Particles Accelerators, A Historical Overview

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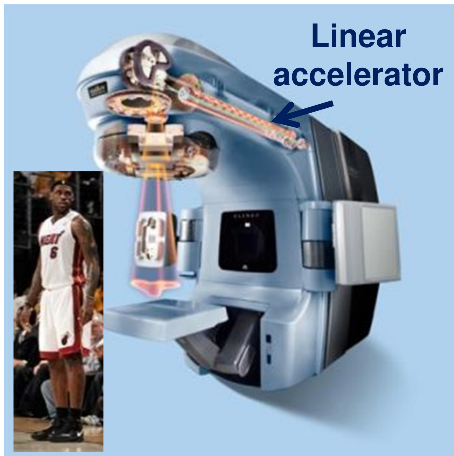
The Question

Accelerators are extremely diffused worldwide. They can be very different …

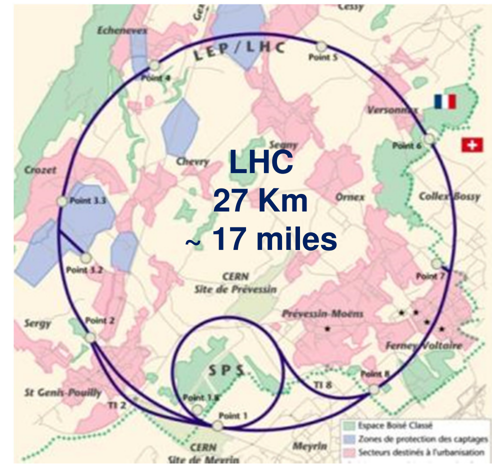


in size:

from meters to tens of km

in cost:

from thousands to billions of $



- **Building an accelerator usually requires years and often a significantly large specialized crew to build and operate it.**

USA alone spends yearly almost a billion dollars of taxpayer money to build new accelerator facilities and to operate existing ones, and several hundred millions for accelerator research and development R&D.

Why do we undertake such an effort and challenge?

The Answer

- **Because accelerators are a formidable tool that allow to probe (measure) nature with unprecedented accuracy and resolution.**

Accelerators can achieve energies, pressures, time and spatial resolutions that no other tool can approach.

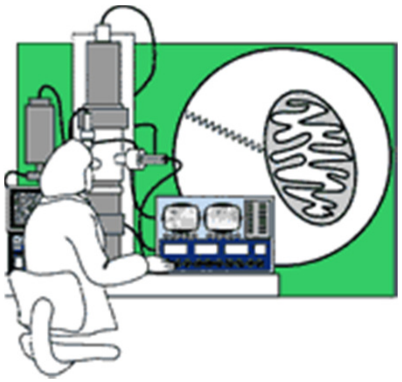
Because of this, accelerators found applications in:

- **Elementary particle physics**
- **Cosmology**
- **Light Sources**
- **Medical applications**
- **Industrial**
- **Homeland Security**

And this is what I will try to demonstrate with the remaining this presentation

Ultra-Precise Electron Microscopy

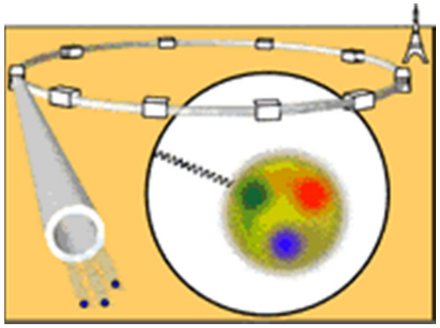
Probing particles such as electrons and protons provided by particle accelerators are required for studies of atomic constituents. The associated de Broglie wavelength of a probing particle defines the minimum object size that can be resolved.



$$\lambda = h/p \text{ , where}$$

$$h = 4\times10^{-15} \text{ eVs} \quad \text{(Planck's Constant)}$$

$$p \quad \text{(Particle Momentum)}$$



Resolving Smaller Objects Requires Higher Momentum Probe Particles

Example 1 : An electron with a 1 keV energy will have a de Broglie wavelength of ~ 0.04 x 10^{-11} m. A photon with ε = 1 keV energy has a wavelength $\lambda = ch/\varepsilon$ ~ 1.2 x 10^{-9} m. This implies ~ 30 times better resolution with and shows why electron microscopes have much better resolution than optical ones.

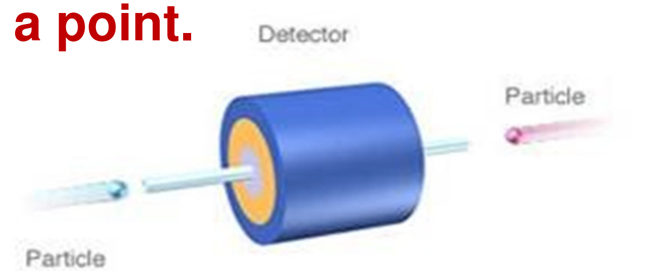
Example 2 : An electron with a 1 GeV/c momentum will have a de Broglie wavelength of 10^{-15}m (10^{-14} m ~ nucleus size, 10^{-15} m ~ proton, 10^{-18} ~ quarks).

Accelerators Can Generate Elementary Particles

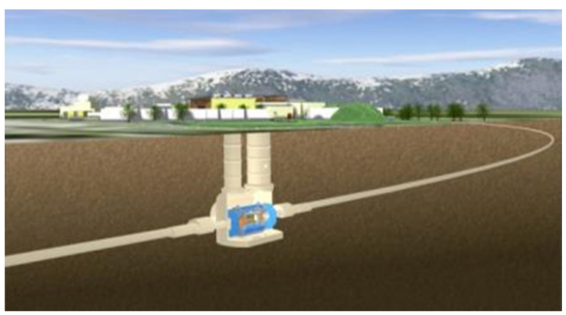
In his special relativity theory, Einstein proved the equivalence between mass an energy:

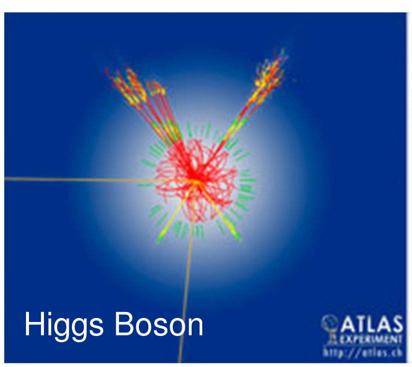
$$E = m_0 c^2$$

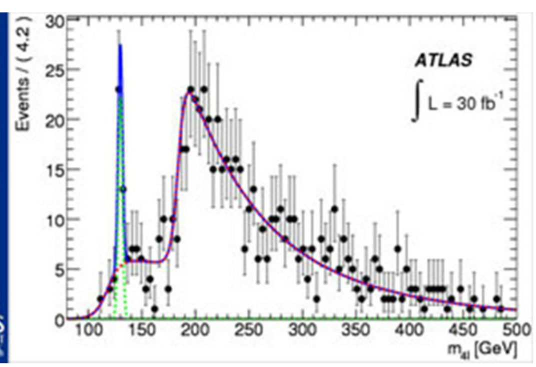
As a consequence, a particle with mass m_0 can be generated if its equivalent in energy is concentrated in a point.

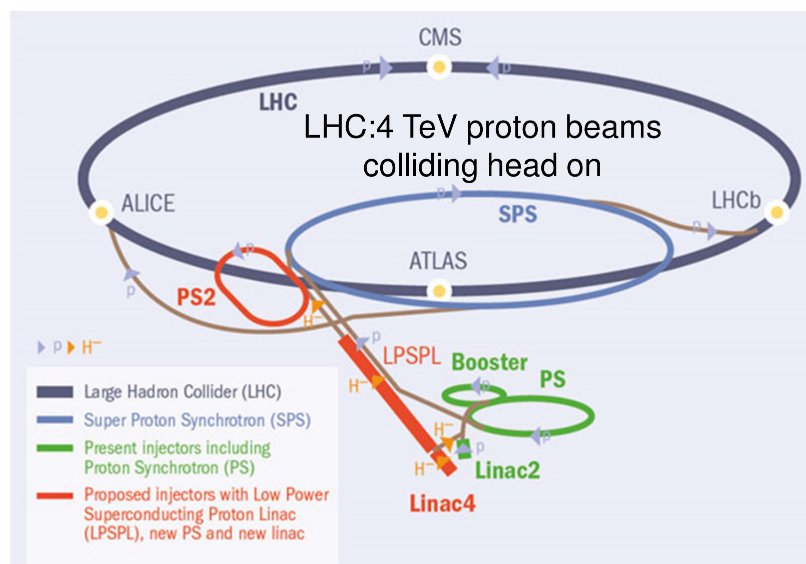


In special accelerators, called colliders, high energy particles travelling on opposite directions collide to create such a situation.



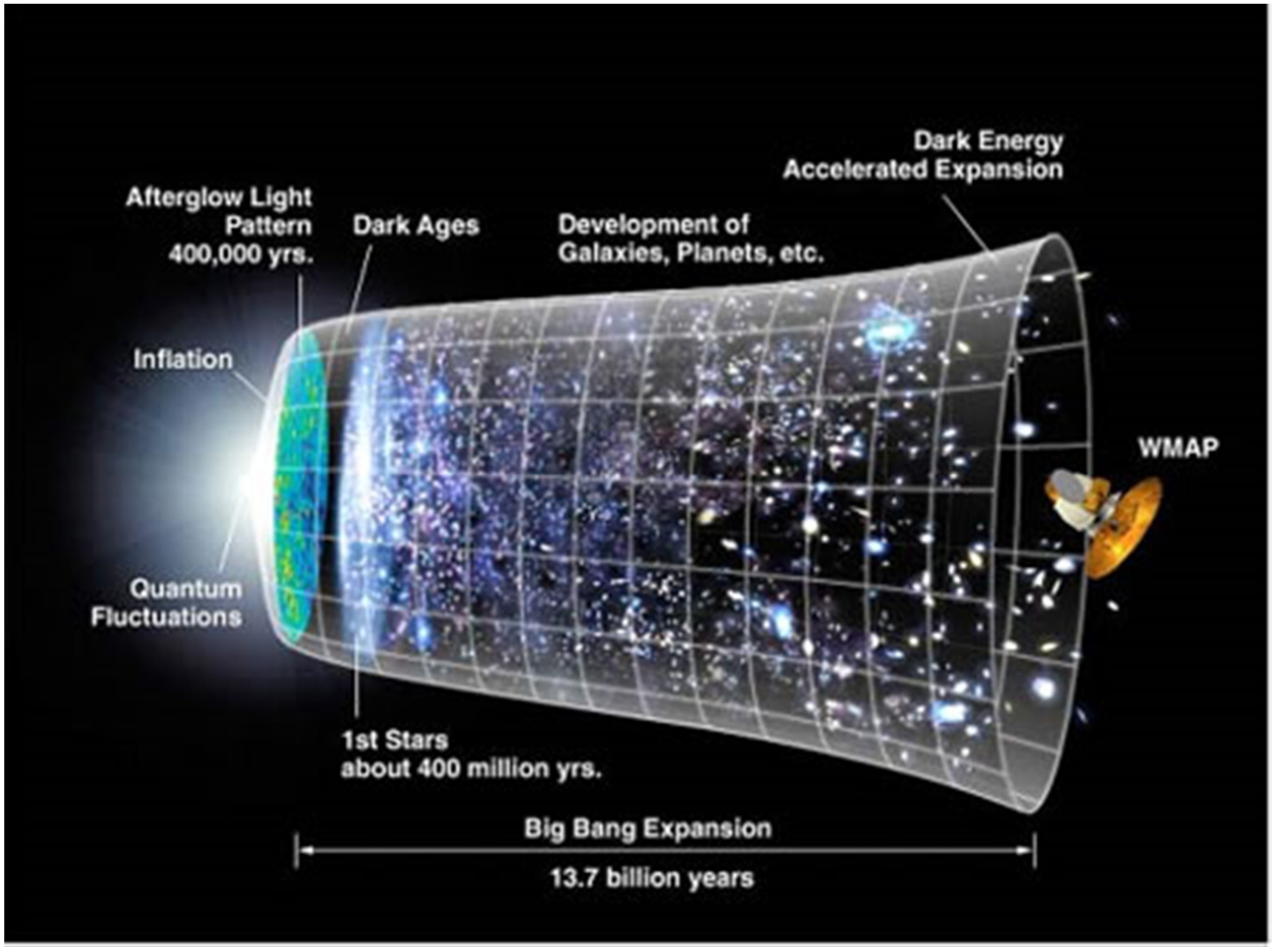






Accelerators as a Probe for Cosmology

Cosmology is the branch of science that studies the origin of the universe

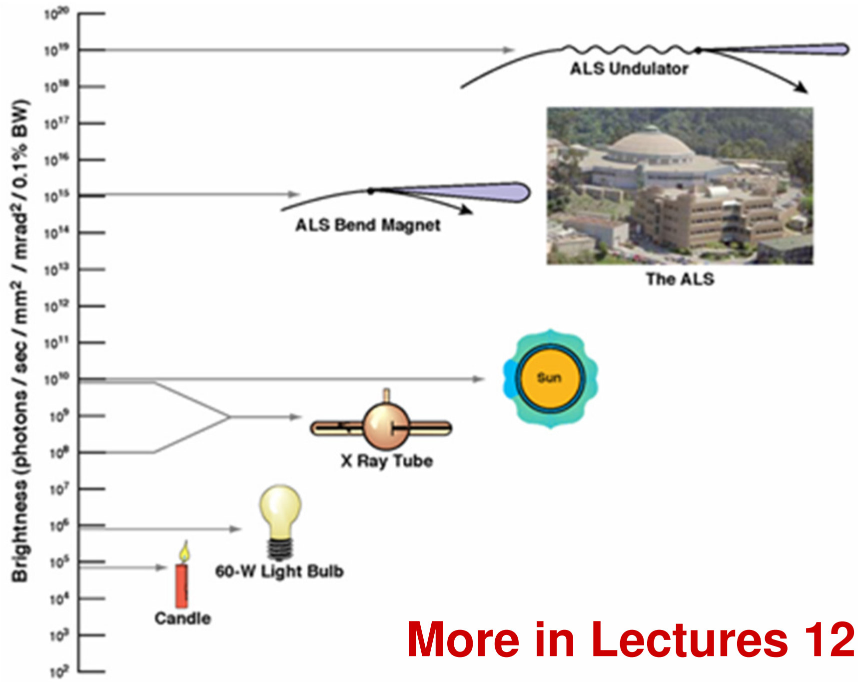


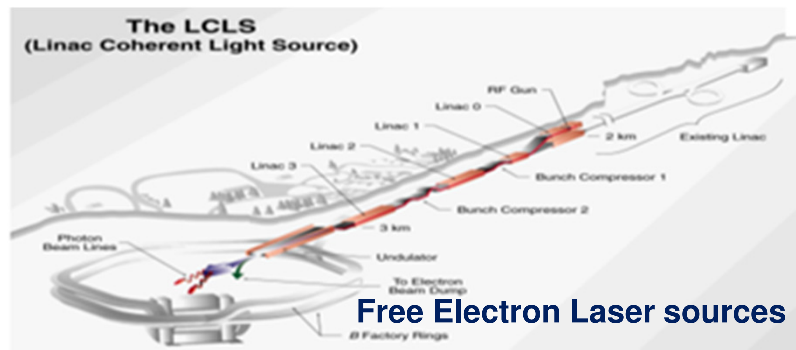
LHC in its collision points creates the energy, temperature and pressures that existed few ms after the big bang!

Accelerator-Based Light Sources

A charged particle when accelerated radiates energy in the shape of electromagnetic waves

$$P_{\perp} = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\gamma^2\left(\frac{d\mathbf{p}_{\perp}}{dt}\right)^2$$





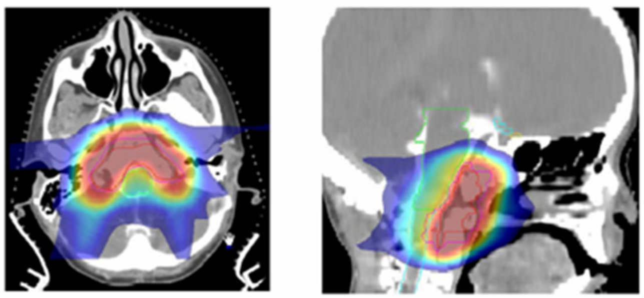
More in Lectures 12 and 13!

Modern light sources are accelerators optimized for the production of electromagnetic waves from the far-IR to the hard x-rays.

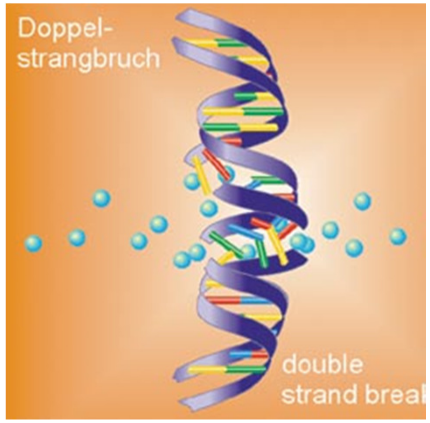
Accelerators in Medicine

Accelerators generate X-ray for tissues imaging (radiography).

Accelerators are used to generate X-rays, electrons, protons and heavy-ions that are used in cancer therapy.

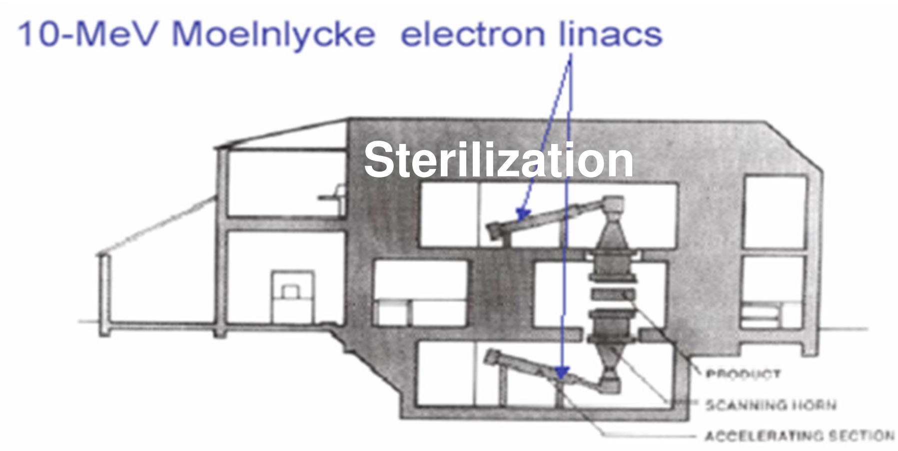


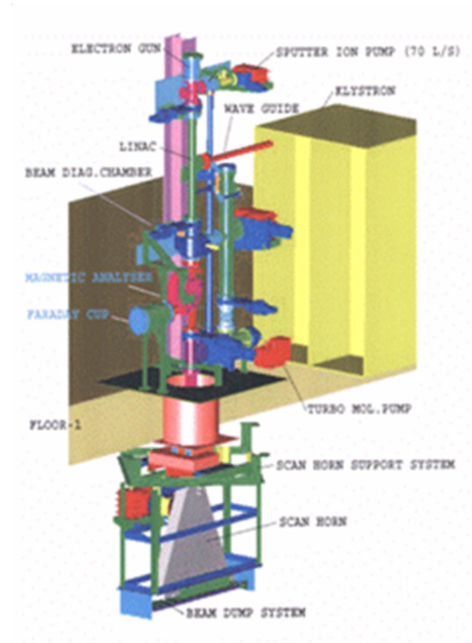
The particles are directed on the cancer cells to break their DNA molecules in a way that it cannot be repaired inducing the cancer cell dead.

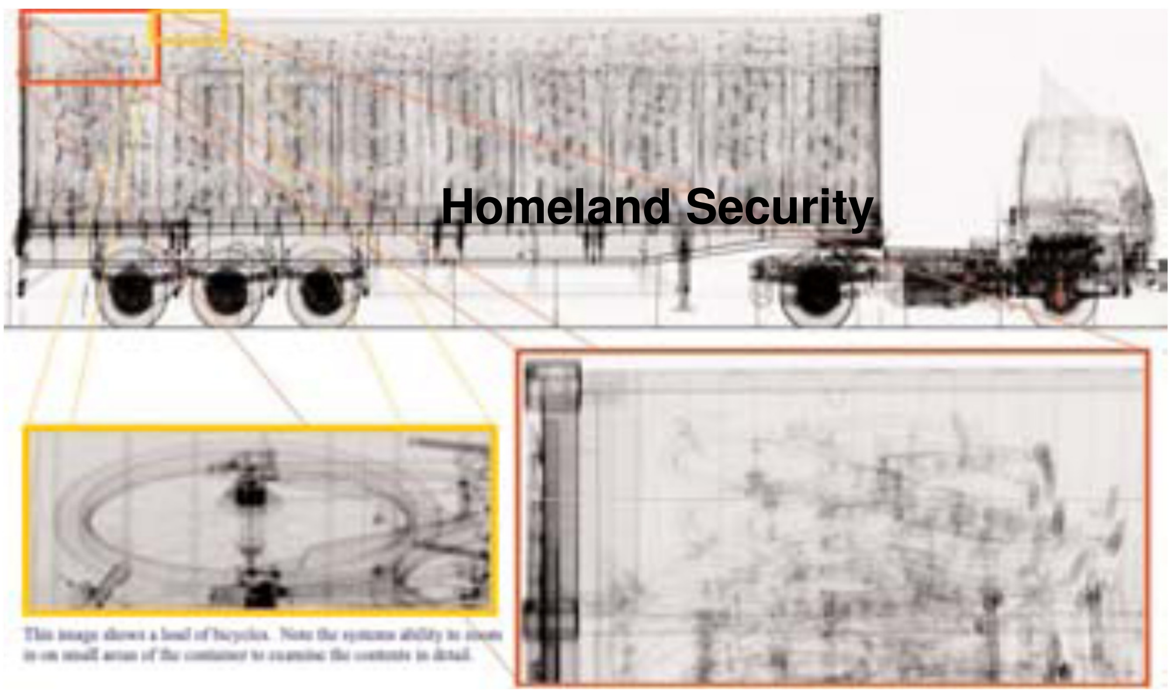


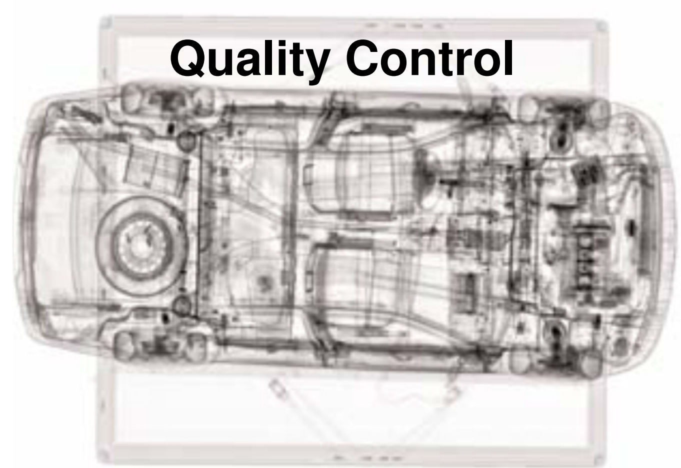
Proton accelerators are also used for the production of unstable isotopes. For example, technetium-99 (6 hour half time decay): emits readily detectable 140 keV gamma rays. Used in to image the skeleton and heart muscle in particular, but also for brain, thyroid, lungs, liver, spleen, kidney, bone marrow, salivary and lacrimal glands, heart blood pool, including infections.

Other Accelerator Applications









And Much More!

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

- About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization.
- The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose

"Accelerating" Particles

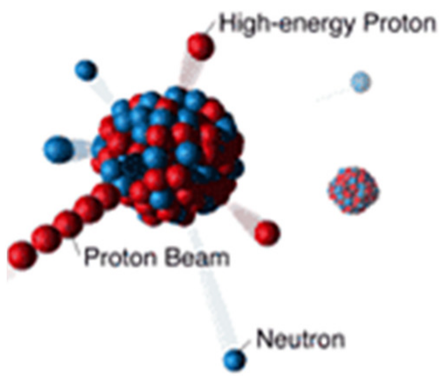
In both the relativistic and non-relativistic case "accelerating" a particle means to modify (mostly increase) its kinetic energy.

In most of accelerator applications the particle energy is one of the fundamental design parameter and tuning knob:

- **In colliders tuning the c.m. energy on resonances allows to create new particles**
- **In light sources the energy is one of the parameters defining the spectrum of the emitted radiation**
- **Energy contributes in defining the penetration depth of a particle inside materials (cancer therapy, …)**

In relativistic particles storage rings the energy losses need to be restored in order to keep the particles stored.

How to Accelerate Particles?



Neutral particles can be accelerated by: scattering, 'spallation'

Charged particles: Electric fields.

$$\overline{F} = q\left(\overline{E} + \overline{v} \times \overline{B}\right)$$

Lorentz Force

$$W = \int \overline{F} \cdot d\overline{l} \quad = q\int \overline{E} \cdot d\overline{l} + q\int \left(\overline{v} \times \overline{B}\right) \cdot d\overline{l}$$

B fields can change the trajectory of a particle
But cannot do *work* and thus change its energy

Large number of schemes and techniques used to generate the required electric fields. Continuous R&D going on

History

Cathode Ray Tubes
Late 1800s

Multipole Gaps
Cockcroft Walton (1920)

Van Der Graff (1930)

Electrostatic Field Based

Time Varying Field Based

Time Varying Fields linear accelerators
Ising (1924) and Wideroe (1928)

Cyclotron
Lawrence (1930)

Synchrotron
Oliphant (1943)

Synchrocyclotron and Betatron
McMillan and Veksler (1944)

Alvarez Linac
McMillan (1946)

Strong Focusing
Courant and Snyder (1952)

Non RF high gradient
accelerators (20??)

Cathode Ray Tubes

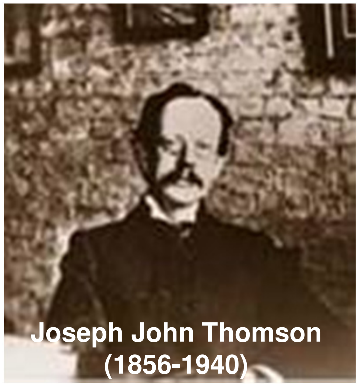
Particle accelerators were used even before being discovered!

Wilhelm Conrad Röntgen (1845-1923)

In 1895 Röntgen, using a cathode ray tube discovered the x-rays.
(1901 Nobel Prize)

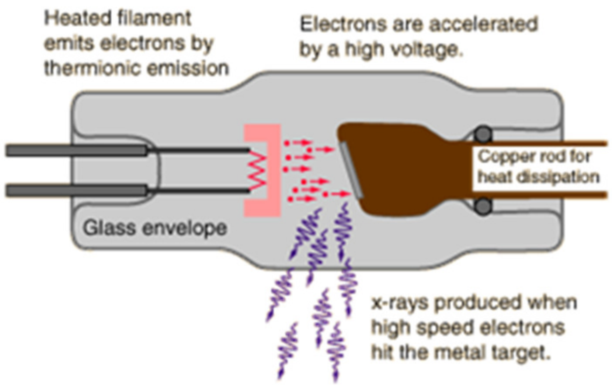
Bertha Röntgen's Hand 8 Nov, 1895

Modern radiograph of a hand



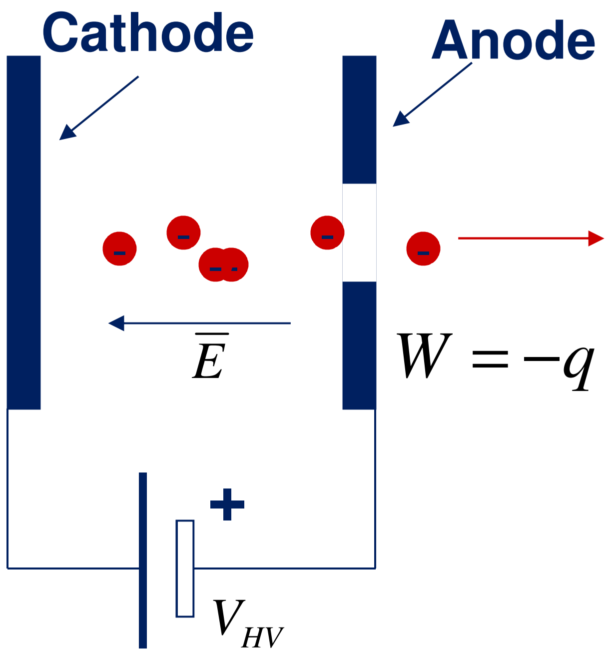
Joseph John Thomson (1856-1940)

But it was only in 1897 that Thomson discovered the electron, showing that the cathode rays were these small negative charged particles being accelerated in the tube.
(1906 Nobel Prize)

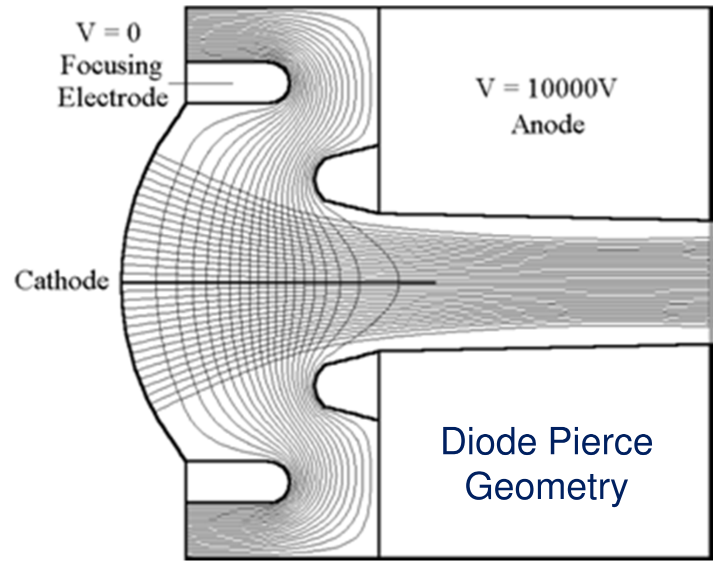


From: hyperphysics.phy-astr.gsu.edu

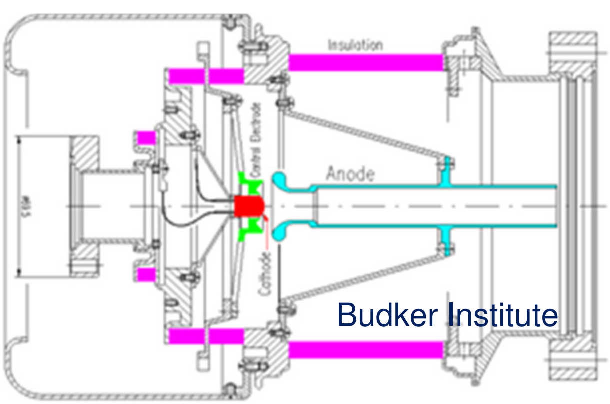
Electrostatic Accelerators: The Simplest Scheme

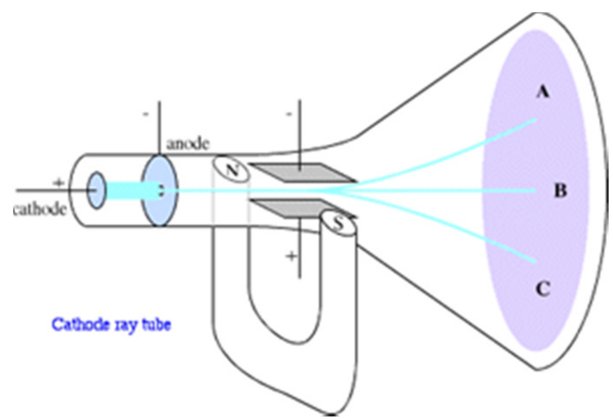


$$W = -q\,V_{HV}$$

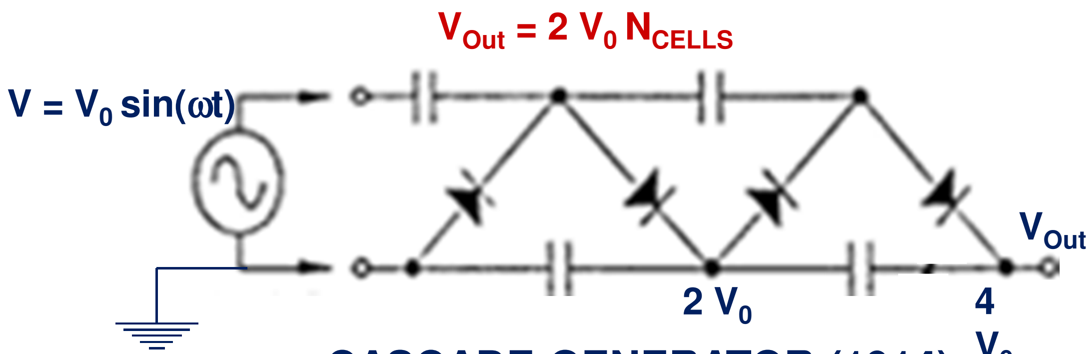


Still one of the most used schemes for electron sources

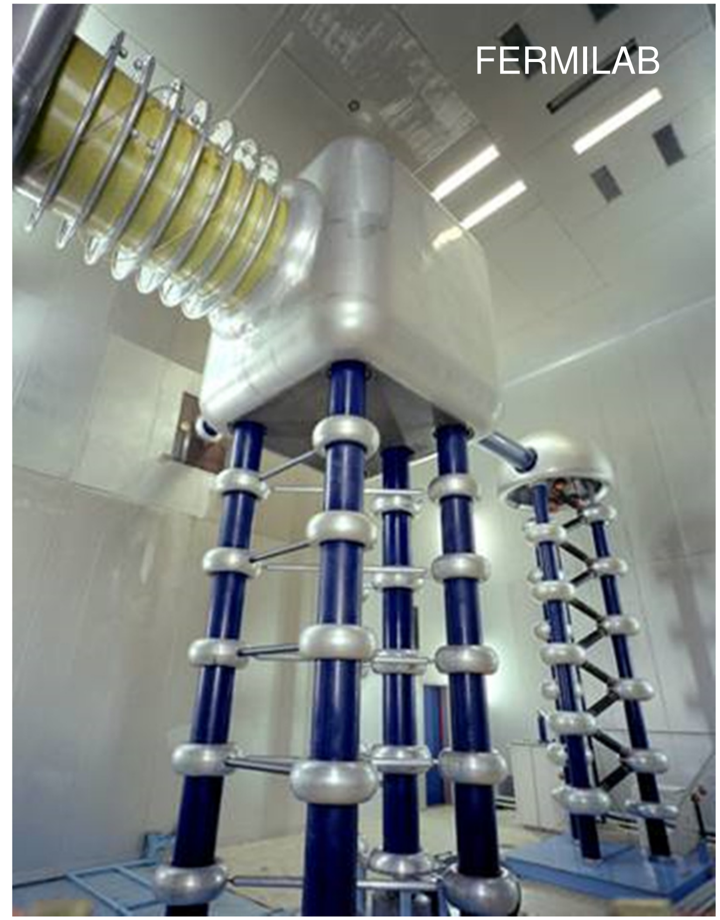




Electrostatic Accelerators. The Cockcroft-Walton Scheme



CASCADE GENERATOR (1914)

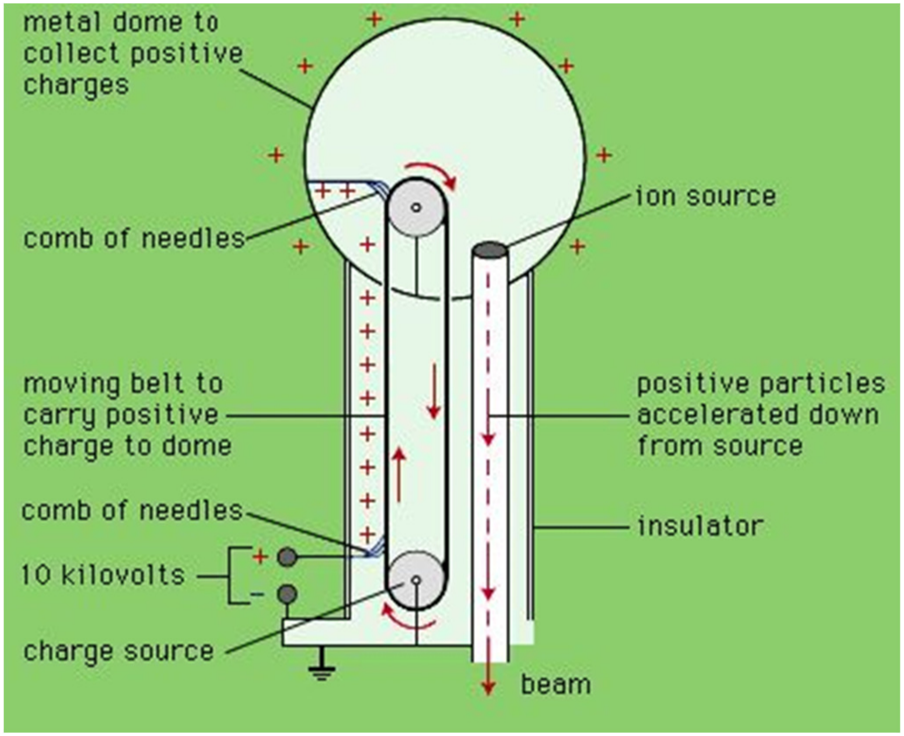


James Cockcroft and Ernest Walton in 1932 accelerated protons to 800 keV and produced fission of Lithium in Helium (Nobel Prize 1951)

$$p + Li \rightarrow 2He$$

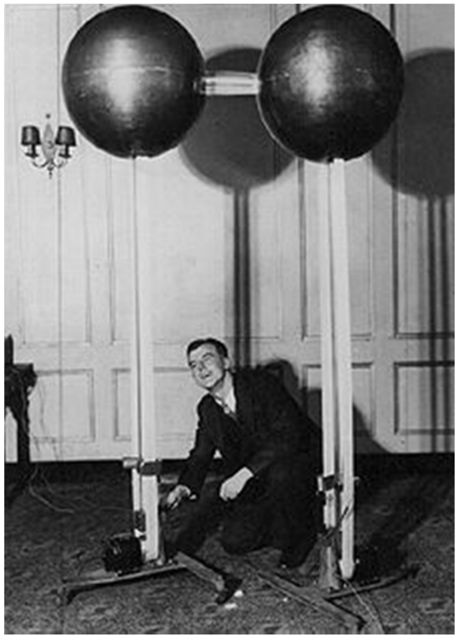
16

Electrostatic Accelerators: The Van de Graaff



•The needle transmits the charge to the belt by glow discharge and/or field emission

•The electric field inside the sphere is zero permitting the passage of the charge from the belt to the sphere



•The maximum voltage is limited by voltage breakdown. Inert gasses (Freon, SF6) help.

7MV in 1933
~ 20 MV nowadays

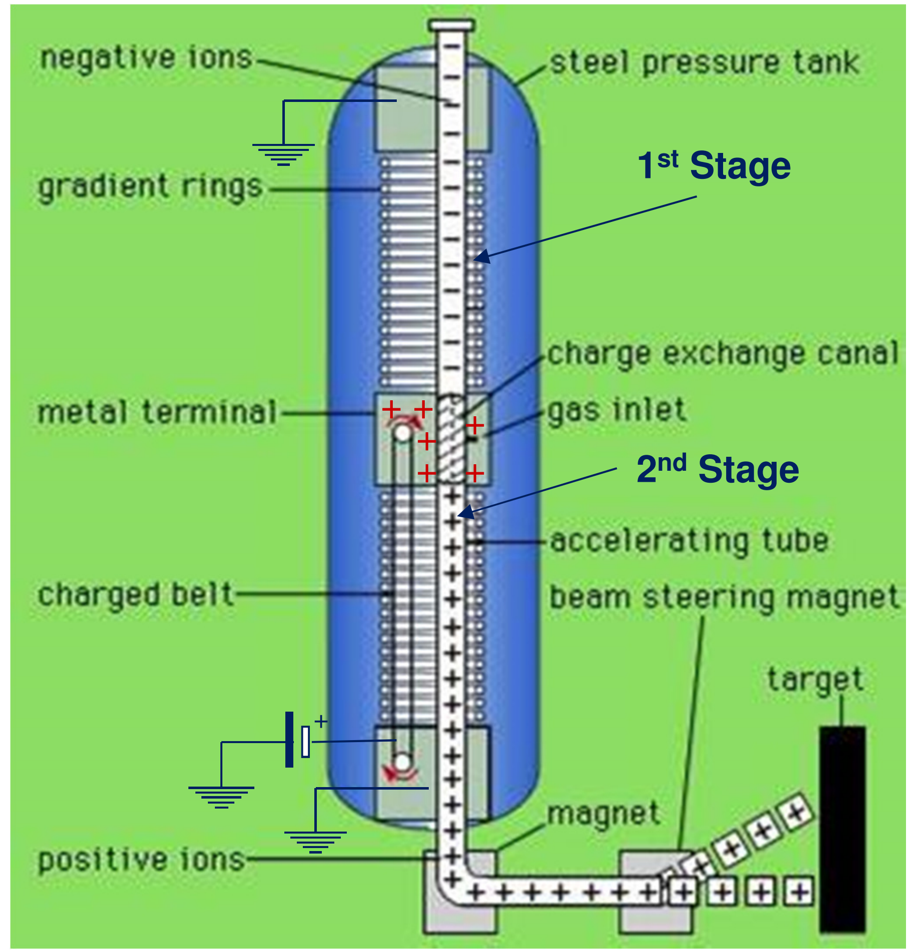
Van de Graaff Accelerator: Applications

•Negative ions (H^- for example) are created and accelerated through the first stage

•At the end of the first stage the electrons are 'stripped' out from the ions (by a gas target for example)

•In the second stage the positive ions (protons in our example) are accelerated. The net energy gain is **twice** the voltage of the Van de Graaff

Tandem Scheme



From DC to Time Variable Fields

Electrostatic accelerators were soon showing their limits in terms of maximum achievable electric field due to voltage breakdown.

On the other hand the parallel development of time varying field accelerators were demonstrating their potentiality in achieving much higher accelerating gradient.

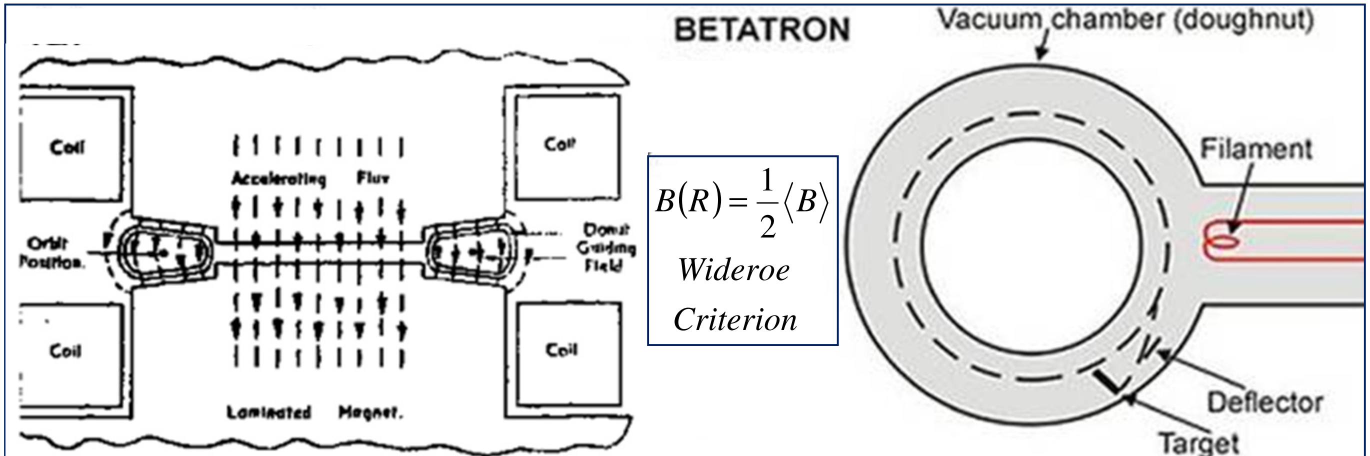
$\omega/2\pi = 0$	$\vec{E}_{MAX} \approx 0.5 \quad MV/m$	**Electrostatic Accelerators**
$\omega/2\pi \approx 10 - 10^3 \;\; Hz$	$\vec{E}_{MAX} \approx 1 \quad MV/m$	**Induction Accelerators**
Present dominant technology		
$\omega/2\pi \approx 10^6 - 10^{11} \;\; Hz$	$\vec{E}_{MAX} \approx 100 \quad MV/m$	**Radio Frequency (RF) accelerators**
$\omega/2\pi \approx 10^{12} - 10^{18} \;\; Hz$	$\vec{E}_{MAX} \approx 10 \quad GV/m$	**Laser, plasma accel. Future accelerators.**

Low Frequency Accelerators: Induction Accelerators

$$\nabla \times \overline{E} = -\frac{d\overline{B}}{dt}$$

Faraday's law

BETATRON ~ 1935 (Wideroe, Kerst, Steenbeck) ~300 MeV Max



$$B(R) = \frac{1}{2}\langle B \rangle$$

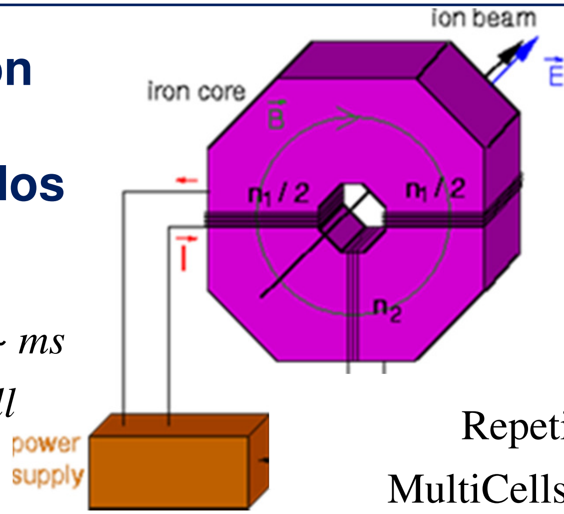
Wideroe Criterion

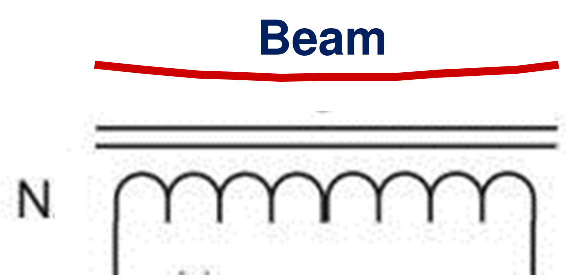
Betatron: ring for beta particles (electrons)

Induction Linac Cristophilos (1964)

$HV\ pulser : \sim ms$

$\sim 150\, kV / cell$





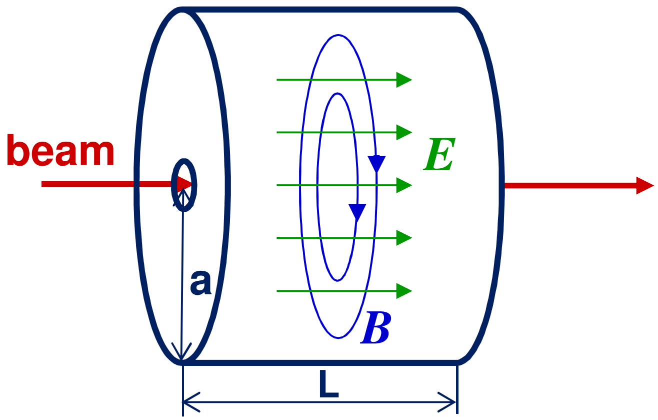
$\text{Repetition rates} \approx \text{few kHz}$

$\text{MultiCells capable of few tens of MeV}$

Induction accelerators can be very efficient (> 50%) and allow for very high currents (~ 1kA) at relatively moderate energies (few tens of MeV)

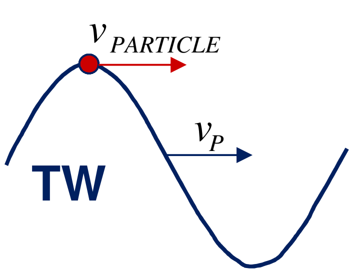
The Radio Frequency (RF) Revolution

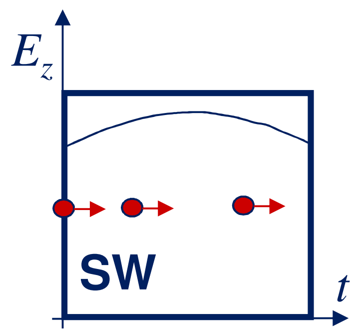
Development of efficient RF accelerating cavities



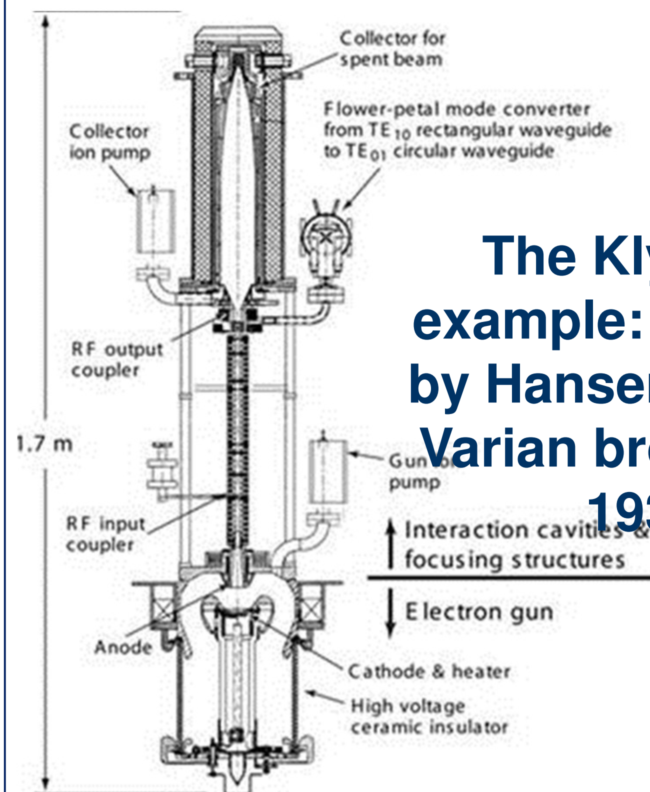
$$E_z^{TM010} = E_0 J_0(k_C r)\cos(\omega_C t)$$

$$B_\theta^{TM010} = -\frac{\omega}{c^2 k_C} E_0 J_1(k_C r)\sin(\omega_C t)$$





Development of powerful RF sources



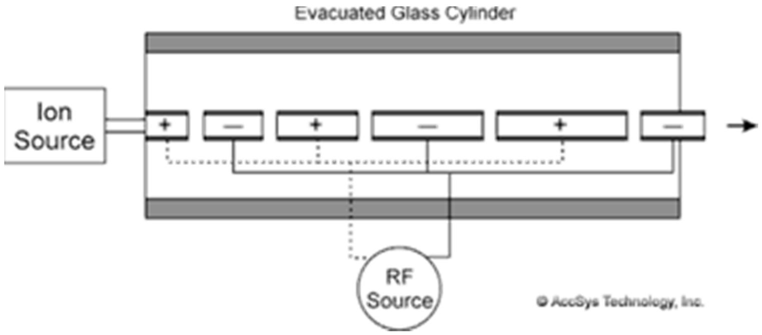
The Klystron example: invented by Hansen and the Varian brothers in 1937

Very powerful source from ~ 100 MHz to more than 10 GHz

RF Accelerators: Wideroe and Alvarez Schemes

In 1925 G. Ising conceived and in 1928 R. Wideroe constructed the first linear accelerator (linac).

The revolutionary device was based on the *drift tubes scheme* where during the decelerating half period of the RF, the beam is shielded inside conductive tubes.

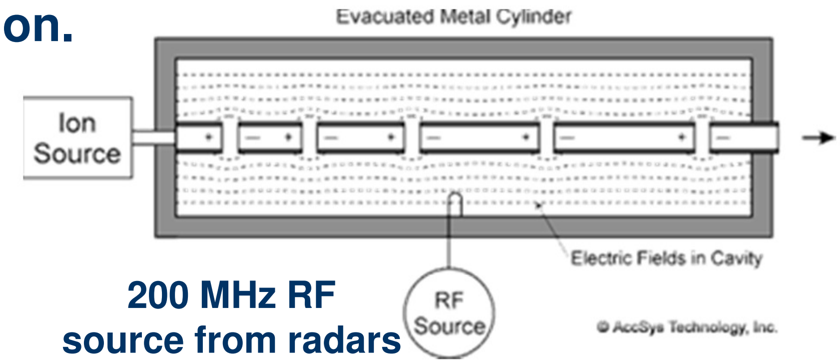


Synchronicity condition:

$$L_i \cong \frac{1}{2} v_i T_{RF}$$

At high frequency the Wideroe scheme becomes lossy due to electromagnetic radiation.

In 1946 Alvarez overcame to the inconvenient by including the Wideroe structure inside a large metallic tube forming an efficient cavity where the fields were confined.



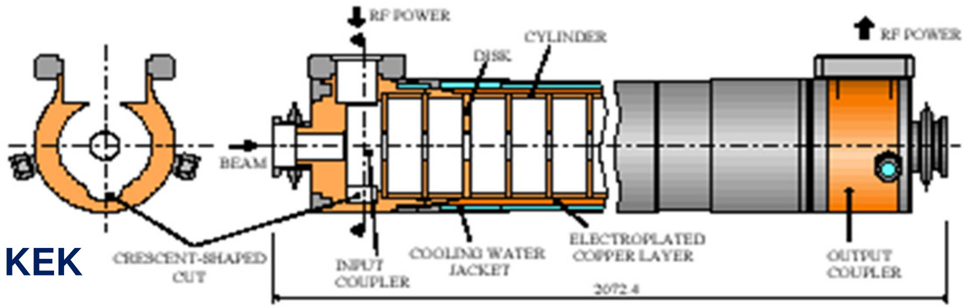
200 MHz RF source from radars

The Alvarez structures are still widely used as pre-accelerator for protons and ions. The particles at few hundred keV from a Cockcroft-Walton for example, are accelerated to few hundred MeV.

Linear Accelerators Evolution

More efficient RF structures were obtained by coupling together many pillbox-like cavities. Ambitious high energy accelerator based on linacs became feasible.

KEK



- The 3-km linear accelerator that started operating in 1966 at the Stanford Linear Accelerator Center, is capable of accelerating electron and positrons up to more than 50 GeV, with an average gradient in the RF structure of ~ 17 MeV/m.

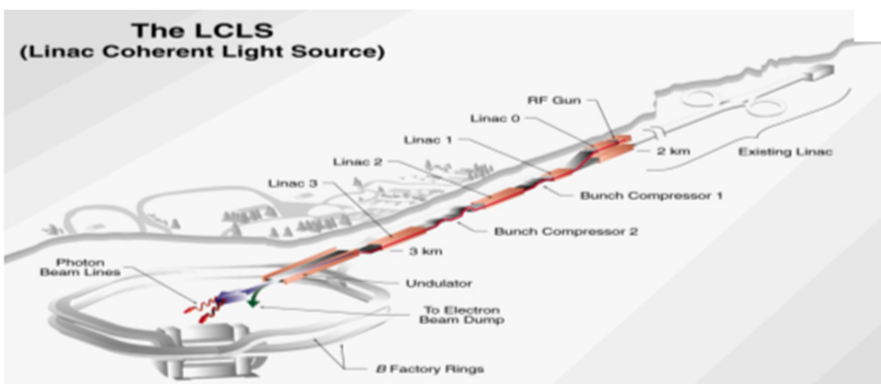
- Nowadays R&D on higher frequency RF structures is demonstrating gradients significantly larger than 100 MeV/m. Superconductive high efficiency accelerating sections have been developed as well.

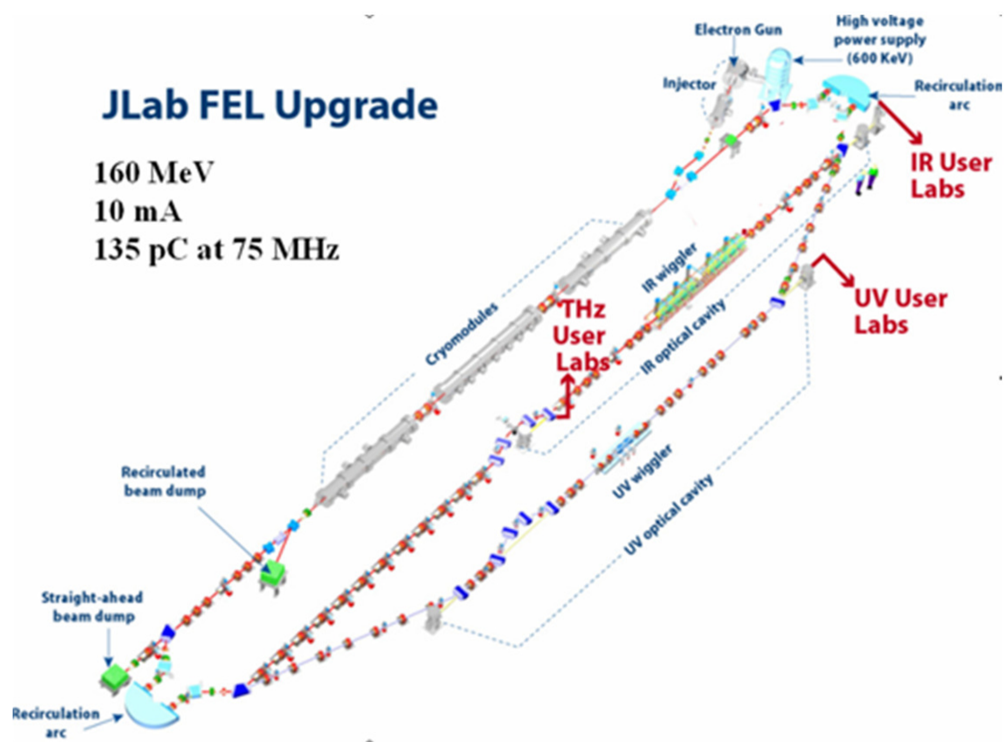
- In the International Linear Collider (ILC) project, electron and positron superconductive linacs longer than 30 Km and with energies over 500 GeV are under consideration.

Linear Accelerators Evolution

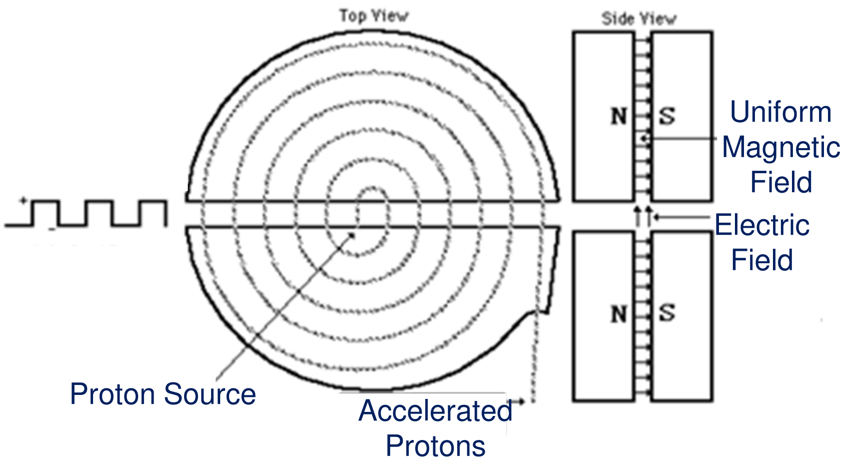
- At the same time, much smaller linacs from few MeV to few hundred MeV are the "backbone" of the injector in most existing electron accelerators and in medical applications.

- Linacs are also finding an extremely important application in the high brightness light sources based on FEL schemes:





Circular Accelerators: Cyclotron & Synchro-cyclotron




The first cyclotron 4.5” diameter (1929).


E. O. Lawrence 1939 Nobel Prize

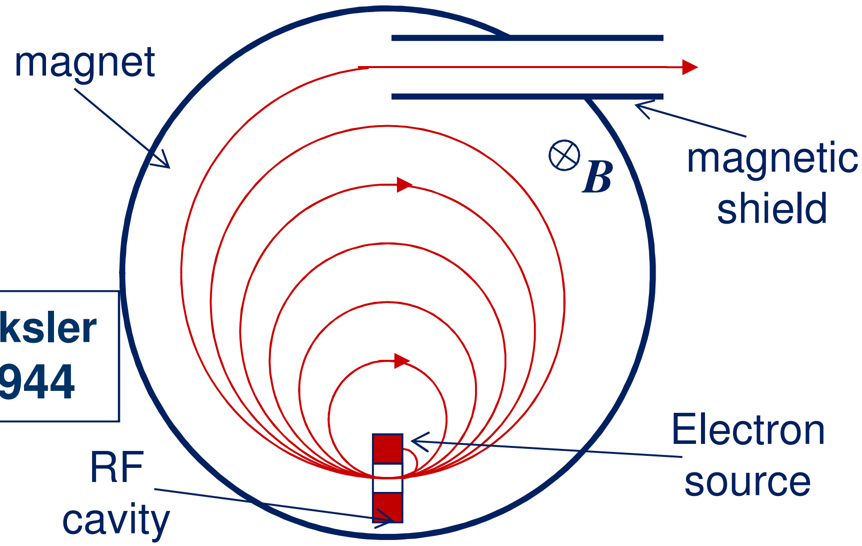
In an uniform magnetic field:

$$T_R = \frac{2\pi r}{v} = \frac{2\pi p}{veB} = \frac{2\pi m_0 v}{veB} = \frac{2\pi m_0}{eB} \quad for \quad v << c$$

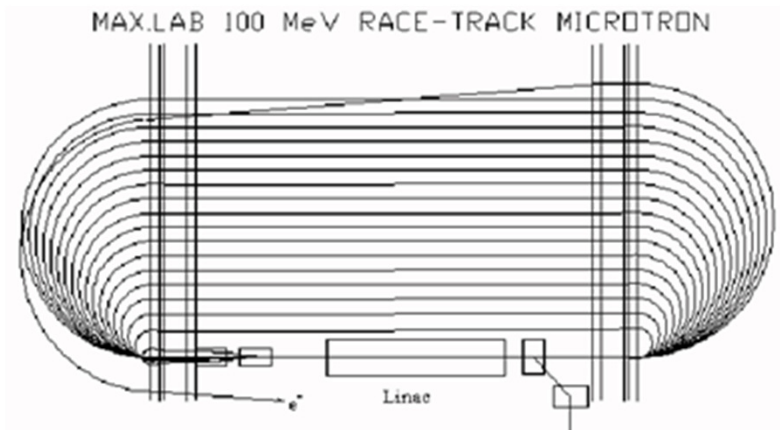
For non-relativistic particles the revolution period does not depend on energy

- **If the RF frequency is equal to the particles revolution frequency synchronicity is obtained and acceleration is achieved.**
- **The synchro-cyclotron is a variation that allows acceleration also of relativistic particles. The RF frequency is dynamically changed to match the changing revolution frequency of the particle**
- **In 1946 Lawrence built in Berkeley the 184” synchro-cyclotron (2.337 m orbit radius) capable of 350 MeV protons. The largest cyclotron still in operation is in Gatchina and accelerates protons to up 1 GeV for nuclear physics experiments.**

Circular Accelerators: Microtrons



Veksler 1944



Moroz and Roberts 1958

Synchronicity condition (energy gain per turn)

$$\Delta\gamma = n \qquad n \text{ is an integer}$$

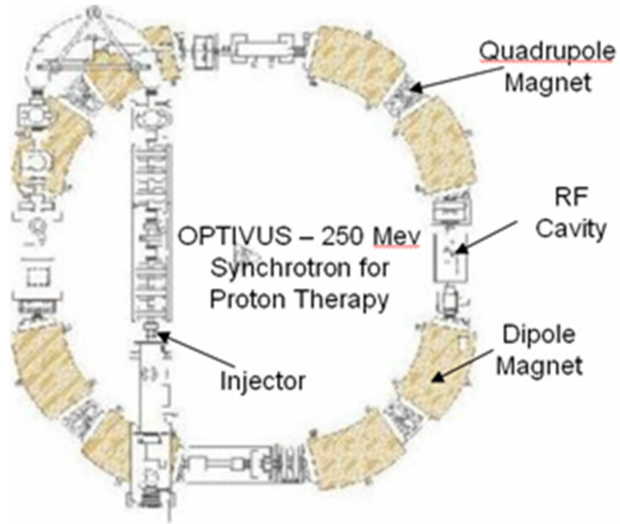
0.511 MeV for electrons
938 MeV for protons

Useful only for accelerating electrons.
The maximum energy is~ 30 MeV (limited by the magnet size)

Synchrotrons & Storage Rings

•Achieving higher energies in cyclotrons requires very large magnets. Above ~ 400 MeV the realization of cyclotrons becomes inconvenient and expensive

• In 1943 M. Oliphant conceived the **synchrotron** where the radius is fixed and all the fields can be confined only around the fixed orbit.



$$R = \frac{\gamma m_0 \beta c}{ZeB} = \text{constant} \Rightarrow B \text{ must scale} \propto \text{ to } \beta\gamma$$

• Synchrotrons have achieved energy as high as 100 GeV for electrons and 1000 GeV for protons

• A **storage ring** is a synchrotron were the particles are not accelerated but just stored at a fixed energy for a relatively long time. Colliders, synchrotron light sources, …

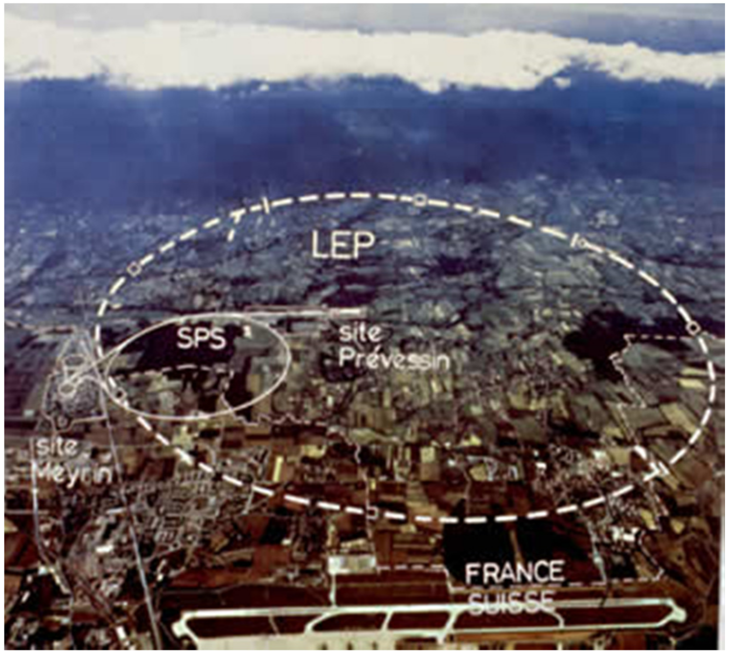
Evolution of Circular Accelerators

The inventions of the synchrotron along with that of an efficient scheme for the transverse confinement of the particles during acceleration (alternate gradient focusing) opened the way for the construction of large high energy synchrotrons.

Two nearly identical very large proton synchrotrons (<u>still in operation</u>) were built: the CERN Proton Synchrotron (PS) (28 GeV, 1959) and the Brookhaven Alternating Gradient Synchrotron (AGS) (33 GeV, 1960).

High energy physics is continuously pushing towards higher energy accelerators: Example: LEP at CERN (1989) was the largest electron-positron collider ever built (~104 GeV/beam).

LEP stopped operation at the end of 2000, and the Large Hadron Collider (LHC) the world largest proton collider (7 TeV/beam), is currently being installed in the 27 km long tunnel and will start operating in 2007.



Evolution of Circular Accelerators

Synchrotron light sources: electron rings with intermediate beam energy (1-8 GeV) optimized as high brightness source of radiation.

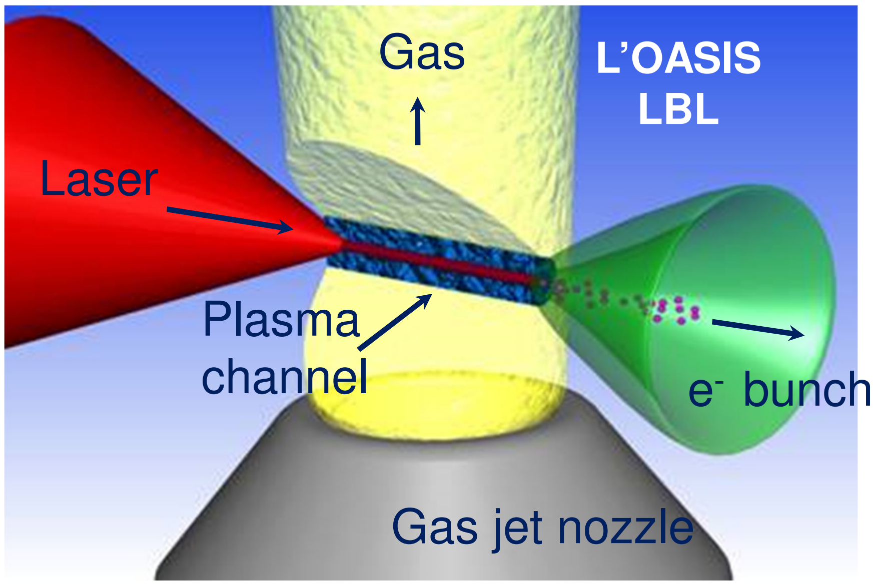
Factories: electron-positron colliders of intermediate energy (1-8 GeV) but with very high stored currents (several Amperes) and very high luminosity.
Dedicated to high resolution measurements of low cross-sections events.

Linear Accelerators vs. Circular Accelerators

- RF cavity technology allowed the development of both linear and circular accelerators.
- The main advantage of circular accelerators is that a single cavity, where the beam passes many times guided by the confinement action of magnetic fields, is capable of very high energy acceleration. This is a very efficient scheme where only a relatively small amount of RF power is required.
- Unfortunately, for light particles the emission of synchrotron radiation can limit the maximum energy achievable (~ 100 GeV for electrons).
- In general, circular accelerators are more efficient with heavy particles and medium energy electrons, while linear accelerators are preferred with high energy electrons.
- Efficiency is not all. For example, circular machines usually show more stable beam characteristics while the beam emittance can be (maintained) smaller in linear accelerators. Different applications can find their best match in either one or the other schemes.

R&D on Future Accelerator Schemes

• The R&D on **new acceleration techniques** is extremely active and addressed towards a very large variety of new accelerating techniques. Results are promising especially from the accelerating gradient point of view where extremely high values have been already obtained.



• As an example of the techniques under study, we want to mention the **laser wakefield acceleration** one.

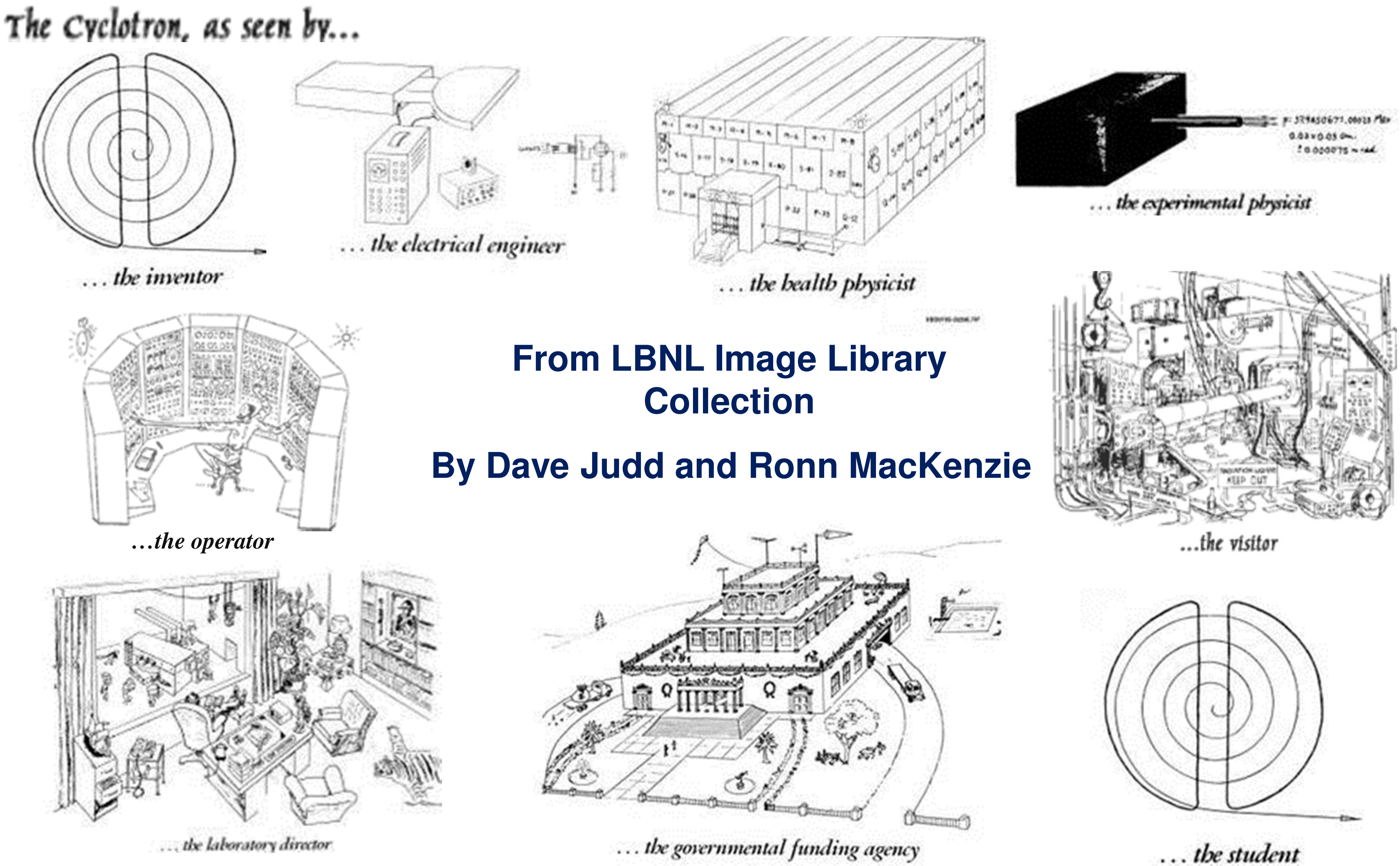
• A high intensity laser is focused on an atomic gas jet.

• The laser ionizes most of the atoms creating a plasma and also stimulating a resonant motion of the electrons in the plasma.

• This electron motion breaks the charge balance inside the very dense plasma inducing extremely high gradients in the plasma area surrounding the laser.

• Electrons in the plasma can find the right phase and can be accelerated to high energies. Gradients of many tens of GeV/m in few mm have been already demonstrated.

The Cyclotron: Different Points of View



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By Dave Judd and Ronn MacKenzie

L2 Homework

1) Using the information on slide 22, calculate the length that an electrode of a 200 MHz Wideroe drift tube should have if the kinetic energy of the protons at its entrance is 1 MeV.
Calculate also the electrode length for the case of electron with the same energy.
Compare the results and comment on the convenience of doing an electron drift tube for those multi-MeV energies.
Useful info: proton rest mass = 1836 electron mass; electron mass = 9.095×10^{-31} Kg

2) For the electron case, calculate the energy at which the cyclotron resonant condition (given in slide 25) is violated by 1%.
Repeat the calculation for protons.
Discuss whether a cyclotron is more appropriate for accelerating at high energies electrons or protons.

3) Make a list of accelerator schemes that could be potentially used for accelerating electrons at an energy of 10 MeV.