Gli acceleratori di particelle

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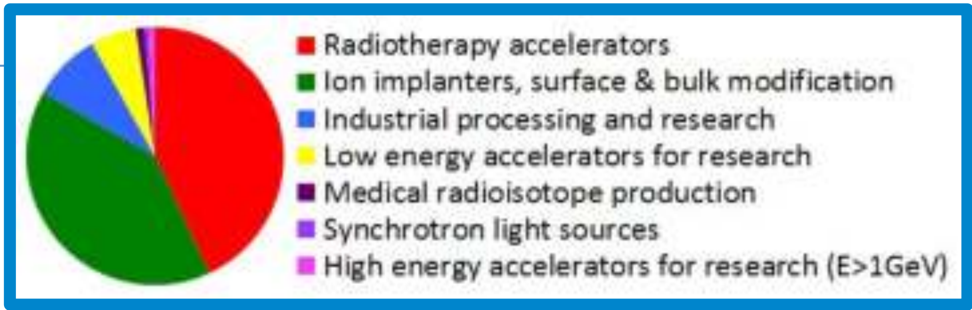
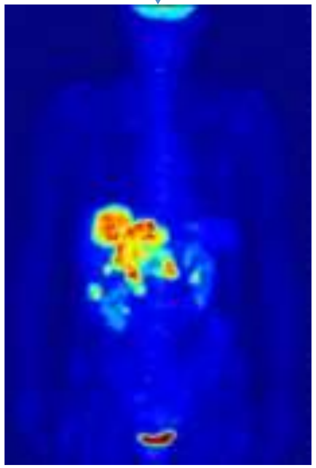
INTERNATIONAL MASTERCLASSES
hands on particle physics

A COSA SERVONO GLI ACCELERATORI DI PARTICELLE?





Produzione di radioisotopi

sicurezza

Produzione di raggi X e γ per fisica della materia

Reattori a fissione controllati

sterilizzazione

Sorgenti di neutroni

Radioterapia e Adroterapia

Impiantazione ionica

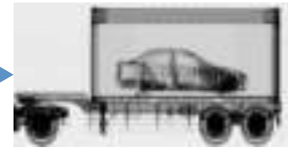
Trattamento materiali

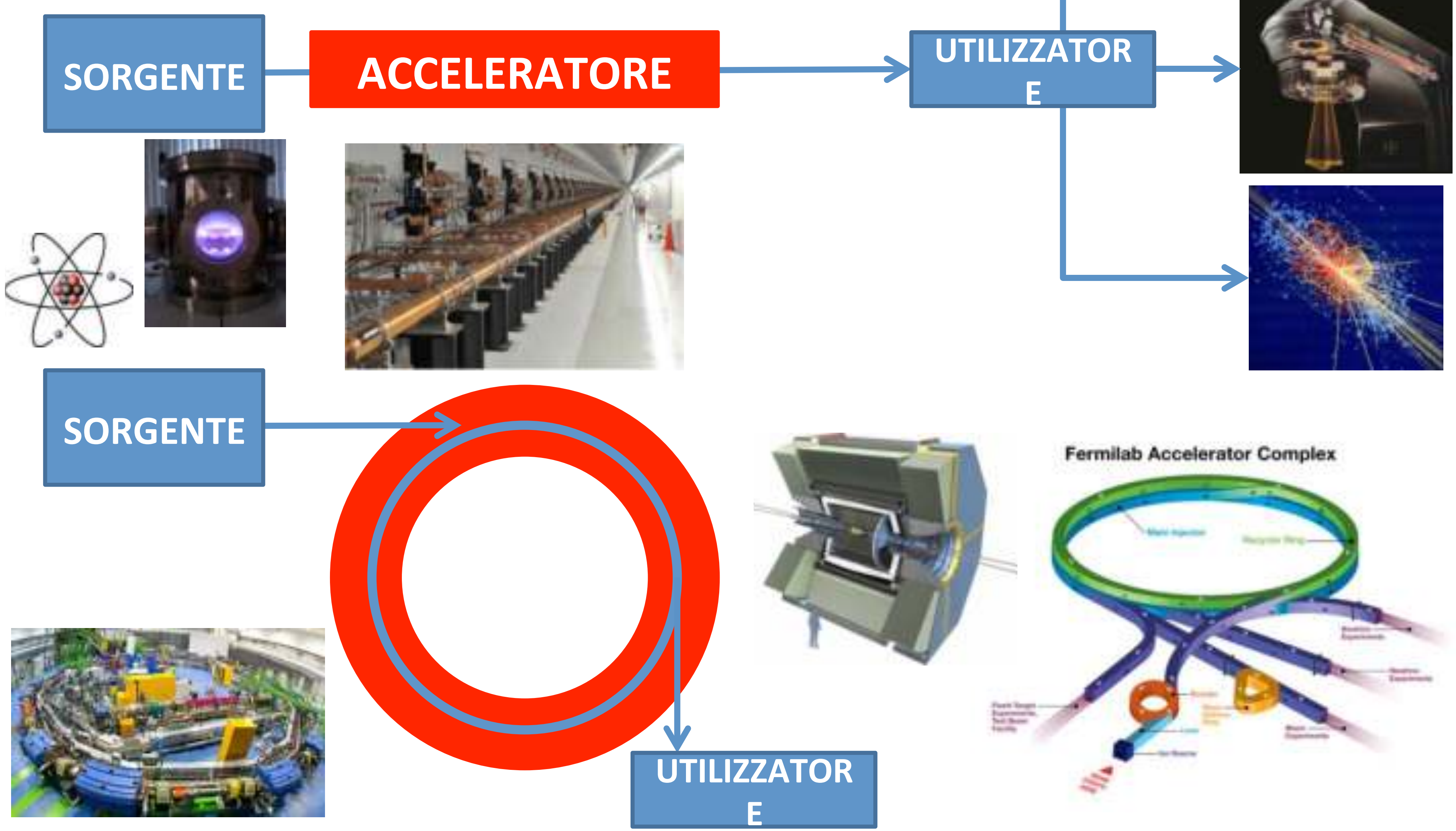
Studi di materiali per fusione nucleare

Fisica delle alte energie

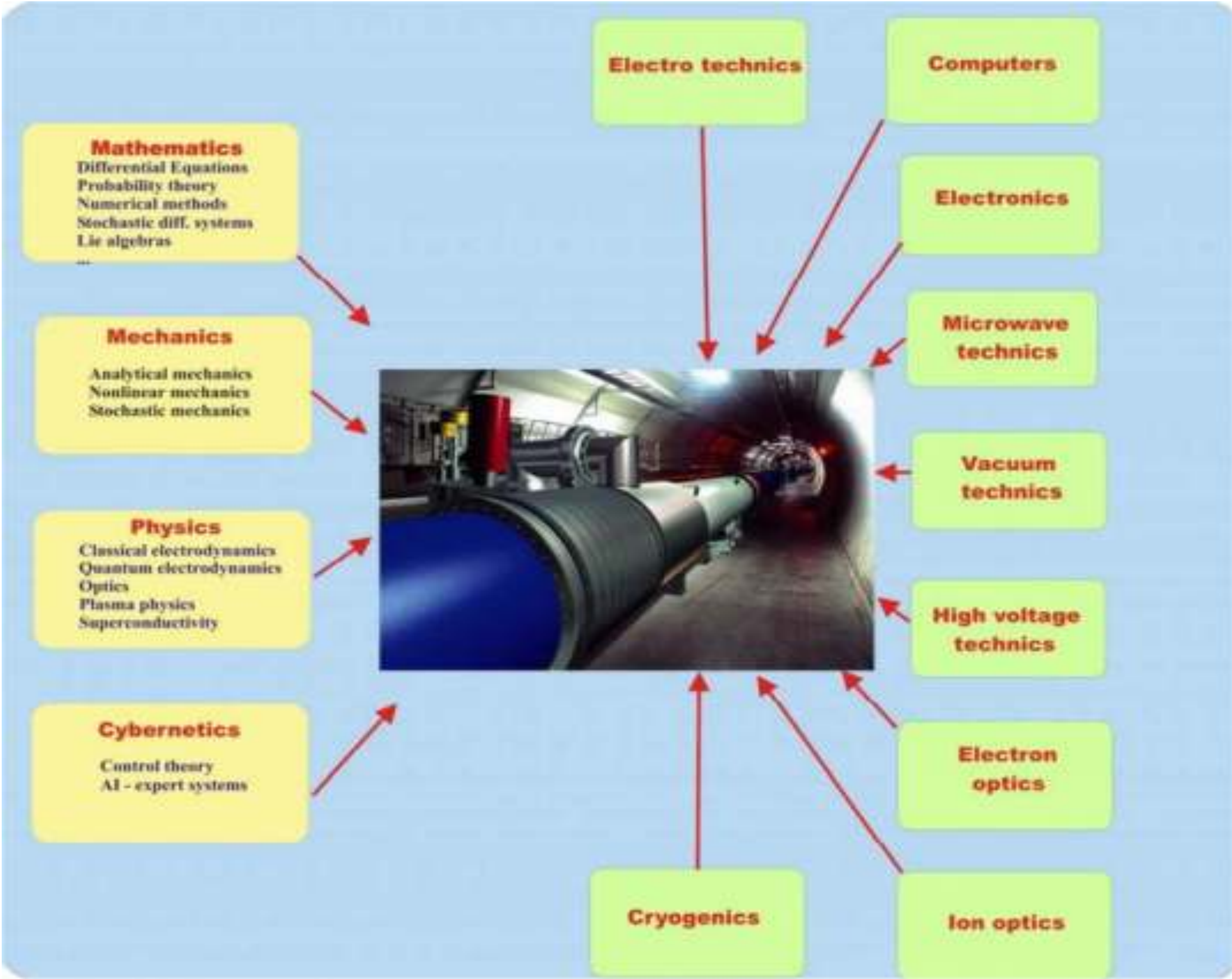
COME FUNZIONANO GLI ACCELERATORI DI PARTICELLE?

Un acceleratore di particelle può essere considerato come un **dispositivo che trasferisce energia a particelle cariche** (elettroni, protoni, ioni,…) attraverso campi elettro-magnetici.



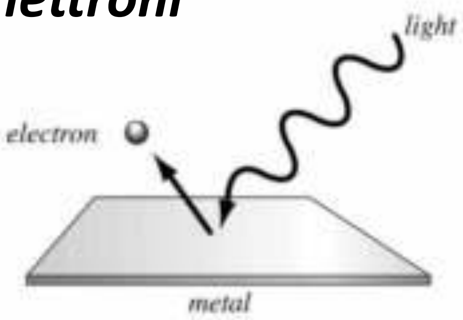


Interdisciplinarietà della fisica e tecnologia degli acceleratori di particelle

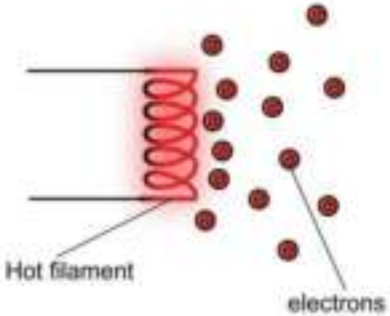


SORGENTI DI PARTICELLE

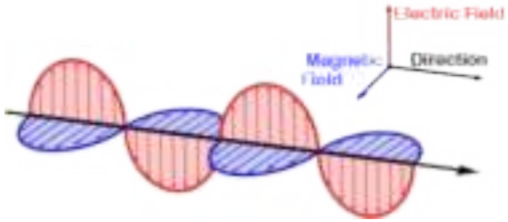
Elettroni

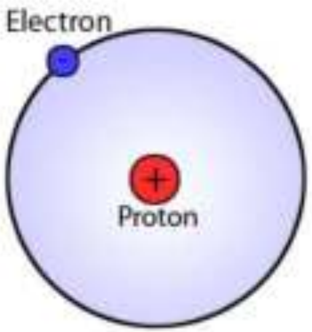


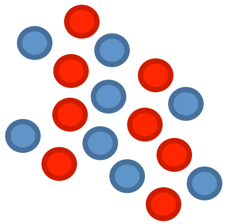
Gli Elettroni possono essere prodotti attraverso impulsi di luce laser che colpiscono una superficie metallica (effetto **foto-elettrico**) o filmenti portati all'incandescenza (**effetto termoionico**).



Protoni







I **protoni** possono essere generati a partire da molecole di **idrogeno** che vengono portate allo stato di plasma da sorgenti a radiofrequenza

BASIC EQUATION FOR PARTICLE ACCELERATORS

Beams of charged particles are accelerated with the use of **electric fields** and are deflected, curved, and focused with the use of **magnetic fields**. The basic equation for the description of the acceleration and focusing processes is represented by the **Lorentz Force**.

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

$\vec{p} = momentum$

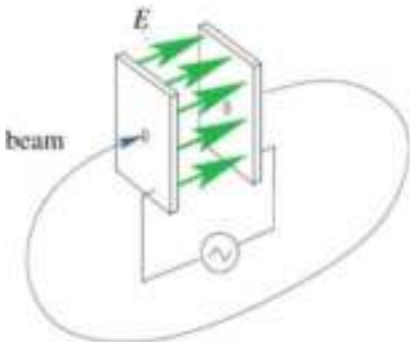
$m = mass$

$\vec{v} = velocity$

$q = charge$

ACCELERATION

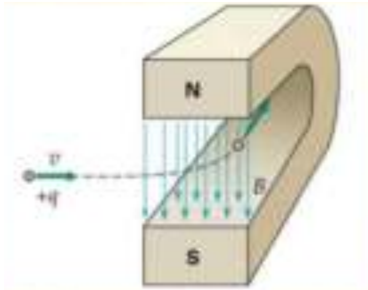
To accelerate, we need a force in the direction of motion

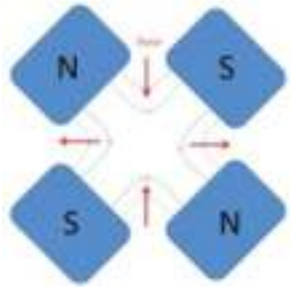


Longitudinal Dynamics

BENDING AND FOCUSING

2nd term always perpendicular to motion => no energy gain

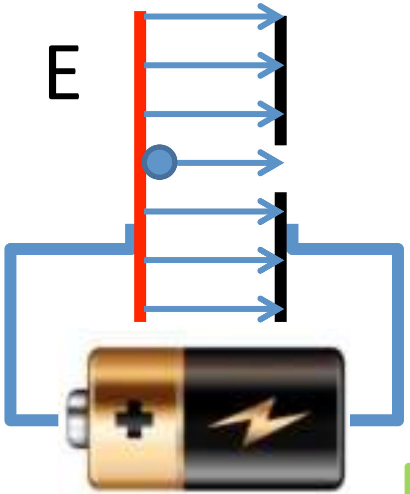




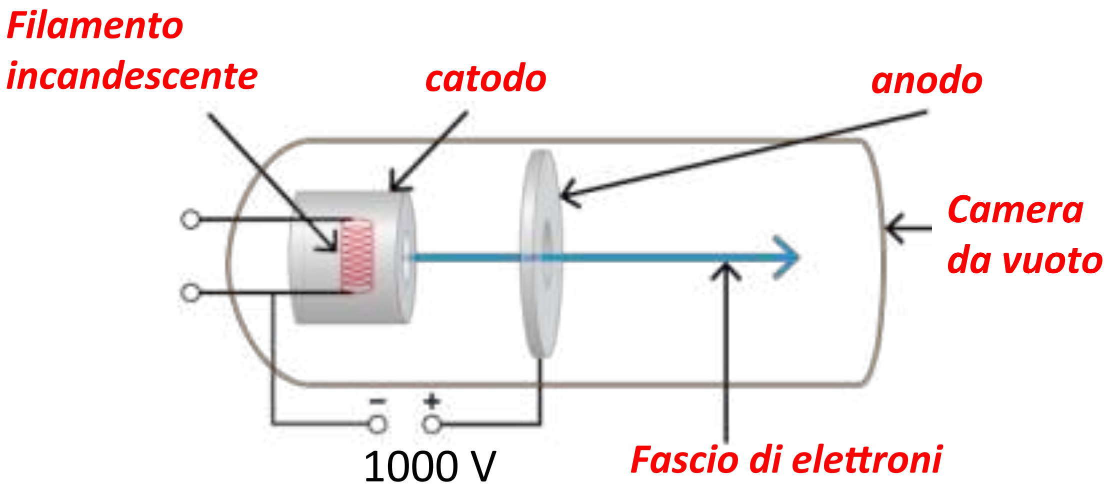
Transverse Dynamics

ACCELERAZIONE DI PARTICELLE: CAMPO ELETTRICO

Le particelle vengono accelerate con l'utilizzo di **campi elettrici**

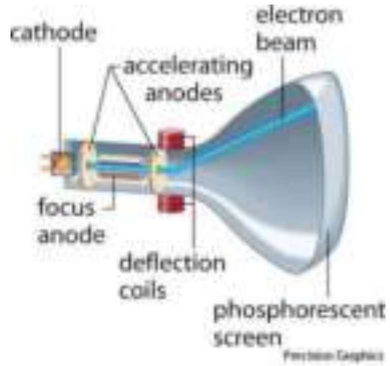


1 V



Guadagno di Energia $\propto$ ddp (V)

220 V

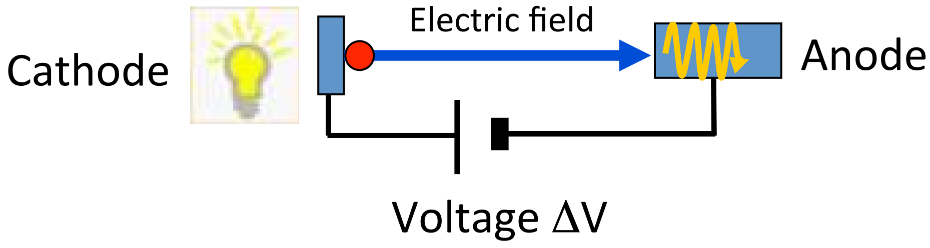


10^9-10^{10} V

10^5 V

ACCELERATION: SIMPLE CASE

The **first historical linear particle accelerator** was built by the Nobel prize Wilhelm Conrad Röntgen (1900). It consisted in a vacuum tube containing a cathode connected to the negative pole of a DC voltage generator. **Electrons emitted by the heated cathode** were accelerated while flowing to another electrode connected to the positive generator pole (anode). Collisions between the energetic electrons and the anode produced **X-rays**.



Bertha Röntgen's Hand 8 Nov, 1895

The **energy gained** by the electrons travelling from the cathode to the anode is equal to their charge multiplied the DC voltage between the two electrodes.

$$\frac{d\vec{p}}{dt} = q\vec{E} \Rightarrow \Delta E = q\Delta V$$

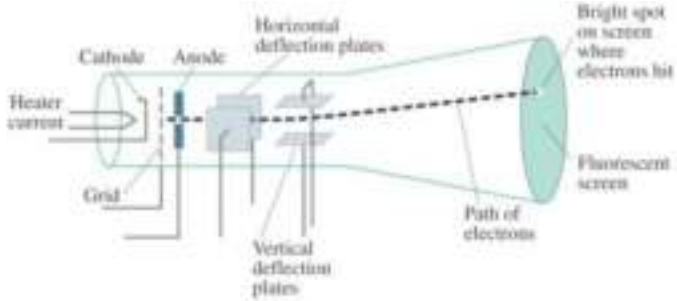
$\vec{p} = momentum$

$q = charge$

$E = energy$

Particle energies are typically expressed in electron-volt [eV], equal to the energy gained by 1 electron accelerated through an electrostatic potential of 1 volt:

1 eV=1.6x10^{-19} J



PARTICLE VELOCITY VS ENERGY: LIGHT AND HEAVY PARTICLES

Single particle
- rest mass m_0
- rest energy E_0 $(=m_0c^2)$
- total energy E
- mass m
- velocity v
- momentum p $(=mv)$
- Kinetic energy $W=E-E_0$

Relativistic factor $\beta = v/c$ (<1)

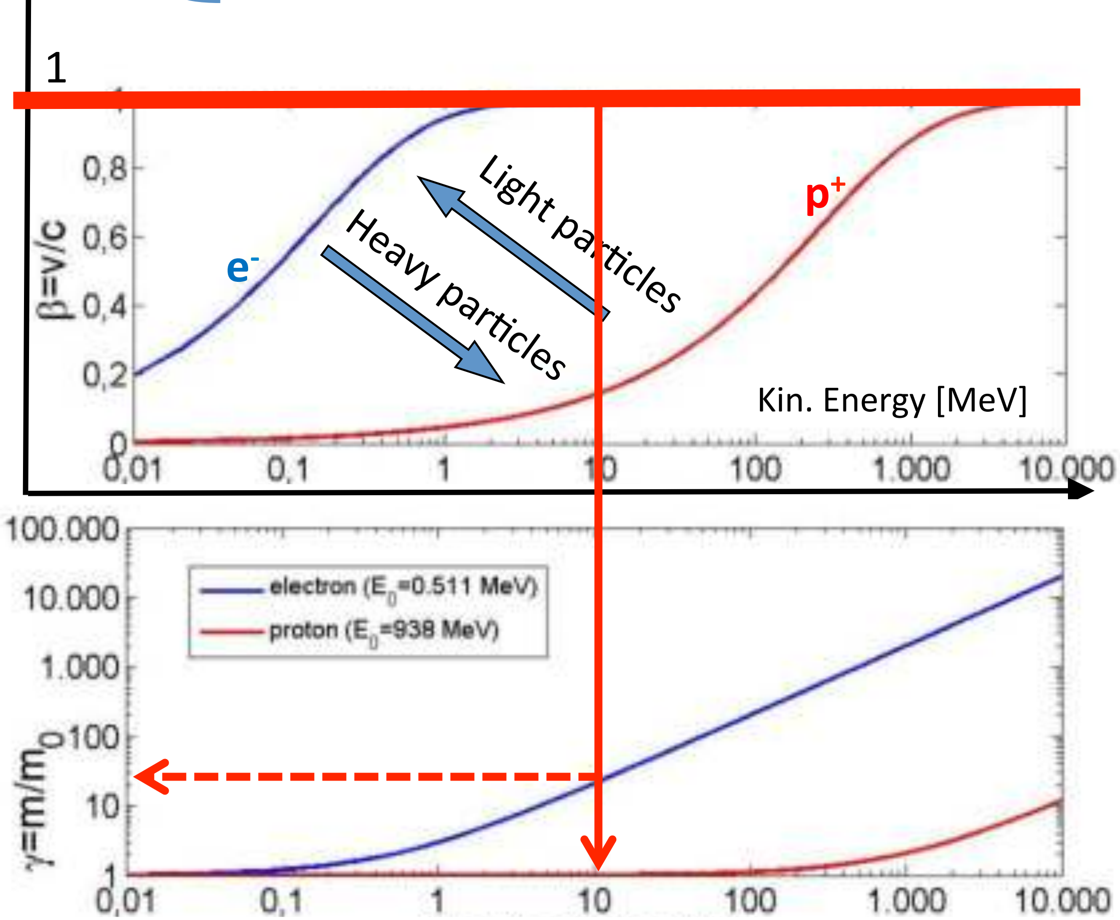
Relativistic factor $\gamma = E/E_0$ (≥1)

+

$$E^2 = E_0^2 + p^2c^2$$

$$\begin{cases} \beta = \sqrt{1-1/\gamma^2} \\ \gamma = 1/\sqrt{1-\beta^2} \qquad (m = \gamma m_0) \\ W = (\gamma-1)m_0c^2 \approx \frac{1}{2}m_0v^2 \quad if\ \beta \ll 1 \end{cases}$$

$$\beta = \sqrt{1-\frac{1}{\gamma^2}} = \sqrt{1-\left(\frac{E_0}{E}\right)^2} = \sqrt{1-\left(\frac{E_0}{E_0+W}\right)^2}$$



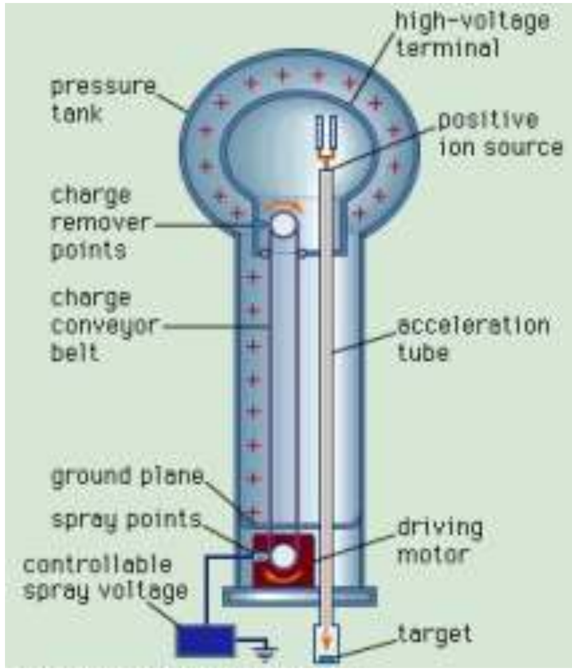
⇒**Light particles** (as **electrons**) are practically fully relativistic ($\beta \cong 1$, $\gamma >> 1$) at relatively low energy and **reach a constant velocity** (~c). The acceleration process occurs at constant particle velocity

⇒**Heavy particles** (**protons and ions**) are typically weakly relativistic and **reach a constant velocity only at very high energy.** The velocity changes a lot during acceleration process.

⇒This implies **important differences** in the technical characteristics of the **accelerating structures**. In particular for protons and ions we need different types of accelerating structures, **optimized for different velocities** and/or the accelerating structure has to vary its geometry to take into account the velocity variation.

ELECTROSTATIC ACCELERATORS

To increase the achievable maximum energy, Van de Graaff invented an electrostatic generator based on a **dielectric belt** transporting positive charges to an isolated electrode hosting an **ion source**. The positive ions generated in a large positive potential were accelerated toward ground by the static electric field.



LIMITS OF ELECTROSTATIC ACCELERATORS

DC voltage as large as ~**10 MV** can be obtained (E~10 MeV). The main limit in the achievable voltage is the **breakdown** due to **insulation** problems.

APPLICATIONS OF DC ACCELERATORS

DC particle accelerators are in operation worldwide, typically at V<15MV (E_{max}=15 MeV), I<100mA.

They are used for:

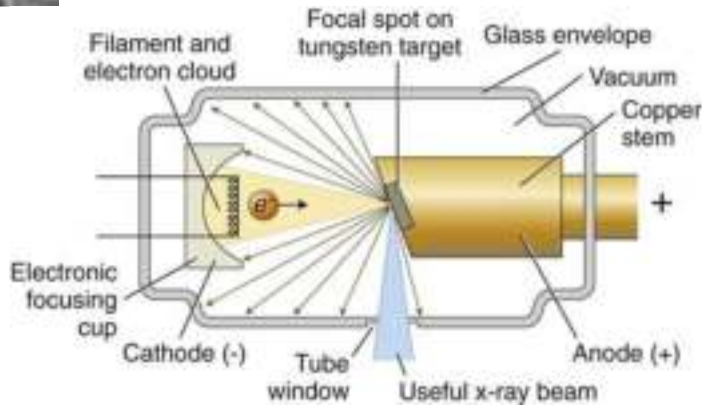
⇒ material analysis

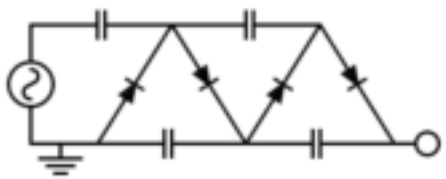
⇒ X-ray production,

⇒ ion implantation for semiconductors

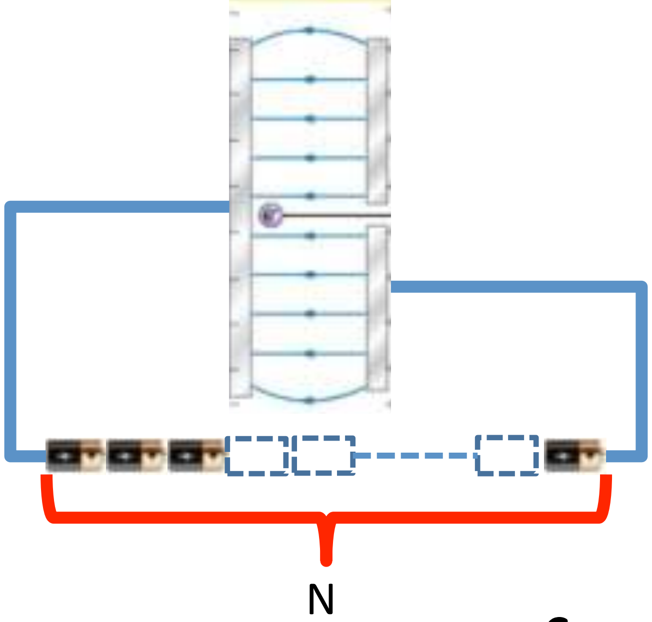
⇒ first stage of acceleration (particle sources)

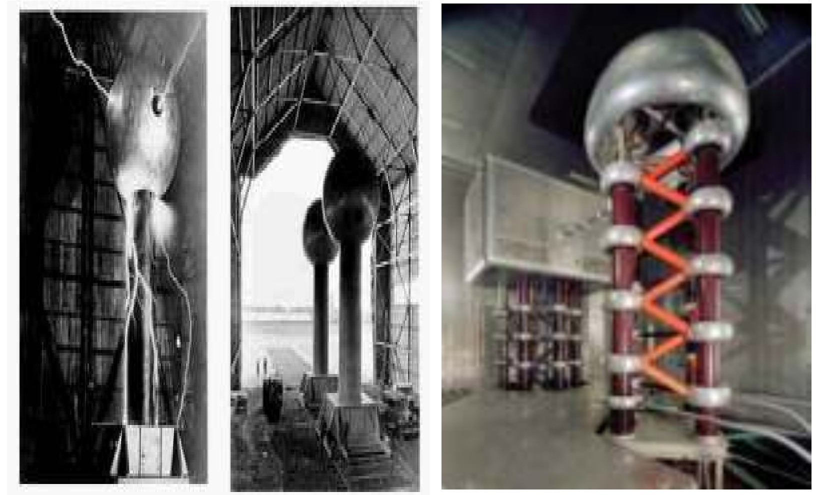
750 kV Cockcroft-Walton Linac2 injector at CERN from 1978 to 1992





ACCELERAZIONE DI PARTICELLE CON CAMPI ELETTROSTATICI E A RADIOFREQUENZA

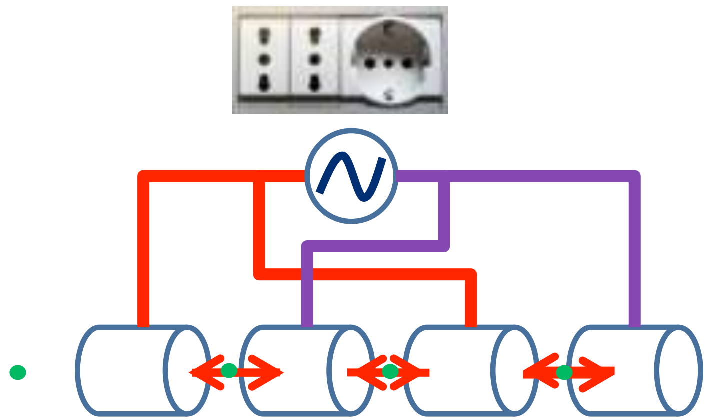




V<5MV (10^6 V)

Campi variabili (a radiofrequenza)

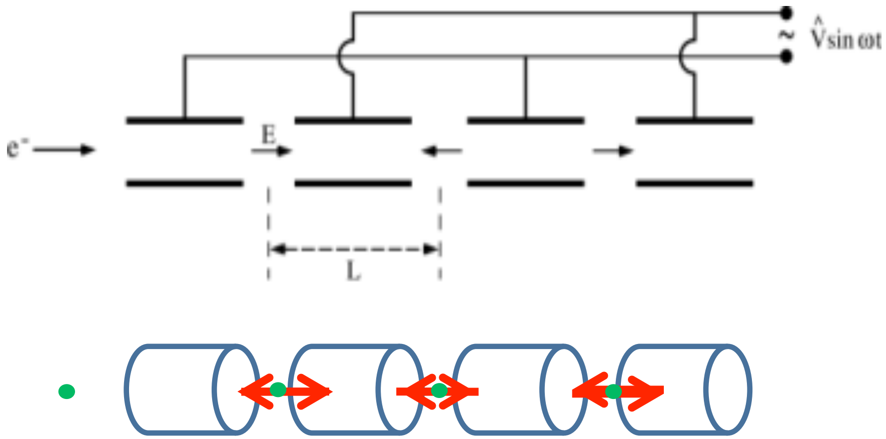
In tali strutture la massima energia è teoricamente limitata soltanto dalla massima lunghezza dell'acceleratore



Si possono ottenere tensioni equivalenti fino a 100 MV/m

RF ACCELERATORS : WIDERÖE "DRIFT TUBE LINAC" (DTL)

Basic idea: the particles are accelerated by the electric field in the gap between electrodes connected alternatively to the poles of an AC generator. This original idea of **Ising** (1924) was implemented by **Wideroe** (1927) who applied a sine-wave voltage to a sequence of **drift tubes**. The particles **do not experience any force while travelling inside the tubes** (equipotential regions) and are **accelerated across the gaps**. This kind of structure is called **Drift Tube LINAC (DTL).**

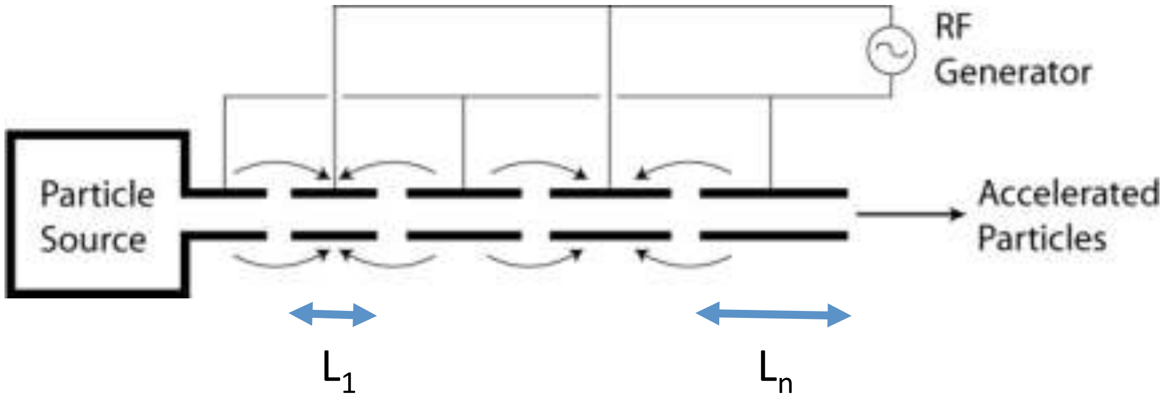


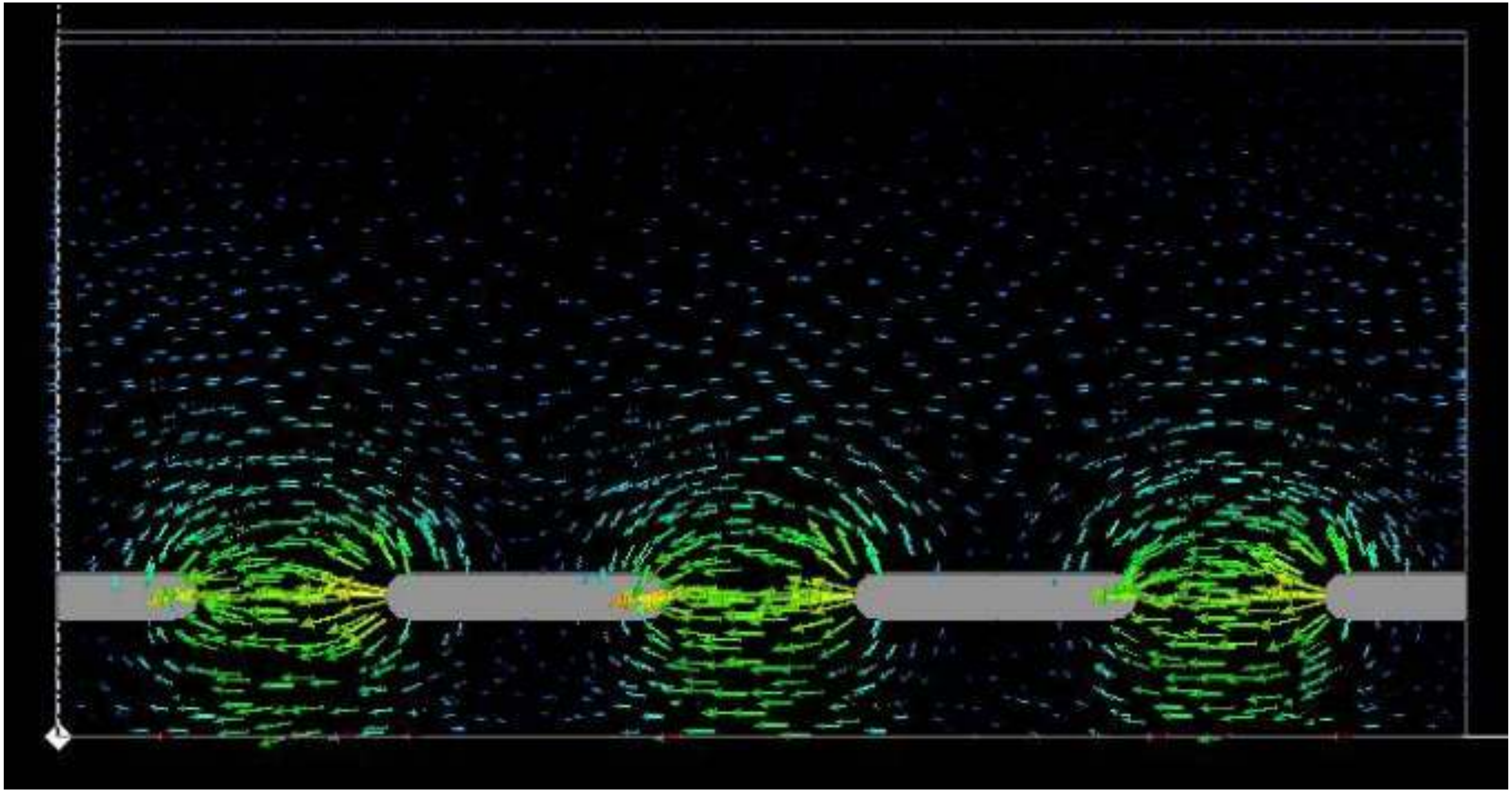
Rolf Wideroe

⇒If the **length of the tubes** increases with the particle velocity during the acceleration such that the time of flight is kept constant and equal to half of the RF period, the particles are subject to a **synchronous accelerating voltage** and experience an energy gain of $\Delta E = q\Delta V$ at each gap crossing.

⇒In principle a single **RF generator** can be used to indefinitely accelerate a beam, **avoiding the breakdown limitation** affecting the electrostatic accelerators.

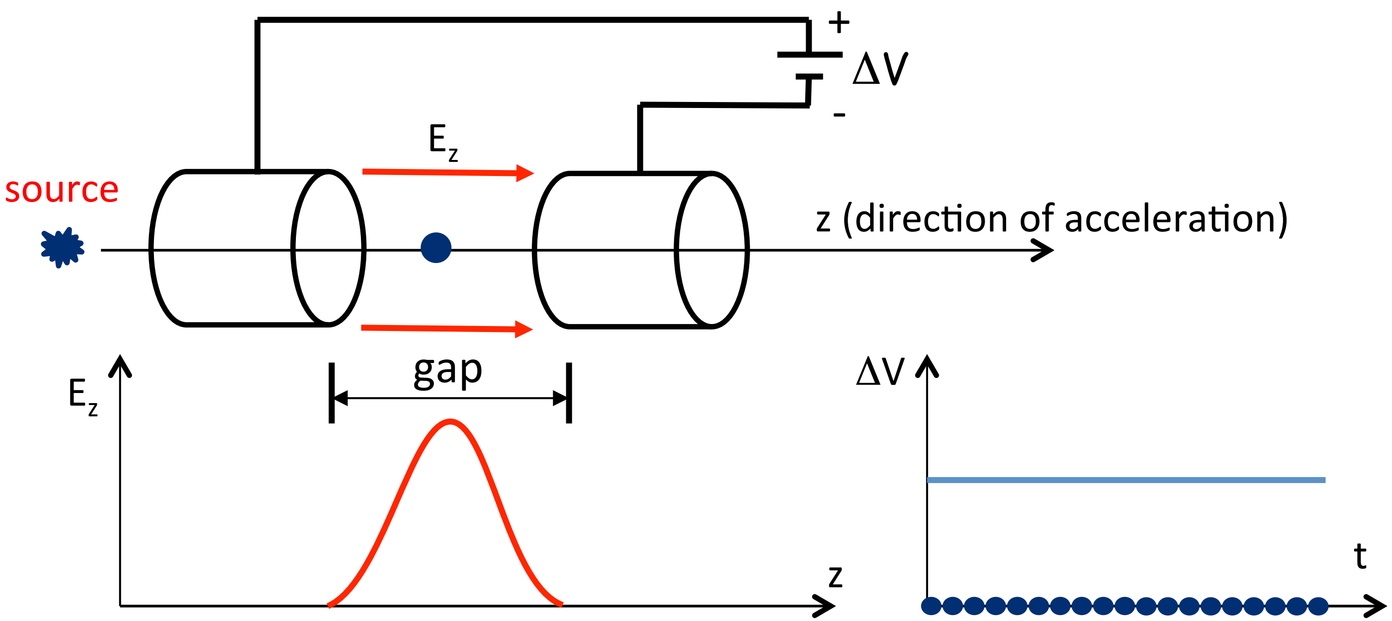
⇒The Wideroe LINAC is the **first RF LINAC**





ELECTROSTATIC ACCELERATION: CONTINUOUS BEAM

We consider the acceleration between two electrodes in DC.



$$E^2 = E_0^2 + p^2c^2 \Rightarrow 2EdE = 2pdpc^2 \Rightarrow dE = v\frac{mc^2}{E}dp \Rightarrow dE = vdp$$

$$\frac{dp}{dt} = qE_z \Rightarrow v\frac{dp}{dz} = qE_z \Rightarrow \boxed{\frac{dE}{dz} = qE_z} \quad \left(\text{and also}\ \frac{dW}{dz} = qE_z\right)$$

$W=E-E_0$

rate of energy gain per unit length

$$\Rightarrow \Delta E = \int_{gap} \frac{dE}{dz}dz = \int_{gap} qE_z \Rightarrow \boxed{\Delta E = q\Delta V}$$

energy gain per electrode

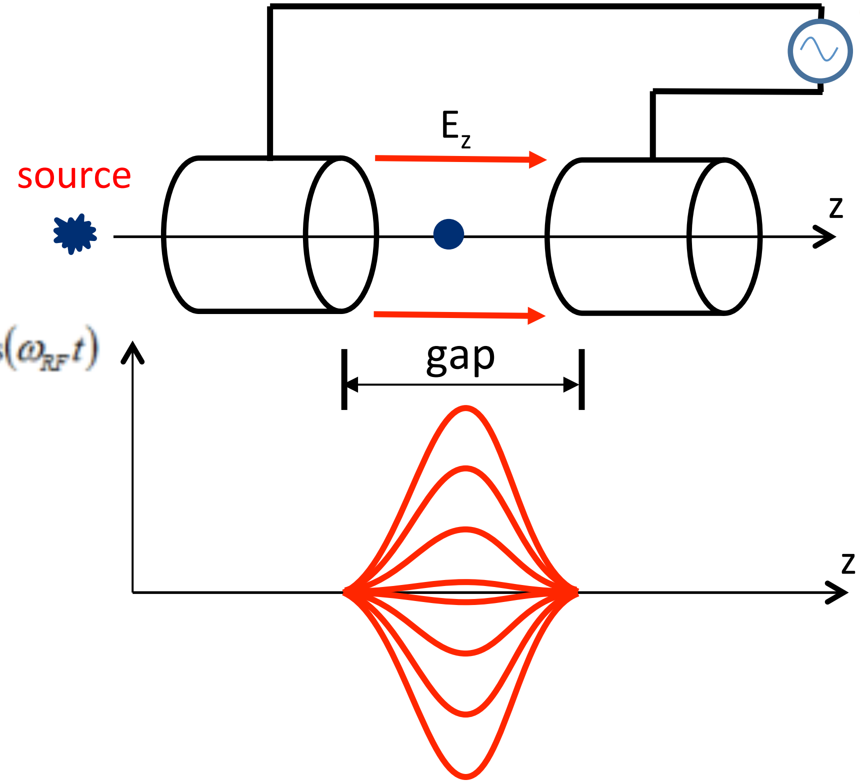
RF ACCELERATION: BUNCHED BEAM

We consider now the acceleration between two electrodes fed by an RF generator

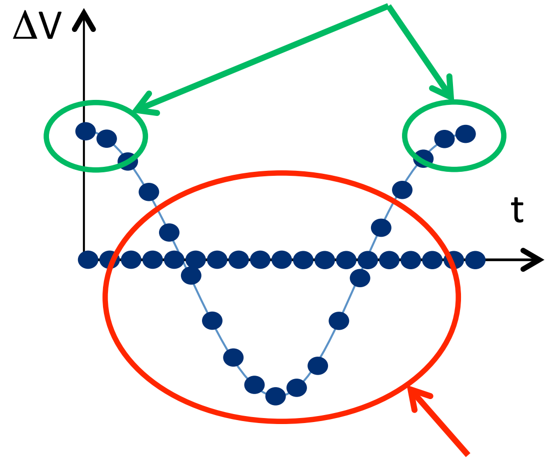
$$\Delta V = V_{RF}\cos(\omega_{RF}t) \qquad \omega_{RF} = 2\pi f_{RF} = \frac{2\pi}{T_{RF}}$$

$$\Rightarrow \Delta E = q\Delta V = qV_{RF}\cos(\omega_{RF}t)$$

$$E_z(z,t) = E_{RF}(z)\cos(\omega_{RF}t)$$

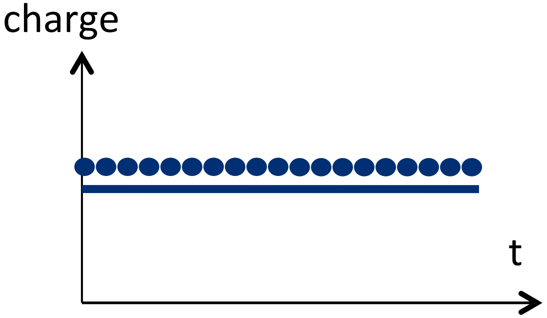


Only these particles are accelerated



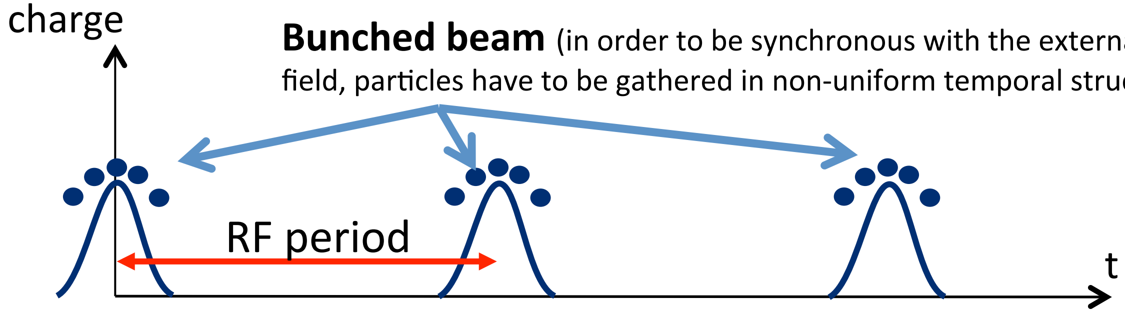
These particles are not accelerated and basically are lost during the acceleration process

DC acceleration



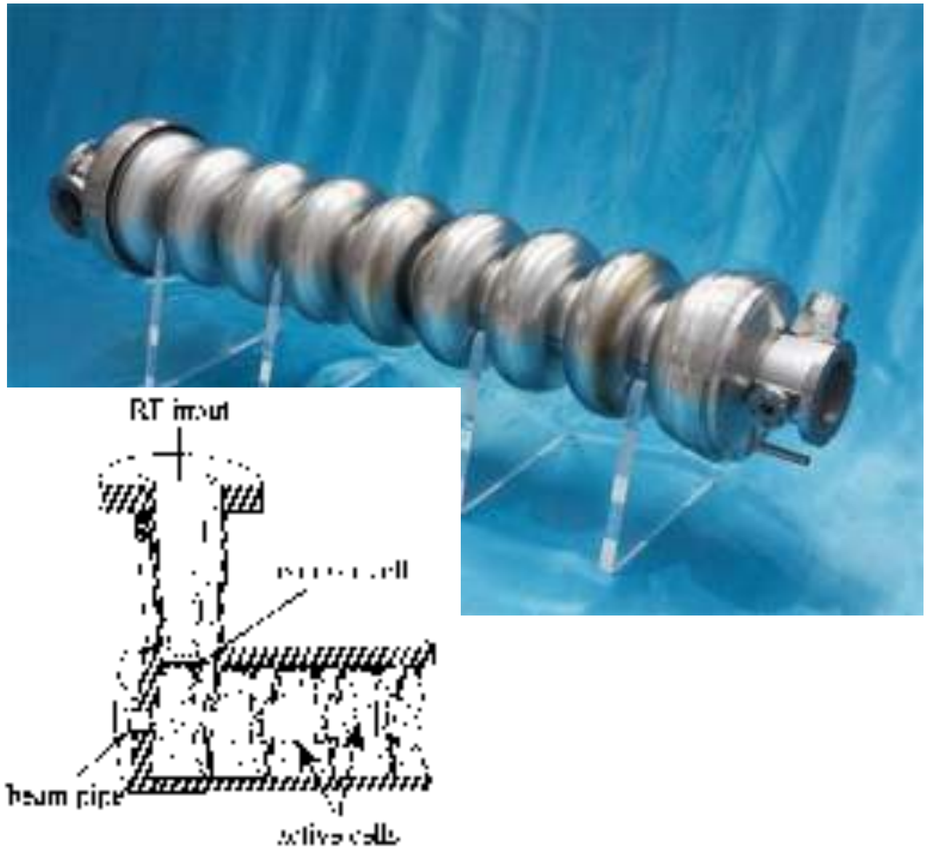
RF acceleration

Bunched beam (in order to be synchronous with the external AC field, particles have to be gathered in non-uniform temporal structure)

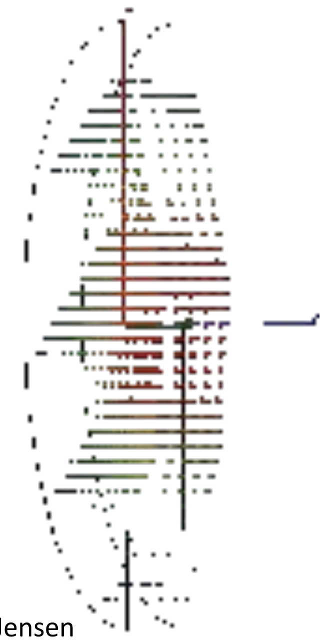


Cavità a Radiofrequenza

Nei LINACs le ***cavità risonanti*** sono quasi sempre raggruppate in ***strutture multicella***. Questa scelta è motivata da ragioni di ***economicità e compattezza***. In una struttura multicella un unico accoppiatore RF è sufficiente ad eccitare il campo. Questo implica l'uso di un numero ridotto di sorgenti di alta potenza RF, a beneficio della semplicità e dei costi dell'acceleratore. L'accoppiamento tra le celle si realizza attraverso **iridi** in ciascuna cella e/o attraverso aperture realizzate appositamente tra le celle (slots di accoppiamento).

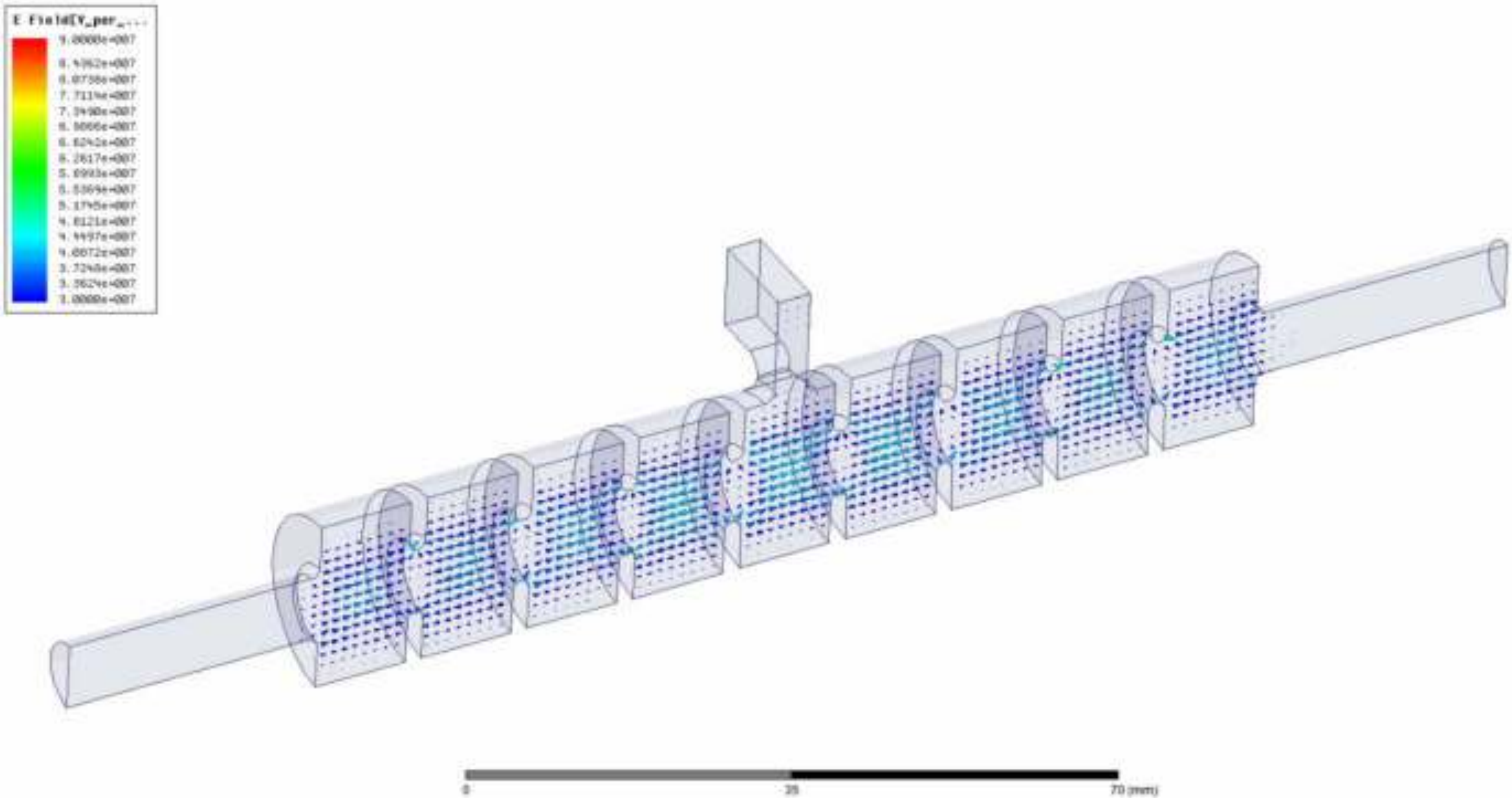


Esistono sia cavità che operano a ***temperatura ambiente*** (tipicamente in rame) che ***cavità superconduttive*** che operano a qualche K.
I ***gradienti acceleranti medi*** che si possono tipicamente ottenere sono dell'ordine di ***qualche 10 MV/m***. Tali gradienti possono arrivare anche a ***>100 MV/m.***



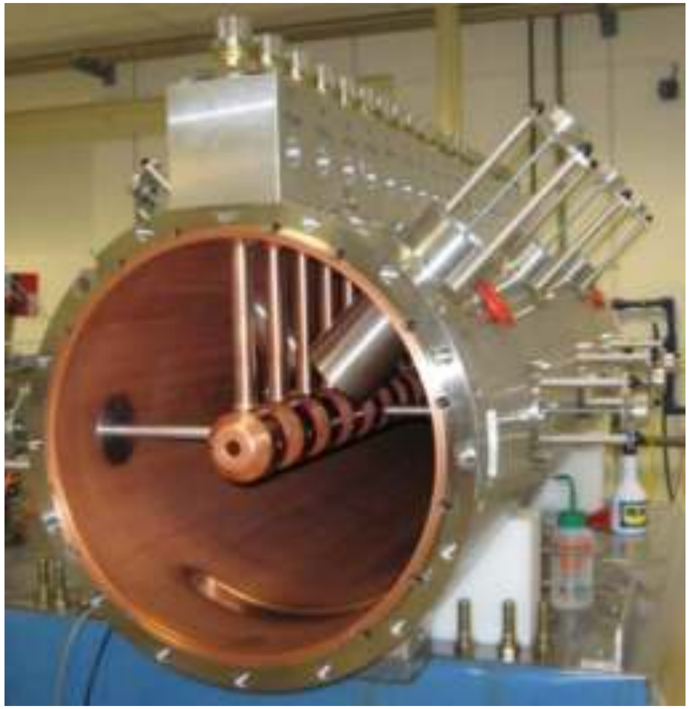
Courtesy E. Jensen

Le ***frequenze di lavoro*** possono andare dal MHz alla decina di GHz a seconda delle applicazioni

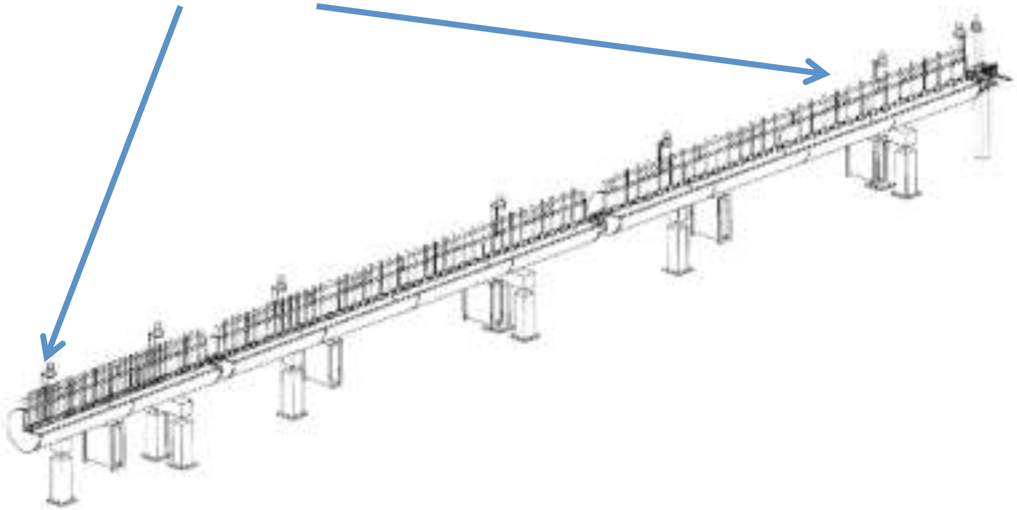

E Field[V_per_...
0
35
70 (mm)

ALVAREZ STRUCTURES: EXAMPLES

CERN LINAC 2 tank 1:
200 MHz 7 m x 3 tanks, 1 m diameter, final energy 50 MeV.



CERN LINAC 4: 352 MHz frequency, Tank diameter 500 mm, 3 resonators (tanks), Length 19 m, 120 Drift Tubes, Energy: 3 MeV to 50 MeV, β=0.08 to 0.31 → cell length from 68mm to 264mm.

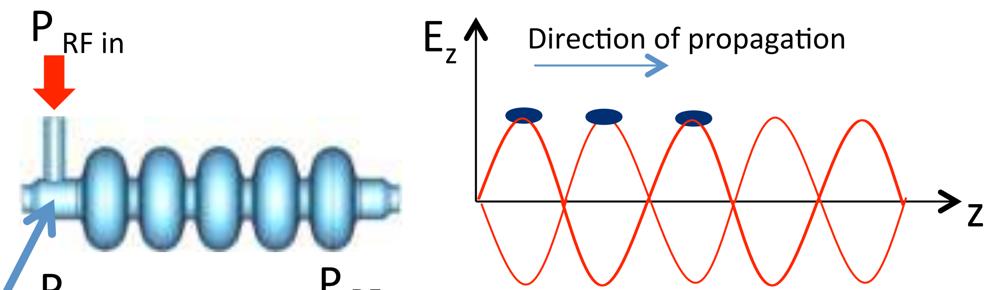


SW AND TW ACCELERATING CAVITIES

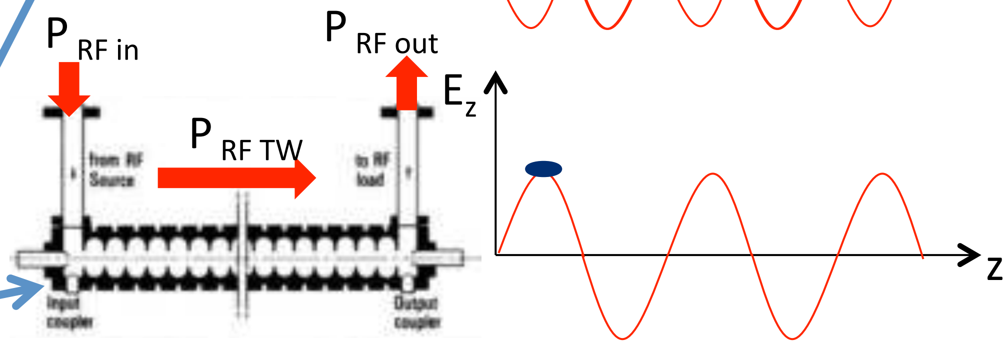
$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + v \times \vec{B}\right)$$

To accelerate charged particles, the RF wave must have an **electric field along the direction of propagation of the particle**. There are basically two possibilities:

1-Using **standing wave (SW)** TM010-like modes in a **resonant cavity** (or multiple resonant cavities) in which the beam is synchronous with the resonating field;



2-Using a **travelling wave (TW) disk loaded** structure operating on the TM01-like mode in which the RF wave is co-propagating with the beam with a phase velocity equal to the beam velocity (c for e^-).



⇒The structures are powered by RF generators (typically **klystrons**).

⇒The cavities (and the related LINAC technology) can be of different material:

- copper for **normal conducting (NC, typically TW)** cavities;
- Niobium for **superconducting cavities (SC, typically SW)**;

LORENTZ FORCE: ACCELERATION AND FOCUSING

Particles are accelerated through electric field and are bended and focalized through magnetic field.
The basic equation that describe the acceleration/bending /focusing processes is the **Lorentz Force**.

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

$\vec{p} = momentum$

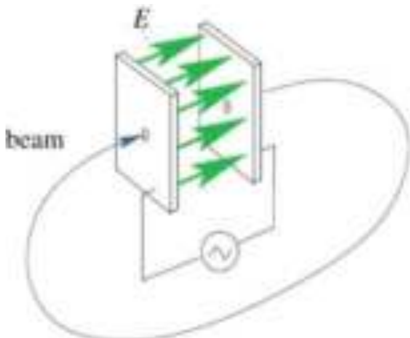
$m = mass$

$\vec{v} = velocity$

$q = charge$

ACCELERATION

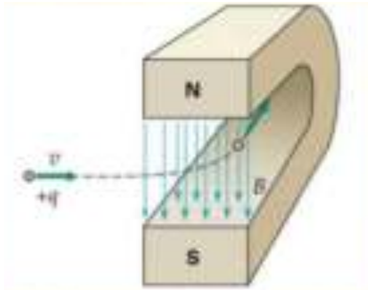
To accelerate, we need a force in the direction of motion

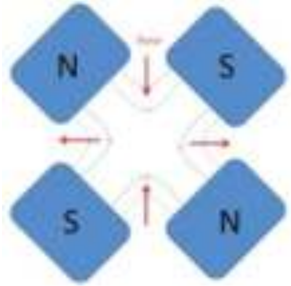


Longitudinal Dynamics

BENDING AND FOCUSING

2nd term always perpendicular to motion => no energy gain

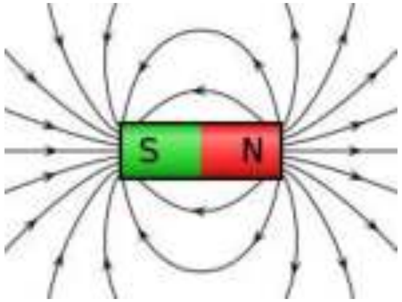


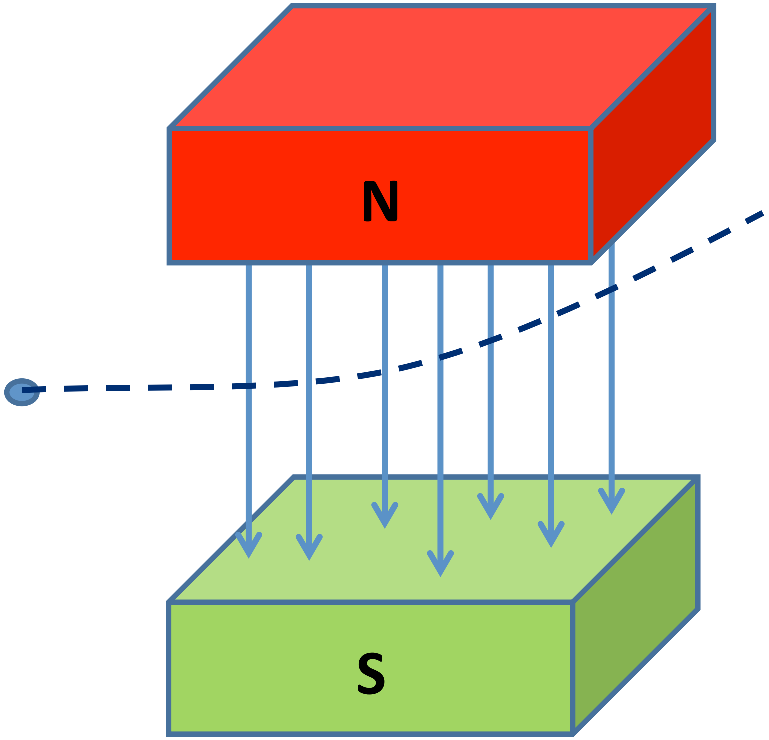


Transverse Dynamics

COME SI CURVANO LE PARTICELLE: CAMPI MAGNETICI

Per curvare le particelle si utilizzano campi magneti generati da magneti permanenti o elettromagneti





QUADRUPOLO

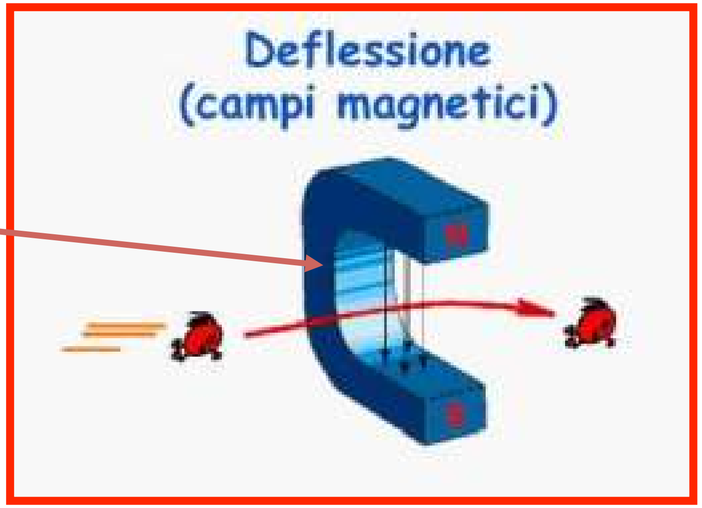
Quando una **particelle carica entra in un campo magnetico è soggetta ad una forza ortogonale alla velocità della particella e proporzionale al campo magnetico esercitato**.

Magneti dipolari sono utilizzati per curvare le particelle
Magneti quadrupolari per focalizzarle

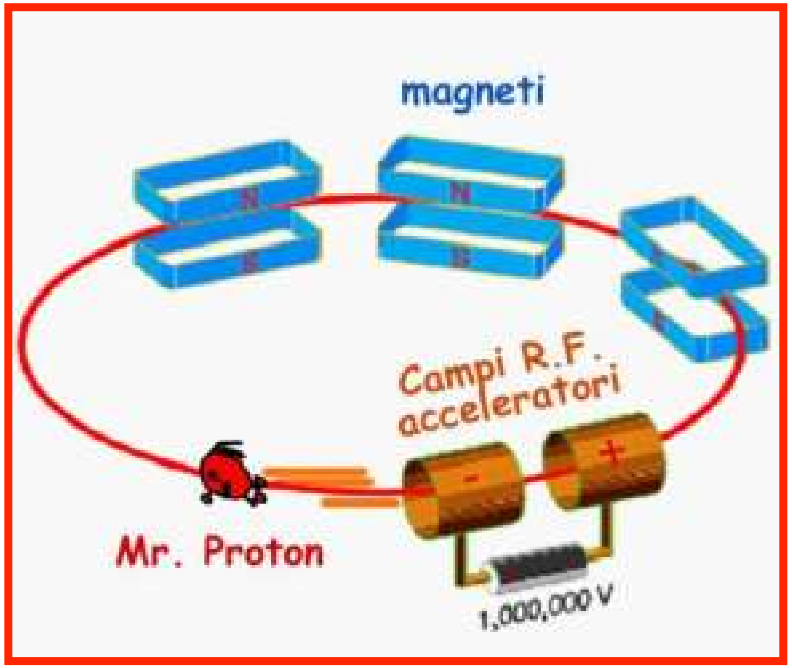
CAMPI MAGNETICI: DEFLESSIONE E FOCALIZZAZIONE

Con ***i campi magnetici è possibile far curvare le particelle cariche in movimento*** a velocità v ed è possibile focalizzarle per mantenerle confinate all'interno della camera da vuoto.

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



E. O. Lawrence (1930) ebbe l'idea di curvare le particelle su una traiettoria circolare, facendole ripassare molte volte nello stesso sistema accelerante

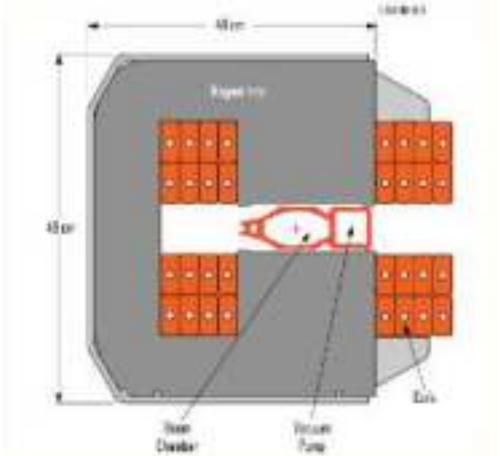


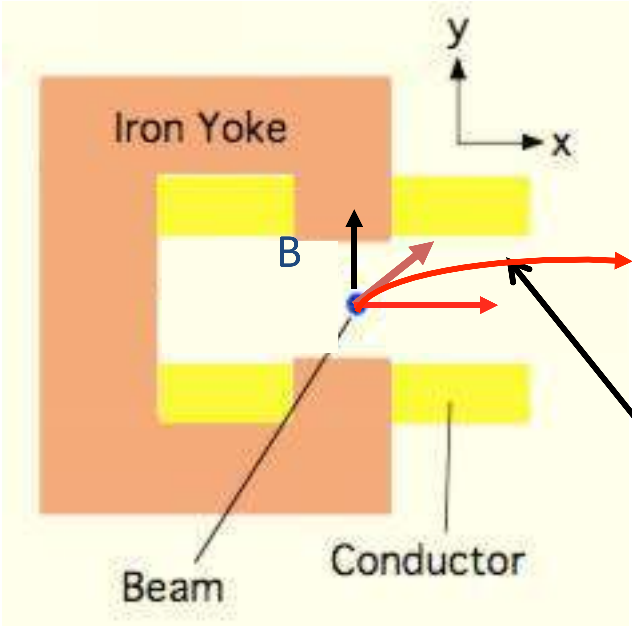
Particelle che viaggiano in un **acceleratore lineare attraversano una sola volta la struttura accelerante** mentre in un acceleratore **circolare attraversano più volte la stessa cavità**.

Ad ogni giro tali pacchetti acquistano energia grazie al campo elettrico accelerante (a radiofrequenza)

DIPOLI: DEFLESSIONE

Consentono di curvare la traiettoria delle particelle. Possono essere realizzati con **magneti permanenti** o **elettromagneti** (poli ferro con avvolgimenti percorsi da corrente).



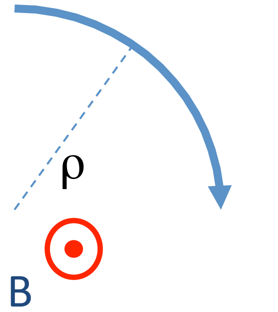


Traiettoria circolare

Raggio di curvatura

$$\rho[m] = \frac{p}{Bq} \cong \frac{W}{cqB}$$

Per particelle ultra-relativistiche

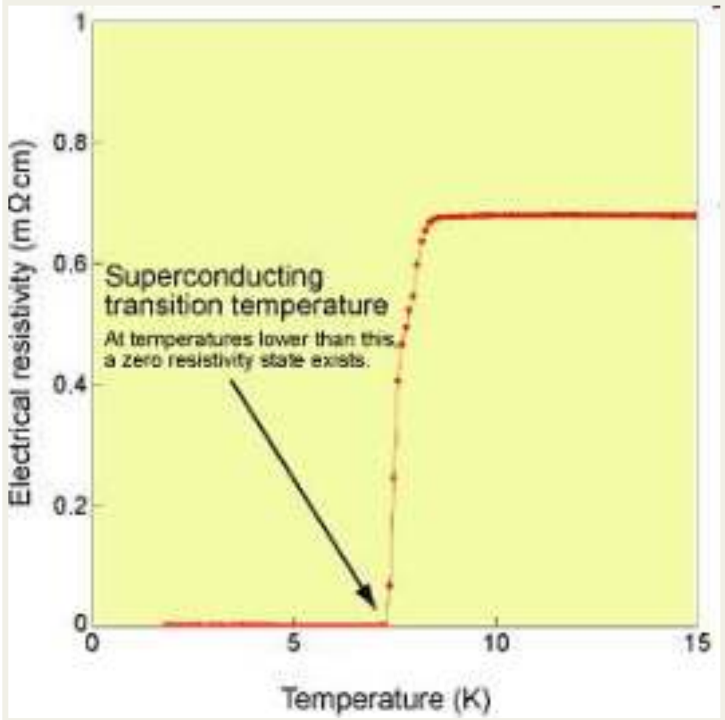


I dipoli elettromagnetici vengono usati per produrre B non oltre 1-2 T.
Per campi magnetici più intensi si ricorre a ***magneti superconduttori***

MATERIALI SUPERCONDUTTORI

I ***materiali superconduttori*** al di sotto di una certa temperatura (dell'ordine di qualche Kelvin) offrono una ***resistenza trascurabile*** al passaggio della corrente.

Possono essere usati per costruire cavità o magneti con generare B fino a 10 T

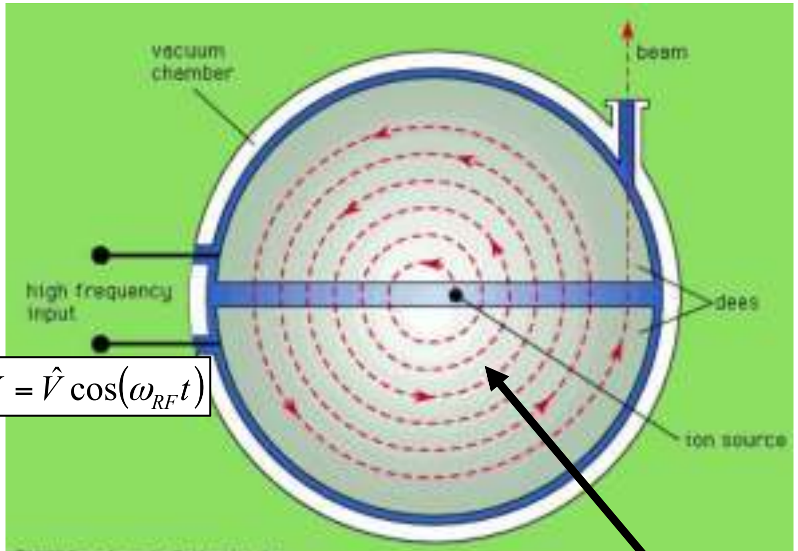


Basse temperature:2 Kelvin = -271° C

Tali temperature sono ottenute raffreddando i conduttori con un dispositivo frigorifero che usa ***He superfluido: il criostato***

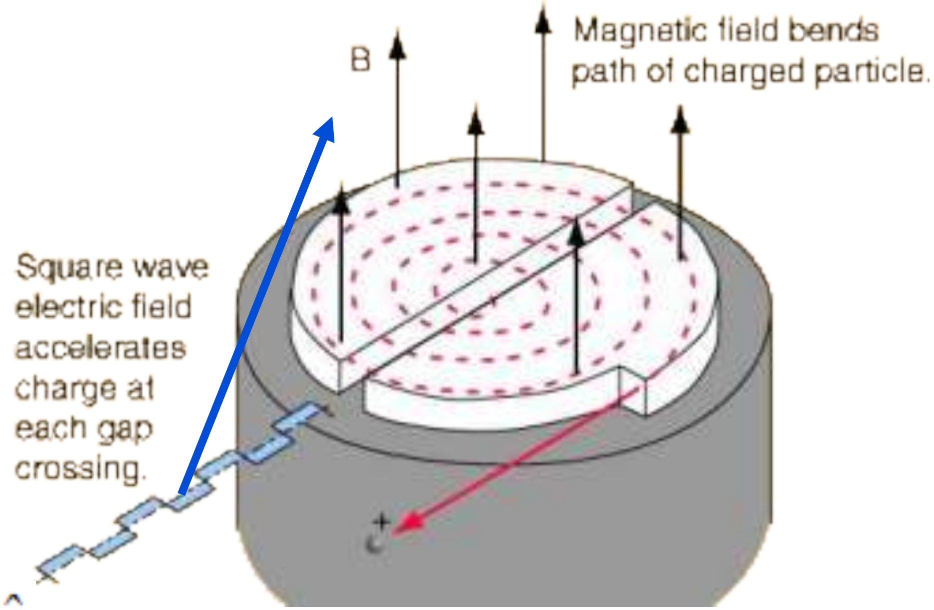
Ciclotroni (1/2)

Nei **ciclotroni l'accelerazione è realizzata tramite un *campo elettrico alternato*** tra due o più elettrodi immersi in un *campo magnetico dipolare costante* (E.O.Lawrence-1930)



$$V = \hat{V}\cos(\omega_{RF} t)$$

Traiettoria a spirale $\rho = \dfrac{mv}{qB}$



Ad ogni ***passaggio nel gap*** tra i due elettrodi le particelle ***guadagnano energia***.

$$\Delta E = q\hat{V}$$

Il ***sincronismo tra campo accelerante e particelle*** si mantiene se è soddisfatta la relazione:

$$f_{RF} = h f_{rev} = h\frac{qB}{2\pi m}$$

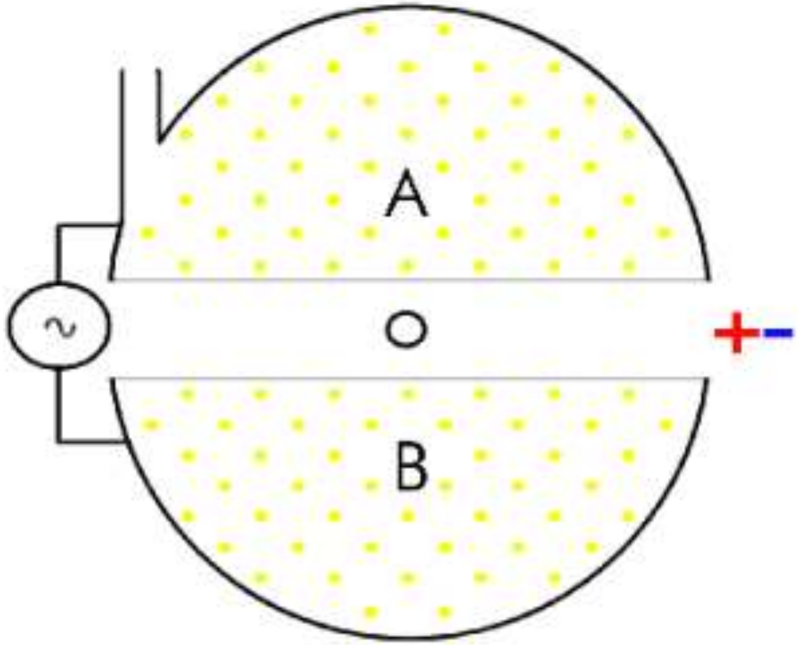
I ciclotroni standard hanno una ***f_{RF} costante*** e, quindi, tale sincronismo è mantenuto perfettamente solo nel caso di ***particelle non relativiche*** ($m=m_0$=costante)

Ciclotroni (2/2)

Il ***ciclotrone è stato progettato con l'intenzione di superare le limitazioni dell'acceleratore lineare***. All'epoca (1930) non era possibile generare onde radio contemporaneamente ad alta frequenza ed alta potenza, per cui gli stadi di accelerazione lineare (DTL) dovevano essere spaziati tra loro ed erano necessari più stadi (per compensare la limitata potenza). ***Per ottenere energie elevate era necessario costruire acceleratori lunghi*** e, oltre un certo limite, troppo costosi.

Poiché il ciclotrone accelera le particelle su un percorso circolare, è possibile ottenere lunghi percorsi in poco spazio e può essere alimentato con un ***unico e relativamente economico sistema elettronico***.

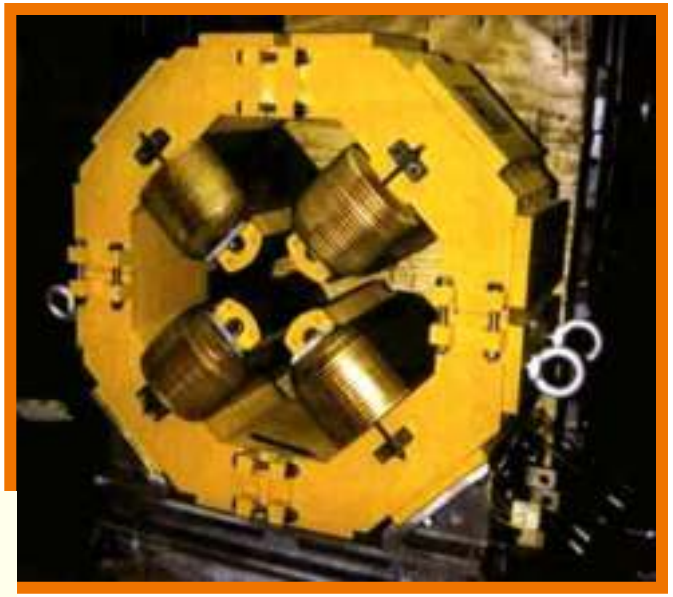
Nonostante i significativi miglioramenti raggiunti nel tempo, la struttura del dispositivo ne limita la convenienza economica per potenze molto elevate. Il problema principale è che per ottenere energie elevate è necessario ***incrementare il diametro della camera a vuoto e del magnete*** e dell'intensità del campo prodotto da questo. Trova comunque moltissime applicazioni nella prima ***accelerazione di ioni***.



https://youtu.be/cutKuFxeXmQ

QUADRUPOLO: FOCHEGGIAMENTO

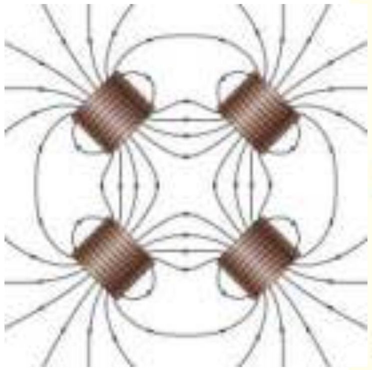
E' un magnete con **4 poli che focheggia le traiettorie delle singole particelle** così come fa una lente con la luce.

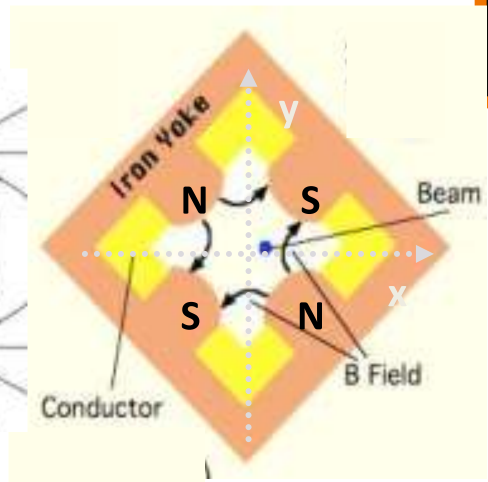


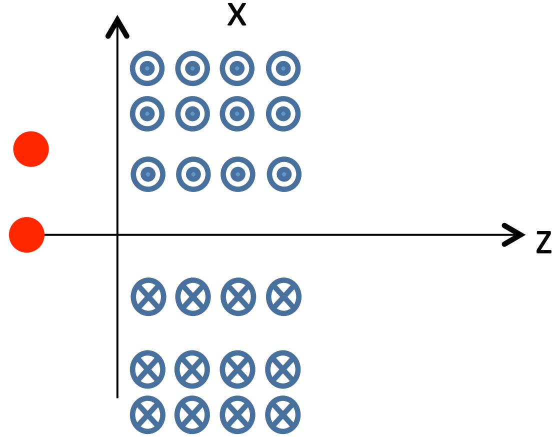
Caratteristiche di B

- B=0 al centro

- L'intensità di **B cresce linearmente** ed in maniera proporzionale allo spostamento rispetto all'asse di riferimento







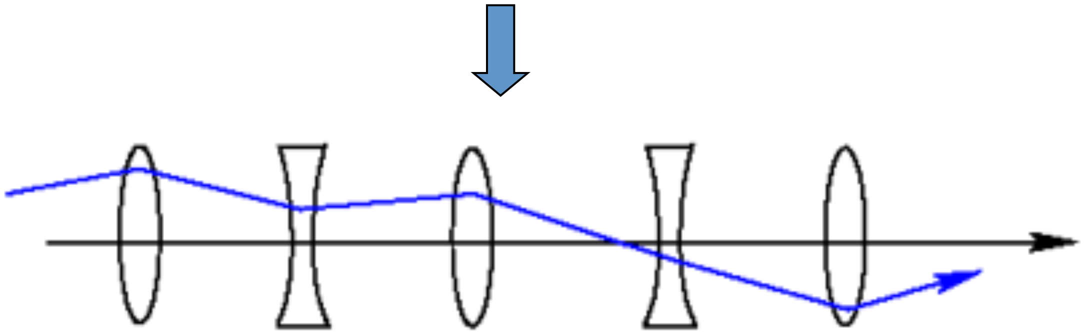
$$B_x = g \cdot y$$
$$B_y = g \cdot x \qquad g = \left[\frac{T}{m}\right]$$

FOCHEGGIAMENTO TRASVERSO: FUNZIONE Β

Un ***quadrupolo focheggia il fascio in un piano e lo defocheggia nell'altro***.

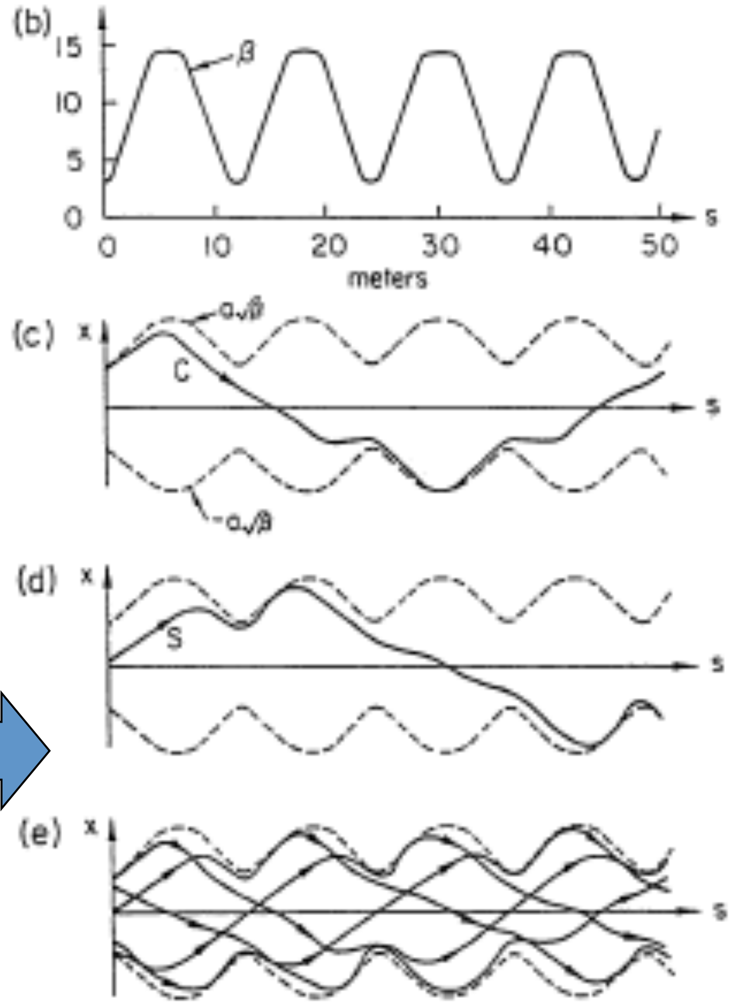
Per ottenere il ***focheggiamento complessivo*** di un fascio di particelle lungo un canale di trasporto o in un acceleratore circolare bisogna usare una ***sequenza di quadrupoli con il segno alternato***

Tale configurazione è in grado di garantire traiettorie stabili.

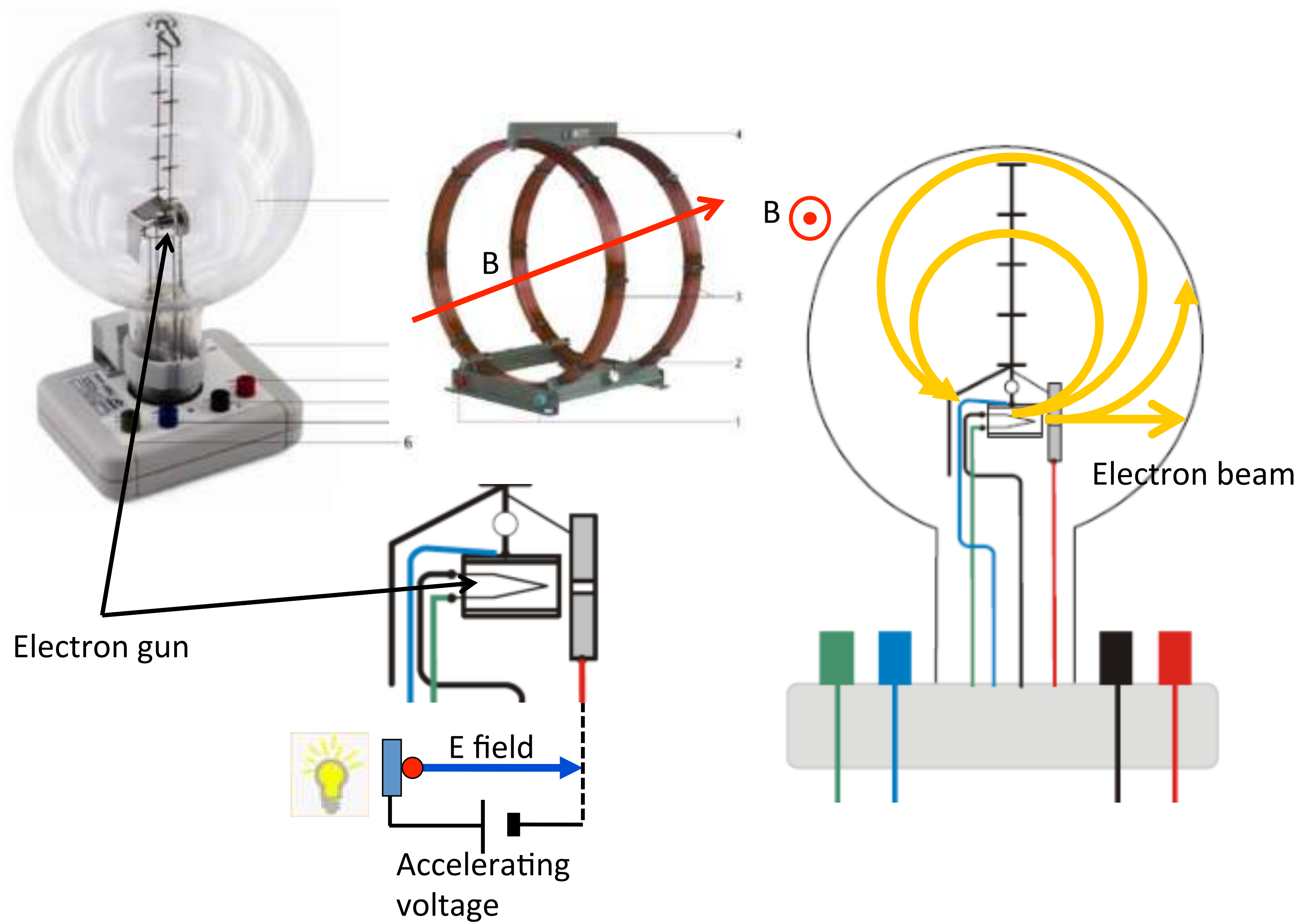


La ***traiettoria trasversa descritta da ogni particella*** è una pseudo-sinusoide.

L' inviluppo all'interno del quale sono confinate tutte le particelle del pacchetto è detto **funzione β**.



EXPERIMENT WITH e- BEAM



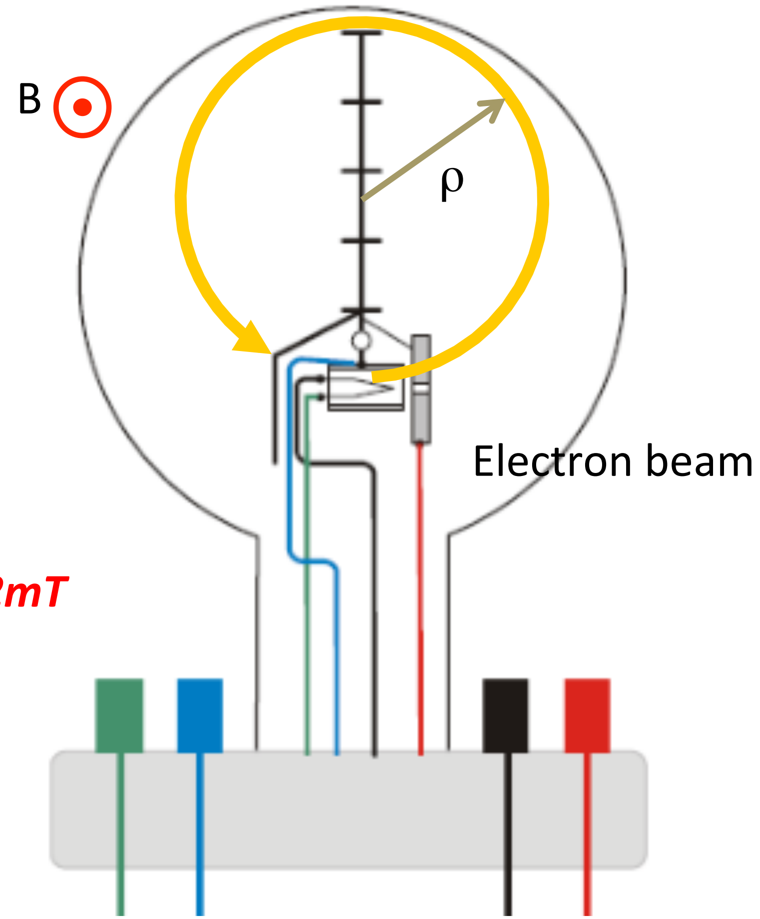
EXERCISE: CALCULATIONS

$$\Delta V = 300V$$

Acceleration: calculate the particle velocity

$$e\Delta V = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{2\frac{e}{m}\Delta V} \Rightarrow v = 10.27 \cdot 10^6 m/s$$

$$\beta = 0.034$$



Deflection: calculate the radius of curvature with B=2mT

$$B = 2 \cdot 10^{-3} T \Rightarrow \rho = \frac{mv}{Be} \cong 3cm$$

$$e = 1.6 \cdot 10^{-19} C$$

$$m = 9.1 \cdot 10^{-31} kg$$