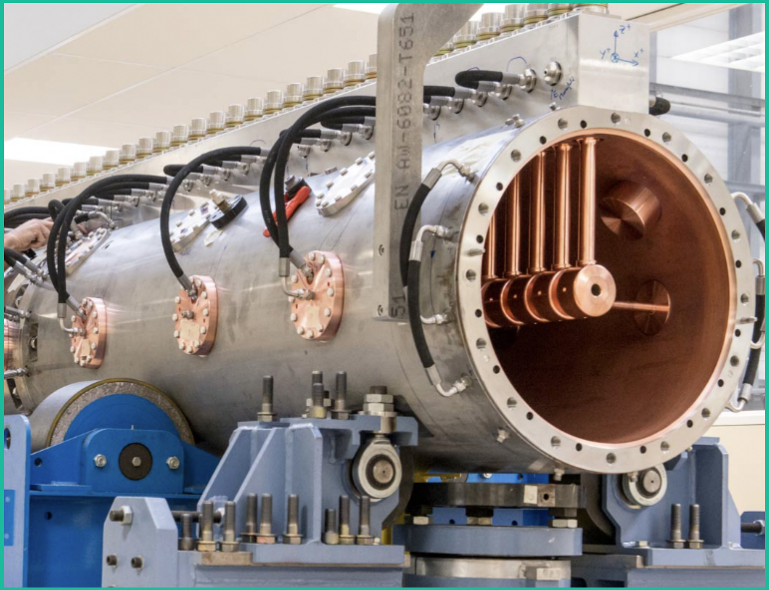

7: Accelerators

Yunsheng Dong

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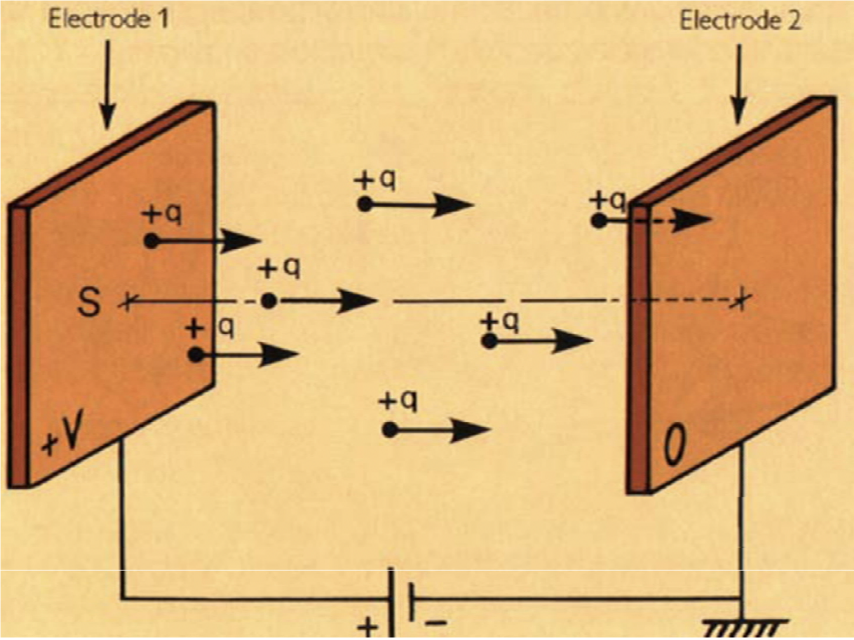
22/05/2024

Electrostatic accelerators

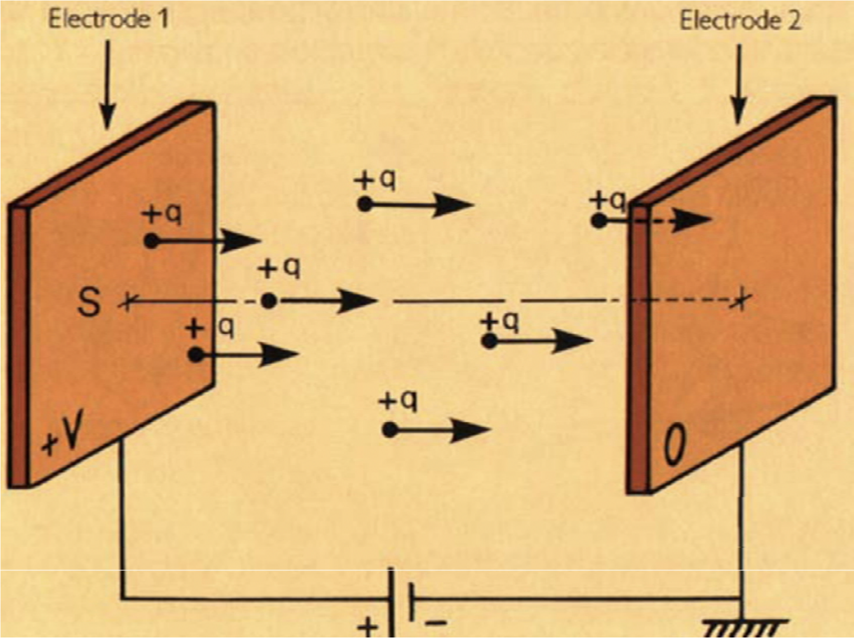


The easiest way to accelerate a charged particle (e.g.: an electron) is to use two electrodes and apply a differential potential

- The energy gain is in qV

Question:
How the energy gain is measured?
(the unit is…)

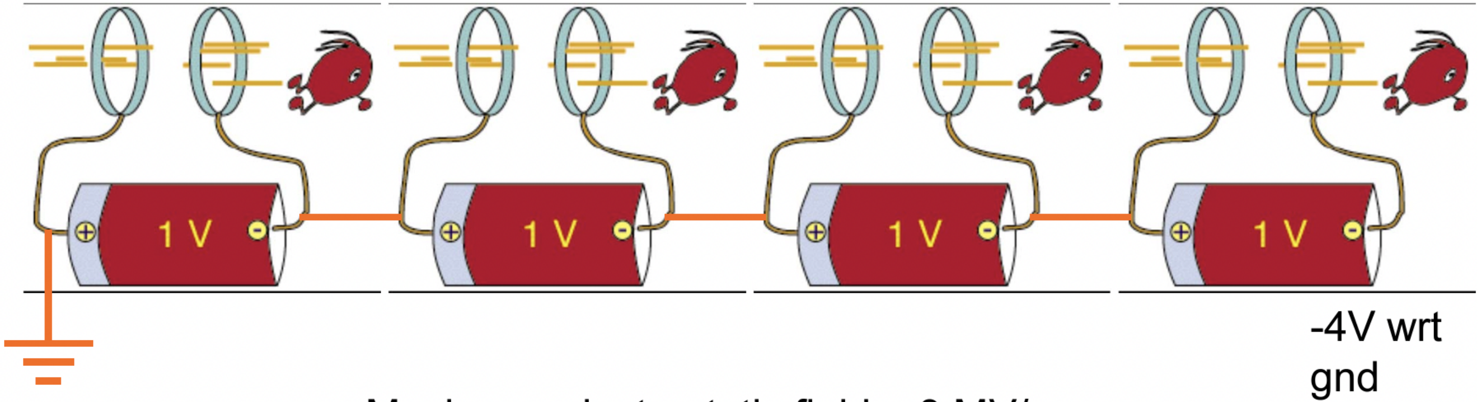
Electrostatic accelerators



The easiest way to accelerate a charged particle (e.g.: an electron) is to use two electrodes and apply a differential potential

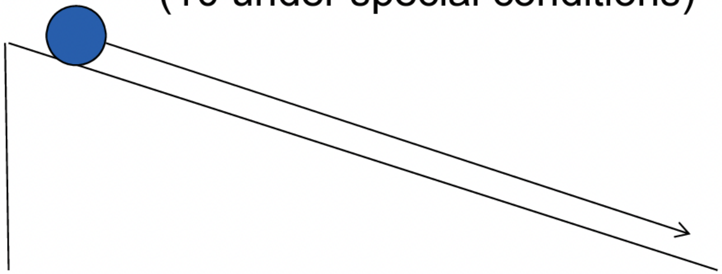
- The energy gain is in qV
- Measured in eV

Electrostatic accelerators

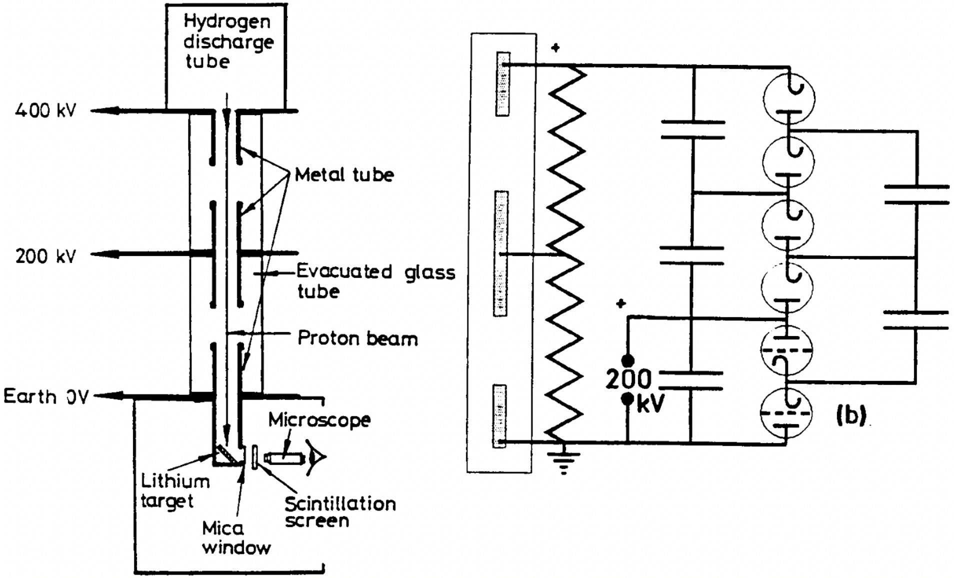


Maximum electrostatic field ~ 3 MV/m

(10 under special conditions)

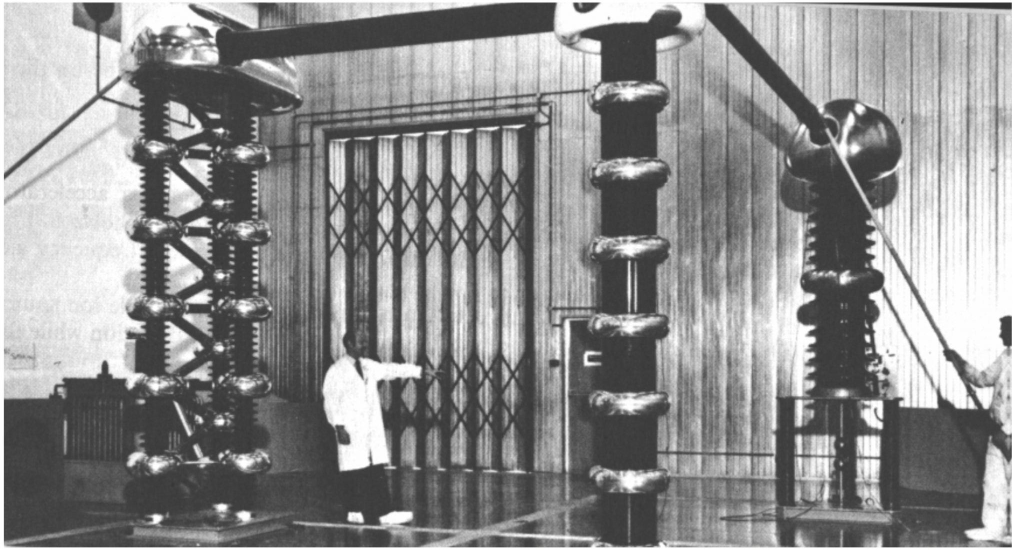


Crockcroft-Walton



(a) Accelerating column (b) DC generator

Fig. 1 Cockcroft and Walton's apparatus for splitting the lithium nucleus

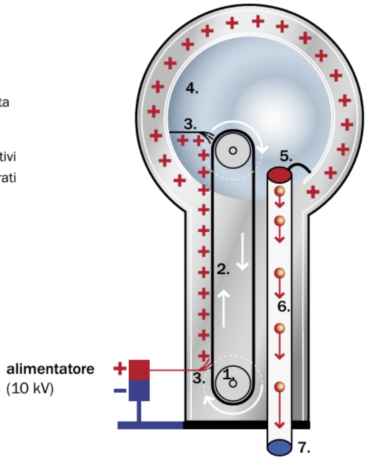


70 MeV Cockcroft-Walton generator supplying the ion source which injected protons into NIMROD, the 7 GeV synchrotron at Rutherford laboratory.

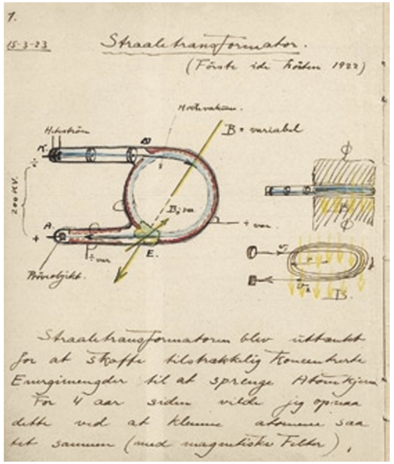
Van de Graaf

1. motore
2. cinghia isolante in movimento
3. pettini
4. cupola metallica elettricamente isolata che raccoglie le cariche positive
5. sorgente di ioni positivi
6. fascio di ioni accelerati
7. bersaglio

c.

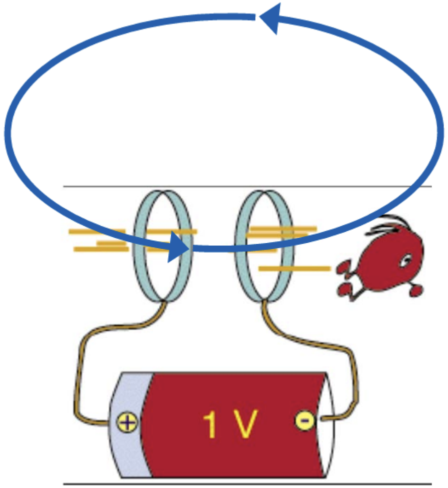


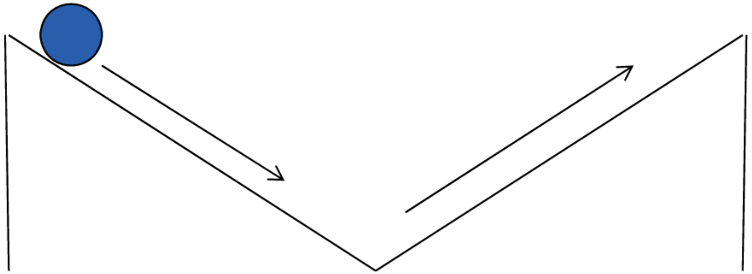
d.



Question:
Can I use/design a circular electrostatic accelerator?

Circular accelerators





The electrostatic field is conservative, thus a circular electrostatic accelerator DOES NOT WORK

Question:
How can I increase the energy? What are the pros and cons?

Resonant acceleration

$$\vec{E} = -\nabla\phi - \frac{\partial}{\partial t}\vec{A}$$

$$\vec{B} = \nabla \times \vec{A} \ .$$

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \ ,$$

1924: Ising proposed **time-varying fields** across drift tubes. This is a “**resonant acceleration**”, which can achieve energies above that given by the highest voltage system

1928: Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions

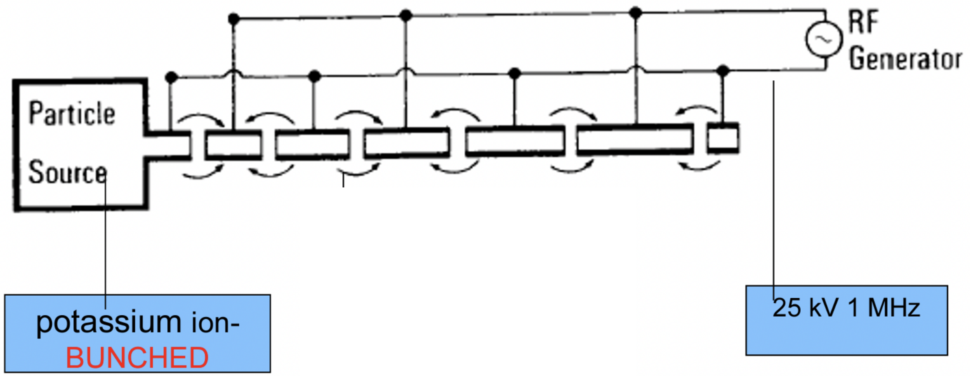
1929: Lawrence, inspired by Wideröe and Ising, conceives the cyclotron

1930: Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV

1932: Lawrence's cyclotron produces 1.25 MeV protons and he also splits the atom just a few weeks after Cockcroft and Walton (Lawrence received the Nobel Prize in 1939).

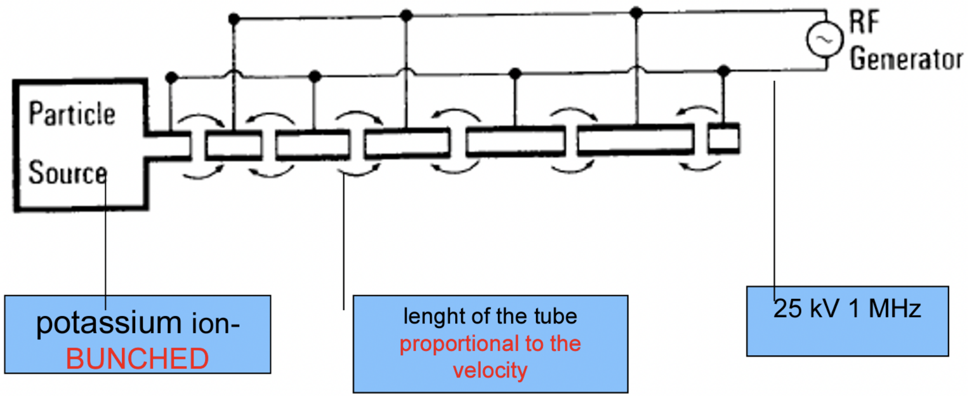
Resonant acceleration

- Alternate drift tubes are connected to the same terminal of an RF generator



Question:
Why are the drift tubes longer?

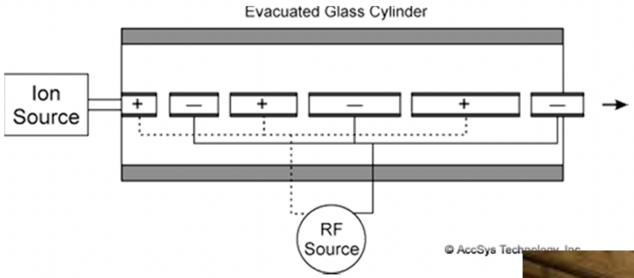
Resonant acceleration

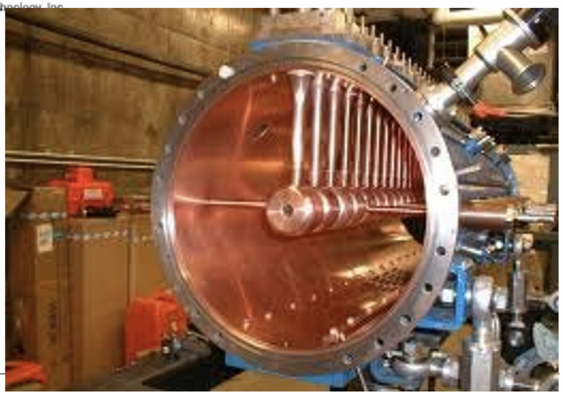


- Alternate drift tubes are connected to the same terminal of an RF generator
- The generator frequency is adjusted so that a particle traversing a gap sees an electric field in the direction of its motion
- As the particle gains energy and speed the structure periods must be made longer to maintain synchronism

Resonant acceleration

From Wideroe to Alvarez

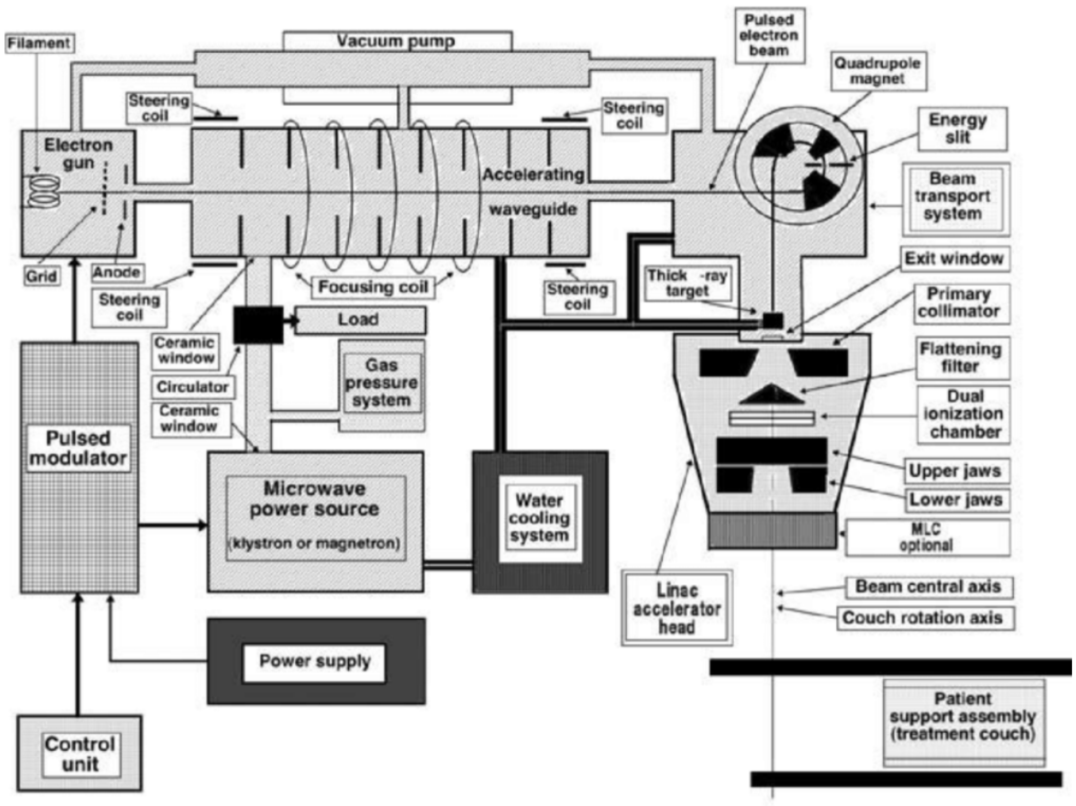




(courtesy of A Lombardi)

- As the velocity increases the drift tubes become inconveniently long
- One can increase the frequency, but at high frequencies the open drift-tube structure is lossy
- This problem is overcome by enclosing the structure to form a cavity or series of cavities at MHz range
- Ising principle is still applied to current accelerators
- Alvarez at University of California in 1955: 200 MHz 12 m long Drift Tube Linac accelerated protons from 4 to 32 MeV.

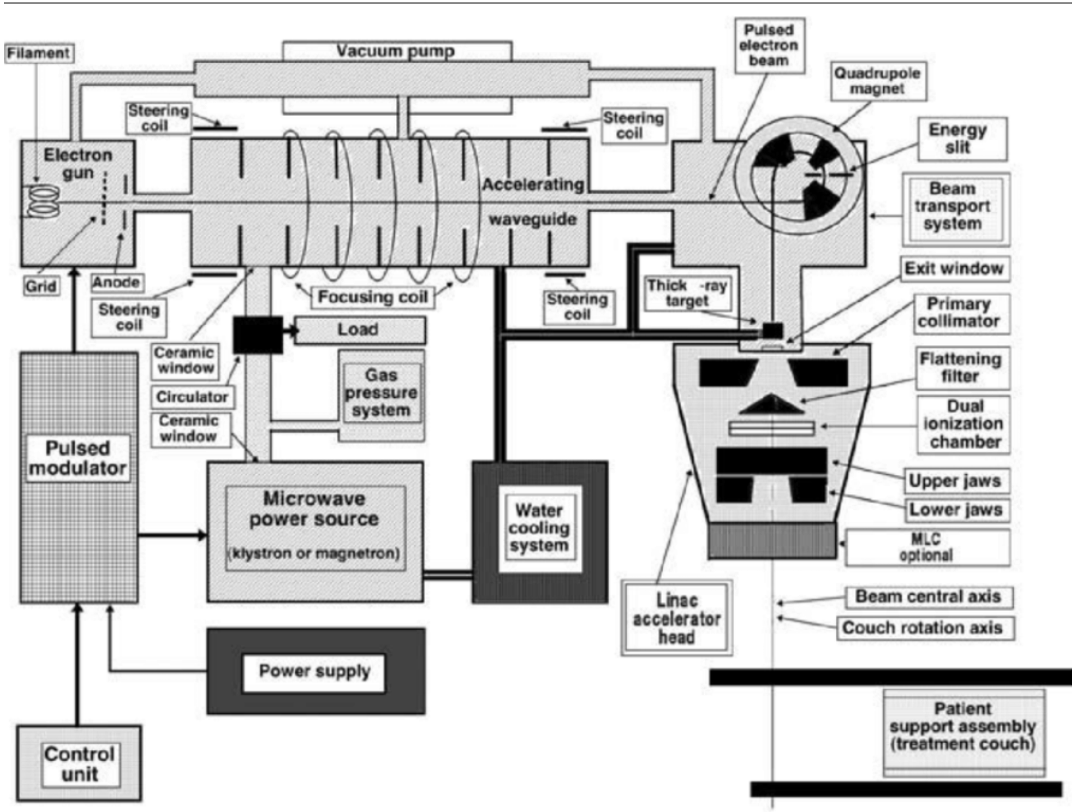
LINAC



LINAC main components:

- **Couch:** support the patient during the treatment, can be moved on XYZ axis
- **Accelerating Waveguide**: A series of microwave resonance cavities used to accelerate the electron beam
- **Bending Magnet**: a magnetic lens used to focus and position the beam
- **Circulator:** to prevent microwave energy from reflecting backwards to the Klystron/Magnetron
- **Cooling System:** water or air cooling system for the losses in microwave generation and acceleration
- **Electron Gun:** produces the electrons which are accelerated in the accelerating waveguide

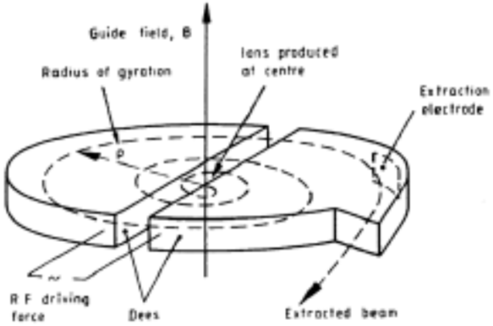
LINAC



- **Energy Selector**: may be placed within the bending magnet array to narrow the allowed electron energy range incident on the target
- **Klystron/Magnetron:** Klystrons and Magnetrons produce the microwave used to power the accelerating waveguide
- **Head:** components required for beam production and shaping including targets, scattering foils, beam shaping collimators and the optical distance indicator.
- **Waveguide**: The waveguide is a channel directing the microwave power from the Klystron/Magnetron to the Accelerating Waveguide

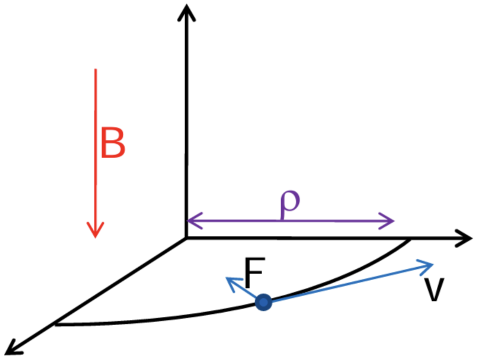
Circular accelerators

It was less than a foot in diameter and could accelerate protons to 1.25 MeV



Question:
How to “bend” charged particles?

Lorentz force and magnetic rigidity



$$F = q\,(E + v \times B)$$

$$qvB = \frac{mv^2}{\rho} \Rightarrow B\rho = \frac{p}{q}$$

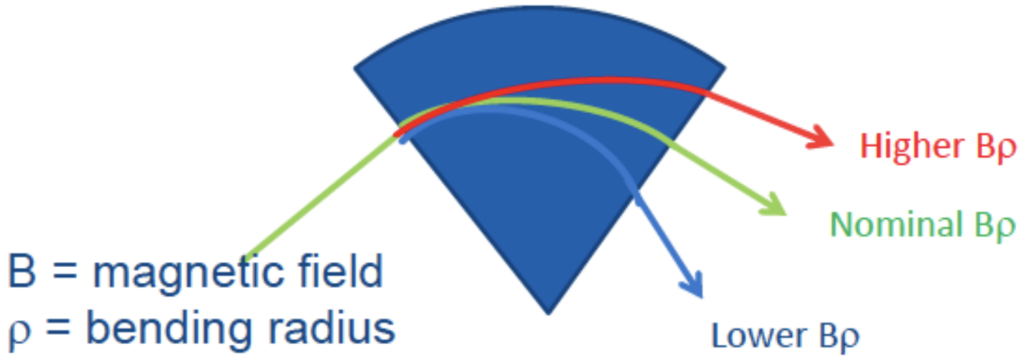
In practical units:

Magnetic rigidity
("Brho")

$$0.2998\, B\,[\mathrm{T}]\,\rho\,[\mathrm{m}] = p\,[\mathrm{GeV/c}]/q\,[\mathrm{e}]$$

↑

Lorentz force and magnetic rigidity



Example: 100 MeV proton

$\gamma = (m_0 c^2 + K)/m_0 c^2$ $\quad \beta = (1-1/\gamma^2)^{1/2}$ $\quad p = \beta \gamma m_0 c^2 / c$ $\quad B\rho = p/(0.2998\ q)$

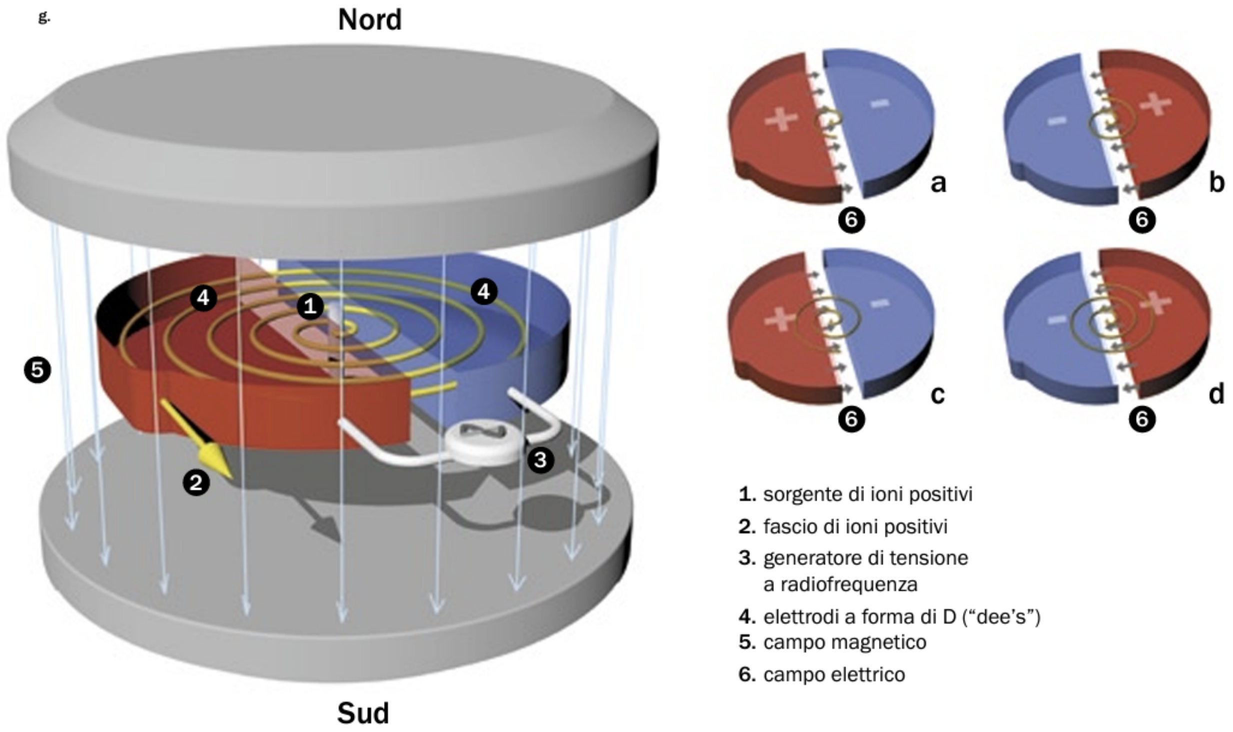
$\gamma = (938+100)/938 = 1.1$

$\beta = 0.43$

$p = 1.1*0.43*0.938 = 0.445$ GeV/c

$B\rho = 0.445/0.2998 = 1.48$ T m

Cyclotron



g.
Schema di funzionamento del ciclotrone. Partendo dalla sorgente posta al centro, un protone, che ha carica positiva, è attratto dal semidisco carico negativamente e viene invece respinto da quello carico positivamente. Entra così all’interno dell’elettrodo dove non vi è campo elettrico ma solo magnetico, e compie quindi una semicirconferenza. Il campo elettrico tra gli elettrodi nel frattempo evolve (essi sono alimentati da un generatore di tensione alternata che, in un semiperiodo, inverte la sua polarità): proprio nel momento in cui il protone ritorna nell’intercapedine, incontra un campo accelerante, subisce un’ulteriore accelerazione, e compie una seconda semicirconferenza con raggio maggiore; il processo si ripete finché il protone, dopo aver compiuto tutto il percorso a spirale, arriva in periferia e viene estratto con la massima energia.

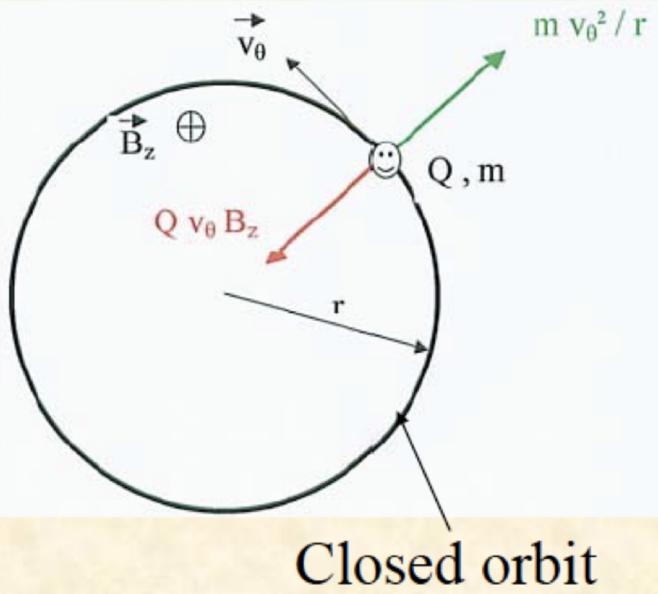
Asimmetrie, rivista dell’INFN, 6 aprile 2008

Cyclotron

- An ion (Q, m) with a speed v_θ, under an uniform magnetic field B_z, has a circle as trajectory with a radius r:

Centrifugal force=Magnetic force

$$\frac{mv_\theta^2}{r} = Qv_\theta B_z$$



- Angular velocity: $\omega_{rev} = \frac{d\theta}{dt} = \frac{v_\theta}{r} = \frac{QB_z}{m}$

(Larmor)

- The magnetic rigidity: $Br = \frac{P}{Q}$

Cyclotron

Classic cyclotrons means *non relativistic* cyclotrons

low energy ⇨ $\gamma \sim 1$ ⇨ $m / m_0 \sim 1$

In this domain $$\omega_{rev} = \frac{QB_z}{m} = const$$

We can apply between the Dees a RF accelerating voltage:

$$V = V_0 \cos \omega_{RF} t$$

with

$$\omega_{RF} = h\omega_{rev}$$

h = 1, 2, 3, … called the RF harmonic

Cyclotron

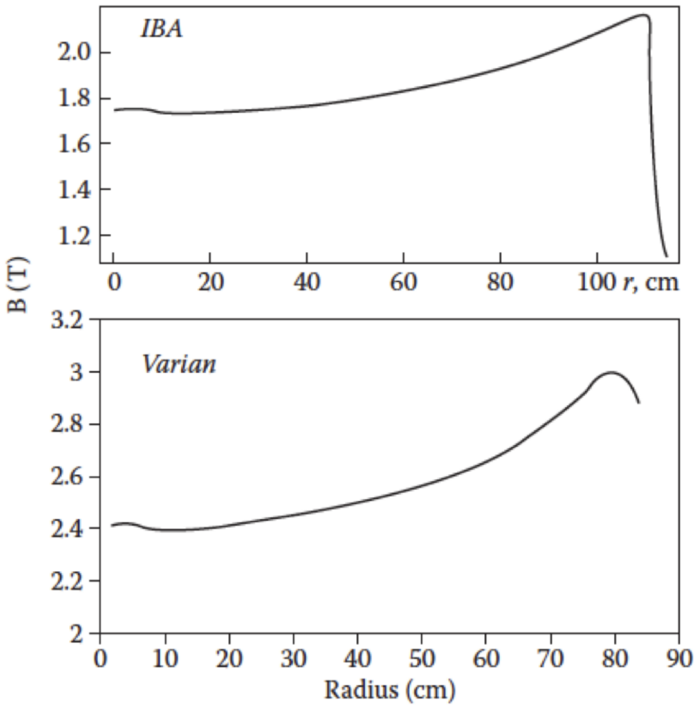
$$m = \gamma m_0 = \frac{m_0}{\sqrt{1-\beta^2}} \quad , \quad \beta = \frac{v}{c} \qquad \boxed{\omega_{rev} = \frac{QB(r)}{\gamma(r) m_0}}$$

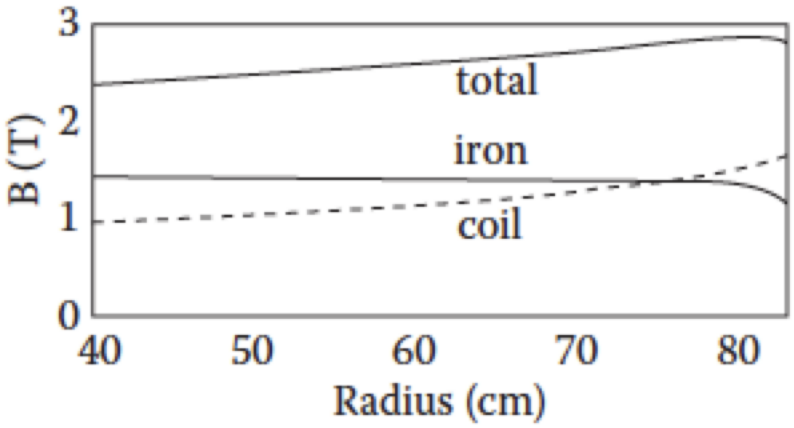
ω_{rev} constant if $B(r)=\gamma(r)B_0$

The revolution frequency decreases when the particle begins to be relativistic ($\gamma > 1$)

To keep synchronization, B(r) shall increase like $\gamma(r)$

B field in cyclotrons used in particle therapy



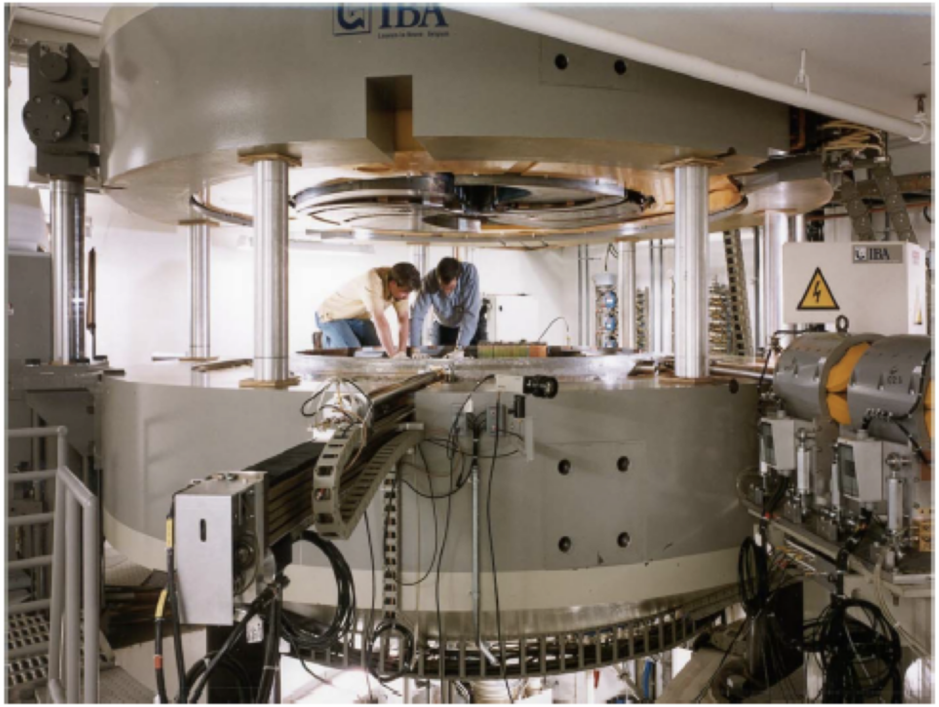


Modern cyclotrons

One of the limit of the classical, weak focussing cyclotron is that the isochronism is maintained at a given value of R

At present, cyclotrons are usually composed of different defocus-focus RF “dee” to improve the overall focusing

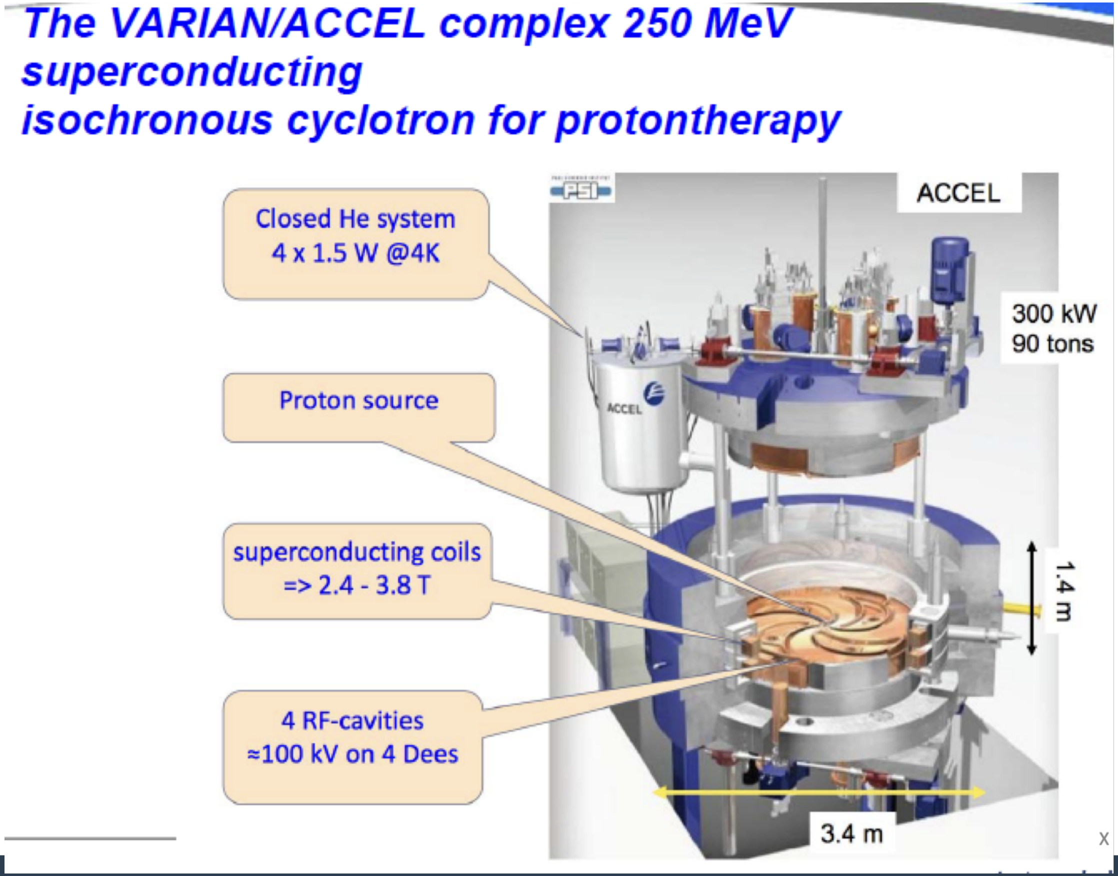
Modern cyclotrons



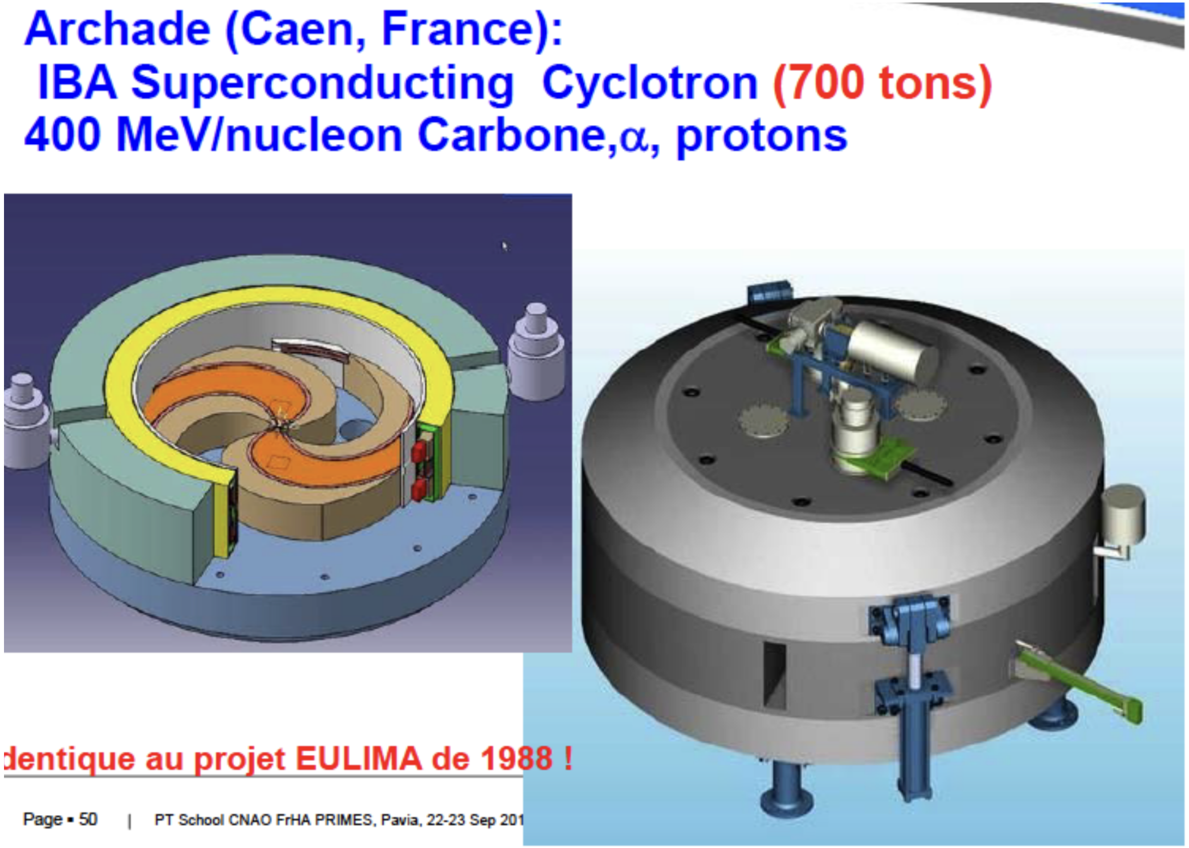
IBA
Varian
Sumitomo
ProNova
Etc…

The IBA 235 MeV
Room temperature
Cyclotron (230 tons)

Modern cyclotrons



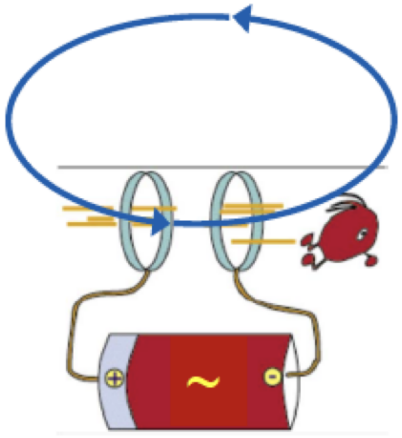
Modern cyclotrons



Question:
Can I reach TeV with a cyclotron?

Synchrotron

The synchrotron (McMillan 1944)

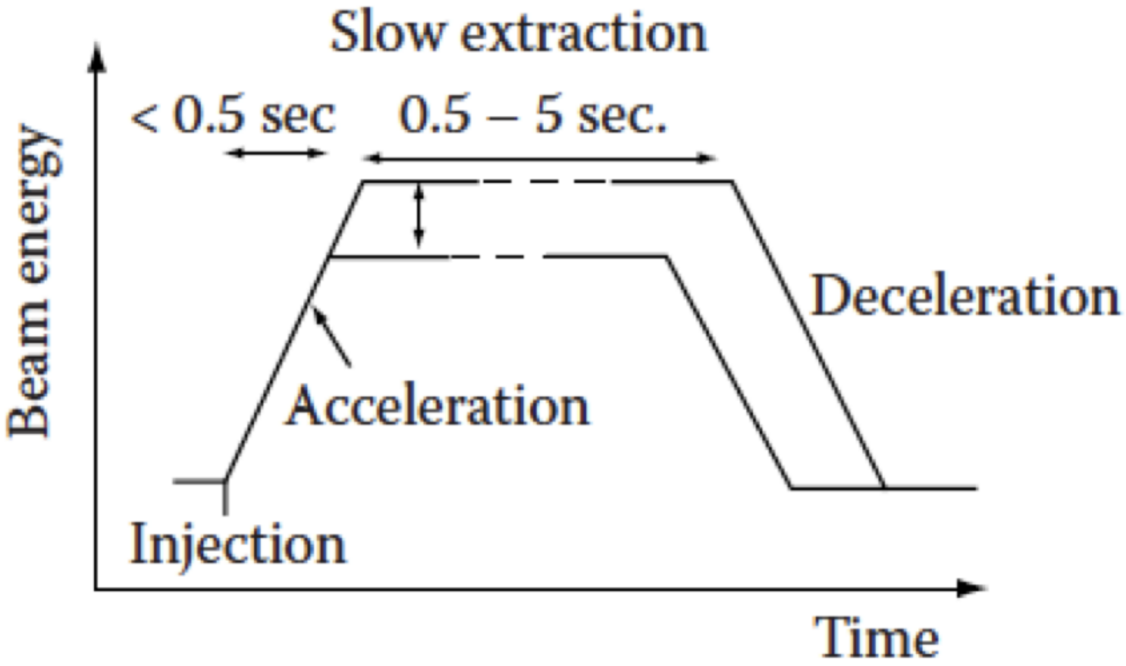


The “old” idea of a circular accelerator works if RF acceleration is used instead of the electrostatic one. In order to keep the particles on the Same track, B has to increase when energy increases. Furthermore Synchronism must be kept between accelerating field and particles

$$\omega_{RF} = h\,\omega_{rev}$$

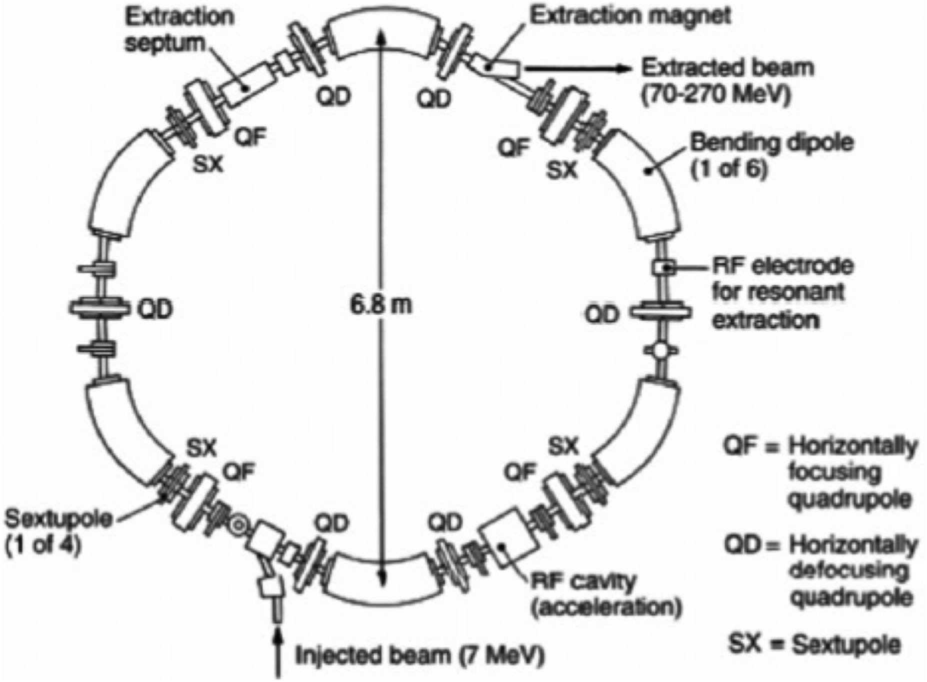
Question:
What is one of the main difference between cyclotrons and synchrotrons in terms of beam properties?

Synchrotron spill

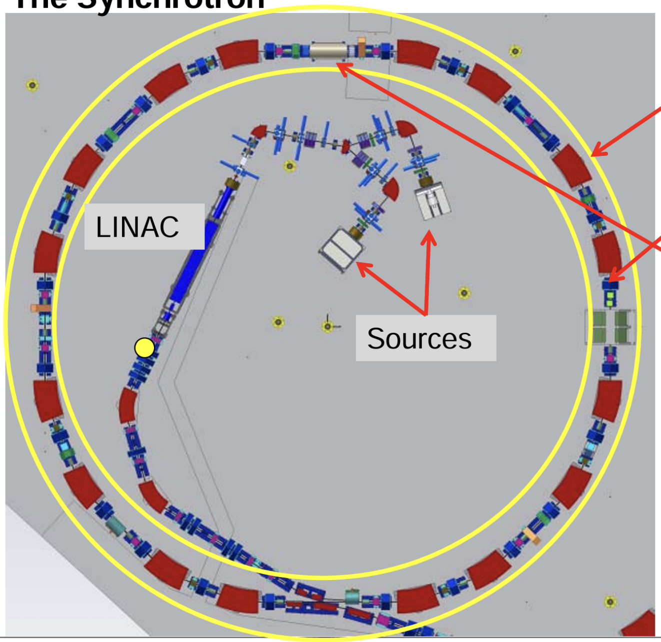


Question:
What is the geometry of a synchrotron?

Synchrotron main components



The Synchrotron



Dipoles (bending)

Quadrupoles (focussing, 100 000 km!)

Vacuum

RF Cavity (acceleration)

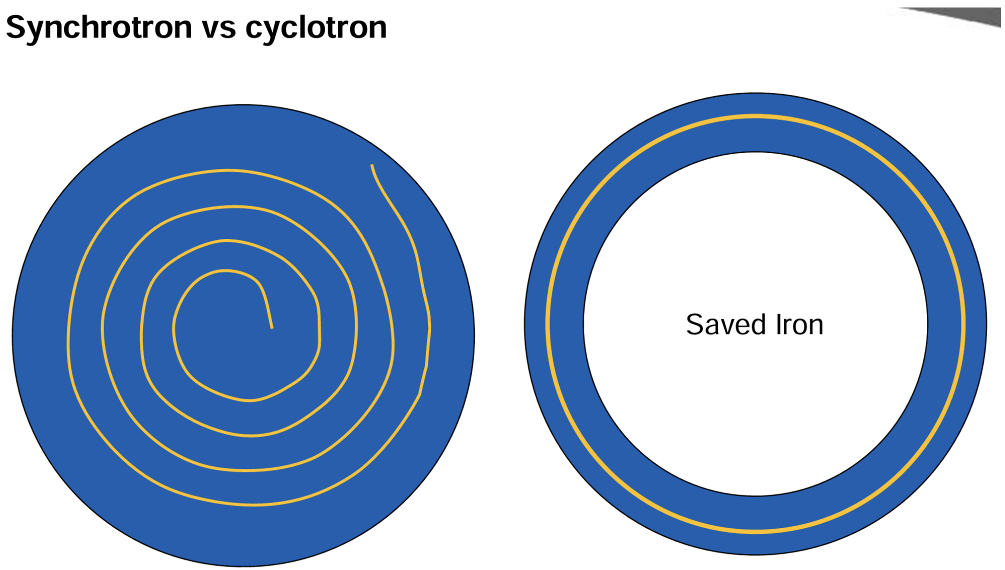
R fixed

E increases

F increases

B increases

Synchrotron vs cyclotron



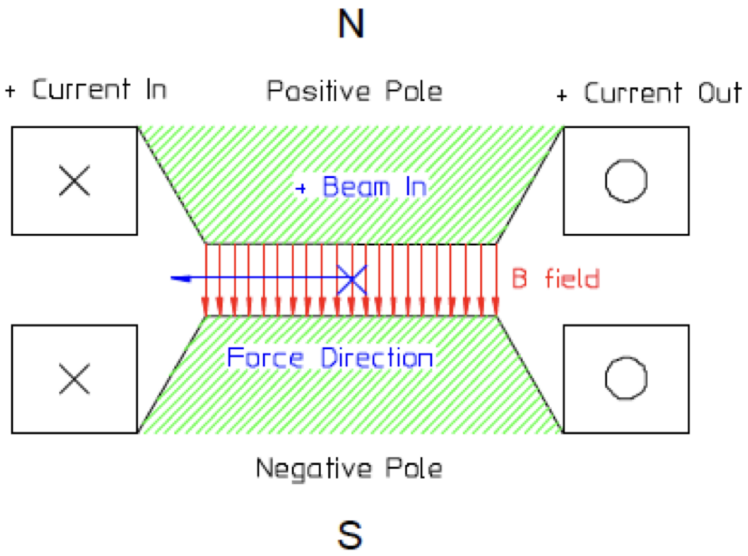
Main differences:

- Cyclotrons accelerate particle with Dees, while synchrotron use RF cavities
- Cyclotrons can send continuous beam, but with fixed extraction energy
- Synchrotrons need injection and extraction systems
- Typically, synchrotrons are bigger and they cost much more than cyclotrons
- Synchrotrons are suitable to accelerate heavy particles at high energy
- Synchrotrons are more “flexible” in terms of energy range and sources
- Cyclotrons used for particle therapy and production of medical isotopes

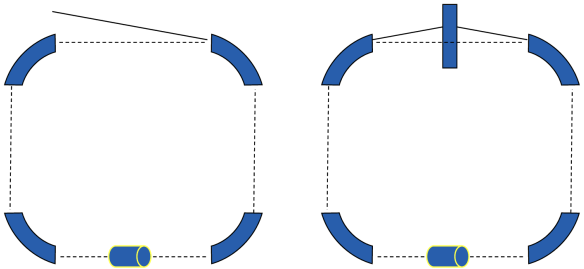
Dipoles

Dipole

Dipoles are used to deflect the beam. They define the shape of beam lines and accelerators.

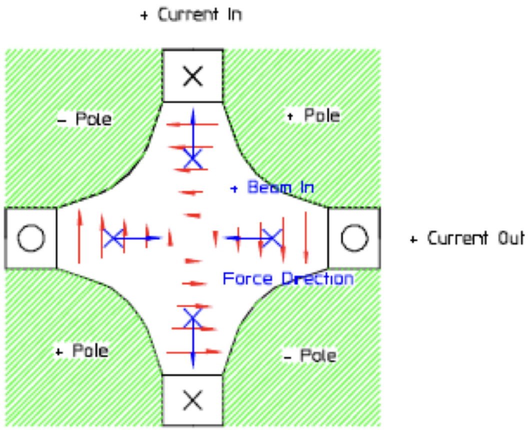


Quadrupole



Quadrupole

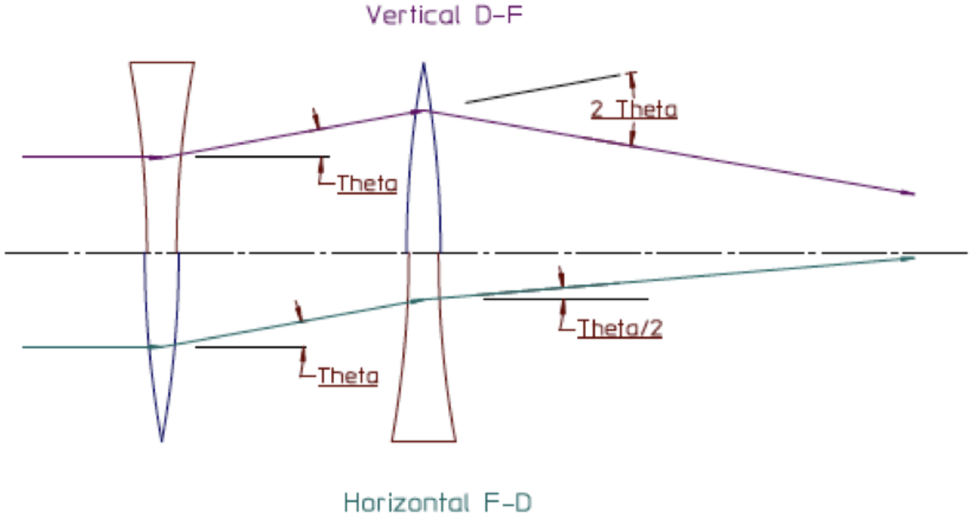
Quadrupoles are used to focus the beam.
The field varies linearly with the distance from the magnet center.
It focuses the beam along one plane while defocusing the beam along the orthogonal plane.



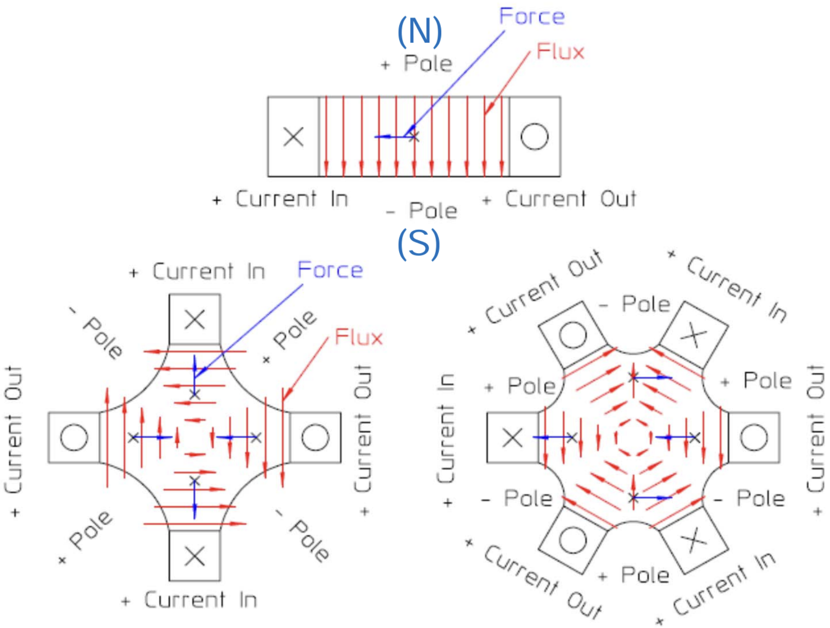
Quadrupole

Strong focusing

A series of F-D or D-F magnets will focus the beam in both planes.

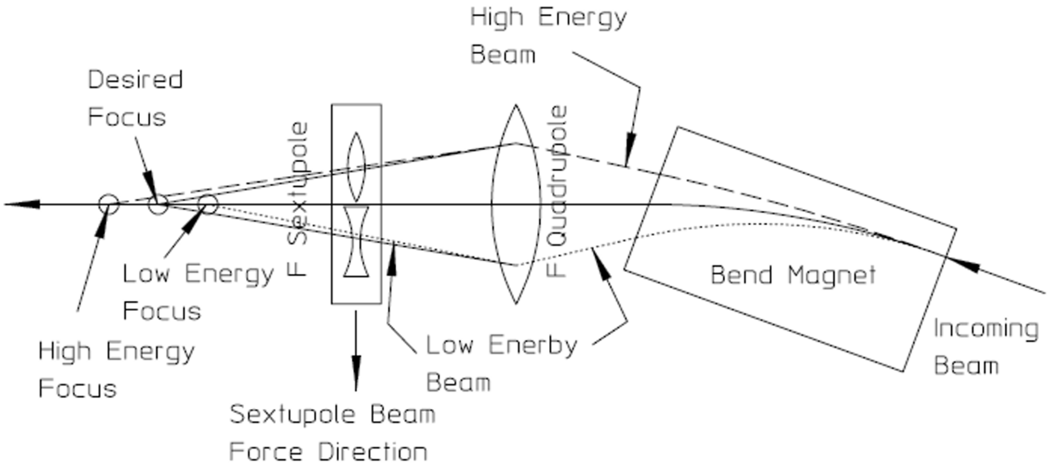


Sextupoles



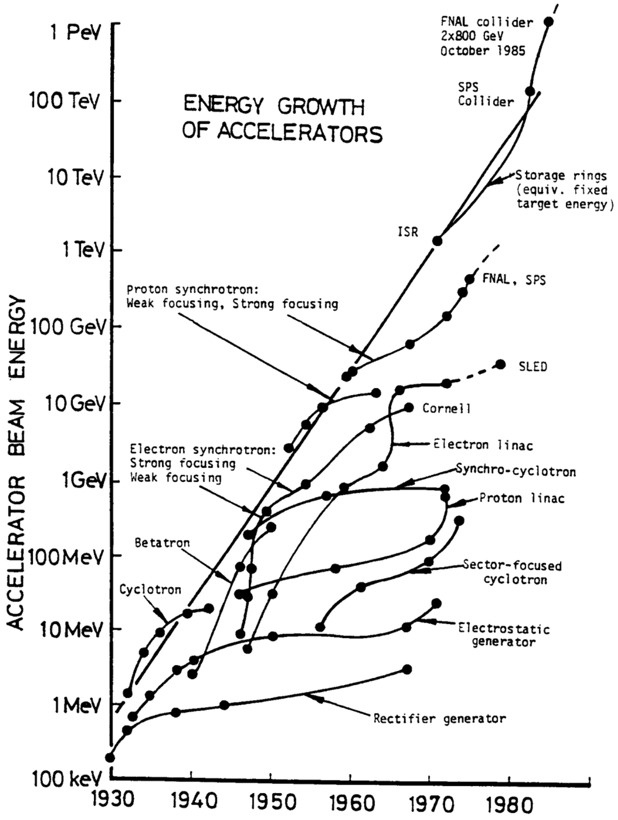
- Dipoles to define the ideal path
- Quadrupoles to keep particles near the ideal path
- Sextupoles to correct Chromatic (momentum) effects

Overall focusing

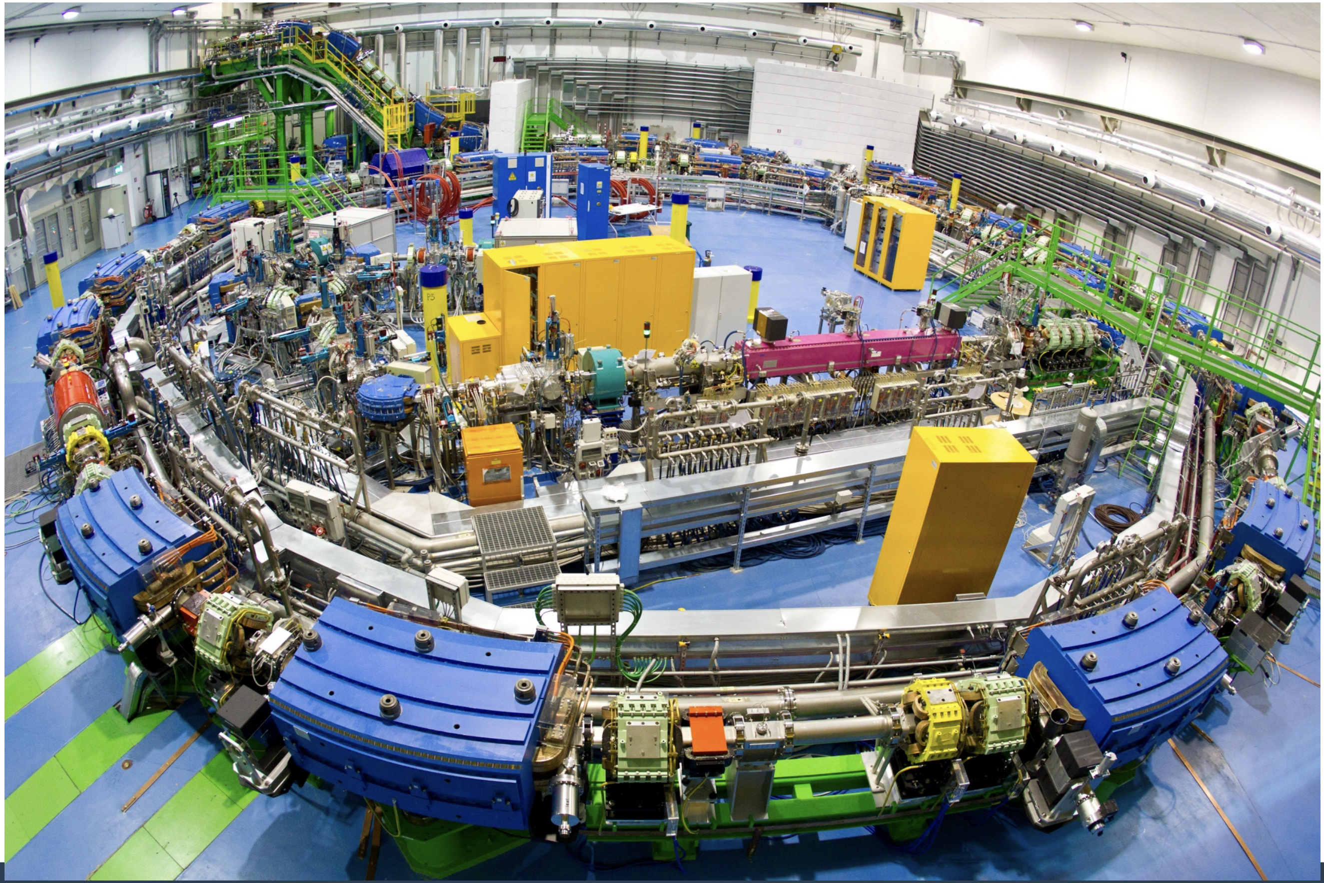


Question:
Can I increase the particle extraction energy limitlessly?

HEP accelerators



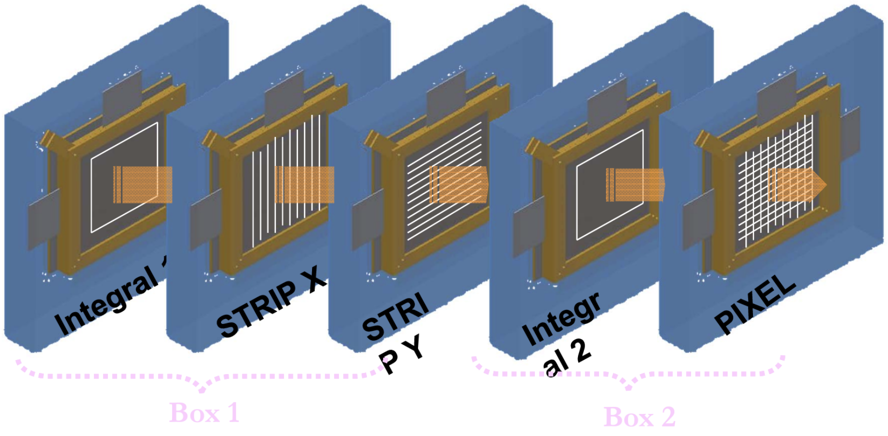
CNAO



CNAO

www.cnao.it

Beam delivery – scanning control



1 Integral chamber:

- Beam Intensity measure every 1 μs

2 Strip chambers (X and Y):

- Beam position measure every 100 μs, with 100 μm of precision

1 Integral chamber:

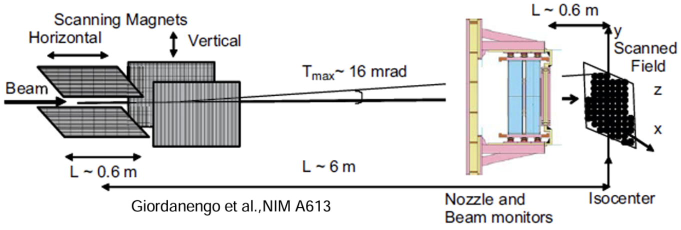
- Beam Intensity measure every 1 μs

1 Pixel chamber:

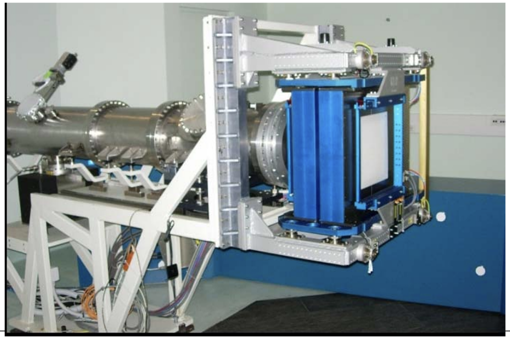
- Beam position and dimension measure every 100 μs/1 ms, with 200 μm of precision

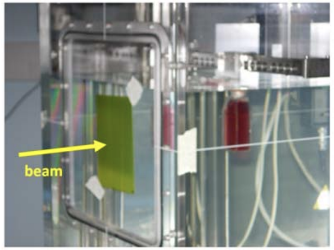
CNAO

Dose delivery



Giordanengo et al.,NIM A613



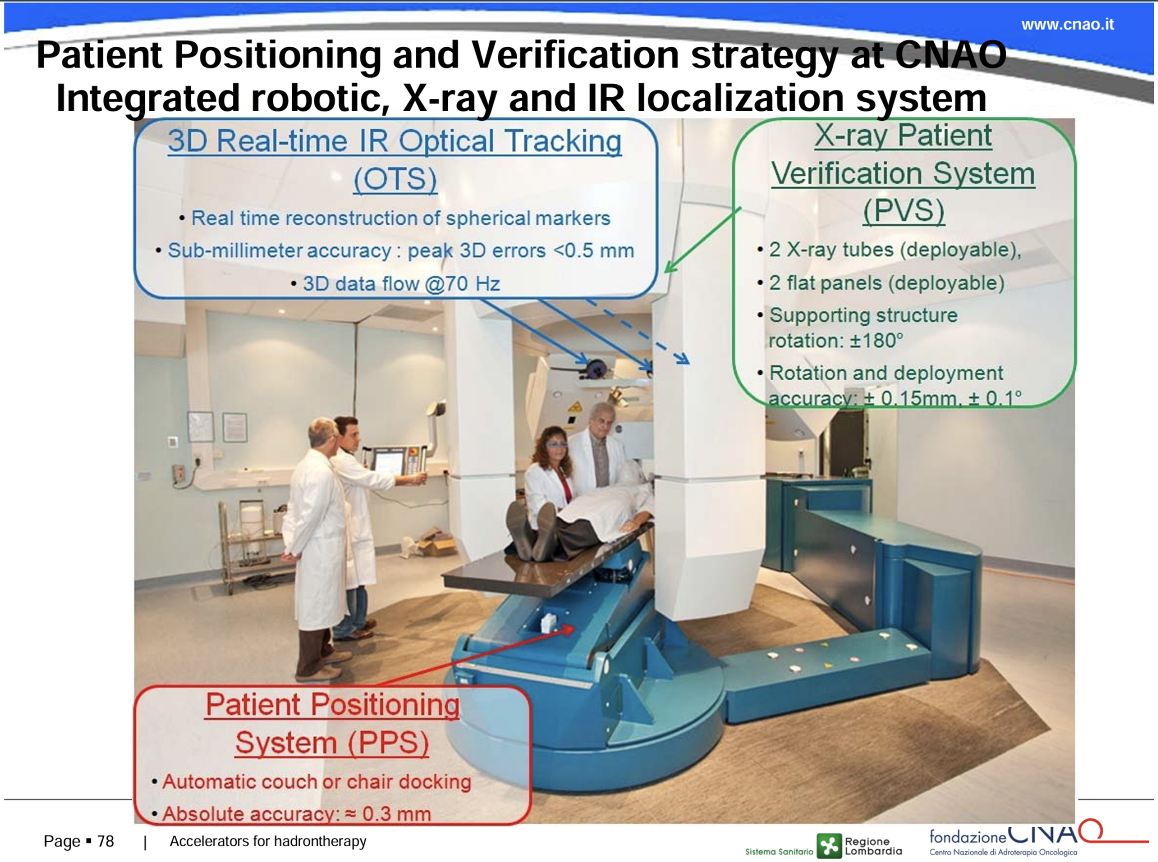


CNAO

CNAO

1	Beam particle species	p, He^{2+}, Li^{3+}, Be^{4+}, B^{5+}, C^{6+}, O^{8+}
2	Beam particle switching time	≤ 10 min
3	Beam range	1.0 g/cm^2 to 27 g/cm^2 in one treatment room 3.1 g/cm^2 to 27 g/cm^2 in two treatment rooms Up to 20 g/cm^2 for O^{8+} ions
4	Bragg peak modulation steps	0.1 g/cm^2
5	Range adjustment	0.1 g/cm^2
6	Adjustment/modulation accuracy	≤± 0.025 g/cm^2
7	Average dose rate	2 Gy/min (for treatment volumes of 1000 cm^3)
8	Delivery dose precision	≤± 2.5%
9	Beam axis height (above floor)	150 cm (head and neck beam line) 120 cm (elsewhere)
10	Beam size[1]	4 to 10 mm FWHM for each direction independently
11	Beam size step[1]	1 mm
12	Beam size accuracy[1]	≤± 0.25 mm
13	Beam position step[1]	0.8 mm
14	Beam position accuracy[1]	≤± 0.2 mm
15	Field size[1]	5 mm to 34 mm (diameter for ocular treatments) 2×2 cm^2 to 20×20 cm^2 (for H and V fixed beams)
16	Field position accuracy[1]	≤± 0.5 mm
17	Field dimensions step[1]	1 mm
18	Field size accuracy[1]	≤± 0.5 mm

CNAO


www.cnao.it
Patient Positioning and Verification strategy at CNAO
Integrated robotic, X-ray and IR localization system
3D Real-time IR Optical Tracking (OTS)
• Real time reconstruction of spherical markers
• Sub-millimeter accuracy : peak 3D errors <0.5 mm
• 3D data flow @70 Hz
X-ray Patient Verification System (PVS)
• 2 X-ray tubes (deployable),
• 2 flat panels (deployable)
• Supporting structure rotation: ±180°
• Rotation and deployment accuracy: ± 0.15mm, ± 0.1°
Patient Positioning System (PPS)
• Automatic couch or chair docking
• Absolute accuracy: ≈ 0.3 mm
Page ▪ 78 | Accelerators for hadrontherapy
Sistema Sanitario Regione Lombardia
fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

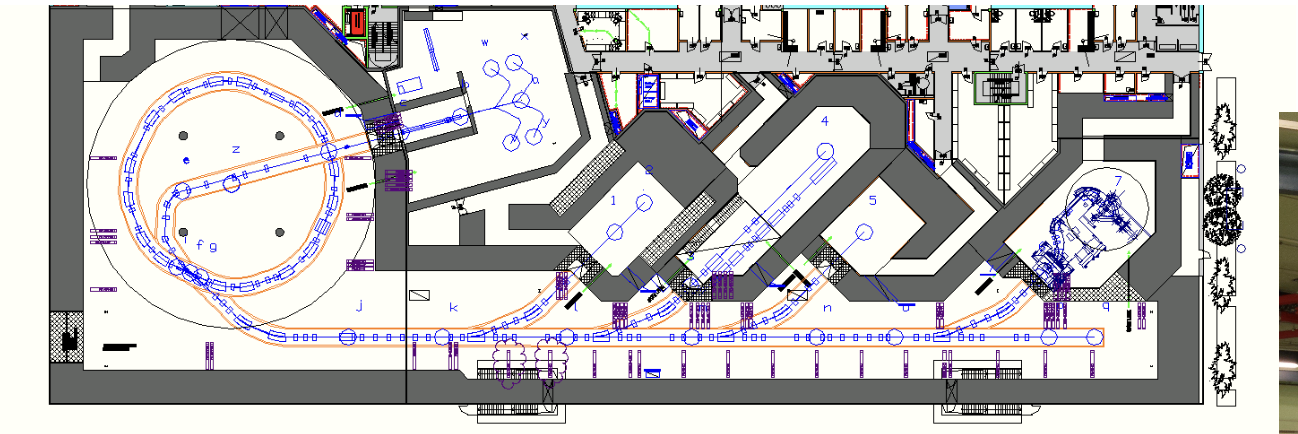
CNAO

Patient positioning

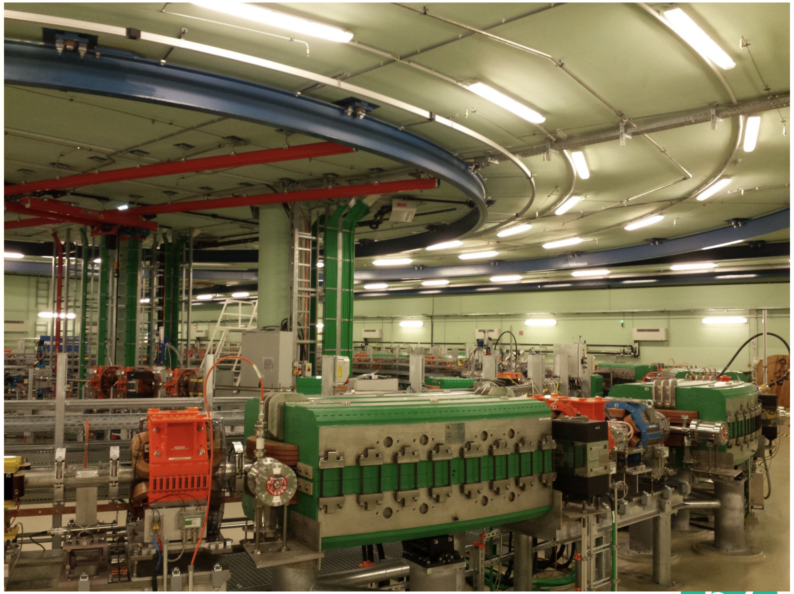
Sistema Sanitario Regione Lombardia

fondazione CNAO Centro Nazionale di Adroterapia Oncologica

MedAustron (near Vienna, Austria)



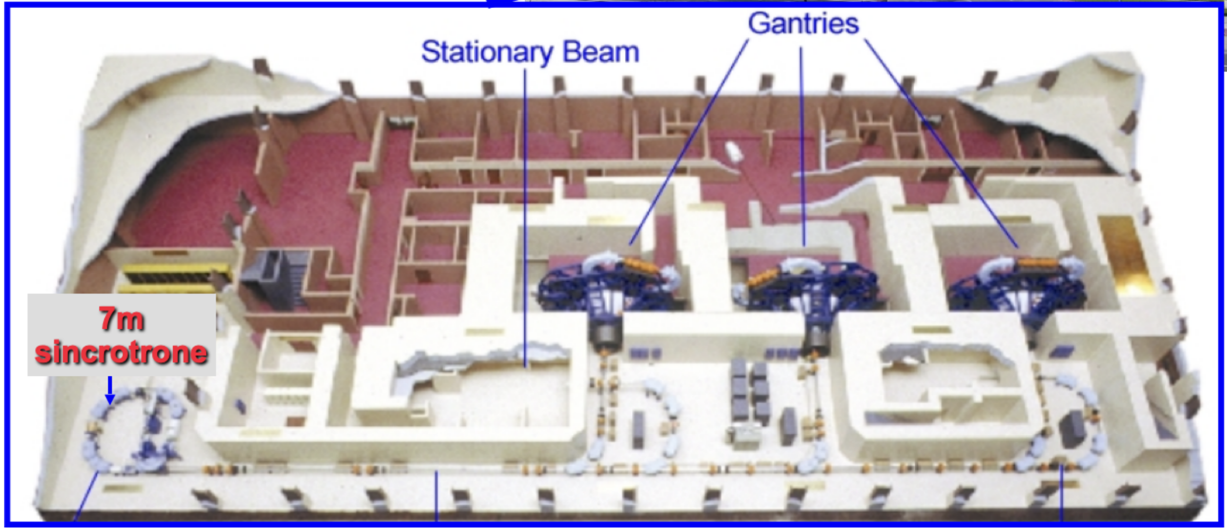
MedAustron (Austria) realizzato su progetti del CNAO



Loma Linda University Medical center (USA)

Primo centro ospedaliero di protonterapia

160 sessioni/giorno

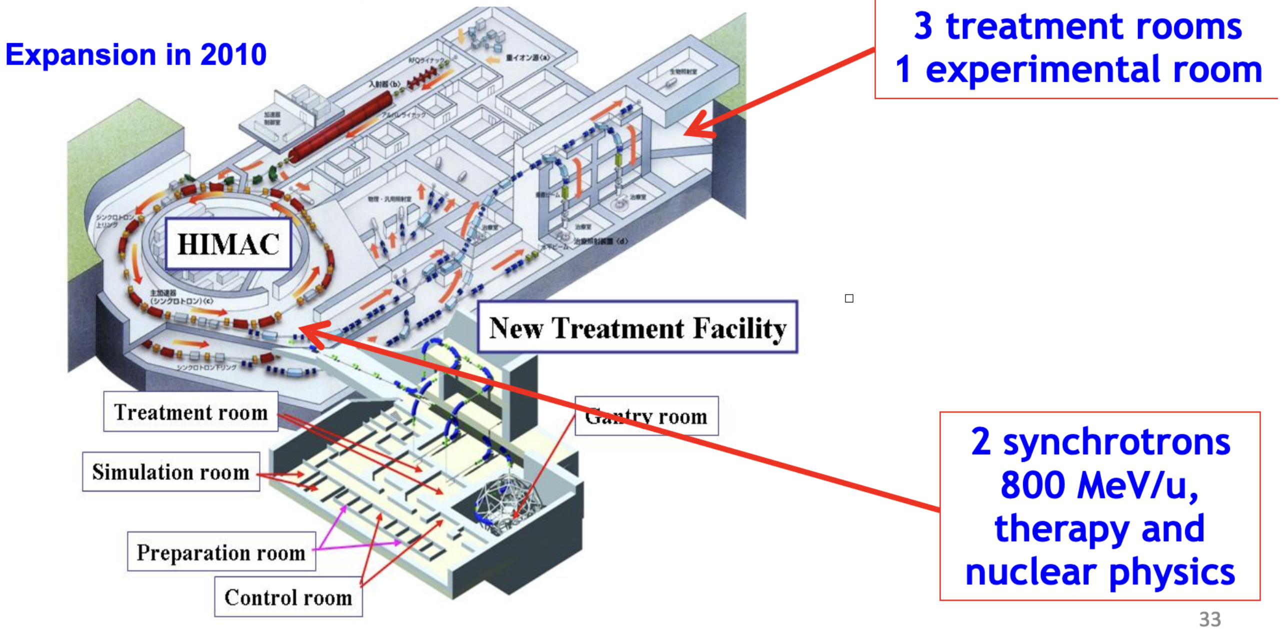


HIMAC (Japan)

HIMAC

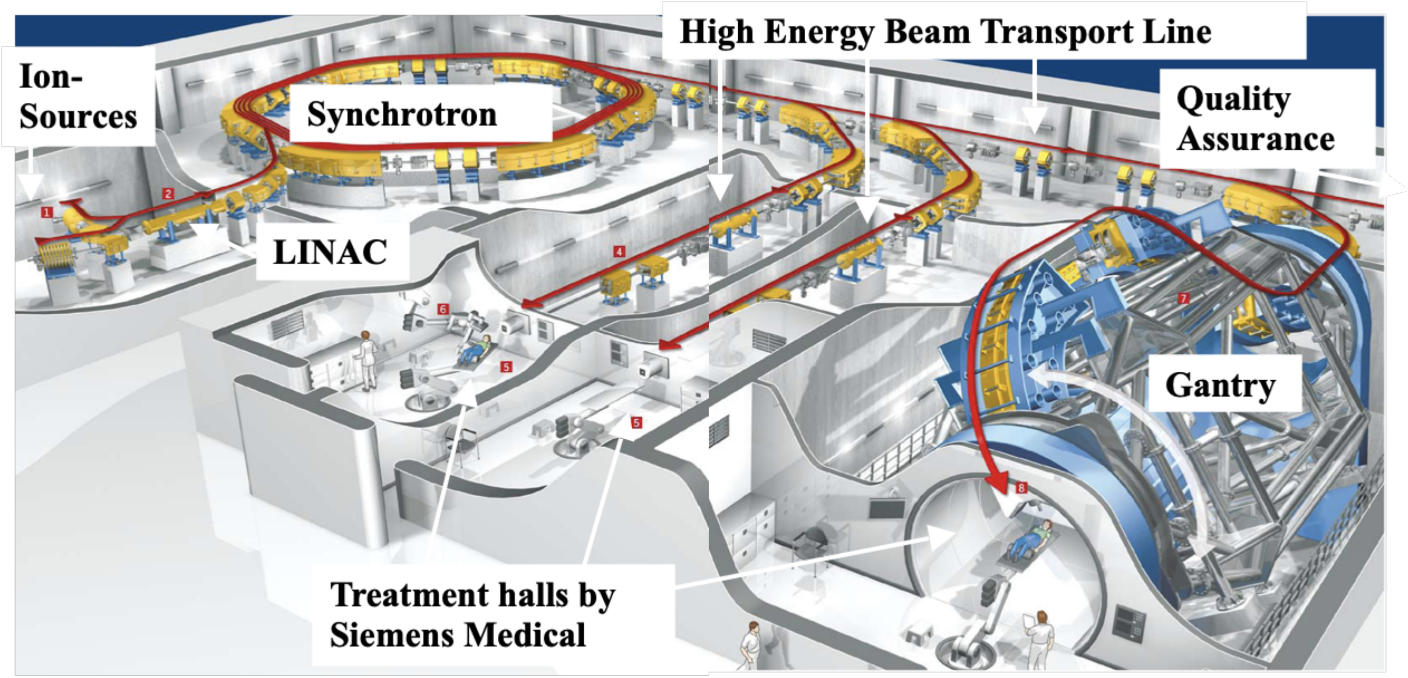
Heavy Ion Medical Accelerator in Chiba

(First patient in 1995)



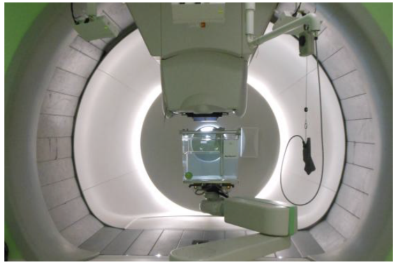
The HIMAC can accelerate various ions (H, He, C, O, Ne, Ar, Fe, Kr and Xe) to high energies (100 MeV/u to 800 MeV/u depending on the ions)

HIT (Heidelberg, Germany)

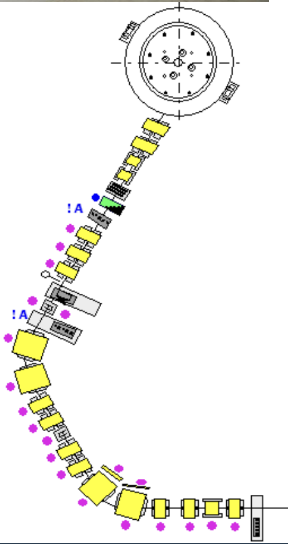
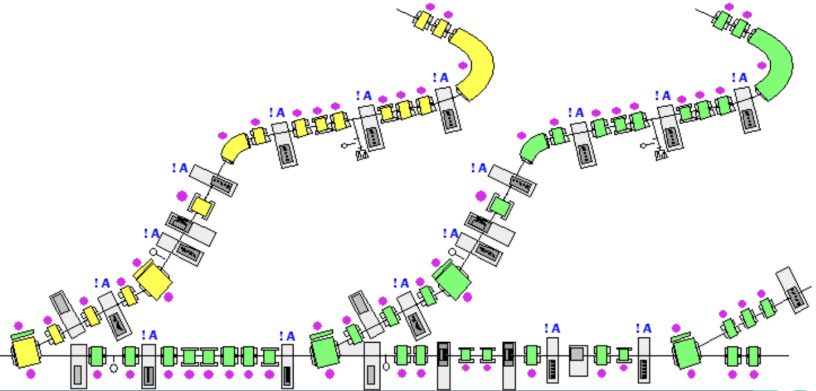


Protonterapia Trento

1 fixed line room for research irradiations
Two scanning-only 360°gantries
Energies at isocentre from 70 to 226 MeV
2D imaging in one gantry room
Ct on rail being installed in the second gantry room



IBA cyclotron

Questions?

Comunicazione di servizio

DirSegrStud/Sett.I/VC/KC

IL RETTORE

VISTA la legge 02 agosto 1999, n. 264 recante "Norme in materia di accessi ai corsi universitari";

VISTO il Decreto Ministeriale n. 472 del 23 Febbraio 2024 recante "Definizione delle modalità e dei contenuti delle prove di ammissione ai corsi laurea magistrale a ciclo unico in Medicina e Chirurgia, Odontoiatria e protesi dentaria e Medicina Veterinaria per l'a.a. 2024/2025";

CONSIDERATO che per lo svolgimento della prova di ammissione al corso di laurea magistrale a ciclo unico in Medicina e Chirurgia e odontoiatria e protesi dentaria del 28 Maggio 2024 sono state individuate le aule dei settori didattici di Celoria 20, Golgi, Venezian, Fisica e Biologia;

CONSIDERATO che per lo svolgimento della prova di ammissione al corso di laurea magistrale a ciclo unico in Medicina Veterinaria del 29 Maggio 2024 sono state individuate le aule dei settori didattici di Celoria 20, Golgi, Venezian;

VALUTATO che, per assicurare la necessaria riservatezza e sicurezza allo svolgimento della prova, tenuto conto del numero dei candidati, è necessario sospendere l'attività didattica nei settori didattici nei giorni di svolgimento delle prove di ammissione dei suddetti corsi di laurea;

DECRETA

I giorni 28 e 29 maggio 2024 le lezioni e le attività didattiche dei settori didattici sopraindicati sono sospese per consentire lo svolgimento delle prove di ammissione ai corsi di laurea magistrale a ciclo unico in Medicina e Chirurgia, Odontoiatria e protesi dentaria e Medicina Veterinaria.