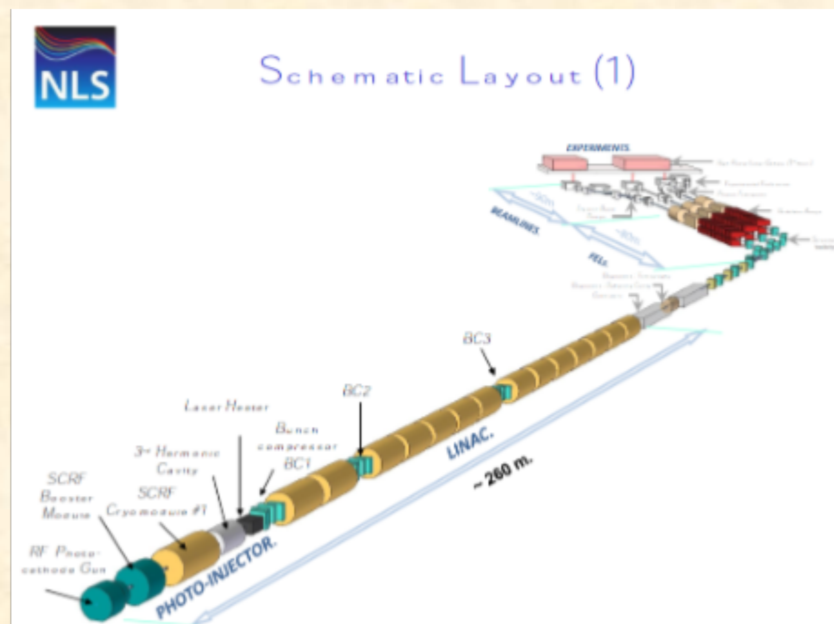
- Light sources have a wide range of applications.
- A light source in England has been used to improve the quality of chocolate!
- Diamond is being used to study old manuscripts too precious to be opened!
- Protein imaging, drugs, material studies,...
- GMR (the phenomena that allows dense magnetic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

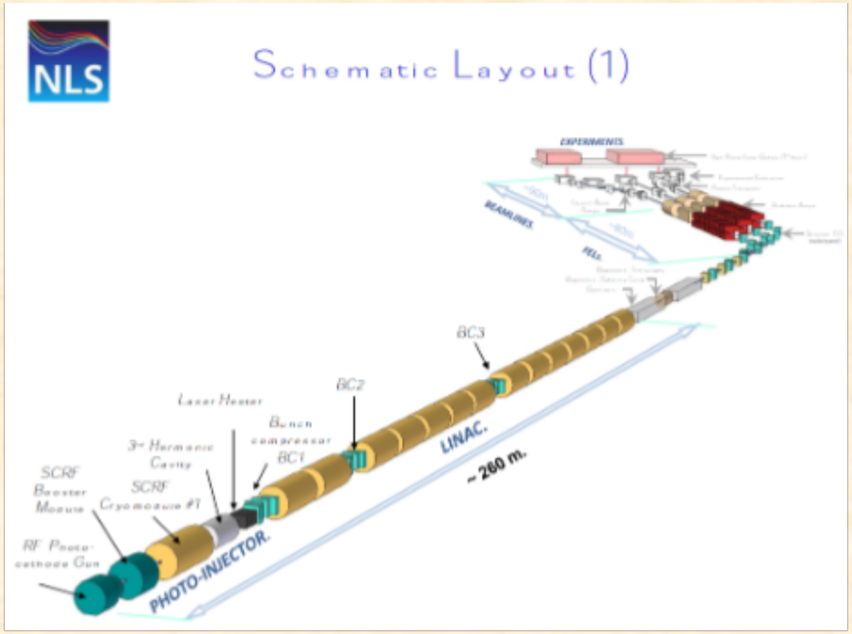
  => Linac-based free electron lasers delivering fs-long X-ray pulses.





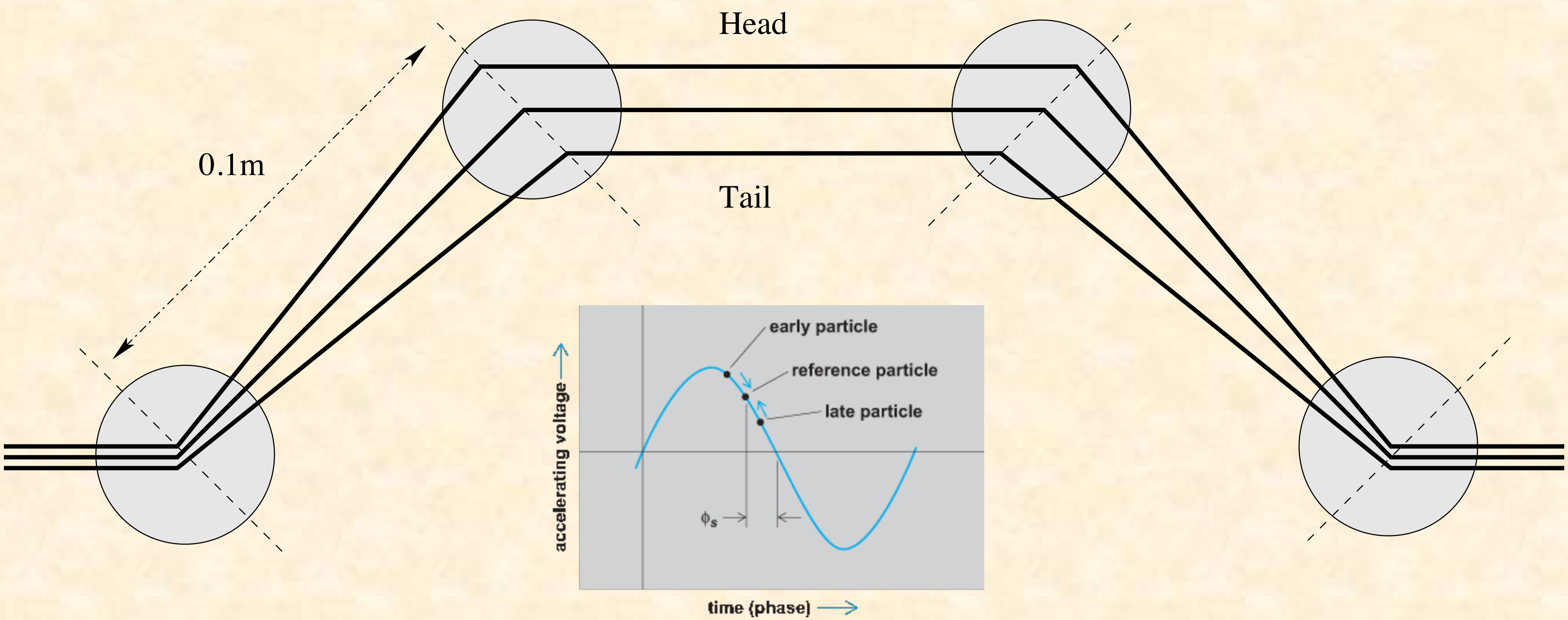
Next generation: Linac based Free electron lasers

- Only linac based accelerators can deliver ultra-short pulses.
- Ultra-short pulses are necessary to get coherent emission of X-rays.
- 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).



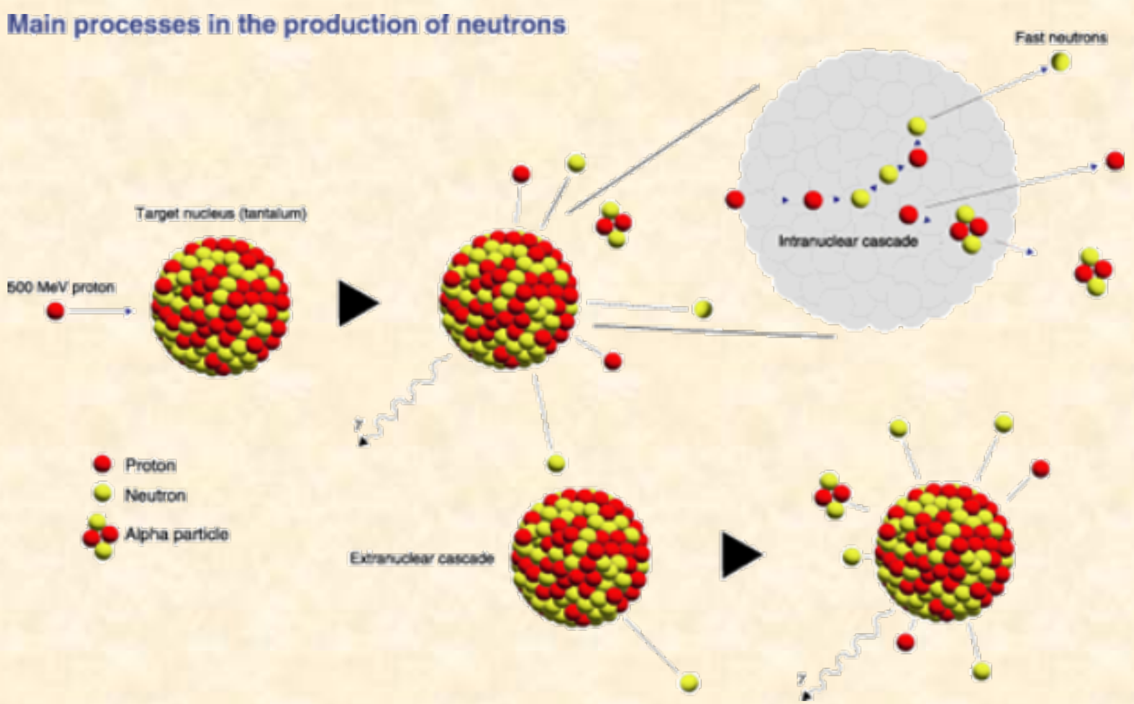
How to make short bunches?

- RF guns can be used to make short pulses.
- To have even shorter pulses one needs to use a compression scheme.

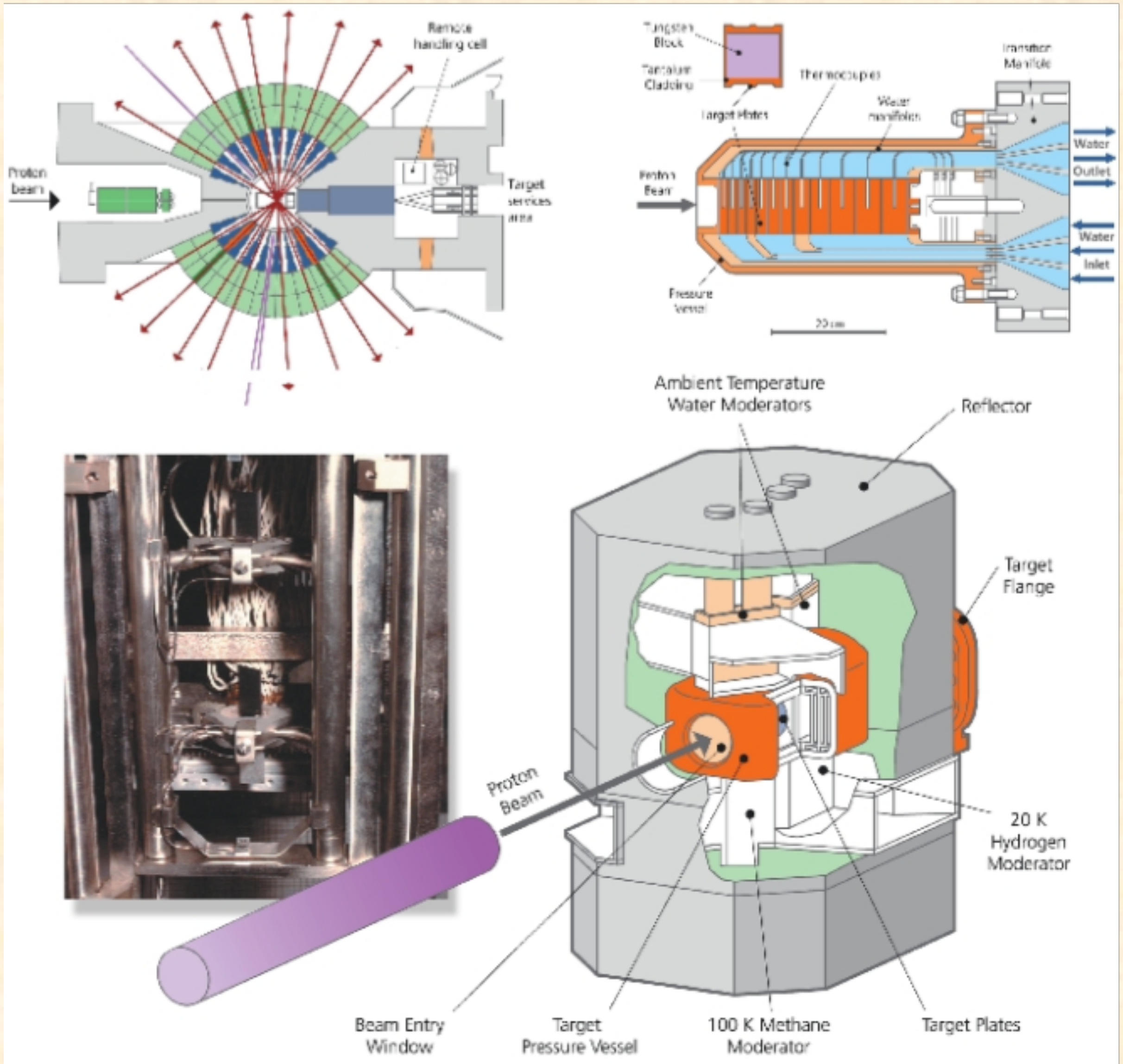


Spallation

- 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.
- However this is the best way to produce pulsed neutrons => applications to study materials (H,…)

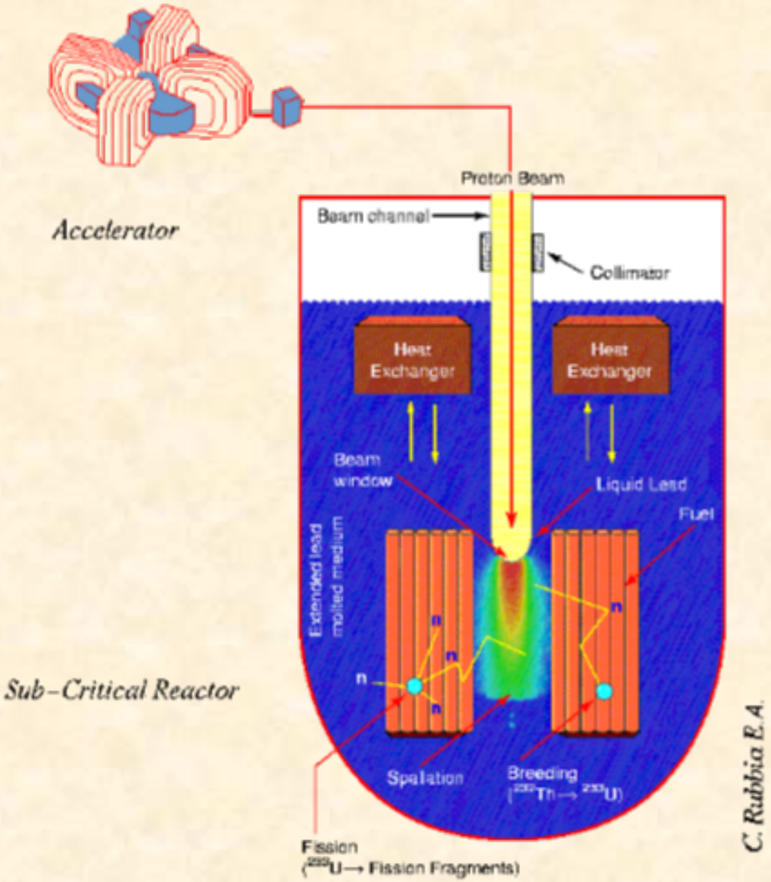


Spallation target



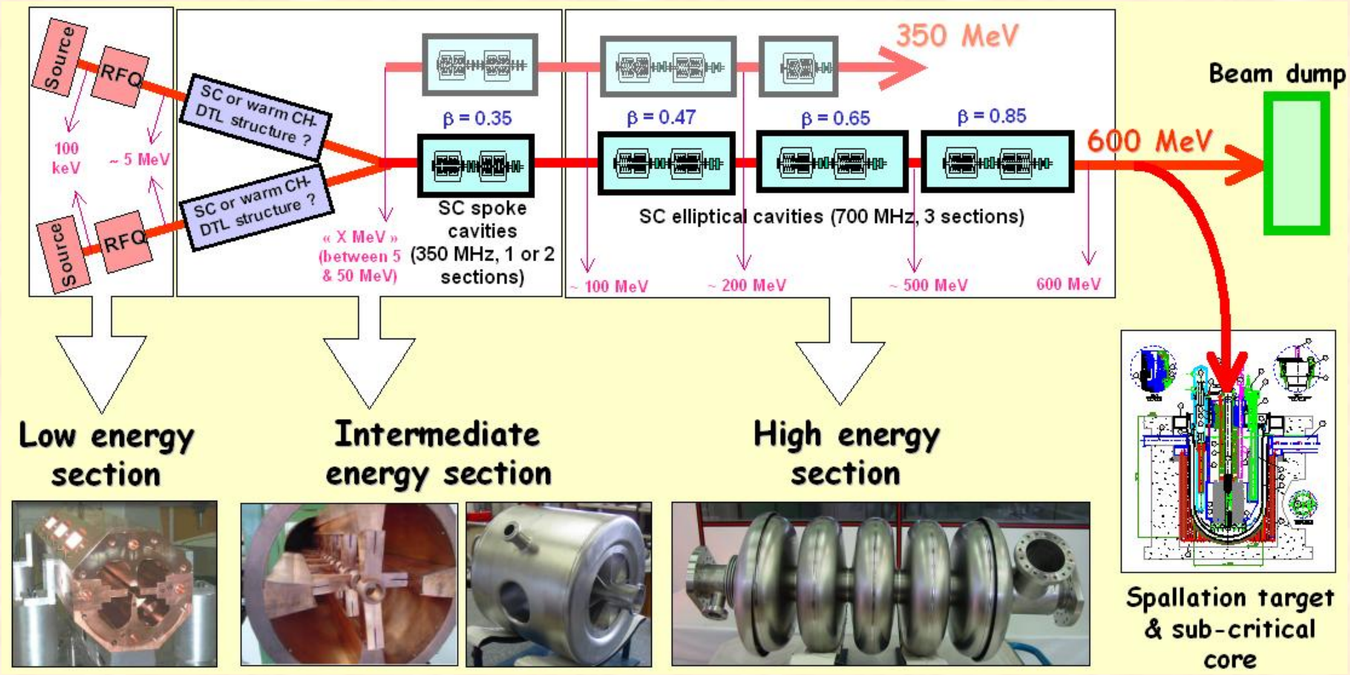
Accelerator Driven sub-critical reactor (ADSR)

- 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).
  => less risk of proliferation.



Need for high redundancy

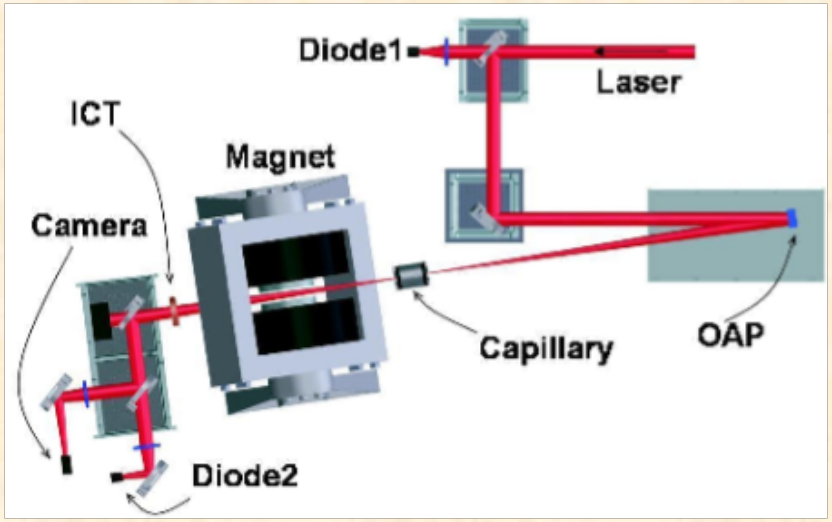
- Even if they do not like it, HEP experiments can cope with an unreliable accelerator.
- In a nuclear reactor a sudden stop of the driver will cause a thermal shock.
- To many thermal shocks might damage the containment vessel
  => The accelerator has to have a high level of reliability.

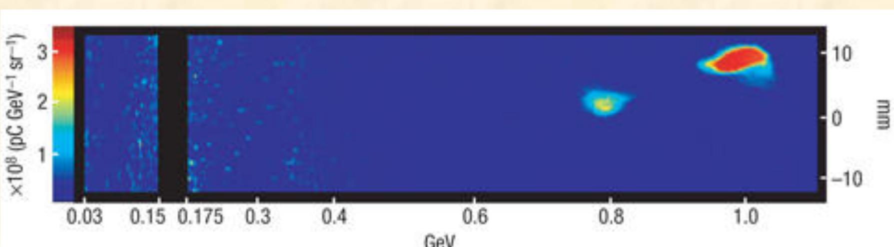


... and much more

- 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.

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



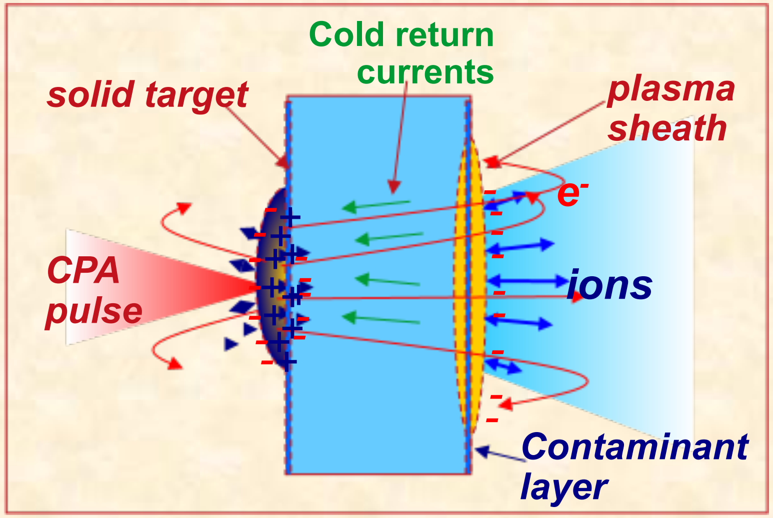


Leemans et al, doi:10.1038/nphys418

- 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.

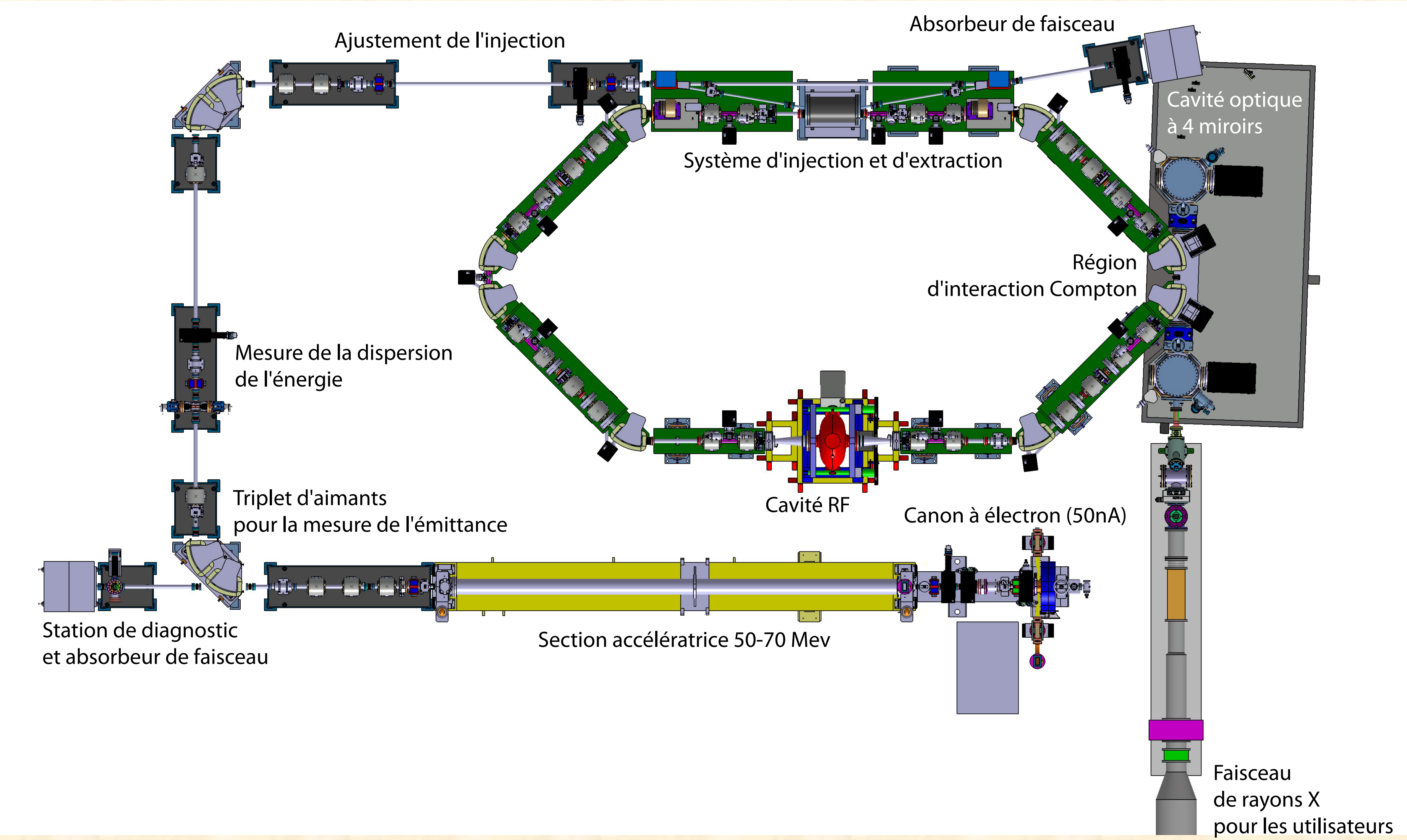
- Recently SLAC achieved significant (>>GeV) energy gain using this technique (stay tuned!)

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



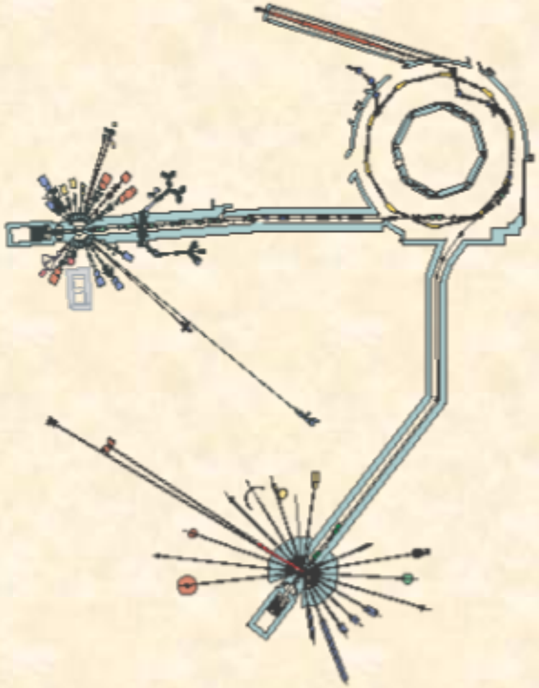
- If a similar laser is shot onto a target, medium energy ions can be produced.
- This could be used for ion therapy.

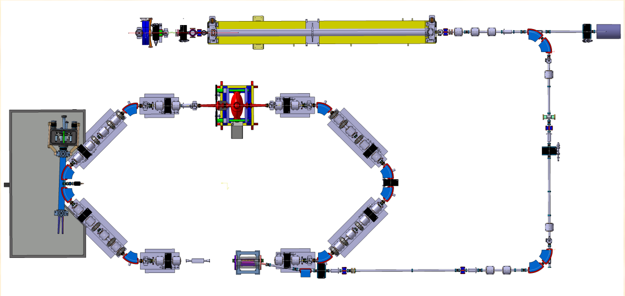
ThomX



- ThomX is an accelerator being built at Orsay

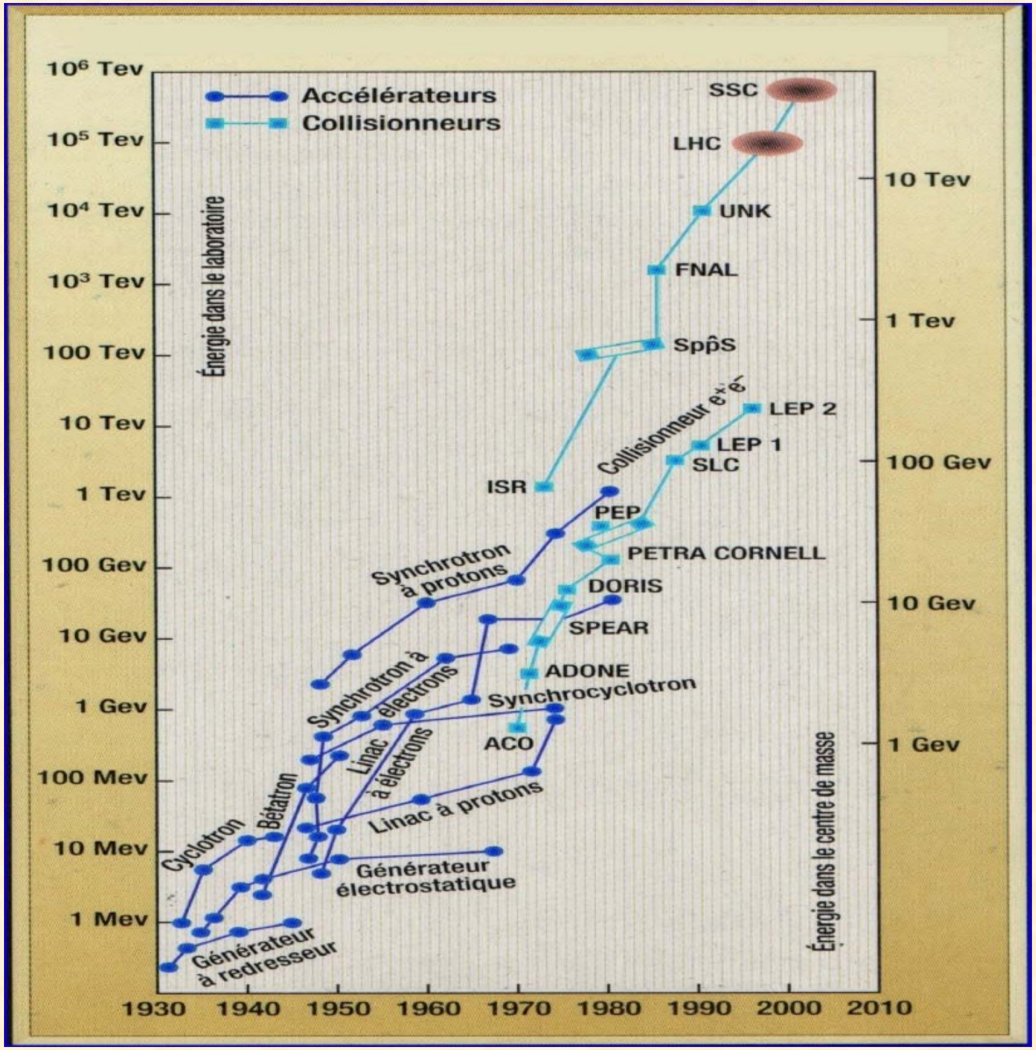
Costs





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

Progress of accelerators

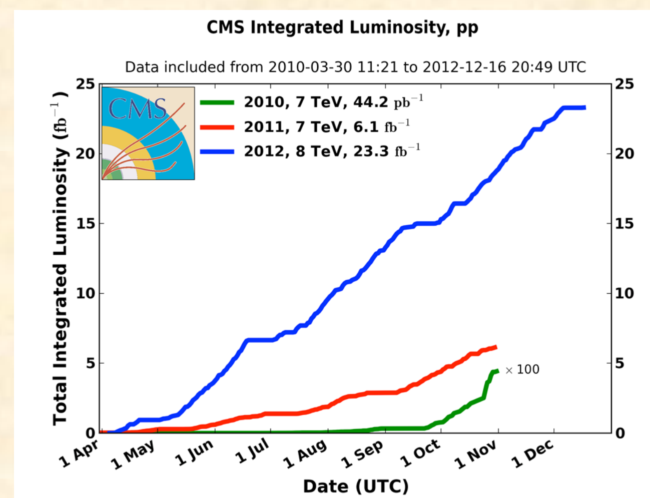


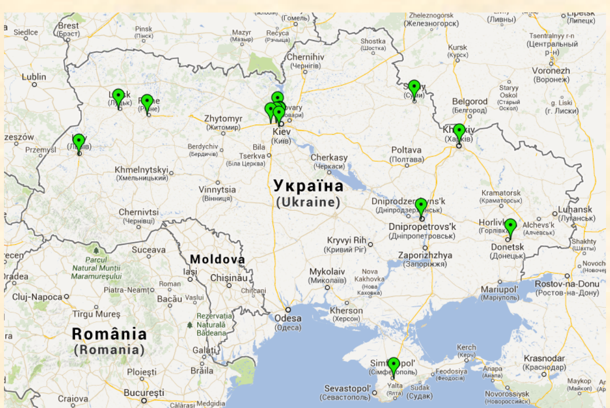
- Accelerators have made tremendous progress over the past 50 years.
- They drove part of the developments of HEP.
- However they have also become very large and expensive.

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, the meals or to email me delerue@lal.in2p3.fr***





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