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LECTURE 1: Introduction

August 2021

Introduction to Particle Accelerator Science and Technology

Motivations and guidelines of this course

Goal:

Give a fast and simple overview of accelerator **physics**, **technologies** and **applications**, focusing on **concepts** with minimum mathematics, to:

a. give to all those who will continue in other fields (e.g. particle physics) some **key elements** that might be useful in their career;
b. give to all those who will continue on specific accelerator subjects a **global picture** that will help them to better understand how their field is part of a system;
c. give some **ideas** and **inspiration** to those who have not yet decided on their next steps.

Guidelines:

- Particular focus on **low energy** acceleration and on **applications** of accelerators.
- Will skip tedious mathematical demonstrations that can be found in books.

Disclaimer:

Time will be too short to give a complete and rigorous description of all accelerator systems and of their applications. Please consider this series of lectures only as an "**appetizer**" for further studies!

Outline

Six modules in 3 groups of 2

Module 1	Lecture1	Introduction, first accelerators, basic principles
	Lecture 2	Linear accelerators and longitudinal beam dynamics
Module 2	Lecture 3	Circular accelerators and transverse beam dynamics
	Lecture 4	Small accelerators, technology and the Radio Frequency Quadrupole
Module 3	Lecture 5	Accelerator challenges and applications
	Lecture 6	Accelerators for medicine

Questions are welcome:

a) during lecture is something is not clear,

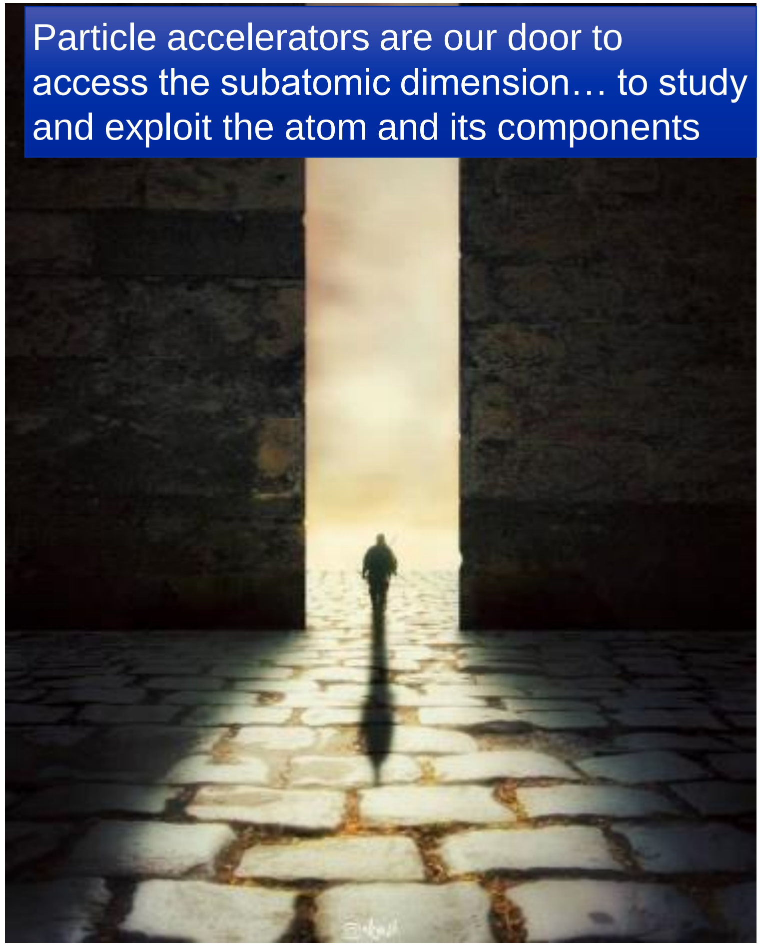
b) after the lecture for additional explanations,

c) informally in the days following the lectures.

d) remember that no question is stupid.

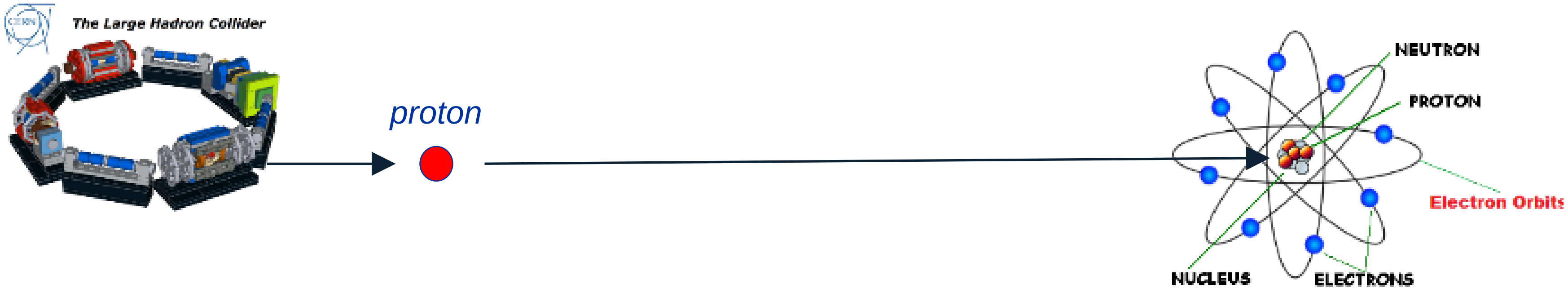
Particle Accelerators can concentrate energy

A particle accelerator is an instrument capable of concentrating large amounts of energy at subatomic dimensions



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?

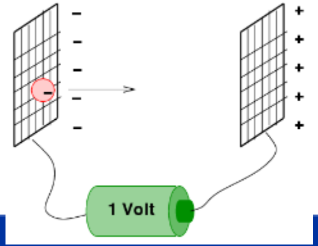
Comparing the energy of a single proton out of the CERN Large Hadron Collider, the largest particle accelerator ever built.

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	$1.5\ 10^{5}$ 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

Accelerator energies in eV
(energy acquired by an
electron in a potential of 1V)
1 eV = 1.6 x 10-19 Joules



Where does the energy go?

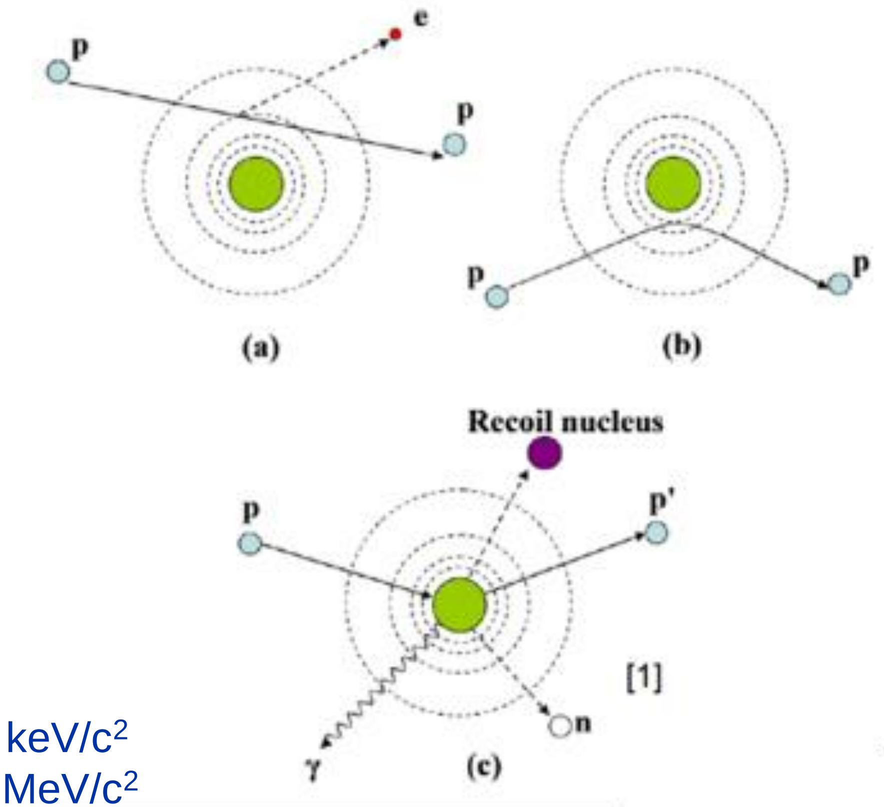
The accelerated particle can:

a) kick an electron out of the atom (ionization) or to a higher orbital (excitation) – in the latter case, the electron can come back generating an **X-ray** (photon).

b) be deflected by the nucleus and give energy to the atom - increase of temperature, **breaking of molecular bonds**.

c) be absorbed by the nucleus bringing it to an excited state that can **generate radiation** or secondary particles.

Scattering of an accelerated beam of particles



We can of course accelerate only charged particles:
Protons, Electrons, Ions (=ionised atoms)

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

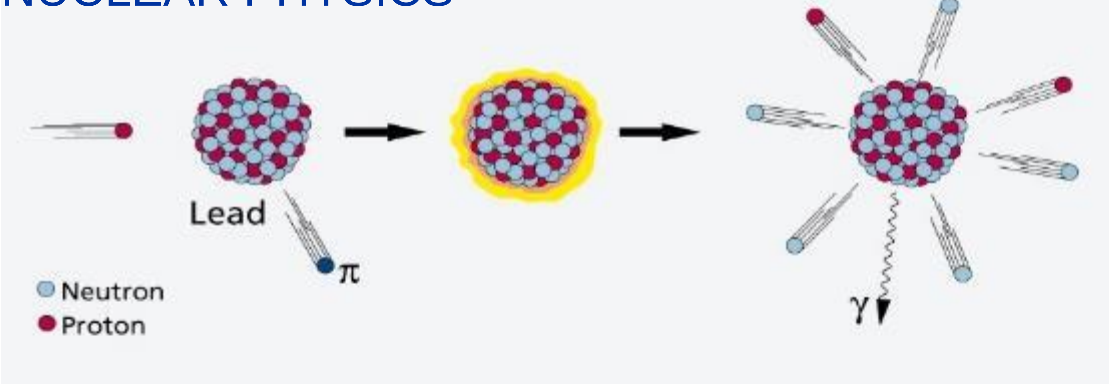
Unit charge 1 e = 1.6×10^{-19} Coulombs
Electron mass 1 $m_e = 9.1 \times 10^{-31}$ kg = 511 keV/c^2
Proton mass 1 $m_p = 1.67 \times 10^{-27}$ kg = 938 MeV/c^2

Accelerators can modify the nuclei and create new particles

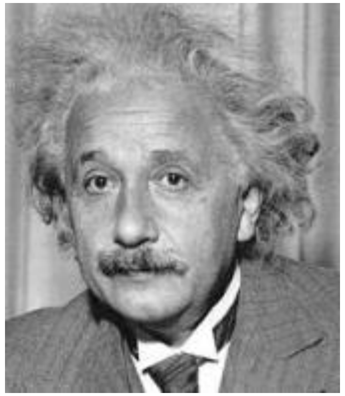
If the energy is sufficiently high, the particles in the beam transfer energy to the nucleus and its components (and are then scattered, reflected or absorbed).

The dream of the ancient alchemists coming true!

NUCLEAR PHYSICS

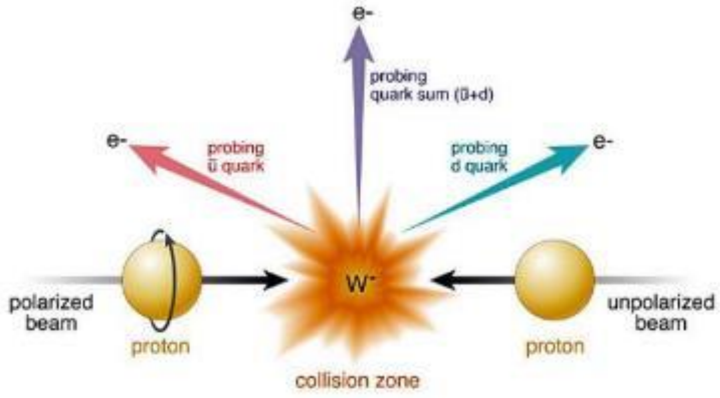


Particles in the beam can break and modify the nucleus (and then generate new elements and transform the matter!)

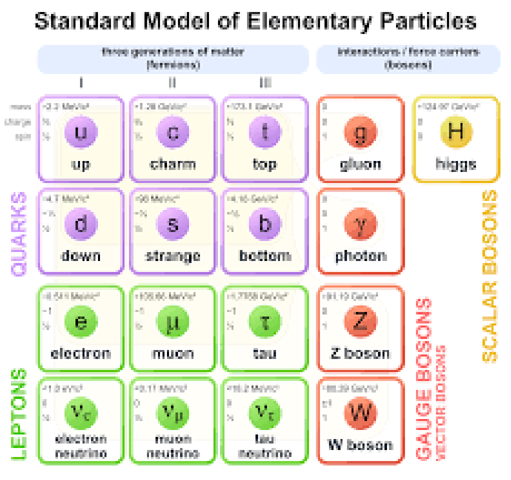


$E = m c^2$

PARTICLE PHYSICS



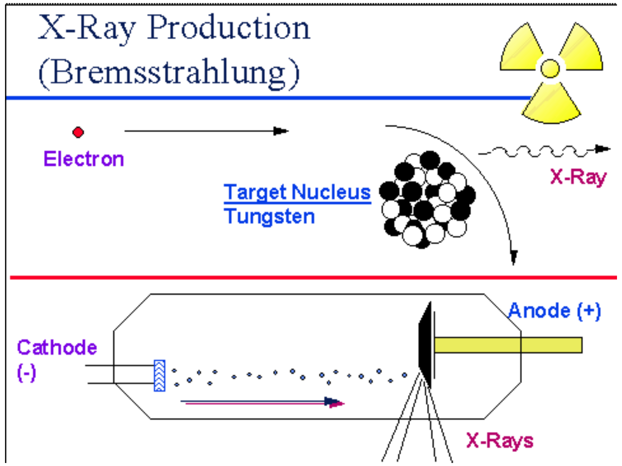
In the collisions can be generated new particles.

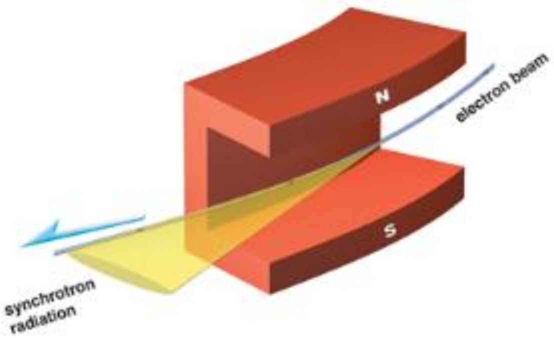


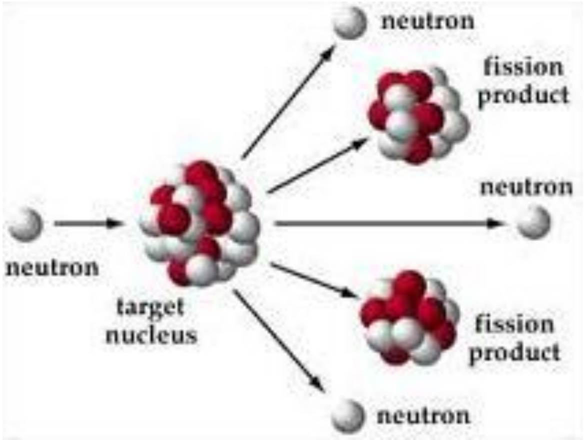
Accelerators can produce intense secondary beams

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



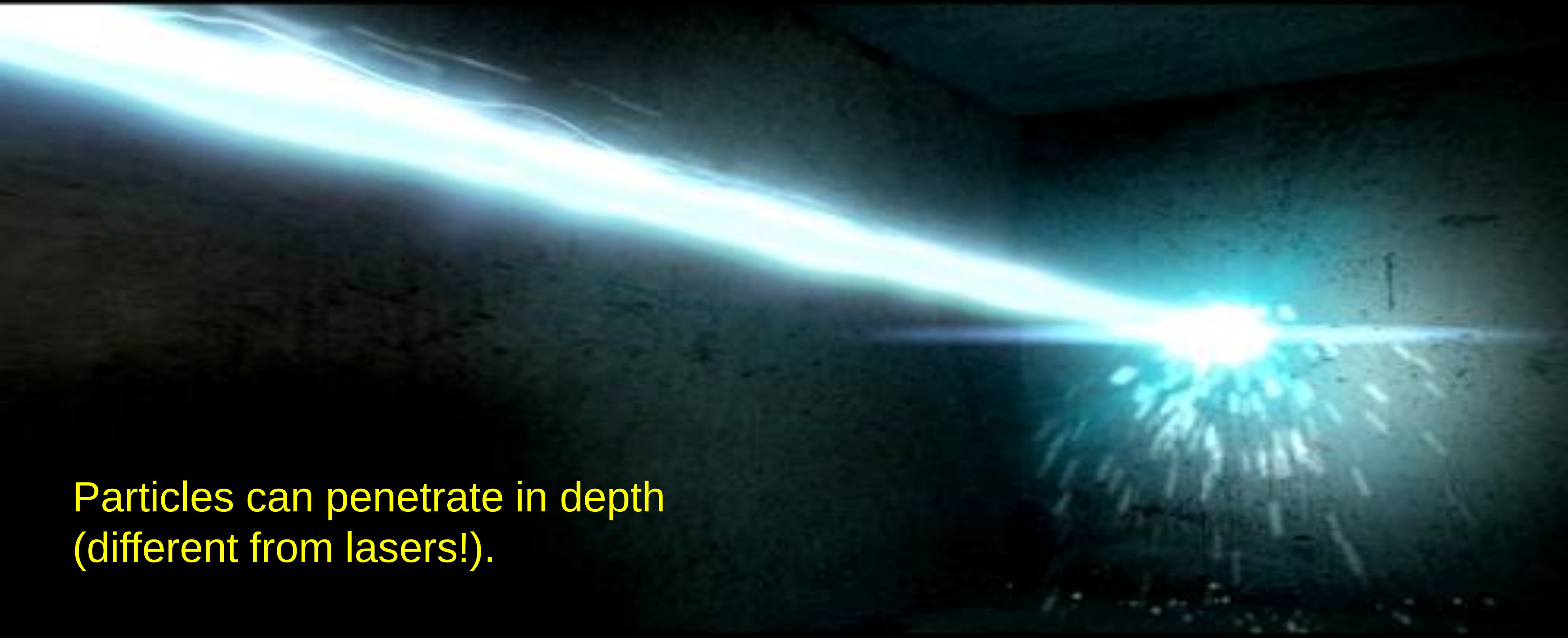




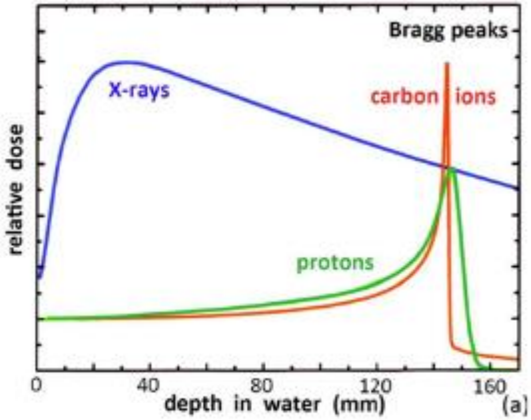
- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications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



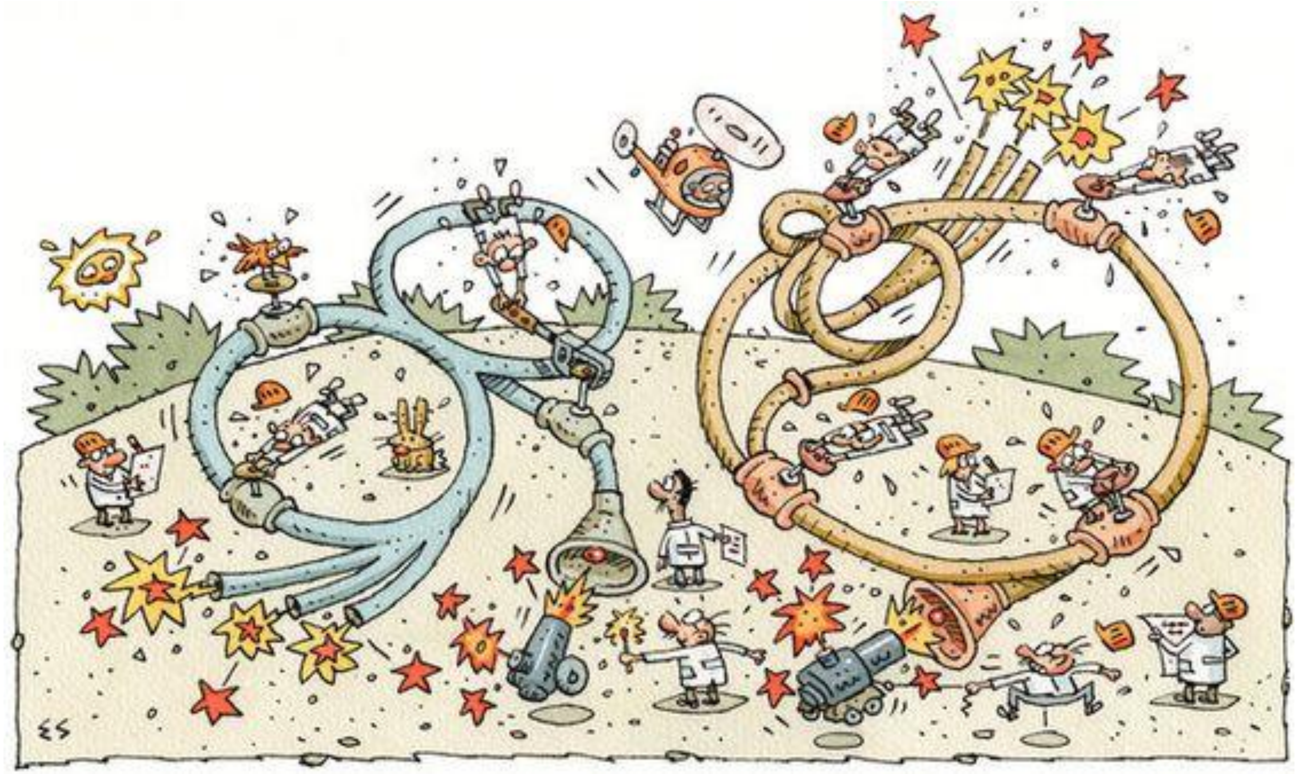
A particle beam can deliver energy to a very precisely defined area, interacting with the electrons and with the nucleus.



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)

Accelerators have a long history…

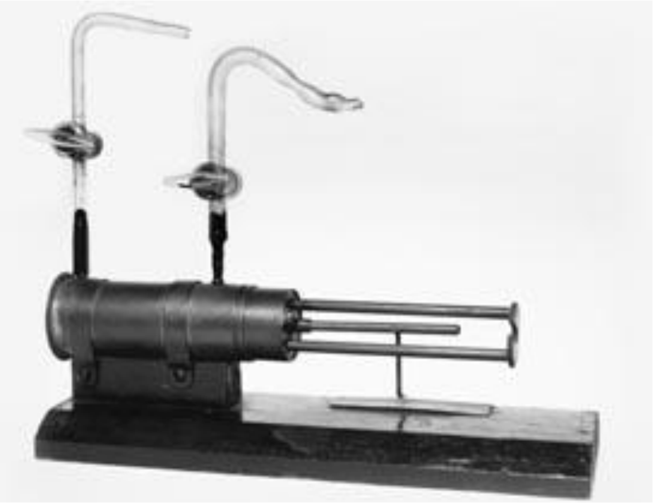


From Rutherford to the Particle Accelerator

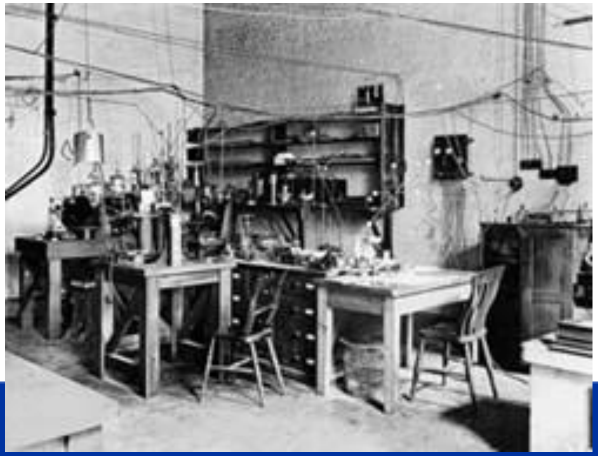
1919: Ernest Rutherford's historical experiment: some nitrogen nuclei are disintegrated by α-particles coming from radioactive decay of Ra and Th → **start of a new era for science**! But only few light atoms can be modified using particles from radioactive decays .

Men can transform the matter, the dream of the ancient alchemists!

1927: Rutherford in a famous speech at the Royal Society asks for "accelerators" capable to disintegrate heavy nuclei. Theory predicts the threshold for penetration of the nucleus at ~500 keV → from 1929, various labs start developing "**particle accelerators**" for >500 keV.



Reproduction of the Rutherford chamber: Bombardment of nitrogen atoms with alpha particles, producing oxygen and hydrogen nuclei.



Early Accelerators

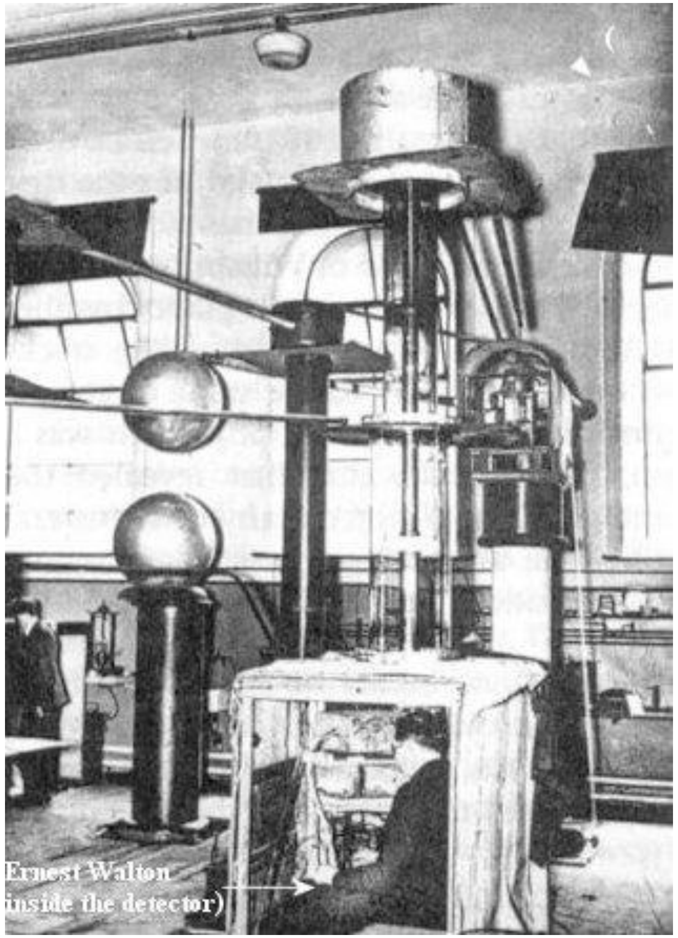
1927 to 1932, development of electrostatic accelerators:

1. Cockcroft and Walton (Cavendish Lab, Cambridge) → extend to higher voltages the "voltage multiplier" used for X-ray production.
2. Van de Graaf (Princeton) → develops the belt-charged static generator.
3. Others explore pulsed techniques, capacitor discharges, transformers, etc.

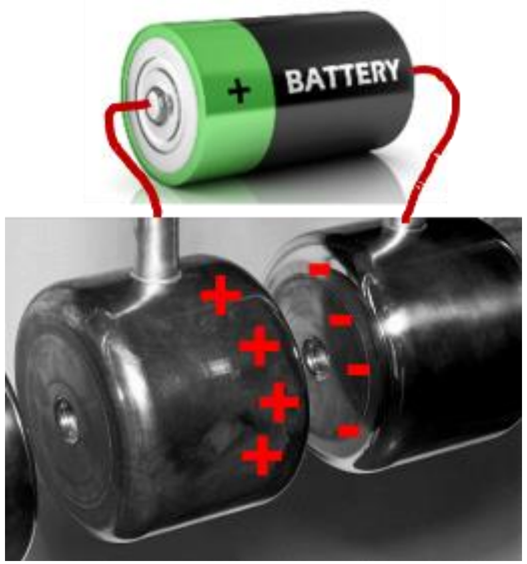
And the winners of the accelerator race are… Cockcroft and Walton, who in 1932 obtain disintegration of lithium by 400 keV protons. But:

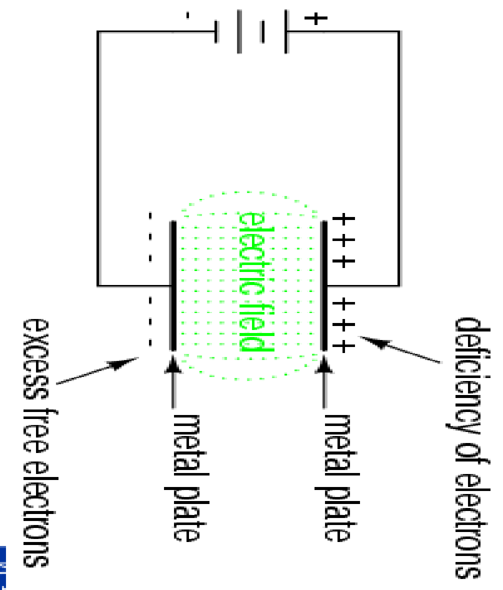
- ➢ higher energies are necessary to disintegrate heavier nuclei in quantities;
- ➢ DC technologies are limited by breakdown to few MeV.

→ A new technology is needed...



Electrostatic accelerators

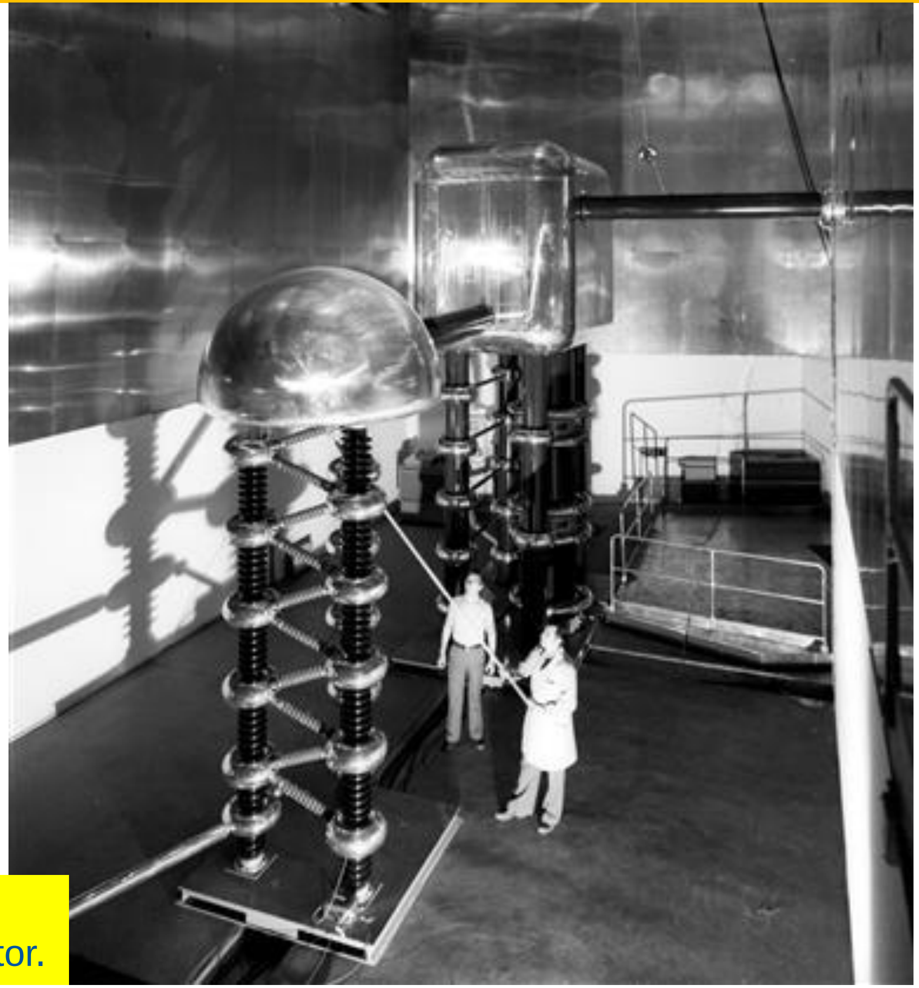




Electrostatic: use a DC voltage between 2 hollow tubes

(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 Cockroft-Walton generator.

Limitation:
Electric discharge (arc) between HV surfaces at voltage above a few MV

An alternative road: radio waves!

1864: Maxwell's equations.

1873, Maxwell: Theoretical basis of wave propagation.

1888, Hertz: Experimental generation/reception of e.m. waves.

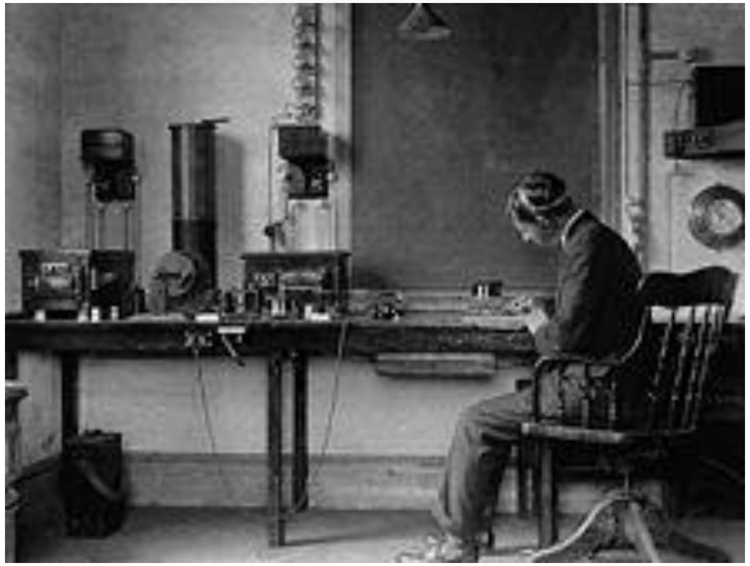
1891, N. Tesla, G. Marconi and others: wireless telegraph.

1905-14: early vacuum tubes (De Forest, triode in 1907).

1914-18: large quantities of tubes produced because of war effort, cost goes down.

1919-20: first attempts to broadcast with vacuum tubes using AM modulation, in the kHz range.

1920-25: start of regular radio broadcasting in most countries (1920: Argentina, US; 1923: Germany).



The invention of modern accelerators: marrying radio technology and particle acceleration

Who was the first to have the idea of using modern radio technology to build (linear) particle accelerators?

Remember:

1. the radio was around since 1920, and the technology became largely used in the 20’s
2. since 1927 the scientific community was looking for ideas to build high-energy particle accelerators…

A 26 year old PhD student…

Rolf Widerøe: a Norwegian student of electrical engineering at Karlsruhe and Aachen.

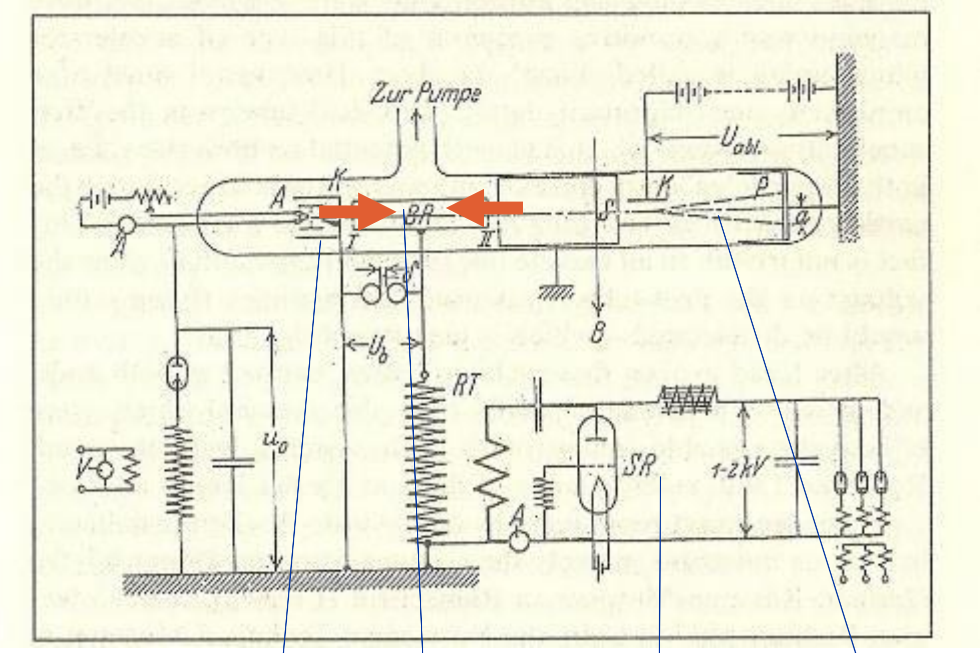
The X-ray transformer that he had chosen for his PhD Thesis at Aachen University did not work, and he was forced to choose quickly another subject. Inspired by a 1924 paper by Ising, a Swedish professor (acceleration of particles using “voltage pulses”), in 1928 he put together for his thesis a device to demonstrate the acceleration of particles by **Radio Frequency** fields.

Modern particle accelerators are 93 years old

In 1928 a PhD Thesis introduced the basic concept of modern particle accelerators, using periodic acceleration provided by electric field at Radio-Frequency (RF).

This was a major step from the previous DC (constant voltage) acceleration, limited to few MeV

Rolf Widerøe's PhD thesis, 1928, University of Aachen
Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration in a 88 cm long glass tube) "at a cost of four to five hundred marks", < 2'000 € today!



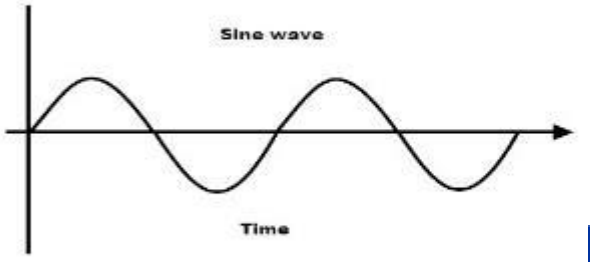
Ion source

Accelerating tube at **$V=V_0\sin\omega t$**

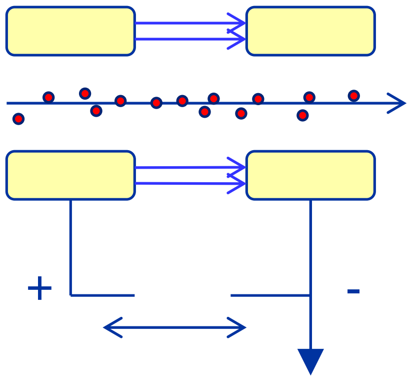
RF generator

Detector

1. use of Radio-Frequency technology (at the time limited to 1-2 MHz) → marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of periodic acceleration.
3. complete accelerator: ion source RF accelerator, detector, all in vacuum.



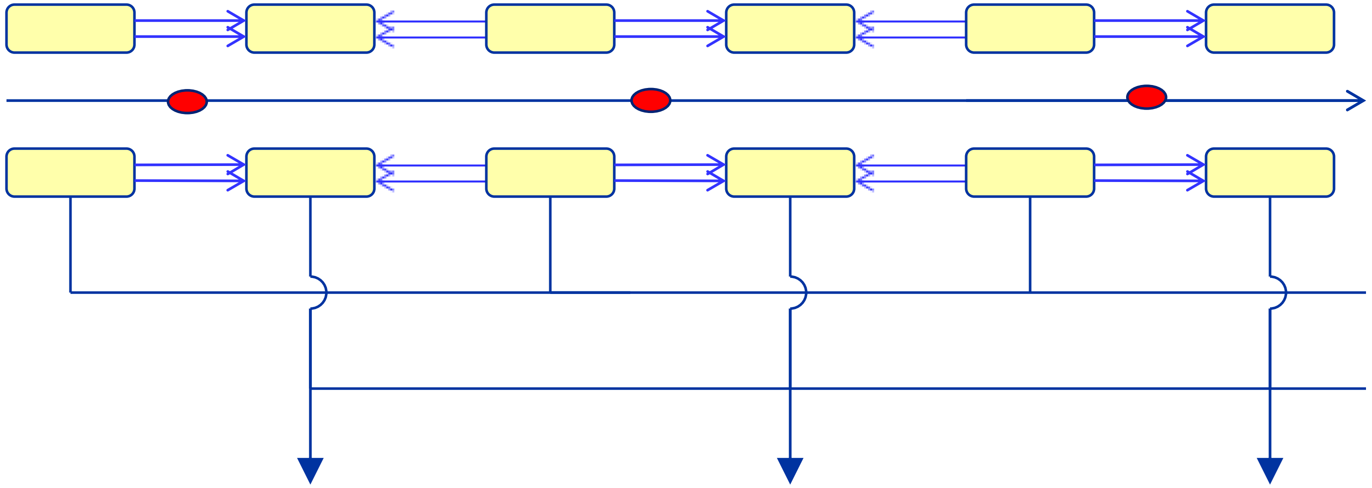
The basic principle of Radio-Frequency Acceleration



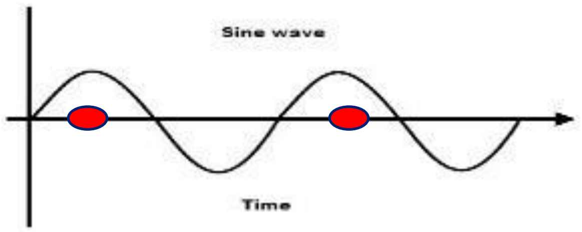
DC voltage $V = V_0$ (const)

ELECTROSTATIC acceleration
The voltage is applied only to one gap

RADIOFREQUENCY acceleration
The voltage adds up over several gaps



RF voltage $V = V_0 \cos\omega t$



Two Consequences:
In an RF accelerator where the voltage changes sinusoidally with time the particles must “ride the wave”:

1. The particle beam cannot be continuous but must be “bunched” in groups of particles
2. The time to travel between two “gaps” at distance d must be equal to half RF period:

$$T / 2 = d / v_{particles} \text{ or } f_{RF} = v_p / 2d$$

After a good start, a stop…

Limitation of the Wideröe device:

Good for heavy ions, but for protons it needs **higher frequencies**

(taking d~10 cm, W=500 keV → f~50 MHz, λ~6 m)

☞ But a) such high frequencies were not possible with the radio generators of the time;

b) even if the 10-100 MHz range was achievable, the RF radiation losses from the circuit would have been too large (dimensions become comparable with the wavelength)

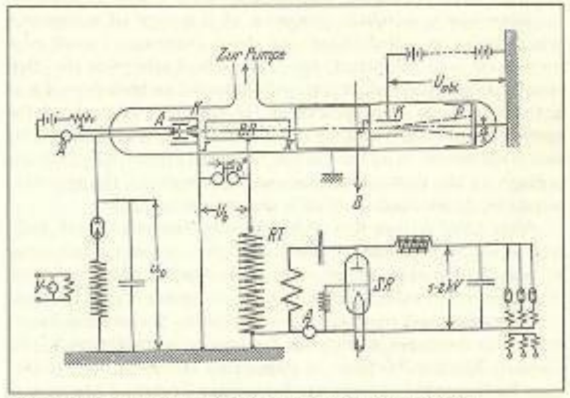


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

→ after the PhD, Rolf Wideröe works for AEG to build HV circuit breakers and his thesis, published in the "Archiv für Elektrotechnik", remains unnoticed.

… But the topic was hot!

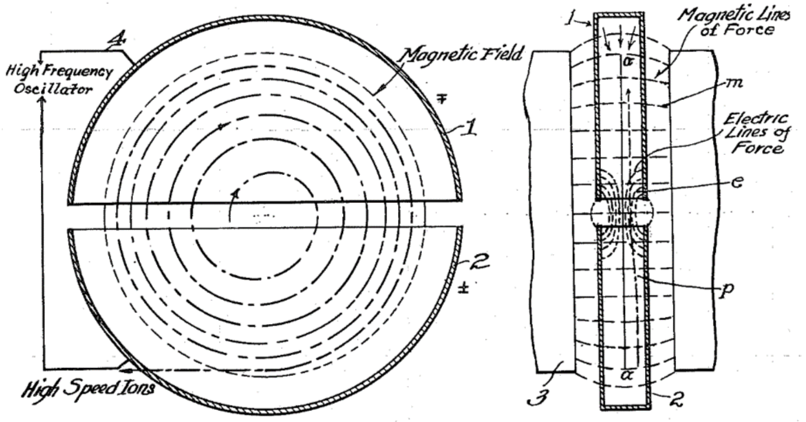
Ideas travel: from Aachen to Berkeley…

In the 1920's, Ernest O. Lawrence (born 1901), young professor of physics at Berkeley, wants to join the "energy race", and is looking for a new idea...

In 1929, during a conference, he goes to the university library and finds Wideröe's thesis in the 1928 "Archiv für Elektrotechnik" (but he did not speak German...).

Immediately, he realised the potential of the idea of Radio-Frequency acceleration, and starts work with his PhD students on 2 parallel activities:

1. A Wideröe "linear accelerator" (linac) with several drift tubes, to accelerate heavy ions (Sloan and Lawrence).
2. A "cyclic" accelerator, bending the particles on a circular path around Wideröe's drift tube (Livingston and Lawrence) → the **cyclotron**.



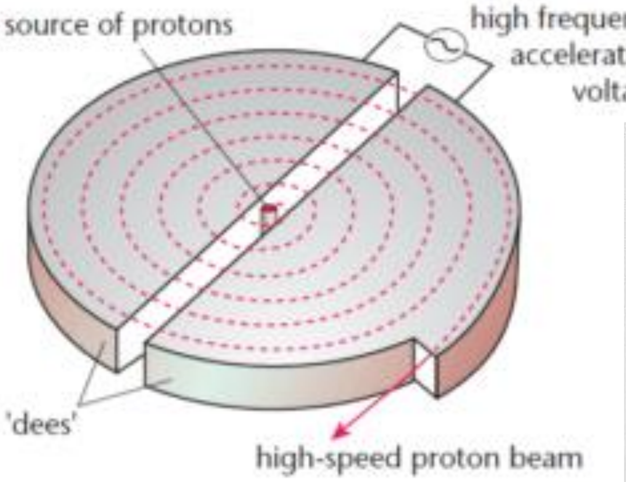
A compact low-energy accelerator: the cyclotron

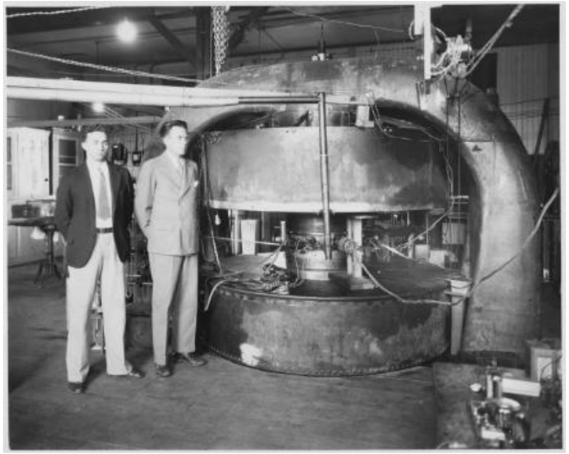
Immediately after R. Wideore's invention of the linear accelerator, Ernest O. Lawrence at Berkeley proposes to perform radio-frequency acceleration in a circular system, inserted in a big magnet.

Basic principle: Use RF **electric field** to accelerate, **magnetic field** to keep particle in a circular orbit

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 !





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

f revolution frequency

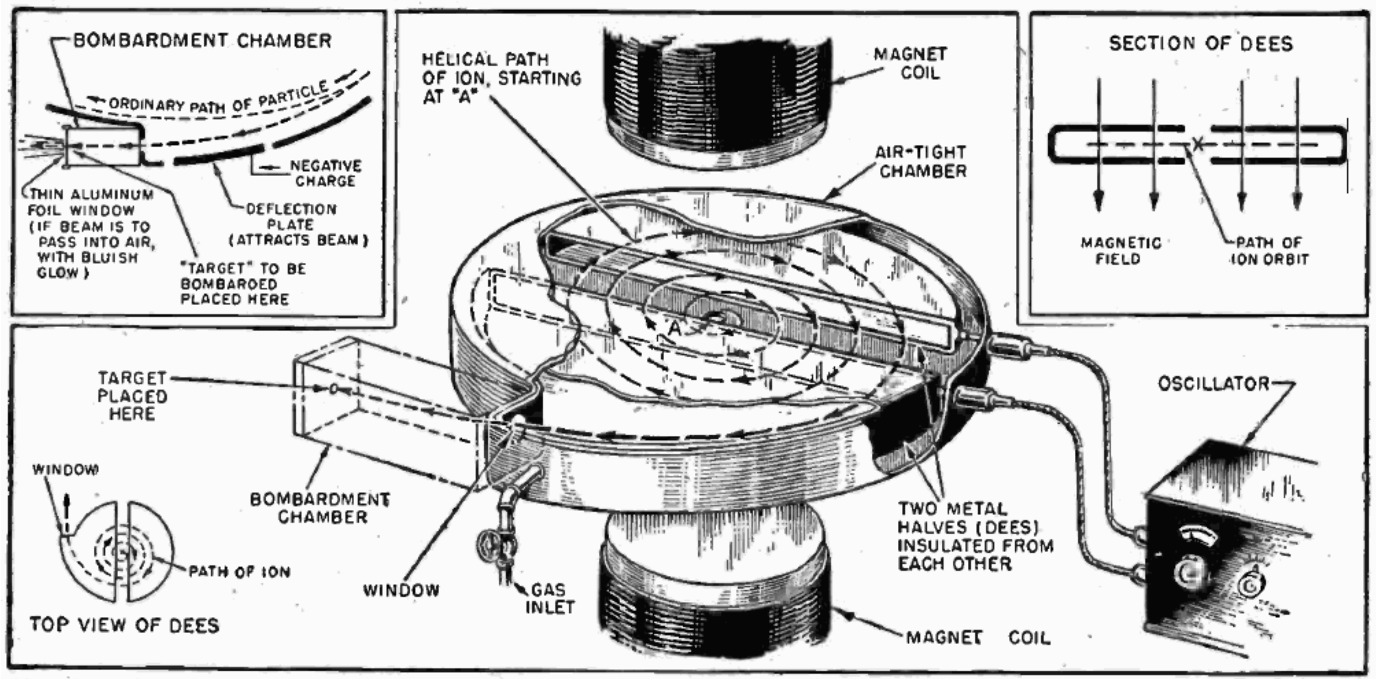
- Protons are produced by a "source" in the centre
- They are accelerated in the gap between 2 electrodes fed with RF
- The protons go in larger and larger spirals, and their velocity increases proportionally to the spiral radius, keeping revolution frequency constant.

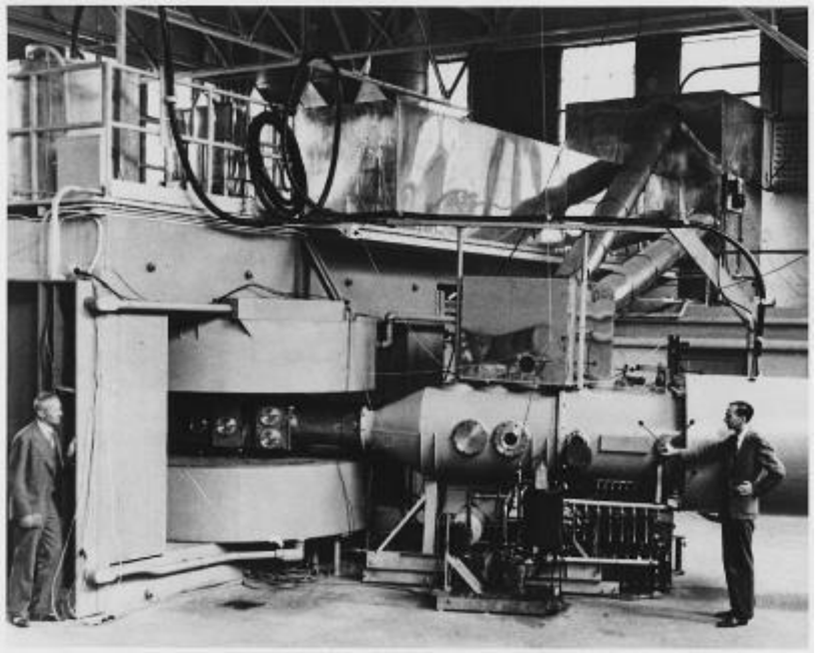
Cyclotrons give a boost to nuclear physics

1931: the Berkeley cyclotron reaches 1.2 MeV with protons. First atom disintegrations in 1932.

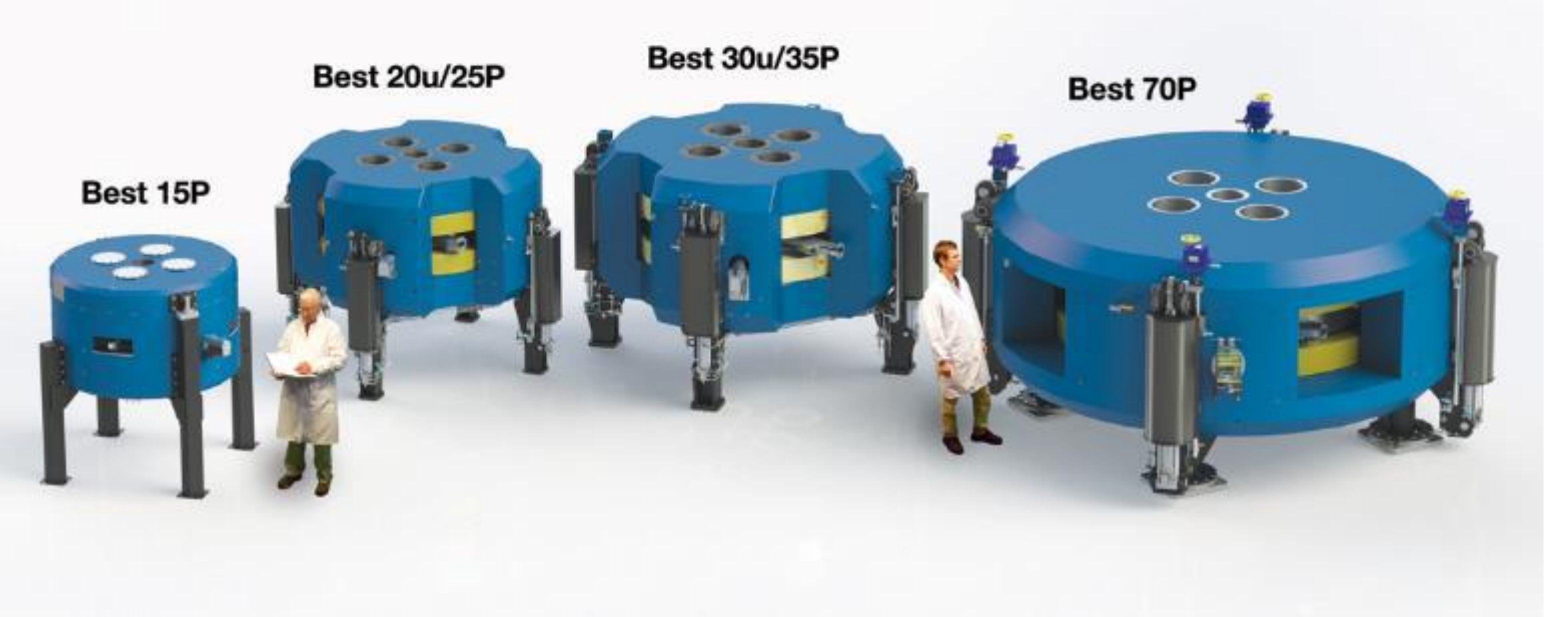
1934: 5 MeV reached on a new larger machine accelerating protons and deuterons (used for the production of neutrons, discovered in 1932).

Many institutes worldwide start the construction of cyclotrons. This technology made artificial production of heavy elements possible and paved the way for the discoveries in nuclear physics that provided the background for the US (and URSS) nuclear programmes.





Examples of modern cyclotrons



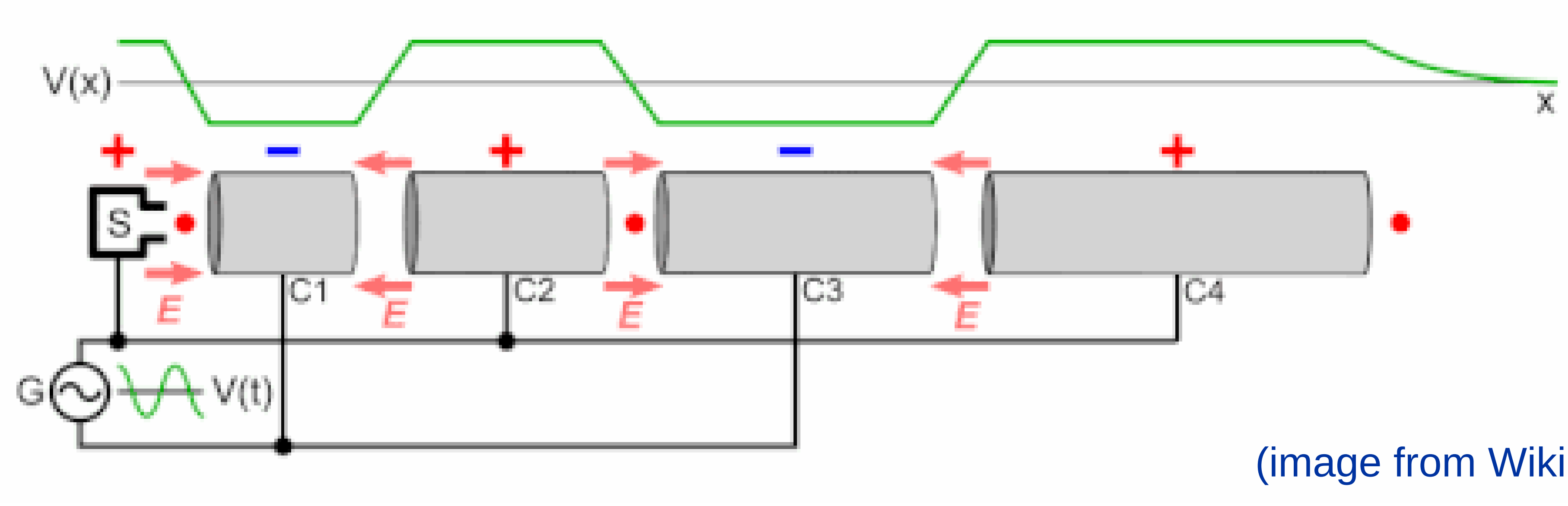
The range of BEST cyclotrons, from 15 to 70 MeV output energy

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).

Higher energies in a Wideröe linac

The Wideröe structure can be used to reach higher energies, if the tubes are made longer and longer as the energy and velocity of the particle increase



$T / 2 = d / v_{particles}$

$f_{RF} = v_p / 2d$

$\mathbf{d = v_p / 2f_{RF}}$

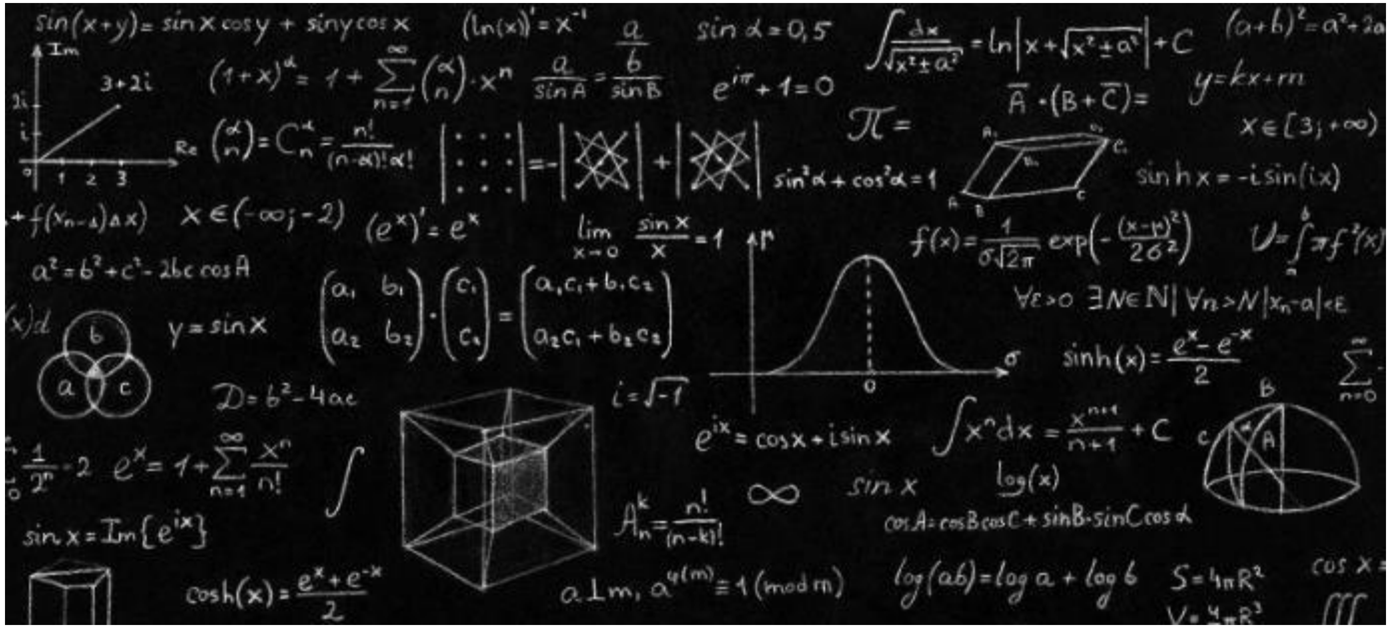
(image from Wikipedia)

This is a “linear accelerator” (linac). Linacs are used as injectors to larger accelerators and as stand-alone when large beam intensities are required

Higher and higher…

Can we build larger and larger cyclotrons or longer and longer Wideröe structures to reach higher energies?

No, we reach some **limitations** and we need some «tricks» to go farther, but to understand these we need some **physics background**.

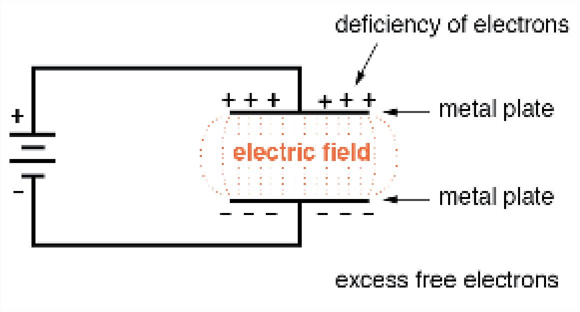


1. From voltage to electromagnetic field

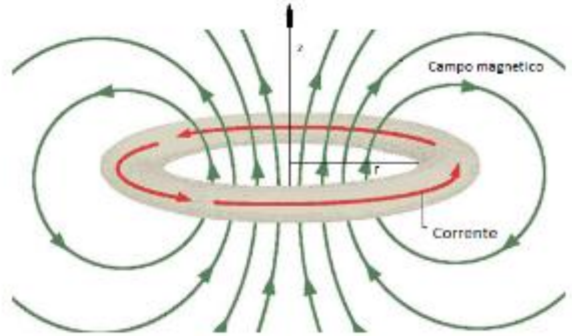
Basic principle:

☐ To accelerate particles we use electric fields
☐ To deflect particles we use magnetic fields

An electric field is easily generated by a voltage

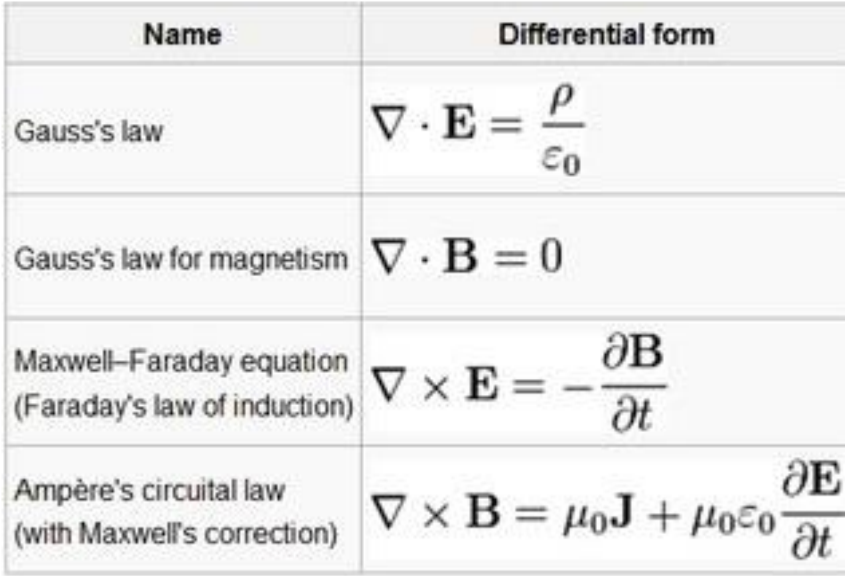


A magnetic field is easily generated by a current in a wire



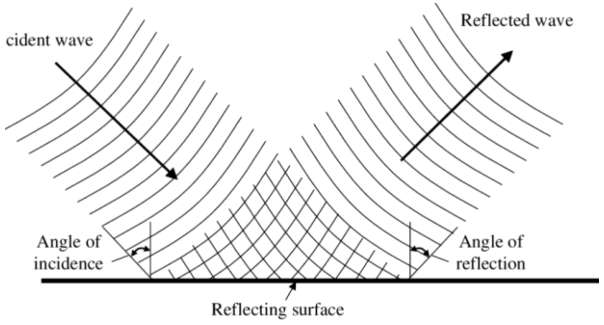
But:
As we have seen, to increase particle energies in accelerators we need to work with time varying fields where electric and magnetic fields are closely related:
Electromagnetic field

Maxwell’s equations and the electromagnetic field



Name	Differential form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$

- Time varying electric and magnetic fields are closely related
- In particular, sinusoidal fields are described by wave equation.
- Electromagnetic «waves» propagate, and are reflected by metallic walls.



Electromagnetic Waves

Maxwell’s equations applied to empty space give the “wave equation”.

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} \qquad \frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

Solutions are electromagnetic sinusoidal waves

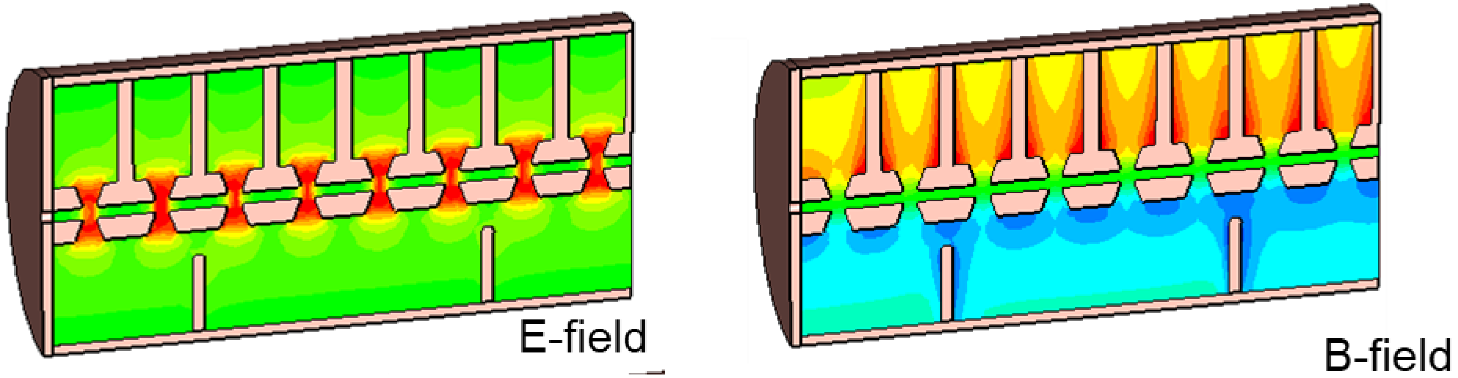
$$E = E_{\max} \cos(kx - \omega t); B = B_{\max} \cos(kx - \omega t)$$

Speed of the electromagnetic wave in empty space is the speed of light

$$v = \frac{\omega}{k} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \equiv c = 2.99792 \times 10^8 \text{ m/s}$$

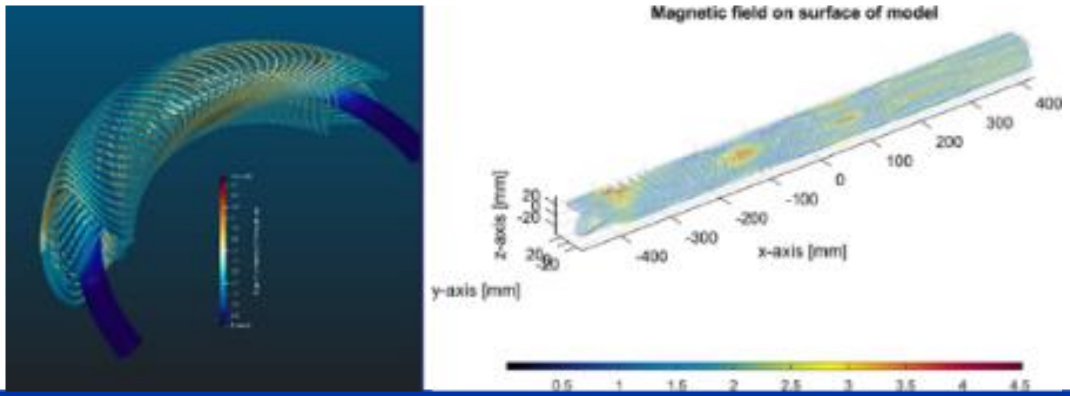
Designing an accelerator electromagnetic field

The problem of building a particle accelerator consists in creating **regions of space** where we use some **energy** to generate an **electromagnetic field distribution** whose fields have **polarity and time structure** such as to transfer to a beam of particles a fraction of the energy contained in the electromagnetic field.

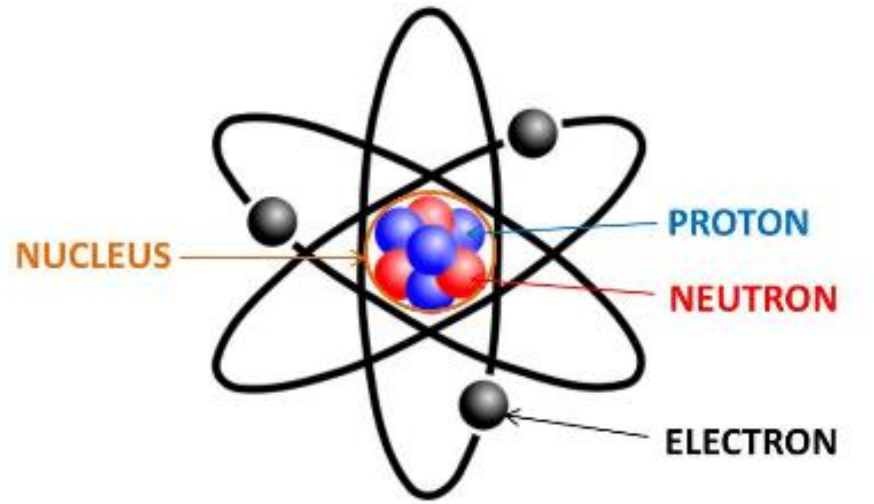


3-dimensional simulations of electric and magnetic field distributions (red=high value, blue=low value) inside a Drift Tube Linac, realised with the CST software.

3-dimensional simulations of magnetic field distribution inside a curved Canted Cosine Theta (CCT) magnet for medical accelerators, realised with the Opera software.



2. Combined effect on particles: the Lorentz force



	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

We extract the particles from the atoms and then:

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

Newton-Lorentz force:

$$\boxed{\vec{F} = \frac{d\vec{p}}{dt} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)}$$

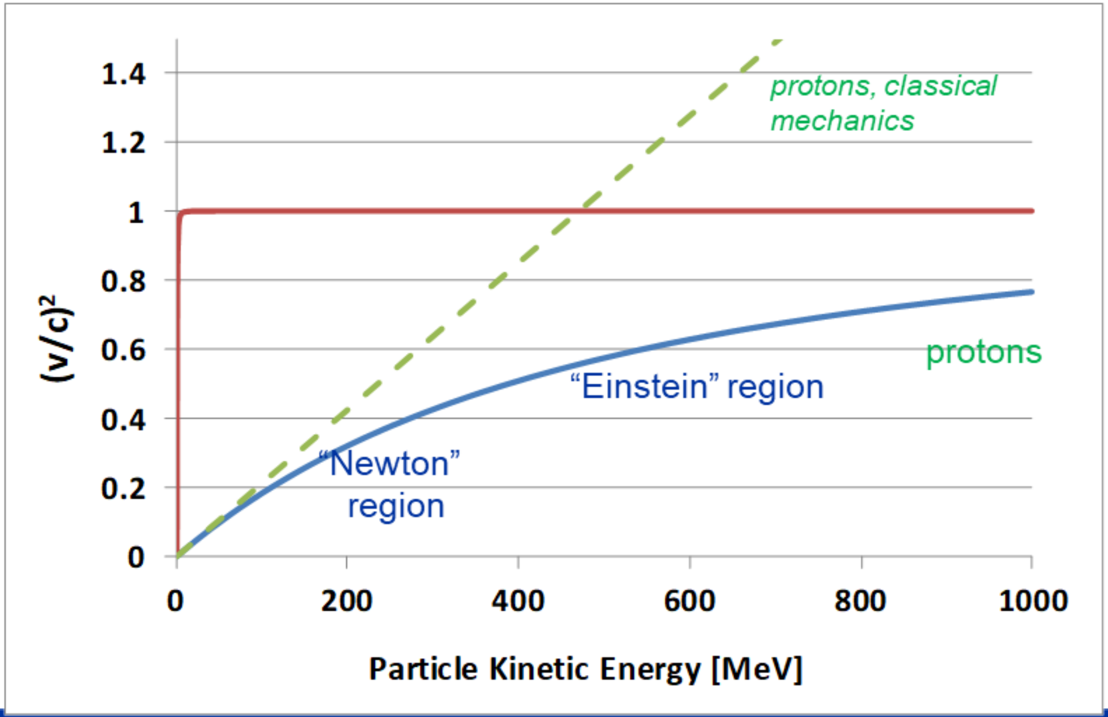
2nd term always perpendicular to motion => no acceleration

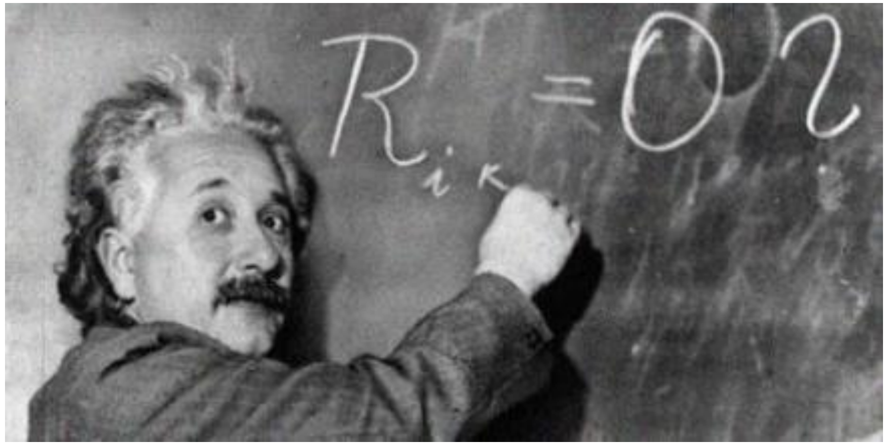
Can be accelerated only particles that have an electric charge: electrons, protons, ions (= charged nuclei)

3. Relativity

When we accelerate, we give energy to the particles that become faster and faster. But a hard limitation is given by special relativity: we cannot exceed the speed of light. Before reaching the speed of light, the energy goes to increasing the mass and not the velocity!

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





Relation kinetic energy / velocity:

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

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

Useful relativistic relations

We are observers at rest, looking at particles travelling near the speed of light.
The particle properties that we observe are defined by the “Lorentz transformations”

$$\gamma \equiv \frac{1}{\sqrt{1-(v/c)^2}} \qquad \beta \equiv \frac{v}{c} = \sqrt{1-\frac{1}{\gamma^2}}$$

$$m = \gamma m_0 \qquad \vec{p} = \gamma m_0 \vec{v} = \frac{m_0 \vec{v}}{\sqrt{1-(v/c)^2}} \qquad \left(\frac{v}{c}\right)^2 = \frac{p^2}{(m_0 c)^2 + p^2}$$

$$E = mc^2 \qquad E_0 = m_0 c^2 \qquad \frac{E}{E_0} = \frac{m_0 \gamma c^2}{m_0 c^2} = \gamma$$

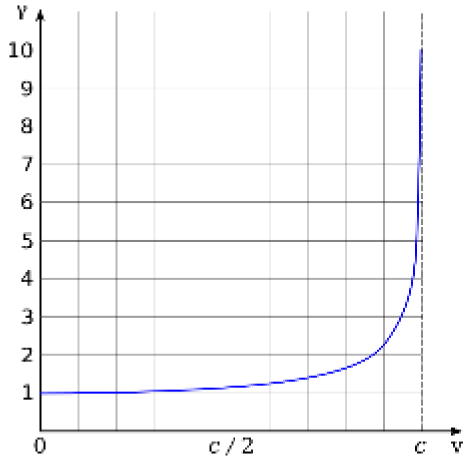
$$T = E - E_0 = m_0 \gamma c^2 - m_0 c^2 = m_0 c^2 (\gamma - 1)$$

β “relativistic velocity” is the fraction of the speed of light reached by a particle: $v = \beta c$

γ “Lorentz factor” measures the change of time and length for a moving particle. Ratio between relativistic mass and rest mass: $\gamma = m / m_0$

p (relativistic) momentum

Total energy $E = mc^2$ is the sum of rest energy E_0 and kinetic energy T : $E = E0 + T$



Lorentz factor γ as a function of velocity. Its initial value is 1 (when v = 0); and as velocity approaches the speed of light (v → c) γ increases without bound (γ → ∞).

Basic limitations of Wideröe linac and cyclotron

Limitation to cyclotrons: relativity

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

The cyclotron principle is valid only for non-relativistic particles:
When the mass start to increase accordingly to $m = \gamma m_0$, the revolution frequency increases and the particles are no longer in phase with the RF excitation frequency.

Some corrections (modulation of the excitation frequency or shaping of the magnet field) can be applied, but conventional cyclotrons are limited in energy to ~ 70 MeV
Some special cyclotrons (synchrocyclotrons) can go higher (~ 500 MeV) but with high complexity and cost
→ invention of the **synchrotron.**

Limitation to Widerøe linacs: frequency

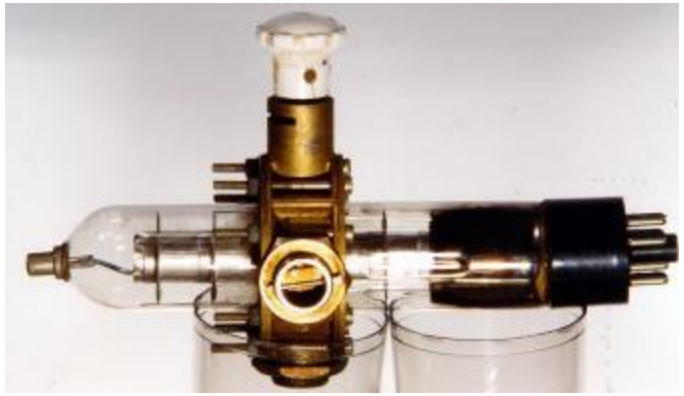
As velocity increases, to keep a reasonable distance between gaps the RF excitation frequency must increase: $f_{RF} = v_p / 2d$
When the RF excitation frequency becomes so high that the dimensions of the accelerator are comparable to the RF wavelength, the gaps start to generate electromagnetic waves and to radiate their energy
→ invention of the **Radio-Frequency linac.**

Higher frequencies – the WWII technology leap

Early RF systems (LC-based) were limited by leakage of RF power at high freq.

→ W. Hansen (b. 1909) at Berkeley starts to work on "cavity resonators" for higher frequency and after moving to Stanford starts developing a new source of RF power, the klystron. But the progress is slow.

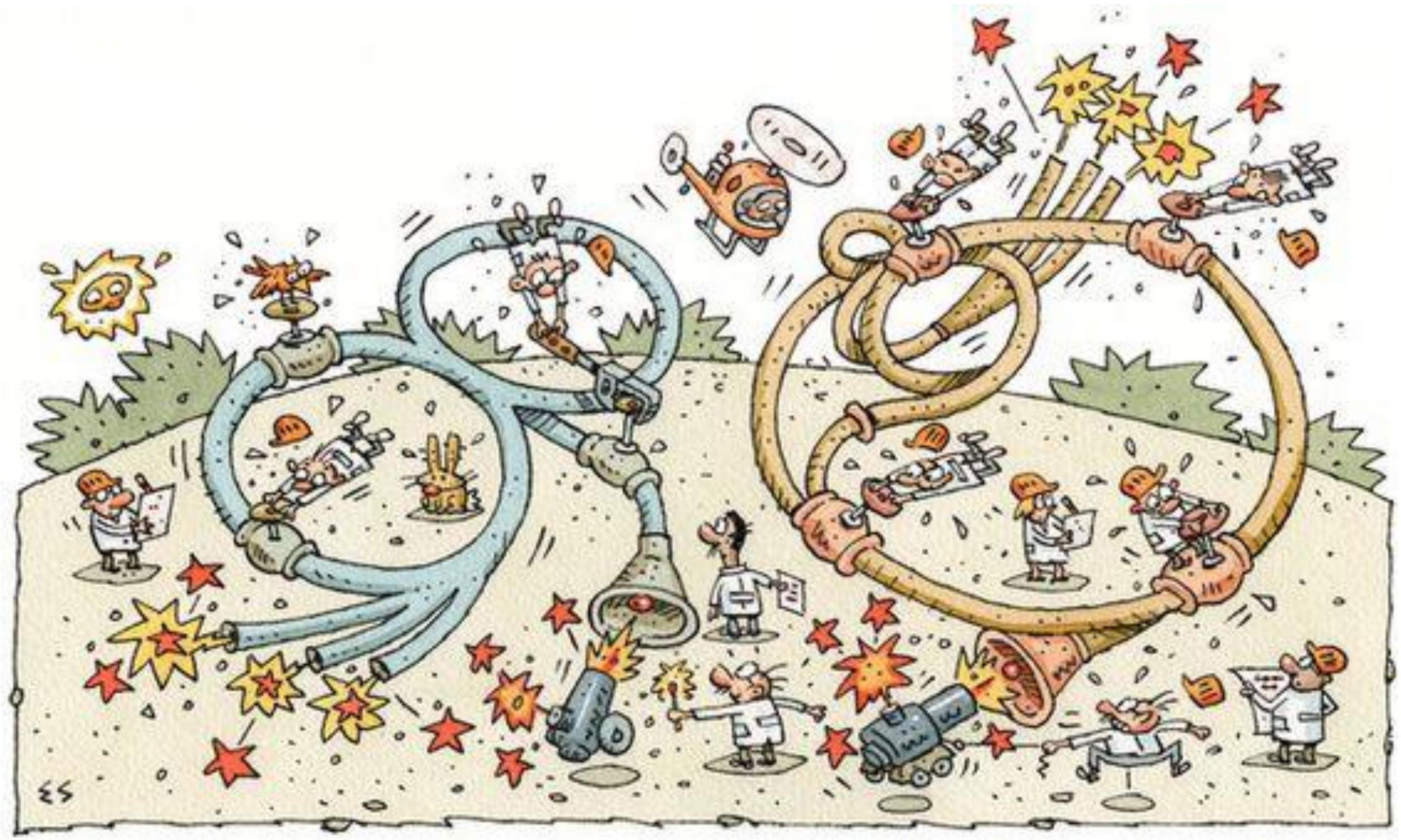
From 1941, the war effort recruited the best UK and US scientists. Accelerator scientists contributed to the development of radars (and then passed to the Manhattan project).



A WW2 3 Ghz klystron

The great boost to Radio Frequency technology that made modern particle accelerator possible came from the **radar development of WW II**.
All the US radar research was made public after the war and helped developing Radio-Frequency technologies for a new generation of accelerators.

Linear accelerators (linacs), taking over from the cyclotron as the most performant and energetic particle accelerators



End of Lecture 1

Thank you for your attention!

The old CERN Cockroft-Walton 750 keV pre-injector

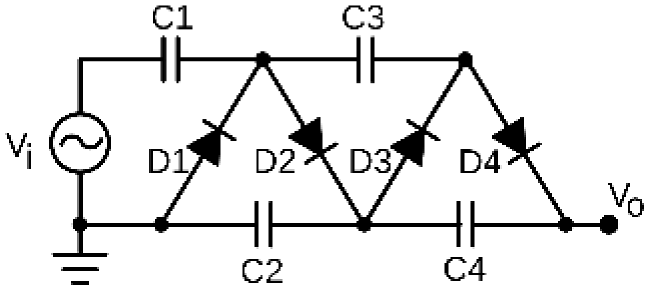
instrumentation cabinet

high-voltage electrode (750 kV)

high-voltage generator

Ion source (inside a voltage shield)

Accelerating column (between 750 kV and ground)



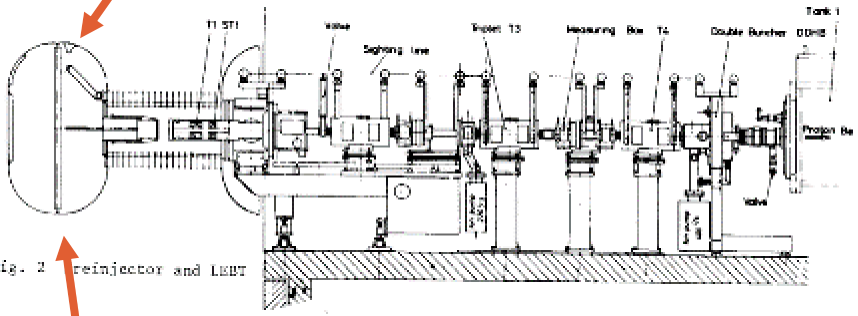
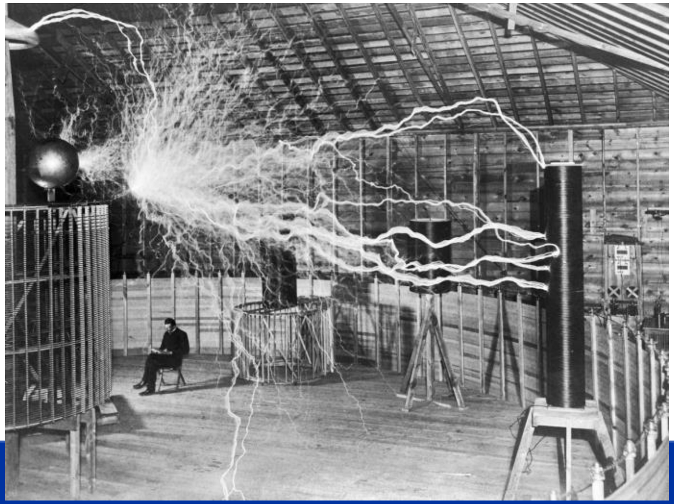
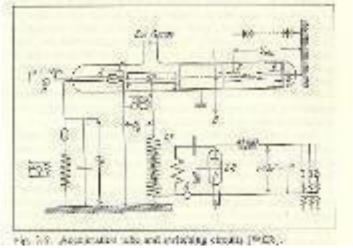


Fig. 2 reinjector and LEBT



Limitation: Electric discharge (arc) between HV surfaces

Innovation in the particle accelerator field



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

XXI century

?

Cyclotron: cyclic acceleration with magnets (Lawrence)

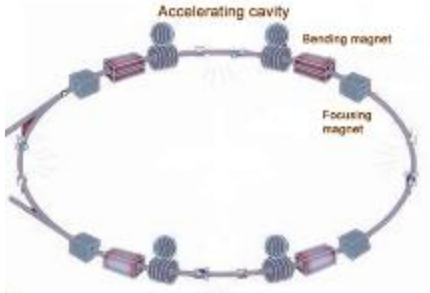
Strong focusing (Courant, Livingston, Snyder, Christofilos)

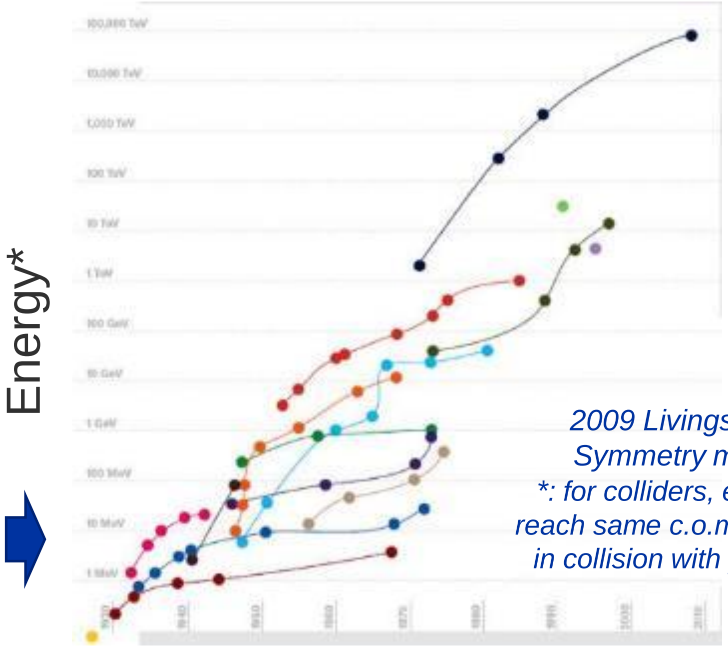
Superconducting magnets and acc. cavities

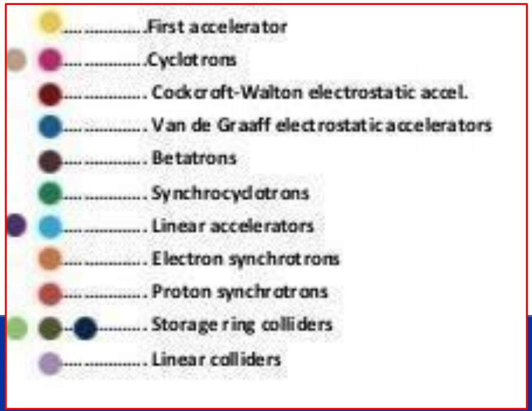
2008: the Large Hadron Collider

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

Succession of enabling technologies (technology leaps)



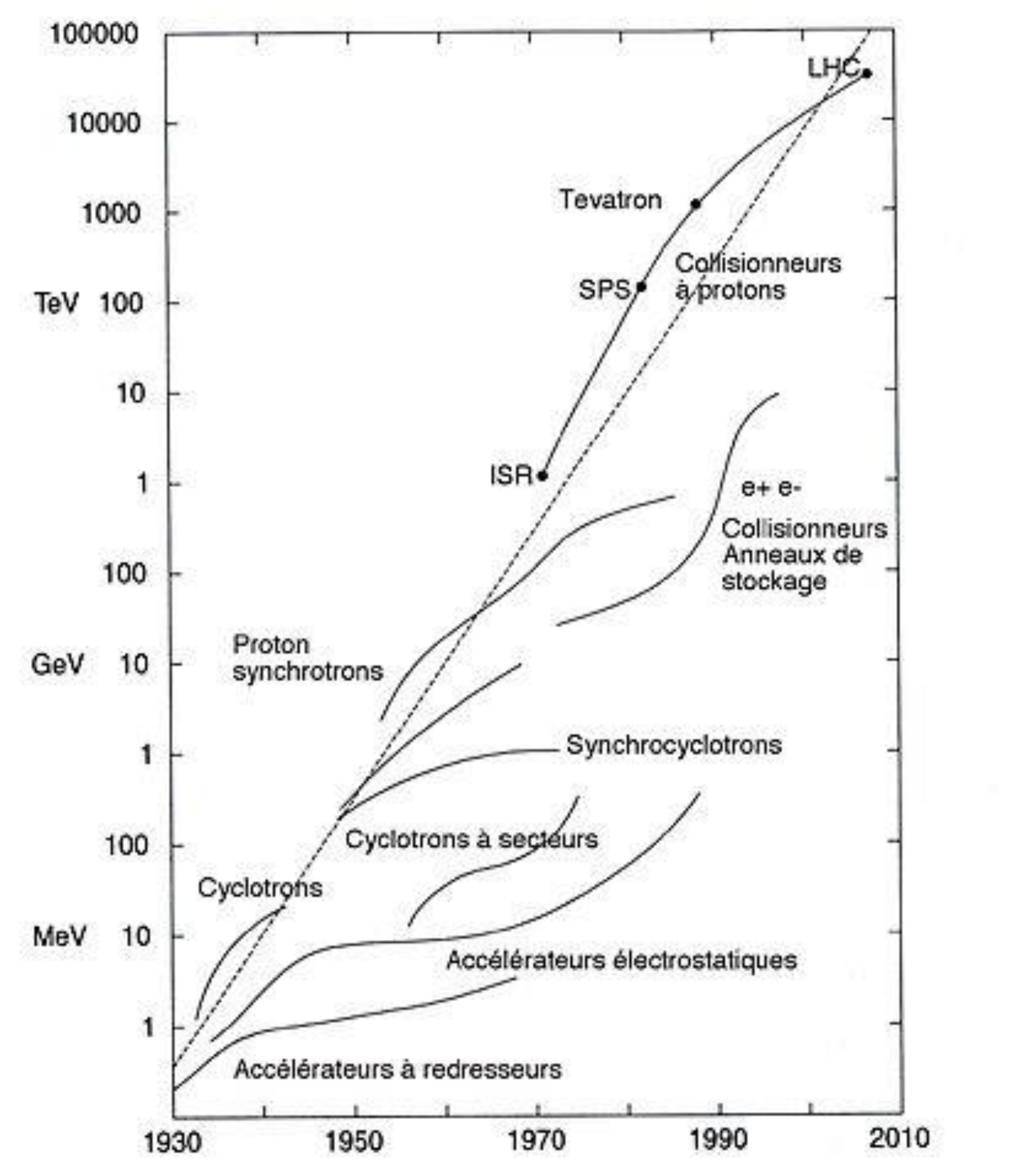




2009 Livingston plot, Symmetry magazine
**: for colliders, energy to reach same c.o.m. energy in collision with proton at rest*

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

Progress in accelerator technology: Livingston plot



Exponential growth of particle accelerator top energy with time thanks to a series of enabling technologies

And now?
Is the evolution of accelerators still following the Livingston diagram?
The answer in the last lecture:
STAY TUNED