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. *How to "see" protons in the LHC?*
IV. What can you do with a particle accelerator (apart from hunting the Higgs)?
   - Accelerators around us
   - Radiocarbon
   - Medical applications
   - Synchrotrons (… and chocolate)
   - Neutron sources
   - Plasma acceleration
   - Example of accelerator: ThomX

Where are we?

- We have seen how to produce particles, how to accelerate them, how ton inject them and how to see that they are in the accelerator.
- So now you know (almost) everything about the operations of an accelerator.
- We have spent a week talking about HEP.
- So let's talk about something else:
  What can you do with a particle accelerator outside HEP?

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
  (e) Other

Answer (d)

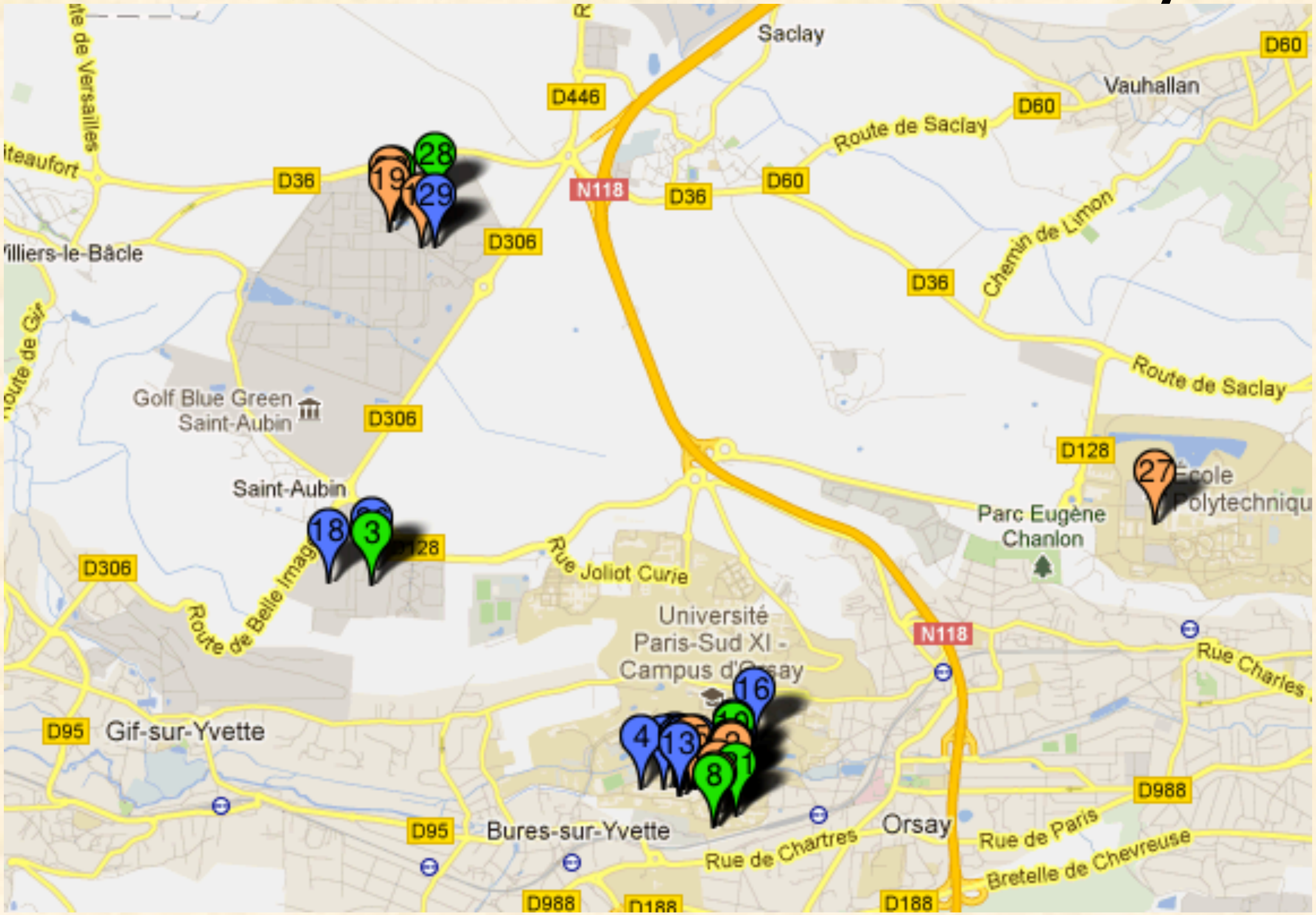
- HEP labs use the biggest particle accelerators in the world but there are only a few of them.
- Non HEP physical science labs use accelerators to produce X-rays. Every large country has 1 or 2 of such accelerators (SOLEIL and ESRF in France).
- Large museums like Le Louvres in Paris use particle accelerators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

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.

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

Accelerators around Orsay

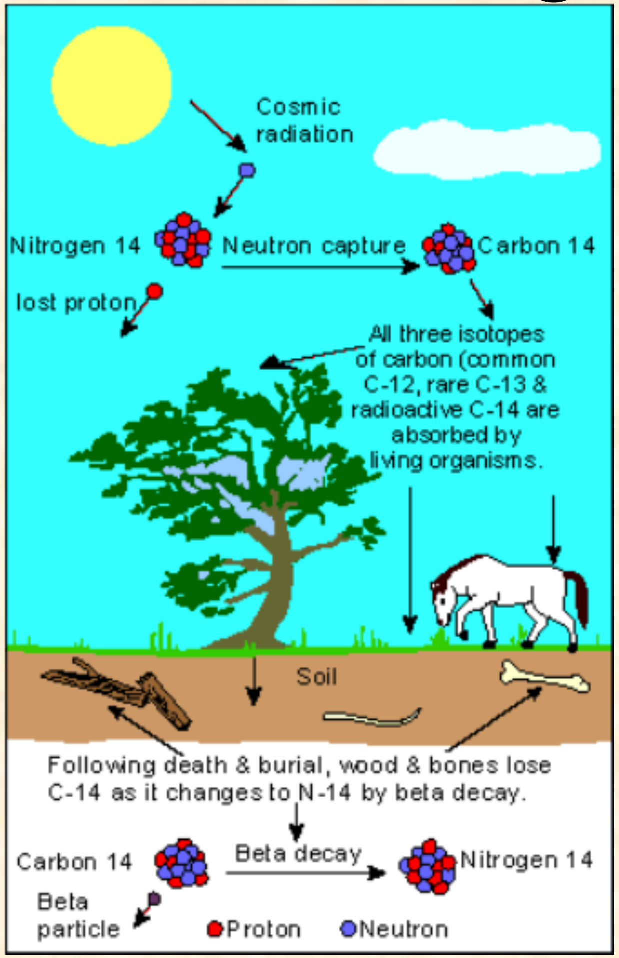


- There are 29 accelerators within 10km radius of LAL. Only few of theme dedicated to HEP.

Accelerators in England & Scotland

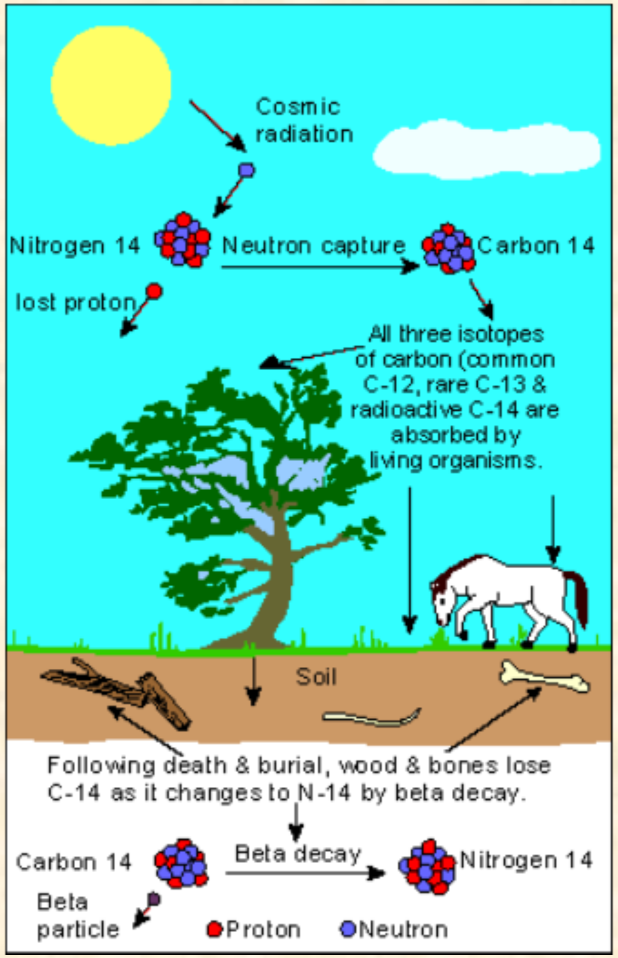
- There more than 150 accelerators.
- Only 1 of them is used to teach HEP, all others are used for non HEP applications!

Non HEP applications
Dating old artefacts



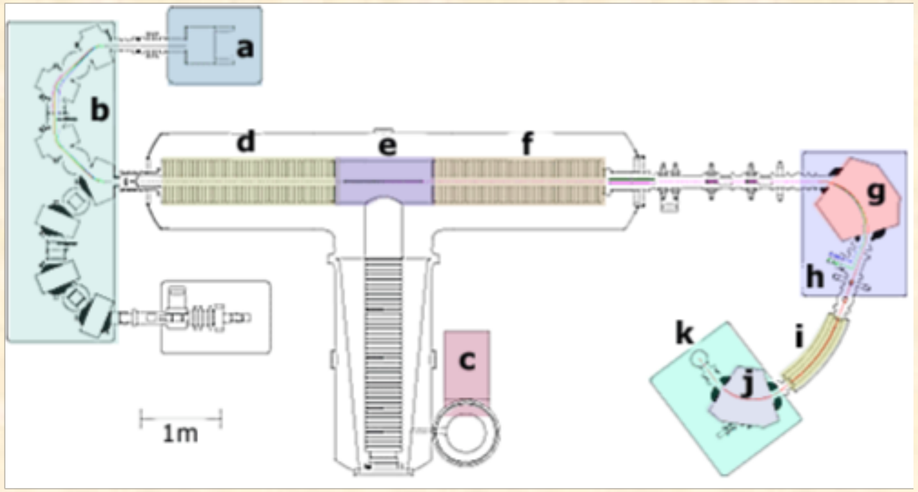
- Radiocarbon dating is allows to measure the age of ancient artefacts.
- The ratio C13 vs C14 can be measured by using an accelerator.
- This technique is called “Accelerator Mass spectroscopy”.

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.

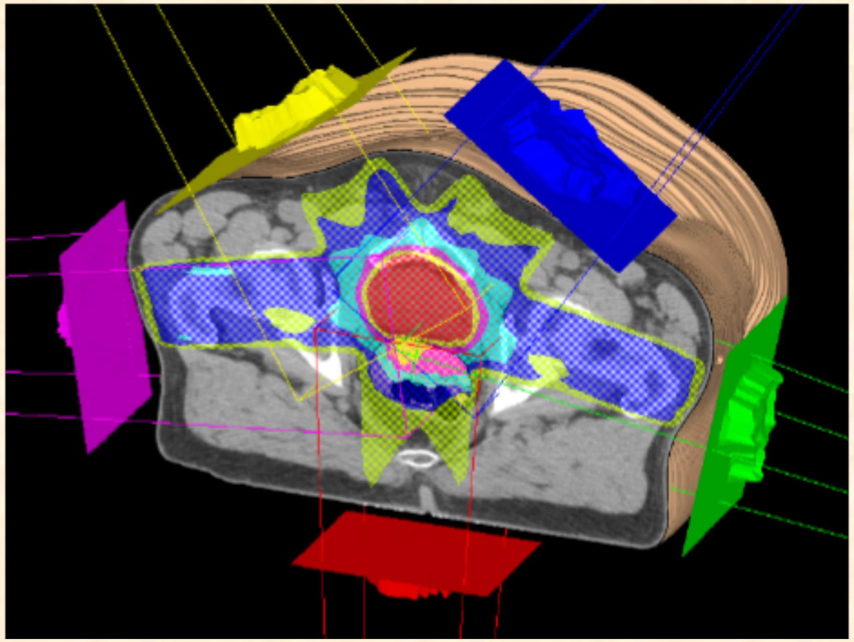
Example of AMS application Vinland map

- 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

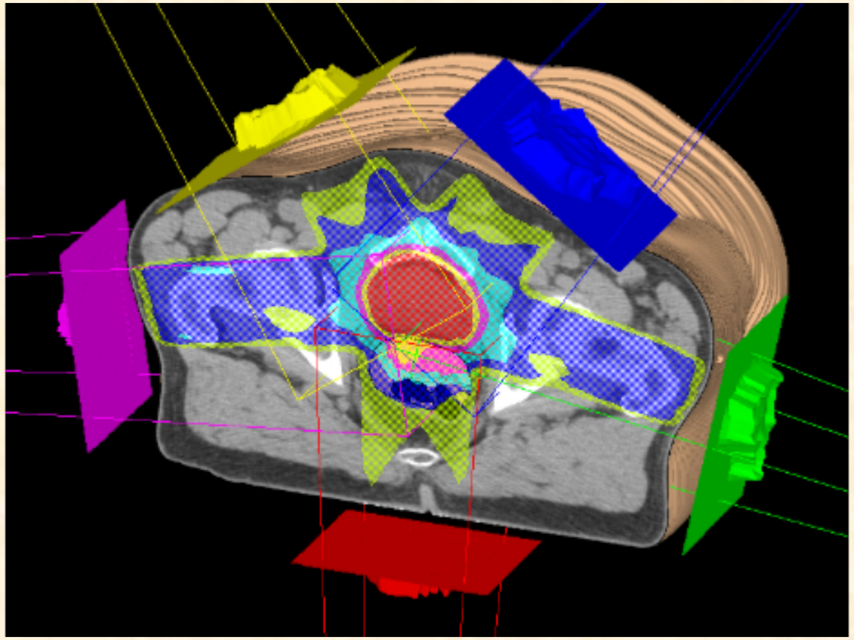


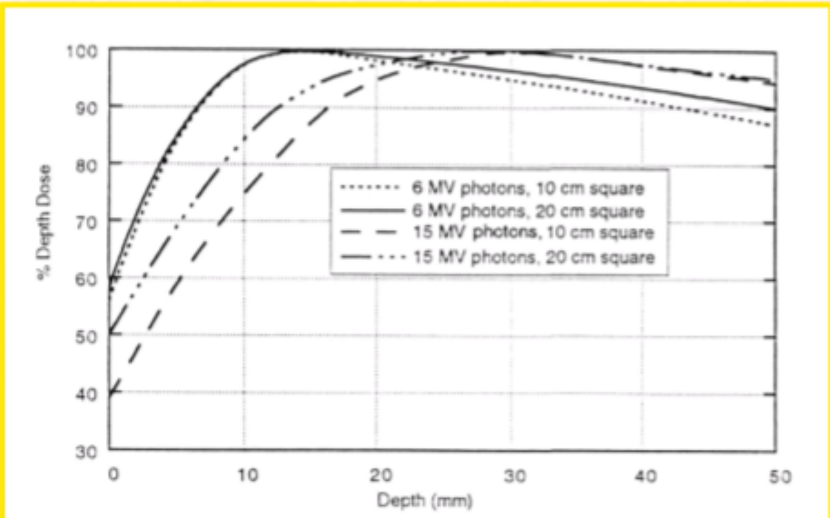
- Some type of cancer tumors are located at places difficult to reach by Surgery.
- X-rays can be used to kill such tumors.
- This is called Radiotherapy.
- Radiotherapy need 10-15 MeV electrons for a few seconds.
- The accelerator needs to be compact so that it fits in an hospital room and fields can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

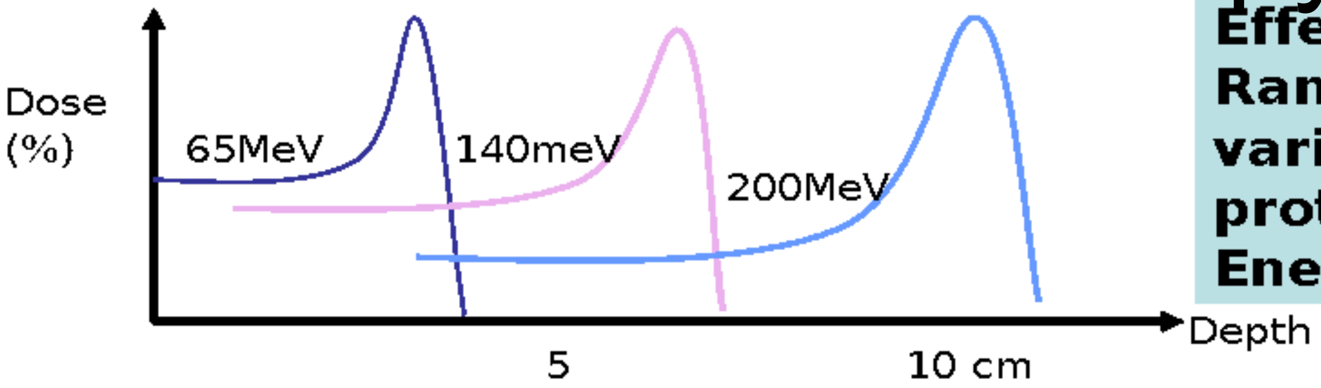
Radiotherapy



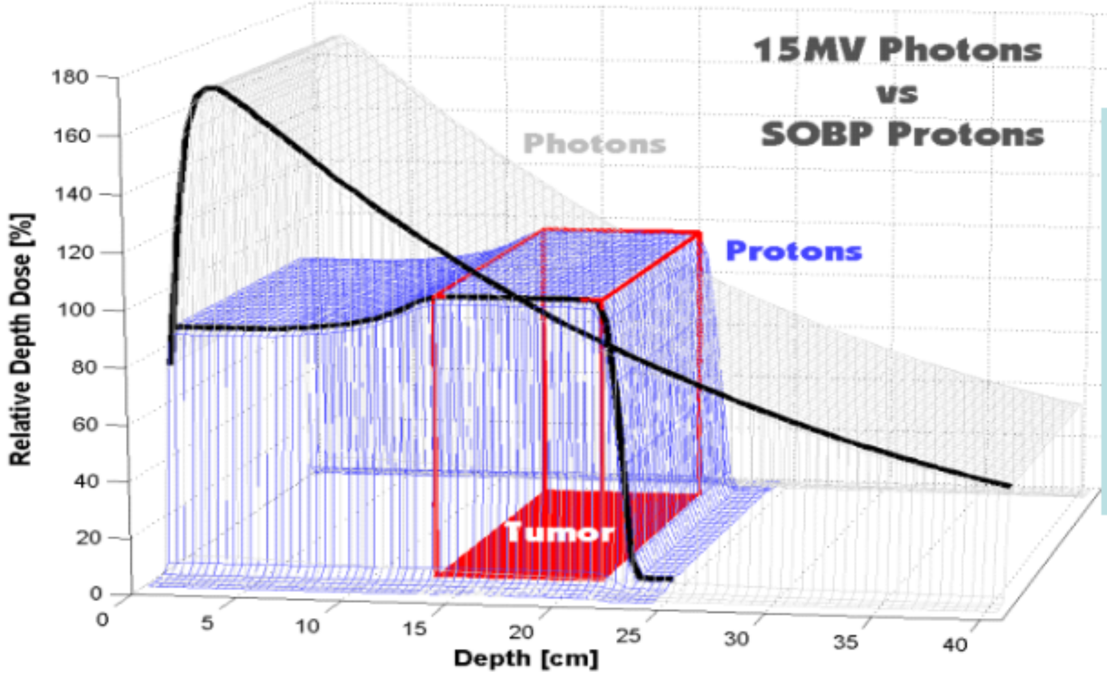


- X-rays are used to kill a tumour.
- To minimize the dose sent on healthy tissues several X-ray beams are sent in turn from different directions.
- However this technique is not ideal due to its impact on healthy tissues.

Proton and ion therapy



Effective Range varies with proton Energy



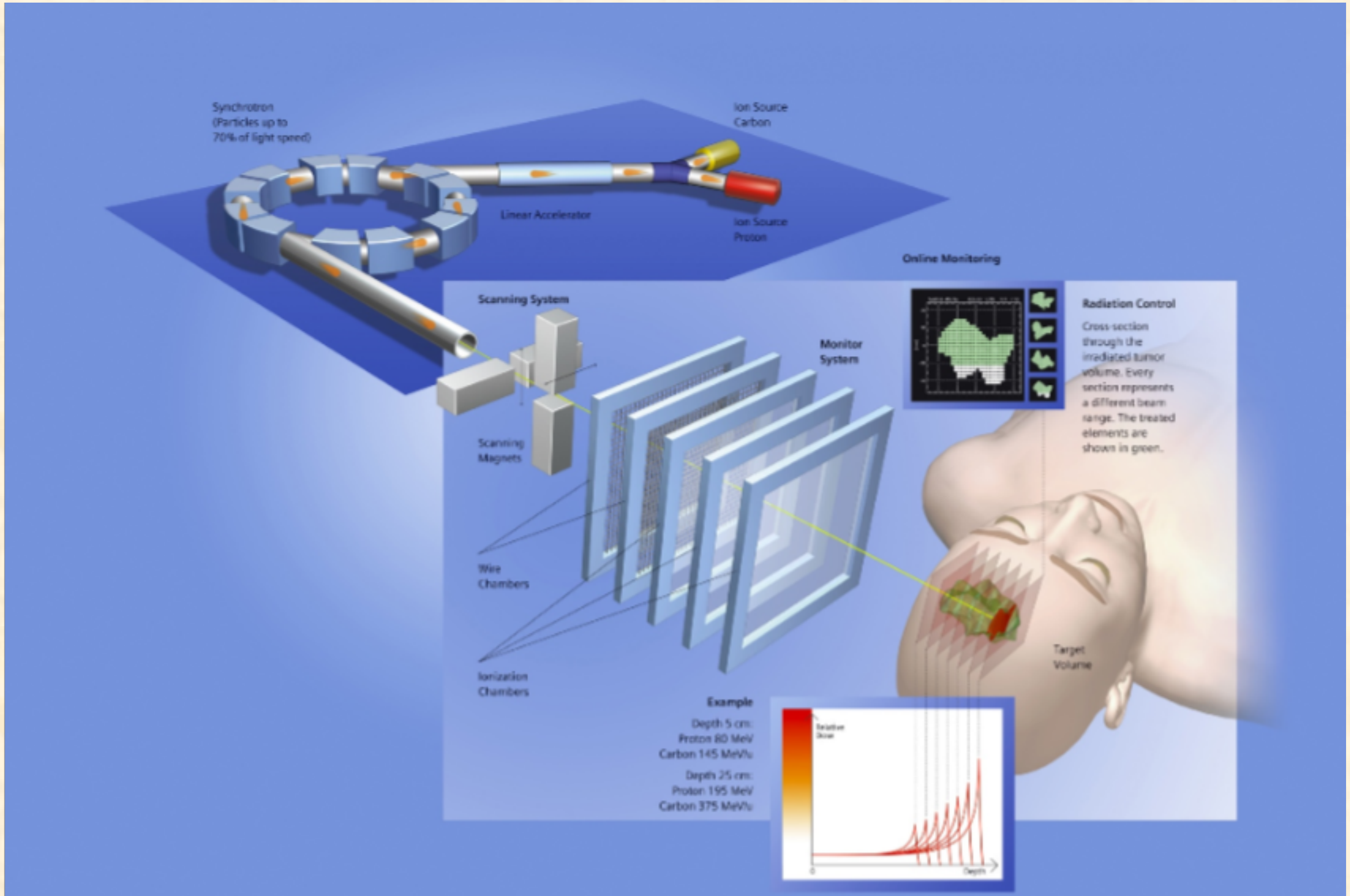
The'spread out' Bragg Peak– plateau effect

[SOBP]

Source: Bleddyn Jones, JAI graduates lectures

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

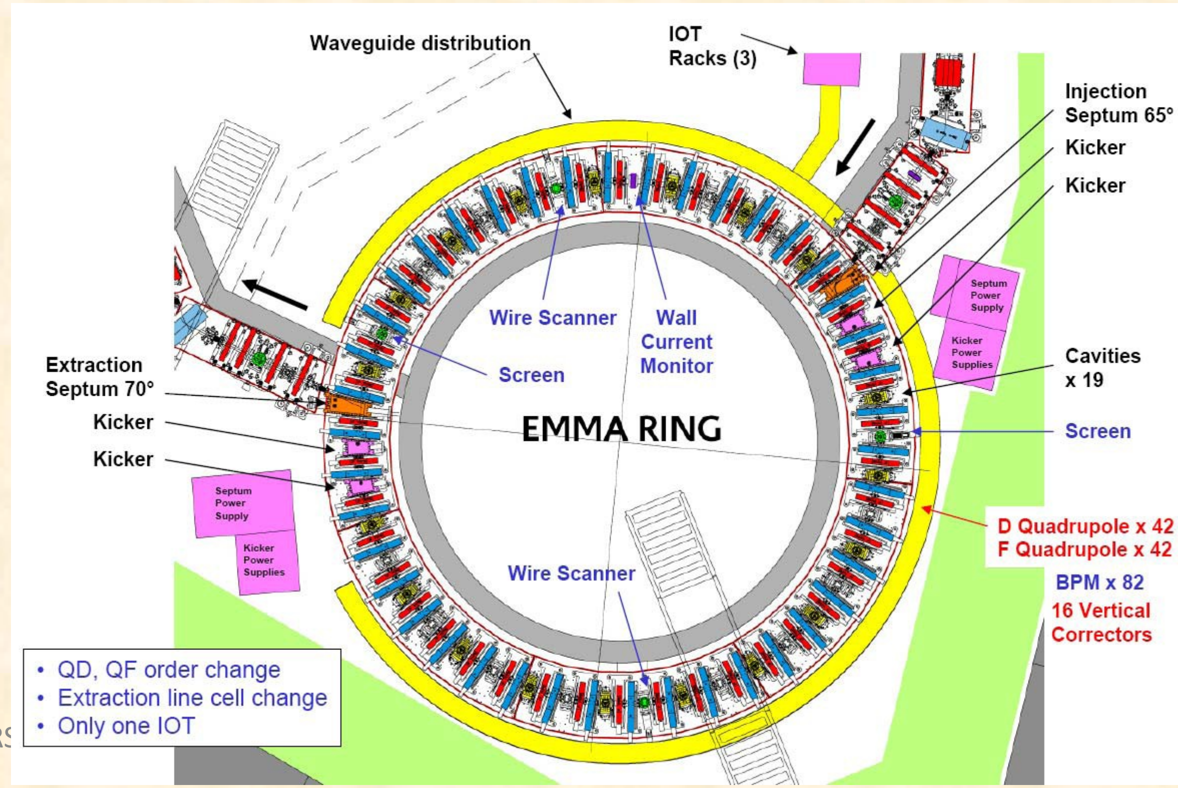
A possible solution...



Source: Bleddyn Jones, JAI graduates lectures

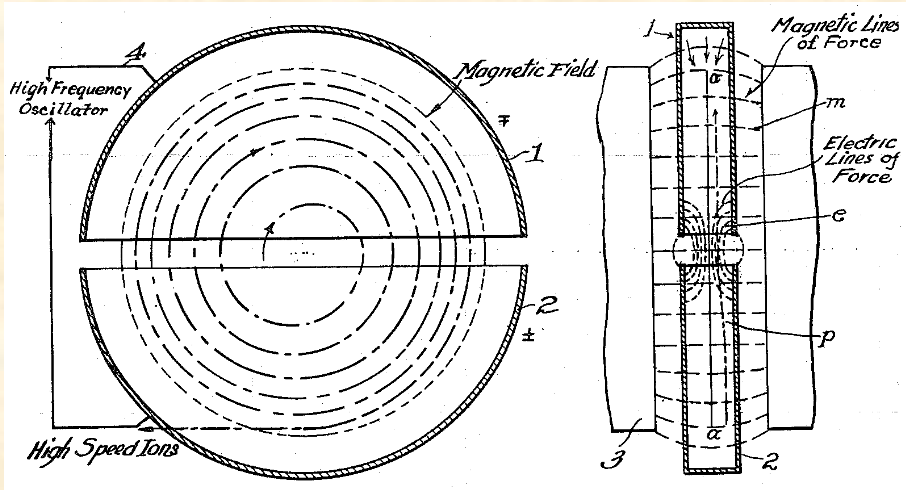
Fast protons rings

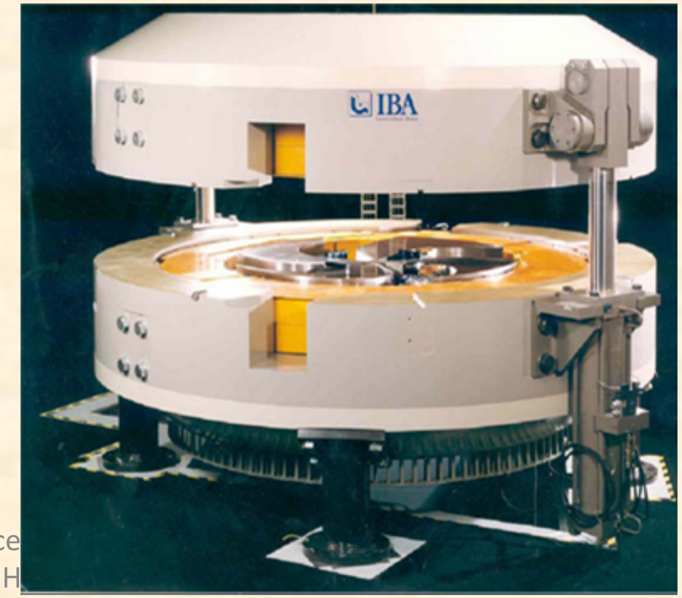
- At the moment accelerating protons in rings is slow due to resonances crossing.
- R&D is ongoing to avoid that problem.



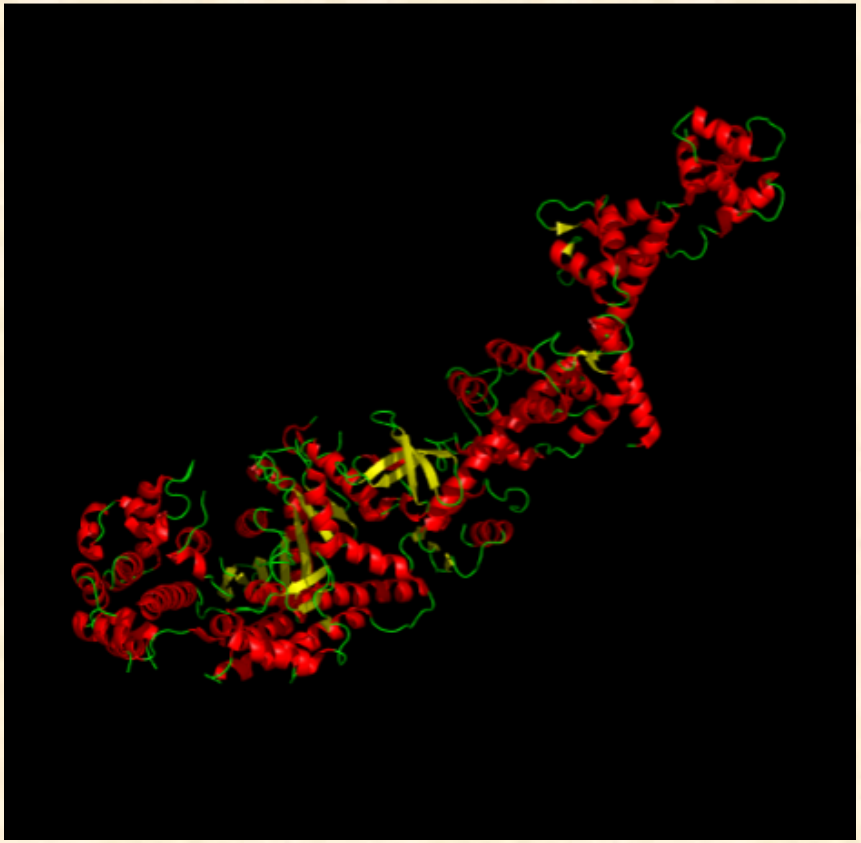
Medical cyclotron

- 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.





Pharmaceutical drugs

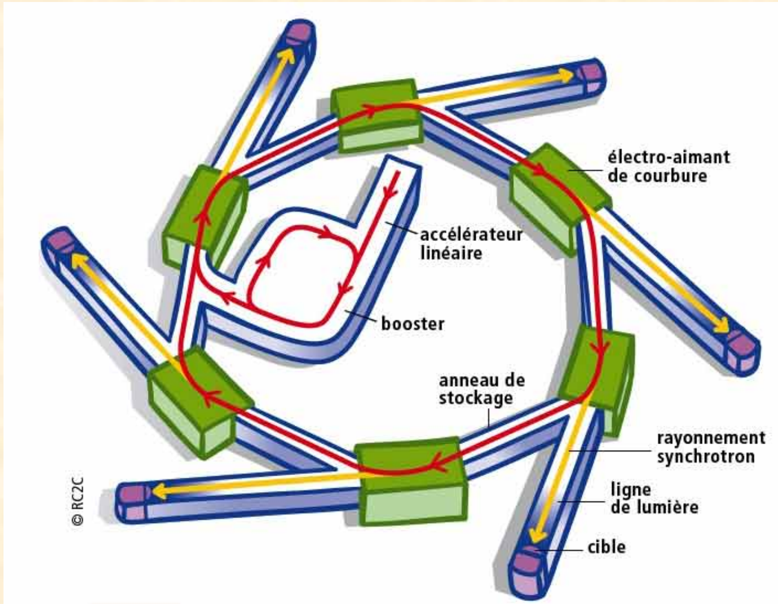


- To be efficient a drug need to target the correct molecule.
- This can only be achieved by studying the diffraction of intense on the molecule.
- What type of machine (gun, accelerator, ...) is best suited to deliver an intense stable beam of X-rays?

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



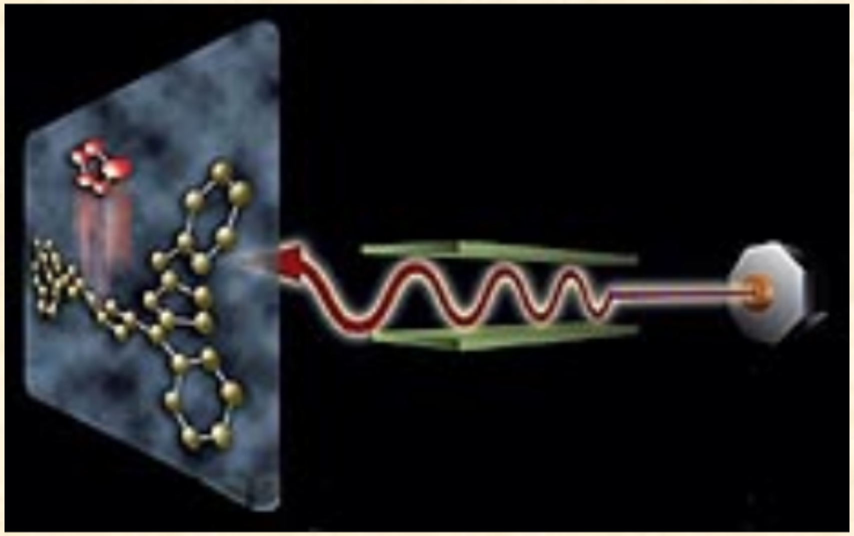
Source: SOLEIL

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.

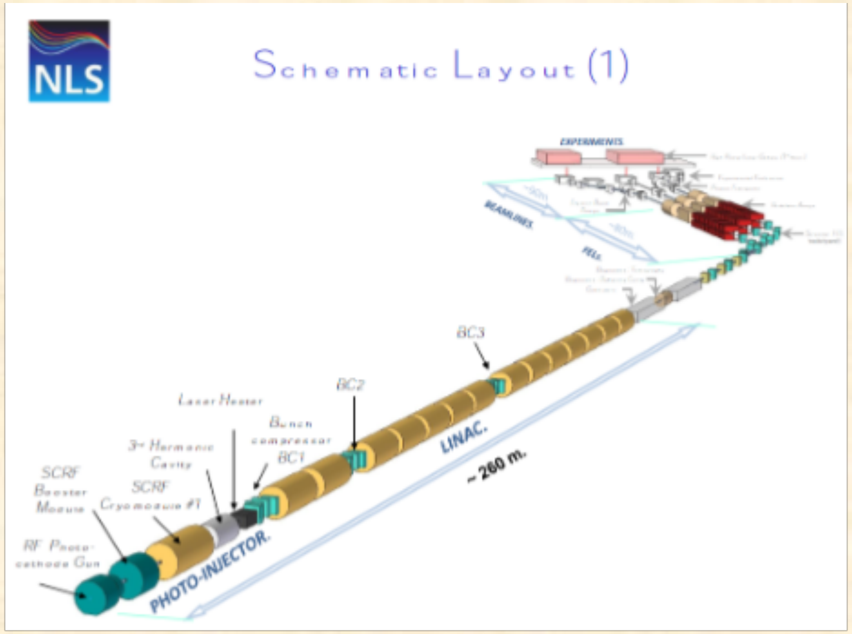
The next generation of light sources

- 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?



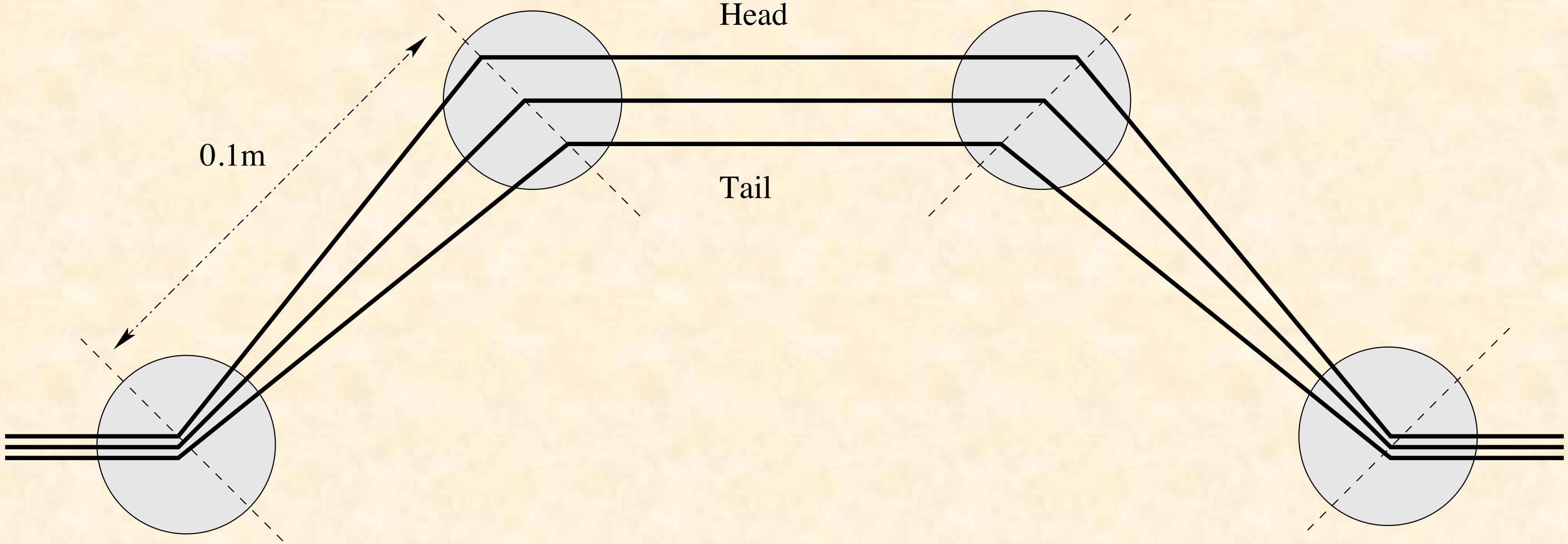
Next generation: Linac based Free electron lasers

- Only linac based accelerators can deliver ultra-short pulses.
- 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.



Neutron crystallography

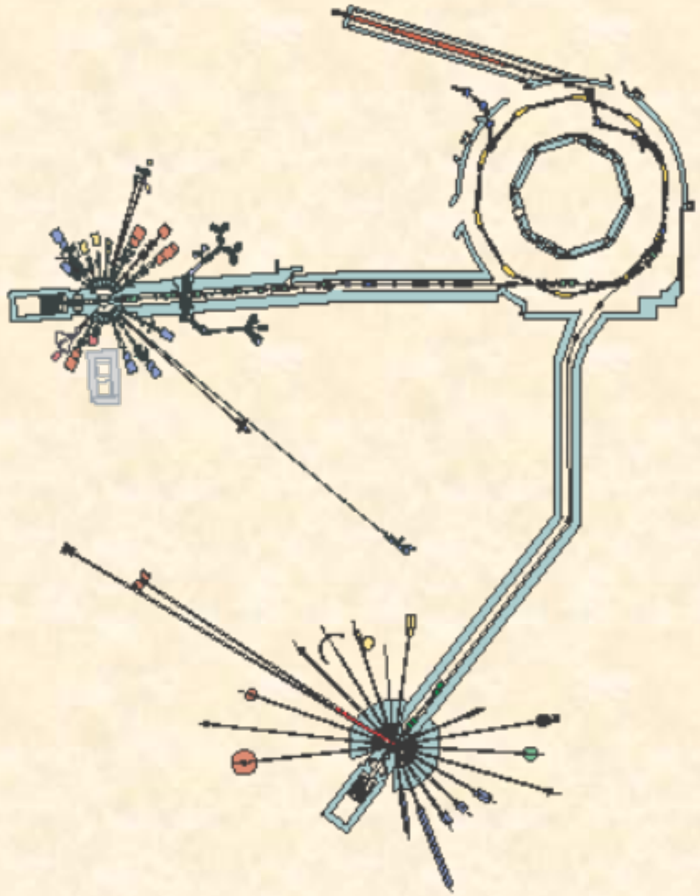
- X-ray crystallography can only be used on matter that is rather transparent to X-rays.
- Other objects such as this Roman vase or the materials used to build an aircraft need a probe that penetrate deeper in the material: Neutrons.
- How can we produce neutrons?

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?

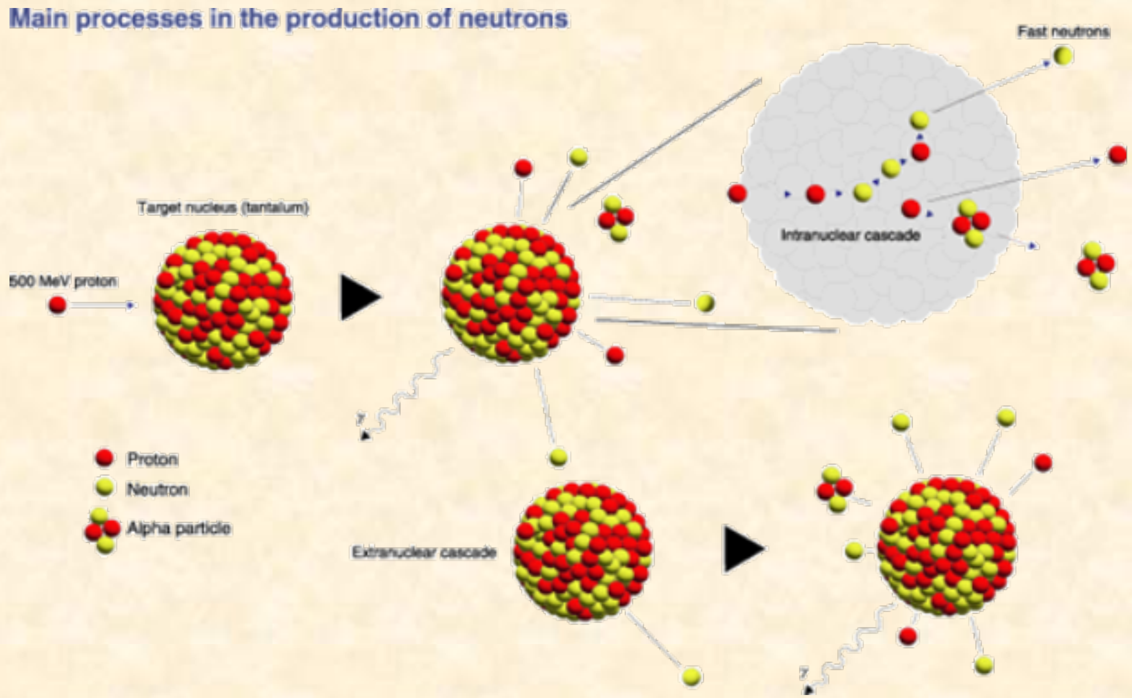
A neutron source: ISIS

- 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+.

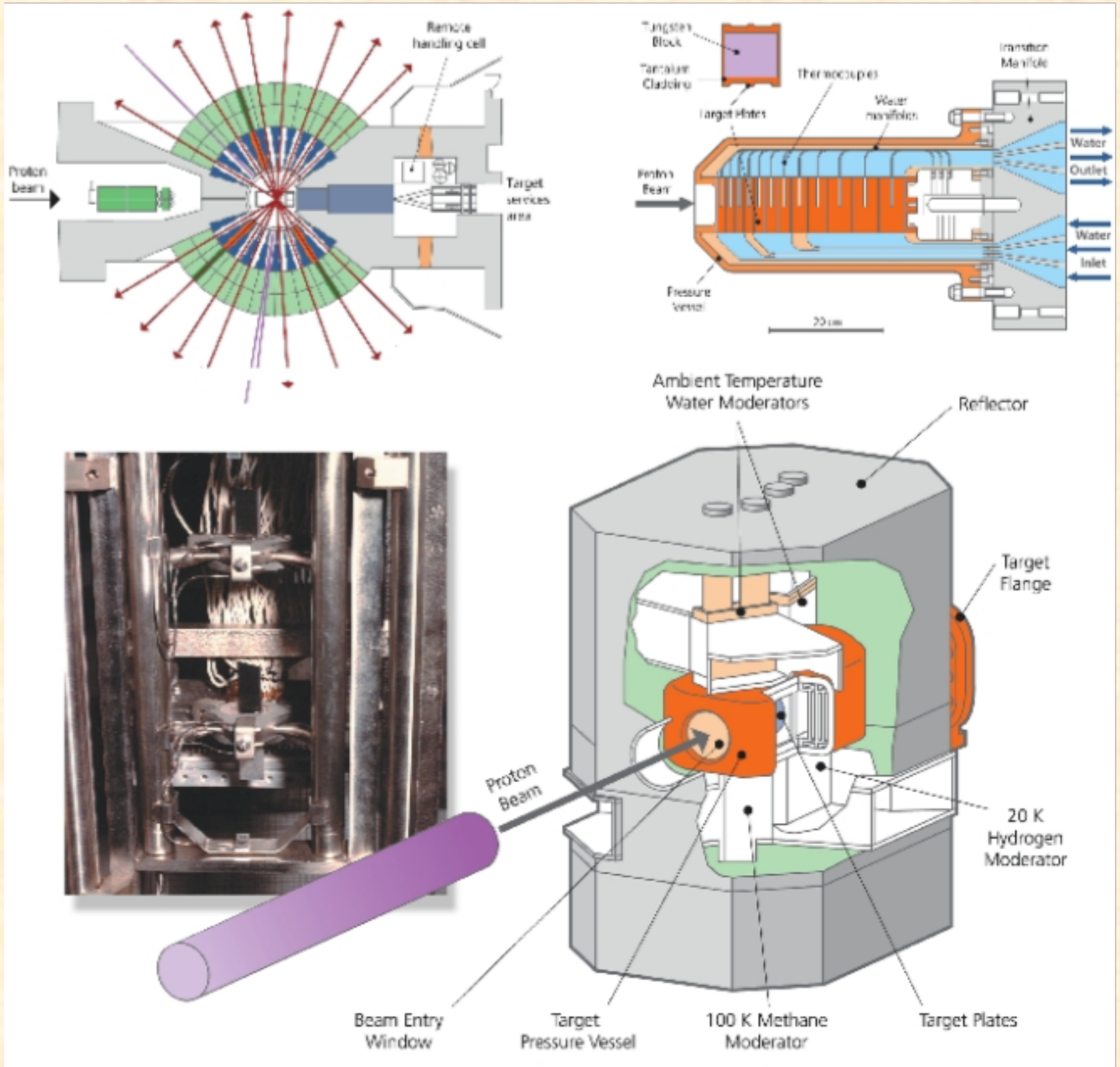


Spallation

- 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.

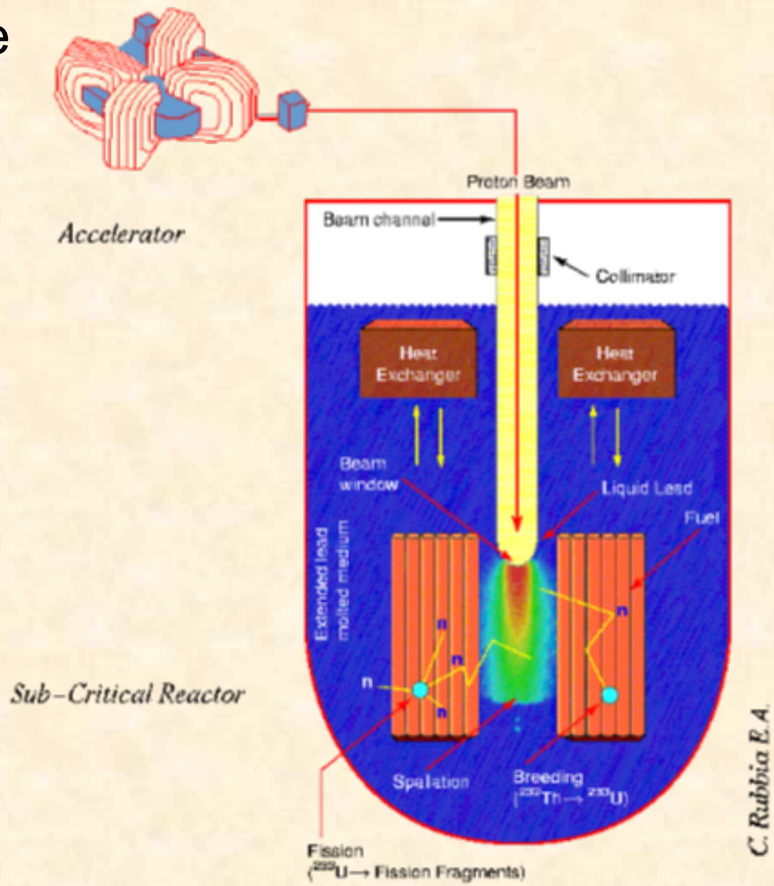


Spallation target



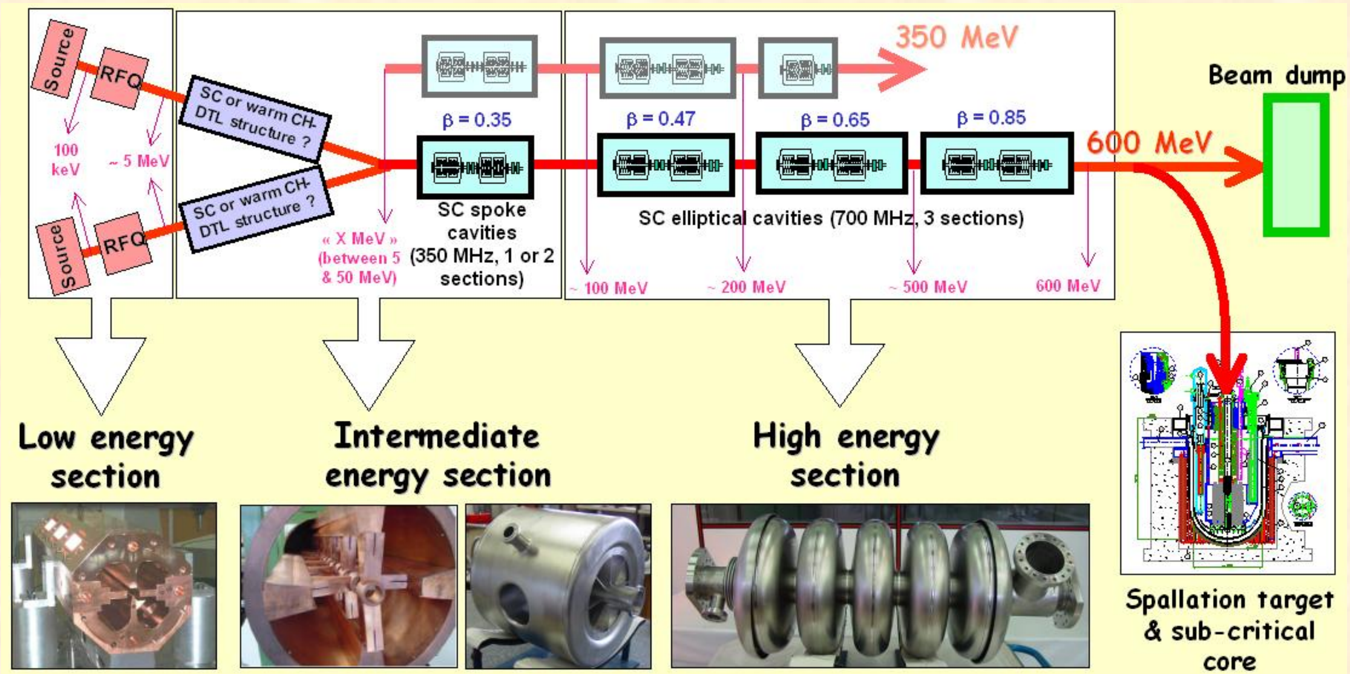
Accelerator Driven sub-critical reactor (ADSR)

- 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.

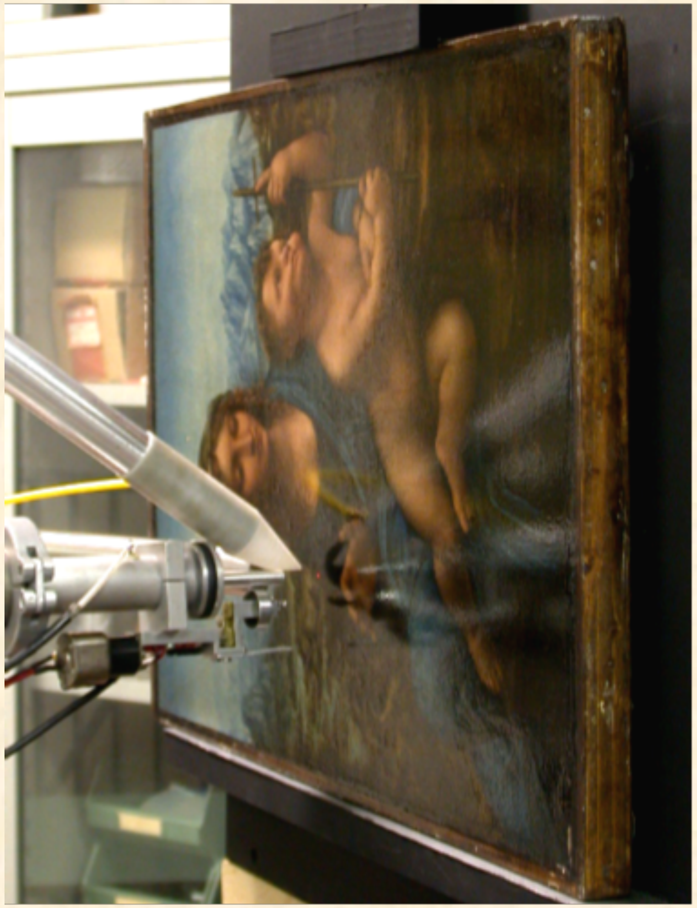


Need for high redundancy

- 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.

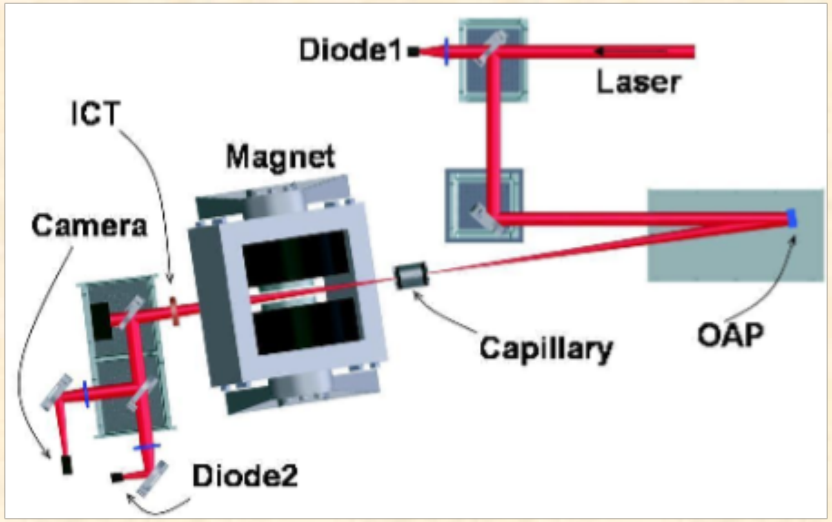


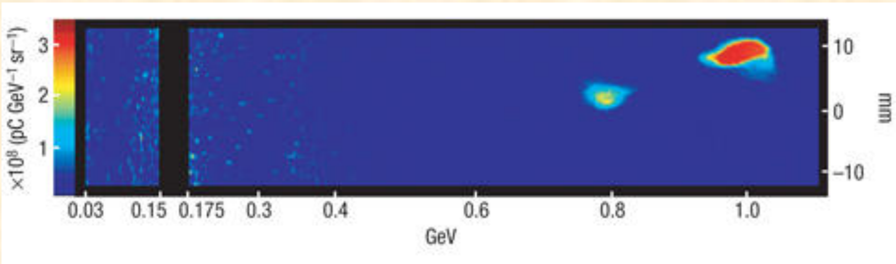
... and much more



- 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)

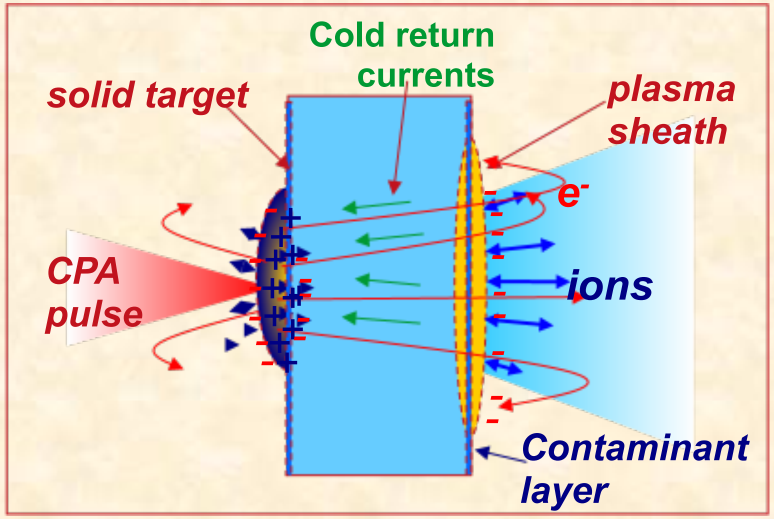




Leemans et al, doi:10.1038/nphys418

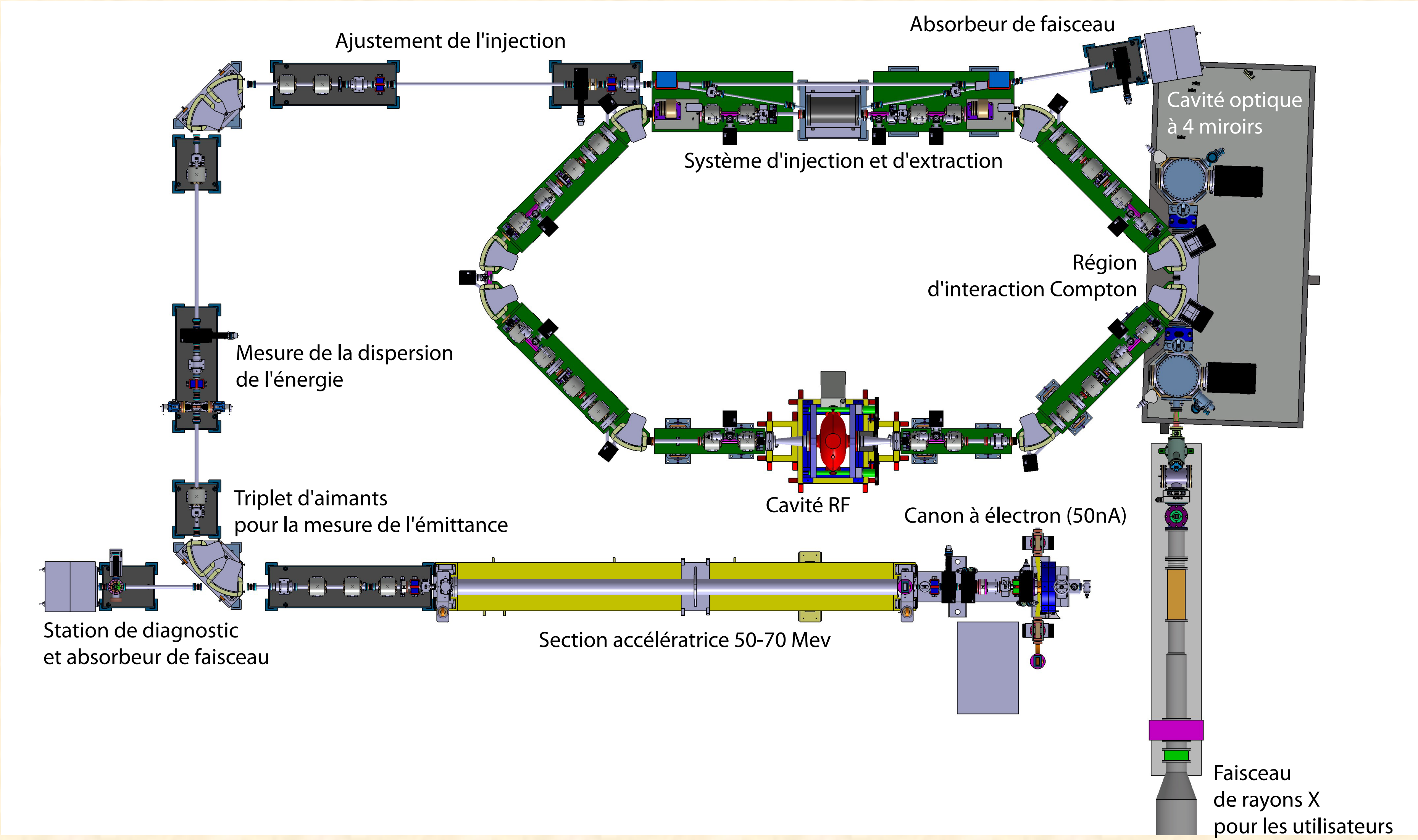
- An intense laser pulse shot in a plasma can accelerate electrons to very high energy: 1GeV over 33mm
- Such electron source could produce high energy low emittance electron beam over very short distances.
- This could be used to drive a compact FEL.

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.

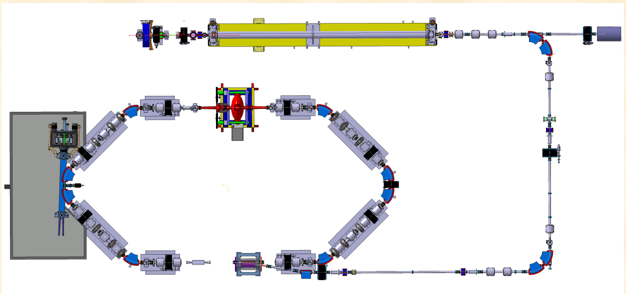
ThomX

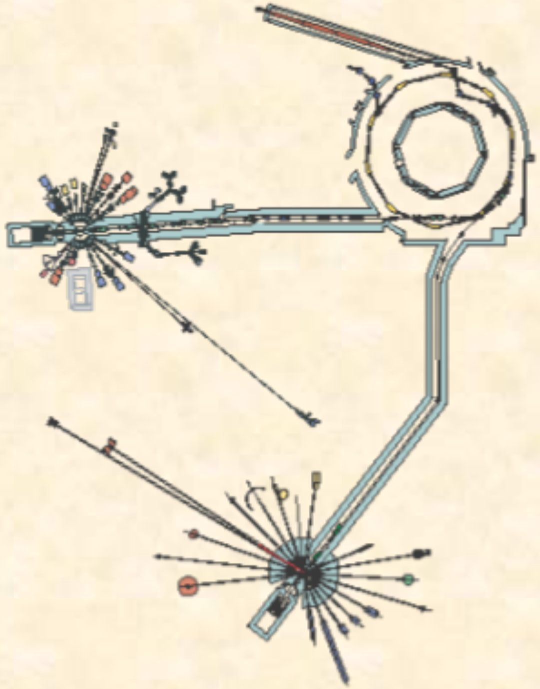


- ThomX is an accelerator being built at Orsay

Costs

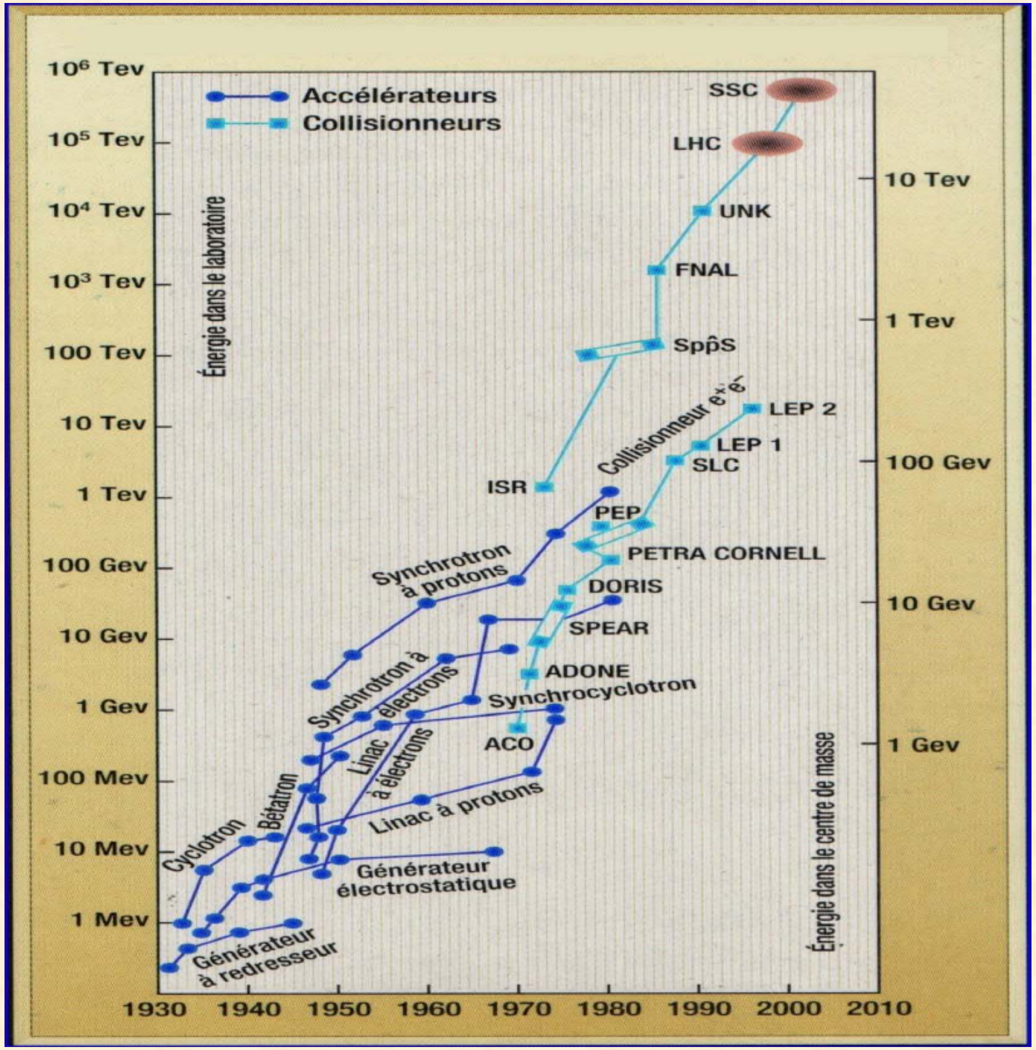


- Small accelerators can be operated by single institutions.
- Large accelerators need to be built as part of international collaborations.

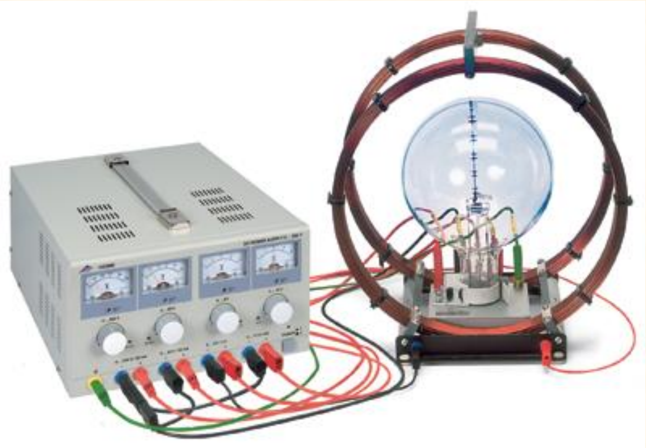
Progress of accelerators

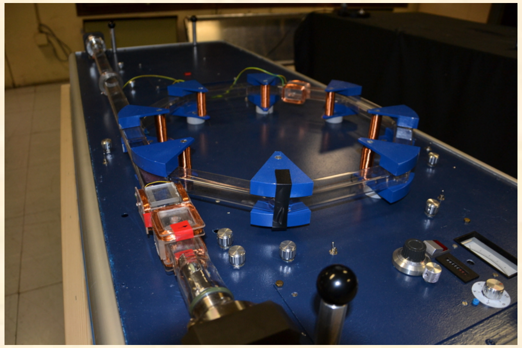


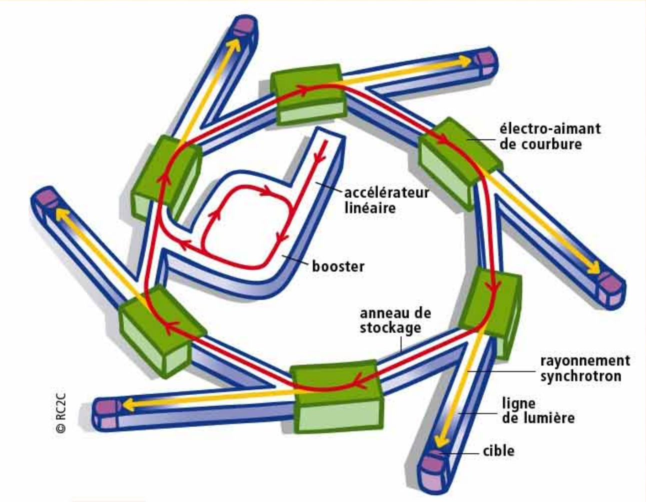
- Accelerators have made tremendous progress over the past 50 years.
- They drove part of the developments of HEP.
- However they have also become very large and expensive.

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 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