Summer Student Lectures 2022

Particle Accelerators and Beam Dynamics
Part 1

by

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29.06.2022

Outline

3 Lectures

L1: Accelerators

→ Why we need (different) accelerators?

L2*: Transverse Beam Dynamics

→ How to circulate particles?

L3*: Longitudinal Beam Dynamics & Colliders

→ How to build a particle collider?

*With focus on synchrotrons and linear beam dynamics.

Acknowledgement

These lectures are based on lectures given at

- ***CERN Accelerator School (CAS)***
- ***CERN Summer Student Program***
- ***AXEL*** – lecture series on particle accelerators, given at CERN within the framework of the Technical Training Program

Mainly by

- **Bernhard Holzer**
- **Verena Kain**
- **Frank Tecker**
- **Rende Steerenberg**

Lectures or proceedings of the above series are freely available on the web.

Some more references .....

Accelerators for Pedestrians
Author: Simon Baird
Reference: CERN-AB-Note-2007-014 (Free from the Web)

The Physics of Particle Accelerators, an introduction
Author: Klaus Wille
Reference: ISBN 0-19-850549-3 (CERN Book shop)

Particle Accelerator Physics (3rd edition)
Author: Helmut Widemann
Reference: ISBN 978-3-540-49043-2 (CERN Book shop)

Accelerator Physics (3rd edition)
Author: S. Y. Lee
Reference: ISBN 978-981-4374-94-1 (CERN Book shop)

What are Particle Accelerators?

Please write your associations and key words into the chat.

Why do we need accelerators?

1st Particle Physics Experiment

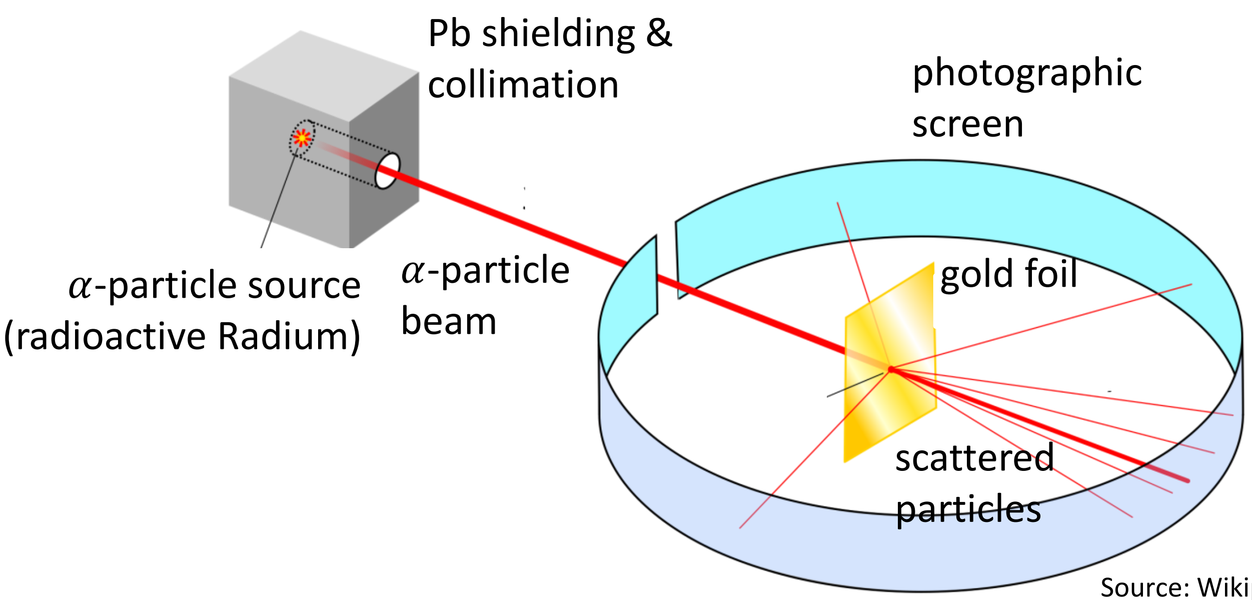
1911

H. Geiger,
E. Marsden und
E. Rutherford

Rutherford Scattering

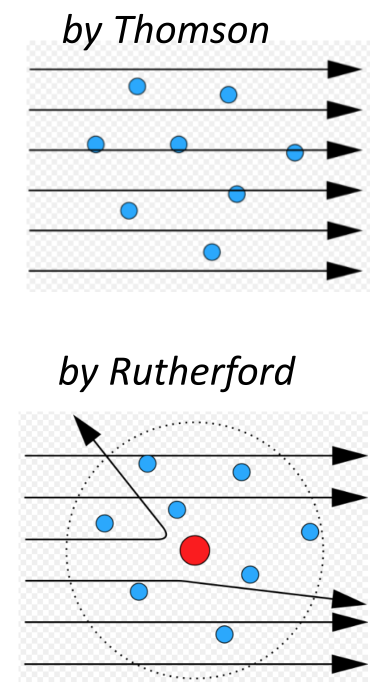
Fire **alpha particles** against a thin **gold foil.**

Observation of scattering behavior revealed entirely new understanding of the **structure within atoms**.



Source: Wikipedia

Atomic Model

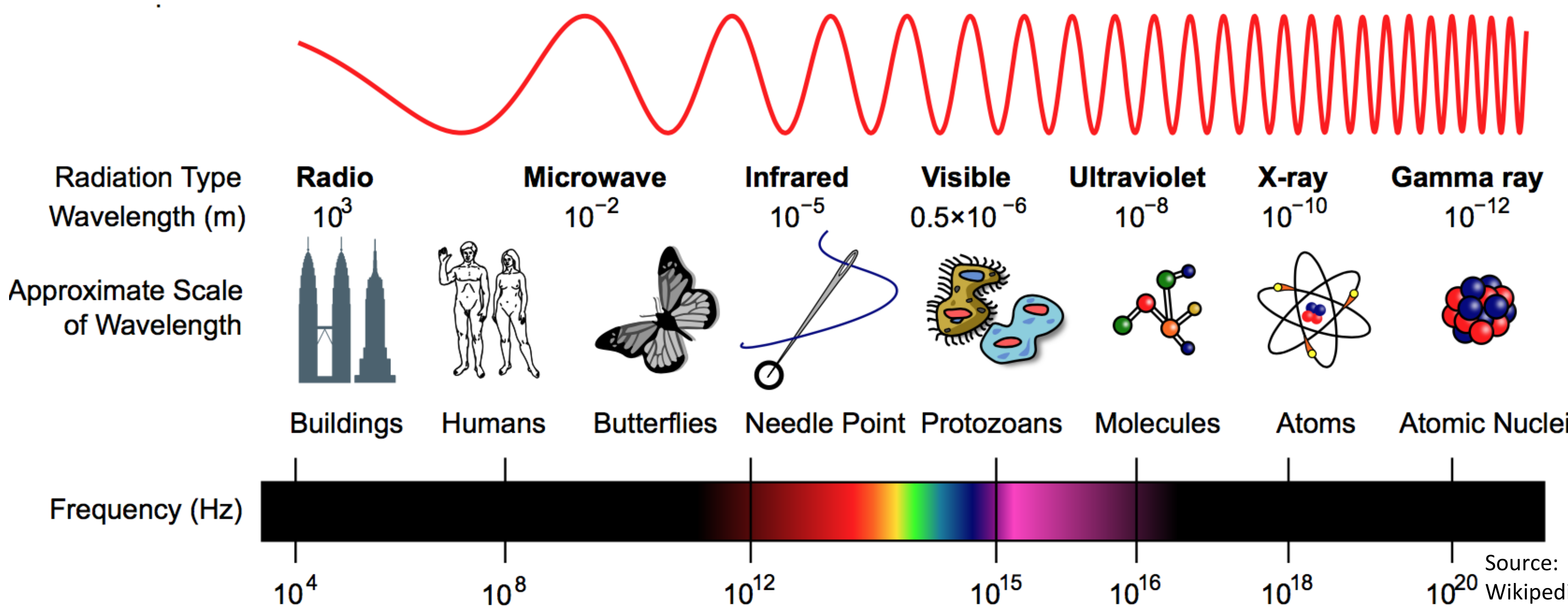


Source: Wikipedia (CC BY-SA 4.0)

α-particle is identical to an helium-4 nucleus (2 protons + 2 neutrons)

View into smaller dimensions

Study the inner structure of matter with scattering experiments.
The wavelength of the probe radiation needs to be smaller than the object to resolve.



Source: Wikipedia (CC BY-SA 3.0)

$$\lambda = \frac{h\,c}{E}$$

Visible

λ = 400 ➔ 700 nm

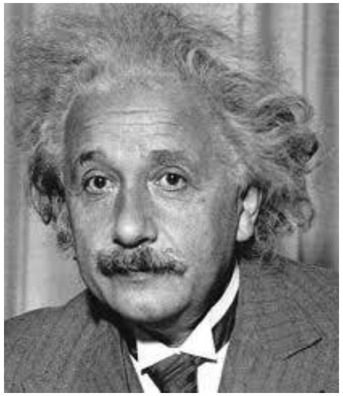
X-ray

λ = 0.01 ➔ 10 nm

Particle accelerators

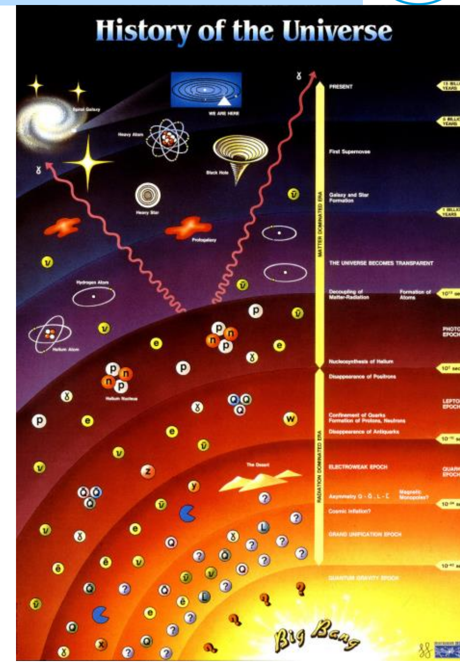
$\lambda < 0.01$ nm

Production of new matter



$$E = m c^2$$

Study of particles that do not exist in our natural environment, since they are too heavy or unstable.



Accelerators give energy to particles.

In particle collisions, this energy is transformed into matter that the detectors observe.

The higher the initial particle's energy, the heavier new particles can be produced.

Where do we need accelerators?

Where are accelerators used?

Security
- Airports & boarders
- Nuclear security
- Imaging

Industry
- Material studies and processing
- Food sterilization
- Ion implantation

Energy
- Destroying radioactive waste
- Energy production
- Nuclear fusion
- Thorium fuel amplifier

World wide about >30’000 particle accelerators are in operation with a large variety of applications.

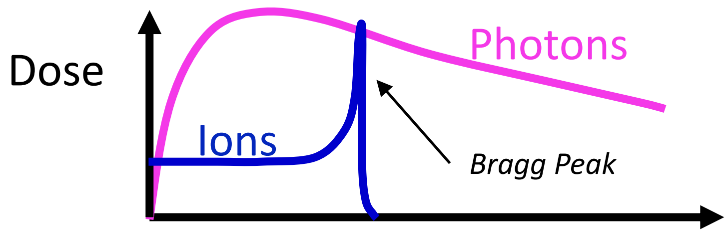
Health
- Diagnostic and imaging
- X-rays
- Cancer therapy
- Radioisotope production

Research (<1%)
- Particle Physics
- Storage rings & Colliders
- Material science
- Light sources
- R&D

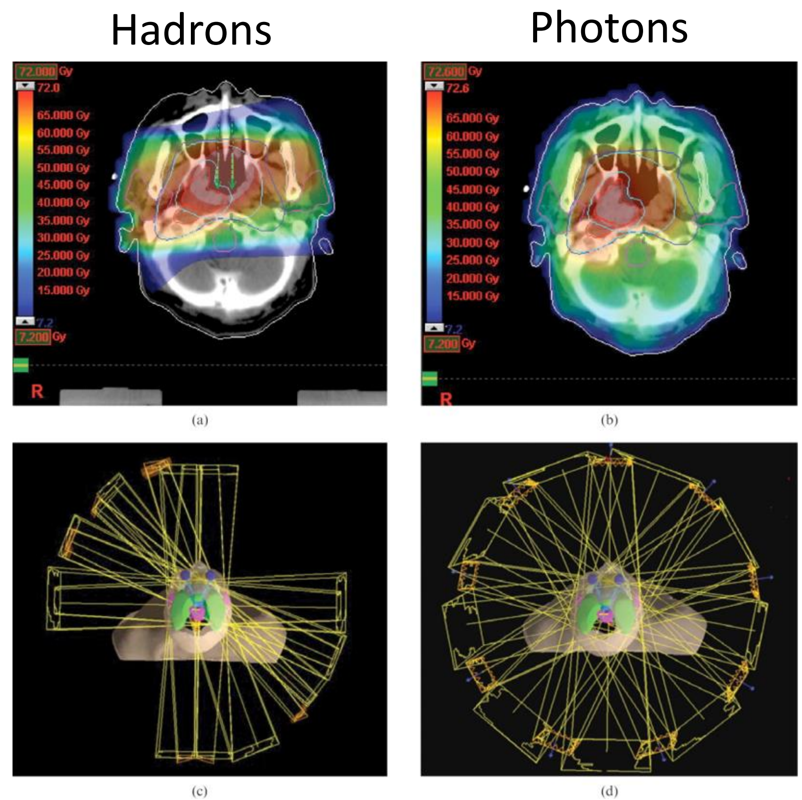
Sources:
A. Faus-Golfe, ‘The brave new world of accelerator application’, TUYPLS1, IPAC’19, Melbourne, Australia, 2019
APAE report, ‘Applications of particle accelerators in Europe’, http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

Applications - Health

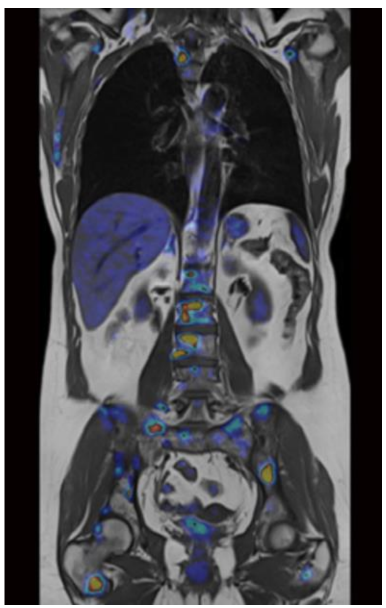
Cancer therapy with photon, proton and ion beams



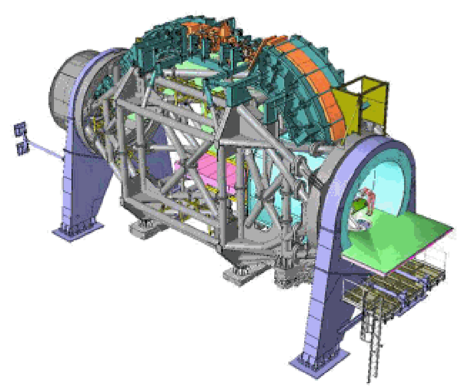
Reduced dose to healthy tissue with ion beam irradiation.



Radioisotope production



A combined PET/MRI image revealing cancer metastases (credit: Siemens/TUM/LMU).

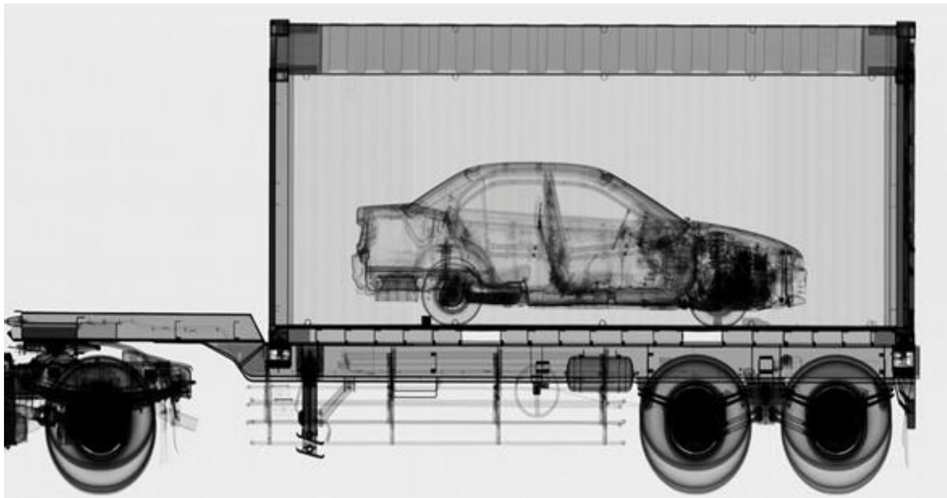


Gantry for beam transport and irradiation from different angles

Image sources:
APAE report, 'Applications of particle accelerators in Europe', http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

Application - Security

Airport & boarder control



Cargo containers scanned at ports and border crossings.

Accelerator-based sources of X-Rays can be far more penetrating (6MV) than Co-60 sources.

Container must be scanned in 30 seconds.

Image source: Varian medical systems

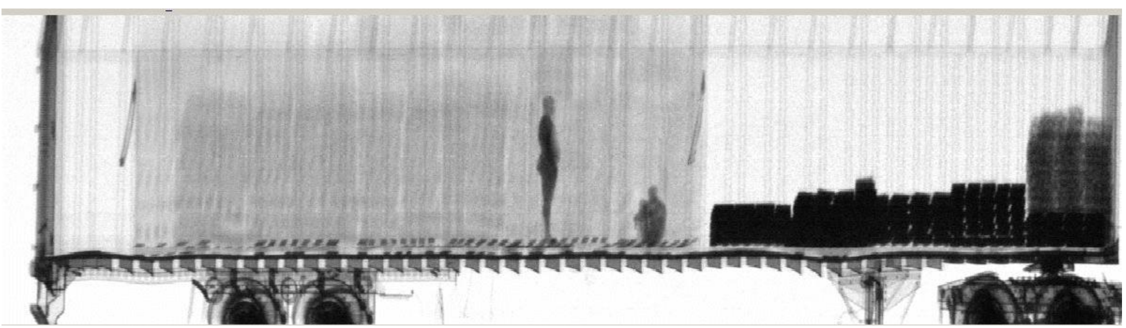
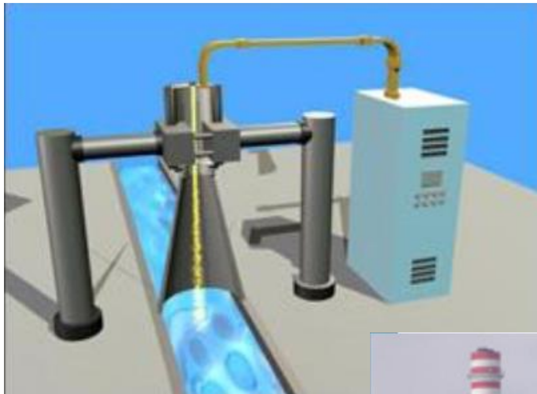


Image: dutch.euro

Slide of Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

Application - Industry

Environmental applications



Treating waste water or sewage
Purifying drinking water

Removal of NO_x and SO_2 from flue gas emissions

Ion implantation in semiconductors

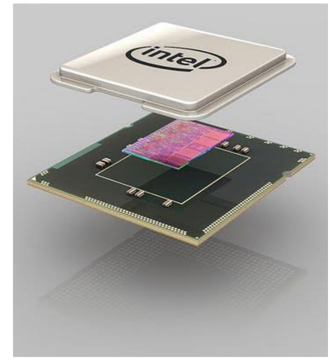


Image courtesy of Intel

Sterilization

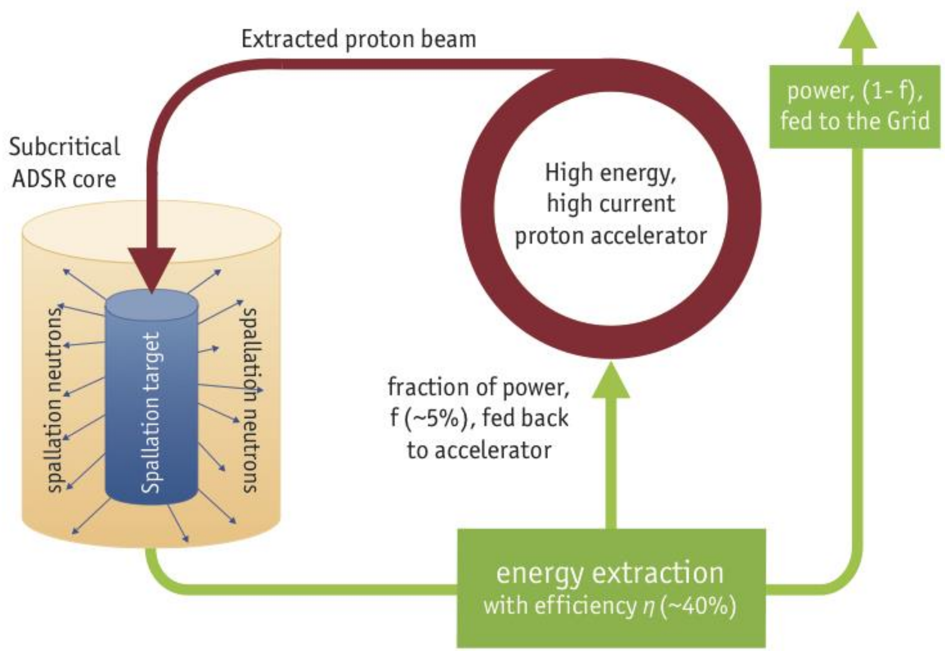
'Cold pasteurization' - **Food irradiation** before packaging

Image Sources:
APAE report, 'Applications of particle accelerators in Europe', http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

Accelerator Driven System (ADS)

Transmutation of nuclear waste isotopes or energy generation

General layout of a ADS



MYRRHA is a *subcritical reactor* which means that it has insufficient fissile material to spontaneously maintain the fission and it needs to be continuously *fed by an external neutron source: a particle accelerator*. This accelerator fires protons at a target, creating the neutrons that will maintain the fission chain reactions in the reactor.

Major challenges for accelerator technology: beam power (>10MW) and reliability.

Developed at the Belgian nuclear research center SCK-CEN in Mol.

Sources:
APAE report, 'Applications of particle accelerators in Europe', http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague
Webpage of SCK-CEN: http://sckcen.be/en/Technology_future/MYRRHA

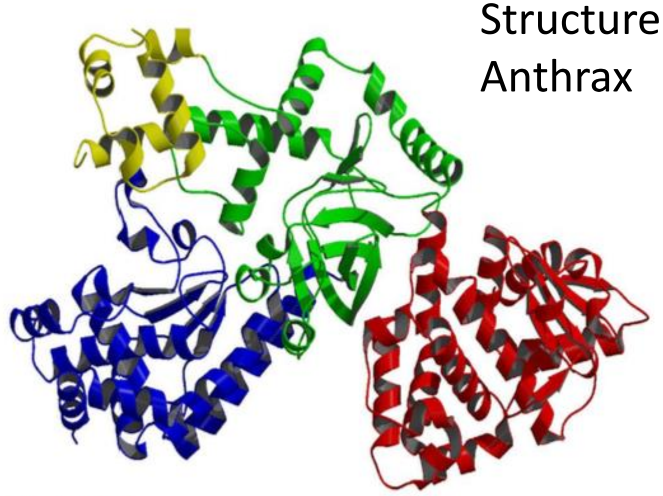
Application - Science

Archeology/Heritage

The "Ritratto Trivulzio" by Antonello da Messina during the analysis with particle accelerator. Image credit: LABEC, INFN's Laboratory for Cultural Heritage and Environment, Italy

Synchrotron Light Sources: Structure of Proteins

Diffraction pattern from pea lectin



Structure of Anthrax

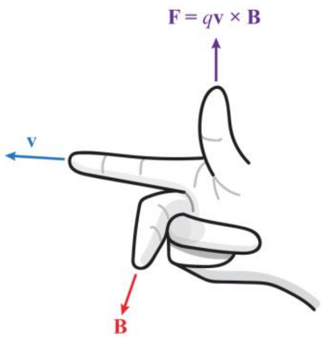
Sources:
APAE report, 'Applications of particle accelerators in Europe', http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

How can we accelerate particles?

How can we increase the energy of a particle?

A *charged* particles that travels through an electro-magnetic field feels the **Lorentz force**:

$$\vec{F} = q(\vec{v} \times \vec{B} + \vec{E})$$



Magnetic field *B*:

Force acts perpendicular to path.

→ **Can change direction of particle**

→ cannot accelerate

Electric field E:

Force acts parallel to path.

→ **Can accelerate**

→ not optimal for deflection

Numeric Example:

$v = c, B = 1\mathrm{T}$

$E = vB = 3\mathrm{x}10^8\ \mathrm{m/s\ x\ 1T}$

$\boldsymbol{E = 300\ \mathrm{MV/m}}$

Technical limit for el. field:
$\mathrm{E} \propto 1\mathrm{MV/m}$

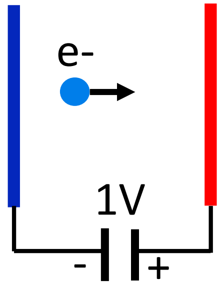
How can we increase the energy of a particle?

The energy gain ΔE of the particle is defined by the integral of the force *F* over the travelled path *dr*:

$$\Delta E = q \int_{r_1}^{r_2} (\vec{v} \times \vec{B} + \vec{E}) d\vec{r}$$

$$= q \int_{r_1}^{r_2} \vec{E} d\vec{r} = qU.$$

$(\vec{v} \times \vec{B}) d\vec{r}$ *= 0*



Energy is measured in units of **electron Volts (eV).**

Energy gain of an electron moved across a potential difference of 1 Volt.

1 eV = 1.602176565(35) x 10^{-19} x 1 J

With $\boldsymbol{E = mc^2}$ unit of mass *m* is **eV/c²**

With $\boldsymbol{E^2 = (mc^2)^2 + p^2c^2}$ unit of momentum *p* is **eV/c**

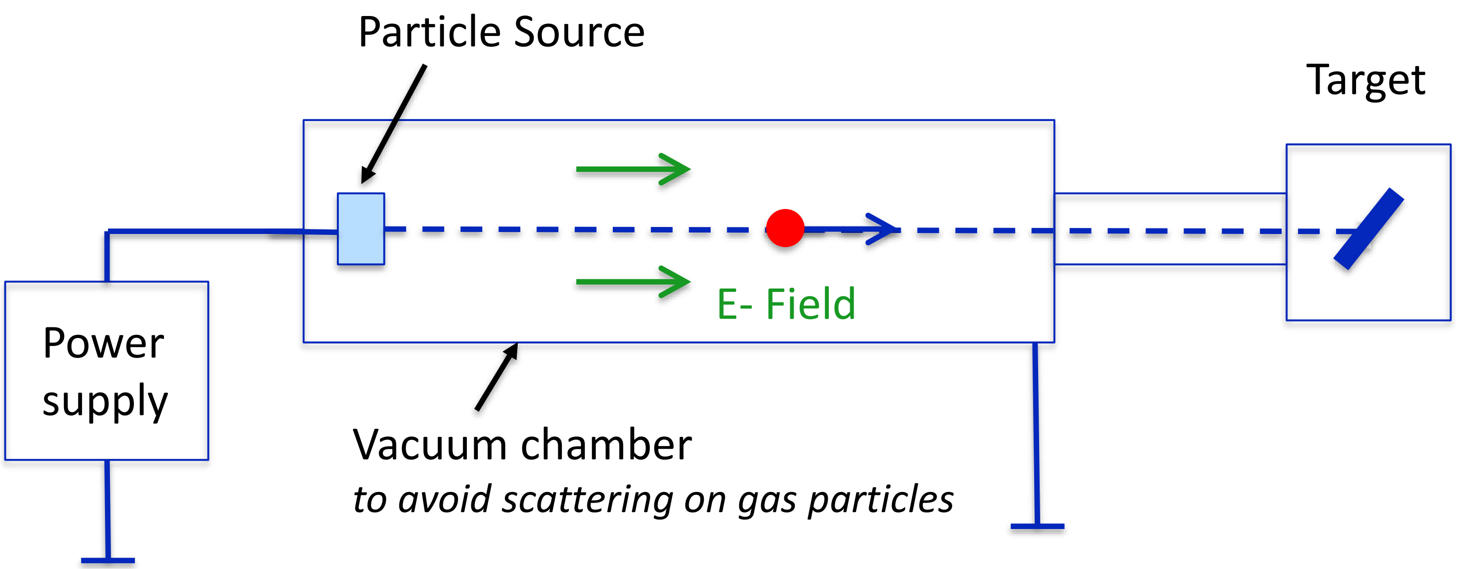
Definition of Units

Which types of accelerators exist?
and
How do they work?

Basic Accelerator

Electro-static accelerator (most basic accelerator)
→ Charged particle travels through a fixed high voltage U

Energy gain: $\Delta \boldsymbol{E} = \boldsymbol{eU}$

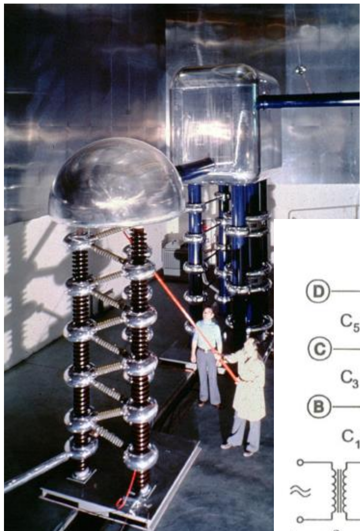


Final particle energy is limited by a maximum reachable voltage.
Max. voltage limited by corona formation and discharge to **~10MV**.

Electrostatic Accelerators – 1930s

Cockcroft-Walton cascade generator

1928



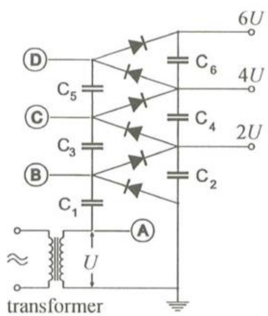


Image Credit: K. Wille

Concept:

rectifier circuit, built of capacitors and diodes

(Greinacker circuit)

Limitation:

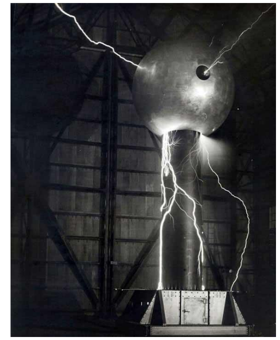
Electrical discharge in air

(Paschen Law)

Max. Voltage ~ 1 MV

Van de Graaff accelerator

1930



Concept:

mechanical transport of charges via rotating belt

Electrode in high pressure gas to suppress discharge (SF_6)

Max. Voltage ~ 1- 10 MV

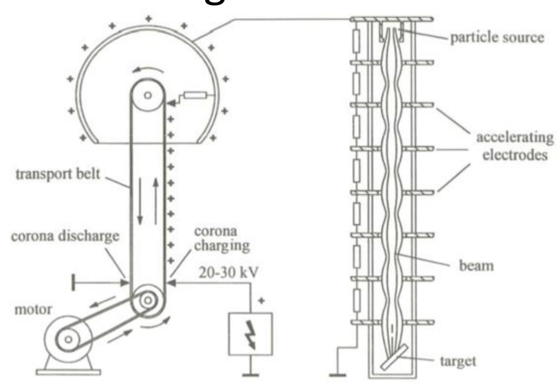


Image Credit: K. Wille

Tandem Van de Graaff accelerator

1936

at MPI Heidelberg

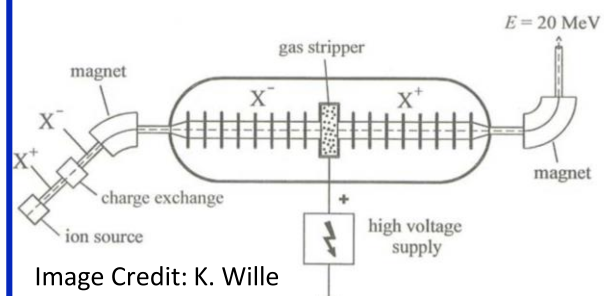


Image Credit: K. Wille

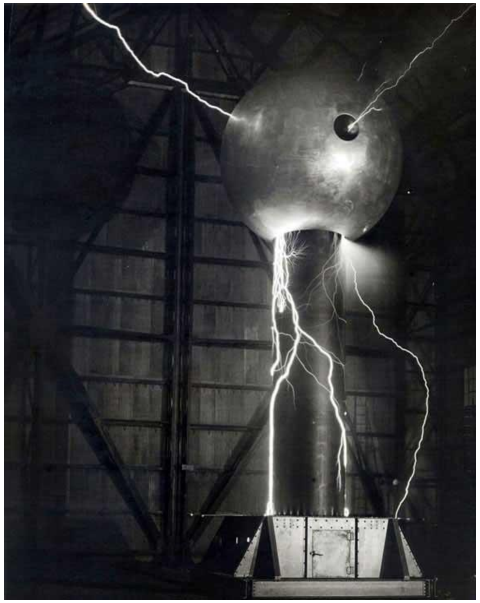
Concept:

Generate negative ions, strip off electrons in the center, use voltage a 2nd time with now positive ions

Max. Voltage ~ 25 MV

Historically largely used as 1st stage accelerators for proton and ion beams.

Electrostatic Accelerator Limitation

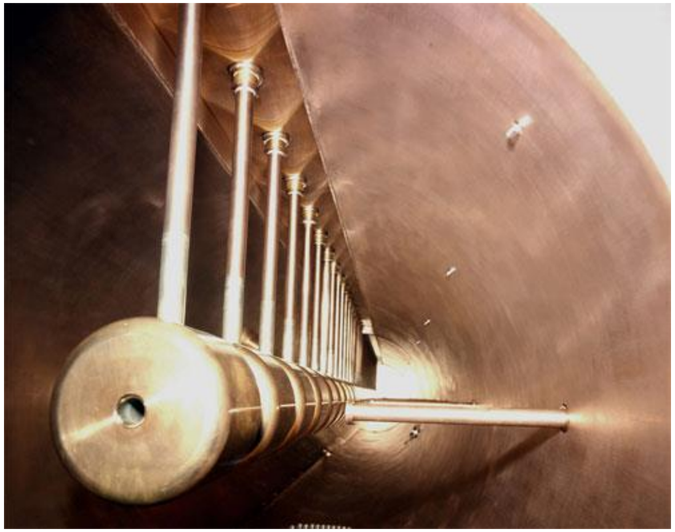


Electrostatic

Limitation:
Generation of max. (direct) voltage before sparking.

Acceleration over one stage or gap.

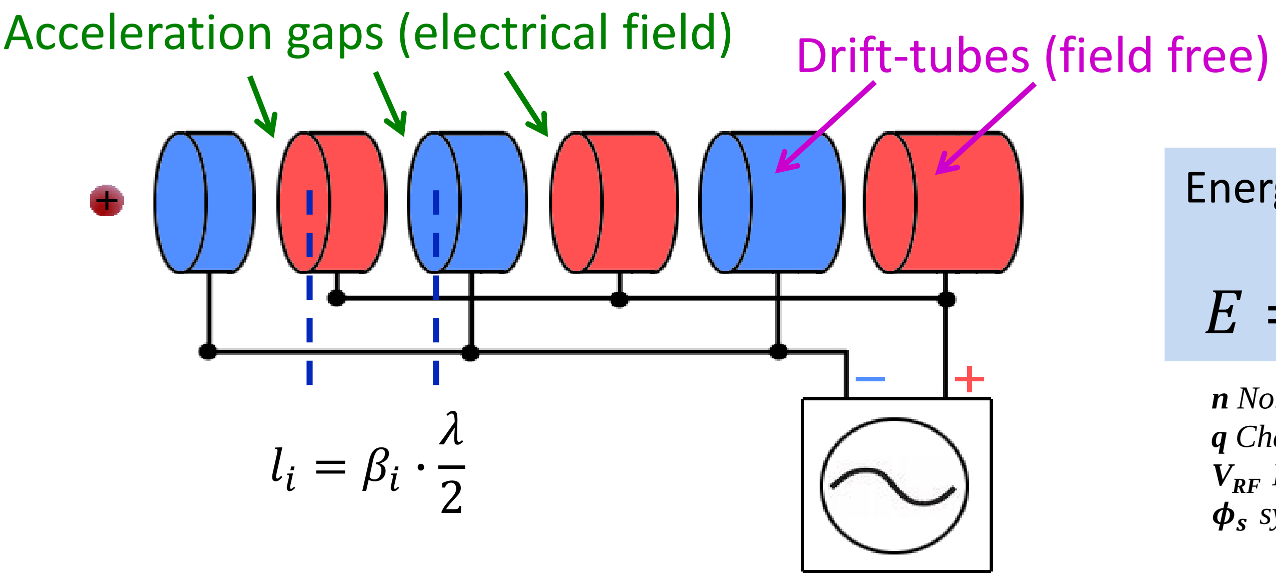
Radio Frequency



Solution:
Use alternating (RF) voltages and pass the particles through many acceleration gaps of the same voltage.

1925 idea by Ising
1928 first working RF accelerator by Wideroe

LINear ACcelerator (LINAC) - Functionality



$$l_i = \beta_i \cdot \frac{\lambda}{2}$$

Energy gain after *n* gaps:

$$E = n\, q\, V_{RF} \sin \phi_s$$

n *No. of acceleration gaps*
q *Charge of the particle*
$\boldsymbol{V_{RF}}$ *Peak voltage of RF System*
$\boldsymbol{\phi_s}$ *synchronous phase w.r.t. RF field*

- High-frequency RF field (turn-over frequency MHz): $\lambda = c/f_{RF}$
- Particle should only feel the field when the field direction is synchronized.
- Drift-tubes screen the field as long as the field has the reversed polarity.
  - The more energy the particle gains, the faster it becomes (non-relativistic regime)
  - → Drifts have to increase in length.

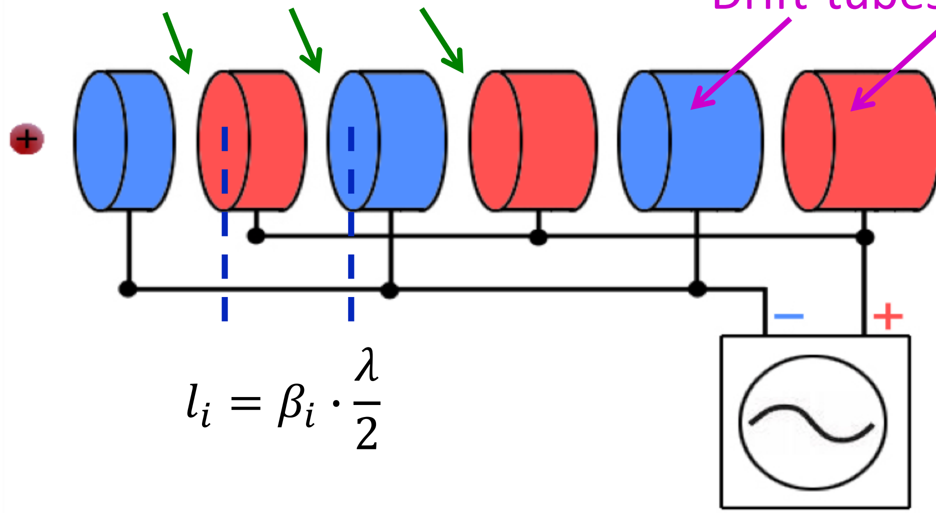
→ Particles have to be clustered into packages (bunches).

Source gif: http://www.lhc-facts.ch

LINAC - Functionality

Acceleration gaps (electrical field)

Drift-tubes (field free)



$$l_i = \beta_i \cdot \frac{\lambda}{2}$$

Solutions are in the back up slides

Exercise:
Once build, can I use my LINAC to accelerate any particle I like?

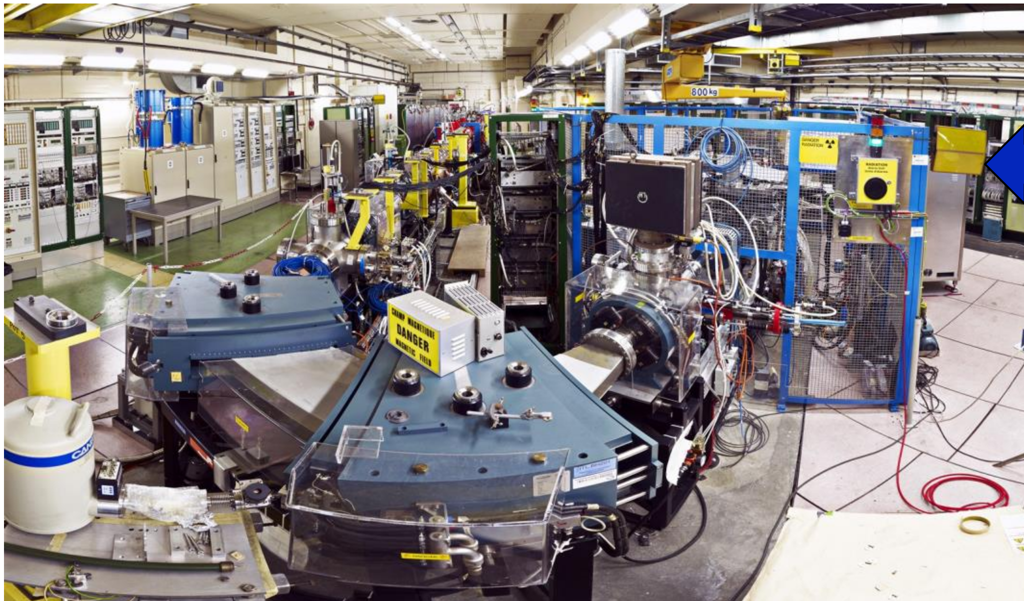
Particles have to be clustered into packages (bunches).

Source gif: http://www.lhc-facts.ch
Photo: https://kuk.verdi.de/darstellende-kunst/juedisches-leben-eine-stadt-in-aktion-585/

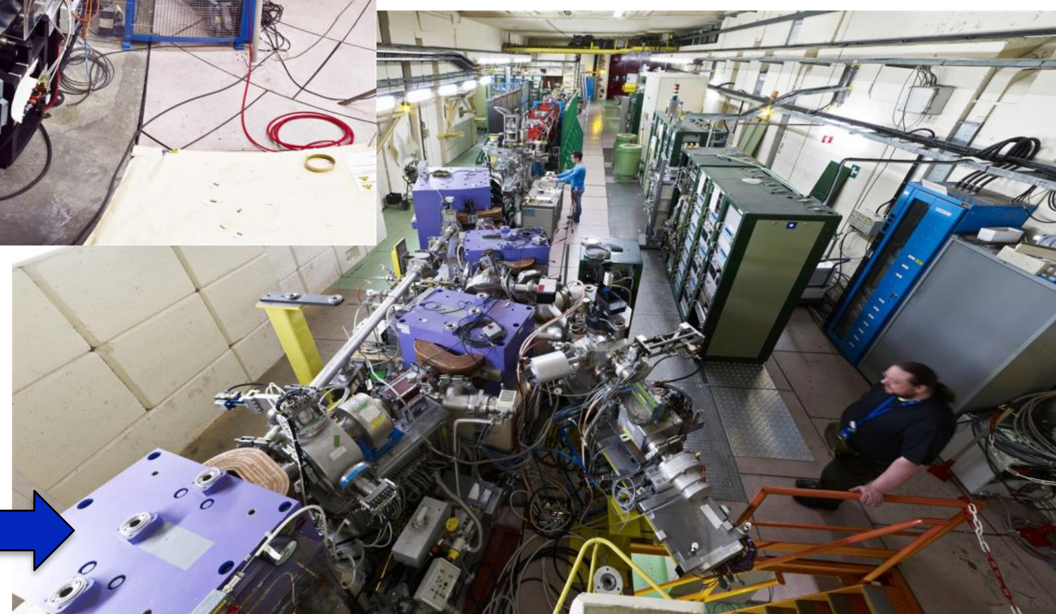
CERN Ion Source & LINAC 3

A LINAC is THE standard proton and ion beam pre-accelerator.

CERN LINAC 3 brings different ion species to LEIR



Ion source (blue cage)
Spectrometer (front)
LINAC (back)



Downstream part of LINAC 3:
Transfer and diagnostics (front)
Accelerating structures (back)

LINAC Limitation

Linear

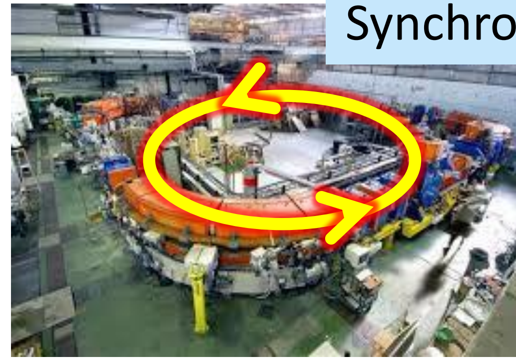
LINAC

Consists of a chain of many accelerating gaps placed on a straight line.

Particles pass the accelerator only ONCE.

The final energy is limited by length.

Circular



Synchrotron

Cyclotron

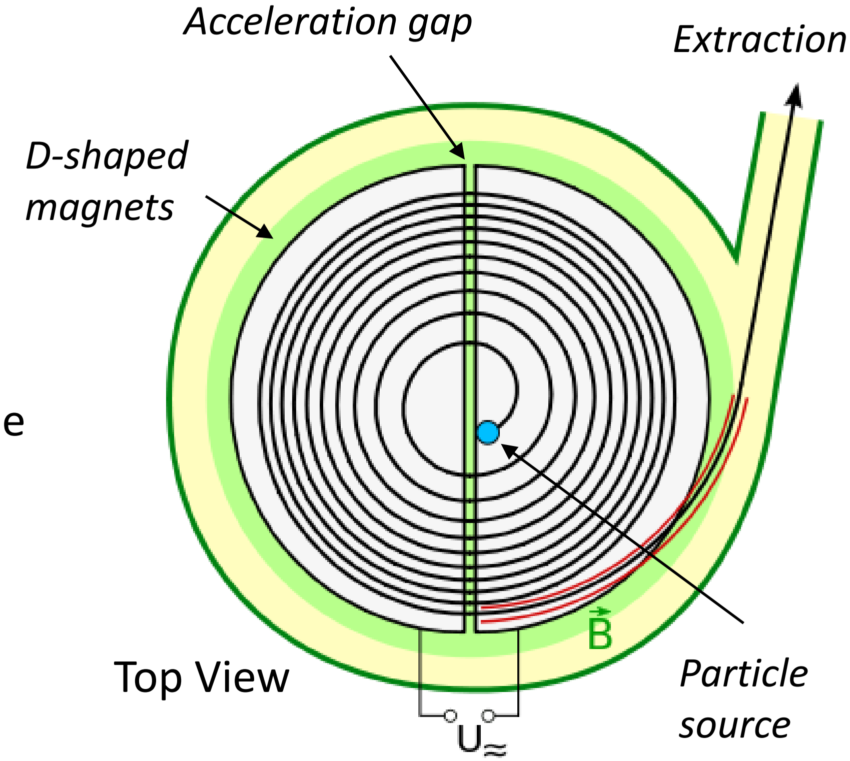
Use magnets that bend particles on a circular orbit.

Particles circulate over MANY turns and can gain more energy at each passage through the acceleration gap.

Cyclotron - "Spiral version of a LINAC"

1929 proposed E.O. Lawrence
1931 built by Livingston

- **Particle Source in the middle**
- Acceleration gap connected to RF source between the two D-shaped magnets.
- **Constant vertical magnetic field** to guide the particles in the horizontal plane. **The radius of particle trajectory becomes larger and larger with larger energy.**
- Particles extracted with a deflector magnet or an electrode.



$\omega_{RF} = \omega_{cyclotron}$

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \longrightarrow F_L = q\,v\,B \longrightarrow$$ Vertical B, No E

$$F_c = m\frac{v^2}{r} \longrightarrow$$ centrifugal force

$$F_L = F_c \longrightarrow \omega = \frac{v}{r} = \frac{qB}{m} \longrightarrow$$ revolution period

f_{RF} = const.
B = const.

Cyclotron Limitation

Constant revolution frequency for constant mass:

$$w = \frac{v}{r} = \frac{Bq}{m} = \frac{Bq}{m(E)}$$

f_{RF} = const.
B = const.

But, for relativistic particles the mass is not constant!

The classical cyclotron only valid for particles up to few % of speed of light.

→ **Not useful for electrons** … already relativistic at ~500 keV.

Modifications:

Synchro-cyclotron	**Isochronous cyclotron**
$f_{RF}(E)$ $B(E)$ or B = const.	f_{RF} = const. $B(r)$

Common accelerator for medium energy protons and ions up to ~60MeV/n, used for nuclear physics, radio isotope production, hadron therapy.

Modern cyclotrons can reach > 500 MeV (PSI, TRIUMF, RIKEN)

PSI Cyclotron

1974

- Diameter ~15m
- Injection energy 72 MeV
- Accelerates protons to E = 590 MeV (i.e. 0.8c) in 186 revolutions

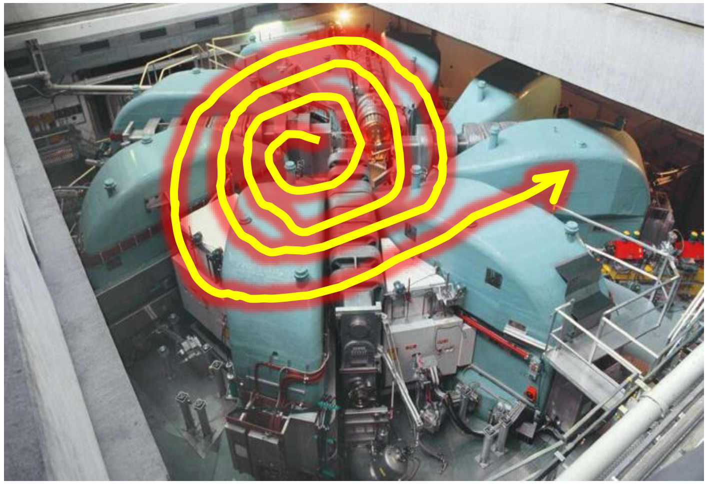
8 sector magnets

4 acceleration cavities

First stage accelerator feeding a smaller cyclotron before the large PSI ring cyclotron is a Cockraft-Walton accelerator.

Source: Paul Scherrer Institute/ Photos: Markus Fischer

Cyclotron Limitation



Cyclotron

Low energy limit.

Not useful for relativistic particles, especially electrons.

Particles pass the accelerator only ONCE.

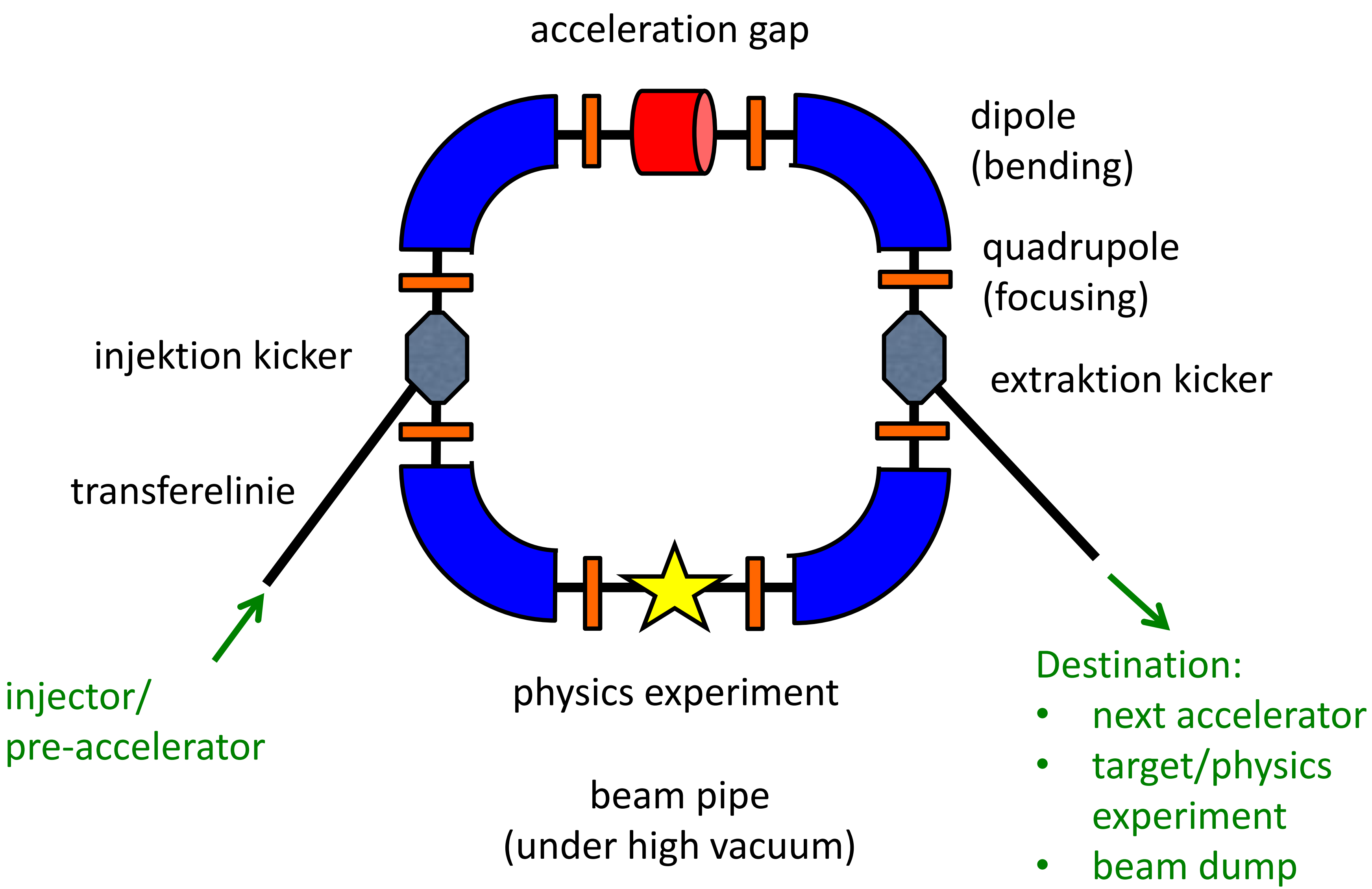
Synchrotron

Define ONE circular orbit (circumference) and vary magnetic field with energy.

Storage over MANY turns (hours).

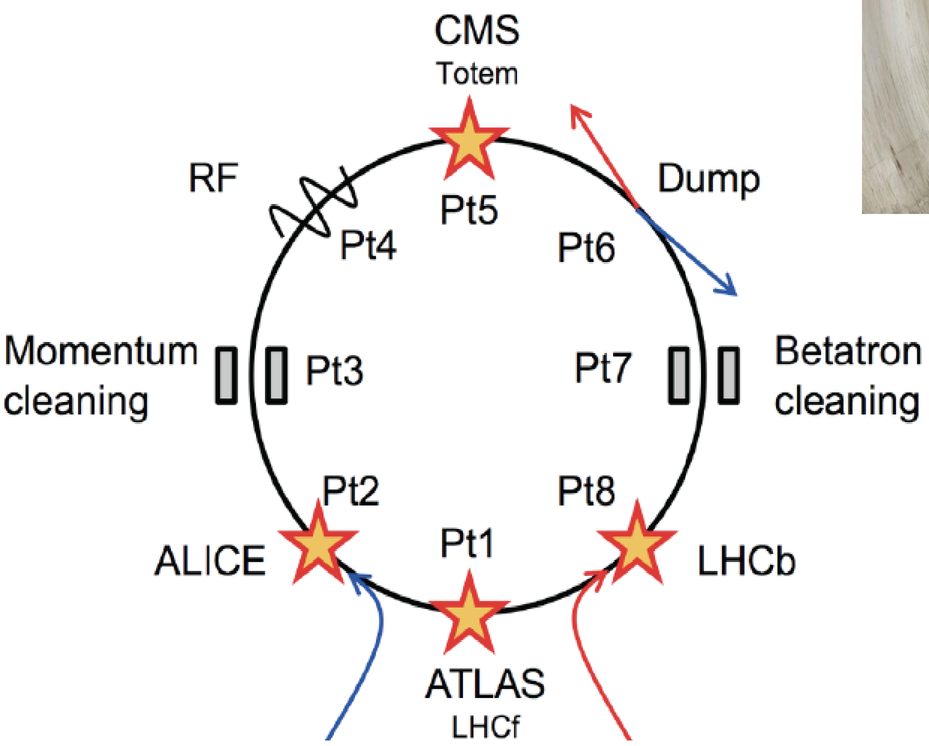
Basic Synchrotron

Synchrotrons are THE accelerators to reach highest particle energies and are able to store the beam over many hours.



Most Famous Example

The largest machine in the world
The Large Hadron Collider (LHC)

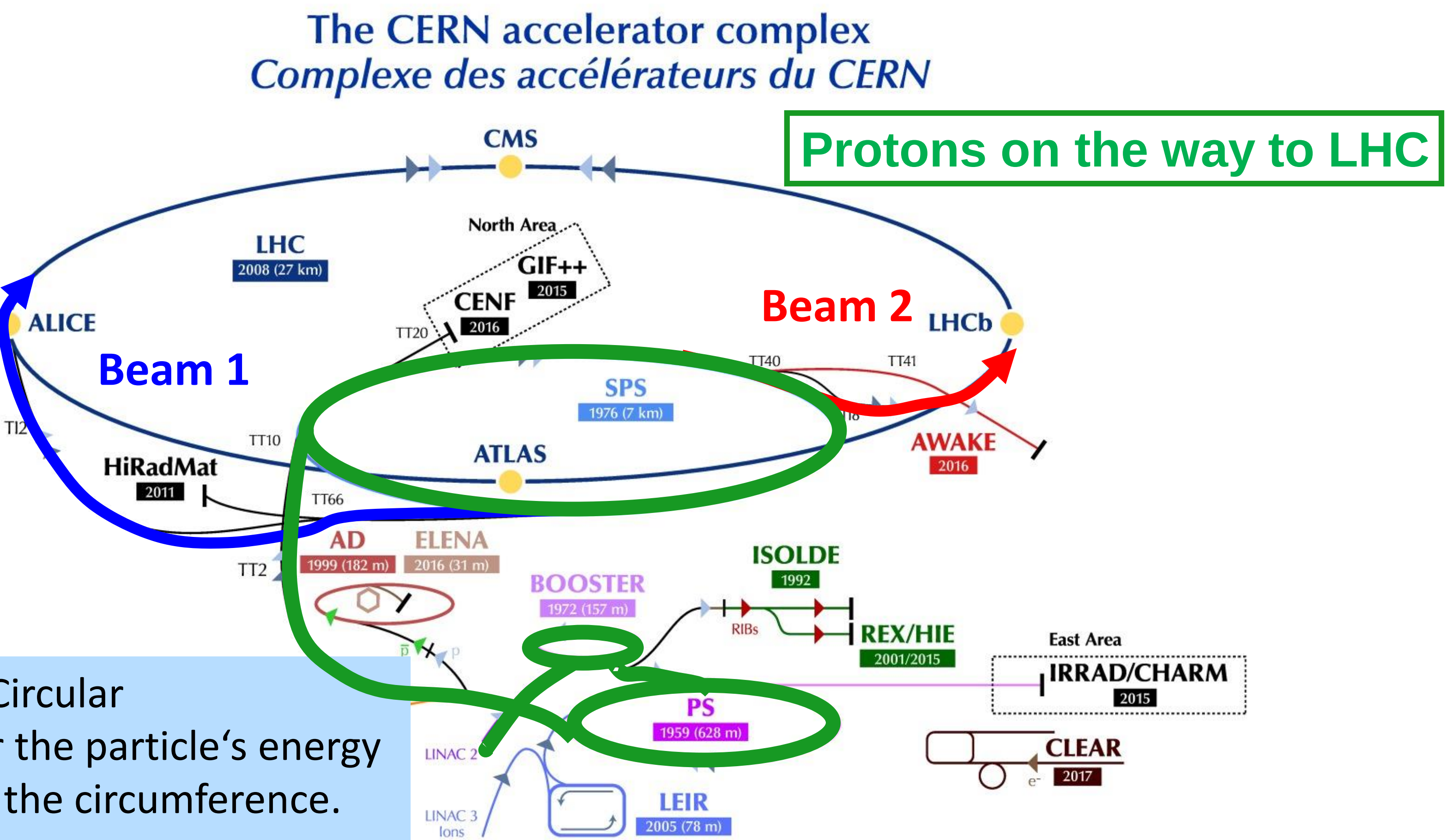


27 km circumference
100m underground

Accelerates protons and heavy-ions to E = 6.8 Z TeV (2022).

Collides 2 counter-rotating beams in 4 physics experiments.

Getting particles into the LHC



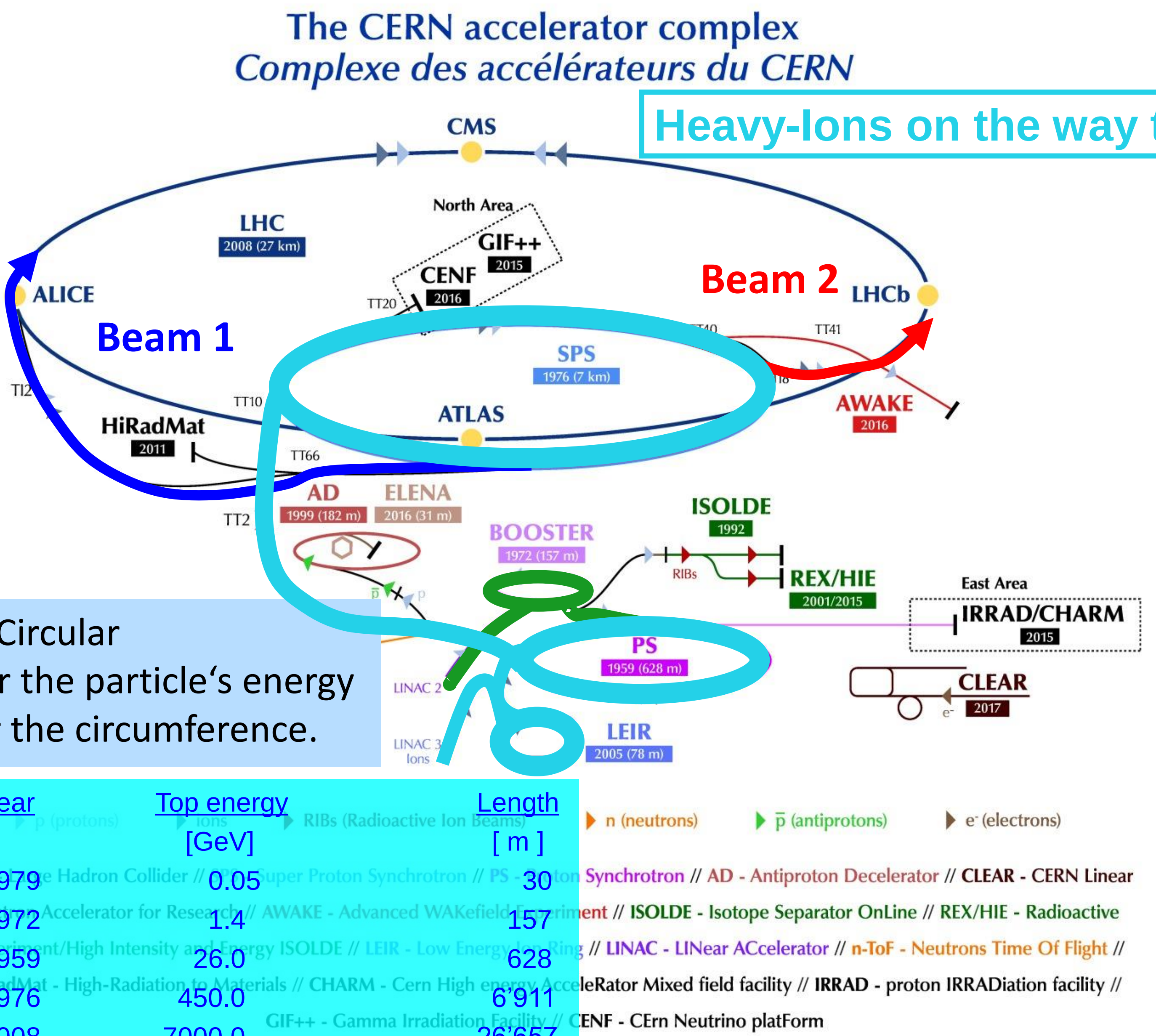
1) Linear → Circular
2) The higher the particle's energy the larger the circumference.

	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

n (neutrons) p̄ (antiprotons) e- (electrons)

Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear
ment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive
// LINAC - LINear ACcelerator // n-ToF - Neutrons Time Of Flight //
leRator Mixed field facility // IRRAD - proton IRRADiation facility //
CENF - CErn Neutrino platForm

Getting particles into the LHC



1) Linear → Circular
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	Year	Top energy [GeV]	Length [m]
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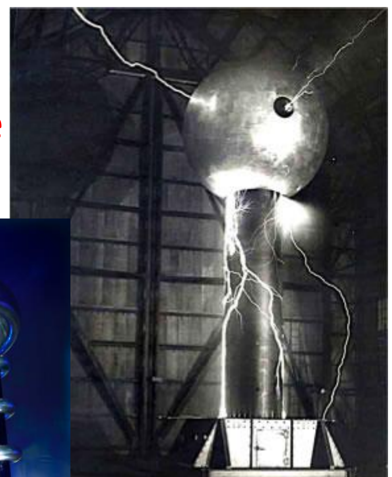
Summary of Accelerator Types and History

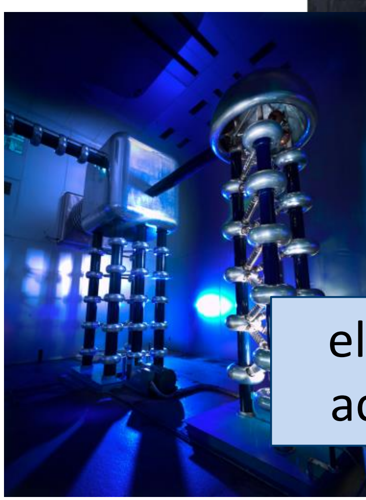
Linear

Limited by length

LINAC

Limited by high voltage discharge

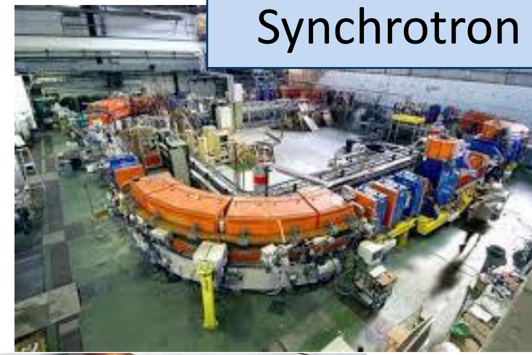




electrostatic accelerators

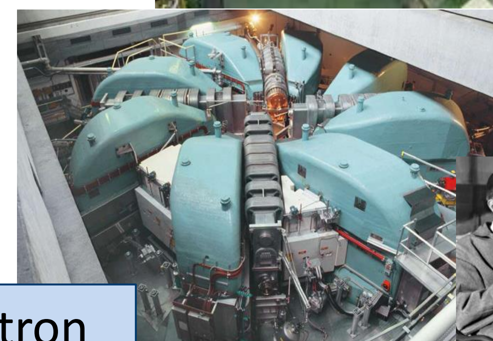
Circular

Limited by max. B-field & radius



Synchrotron

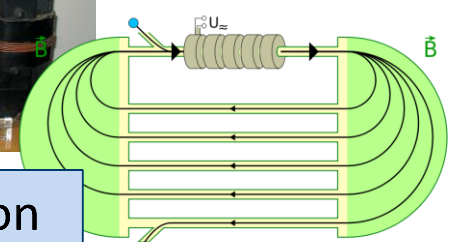
Limited by const. mass & size



Cyclotron

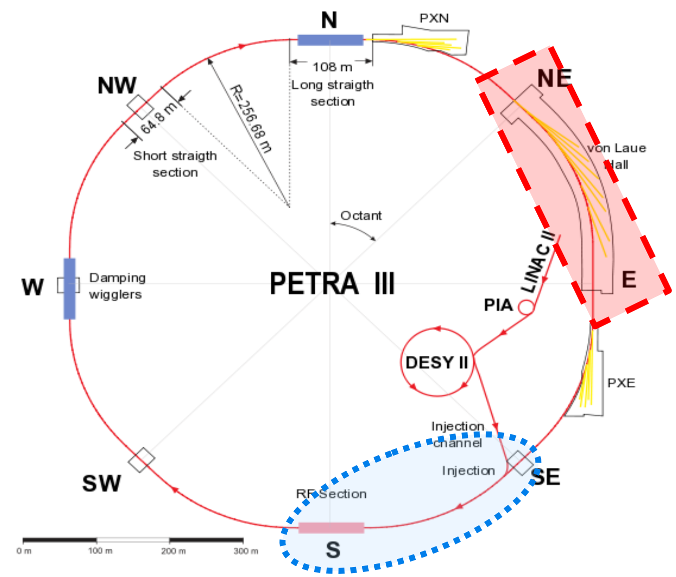
Other types of circular accelerators (not discussed here)

Betatron



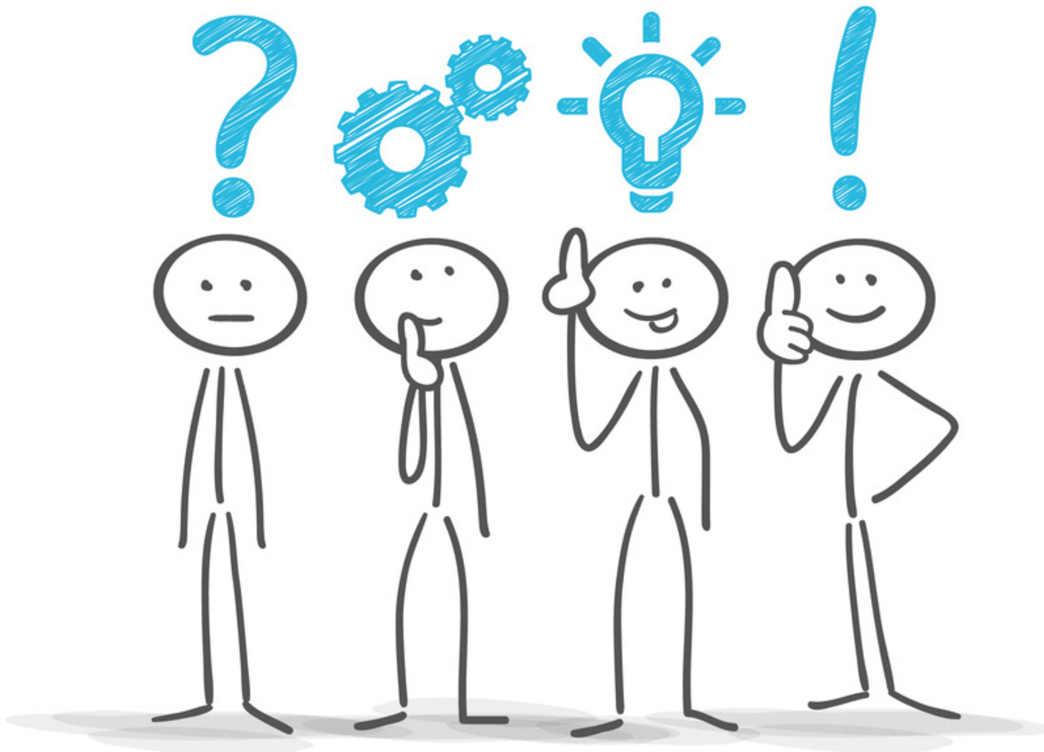
Microtron

Bike Ride through PETRA III @ DESY



Injection, FoDo cell structure, acceleration cavities

Max von Laue Experimental hall: Double Bend Achromat cell structure and undulators for photon beam production



Everything clear! Hmm ….

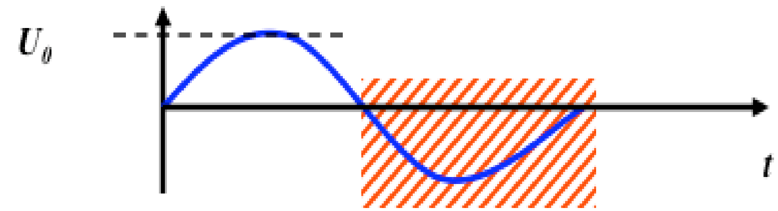
Solutions to Exercises

Exercise: LINAC

Once build, can I use my LINAC to accelerate any particle I like?

This question could be rephrased to:
How does the drift tube length l_i depend on the particle type?

Drift tubes provide shielding of the particles during the negative half wave of the RF.



Time span of the negative half wave: $\tau_{RF}/2$

Length of the Drift Tube: $l_i = v_i * \frac{t_{rf}}{2}$

Kinetic Energy of the Particles $E_i = \frac{1}{2} m v^2$

$$v_i = \sqrt{2E_i/m}$$

$$l_i = \frac{1}{f_{RF}} \sqrt{\frac{i\, q\, V_{RF}\, \sin\phi_s}{2m}}$$

valid for non-relativistic particles ...

So the answer is no. The drift tube length depends on the charge-to-mass-ratio (*q/m*) of the particle and the RF system. For a given RF system bandwidth only a certain range of *q/m* leads to a synchronized acceleration. One knob to play could be the charge state for ions, which may allow to get closer to the design *q/m*.