CERN

An Introduction to Particle Accelerators

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A question:
How old are particle accelerators?
Or:
How many years ago was invented the first modern accelerator?

1928: 89 years since the invention of the first modern accelerator

(i.e. using periodic acceleration provided by high-frequency fields):

PhD thesis of Rolf Wideröe, a Norwegian student in Aachen

A relatively young technology!

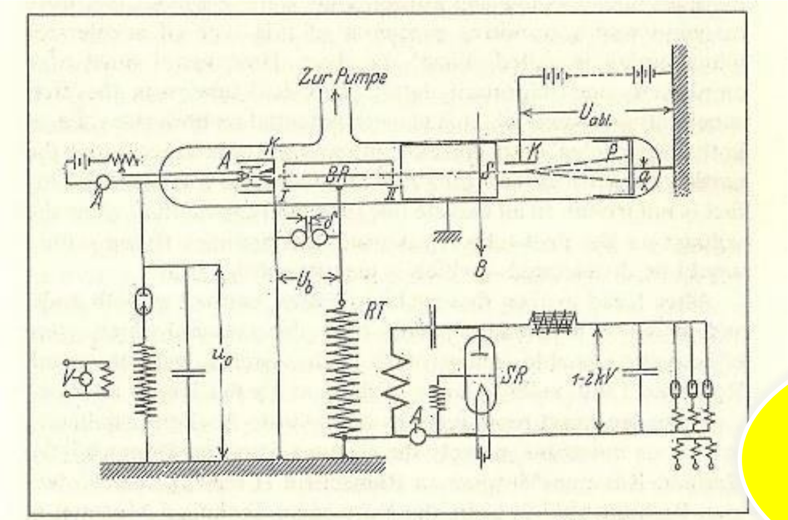
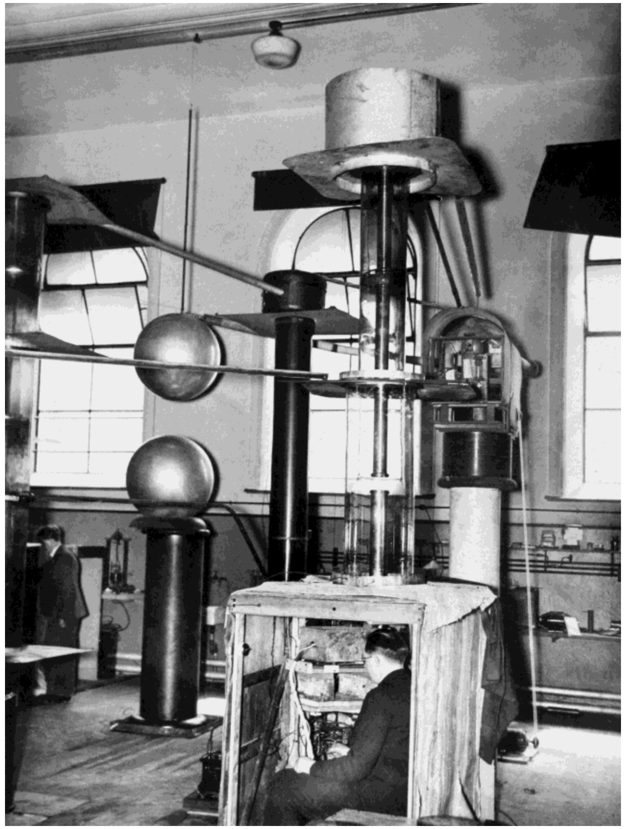


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz $\rightarrow$ 50 keV acceleration ("at a cost of four to five hundred marks"…) in a 88 cm long glass tube.

A small proof-of-principle device that will take years to develop into large accelerators



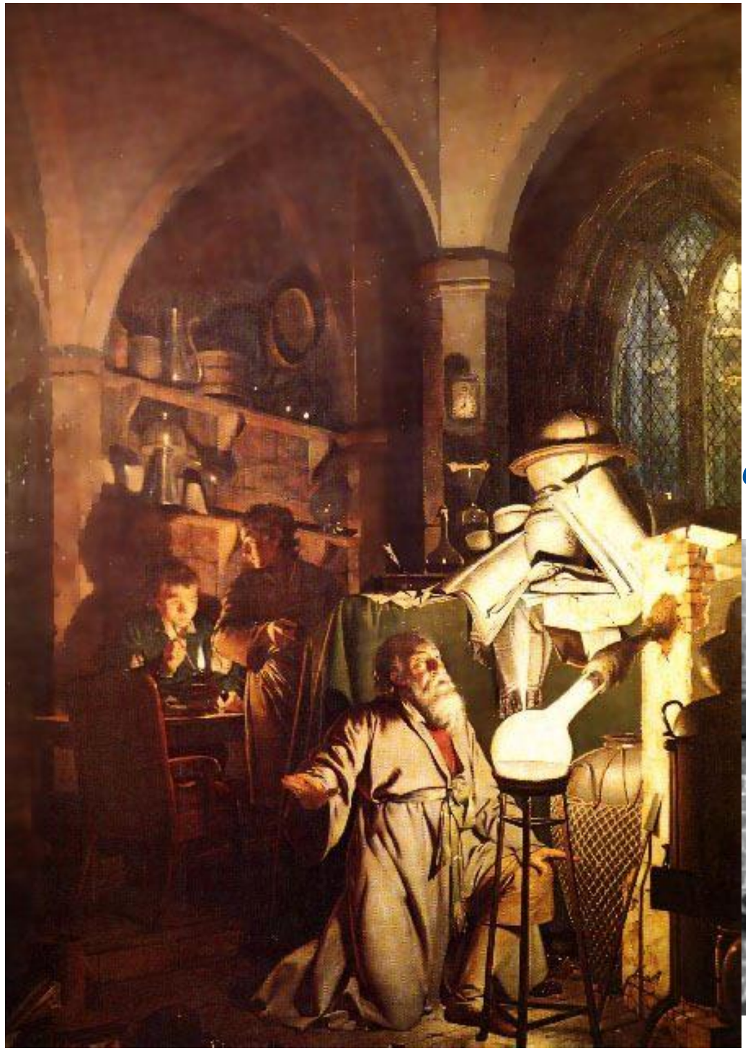
In parallel, John Cockcroft and Ernest Walton, develop an electrostatic particle accelerator in Cavendish Labs that in 1931 will be the first to disintegrate lithium after accelerating protons to 400 keV.

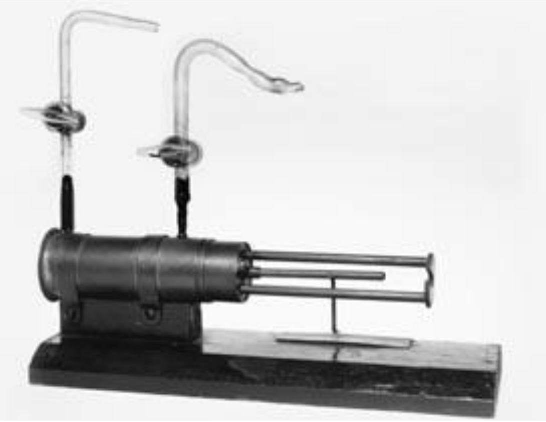
Why all this excitement about “accelerators”?

1919: E. Rutherford transmutation experiment: a nitrogen nucleus bombarded by α-particles (from Ra and Th decay) converts into oxygen and hydrogen → start of a new era for science!

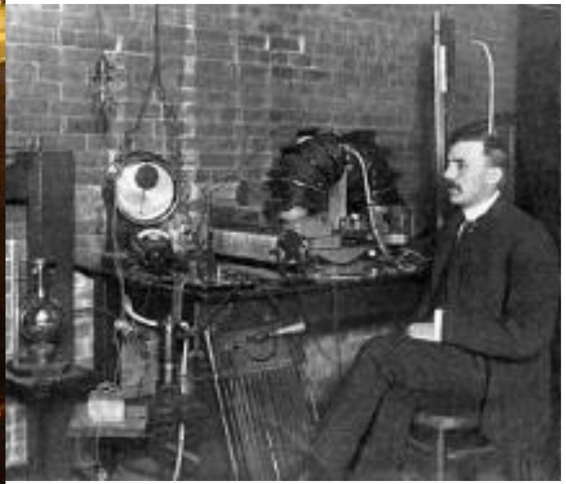
But using particles from radioactive decays only few light atoms can be modified.

1927: Rutherford in a speech at the Royal Society urges scientists to develop “accelerators” producing a large number of energetic particles and capable to disintegrate heavy nuclei,

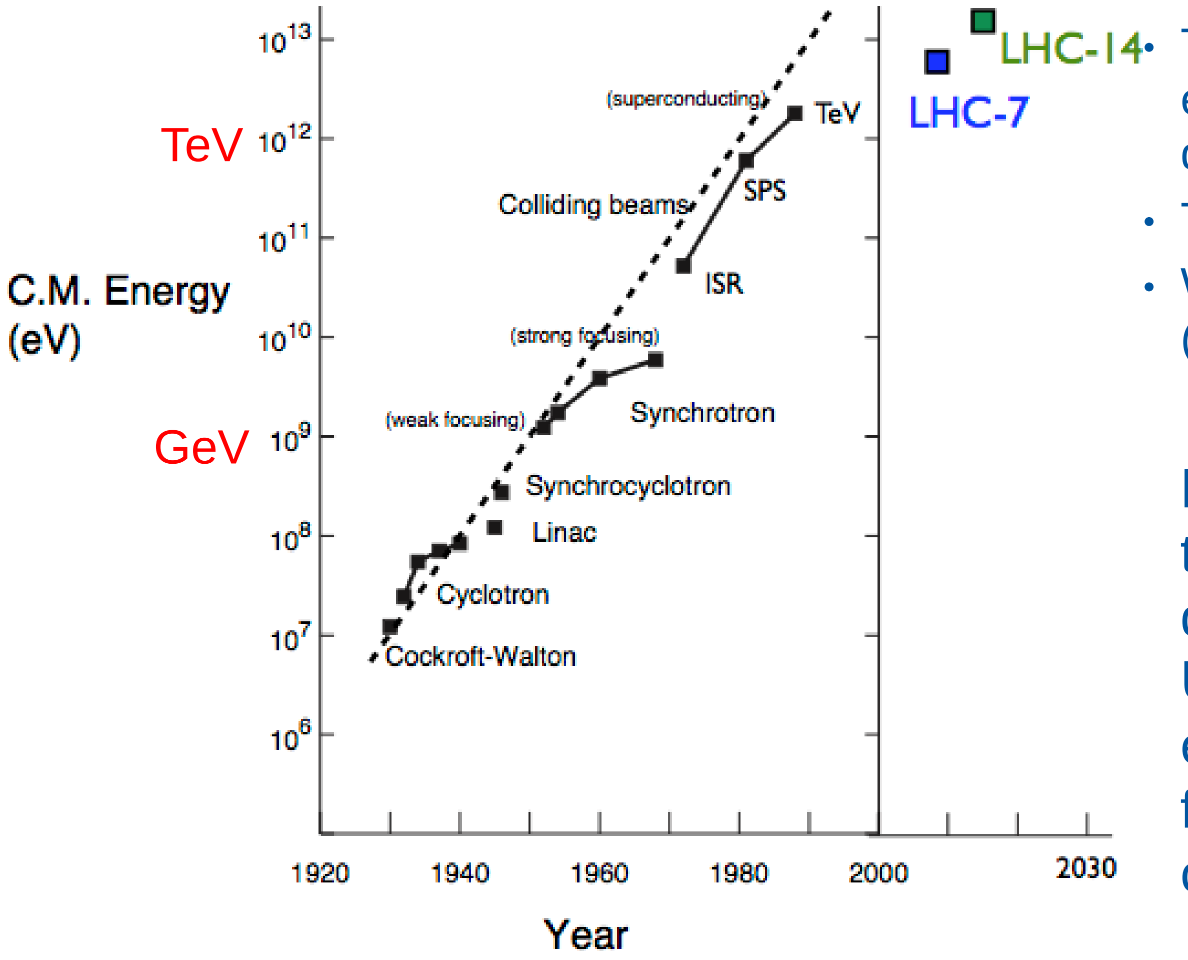




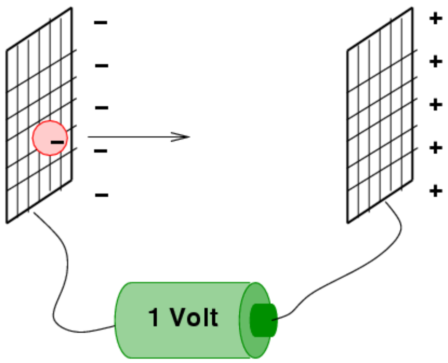
e original Rutherford chamber:



The race to higher energies starts…



- The energy acquired by an electron in a potential of 1 Volts is defined as being 1 eV
- Thus 1 eV = 1.6 x 10^{-19} Joules
- We use KeV, MeV, GeV, TeV (10^{12})

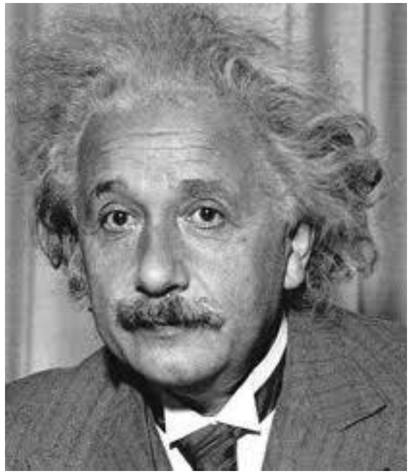


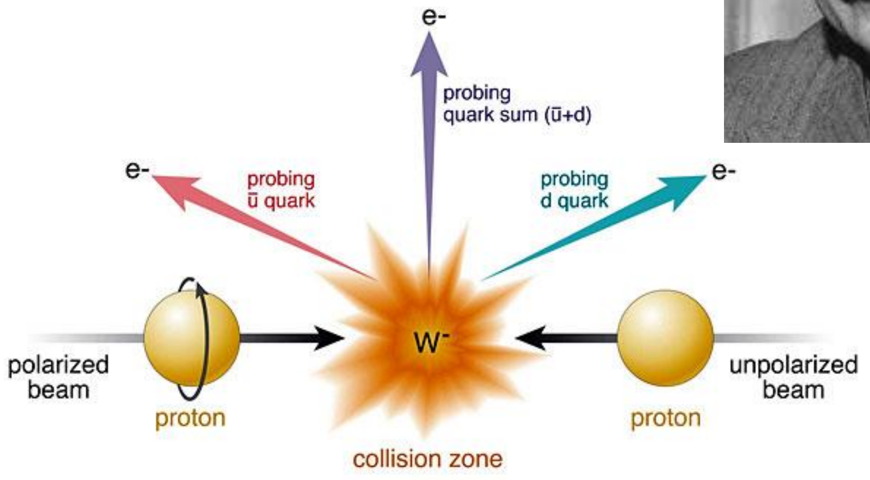
From the first accelerators in the 1930's the technology has evolved with the invention of new designs and principles.
Until the 1990's, constant exponential increase of energy with time (Moore-type exponential growth) followed by a change of slope because of size and cost of new projects.

Why higher energies?

Not only to break the nucleus but to create new particles !

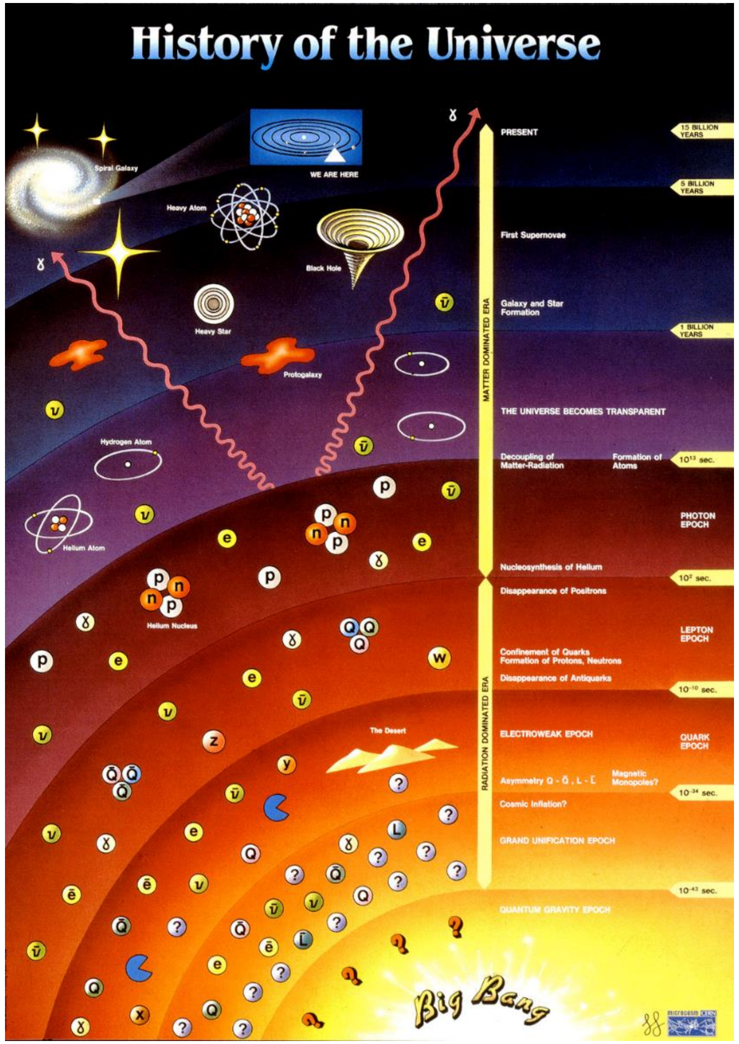
$$E = m\,c^2$$



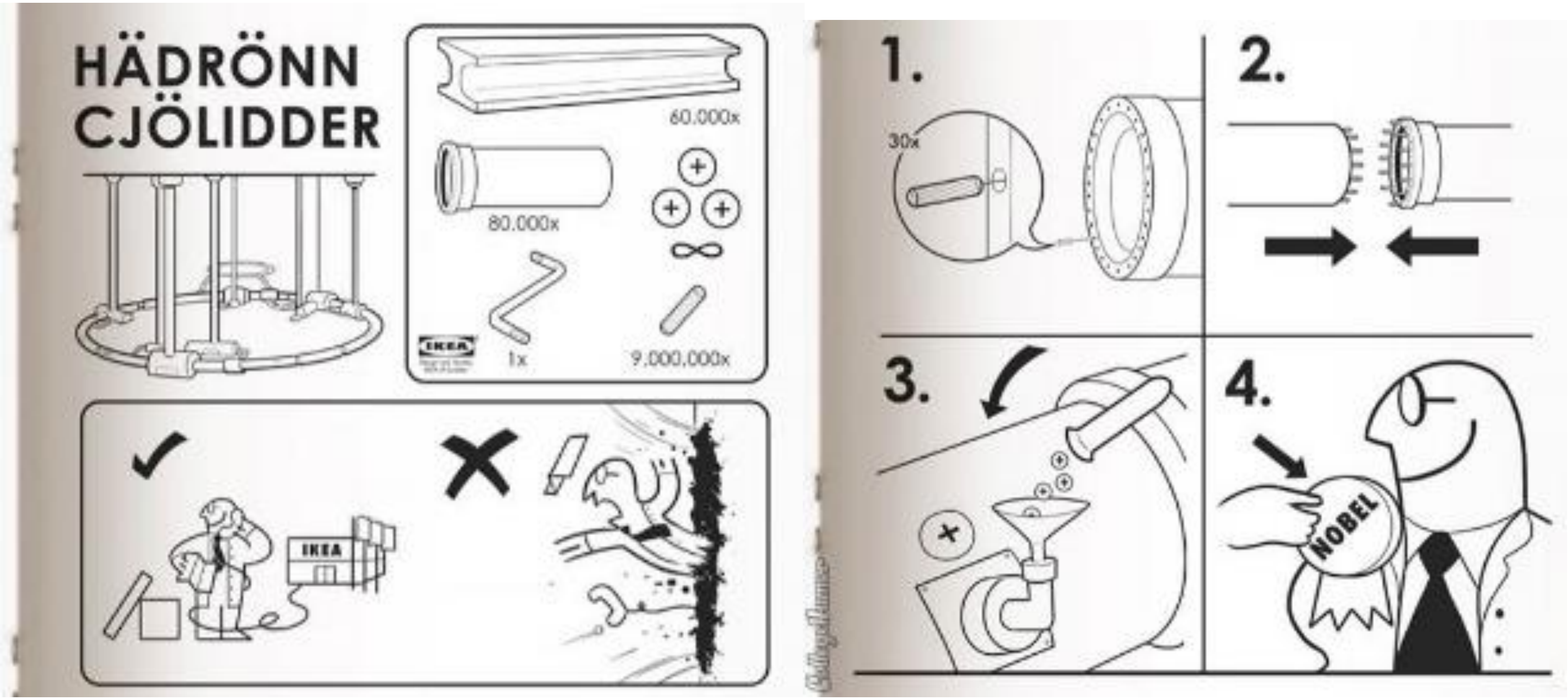


In our accelerators we provide energy to the particles we accelerate.

In the detectors we observe the matter created



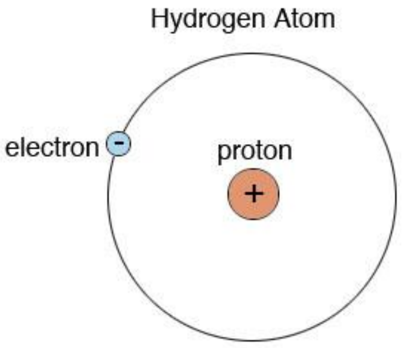
And now, let's build together our particle accelerator



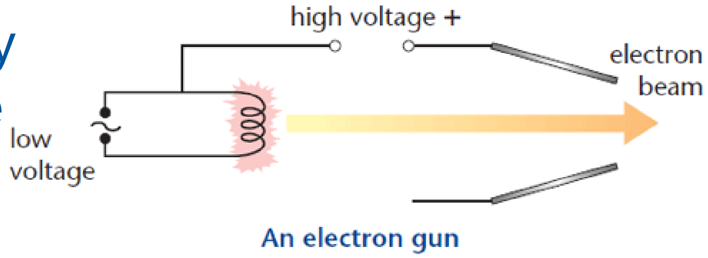
First of all, you need the charged particles

You find them inside the atoms!

Protons are obtained heating an hydrogen gas into a plasma and then extracting the protons with a high voltage



Electrons are obtained by heating of a filament (like an electric bulb)



In both cases, after production you need to give a first small acceleration (< 100 keV) with an electrostatic section

The origin of all CERN protons

A 5 kg bottle of hydrogen contains 3’000’000’000’000’000’000 billions of protons!

And the LHC needs only 1’200’000 billions of protons per day.

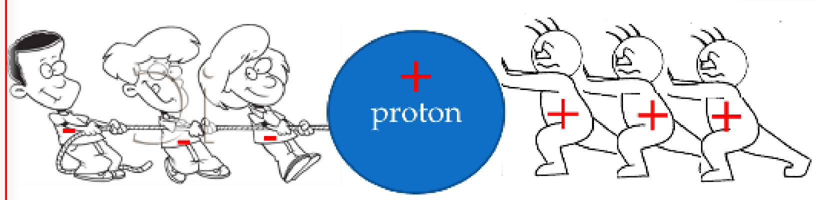
And now you need to give them energy and to control their motion

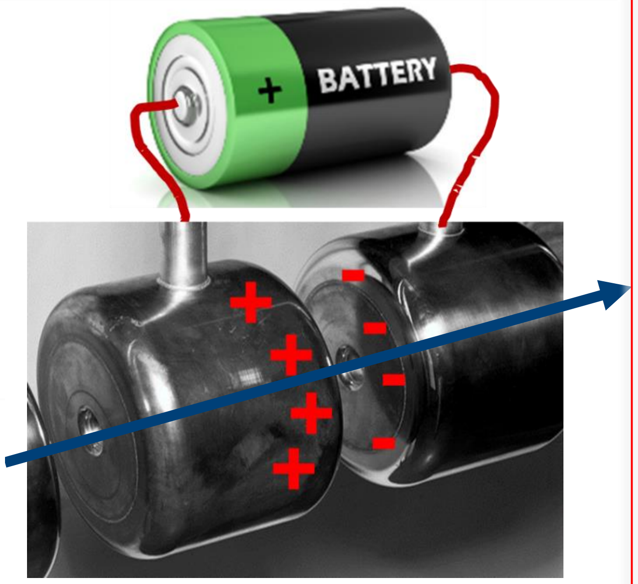
The key to the process:
Lorentz force experienced by a charged particle going through an electric and/or magnetic field

$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

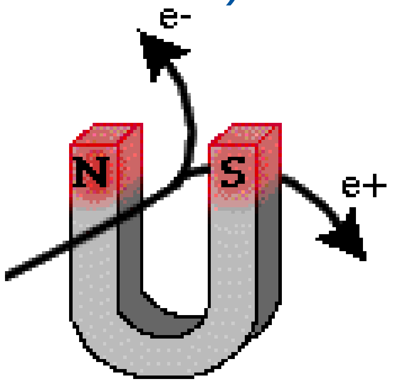
q=electric charge, v=velocity

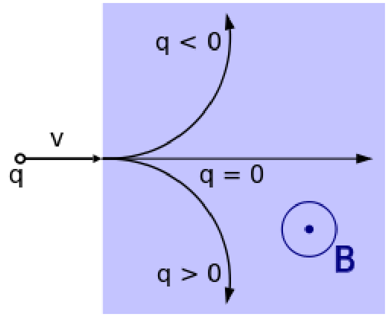
An **electric fields** produced by a voltage applied between 2 electrodes (tubes) gives energy
A tube allows particles to go out of the electric field region



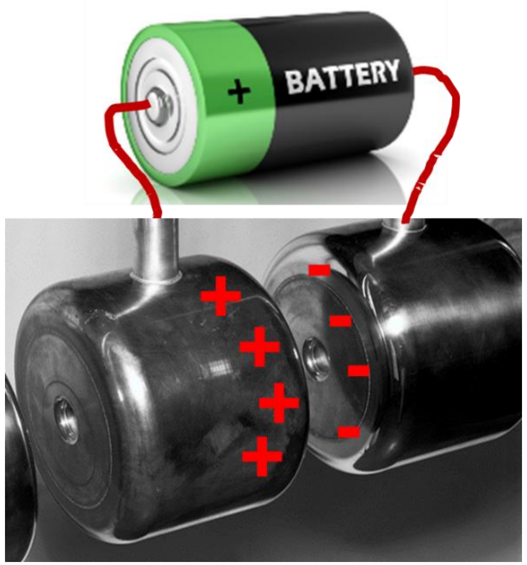


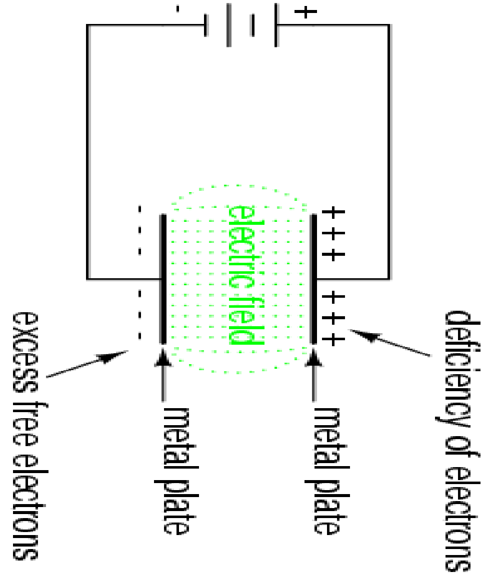
A **magnetic fields** produced by a magnet (electromagnet or permanent) will deflect the particles.





The initial acceleration stage

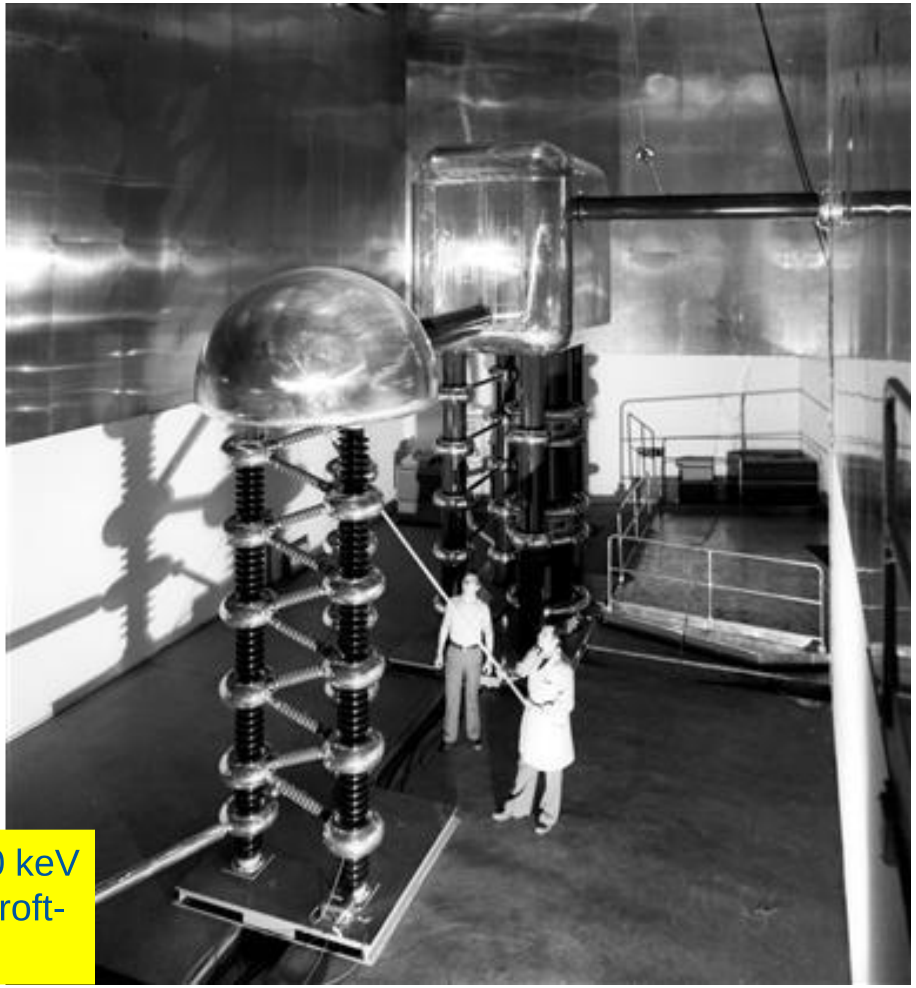




Electrostatic: use a DC voltage between 2 tubes

Corresponds to a capacitor

Limitations: few 100 kV are possible but difficult, few MeV possible but require huge installations

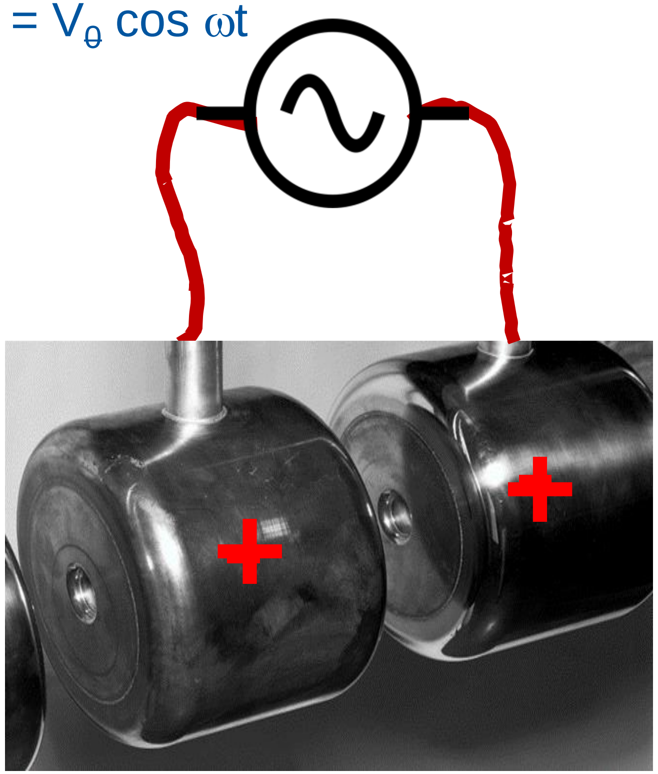


The old (1975-92) CERN 750 keV pre-accelerator, fed by a Cokroft-Walton generator.

And then? Use Wideröe's idea: Radio-Frequency (RF) fields

Innovation by cross-fertilization: use the radio transmission technology that was rapidly developing in the 20's and connect a radio transmitter to a system of tubes to obtain incremental acceleration.

$V = V_0 \cos \omega t$



Ion Source
Ionised potassium atoms

Drift tube
2 gaps, one on each side

Spectrometer
Transverse electric field

System in vacuum
To avoid losing particles on air molecules

Radio generator
1 MHz, 25 kV

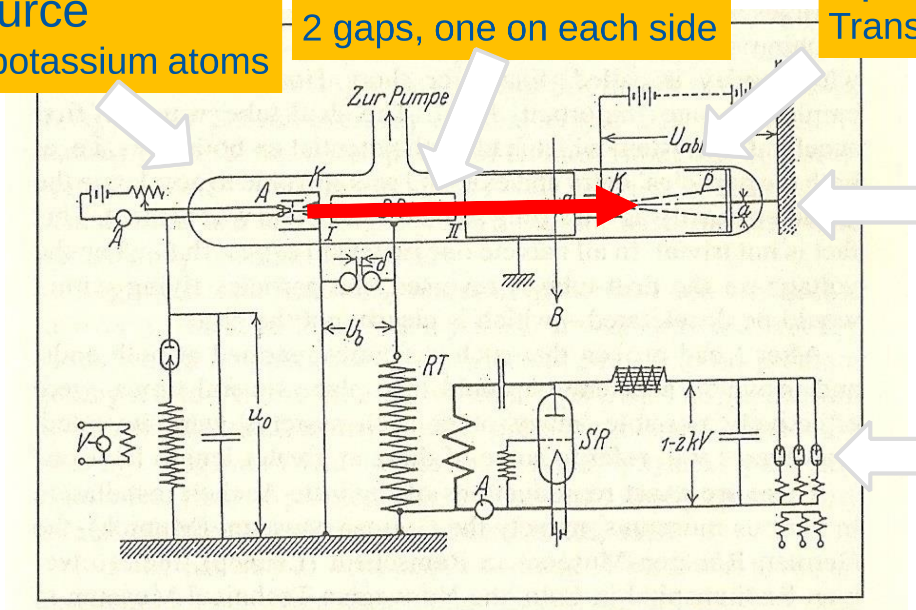
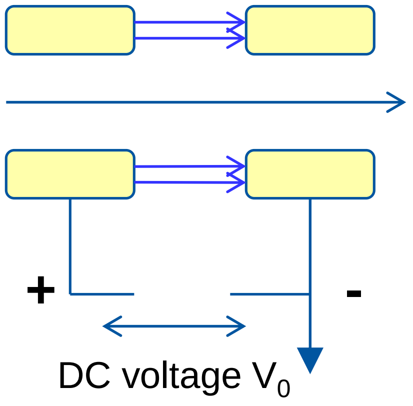


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

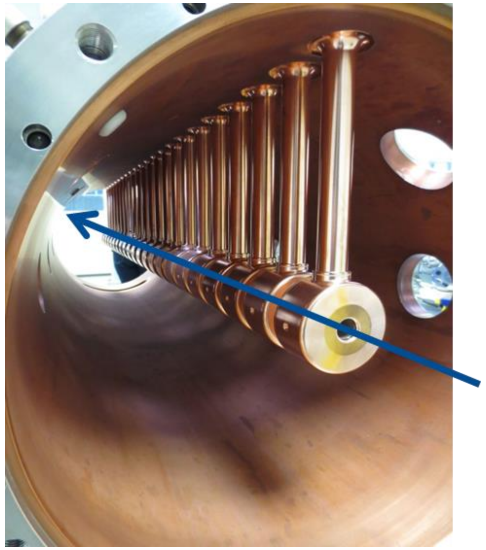
Demonstrated acceleration of potassium ions 1+ at 50 keV with 25kV of RF at 1 MHz

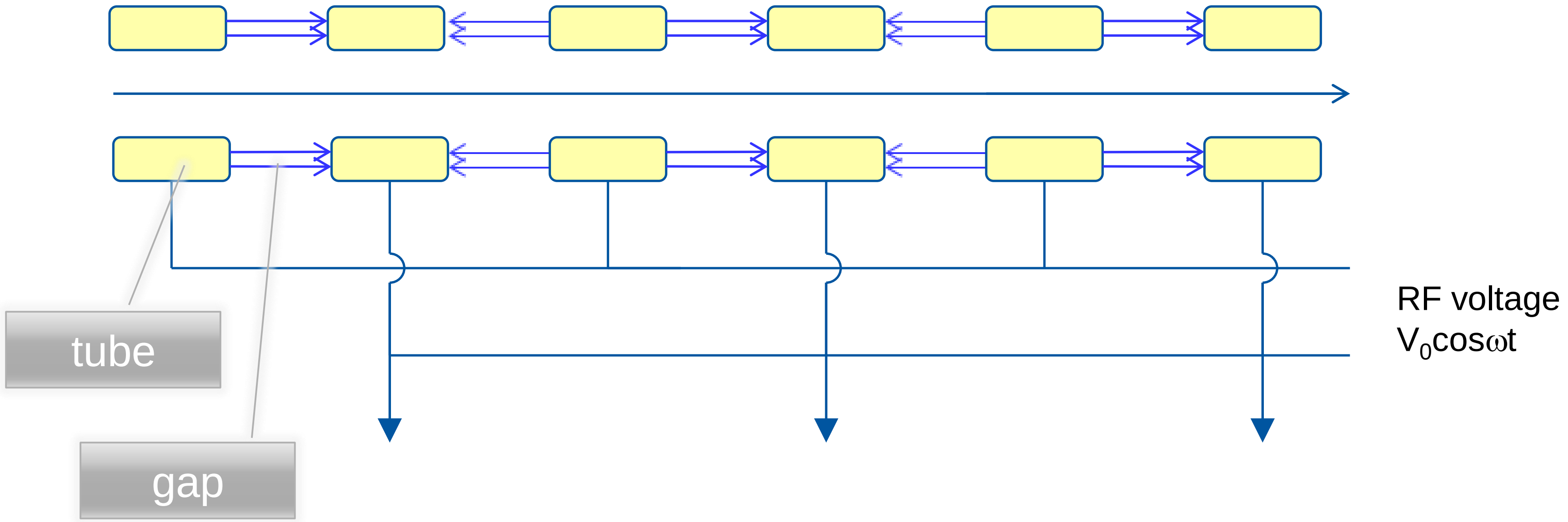
The principle of radio-frequency acceleration



ELECTROSTATIC acceleration
The voltage can be applied only to one gap

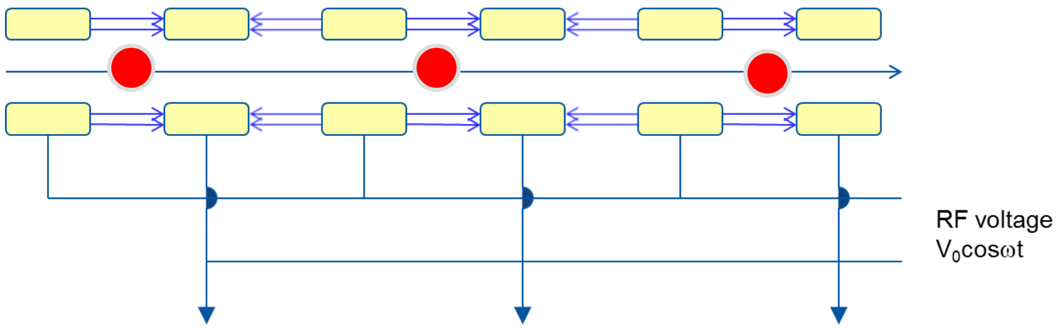
RADIOFREQUENCY acceleration
The voltage adds up over several gaps



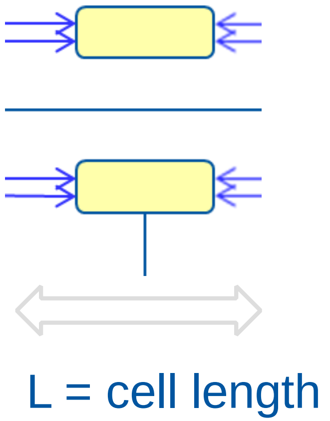


Two important consequences of using variable RF electric fields

1. The beam of particles cannot be continuous. Particles must be grouped in “bunches” at the period of the radio-frequency



2. The length of the tubes must be proportional to the velocity of the particle



Time to travel L = period / 2

L / v = T / 2 = 1 / 2 f

L = v / 2f

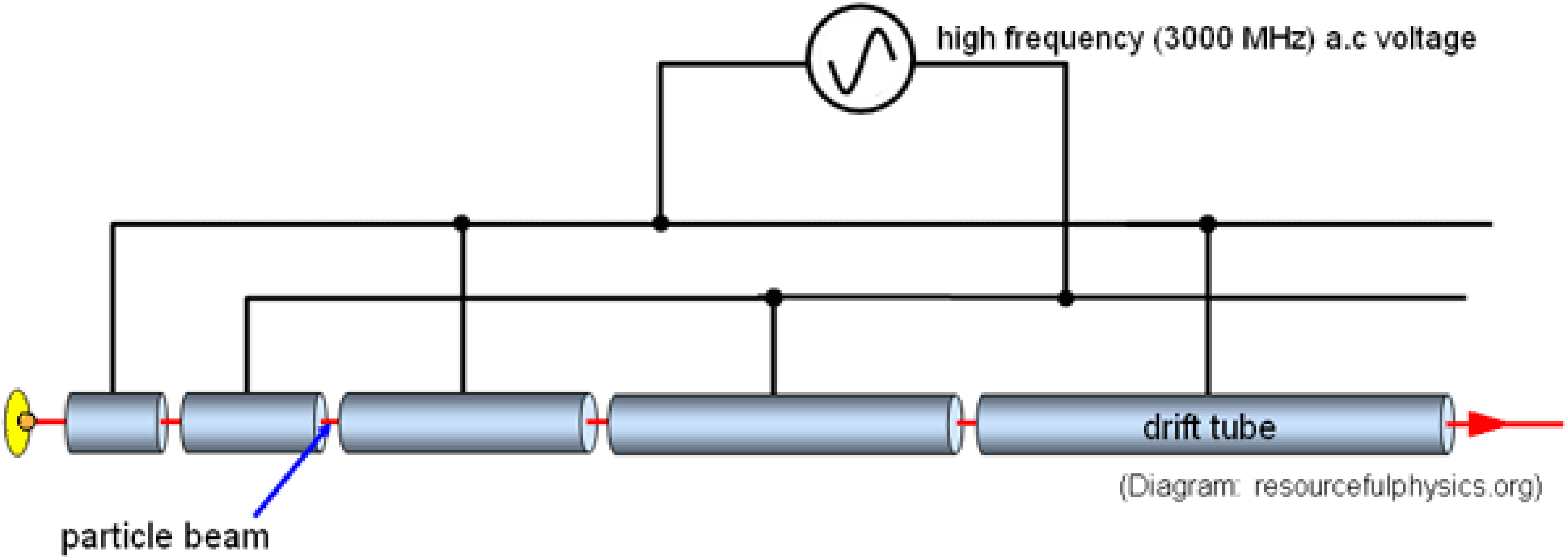
v = velocity of the particle

f = frequency of our generator

Consequence:

The tubes must become longer and longer as the energy and velocity of the particle increase

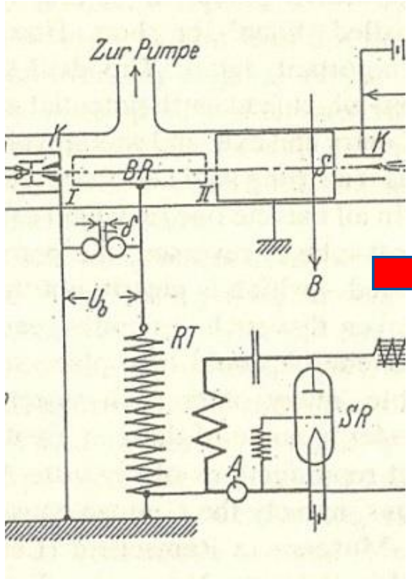
We have built a linear particle accelerator!

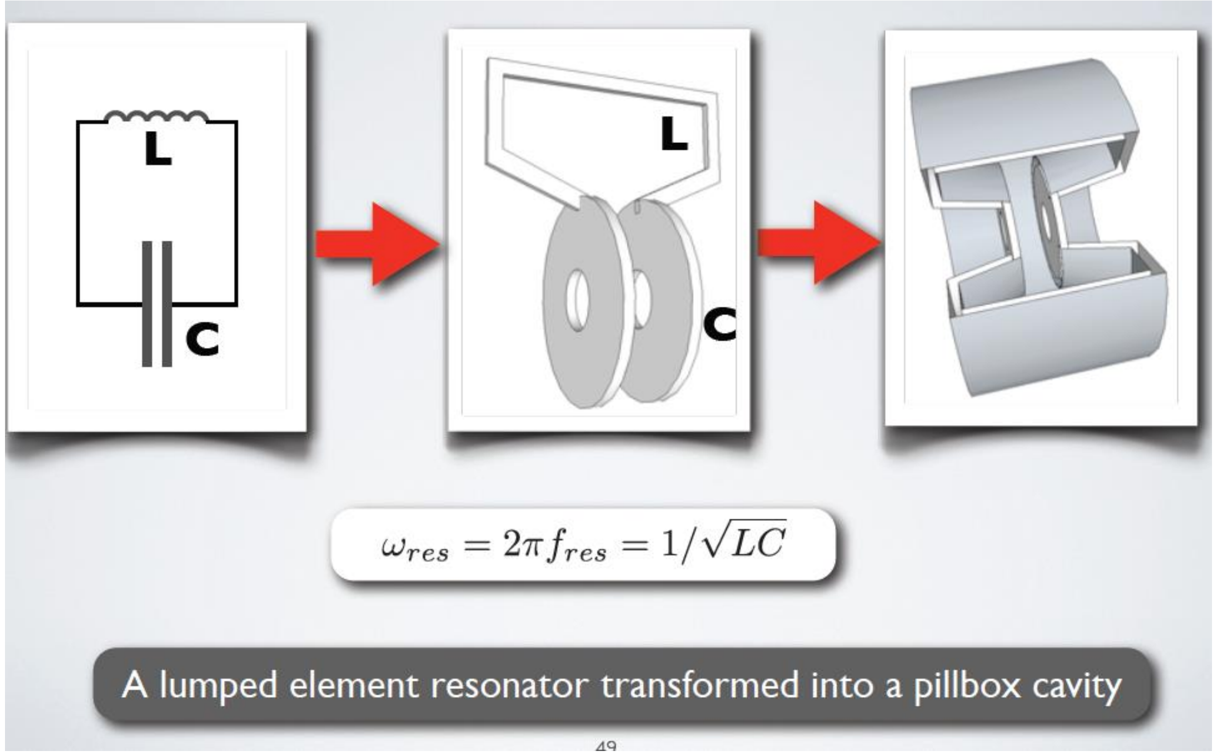


Linear accelerators are used as injectors to larger accelerators and as stand-alone when large beam intensities are required

The Drift Tube Linac of Linac4, the new linear injector for the LHC

In modern accelerators, we use high frequencies and cavity resonators around our gaps

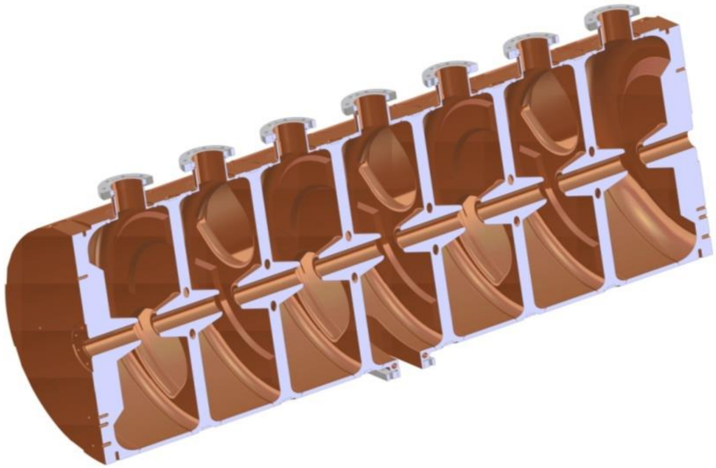


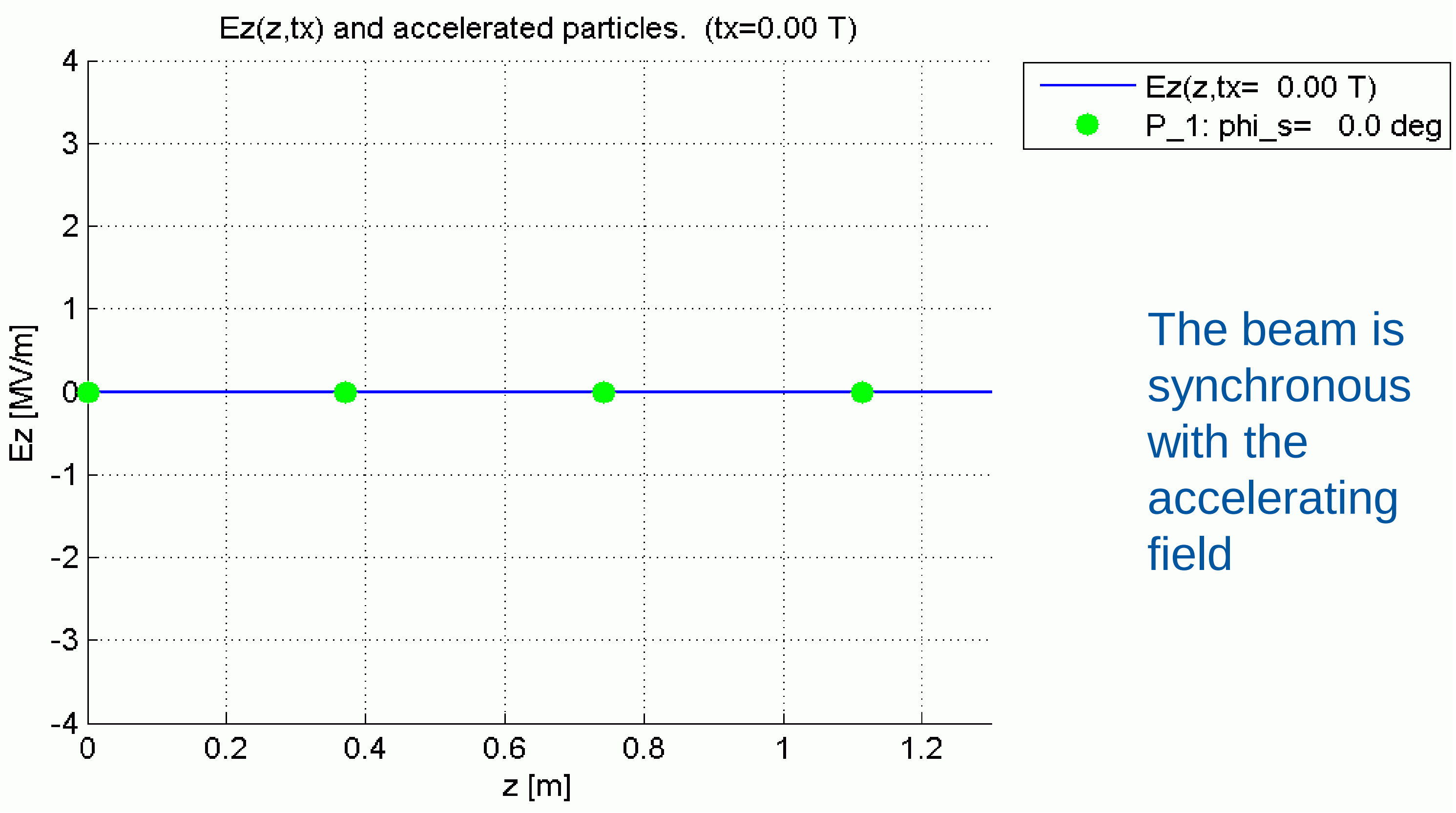


Single-gap cavity 88 MHz

Multi-cell cavity 3 GHz

Synchronism in the PIMS cavity of Linac4





The beam is synchronous with the accelerating field

7-gap cavity (6 tubes and 2 half-tubes)

The new Linac4 (looking from the ion source)

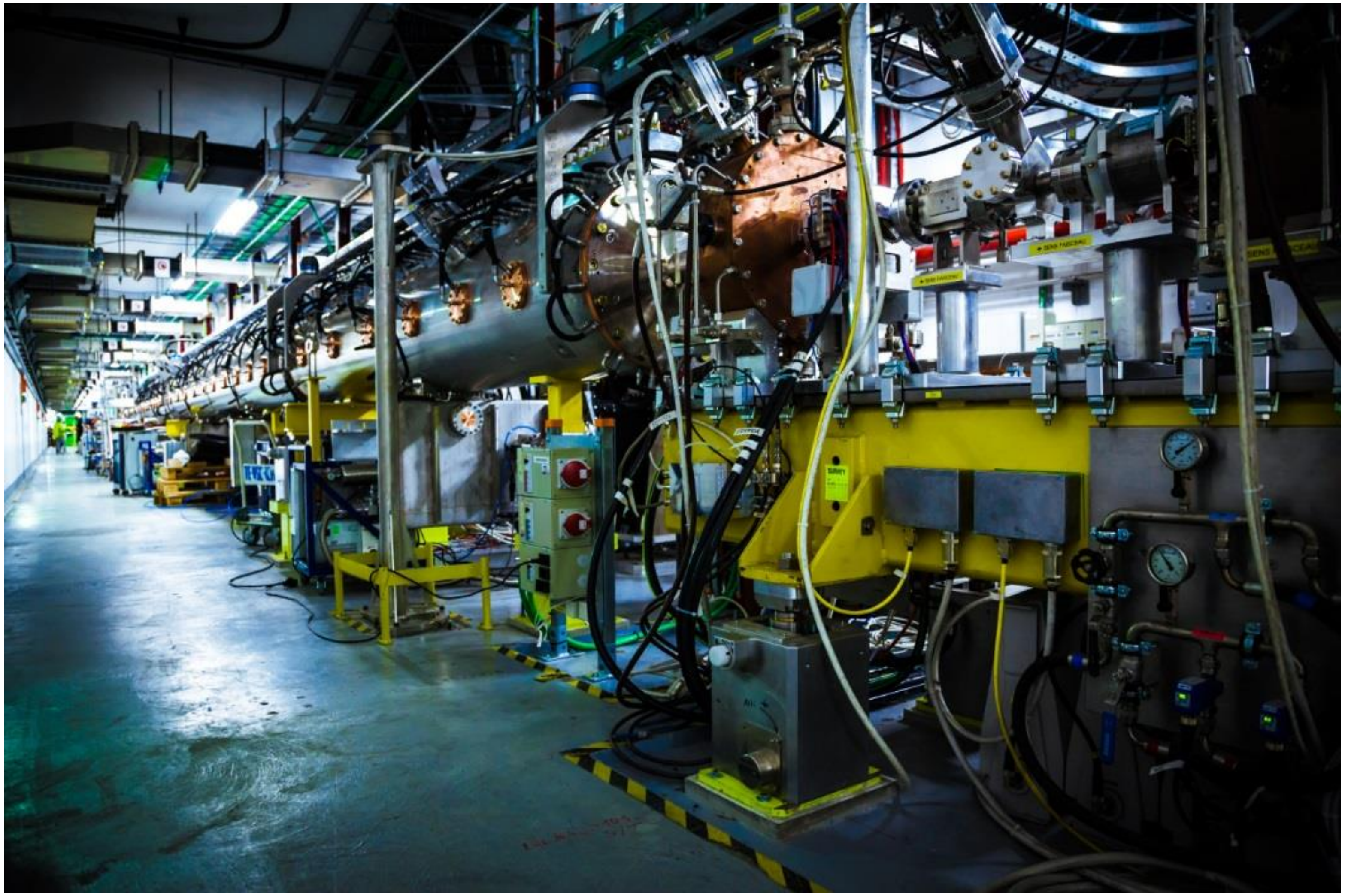
100-m long linear accelerator

160 MeV proton energy

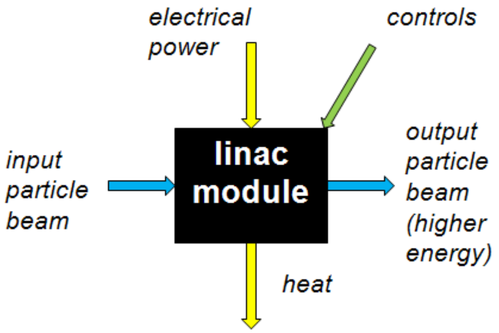
Built 2008-2016

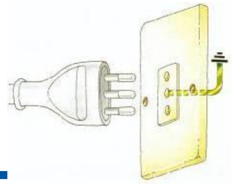
Will be connected to the LHC injector chain in 2020.

Will allow increasing by a factor of 2 the amount of protons in the LHC



Energy flow: from the grid to the particles



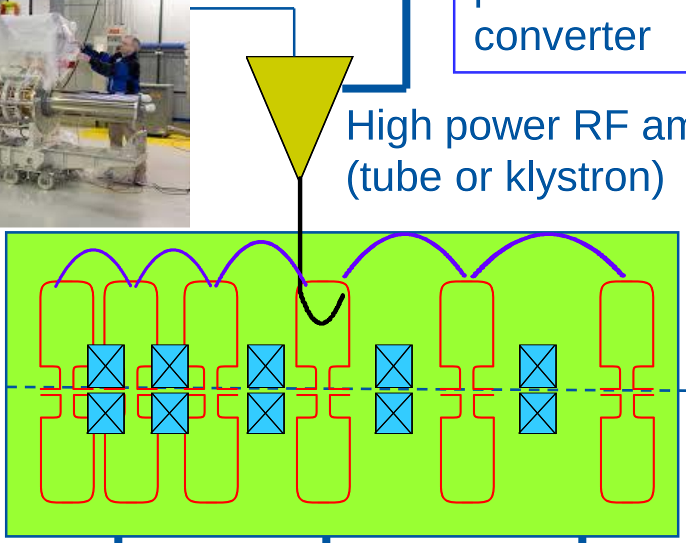


HV AC/DC power converter

AC to DC conversion efficiency ~90%

High power RF amplifier (tube or klystron)

DC to RF conversion efficiency ~50%



RF to beam voltage conversion efficiency = SHUNT IMPEDANCE ZT^2 ~ 20 - 60 MΩ/m

magnet powering system

vacuum system

water cooling system

ACCELERATING STRUCTURE
accelerating gaps + focusing magnets

The LHC needs about 80 MW of electricity from the grid!

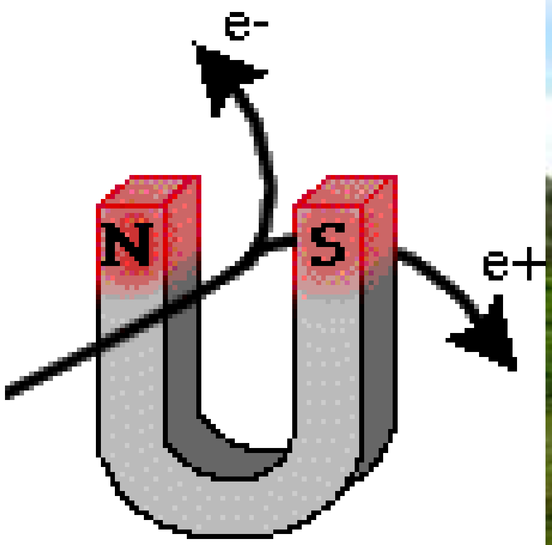
Can we use a linac to go to very high energy?

A quick calculation:

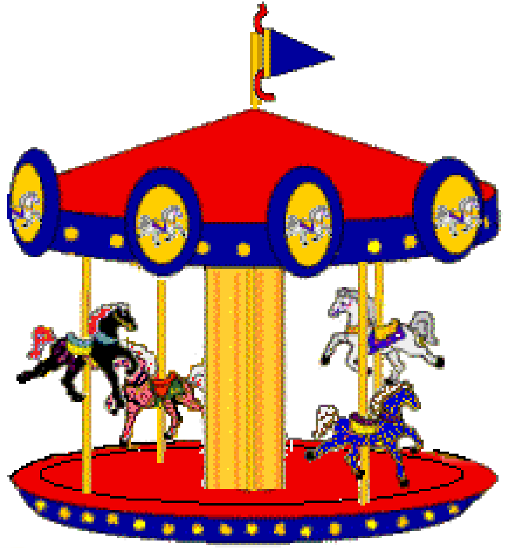
With tubes we can make about 2 MeV per meter. At higher fields we have electric arcing between the tubes.

A linear LHC (7 GeV) would be long 3’500 km !

We need another trick: bending the particles in a magnetic field

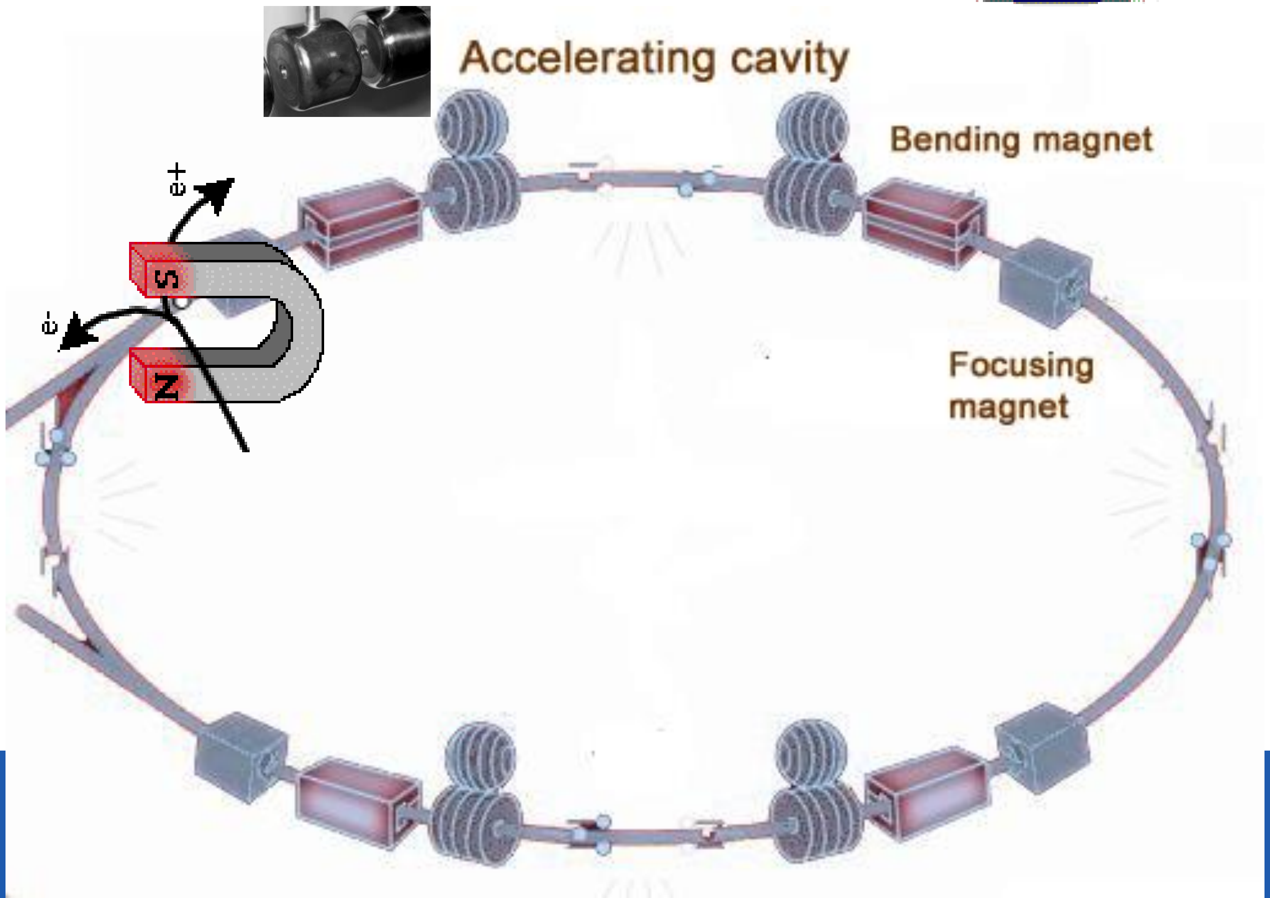


Adding many magnets around a circle we force the particles to go round



And adding few RF accelerating tubes (or cavities) along the ring, the particle will gain some energy at every turn

We have (almost) built a **synchrotron**…



A few important relations

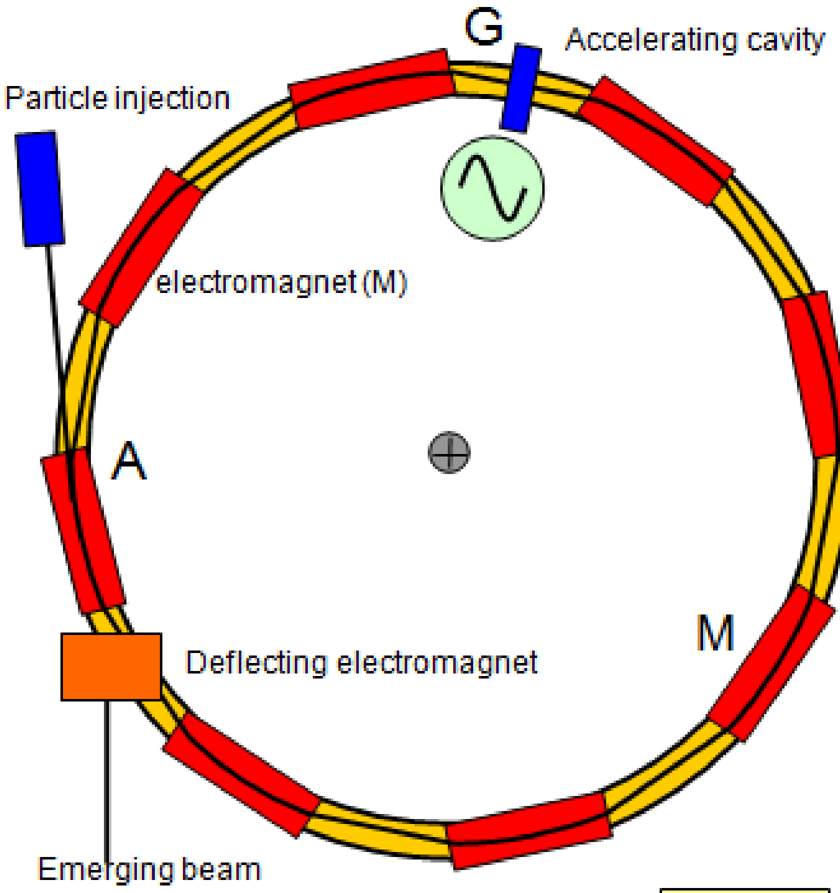


Figure 1

Revolution period:

$T = 2\pi R / v$ ➡ decreases with velocity

Radius (from Lorentz formula):

$R = p / eB$ ➡ increases with velocity
decreases with magnetic field

Still not enough!
We can store our beam, but when we accelerate the bunches are not synchronous with the RF fields…

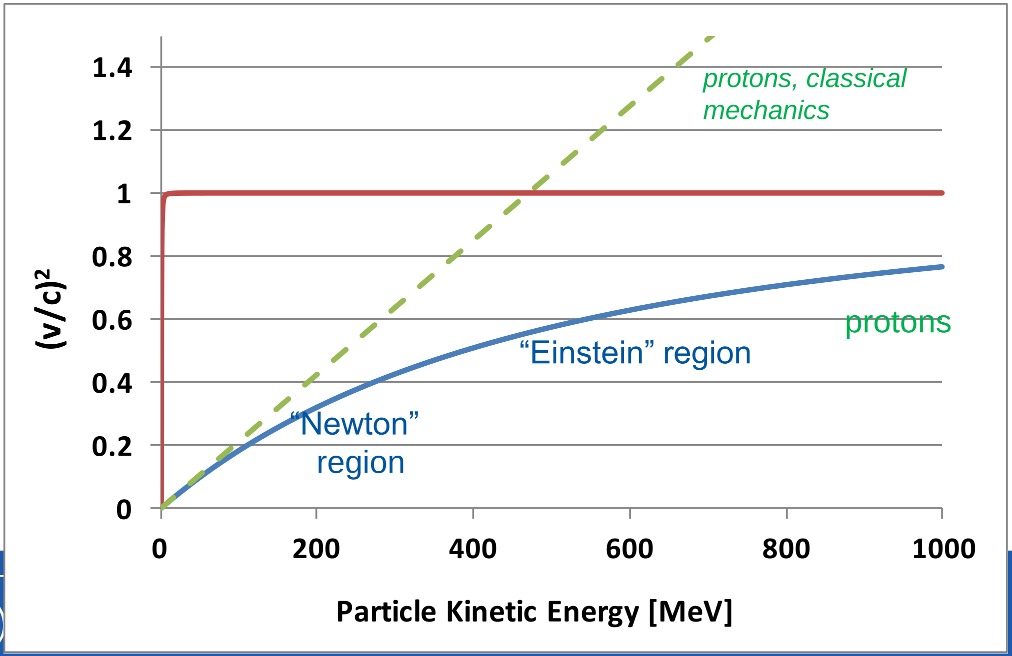
Relativity comes at our help!

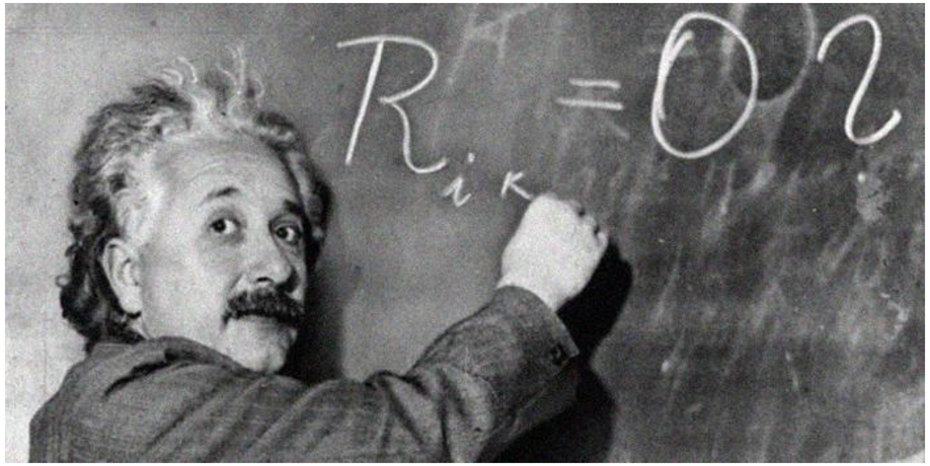
We have seen that the length of the tubes must be proportional to the velocity of the particle, and in a linear accelerators the tubes must be longer and longer.

Forever?

No, until we come in the hands of Einstein!

$\beta^2=(v/c)^2$ as function of kinetic energy T for protons





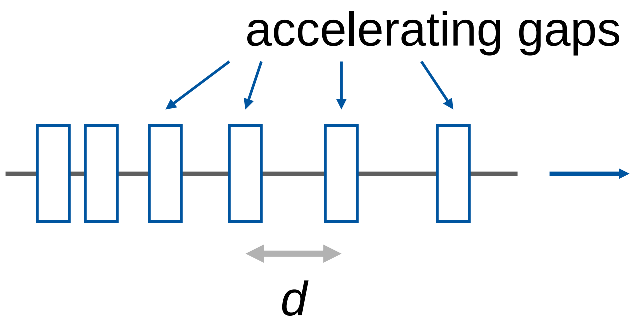
Classic (Newton) relation

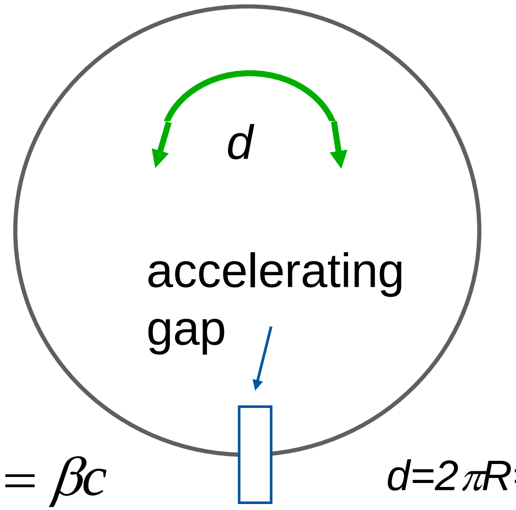
$$T = m_0 \frac{v^2}{2}, \quad \frac{v^2}{c^2} = \frac{2T}{m_0 c^2}$$

Relativistic (Einstein) relation

$$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1 + T/m_0 c^2}}$$

Linear and circular accelerators





$d=\beta\lambda/2=$variable

$$d=\frac{\beta c}{2f}=\frac{\beta\lambda}{2}$$

$$2d\,f=\beta c$$

$d=2\pi R=$constant

Linear accelerator:

Particles accelerated by a sequence of gaps (all at the same RF phase).

Distance between gaps increases proportionally to the particle velocity, to keep synchronicity.

Used in the range where β increases. "Newton" machine

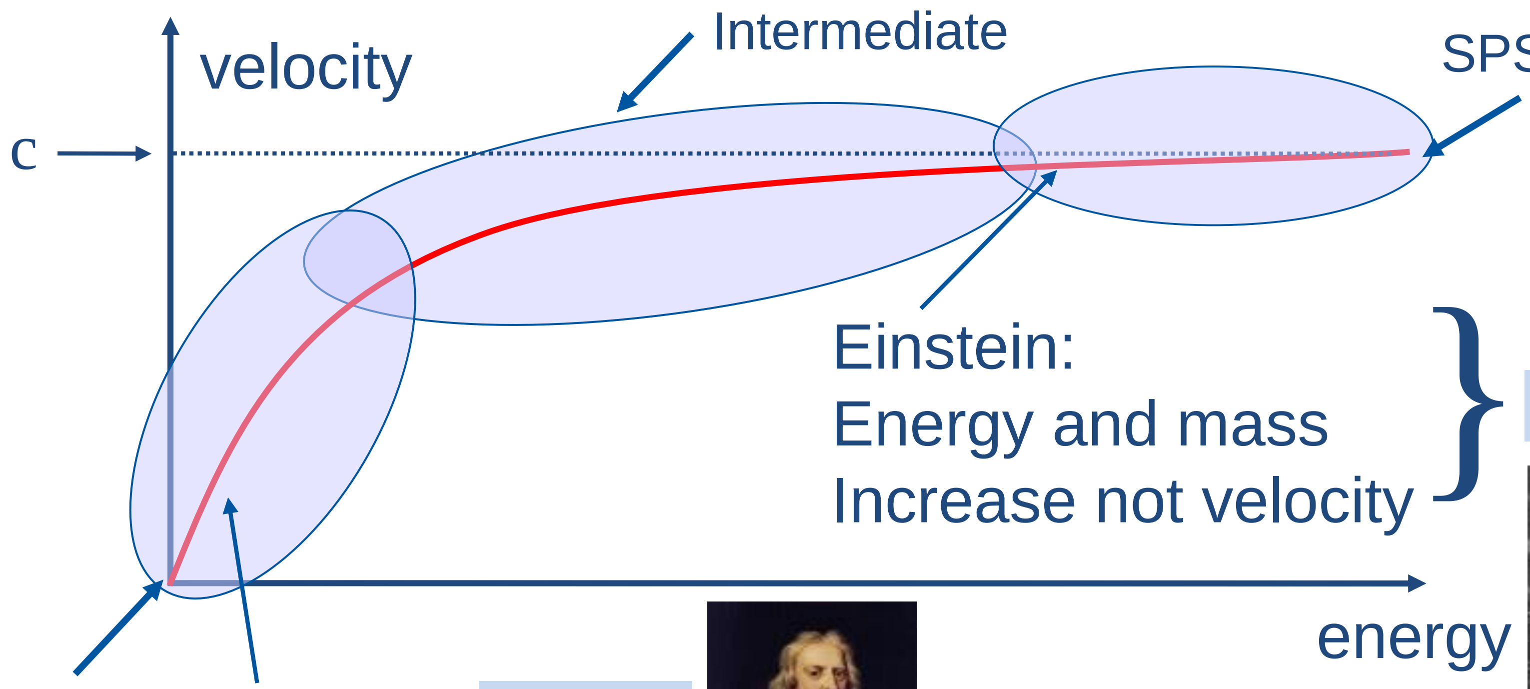
Circular accelerator:

Particles accelerated by one (or more) gaps at given positions in the ring.

Distance between gaps is fixed. Synchronicity only for β~const, or varying (in a limited range!) the RF frequency.

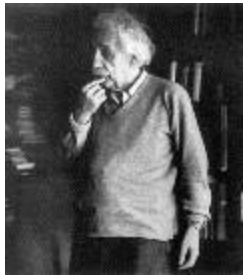
Used in the range where β is nearly constant. "Einstein" machine

Newton and Einstein regions



Einstein:
Energy and mass
Increase not velocity

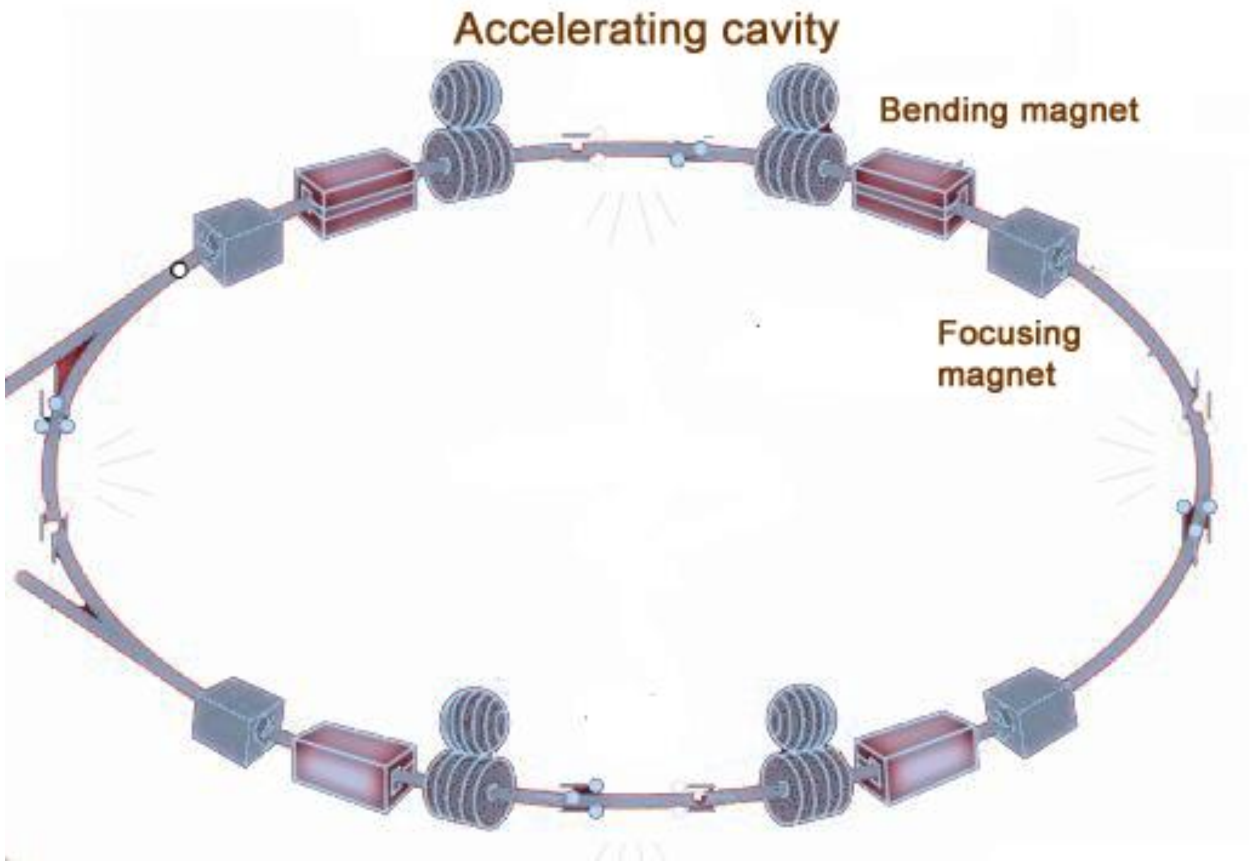
$$E = mc^2$$



Linear accelerator

Newton: $E = \frac{1}{2} m v^2$

The synchrotron



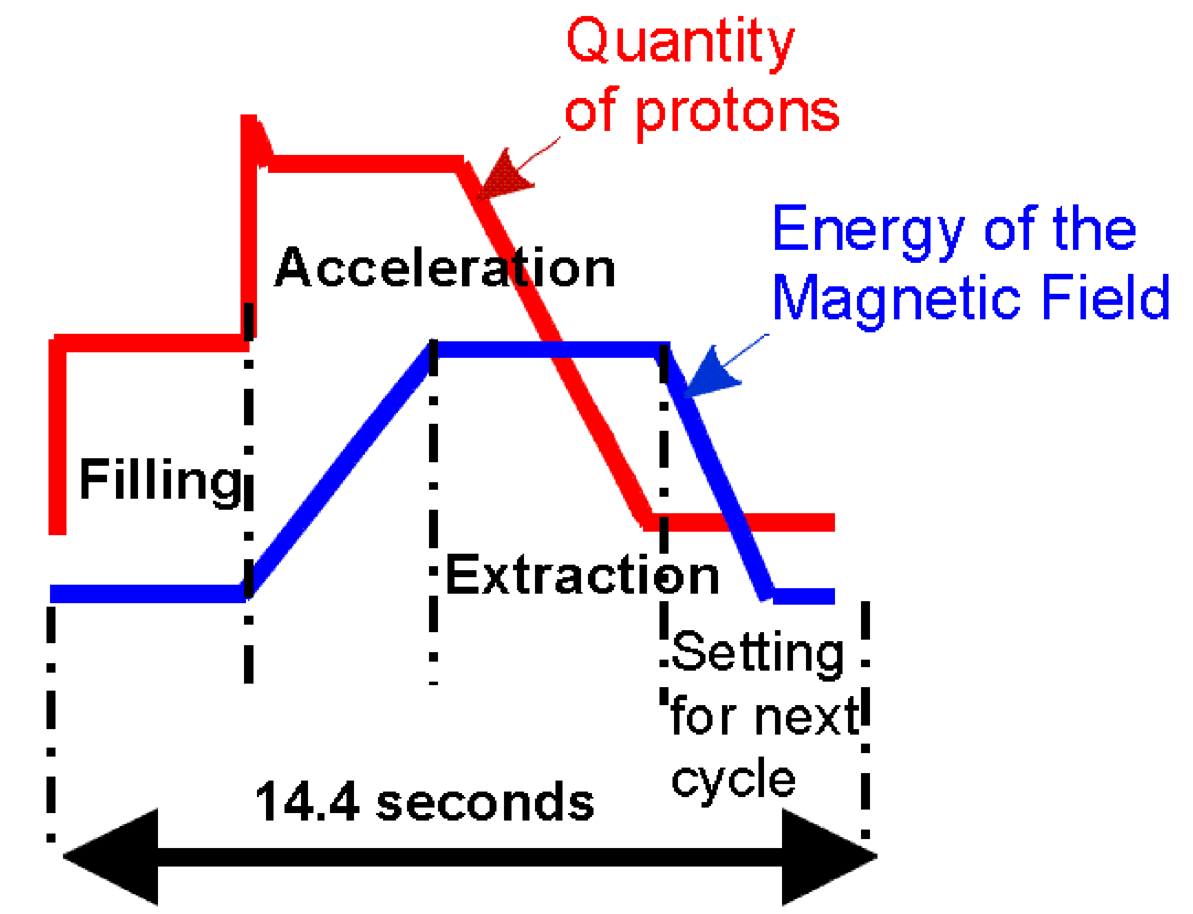
Operates in the energy range where the velocity of particles is nearly constant (=c)

Acceleration is provided by some **gaps and tubes** placed in one or more positions on the ring. The revolution period is constant and the bunches of particles will always find an accelerating field.

The **magnets** cover (almost) the entire circumference. Their magnetic field must progressively increase to follow the increase in momentum (~ mass) of the particles.

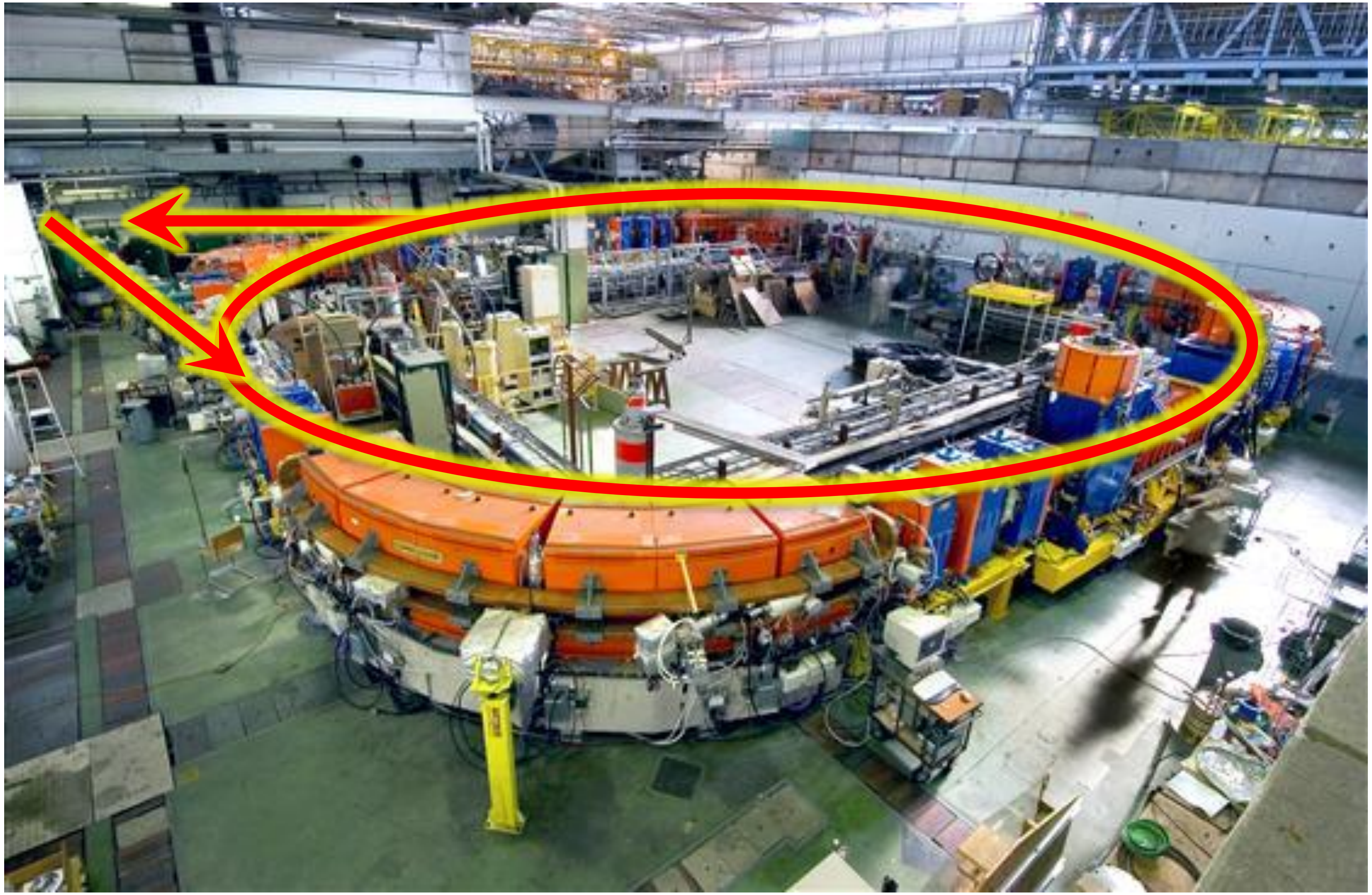
Ultra-high vacuum (10^{-6}-10^{-10} mbar) in the ring to avoid losing particles by collisions with air molecules

Magnetic cycle

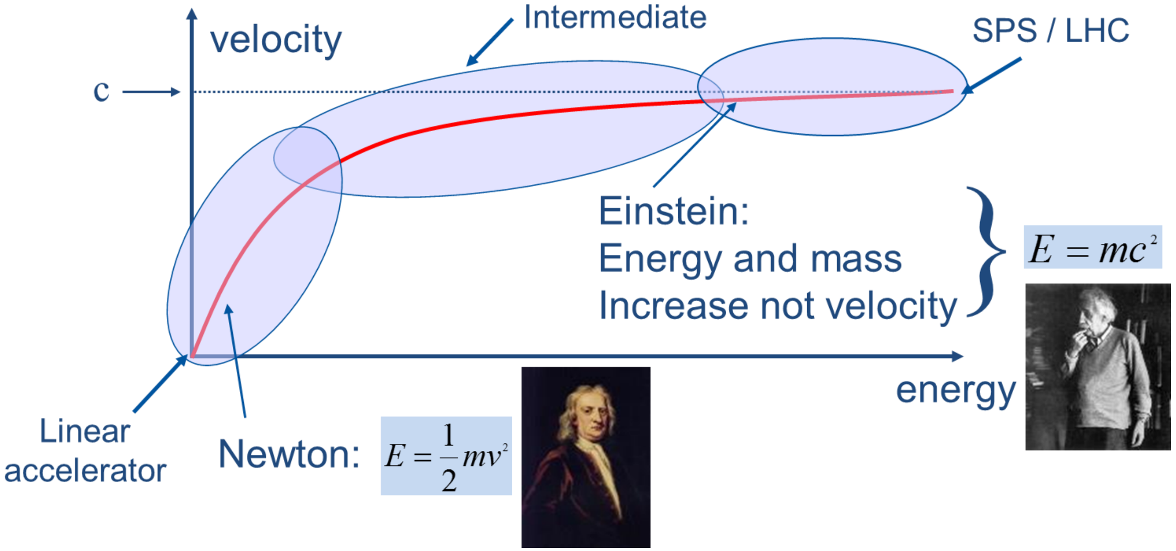


Example of a SPS Magnetic cycle

The smallest CERN synchrotron: LEIR



The intermediate region



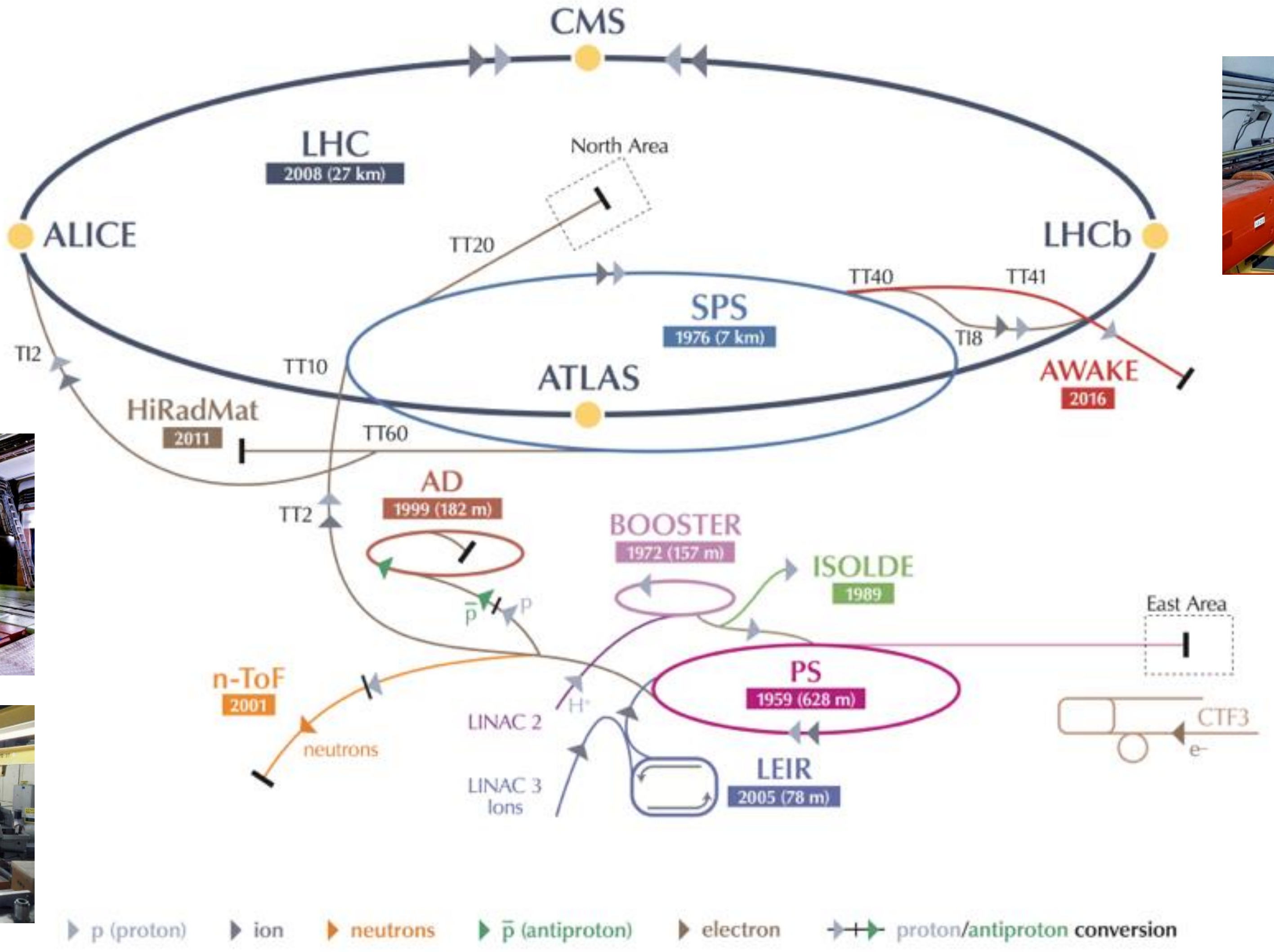
In the intermediate region we can use long linear accelerators or small synchrotrons.

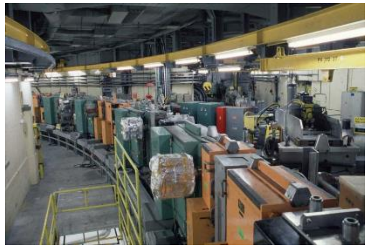
Linear accelerators are more expensive but can accelerate a larger number of particles.

Synchrotrons can accept a small variation of velocity by changing the frequency of their RF accelerating system (within some limits).

The CERN accelerator system was designed for high energy and the the old linac (Linac2) goes up to only 50 MeV (beta 0.31). The new Linac4 goes up to 160 MeV (beta 0.53).

The CERN chain of accelerators

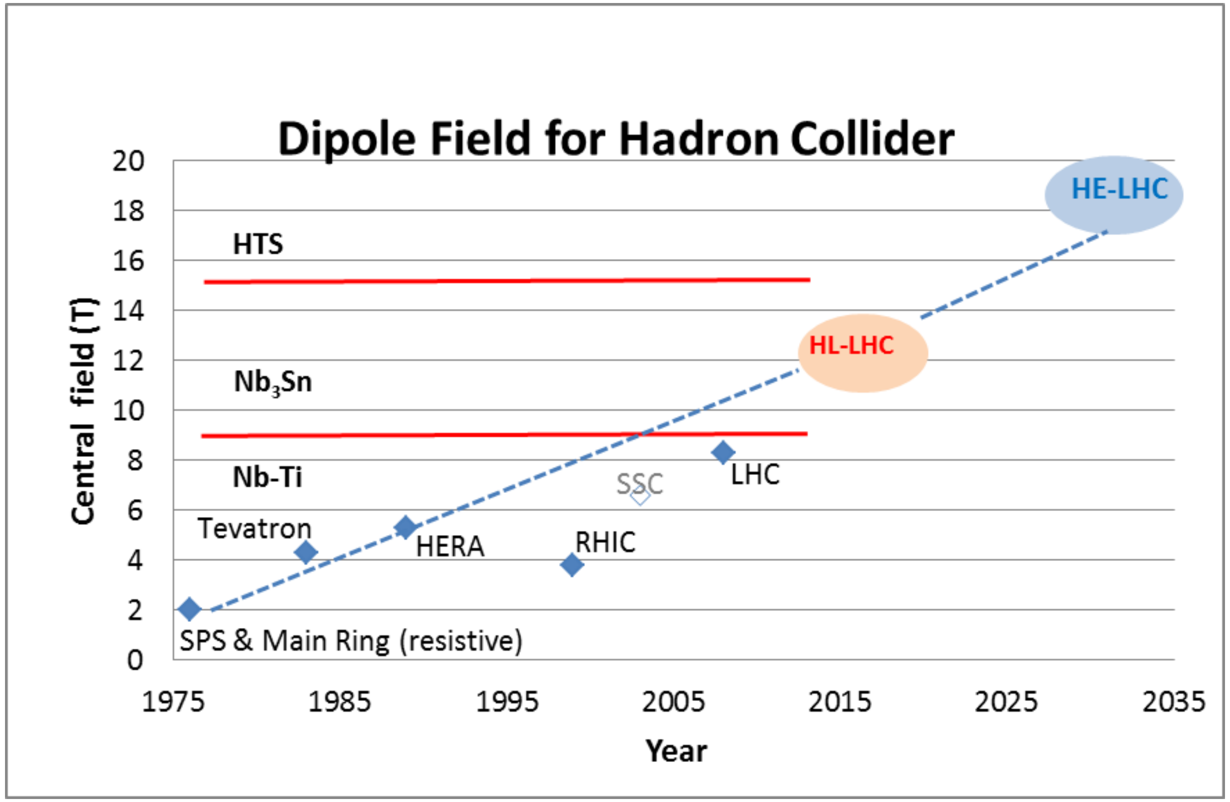




Linear Accelerator (50 MeV)
plus a chain of synchrotrons of increasing energy and radius:

Booster	1.4 GeV
PS	25 GeV
SPS	450 GeV
LHC	7 TeV

The magnetic field limitation

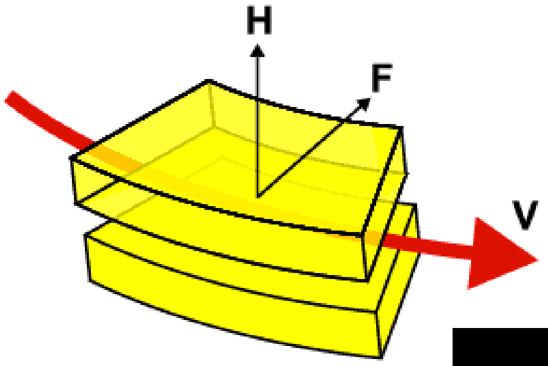


The final limitation to the size and to the energy of a synchrotron comes from the magnetic field that can be achieved.

Technological limit:
about 2 T normal conducting magnets
8 T Nb-Ti superconducting magnets
12 T future Nb3Sn superconducting magnets

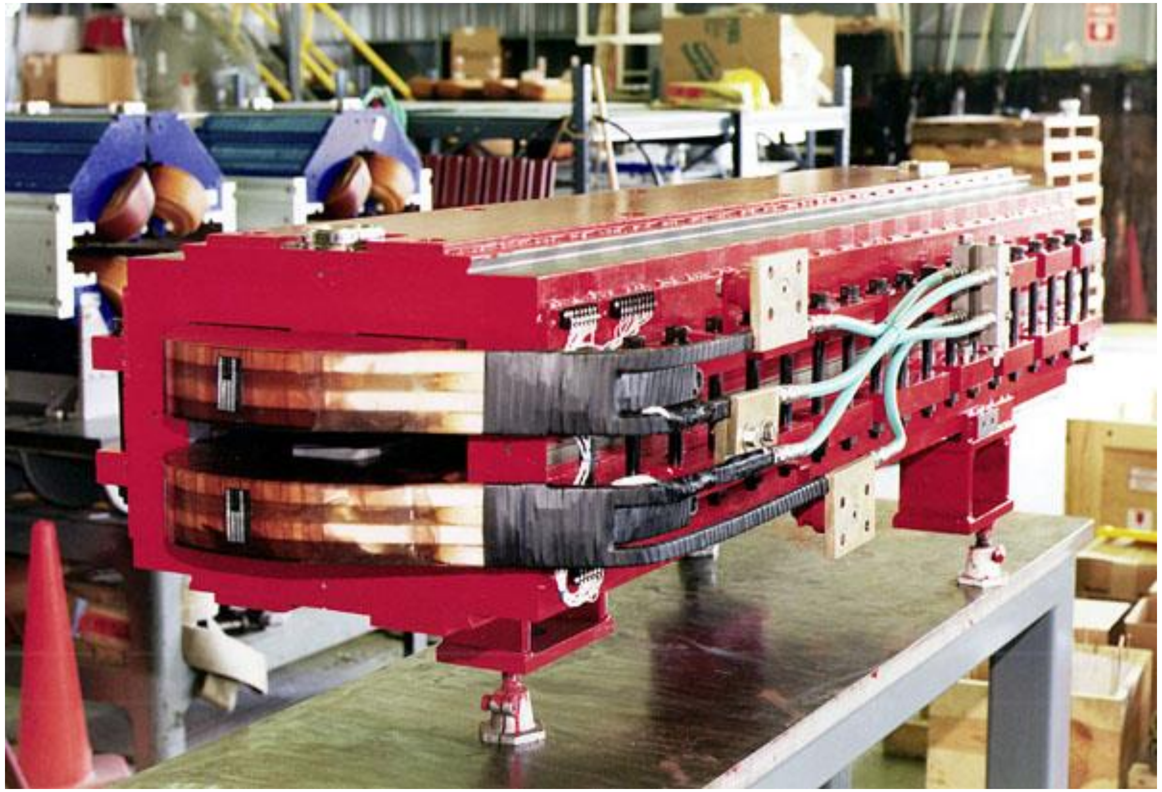
$$B\rho = \frac{p}{e} \approx \frac{E}{ce} \text{ so } E[\text{GeV}] \approx 0.3\, B[\text{T}]\, \rho[\text{m}] \text{ per unit charge}$$

The magnets

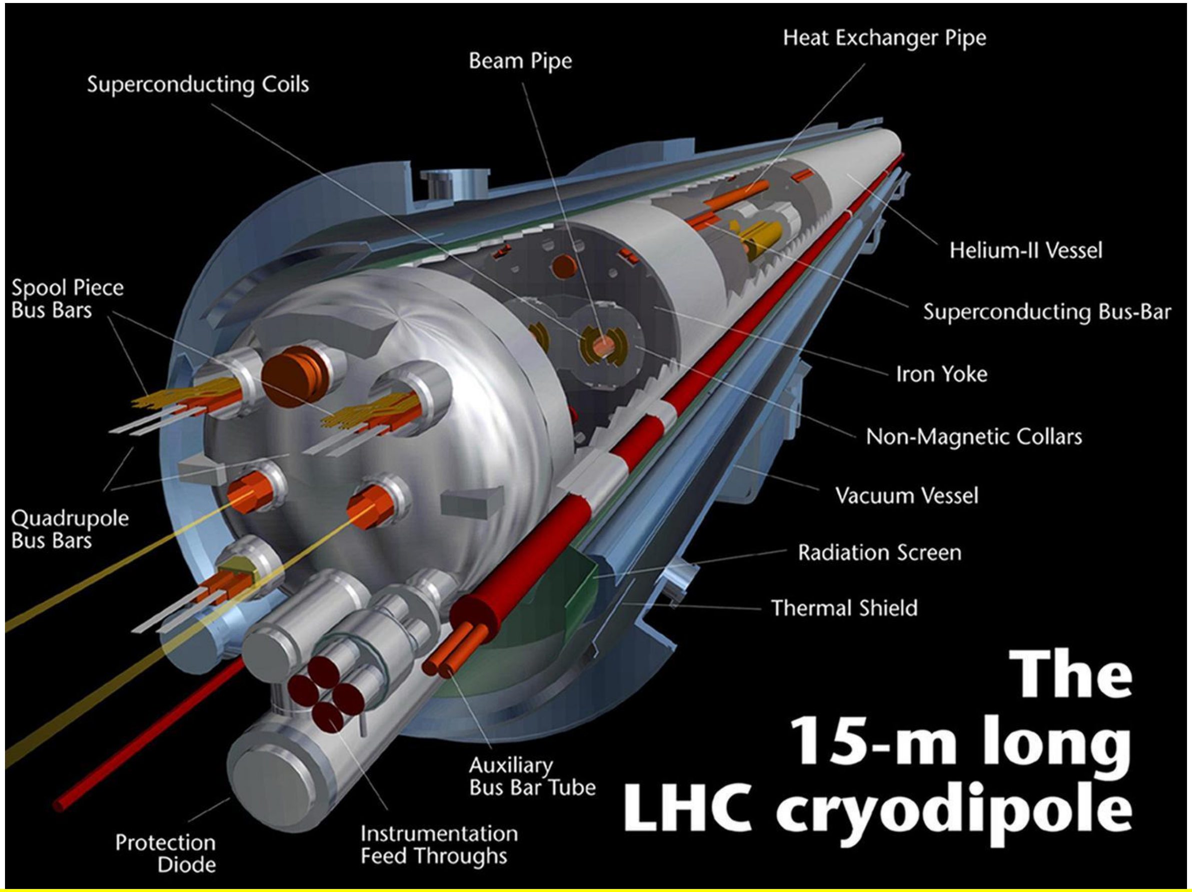


dipole

Normal conducting



Superconducting

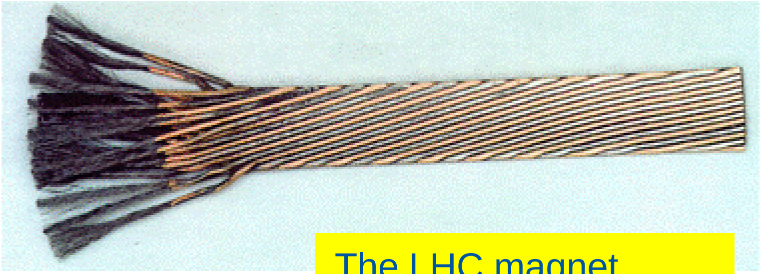


15 metres length, maintained at -269 degrees by a flow of liquid helium. Magnetic field 8 T, 5 times more than conventional magnets and 10’000 times a small house magnet

Superconductivity and particle accelerators

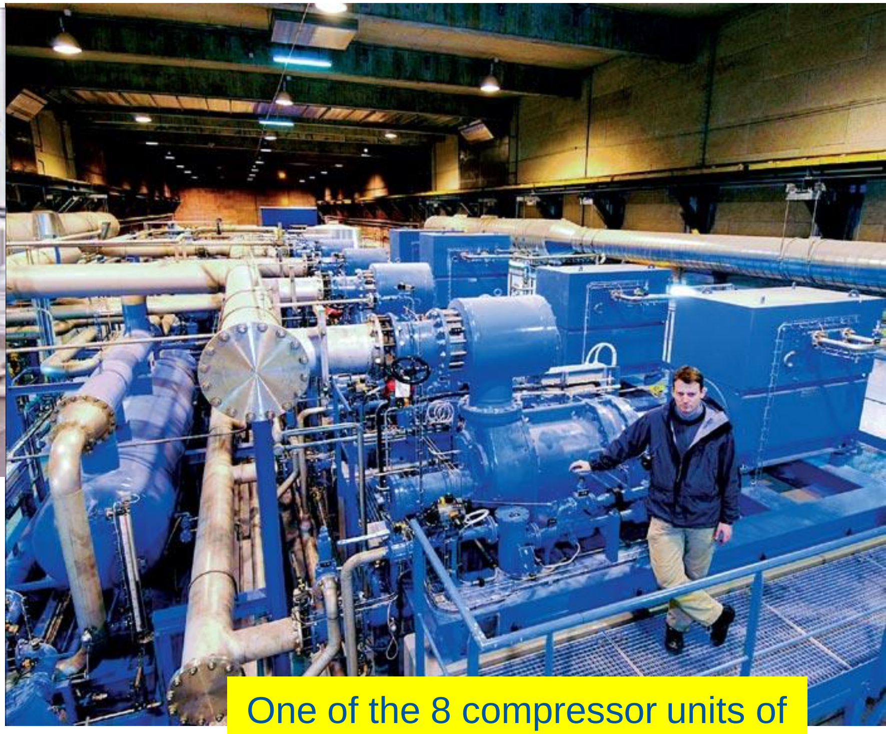
Some materials present a zero electrical resistance when cooled below a characteristic temperature.
Discovered in 1911, explained in 1958, started to be used for accelerators in the 1970’s.
Allows to build magnets that can stand higher electric currents and higher fields (not limited by water cooling) and accelerating RF cavities that do not dissipate power and have higher electrical efficiency.

Materials used in accelerators are
Niobium-Titanium for magnets
Niobium for RF cavities.



The LHC magnet superconducting cable

Clean room assembly of superconducting RF cavities

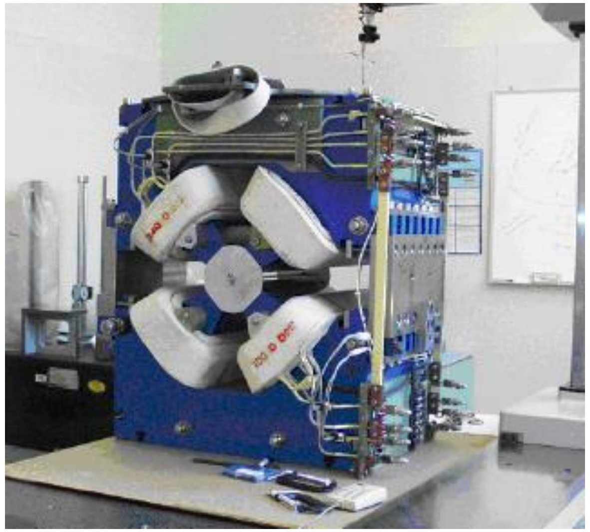


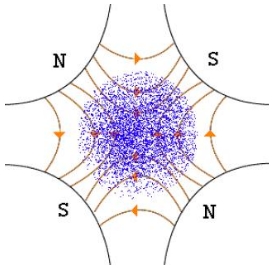
One of the 8 compressor units of the 4.5 K refrigerator for LHC

BUT: a superconducting accelerator requires a huge cooling system
That keeps all elements at liquid helium temperature

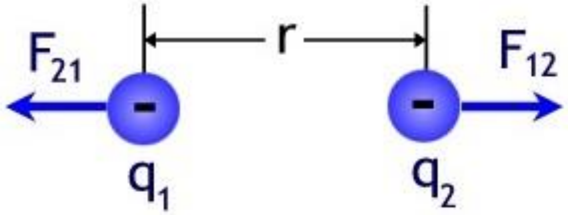
Fighting Coulomb – beam intensity and focusing

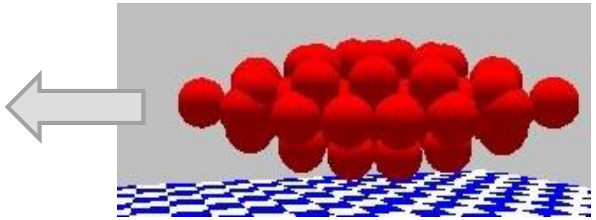
Up to now we have been considering only one particle, but in reality in a bunch there are 10^{10}-10^{13} particles in a few square mm...
They all have the same sign and they tend to repel each other (Coulomb force)!
If we do nothing, our beam will explode…

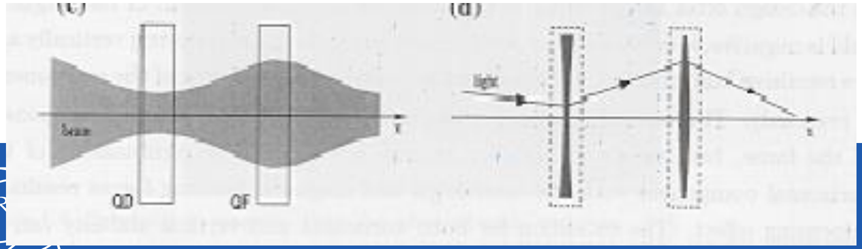




Solution:
Alternating gradient strong focusing
Add quadrupole magnets every few dipoles.
The beam envelope oscillates but the particles remain confined.







Dealing with Energy

- The energy in one LHC beam at high energy is about 320 Million Joules
- This corresponds to the energy of a TGV engine going at 150 km/h

...... but then concentrated in the size of a needle

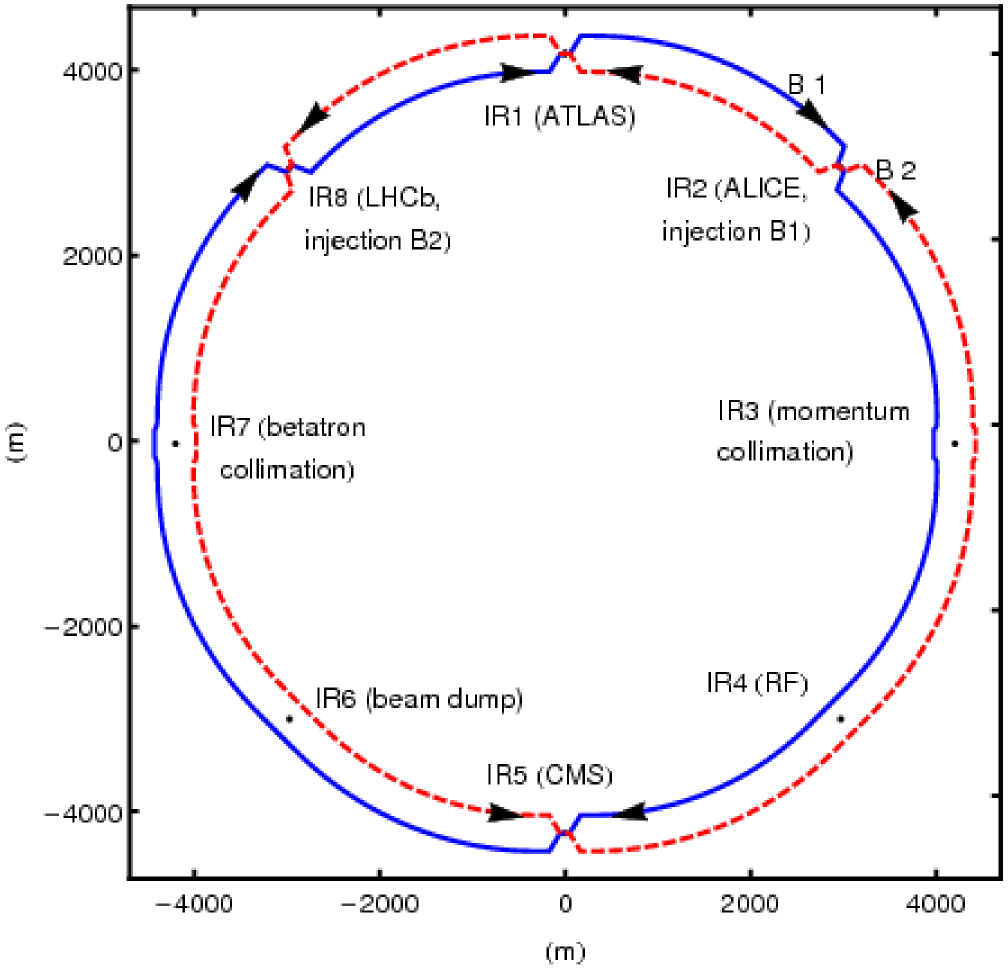
Understanding the Large Hadron Collider

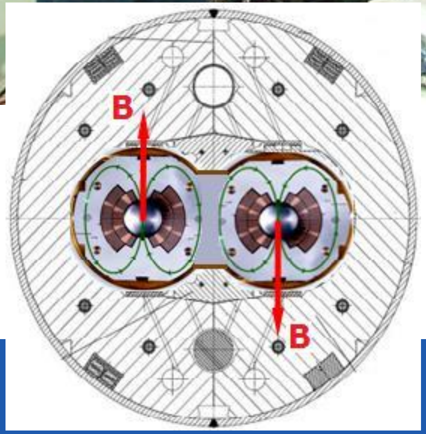
27 km !

protons and nuclei are hadrons

?

2 flows of particles in opposite direction make a collider





The 1232 LHC magnets contain two pipes, one for each of the counterrotating beams.

Fixed Target Accelerators vs. Colliders

Fixed Target

$$E \propto \sqrt{E_{beam}}$$

Much of the energy is lost in the target and only part is used to produce secondary particles

Collider

$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

Luminosity, the Collider Figure of Merit

$$LUMINOSITY = \frac{N_{event/sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4p s_x s_y} F$$

Intensity per bunch

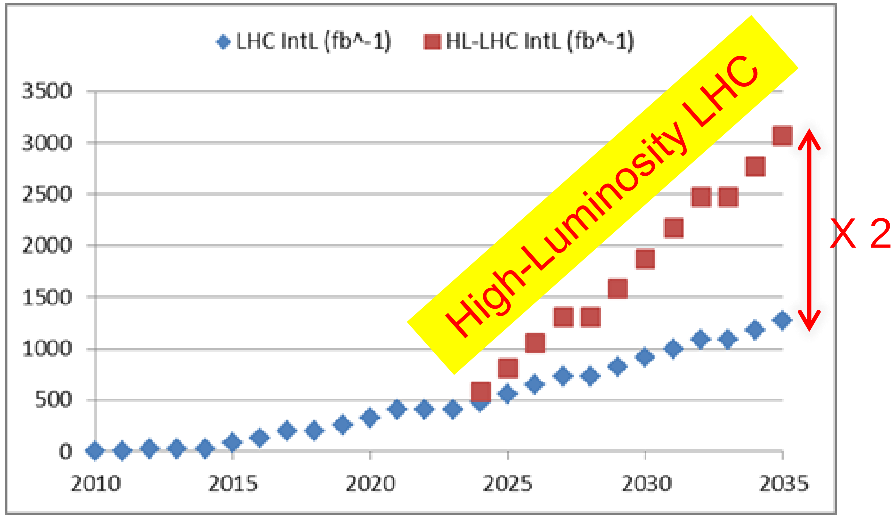
Number of bunches

Geometrical Correction factors

Beam dimensions

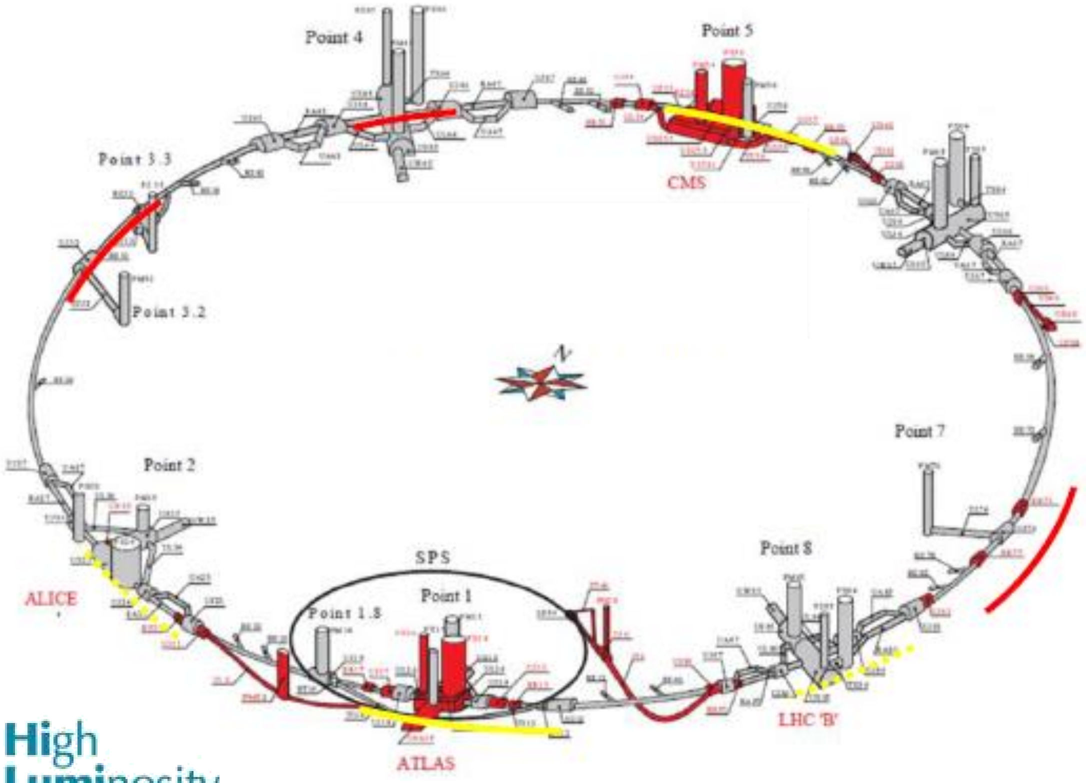
- More or less fixed:
  - Revolution period
  - Number of bunches

- Parameters to optimise:
  - Number of particles per bunch
  - Beam dimensions
  - Geometrical correction factors



The High-Luminosity LHC Project

Is the major ongoing accelerator project at CERN – to be completed in 2026



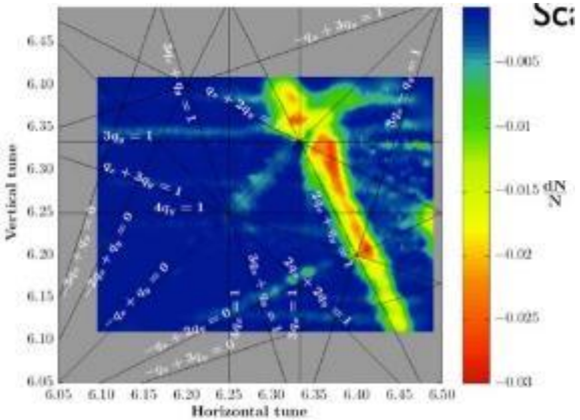
- New IR-quads (inner triplets)
- New 11T short dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major interventions on more than 1.2 km of the LHC

The LHC injectors for higher luminosity

- LINAC4 – PS Booster:
  - New LINAC 4 with H^- injection
  - Higher injection energy
  - New Finemet® RF cavity system
  - Increase of extraction energy

- PS:
  - Injection energy increase from 1.4 GeV to 2 GeV
  - New Finemet® RF Longitudinal feedback system
  - New RF beam manipulation scheme to increase beam brightness



Courtesy of A. Huschauer

- SPS
  - Machine Impedance reduction (instabilities)
  - New 200 MHZ RF system
  - Vacuum chamber coating against e-cloud

These are only the main modifications and this list is not exhaustive

Other applications of accelerators

Beyond basic science

How many particle accelerators there are in the world?

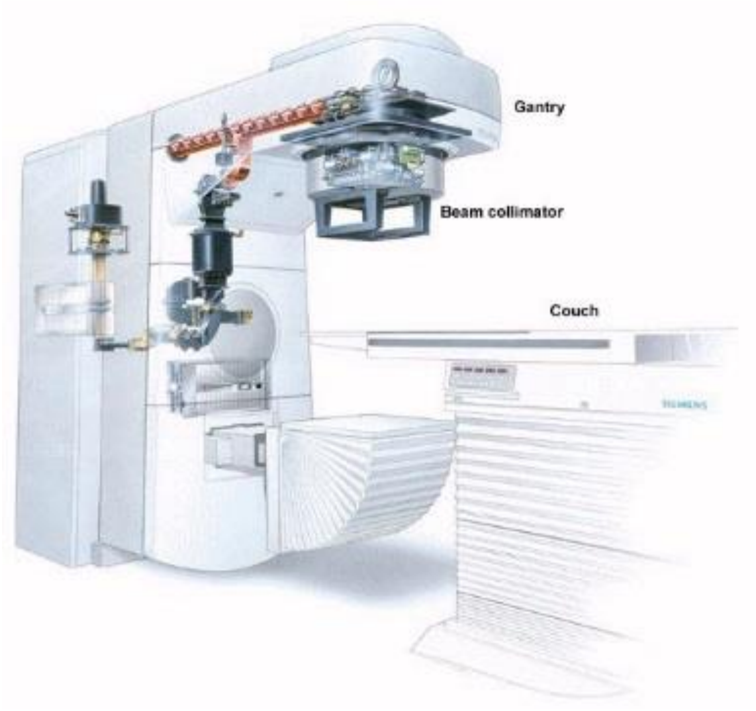
More than 30’000 !

Recherche		**6%**
	Physique des particules	0,5%
	Physique nucléaire, de l’état solide, des matériaux	0,2 a 0,9%
	biologie	5%
Applications médicales		**35%**
	Diagnostic/traitement par X ou électrons	33%
	Production de radio-isotopes	2%
	Traitement par protons et ions	0,1%
Applications industrielles		**60%**
	Implantation d’ions	34%
	Découpage et soudure par électrons	16%
	Polymérisation, …	7%
	Traitement par neutrons	3.5%
	Tests non destructifs	2,3%

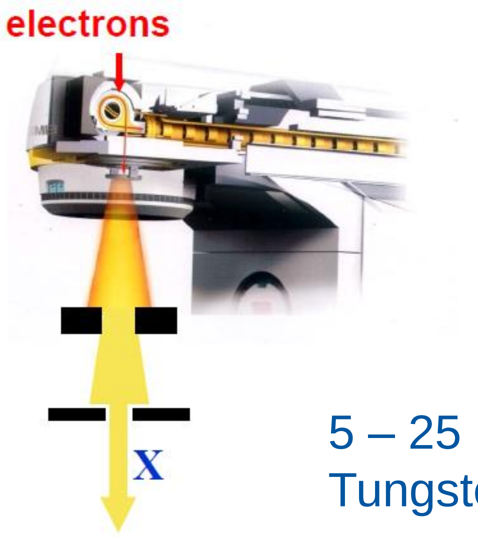
CERN

The most widespread accelerator

Electron Linac (linear accelerator) for radiotherapy (X-ray treatment of cancer)



More than 10’000 in use



5 – 25 MeV
Tungsten target

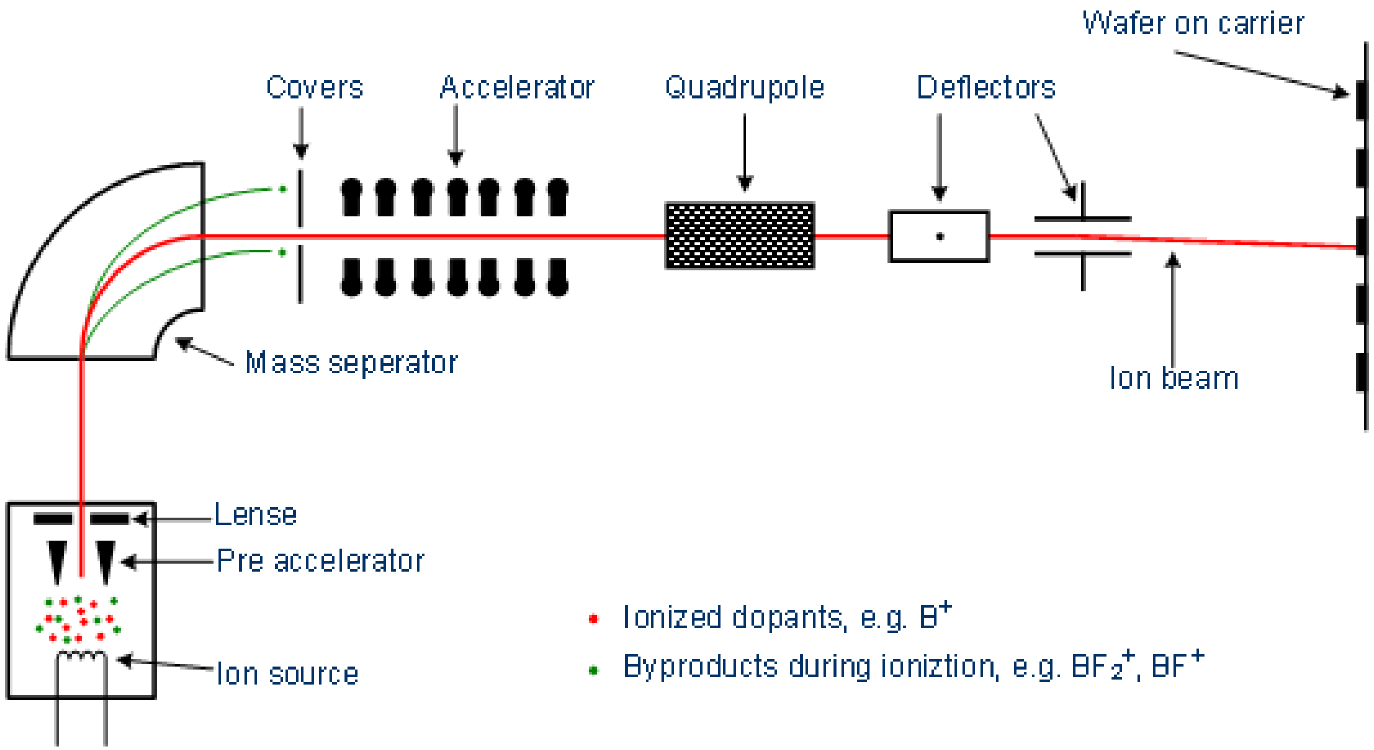
2000 patients/year every in 1 million inhabitants

Commercialised by several companies, available in all major hospitals

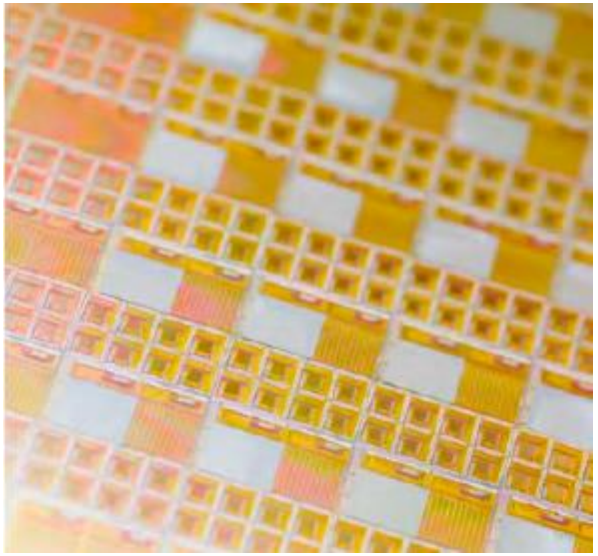
Industrial applications of accelerators

	Goal	Examples	Accelerator
Material processing (electrons)	Improve polymer resins inducing cross-linking of polymer chains → higher stress resistance	Heat-shrinkable films for food packaging, tires and cable insul. Gemstone irradiation	Electrons, 100 keV-10 MeV
Sterilization	Kill microroganisms	Sterilization of medical products Food processing (public acceptance!)	Electrons, ~10 MeV
Wastewater treatment	Distruction of organic compounds	Russia, Korea, USA, Brazil	Electrons, ~10 MeV
Non-destructive testing	Detect discontinuities in a material (cracks, etc.)	Inspection of pipelines, ships, bridges, etc. (depth + variable energy)	Electrons for X-rays, 1-15 MeV, portable (9 GHz)
Cargo inspection	Screening of trucks or containers for illegal objects	Many ports, customs, etc.	Electrons for X-rays, 3-6 MeV
Ion implantation	Alter near-surface properties of semiconductors (doping)	Semiconductor industry (arsenic, boron, indium, phosphorus,…)	Ions, from low to high energy (5 MeV)
PET isotope production	Production of radiotracers for Positron Emission Tomography	Linacs are smaller and have less res. activation than cyclotrons	Protons, 7 MeV
Neutron testing	Neutron generation for non-destructive inspection	Inspection of materials, cargo, etc.	Protons, 1-10 MeV

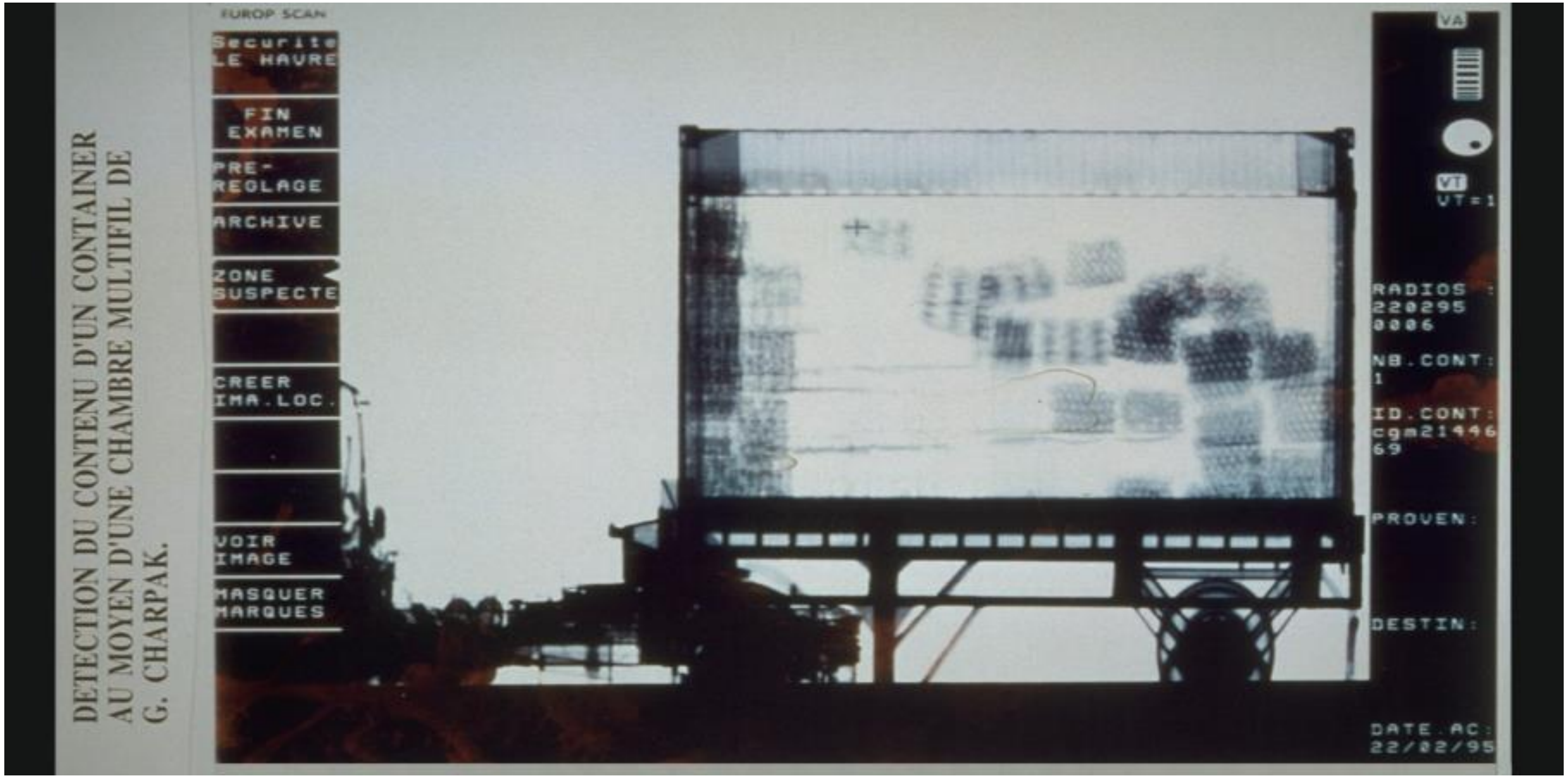
Ion implantation



More than 10’000 accelerators used in semiconductor industry

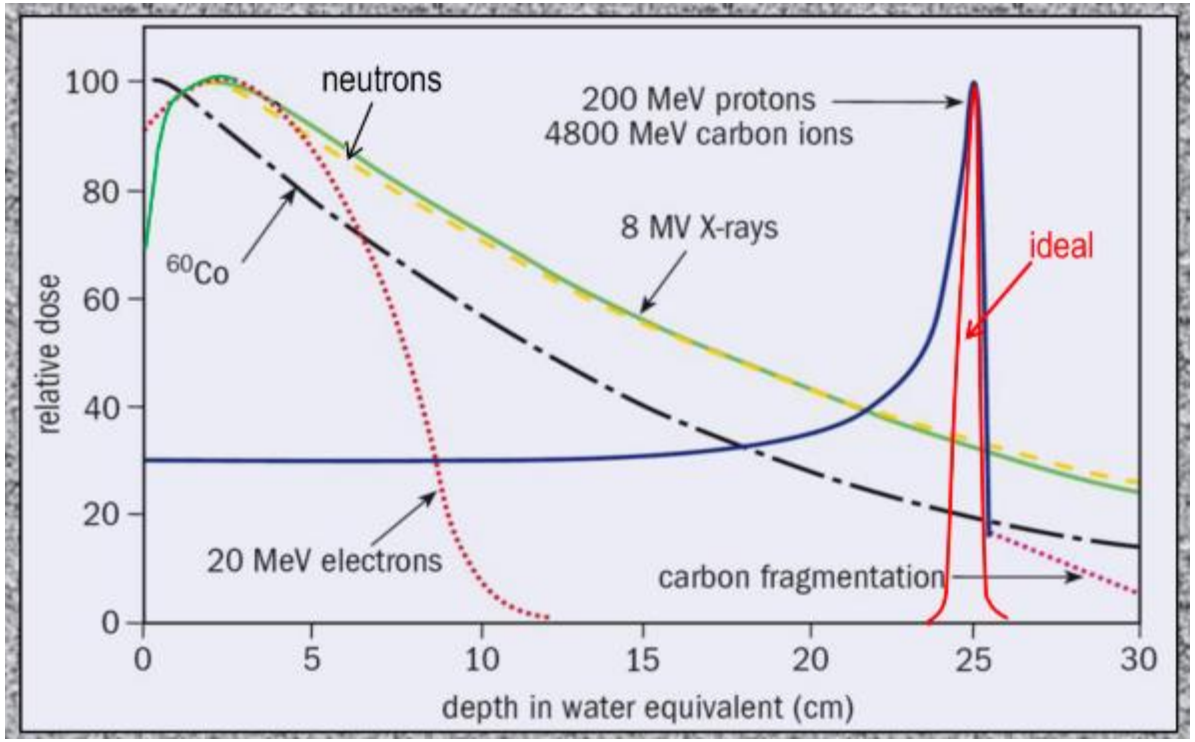


Cargo screening



Particle therapy of cancer

Proton and Ion cancer therapy: irradiate the tumour with beams of particles. The “Bragg peak” allows to concentrate the radiation dose on a deep tumour, minimising the dose to the adjacent tissues. Complements the usual irradiation with X-rays from e- linacs, for deep cancers or close to vital organs. Carbon ions are effective for radio resistant tumours.

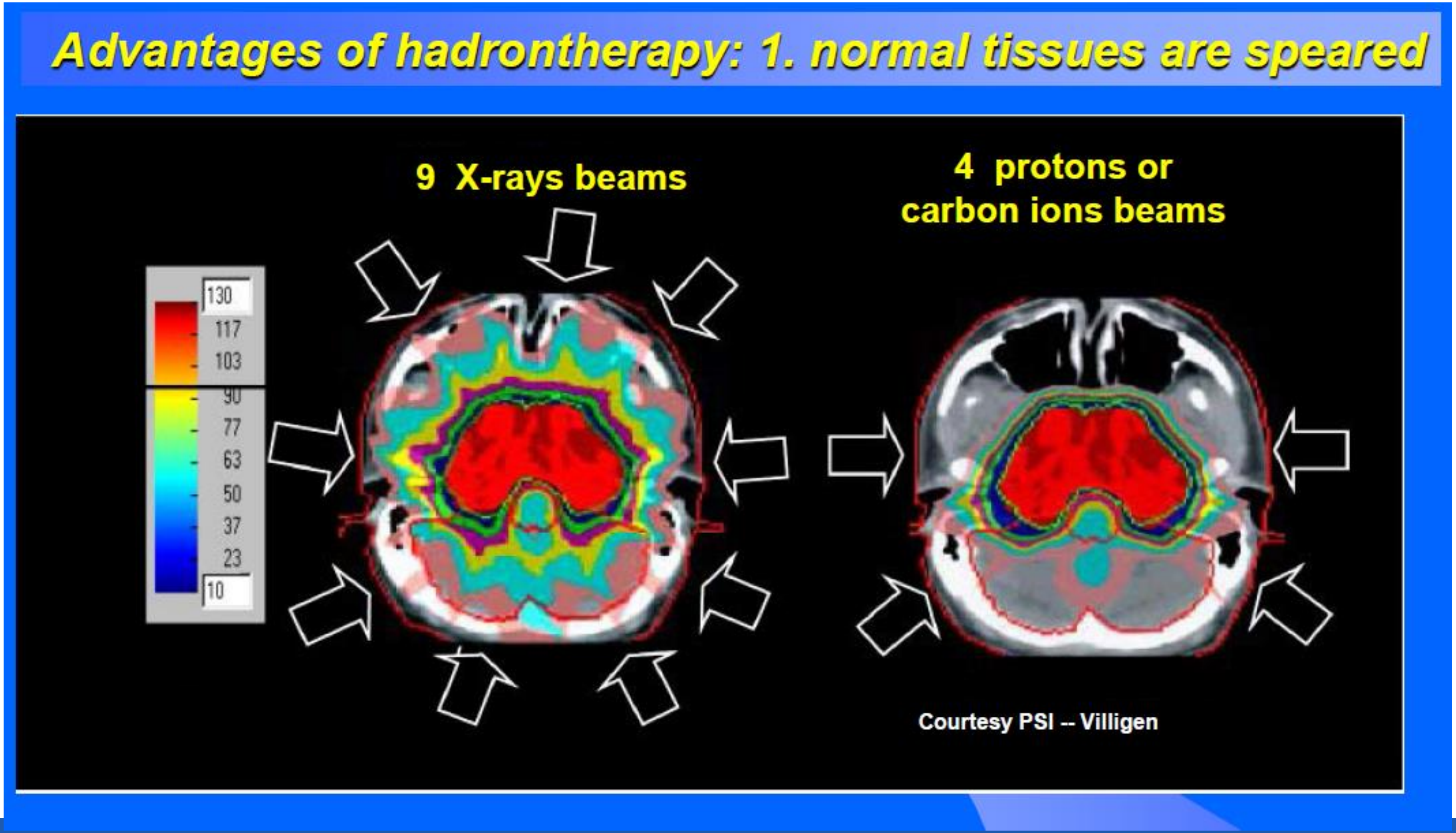


Most used: protons and carbon ions.

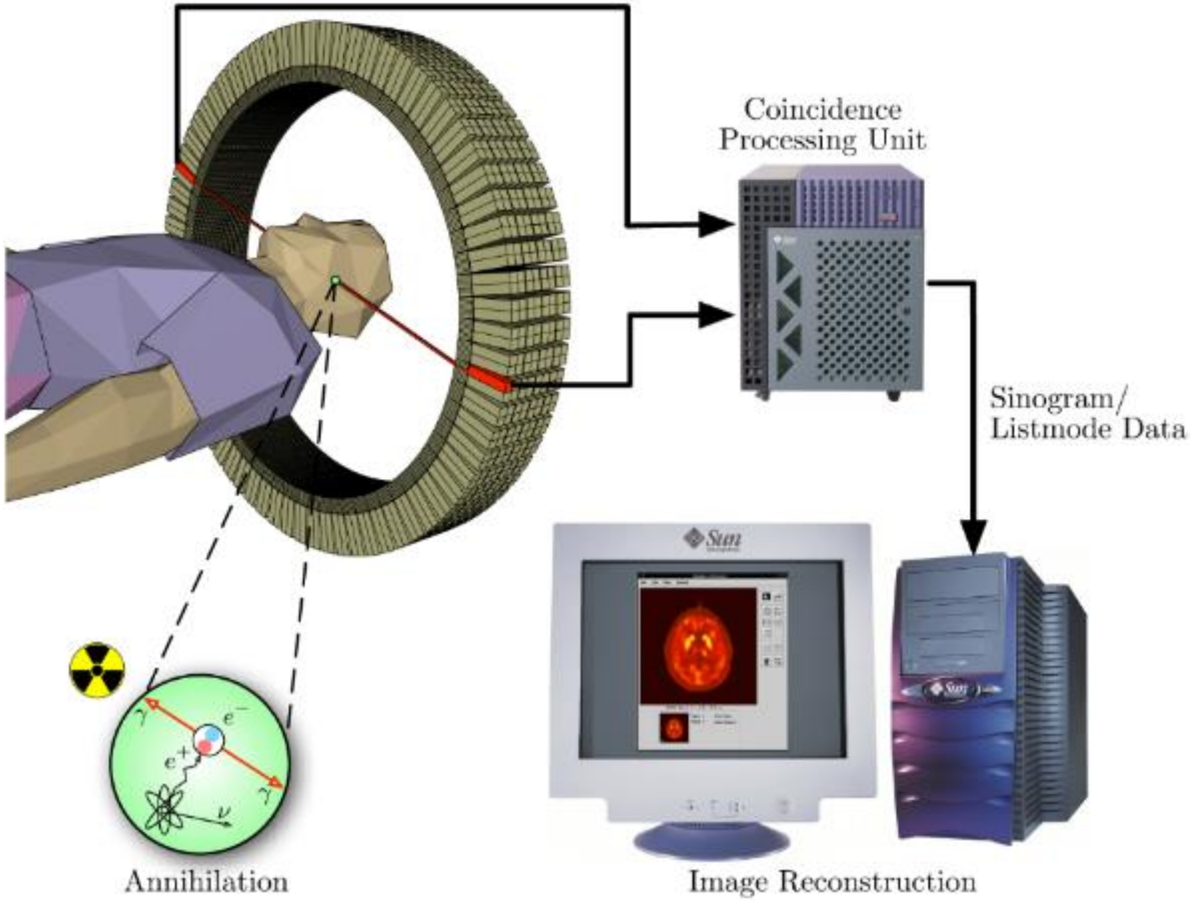
- Protontherapy is rapidly developing: more than 65'000 patients treated, 5 companies offer turn-key solutions.

- Carbon ions, used for about 6000 patients, have a larger radiobiological effectiveness and require more radiobiological and clinical studies to define the best tumour targets.

Advantages of particle therapy



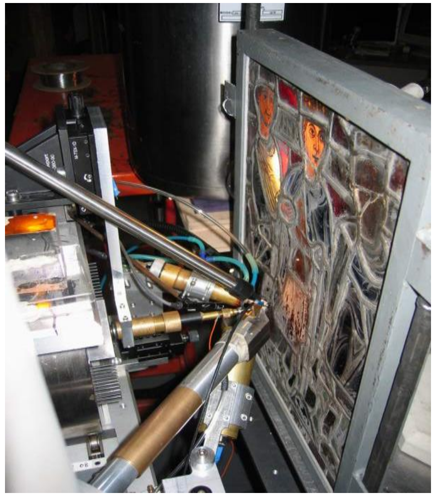
Production of radio isotopes for PET



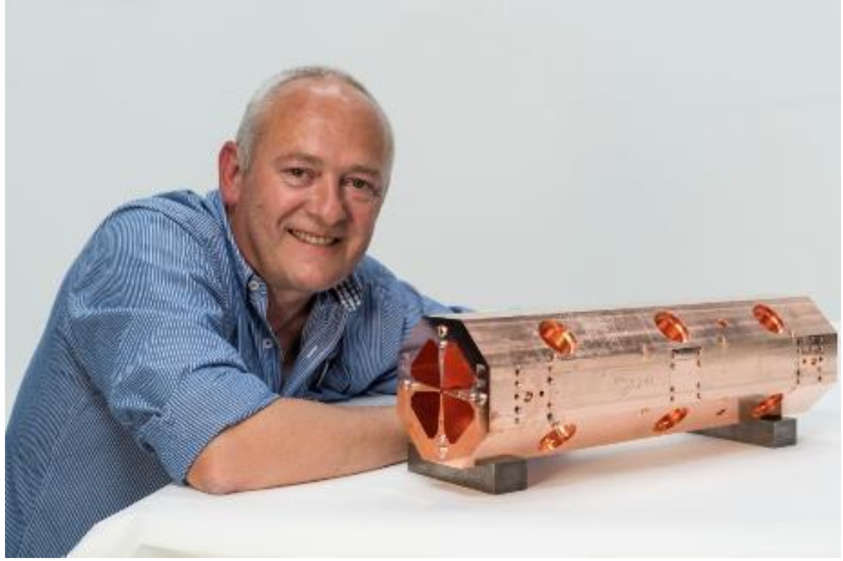
AMIT superconducting cyclotron for isotope production in hospitals
(CIEMAT, Spain, with CERN contribution)

A miniature accelerator for cultural heritage analysis

Developing a small **portable accelerator (1 m length)** for 2 MeV protons equipped with a PIXE detector (Proton Induced X-ray Emission), used for non-destructive in-situ analysis in the domain Archeometry (surface composition of cultural artefacts: paintings, jewellery, etc.).
Ion Beam Analysis is presently performed with large electrostatic accelerators based in research centres. A portable accelerator could be installed in small museums or for artefacts that cannot be displaced.



Stained glass panel analysed by PIXE/PIGE/RBS with 3-MeV protons



Conclusions

Particle accelerators are 90 year old but are still in their infancy. They are marvelous scientific instruments that have paved the way for modern science: 25 out of the last 74 Nobel prizes in physics were related to particle accelerators.

It is a vivid field, with more than 4'000 people presently employed in Europe in accelerator construction, operation and research and a focus now moving from basic science to applied science, medicine and industry. Several companies are interested in these technologies that are being rapidly industrialized.

The LHC is the largest single "machine" ever built by humanity. And we are not going to stop there!

Welcome to CERN!

Elwood Smith