Heavy Ion Therapy Research Integration

A BRIEF INTRODUCTION TO PARTICLE ACCELERATORS

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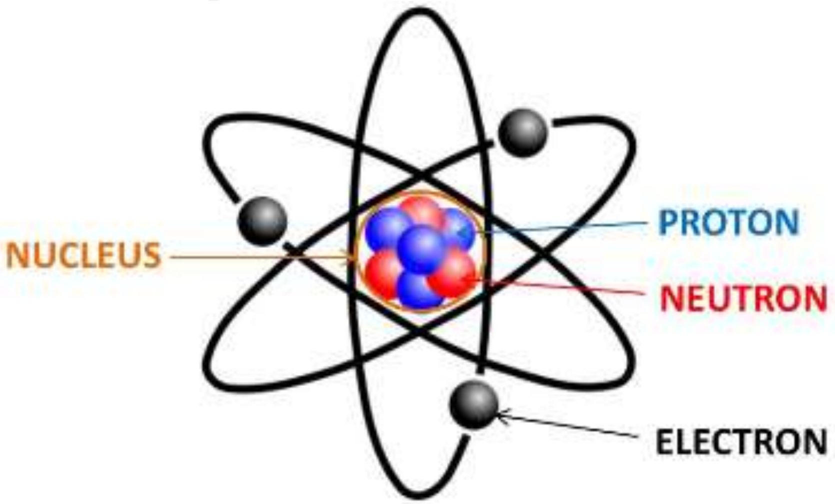
Motivations and outline of this lecture

Motivation:
- Give an overview of accelerator technologies and applications, with no maths;

Outline:
- Accelerators as a tool to access the subatomic world
- Origin and development of particle accelerators
- Accelerator technologies
- Types of accelerators
- Challenges for present and future accelerators

Particle accelerators: what we accelerate and how?



	Charge	Mass
Electrons	-1 e	1 m_e
Protons	+1 e	1 m_p
Ions	+1 / +82 e	1 – 238 m_p

Unit charge 1 e = 1.6×10^{-19} Coulombs
Electron mass 1 m_e = 9.1×10^{-31} kg = 511 keV/c^2
Proton mass 1 m_p = 1.67×10^{-27} kg = 938 MeV/c^2

Subatomic particles are inside the atoms

We can extract the particles from the atoms and then:

- give them energy using electric fields,
- guide them using magnetic fields

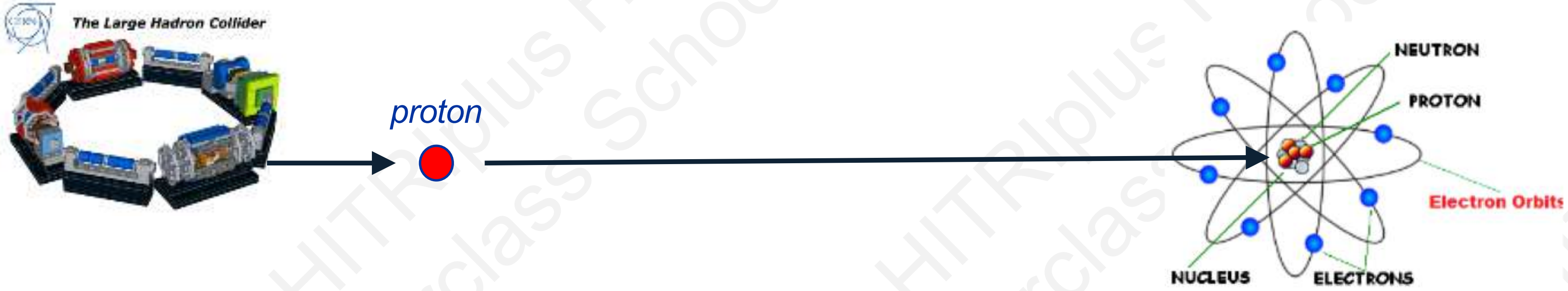
Lorentz force: $$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

Can be accelerated only particles that have an electric charge: electrons, protons, ions (= charged nuclei)

Particle Accelerators can concentrate energy

Particle accelerators are our door to access the subatomic dimension… to study and exploit the atom and its components

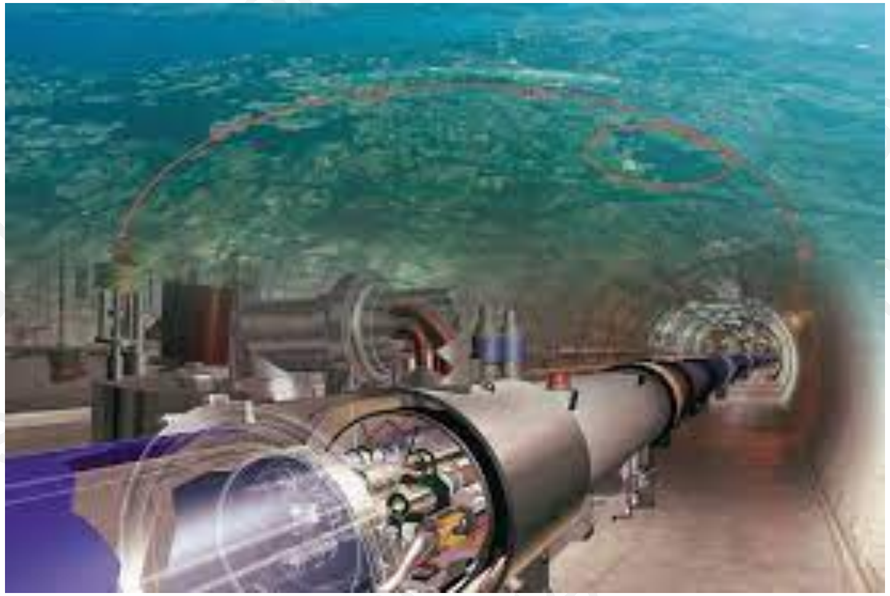
When we extract particles from an atom and we accelerate them, we concentrate **enormous amounts of energy in tiny volumes**



Where will this energy go? An accelerated subatomic particle sent towards an atom will:

1. Deliver some **energy to the electrons**.
2. Deliver some **energy to the nucleus** (if the particle has sufficient energy to penetrate the atom.

How large is the energy of a particle beam?



Comparing the energy of a single proton out of the CERN Large Hadron Collider, the largest particle accelerator ever built.

The energy is small, but the energy density is enormous!

	Proton out of LHC	150g Yoghurt	TGV train
	•		
Energy	$1.1\ 10^{-6}$ J	$5\ 10^{5}$ J	$3.6\ 10^{8}$ J
Energy density	$5.3\ 10^{38}$ J/m^3	$3.3\ 10^{9}$ J/m^3	$1.5\ 10^{11}$ J/m^3
Type of energy	Kinetic Subatomic scale	Chemical Macroscopic scale	Kinetic Macroscopic scale
Energy full LHC beam	$3.6\ 10^{8}$ J		

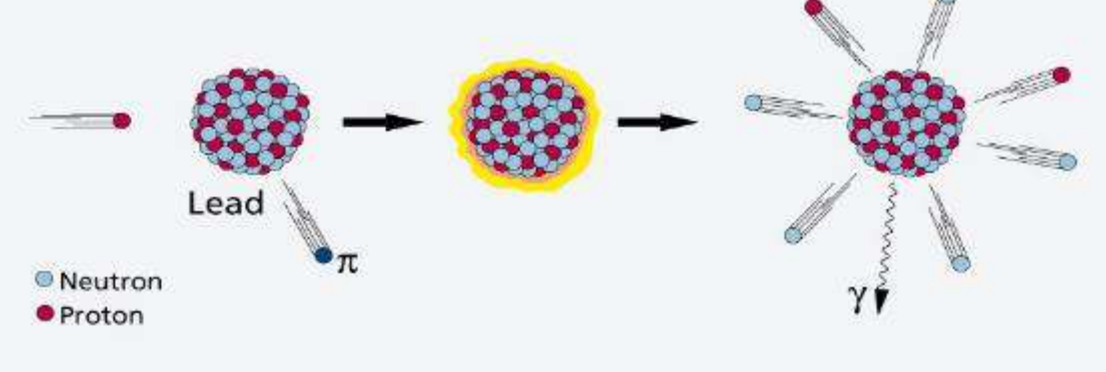
TGV train:
400 tons, 200 m,
150 km/h

Accelerators can modify the nuclei and create new particles

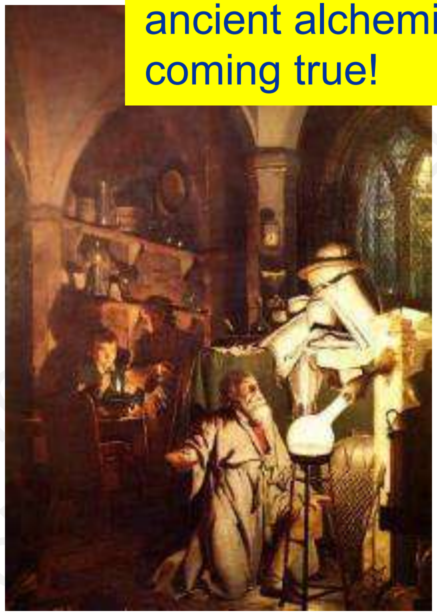
If the energy is sufficiently high, the particles in the beam transfer energy to the nucleus and its components (and are then scattered, reflected or absorbed).

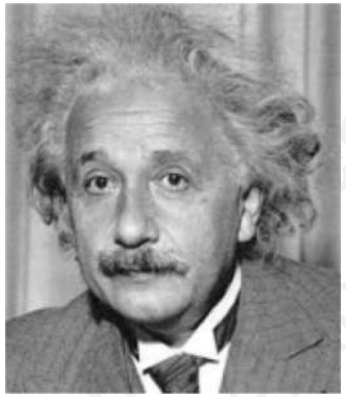
It's the dream of the ancient alchemists coming true!

NUCLEAR PHYSICS



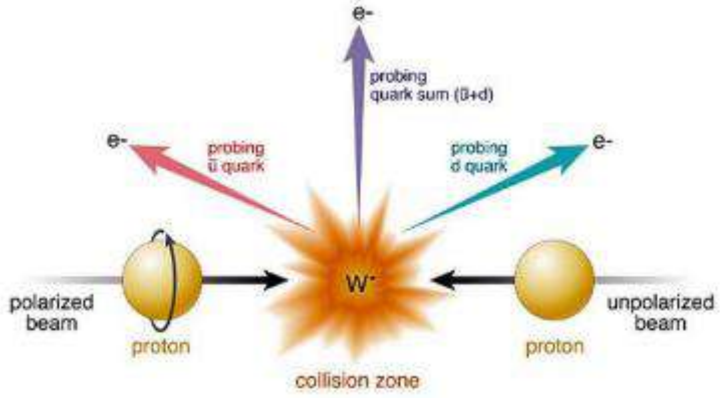
Particles in the beam can break and modify the nucleus (and then generate new elements and transform the matter!)



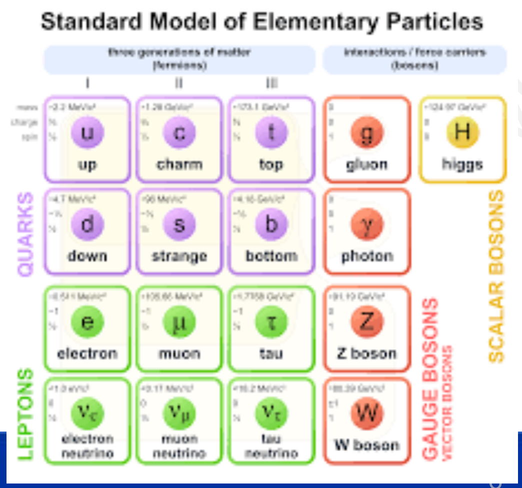


$E = m c^2$

PARTICLE PHYSICS



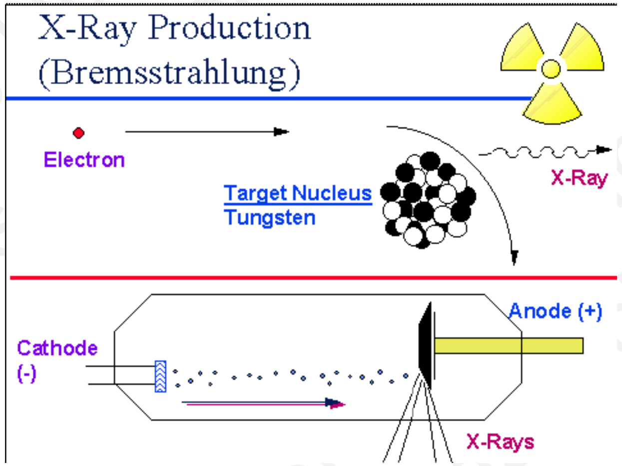
In the collisions can be generated new particles.

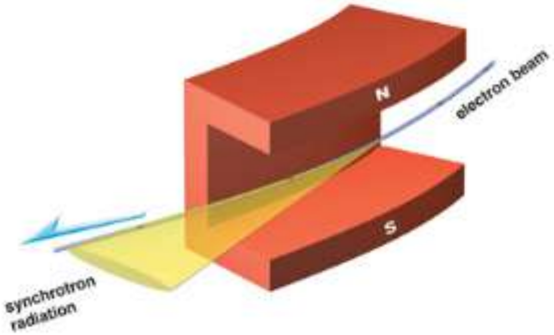


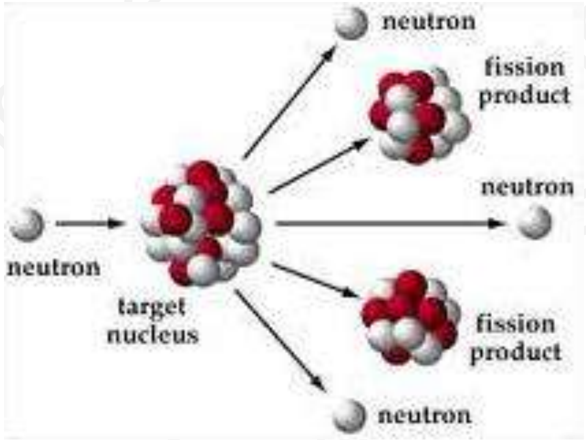
Accelerators can produce intense secondary beams

Accelerated electrons produce X-ray beams by interaction with a metal target (bremsstrahlung) or by synchrotron radiation in accelerator magnets)

Accelerated protons produce neutron beams by spallation reactions in a heavy metal target



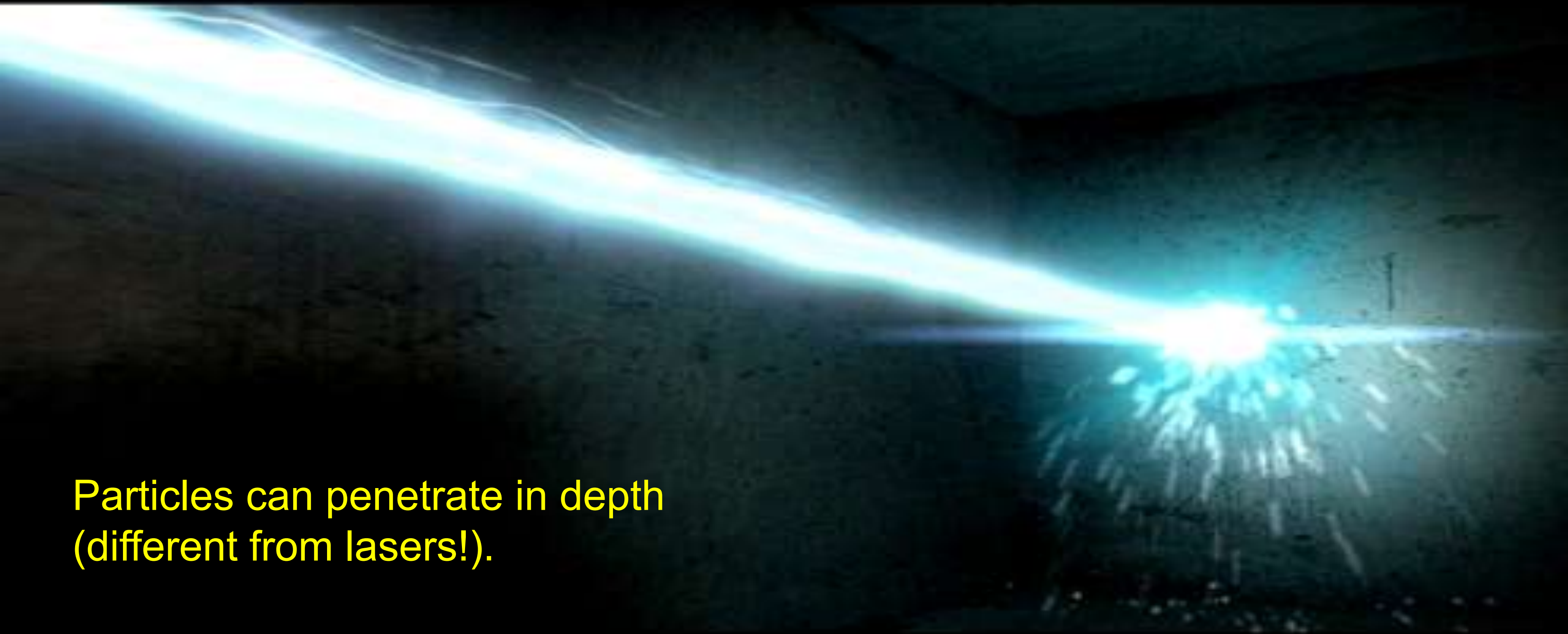




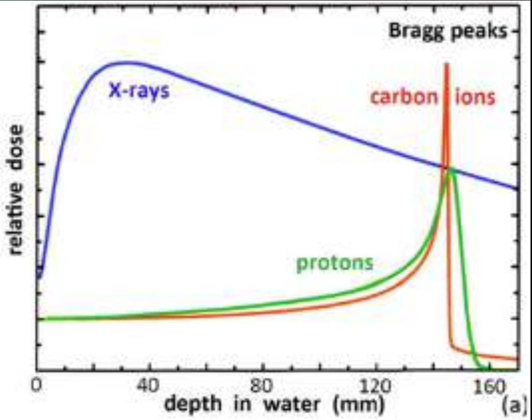
- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications are appearing for other types of secondary beams.

Accelerators can precisely deliver energy

A «beam» of accelerated particles is like a small "knife" penetrating into the matter



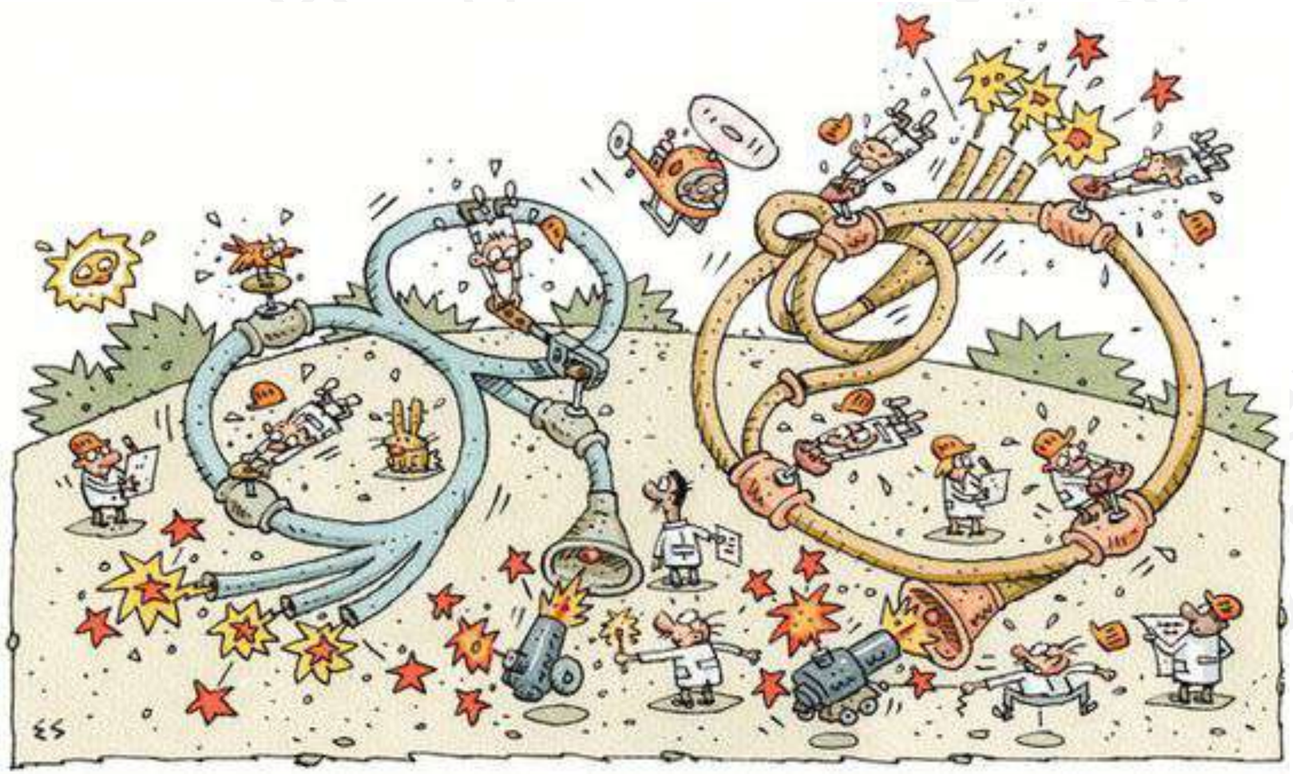
A particle beam can deliver energy to a very precisely defined area, interacting with the electrons and with the nucleus.



Particles can penetrate in depth (different from lasers!).

Particle beams are used in medical and industrial applications, e.g. to cure cancer, delivering their energy at a well-defined depth inside the body (Bragg peak)

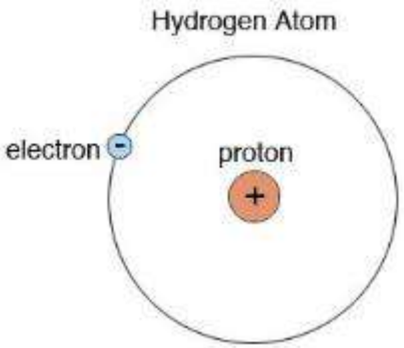
How do accelerators work?



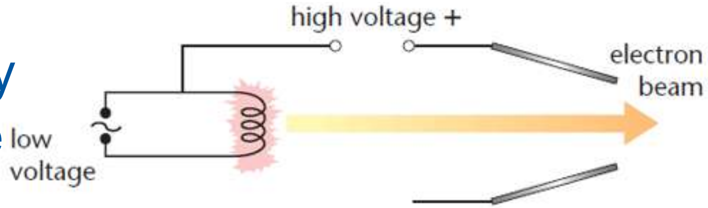
First of all, you need the charged particles

You find them inside the atoms!

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

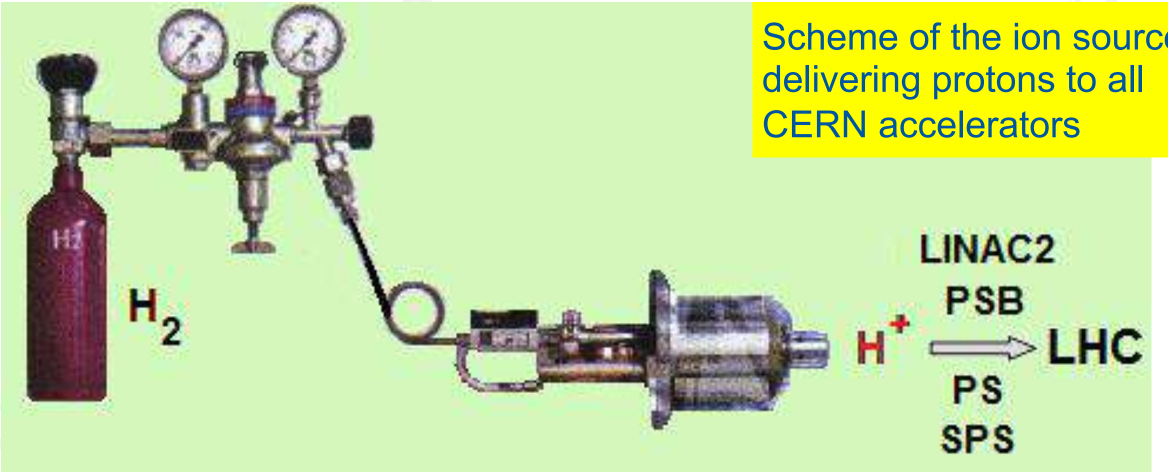


Electrons are obtained by heating of a filament (like an electric bulb)

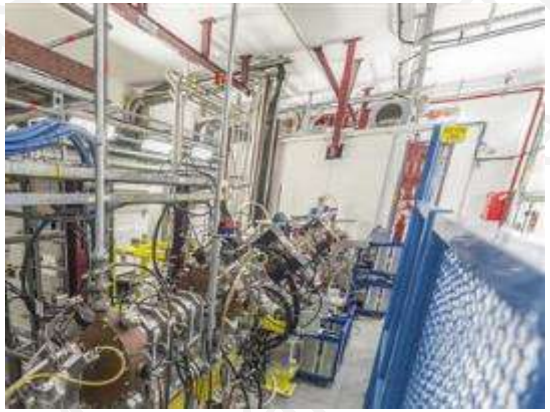


An electron gun

Ions are obtained in a similar way to protons



Scheme of the ion source delivering protons to all CERN accelerators



The ion source at the CNAO hadron therapy facility

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 at CERN needs only 1’200’000 billions of protons per day.

How to give energy to particles and to control their motion

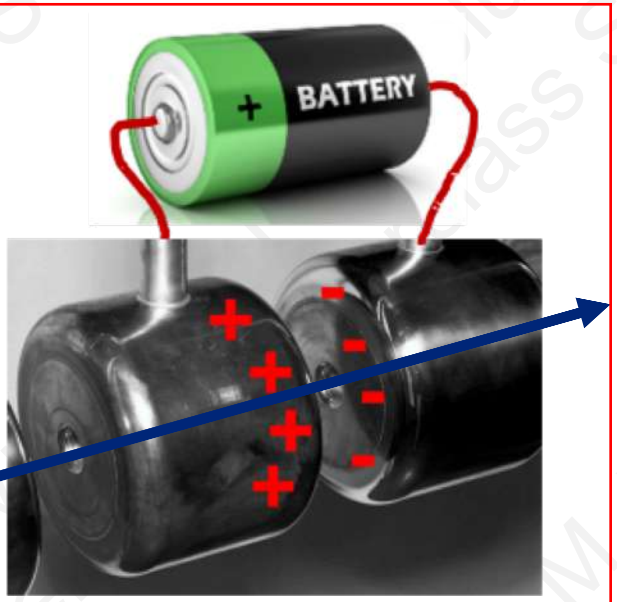
The key to the process:
Lorentz force experienced by a charged particle going through an electric and/or magnetic field

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

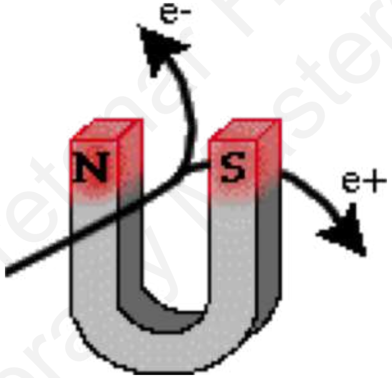
q=electric charge, v=velocity

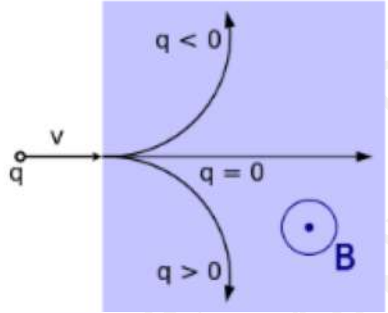
An **electric fields** produced by a voltage applied between 2 electrodes (tubes) gives energy

A tube allows particles to go out of the electric field region

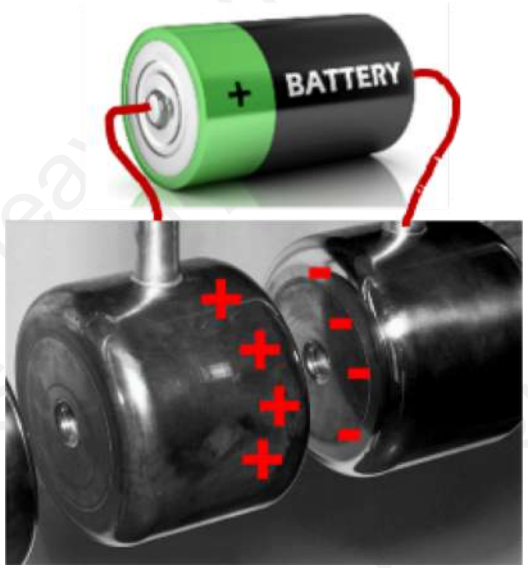


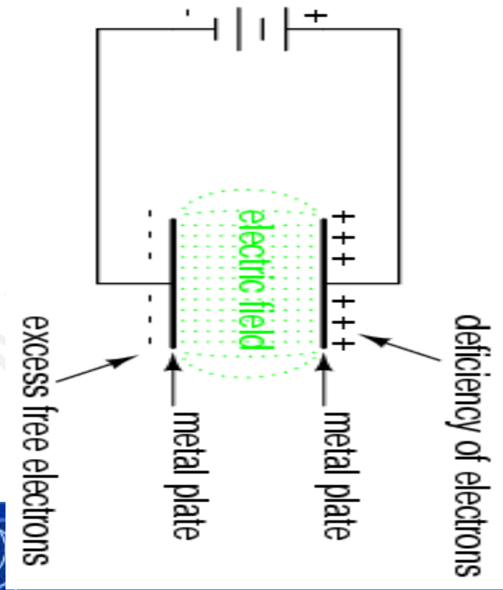
A **magnetic fields** produced by a magnet (electromagnet or permanent) will deflect the particles.





The initial acceleration stage

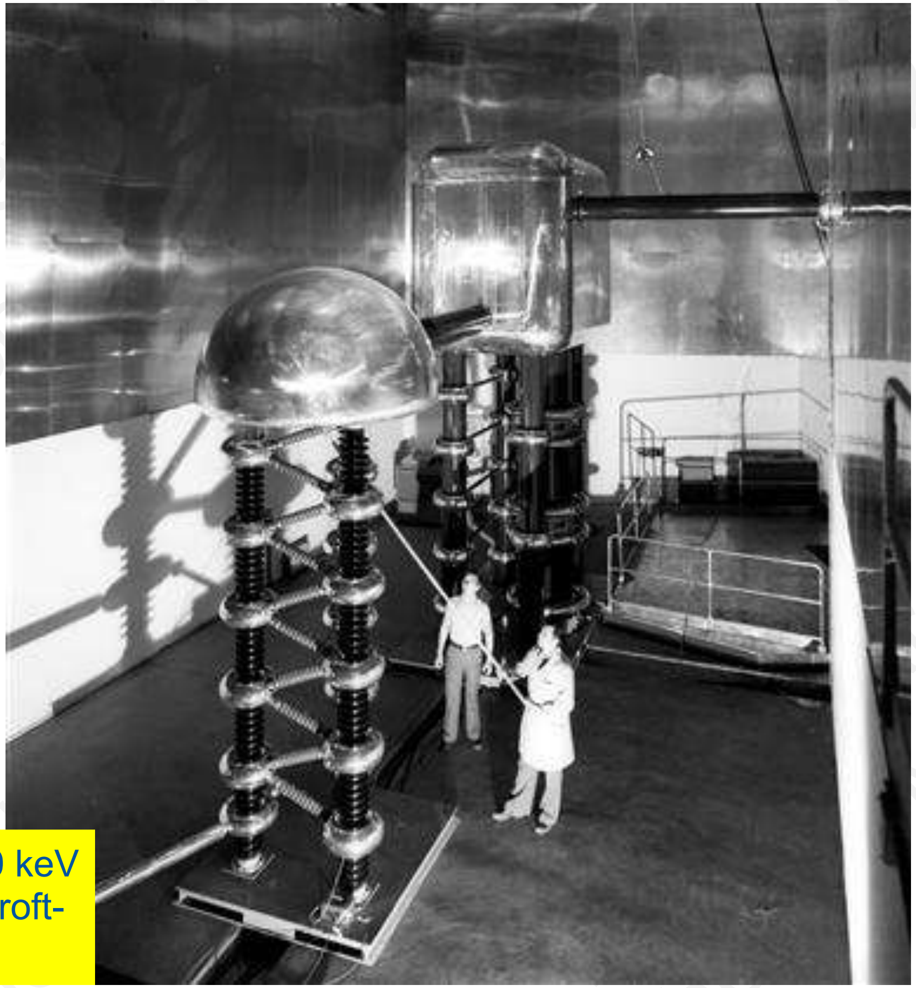




Electrostatic: use a DC voltage between 2 tubes

(A simple 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.

How can we increase particle energy?

A historical digression:

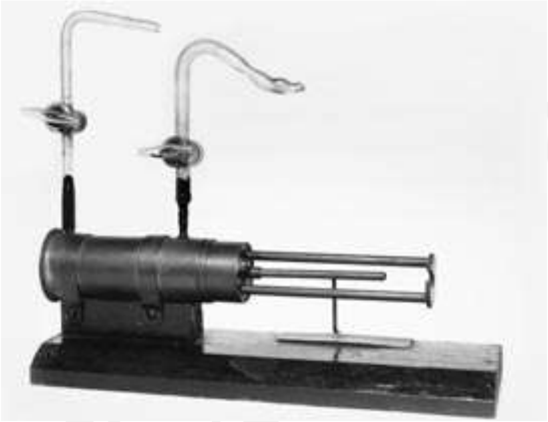
1919: E. Rutherford transmutation experiment: a nitrogen nucleus bombarded by α-particles (from Ra and Th decay) converts into oxygen and hydrogen → start of a new era for science!

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

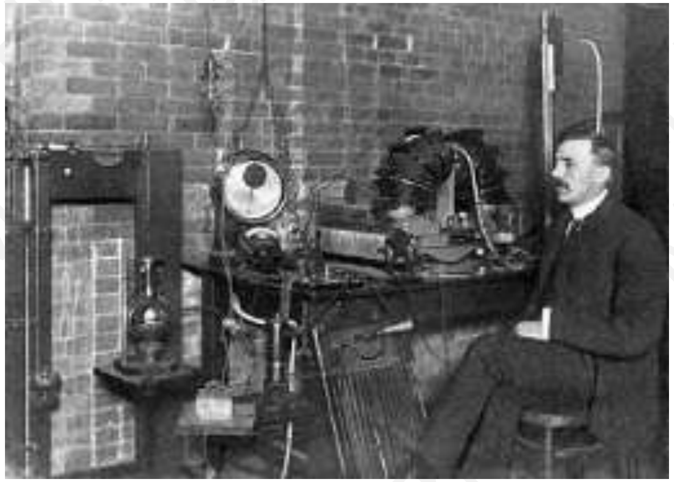
1927: Rutherford in a speech at the Royal Society urges scientists to develop “accelerators” producing a large number of energetic particles and capable to disintegrate heavy nuclei.

1928 – 1931: scientists develop larger electrostatic accelerators, capable of breaking some light nuclei, but limited in energy by high-voltage discharge.

A new technology is needed to reach higher energies!



Copy of the original Rutherford chamber:



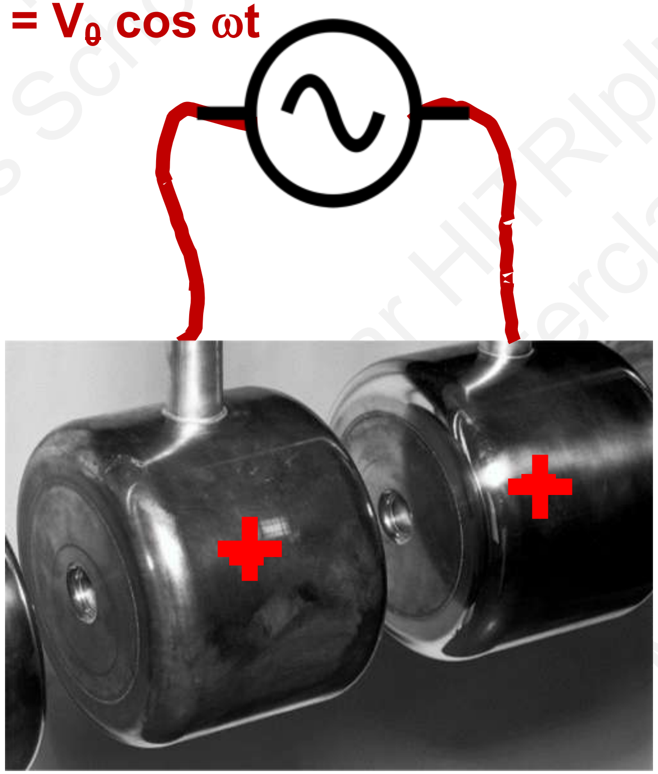
Acceleration using oscillating electric fields (RF)

In 1928 a PhD Thesis introduced the basic concept of modern particle accelerators:

Periodic acceleration provided by electric field at Radio-Frequency (RF).

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.

$V = V_0 \cos \omega t$



Rolf Wideroe, inventor of Radio-Frequency acceleration

Ion Source
Ionised potassium atoms

Drift tube
2 gaps, one on each side

Spectrometer
Transverse electric field

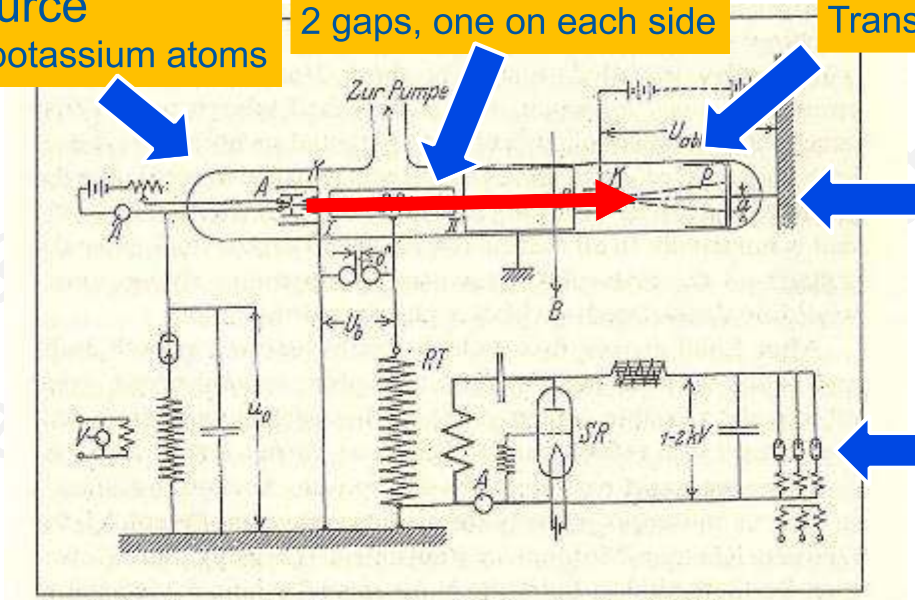


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

System in vacuum
To avoid losing particles on air molecules

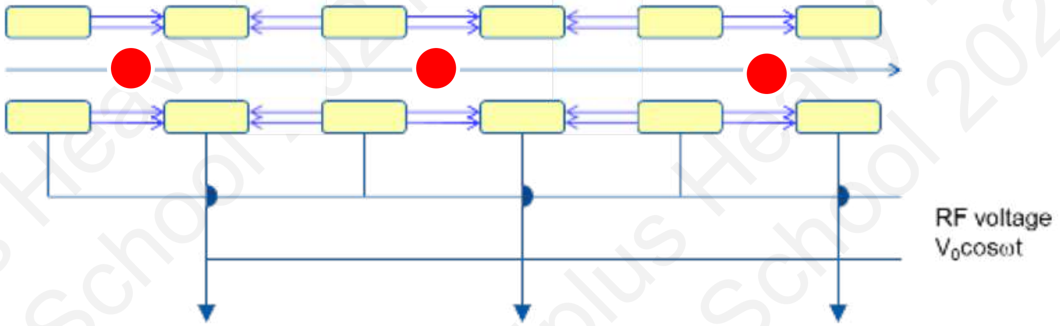
Radio generator
1 MHz, 25 kV

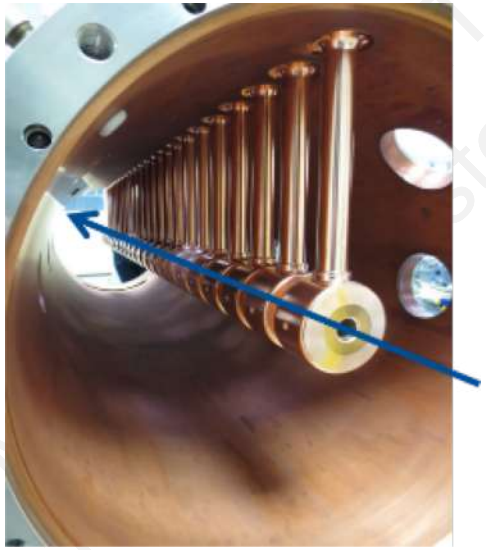
The principle of Radio Frequency acceleration

Two consequences of using **variable E-fields**:

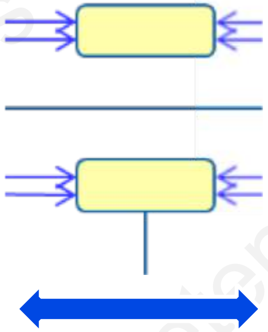
1. The beam of particles cannot be continuous. Particles must be grouped in "bunches" at the period of the radio-frequency

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





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



L = cell length

Time to travel L = period / 2

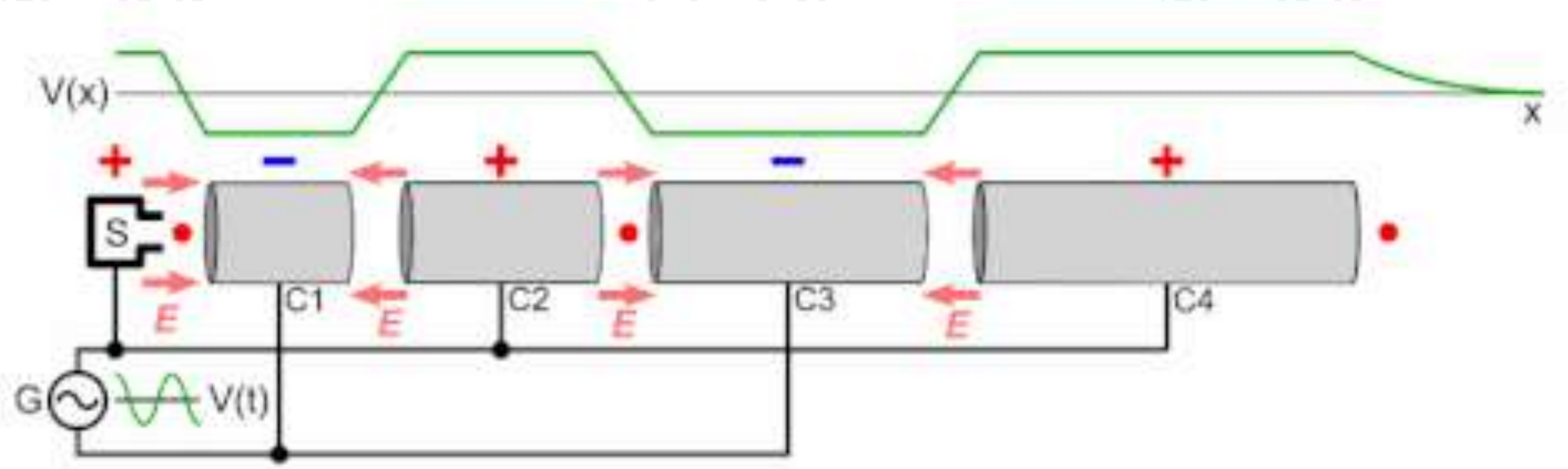
L / v = T / 2 = 1 / 2 f

L = v / 2f

v = velocity of the particle

f = frequency of our generator

We have built a linear particle accelerator (linac)!



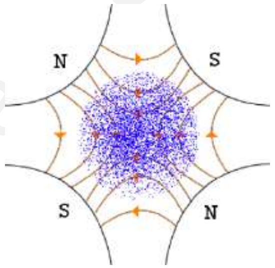
(image from Wikipedia)

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

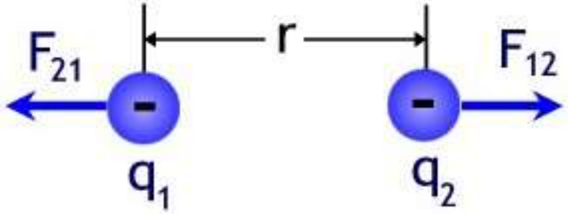
An example: the Drift Tube Linac of the CERN Linac4

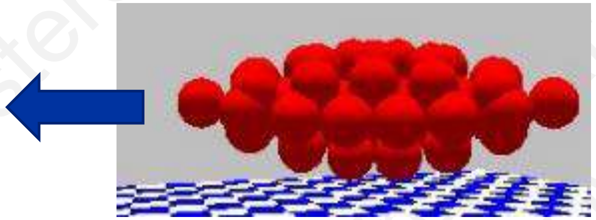
Fighting electric repulsion: beam intensity, focusing

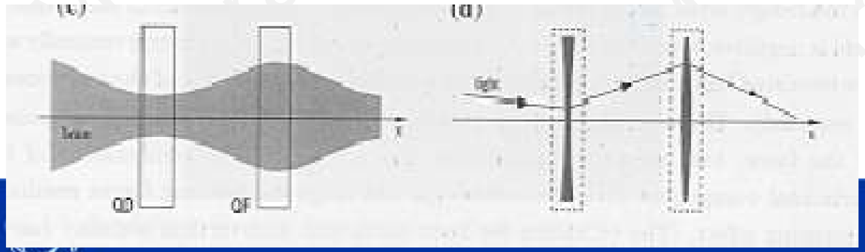
Up to now we have been considering only one particle, but in reality in a bunch there are 10^{10}-10^{13} particles in a few square mm...
They all have the same sign and they tend to repel each other (Coulomb force)!
If we do nothing, our beam will end up in every direction…



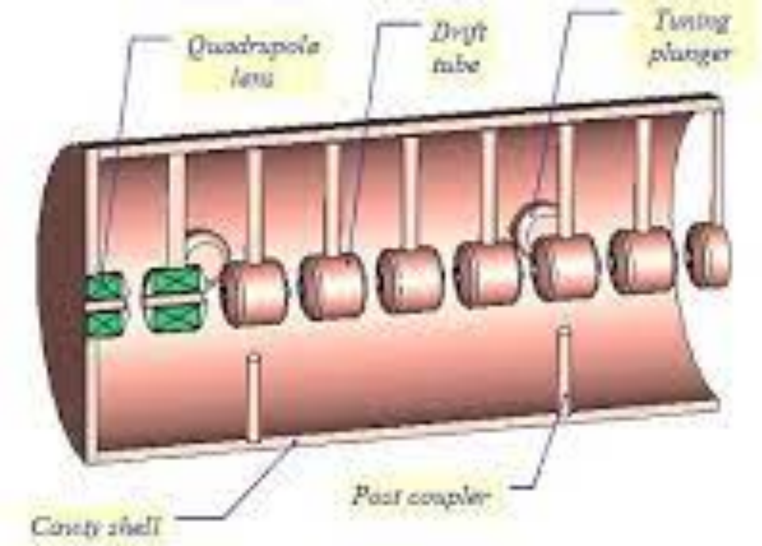
Solution:
Alternating gradient strong focusing
Add quadrupole magnets every few dipoles.
The beam envelope oscillates but the particles remain confined.

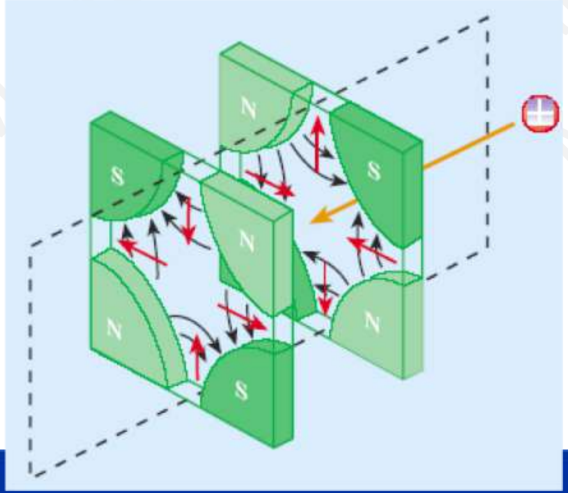


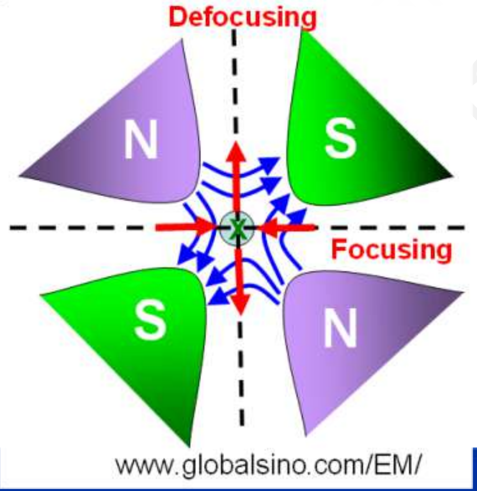




Example of focusing: Drift Tube Linac quadrupoles







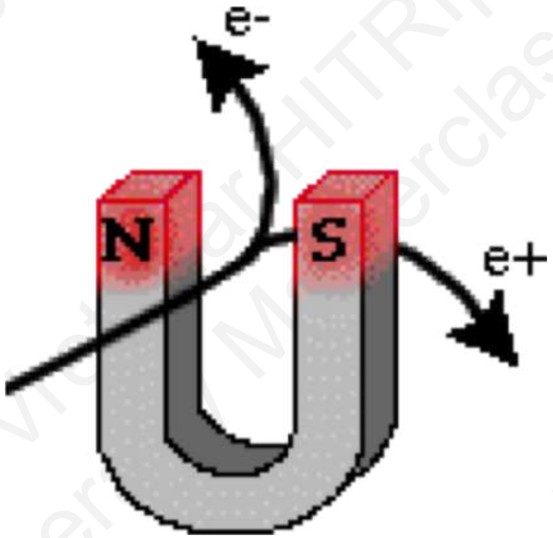
Can we use a linac to go to very high energy?

A quick calculation:

With tubes we can make about 2 MeV per meter. At higher acceleration rates the electric field is too high and we will have electric discharges between the tubes.

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

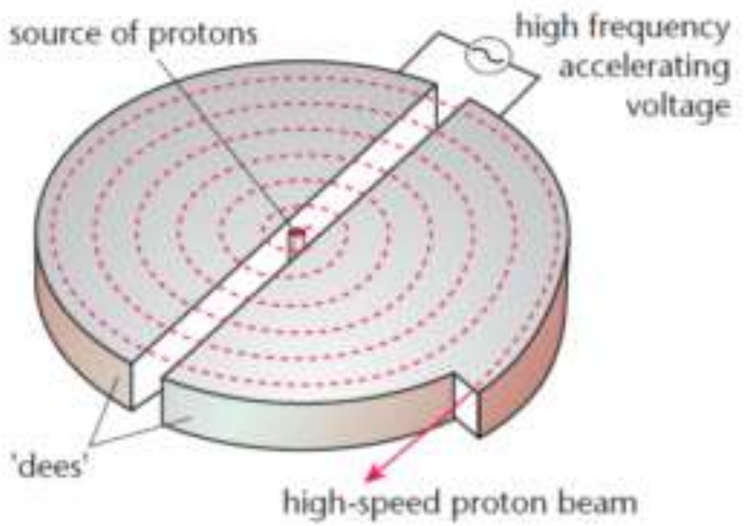
We need another trick: bending the particles in a magnetic field



A compact low-energy accelerator: the cyclotron

Immediately after R. Wideore's invention of the linear accelerator, Ernest O. Lawrence at Berkeley proposes to perform radio-frequency acceleration in a circular system, inserted in a big magnet.

The cyclotron is born!



1. Acceleration in the gap between two "D" → long path of the particles in the D, frequencies ~1 MHz can be effectively used (3.5 MHz, 1st Berkeley cyclotron).
2. Fortunate "coincidence": the revolution frequency does not depend on the beam energy → RF frequency is constant !

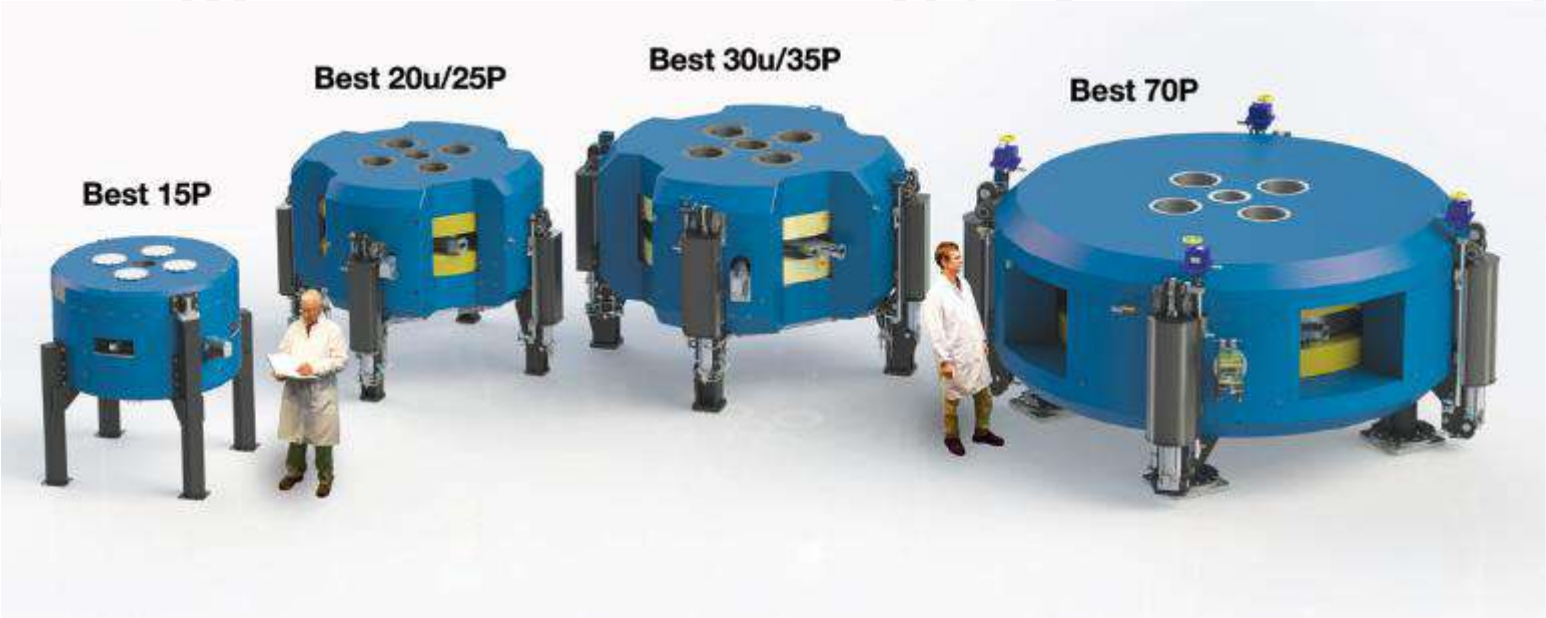
(but: this limit the use of cyclotron to non-relativistic energies !)

$$\frac{mv^2}{r} = evB \qquad f = \frac{1}{\tau} = \frac{2\pi r}{v} = \frac{2\pi r\, m}{eBr} = \frac{2\pi m}{eB}$$

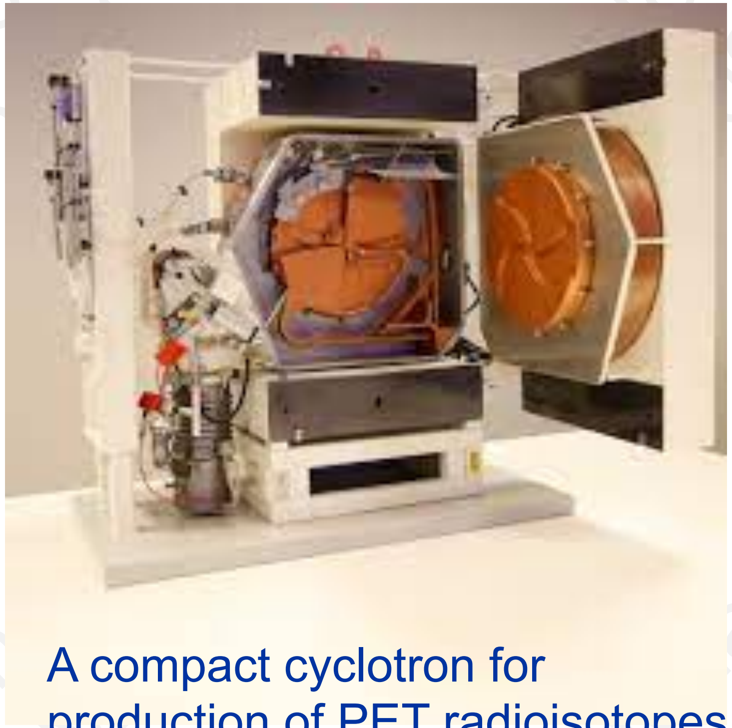
revolution frequency

- Protons are produced by an ion source in the centre
- They are accelerated in the gap between 2 électrodes fed with radio-frequency
- The protons go in larger and larger spirals, and their velocity increases proportionally to the spiral radius, keeping their revolution frequency constant.

Examples of cyclotrons



The range of BEST cyclotrons, from 15 to 70 MeV output energy



A compact cyclotron for production of PET radioisotopes (GE Healthcare)

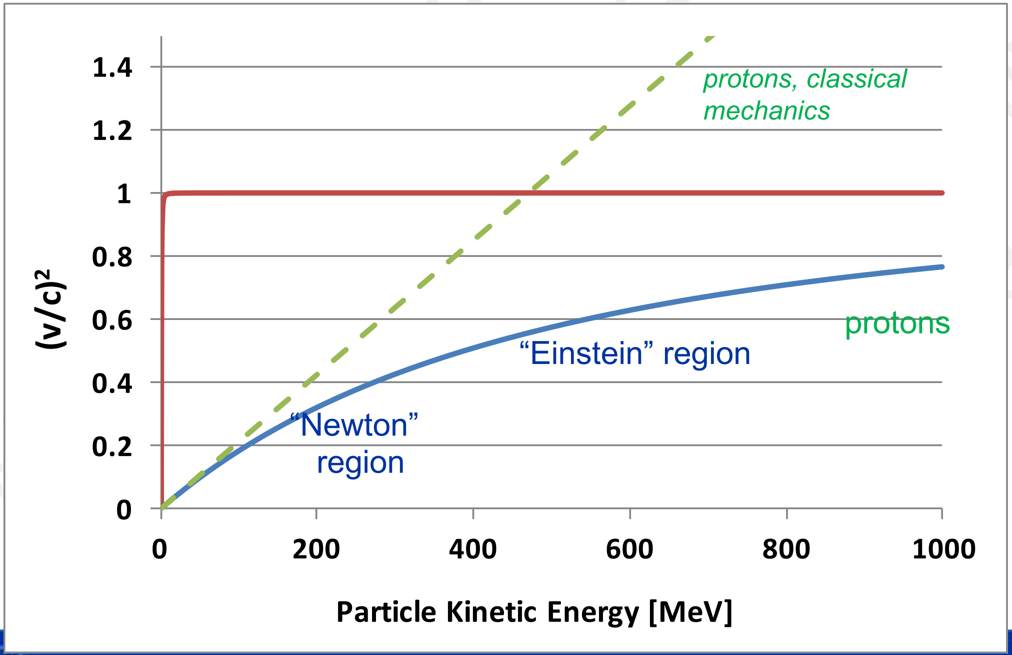
Very compact, can accelerate large particle intensities, but their construction and operation are simple only when the particle energy is low (non relativistic).

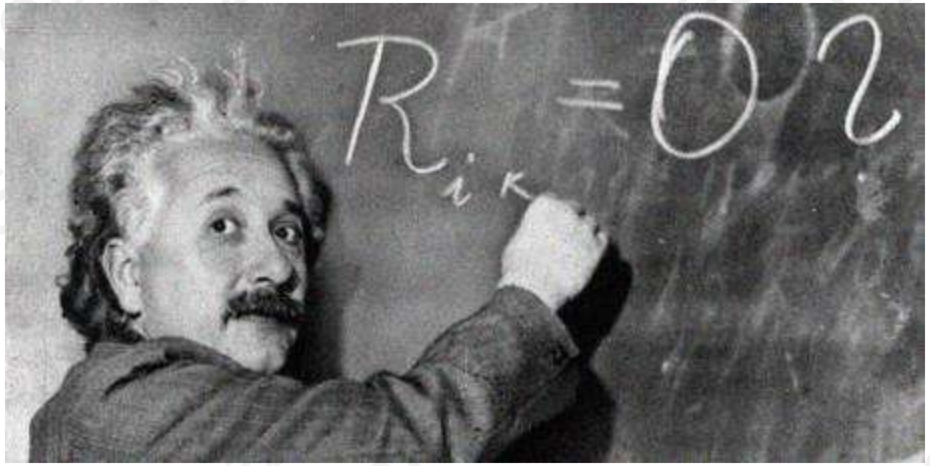
Where is the limit? Into the hands of Einstein…

We give energy to the particles, they become faster and faster, but then…
The energy starts going into increasing the mass and not the velocity!

We come into the realm of special relativity,
Where we are in the hands of Einstein!

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



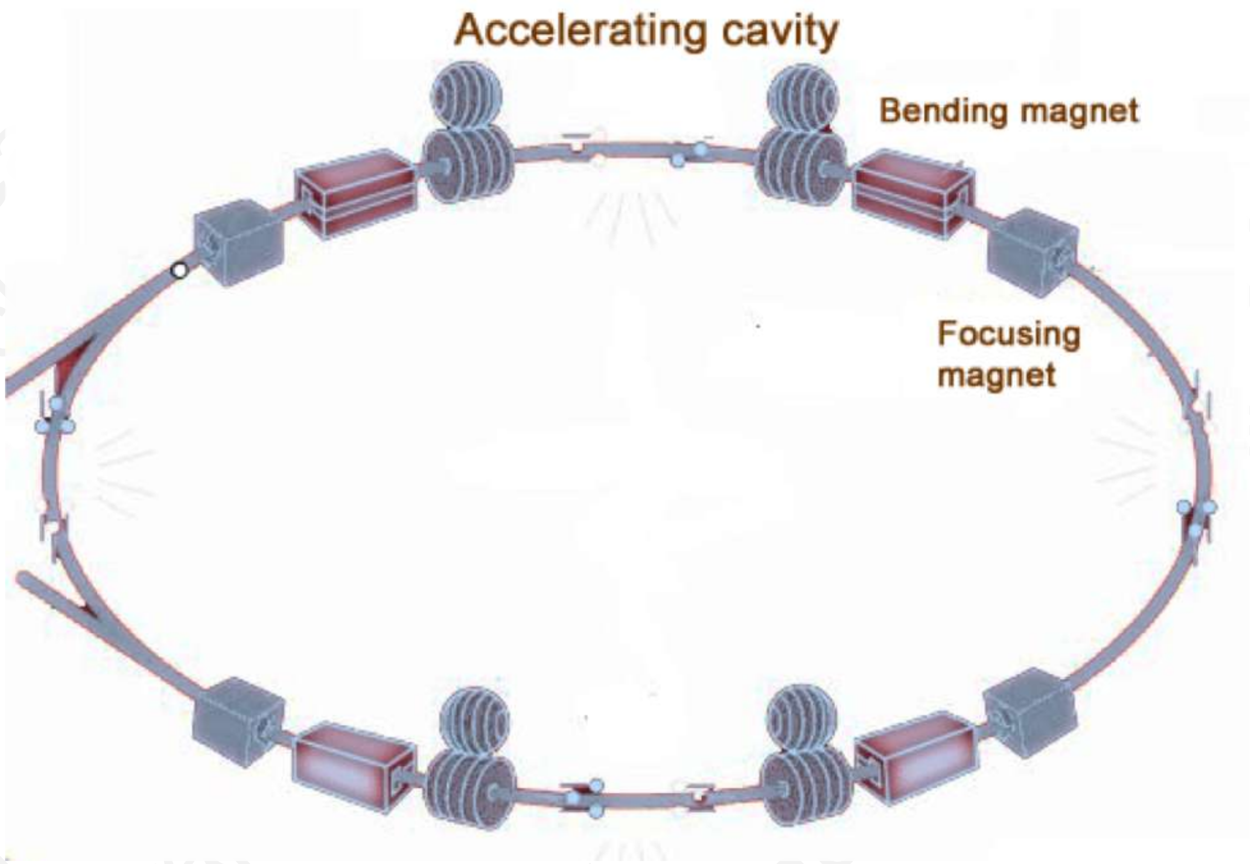


Classic (Newton) relation	Relativistic (Einstein) relation
$T = m_0 \frac{v^2}{2}, \quad \frac{v^2}{c^2} = \frac{2T}{m_0 c^2}$	$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1+T/m_0 c^2}}$

Limit for conventional cyclotrons: ~ 70 MeV
Limit for special cyclotrons (synchrocyclotrons): ~ 500 MeV

We need something special to enter the realm of Einstein!

The synchrotron



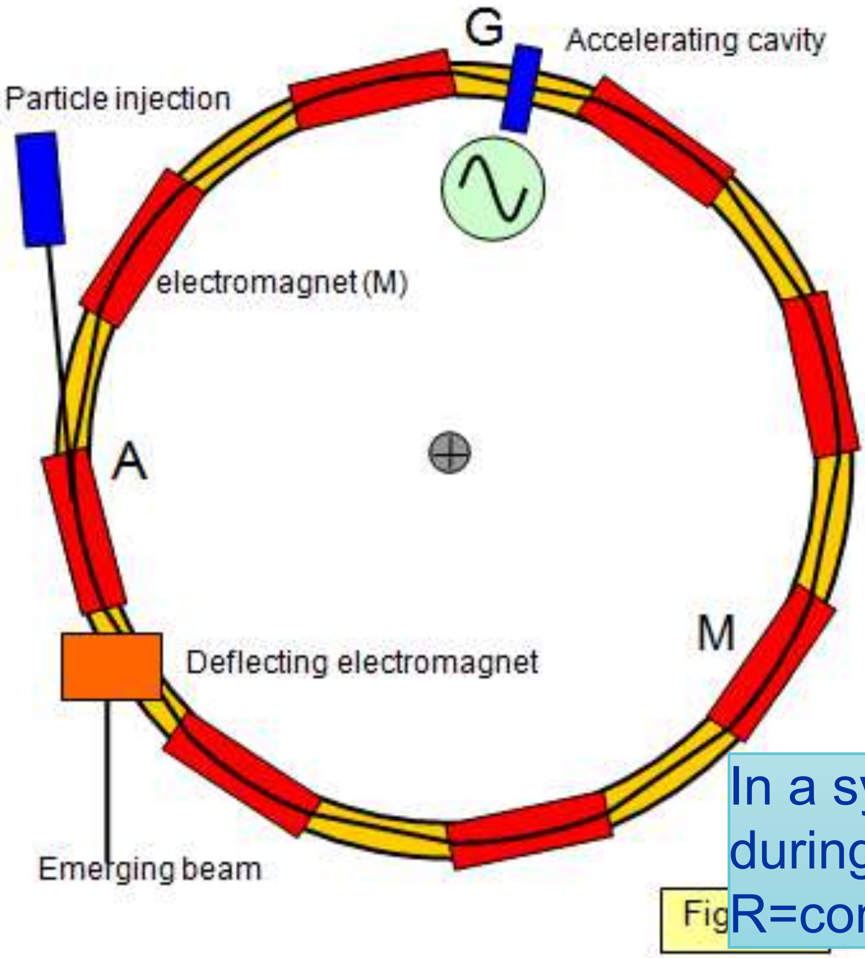
Operates in the energy range where the velocity of particles is nearly constant (=c)

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 between the tubes.

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

Going to higher energies: the synchrotron



Revolution period:

$T = 2\pi R / v$ ➡ fixed, when v is constant

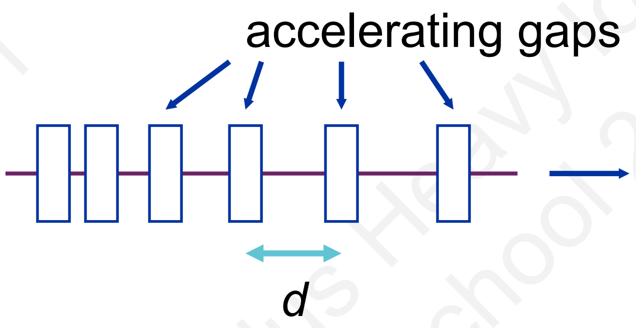
Radius (from Lorentz formula):

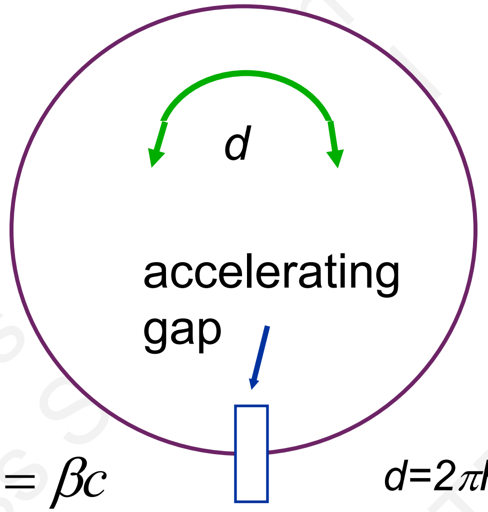
$R = p / eB$ ➡ increases with velocity
decreases with magnetic field

In a synchrotron, we increase the magnetic field in the magnets during acceleration to keep the particles on the central orbit.
R=const., we increase B proportionally to momentum p

$$E^2 = (pc)^2 + \left(m_0 c^2\right)^2$$

Linear and circular accelerators





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

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

$$2df=\beta c$$

$d=2\pi R$=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

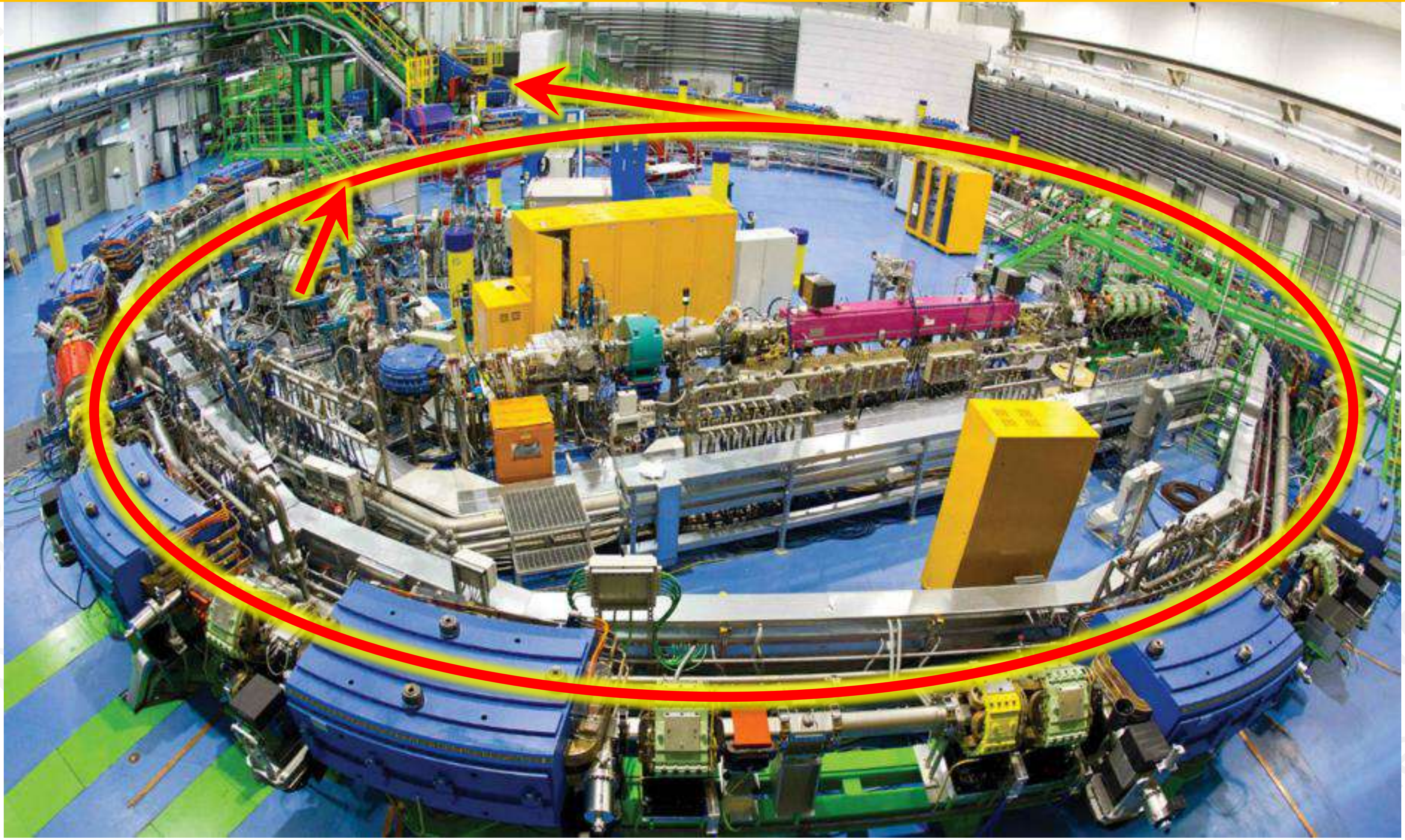
Circular accelerator:

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

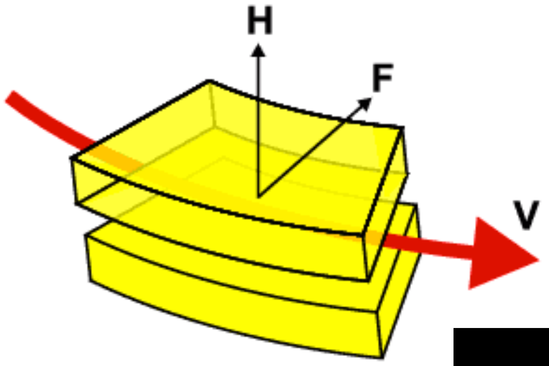
Distance between gaps is fixed. Synchronicity only for β~const, or varying (in a limited range!) the RF frequency.

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

The CNAO synchrotron

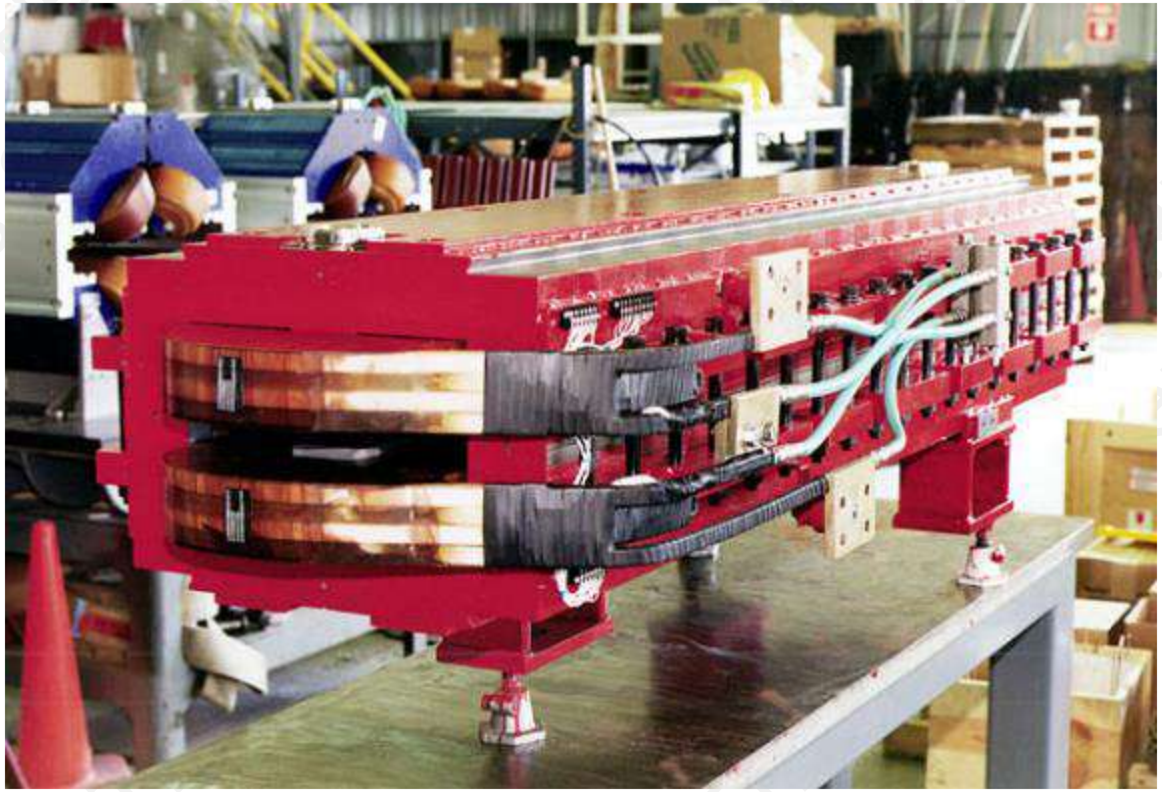


The magnets

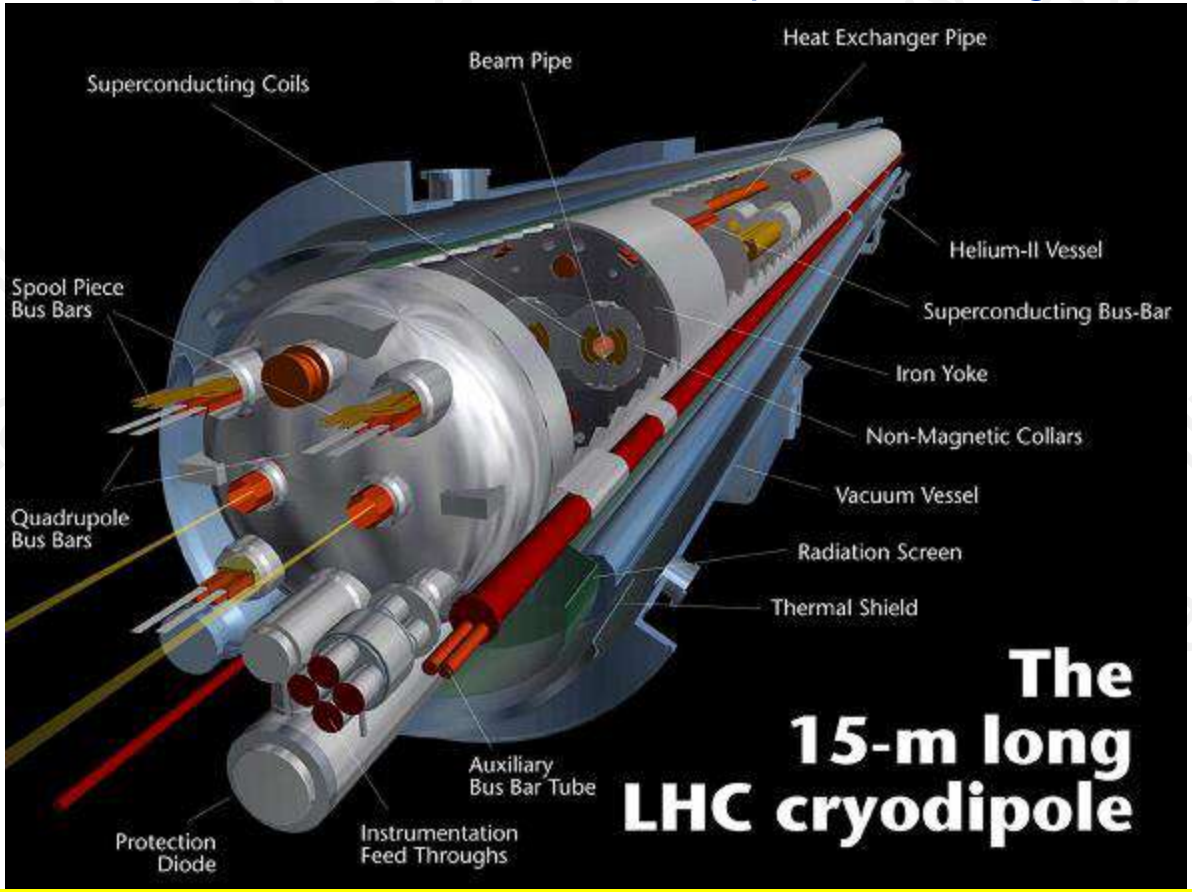


dipole

Normal conducting

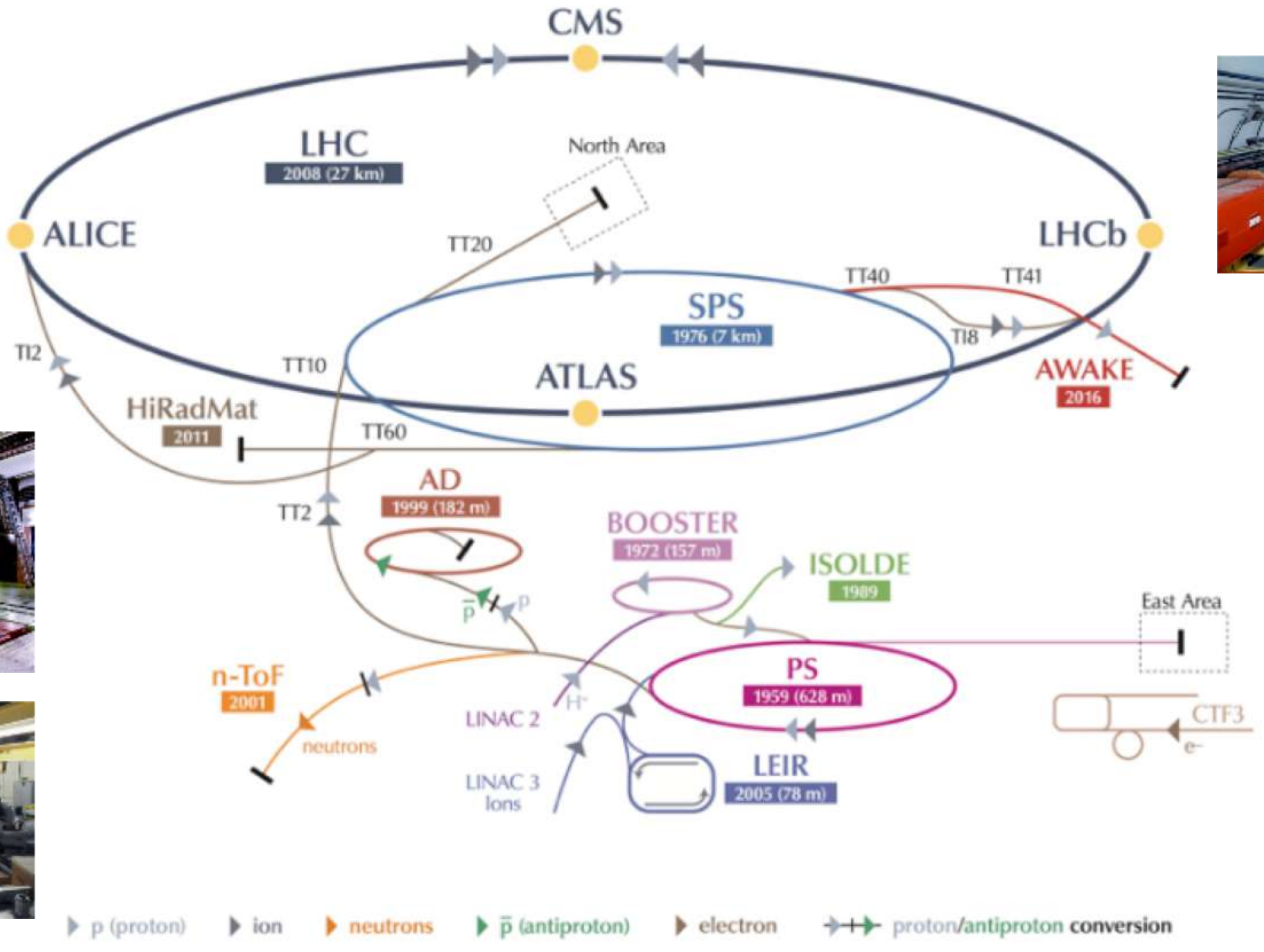


Superconducting



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

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

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.

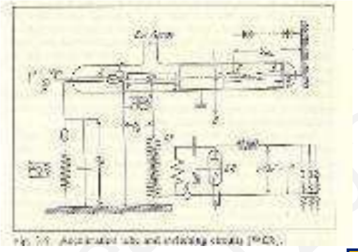
The LHC magnet superconducting cable

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

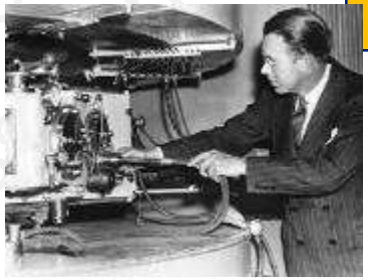
Innovation in the particle accelerator field



1931…………1945/48….1952…………..1965/90's…….

XXI century

?



Cyclotron: cyclic acceleration with magnets (Lawrence)

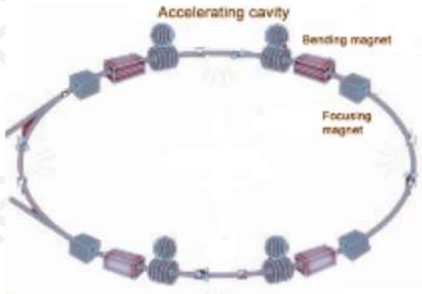
Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconducting magnets and acc. cavities

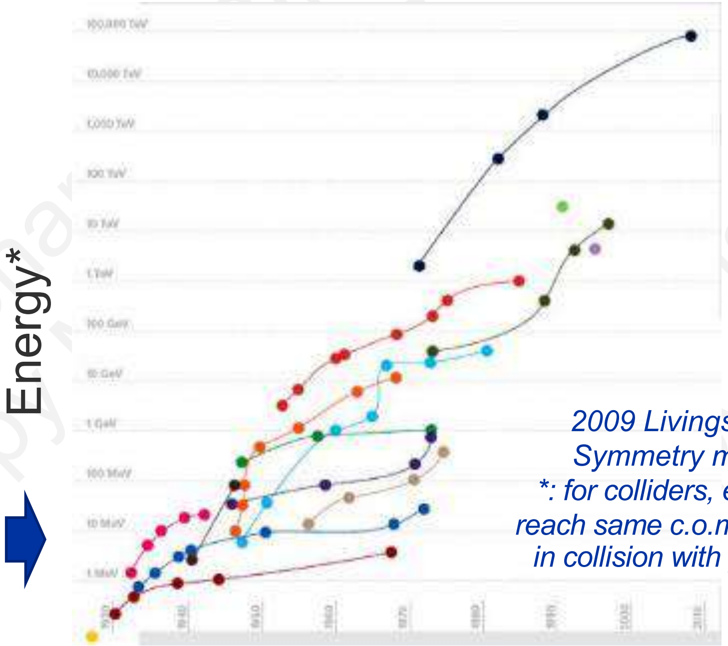
2008: the Large Hadron Collider

Application of WW2 radar technology to accelerators (Hansen, Alvarez)

Succession of enabling technologies (technology leaps)



- First accelerator
- Cyclotrons
- Cockcroft-Walton electrostatic accel.
- Van de Graaff electrostatic accelerators
- Betatrons
- Synchrocyclotrons
- Linear accelerators
- Electron synchrotrons
- Proton synchrotrons
- Storage ring colliders
- Linear colliders



S. Livingston, 1959:
Accelerator energy increases by a factor of 10 every 6 years
(Moore's law of accelerators)

2009 Livingston plot, Symmetry magazine
**: for colliders, energy to reach same c.o.m. energy in collision with proton at rest*

Towards the miniature accelerator?

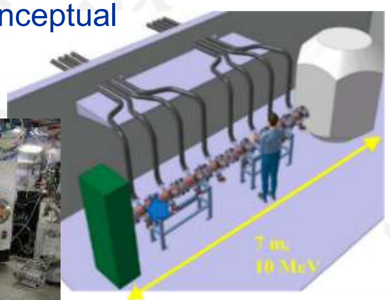
Important trend towards miniaturization of accelerators, for use in medicine and industry

Here are presented only three examples of recent developments at CERN:

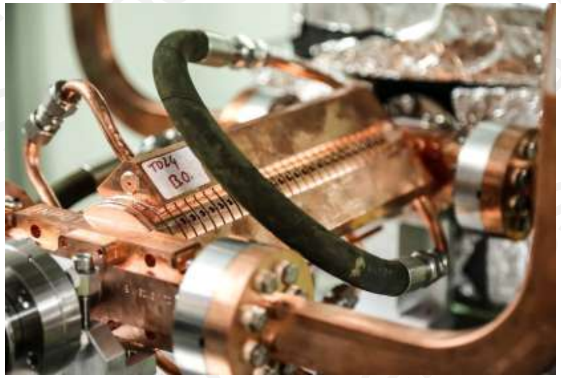
The mini-RFQ

750 MHz
92 mm diameter
2.5 MeV/m

Proton therapy injector (in operation)
Artwork PIXE analysis (in construction, transportable)
Isotope production (design)
Neutron radiography (conceptual stage)

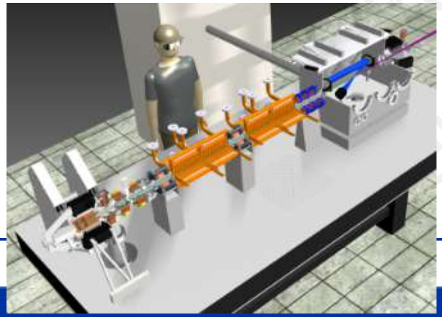


X-band structures

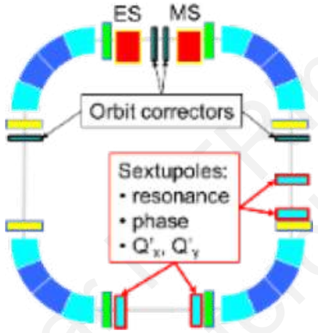


12 GHz
100 MeV/m

Developed for CLIC, in operation at CLIC test stand
- Compact XFEL (CompactLight Design Study)
- VHEE and FLASH therapy linac (design)
- SmartLight (table top inverse Compton scattering light source, design)

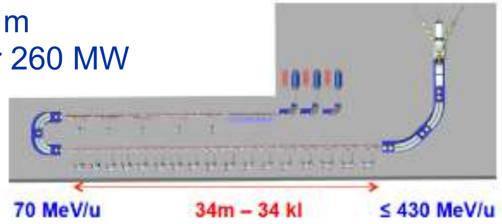


Compact accelerators for ion therapy



Superconducting C-ion synchrotron
Bmax 3.5 T
27m circumference

Folded C-ion linac,
Tot. length 53 m
Tot. RF power 260 MW



Thank you for your attention!

Heavy Ion Therapy Research Integration

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