Particle accelerators and their medical applications

Varchaswi K S Kashyap

School of Physical Sciences

National Institute of Science Education and Research (NISER)
Bhubaneswar

What are accelerators?

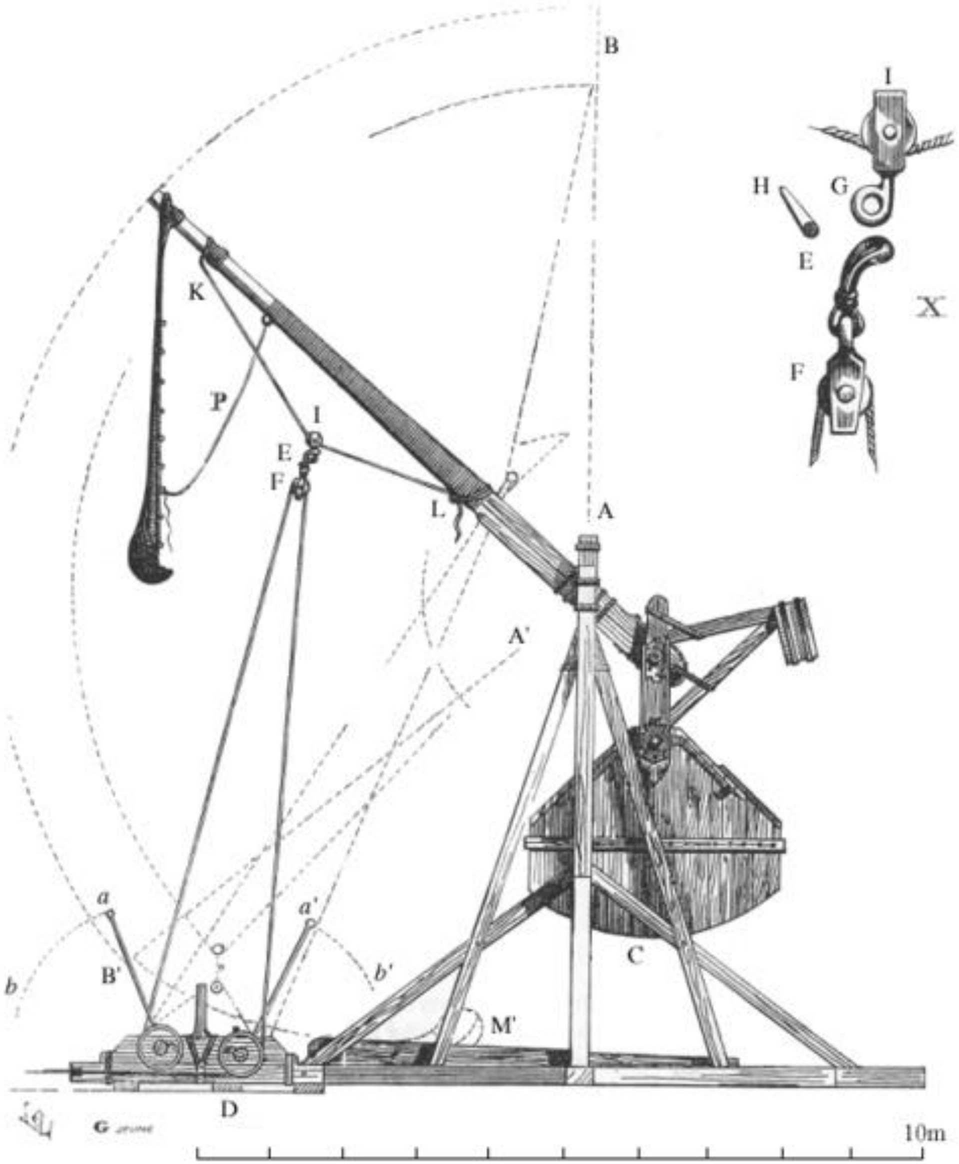
Accelerators are devices that increase the velocity/speed of objects at rest or in motion.

[Accelerator | Driving Lessons Online UK (teachable.com)]

COUNTER-WEIGHT TREBUCHET

Picture of several counter-weight trebuchets
Source: Wikipedia

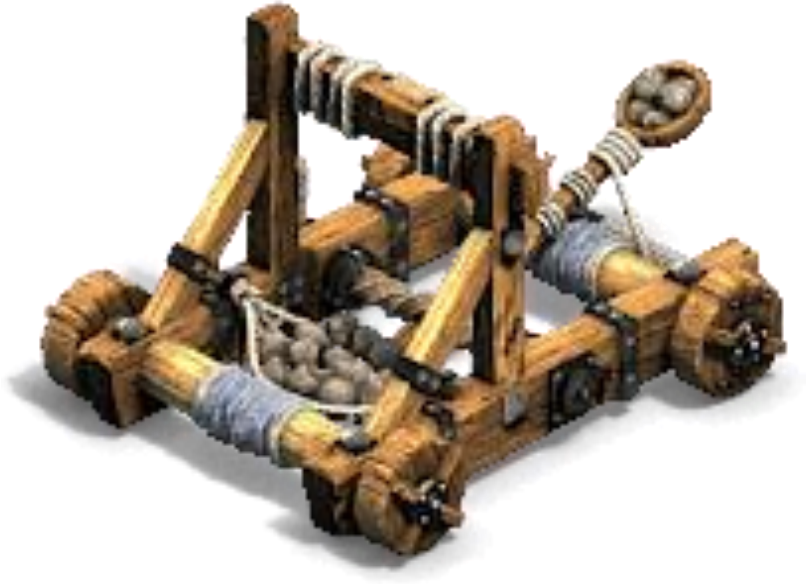
A screenshot in AOE2 from the internet



Source: Wikipedia

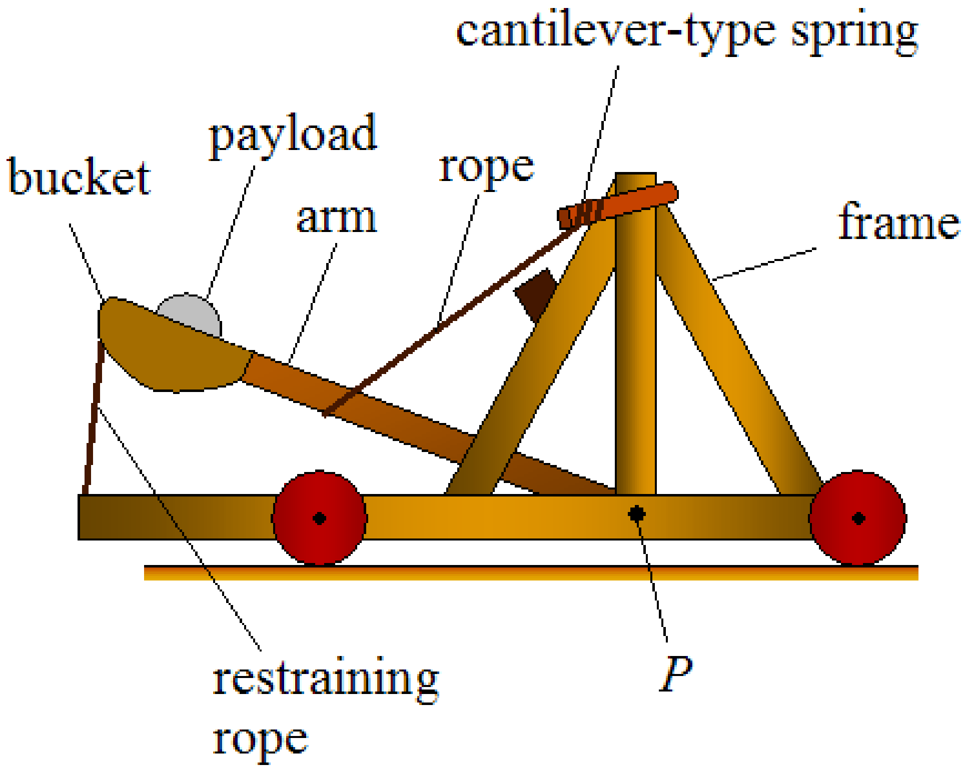
Are these accelerators?

A picture of an onager
Source: [I Have You Now: The Onager, a double-edged sword (armadaihaveyounow.blogspot.com)](armadaihaveyounow.blogspot.com)



A picture of an onager as modelled in AOE2

ONAGER/MANGONEL



Source: Wikipedia

SLINGSHOT

Source: Wikipedia

Are these accelerators?

Particle accelerators in physics and their need

- Development of particle accelerators was driven by the curiosity to probe more and more in to the constituents of matter
- De Broglie's principle is what guides the energy of particles needed to probe into matter

$$\lambda = \frac{h}{p}$$

Dimension to be probed	1 Å (Atomic size)	1 fm (Nuclear size)
Energy of electron required	**~150 eV**	**~ 1 TeV**

Where λ is the wavelength, h is the Planck's constant and p is the momentum.

- Larger the momentum (Energy), lower is the wavelength and hence smaller is the object that can be probed

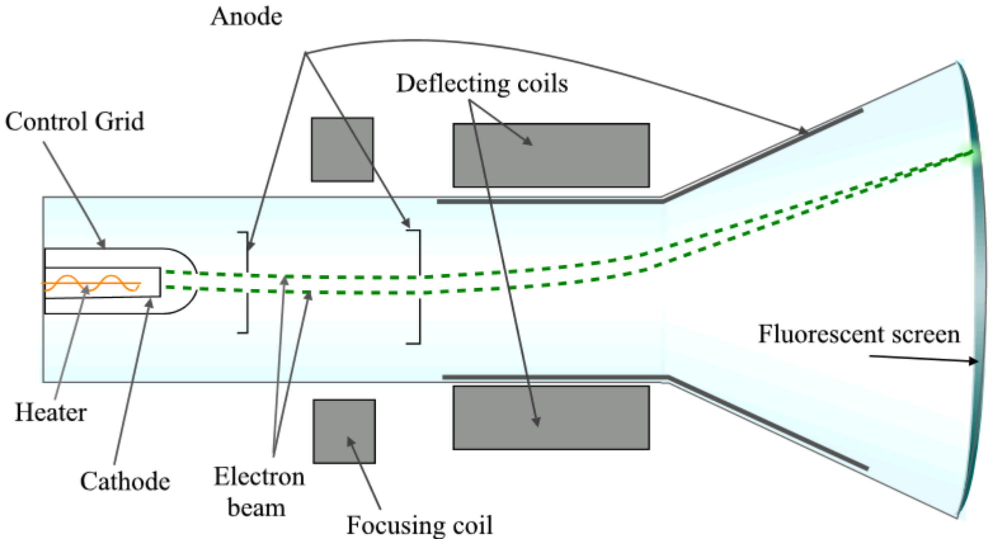
Have you come across any particle accelerators in your daily life?

What about these?

CRT television

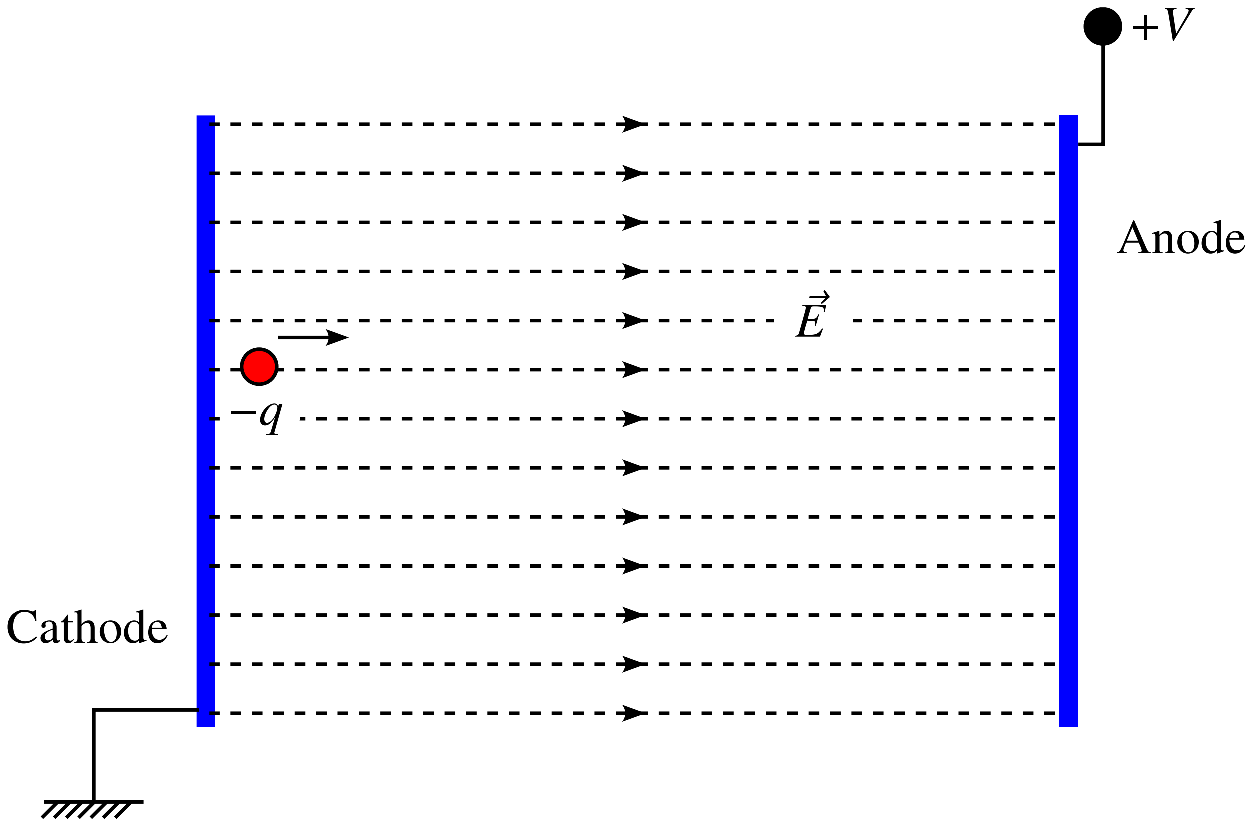
CRT monitor

CR Oscilloscope



They have small accelerators that can accelerate electrons up to few keV

Kinetic energy of a charged particle in an electric field



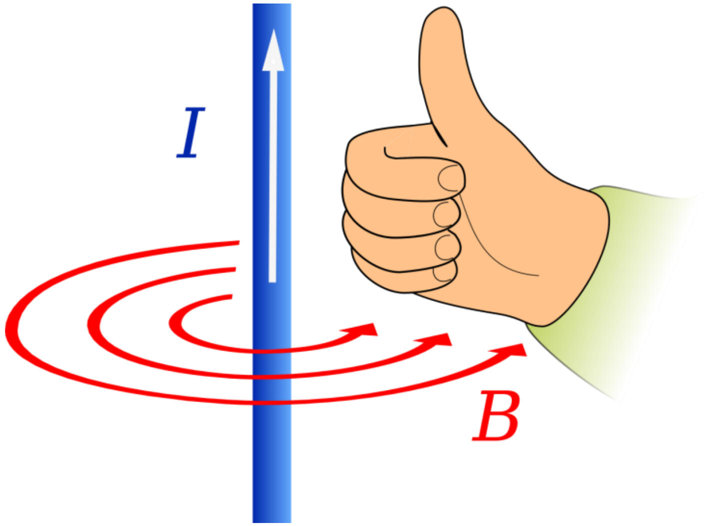
$$\text{K.E} = qV$$

Speed of the particle is given by

$$qV = \frac{1}{2}mv^2$$

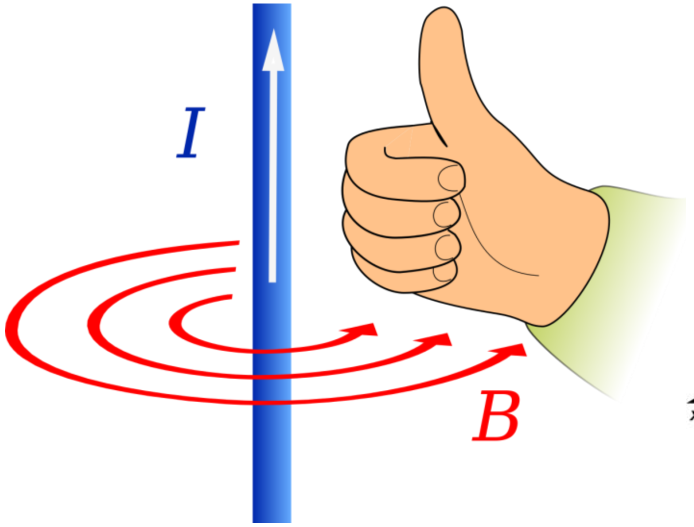
$$v = \sqrt{\frac{2qV}{m}}$$

Ampere's law



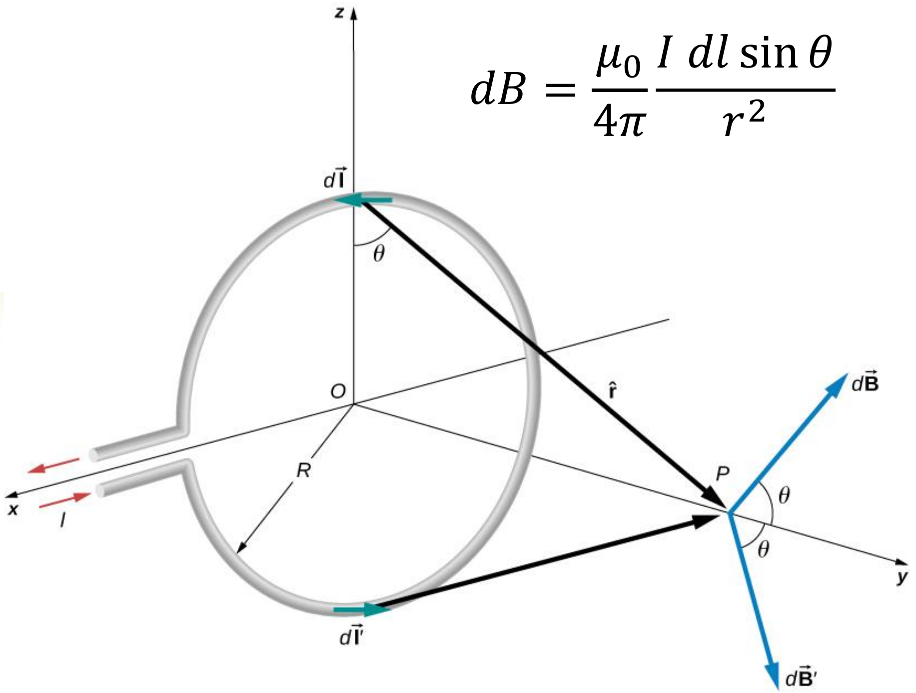
Source:
Jfmelero - Own work, CC BY-SA 4.0,
https://commons.wikimedia.org/w/index.php?curid=3634402

Ampere's law



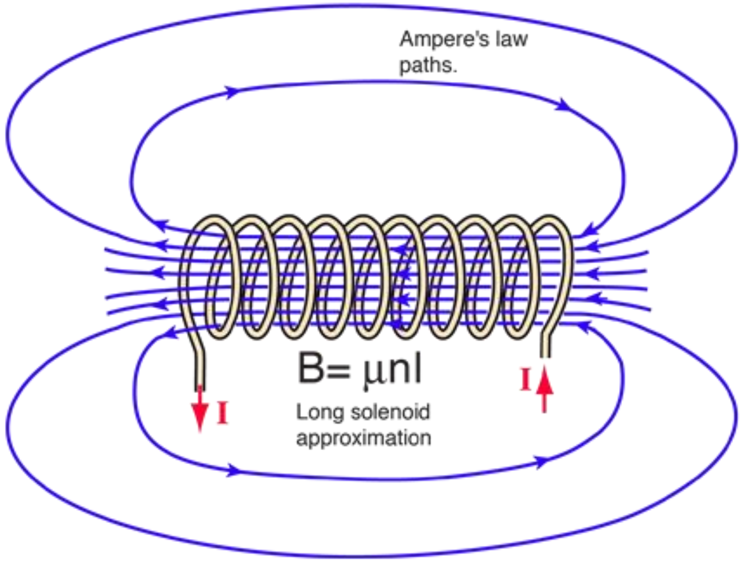
Biot-Savart's law

$$dB = \frac{\mu_0}{4\pi}\frac{I\, dl \sin\theta}{r^2}$$



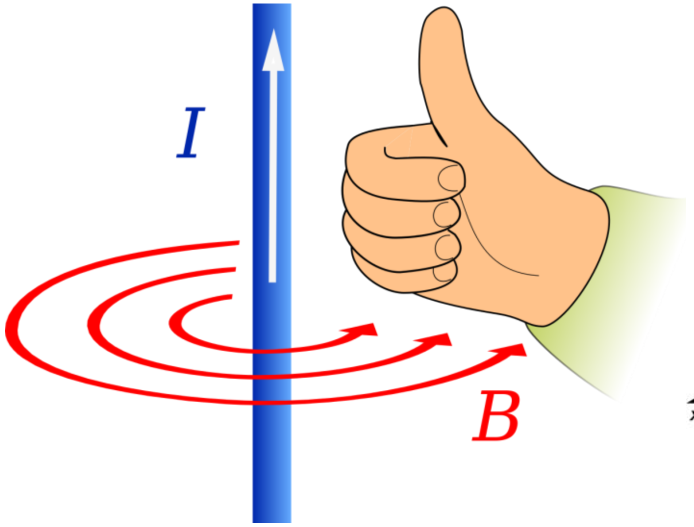
Source:
Magnetic Field of a Current Loop. **Authored by**: OpenStax College. **Located at**: https://openstax.org/books/university-physics-volume-2/pages/12-4-magnetic-field-of-a-current-loop.

Solenoid



Source:
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html

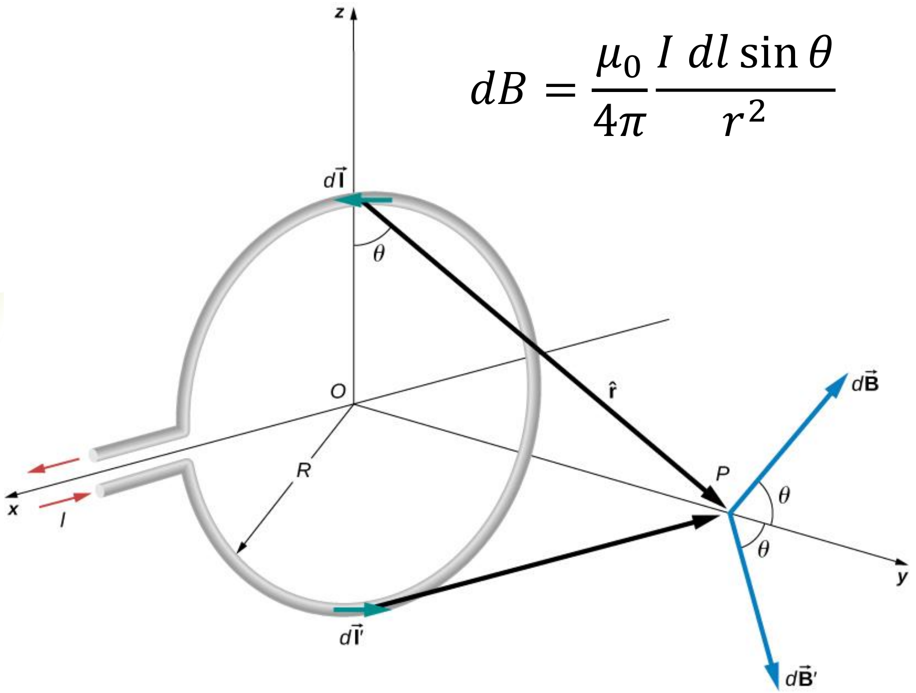
Ampere's law



Source:
Jfmelero - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=3634402

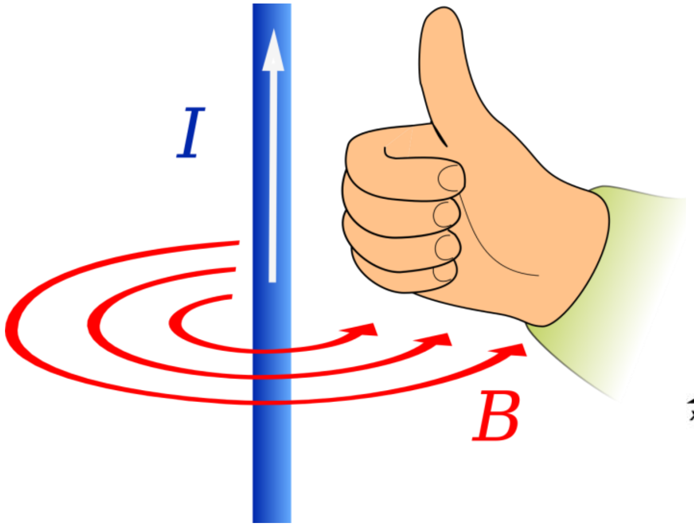
Biot-Savart's law

$$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\theta}{r^2}$$



Source:
Magnetic Field of a Current Loop. **Authored by**: OpenStax College. **Located at**: https://openstax.org/books/university-physics-volume-2/pages/12-4-magnetic-field-of-a-current-loop.

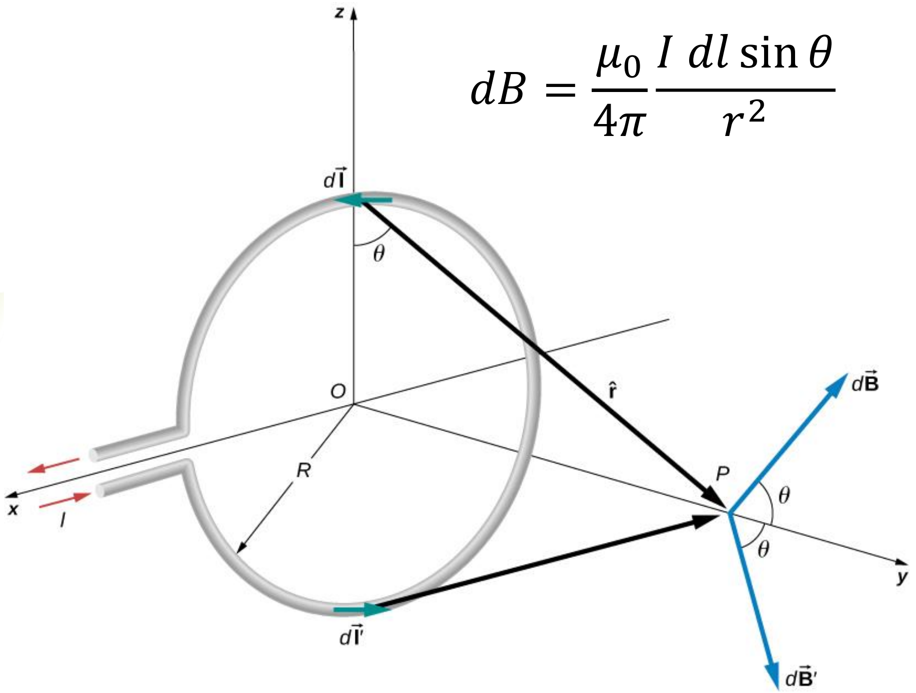
Ampere's law



Source:
Jfmelero - Own work, CC BY-SA 4.0,
https://commons.wikimedia.org/w/index.php?curid=3634402

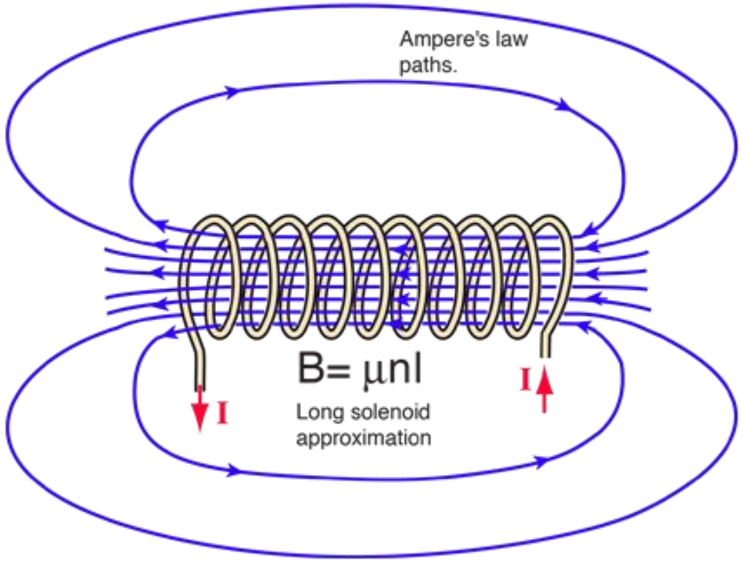
Biot-Savart's law

$$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\theta}{r^2}$$



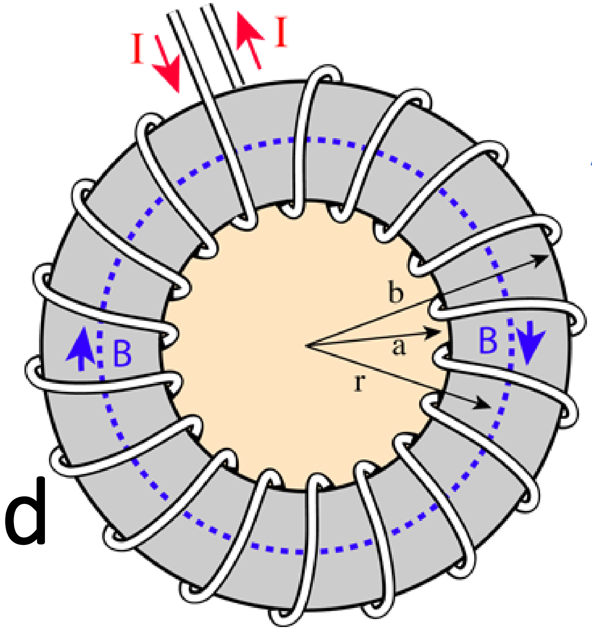
Source:
Magnetic Field of a Current Loop. **Authored by**: OpenStax College. **Located at**: https://openstax.org/books/university-physics-volume-2/pages/12-4-magnetic-field-of-a-current-loop.

Solenoid



Source:
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html

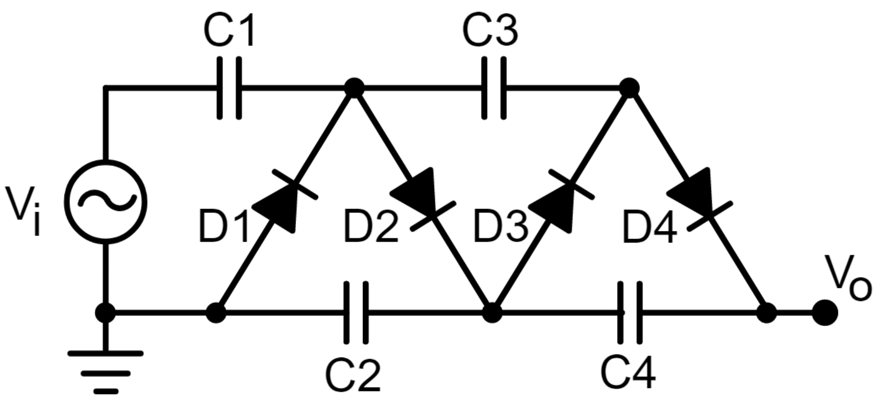
Toroid



Types of accelerators

Electrostatic accelerators	Induction accelerators	Radio-Frequency (RF) accelerators
• Cockroft – Walton accelerator • Van de Graaff accelerator • Pelletron	• Induction Linear accelerator • Betatron	• **RF Linac** • RF quadrupole • **Cyclotron** • Microtron • **Synchrotron**

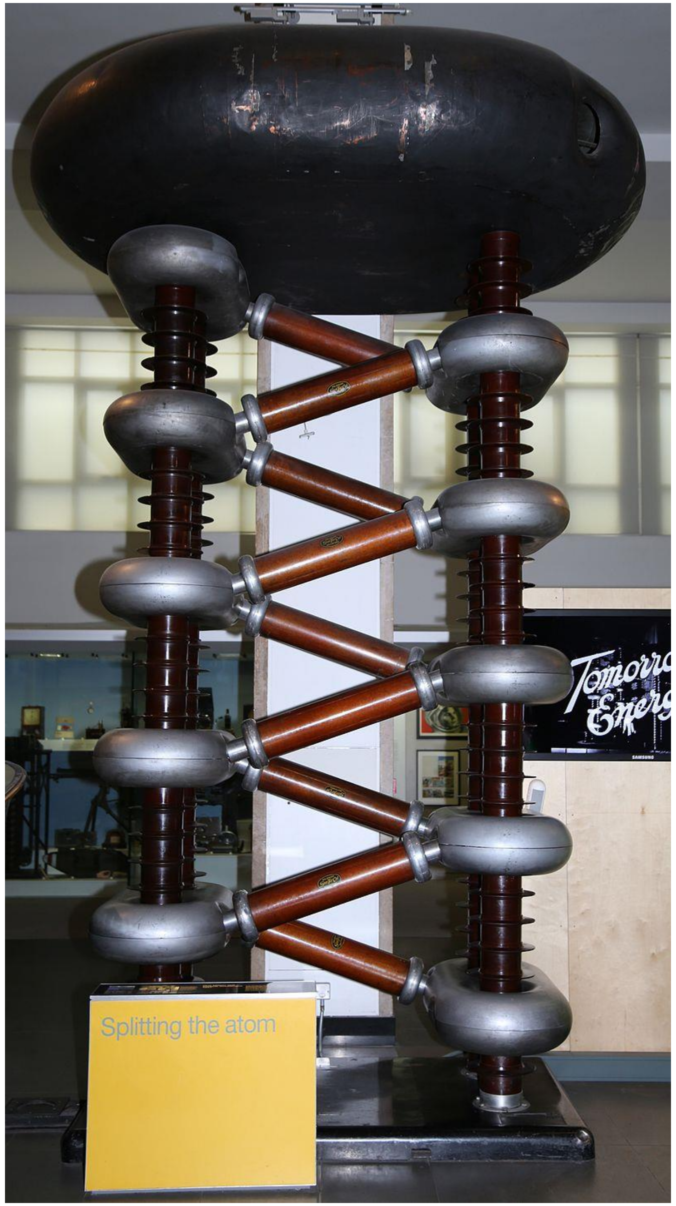
Cockroft – Walton accelerator



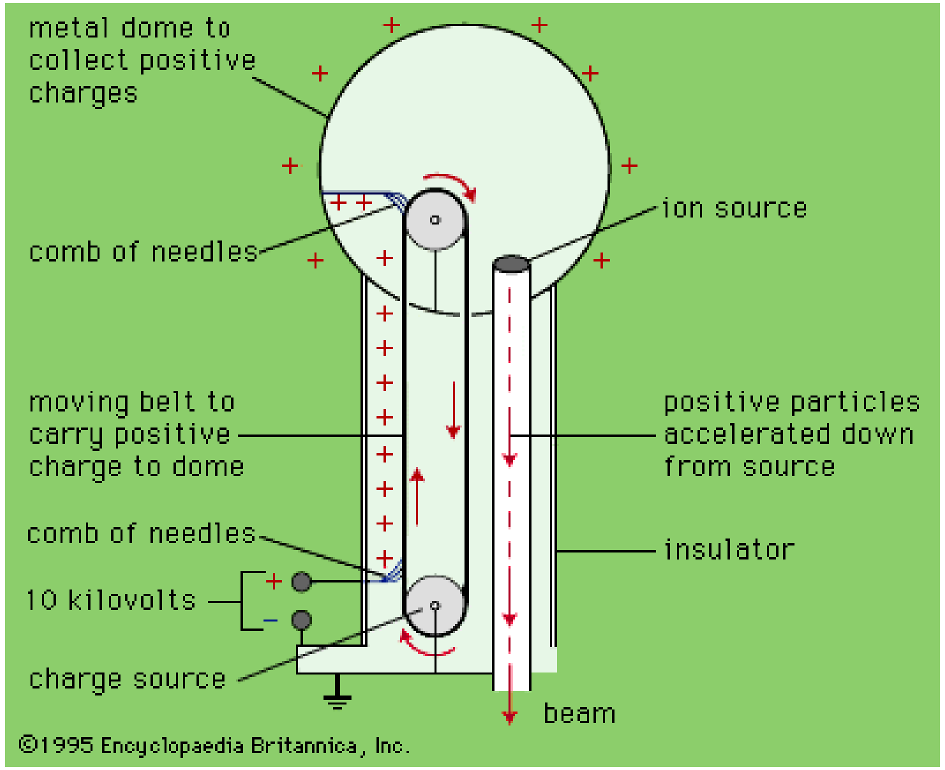
- Converts AC voltage to very high DC voltage
- Simple in principle and less bulky compared to transformers
- Voltages can be tapped at different levels

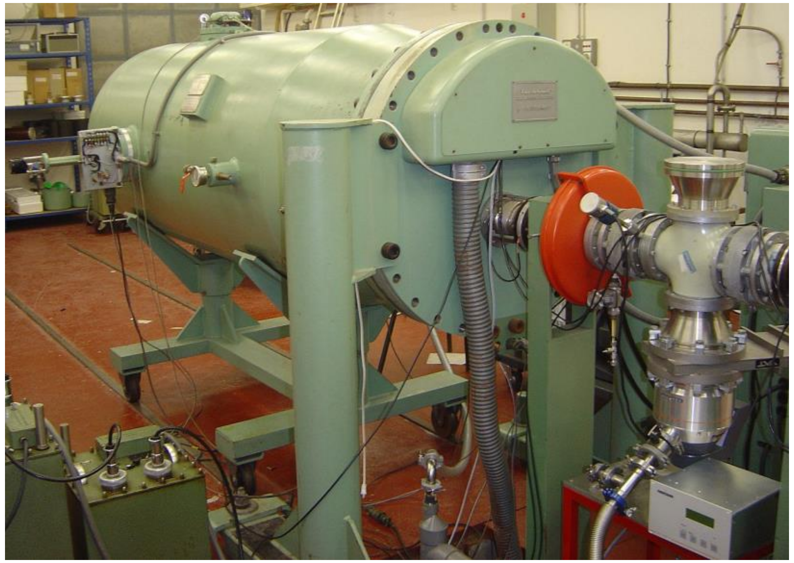
K.E.$= qV$

Source: Wikipedia



Van de Graaff accelerator



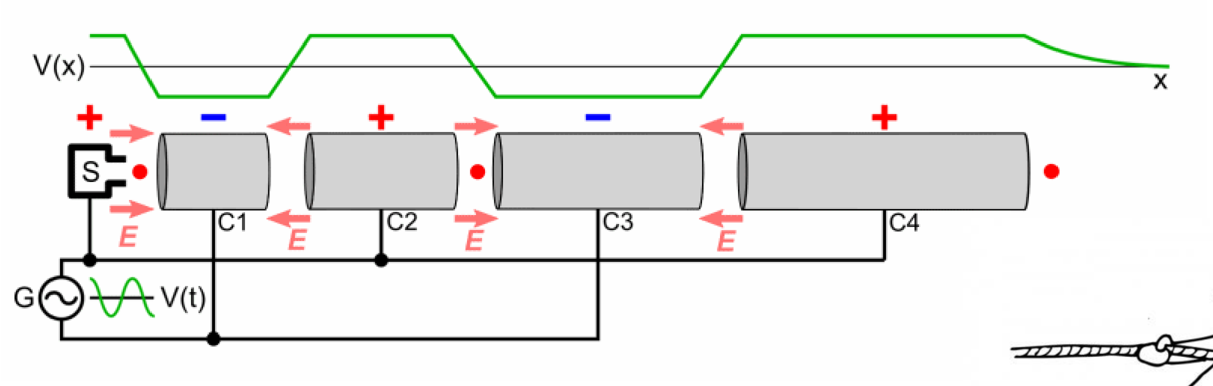


A Van de Graaff particle accelerator in a pressurized tank at Pierre and Marie Curie University, Paris (**Source:** Wikipedia, Copyright © 2004 David Monniaux)

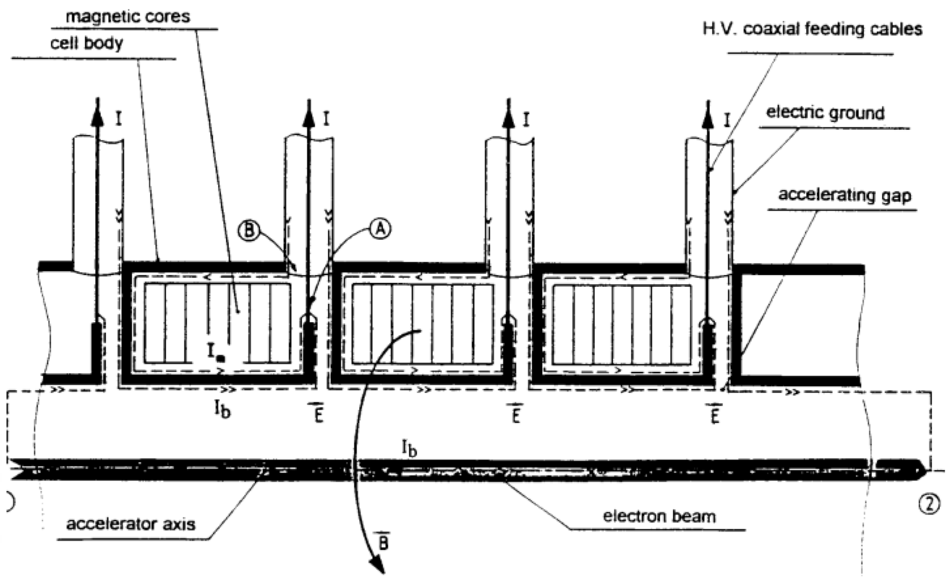
$$\text{K.E.} = qV$$

- Voltages of the order of a few MV can be achieved.
- A high voltage supply provides charges to be transported to the metal dome
- Charges are collected in a metal dome over time
- The potential difference between the dome and the ground can be used to accelerate particles
- A Pelletron is very similar to the Van de Graaff having a metal belt with pellets instead of a rubber belt.

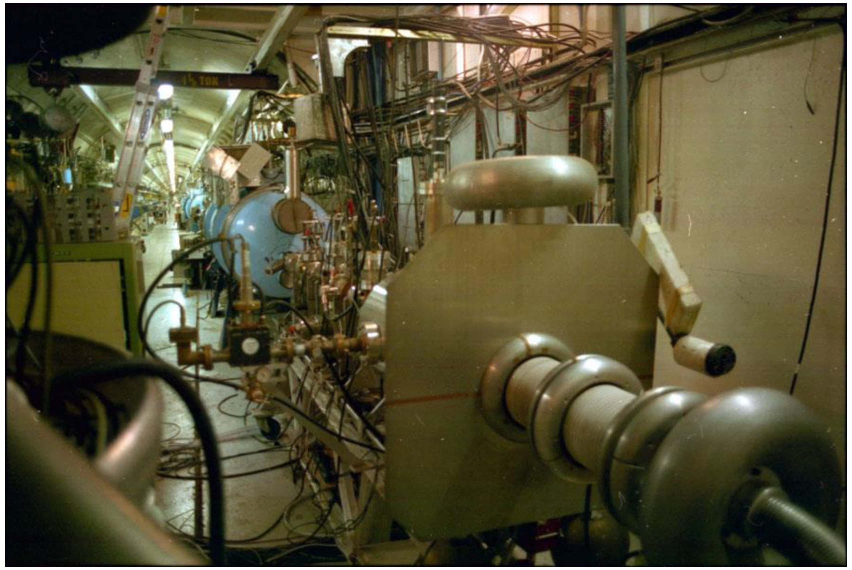
Linear accelerator



RF LINAC (**Image credit**: Wikipedia)



INDUCTION LINAC (**Image credit**: INDUCTION, J De Mascureau, 1996)

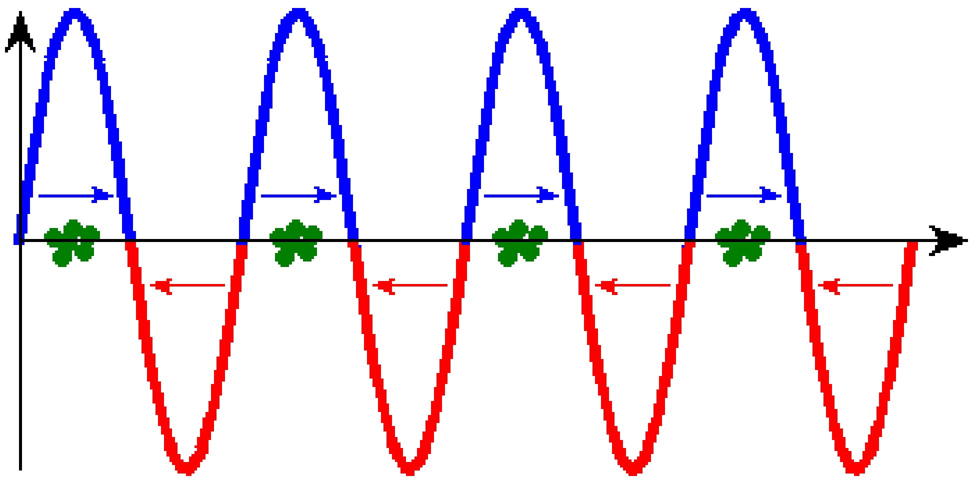


The Stanford University superconducting linear accelerator, housed on campus below the Hansen Labs until 2007. This facility is separate from SLAC (**Image credit:** Wikipedia)

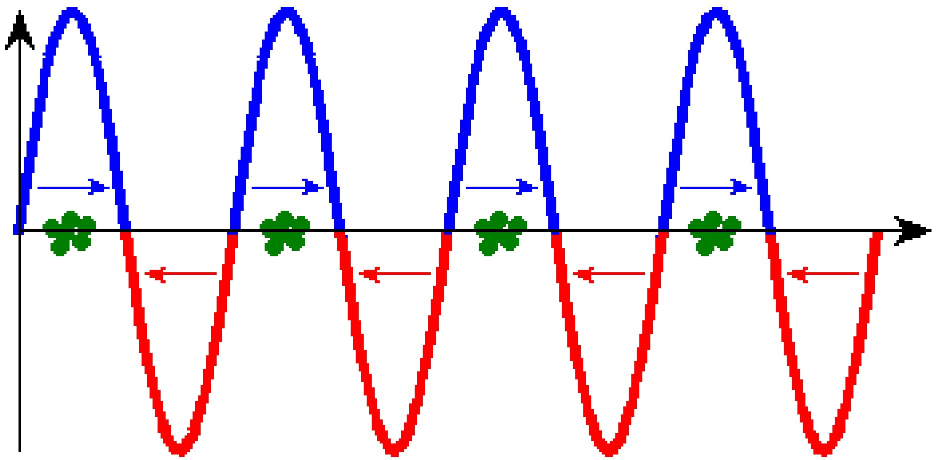
RF LINAC	INDUCTION LINAC
Smaller length	Longer length
Higher acceleration gradient	Lower acceleration gradient
Requires lower power	Requires higher power
Low current and short pulse duration	High current and longer pulse duration

Linear accelerator (LINAC) contd.

RF LINAC configurations



Standing wave



Travelling wave

Image credit: By Patrick87 - https://commons.wikimedia.org/w/index.php?curid=29590284

Medical LINAC

Image credit: www.iaea.org

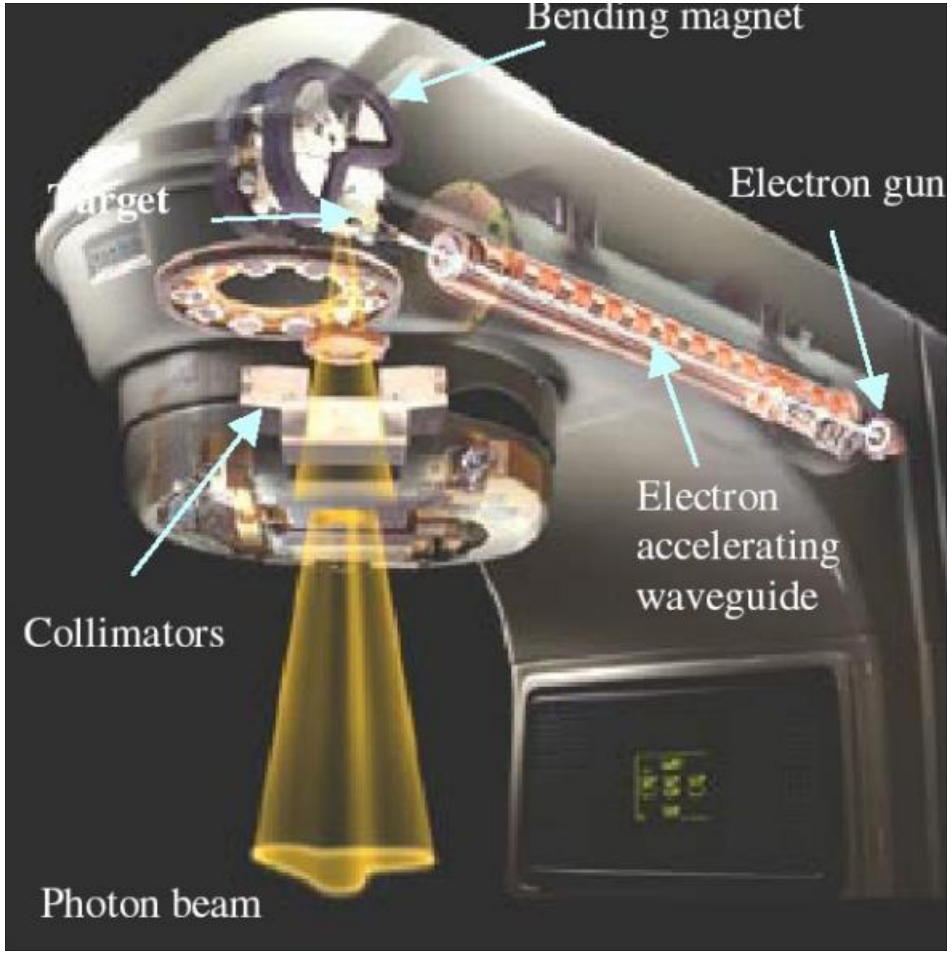
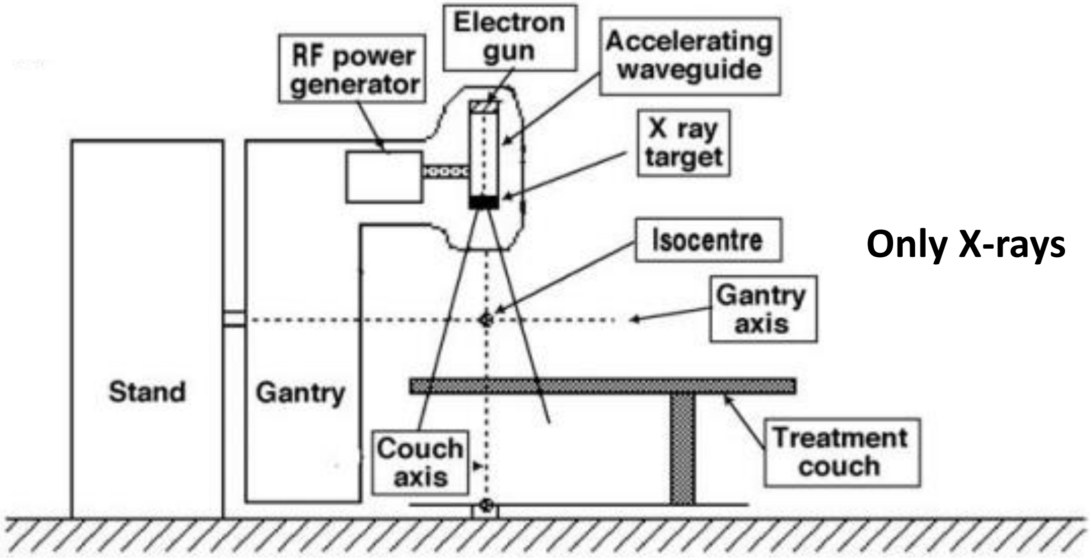


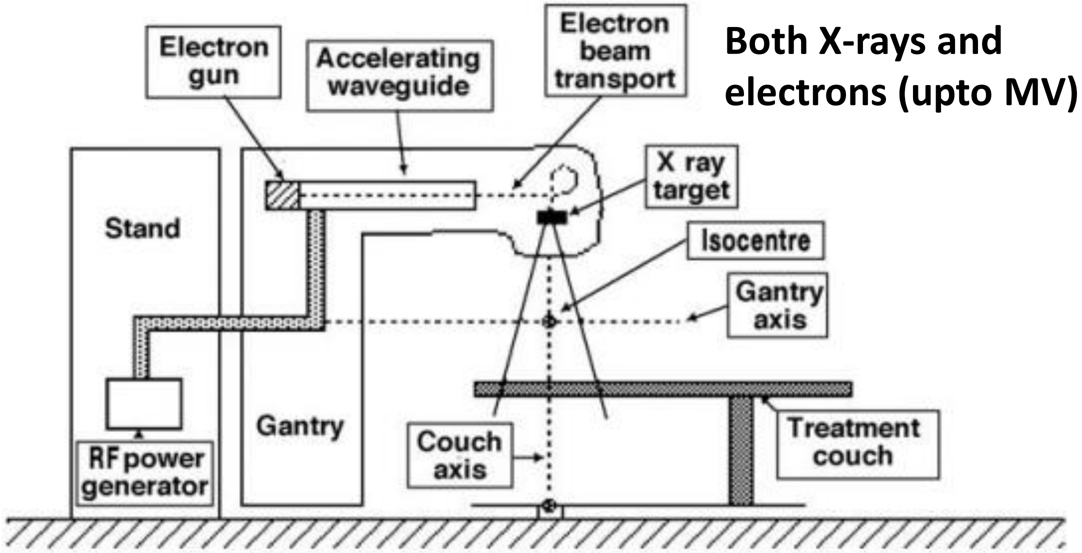
Image credit: Medical Linear Accelerators in Radiation Therapy, Presentation by Haijun Song, Ph.D. Dept. of Radiation Oncology Duke University Medical Cente

Medical LINAC configurations



Only X-rays

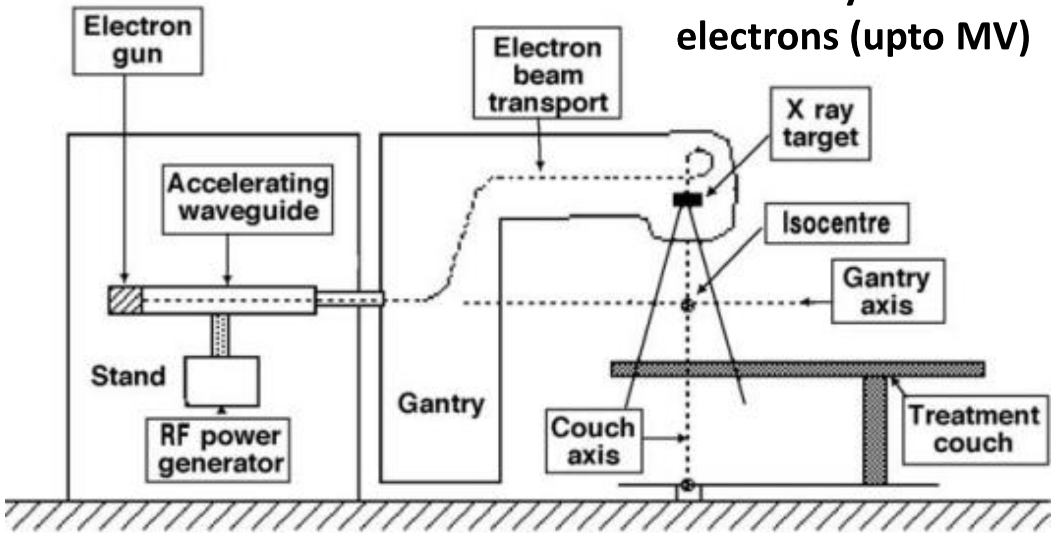
RF power generator and waveguide are both in the gantry and the waveguide is directed straight towards the patient



Both X-rays and electrons (upto MV)

RF power generator is in the gantry stand and waveguide is in the gantry directed towards the target above the patient

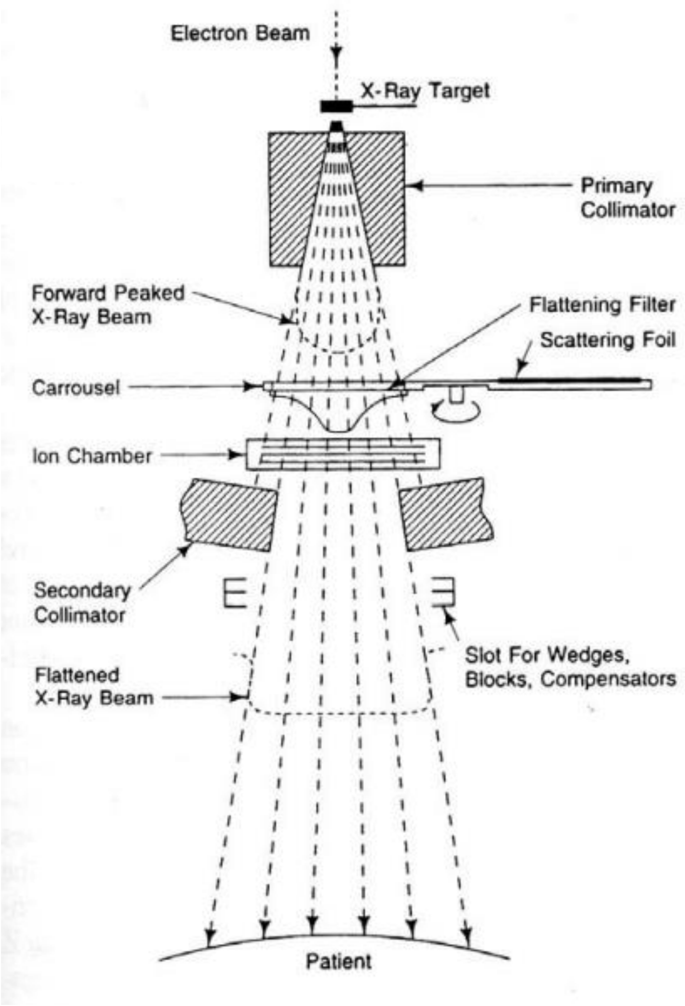
Both X-rays and electrons (upto MV)



Both RF power generator and waveguide are in the gantry stand. The electrons have to be transported to the target.

Image credit: Treatment machines for external beam radiotherapy, E.B. Podgorsak, Department of Medical Physics, McGill University Health Centre, Montreal, Quebec, Canada

Medical LINAC configurations contd.



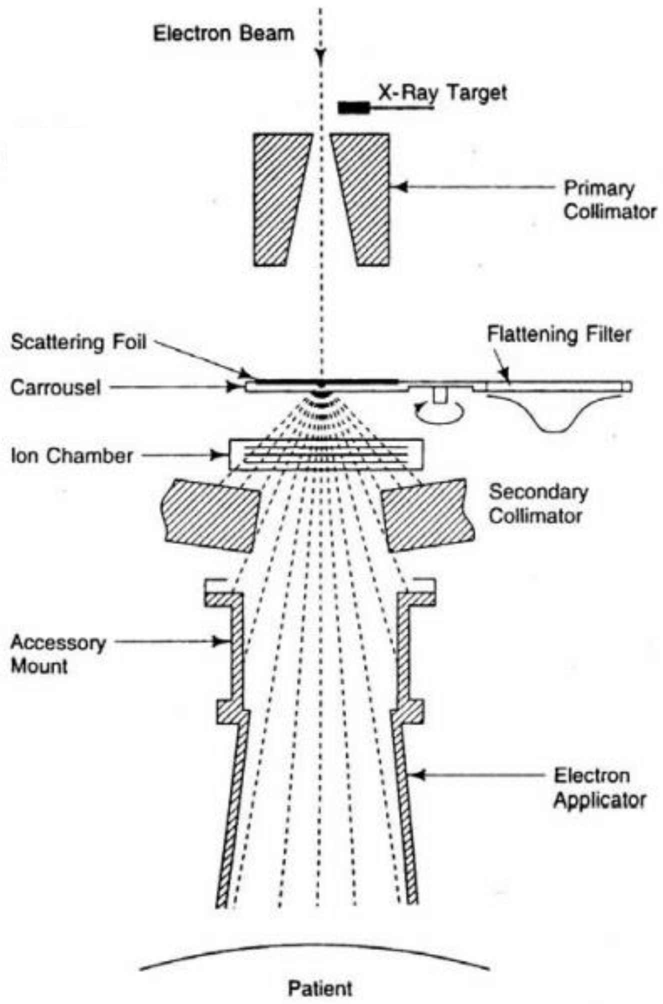


Image credit: Medical Linear Accelerators in Radiation Therapy, Presentation by Haijun Song, Ph.D. Dept. of Radiation Oncology Duke University Medical Centre

Cyclotron

$$T = \frac{2\pi m}{Bqv}$$

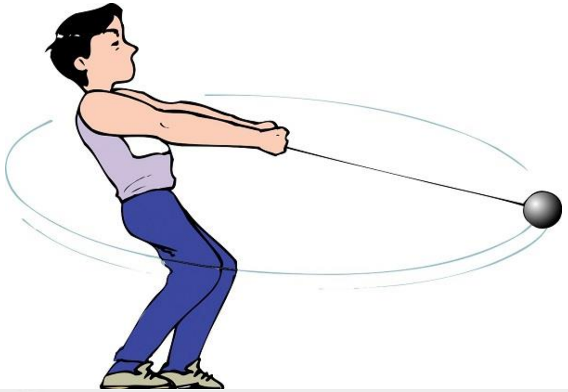


Image credit: Hammer Throw - How to Play? (tutorialspoint.com)

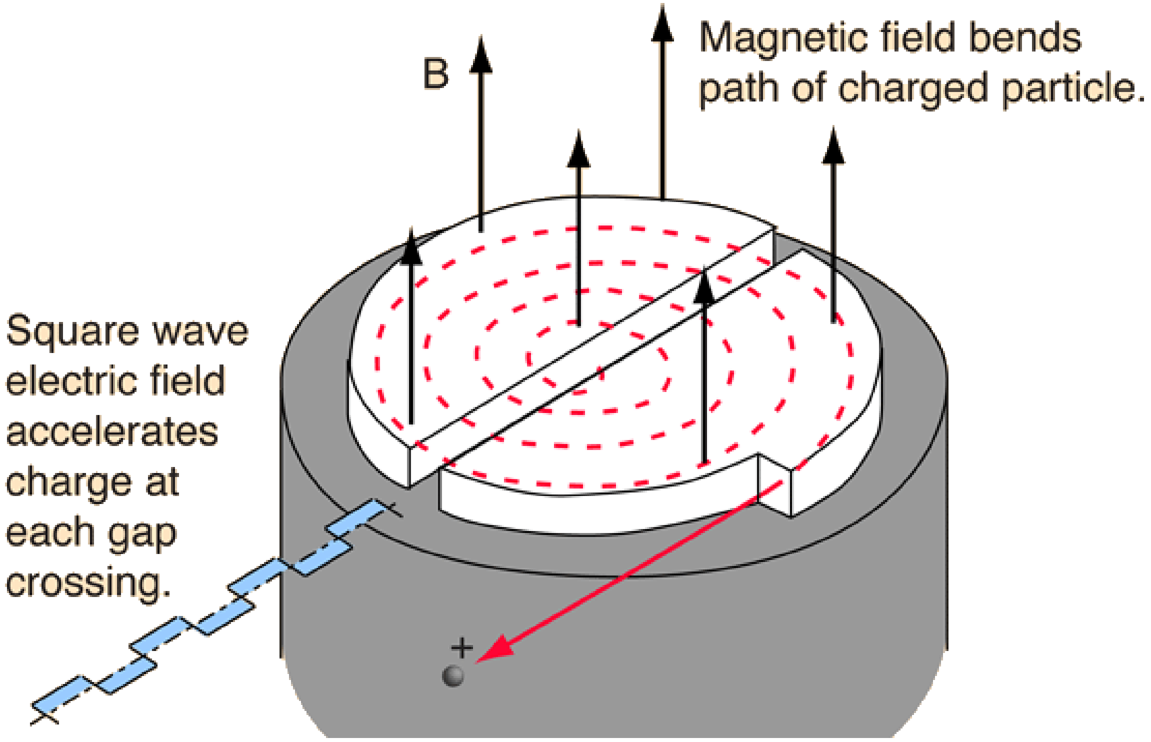
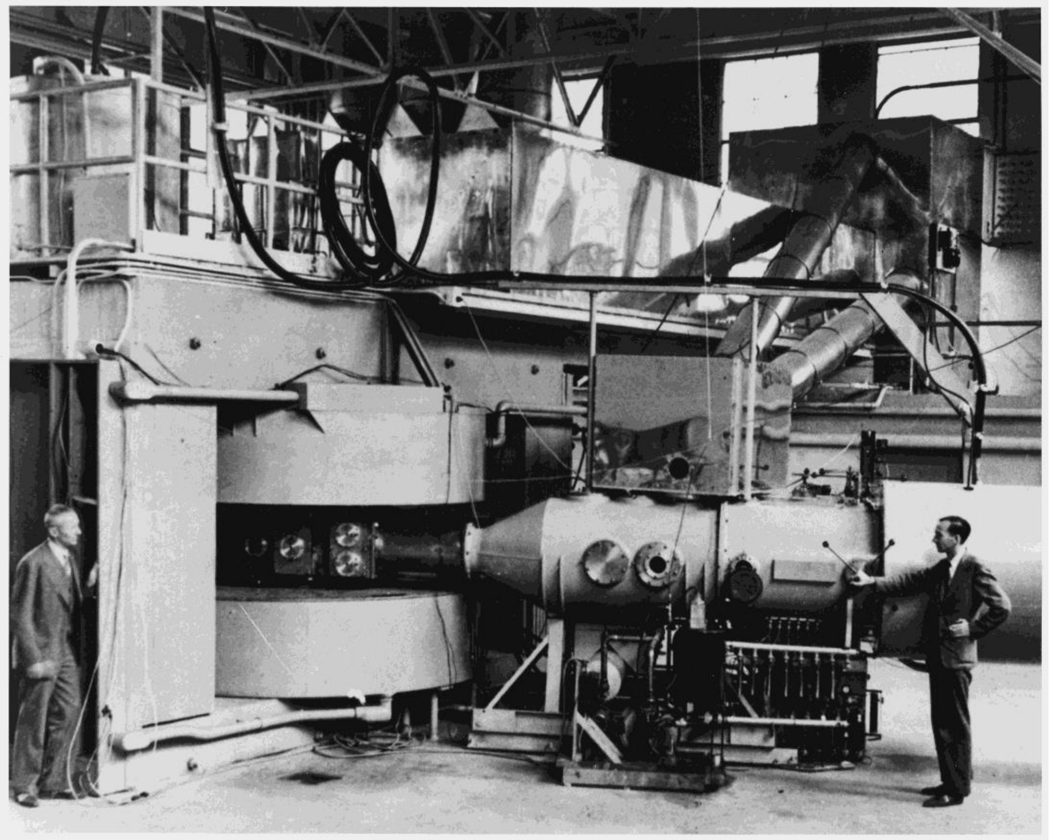


Image credit: Cyclotron (gsu.edu)



Lawrence's 60-inch cyclotron, with magnet poles 60 inches (5 feet, 1.5 meters) in diameter, at the University of California Lawrence Radiation Laboratory, Berkeley, in August, 1939. **Image credit:** Wikipedia

What to do if particle becomes relativistic?

Iso-cyclotron (Isochronous)

Keep frequency constant and vary the magnetic field

Image credit: COMET Cyclotron | CPT | Paul Scherrer Institut (PSI)

Synchro-cyclotron

Keep magnetic field constant and vary the frequency

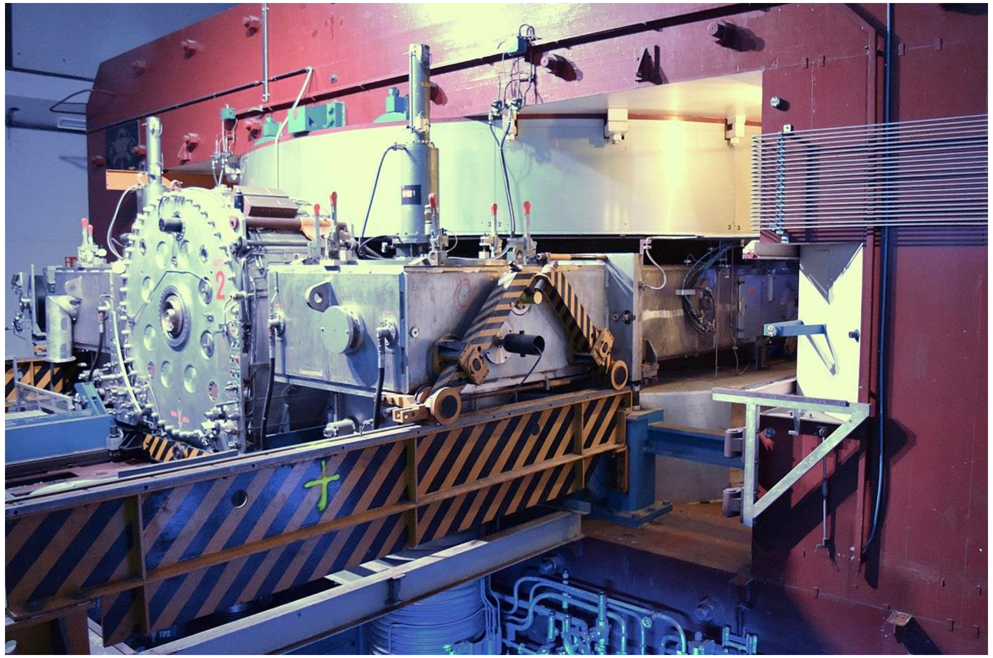
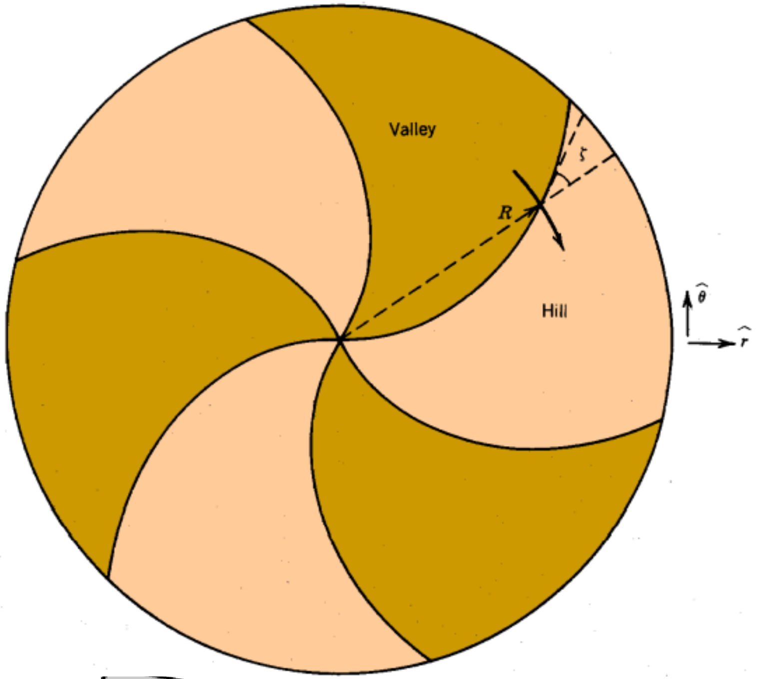


Image source: Wikipedia

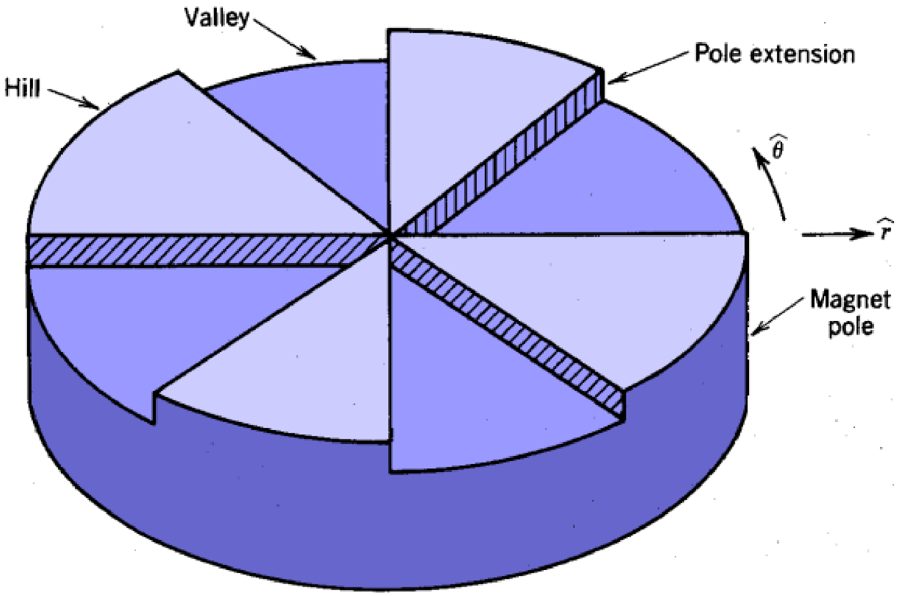
What to do if particle becomes relativistic?



Iso-cyclotron (Isochronous)

Keep frequency constant and vary the magnetic field

Alias: Azimuthal varying field cyclotron



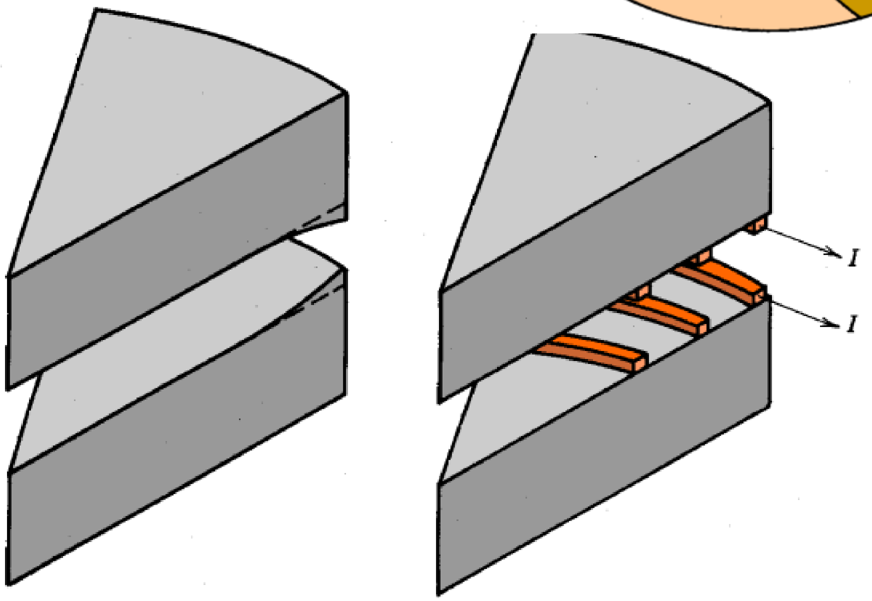


Image credit: http://www.geology.wisc.edu/~johnf/g777/Misc/chap15.pdf

What to do if particle becomes relativistic?

- Higher energy achievable
- Lower average beam current
- Compact dimension

Synchro-cyclotron

Keep magnetic field constant and vary the frequency

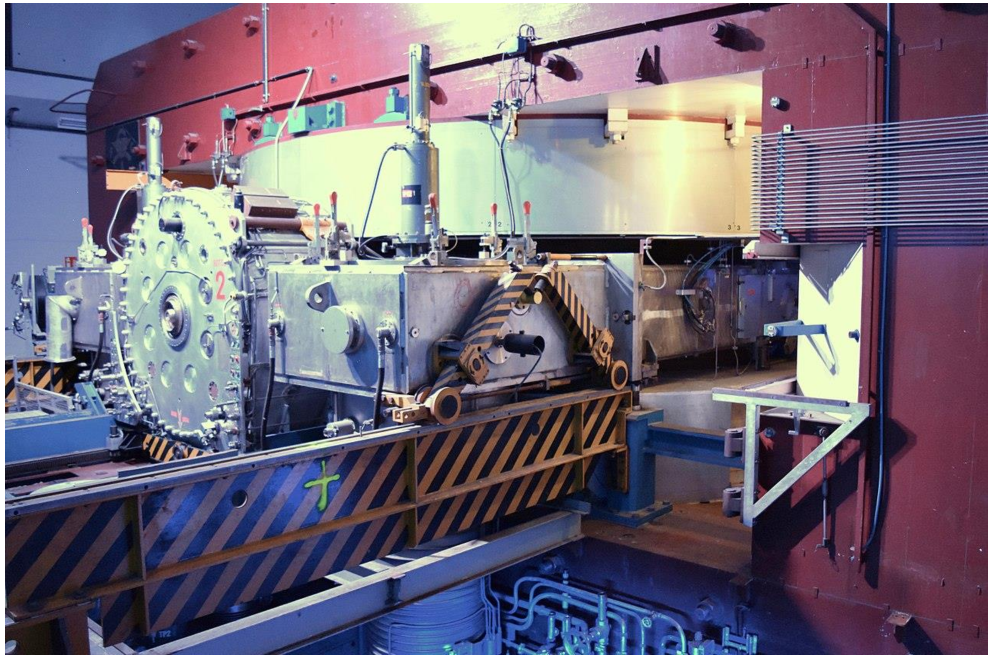


Image credit: Wikipedia

Layout of a cyclotron complex for proton therapy

PSI

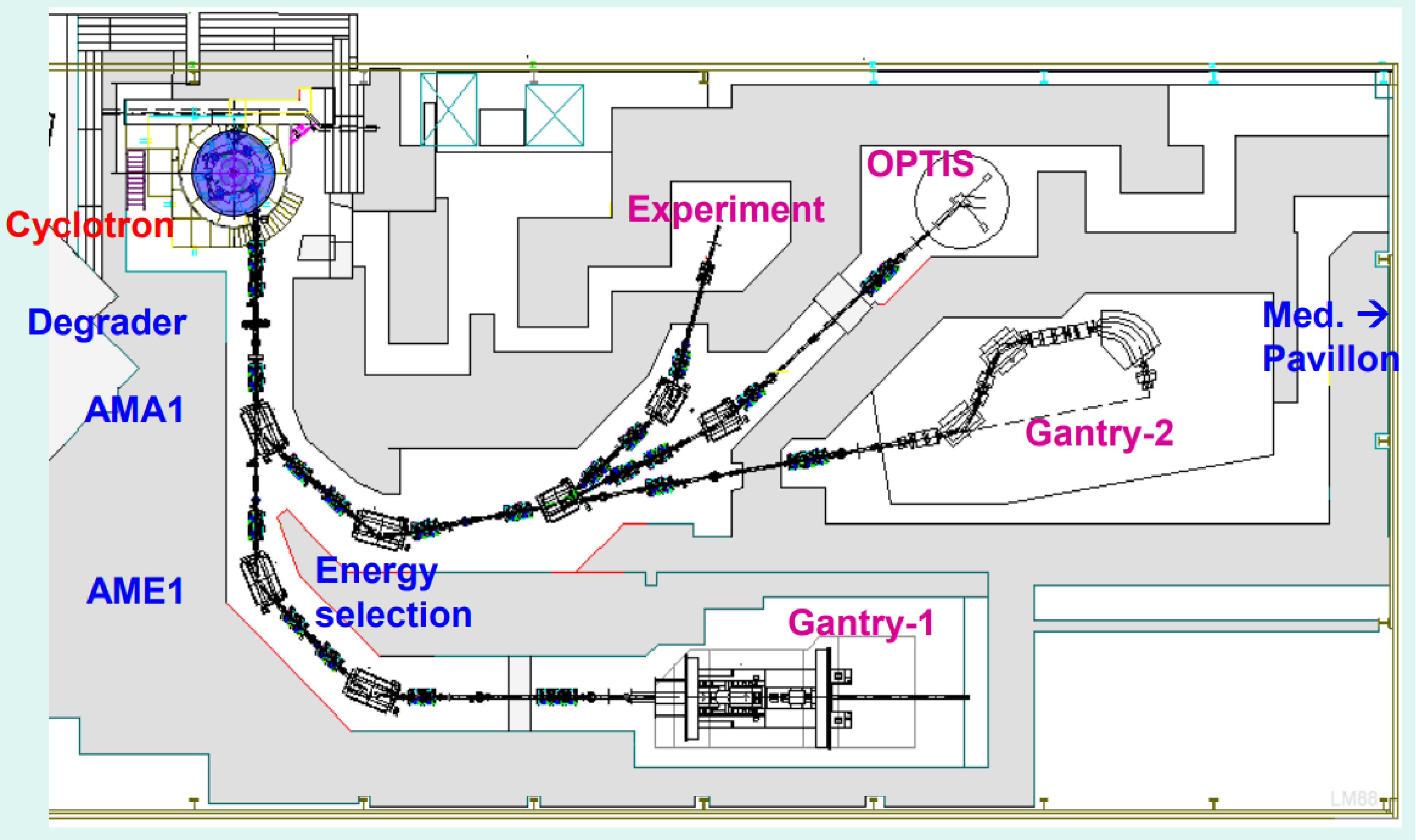


Image credit: Accelerators for proton therapy, Presentation by, Marco Schippers, PSI - JUAS

What if both the frequency and magnetic field can be changed?

Synchrotron

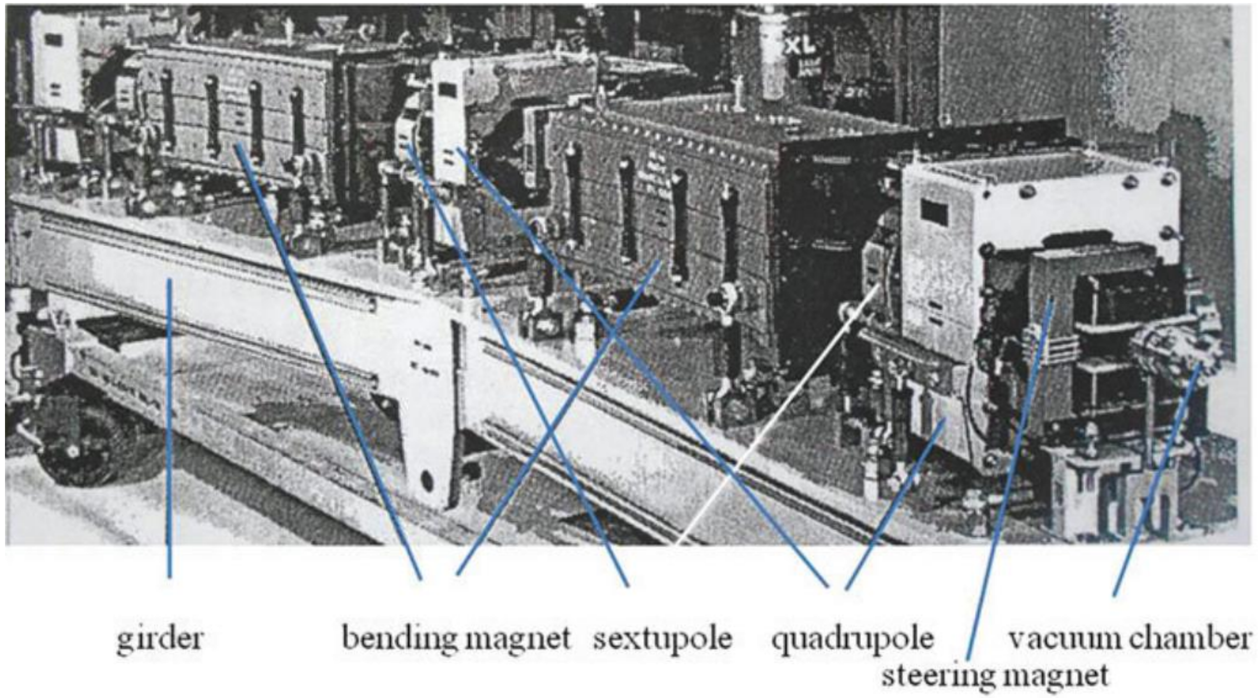


Image credit: Particle Accelerator Physics, Helmut Wiedemann, 4th edition, Springer

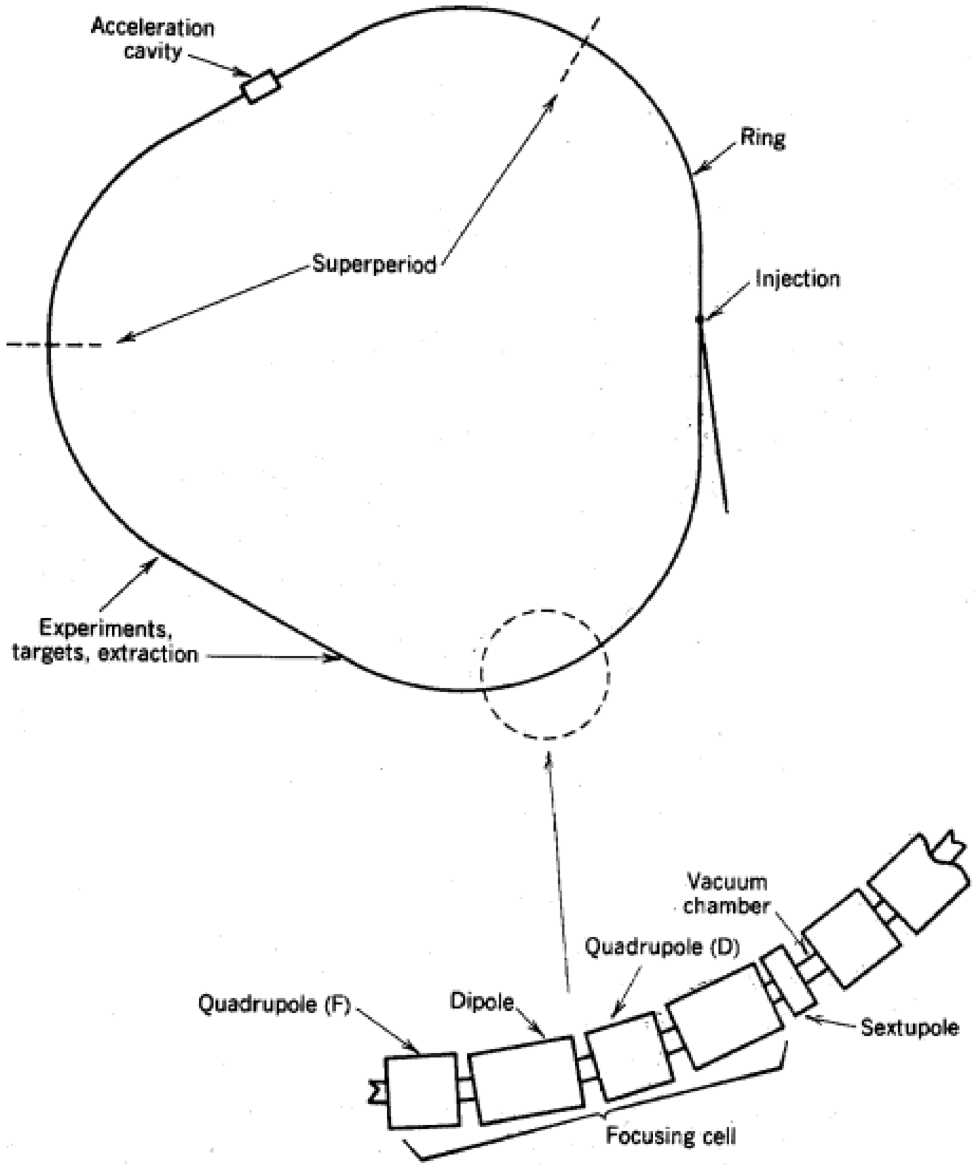


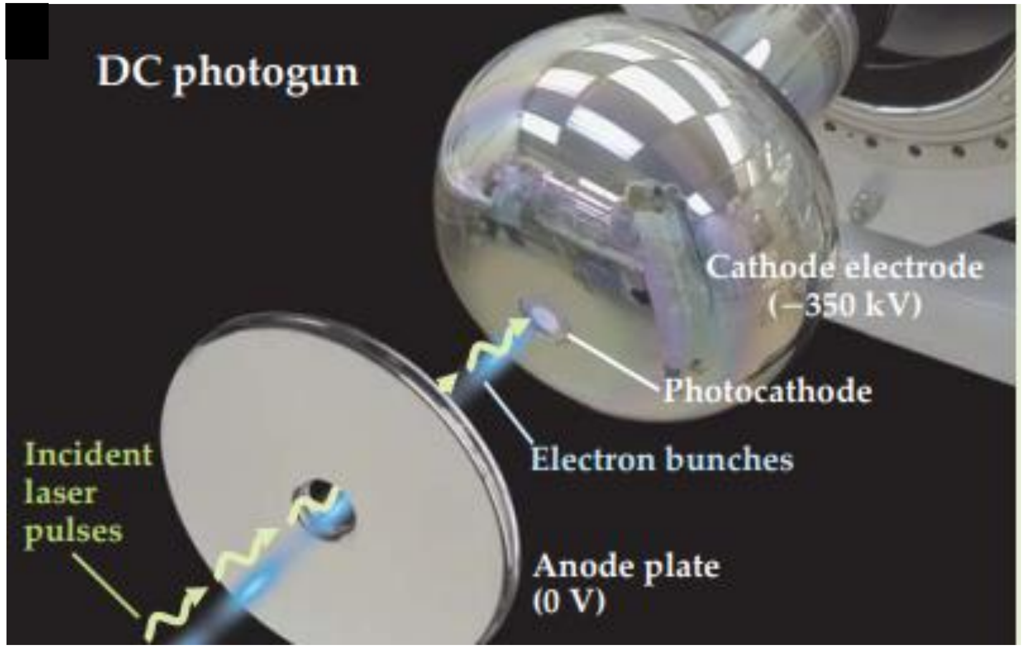
Image credit: http://www.geology.wisc.edu/~johnf/g777/Misc/chap15.pdf

Particle accelerators and medical use

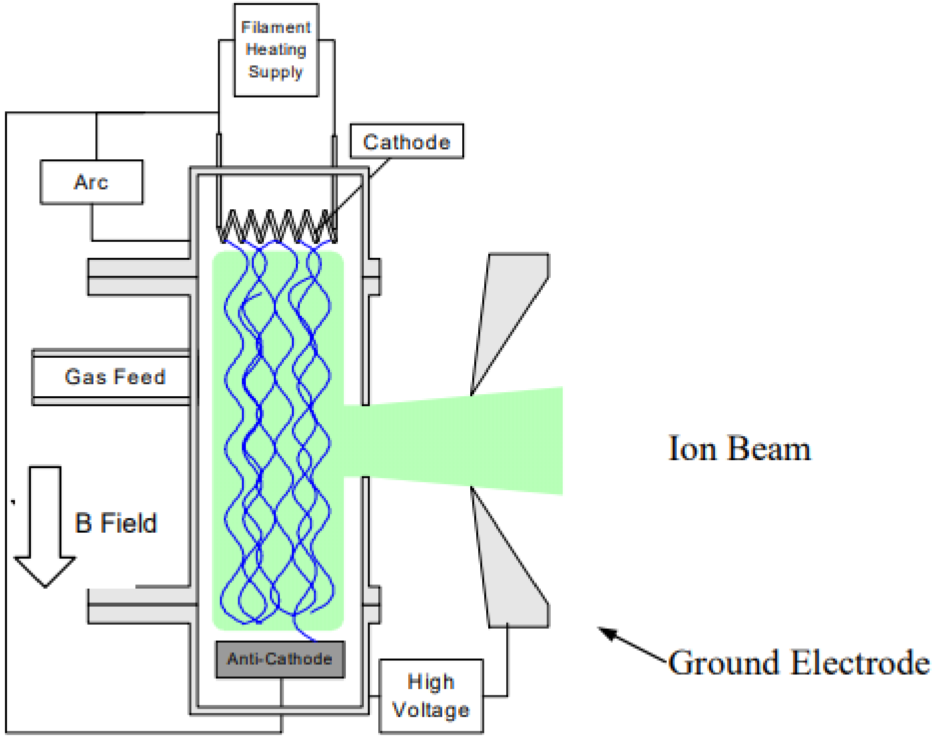
Particle	Accelerator	Energy	Use
Electron	LINAC	~6-25 MeV	Cancer treatment
X-rays	LINAC	~6 MeV	Cancer treatment
	Synchrotron	~100s of keV	Imaging - coronary angiography, bronchography, mammography, computed tomography, x-ray microscopy
Proton	Cyclotron	~20-100 MeV	Radioactive assay preparation for PET, SPECT scanning
	Synchrocyclotron	~250 MeV	Cancer treatment
Carbon	Synchrotron	~400 MeV/u	Cancer treatment

How do you get free electrons?

Particle sources?



Photocathode based electron source.
Image credit: Electron sources for accelerators Carlos Hernandez-Garcia, Patrick G. O'Shea, and Marcy L. Stutzman, Physics Today, February 2008 (Volume 61, Issue 2).



Penning ion source
Image source: electron and ion sources for particle accelerators R. Scrivens

Thank you.

Hope you’ve all been accelerated!!

Some questions to think about

- **Q1:** Can you design a multistage accelerator using the gravitational force?
- **Q2:** Is it possible to calculate the electric field at the centre of a Toroid?
- **Q3:** Suppose you want to build a LINAC to accelerate protons to energies of 1 TeV. How long would it have to be?
- **Q4:** What is fundamental? Force/field or the particle charge?