Particle Accelerators - Part 1

DESY Summer Student Lectures 2025

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HELMHOLTZ

Taking a ride through an accelerator …

4 Lectures

Today

Part 1: General introduction:

- **What are particle accelerators?**
- **Why and where do we need them?**
- **What types do exists?**

Part 2: Accelerator Technology (Gregor Loisch)

Tomorrow

Part 3: How to build a particle accelerator

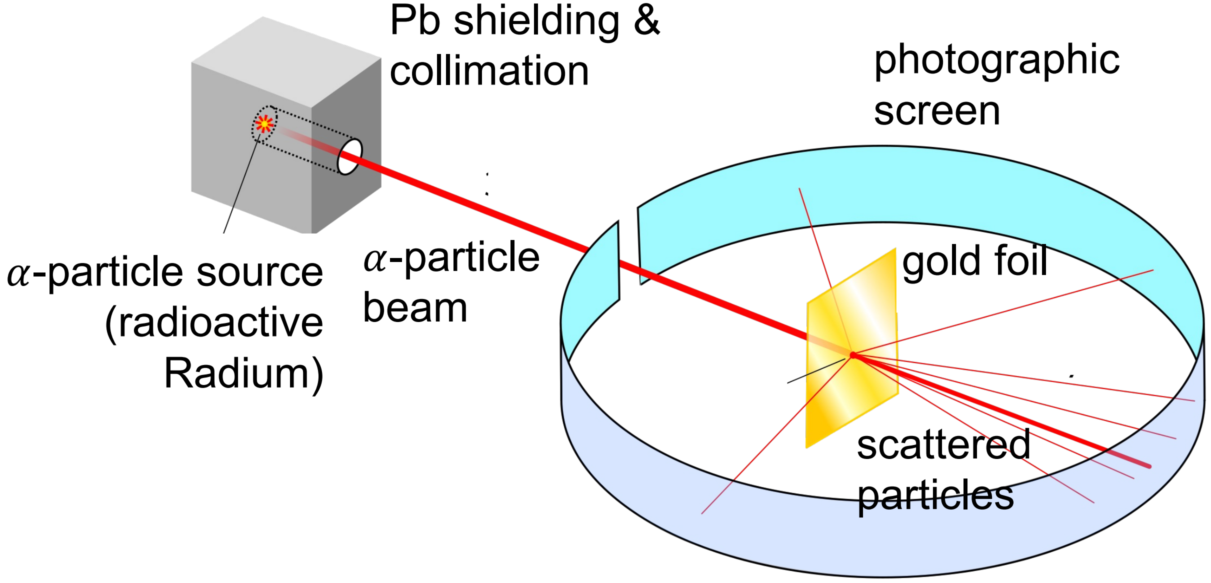
Part 4: What Users need and how to deliver

Why do we need accelerators?

Rutherford Scattering - 1st Particle Physics Experiment

Fire alpha particles against a thin gold foil.

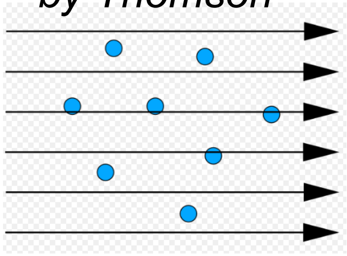
Observation of scattering behavior revealed entirely new understanding of the **structure within atoms**.



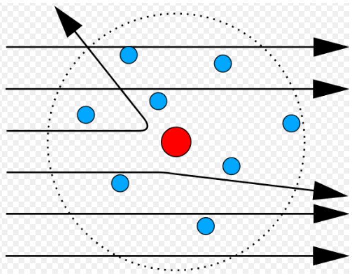
Source: Wikipedia

Atomic Model

by Thomson



by Rutherford



Source: Wikipedia (CC BY-SA 4.0)

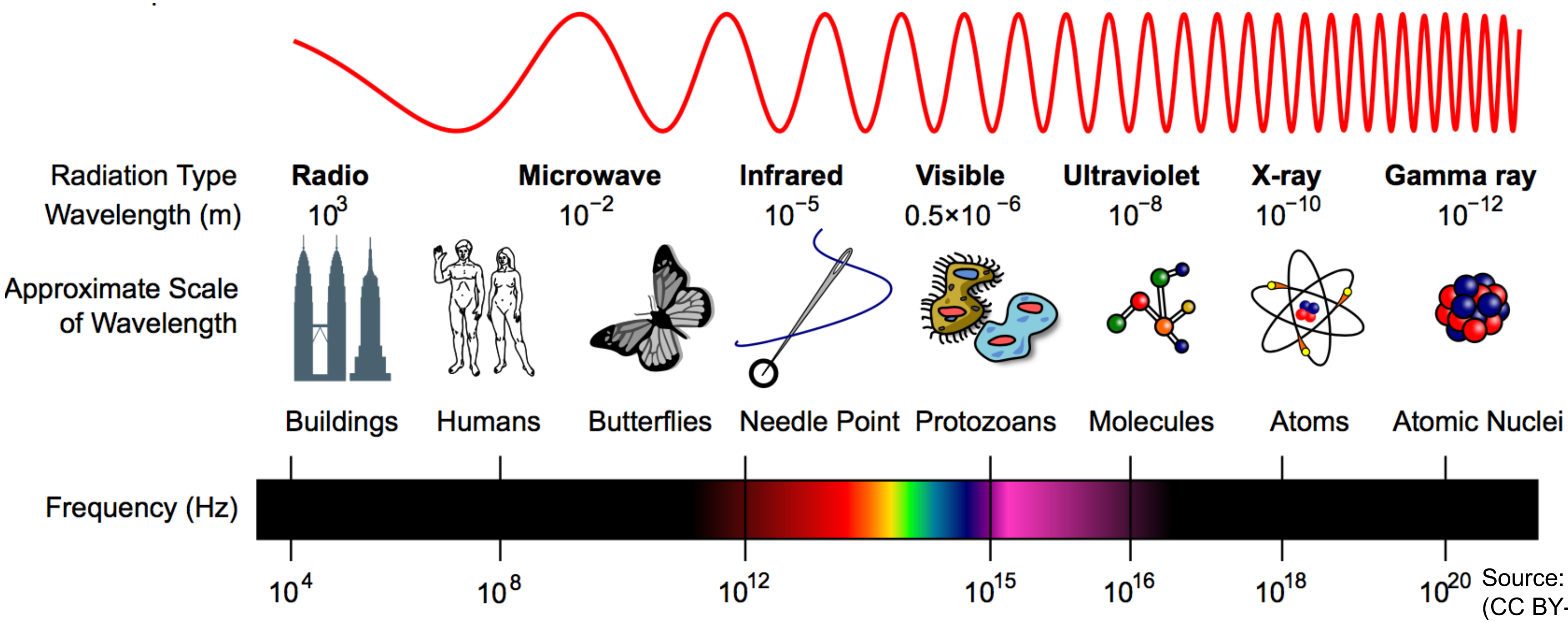
1911

H. Geiger,
E. Marsden und
E. Rutherford

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

Study the inner structure of matter with scattering experiments

The wavelength of the probe radiation needs to be smaller than the object to resolve.

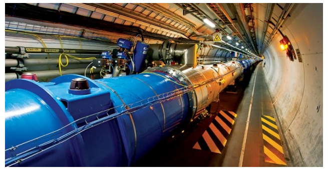


Source: Wikipedia (CC BY-SA 3.0)

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

Visible
λ = 400 ➔ 700 nm

X-ray
λ = 0.01 ➔ 10 nm



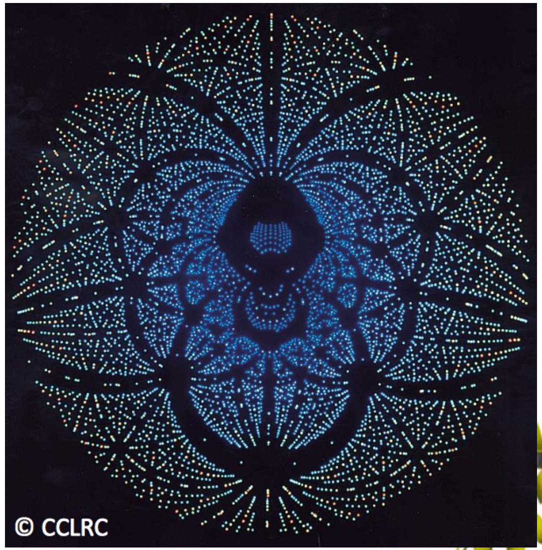
Particle accelerators
λ < 0.01 nm

Synchrotron Light Source:
Study of the tiniest structures and processes

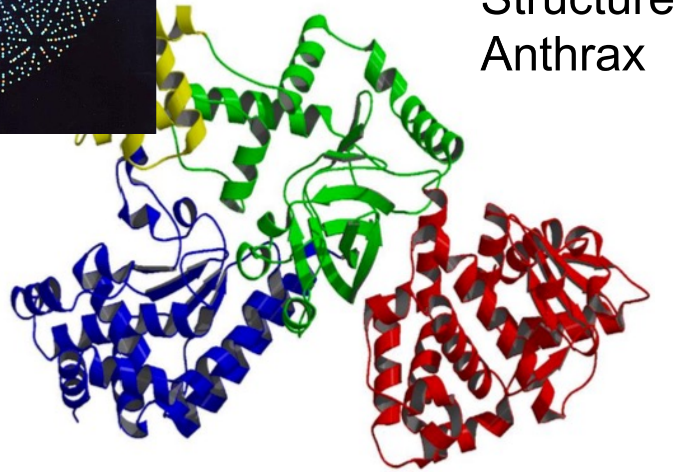
Archeology/Heritage

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

Structure of Proteins



Diffraction pattern from pea lectin

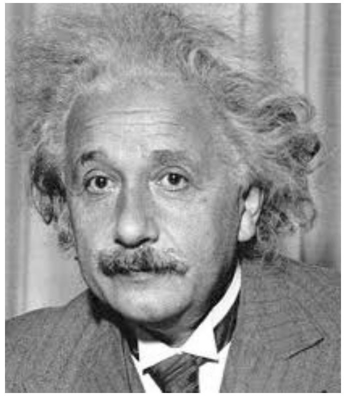


Structure of Anthrax

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

Particle colliders: Production of new matter

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

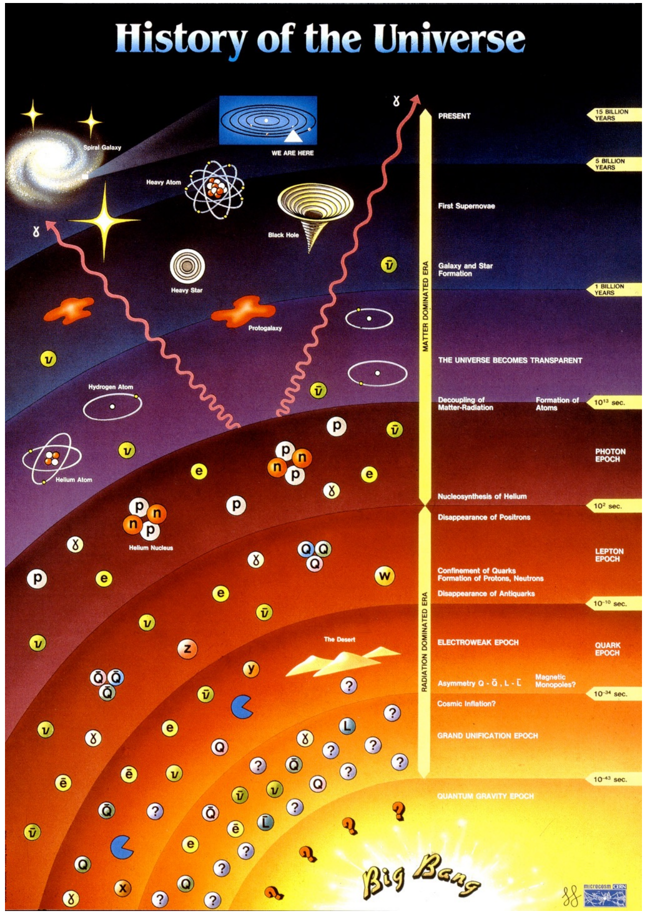


$$E = m\,c^2$$

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 else (outside science) do we need accelerators?

Security
- Airports & boarders
- Nuclear security
- Imaging

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

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

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

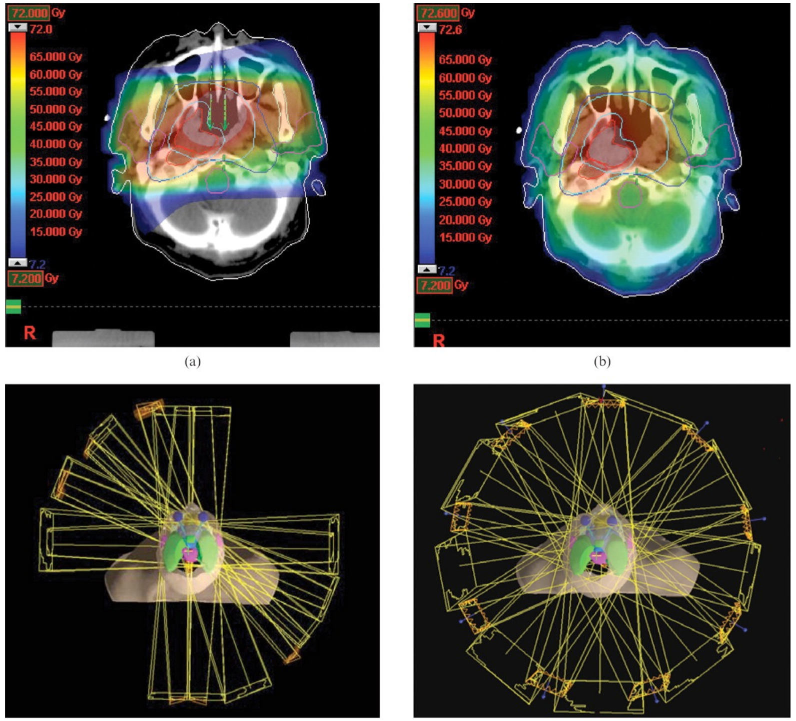
Research (<1%)
- Particle Physics
- Storage rings & Colliders
- Material science
- Light sources
- R&D

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

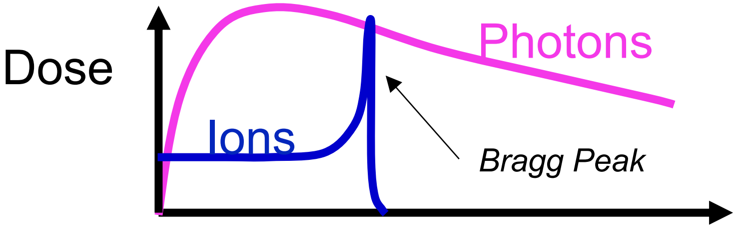
Applications - Health

Cancer therapy with photon, proton and ion beams

Hadrons | Photons

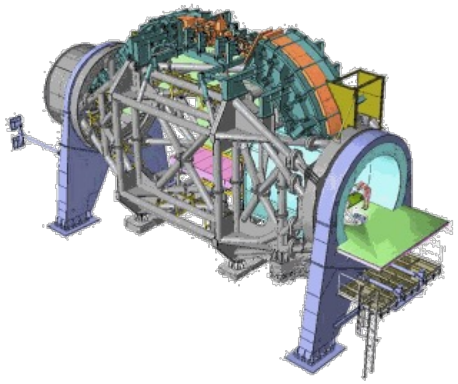


(a) (b) (c) (d)

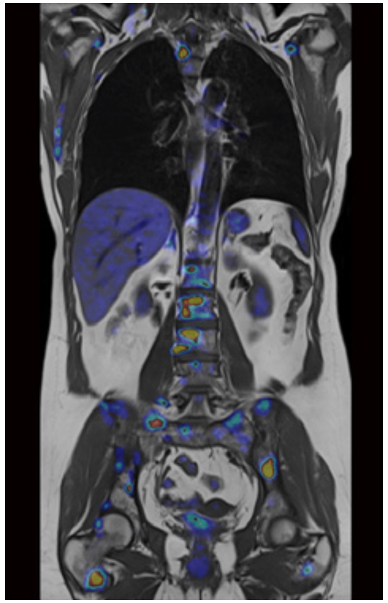


Reduced dose to healthy tissue with ion beam irradiation.

Gantry for beam transport and irradiation from different angles



Radioisotope production



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

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

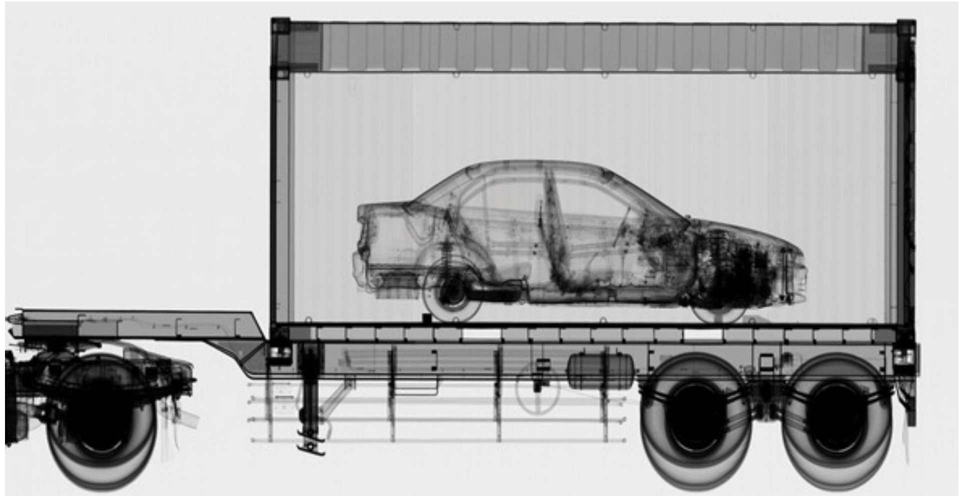
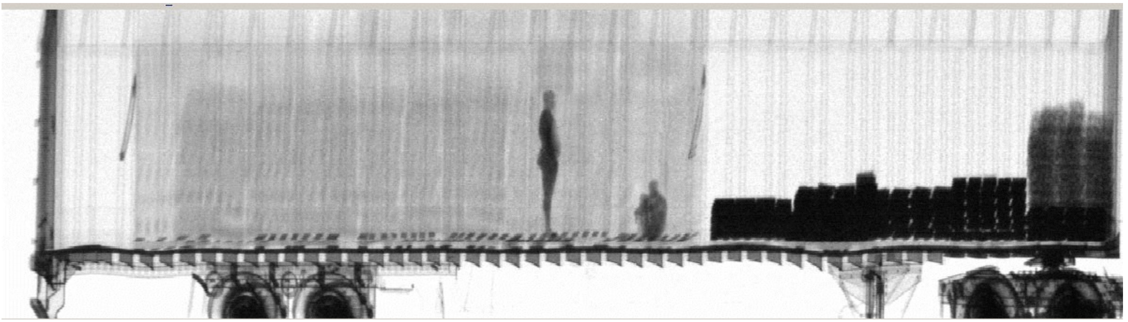


Image source: Varian medical systems



Cargo containers scanned at ports and border crossings.

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

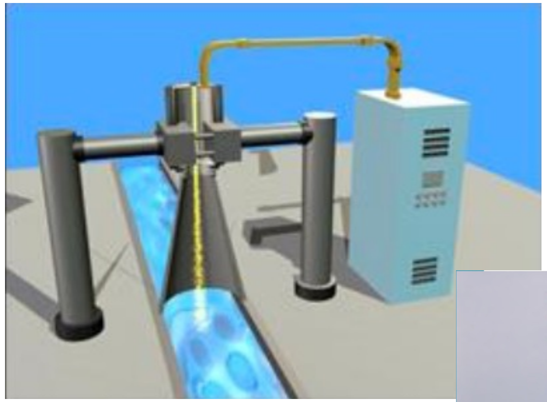
Container must be scanned in 30 seconds.

Image: 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

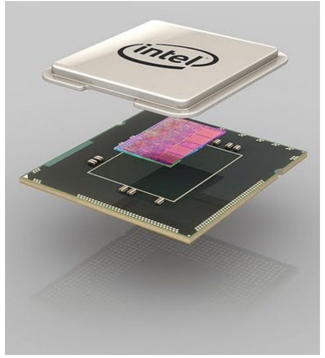


Image courtesy of Intel

Sterilization

‘Cold pasteurization’ - **Food irradiation** before packaging

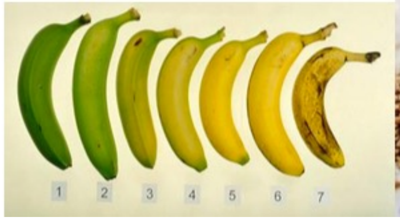


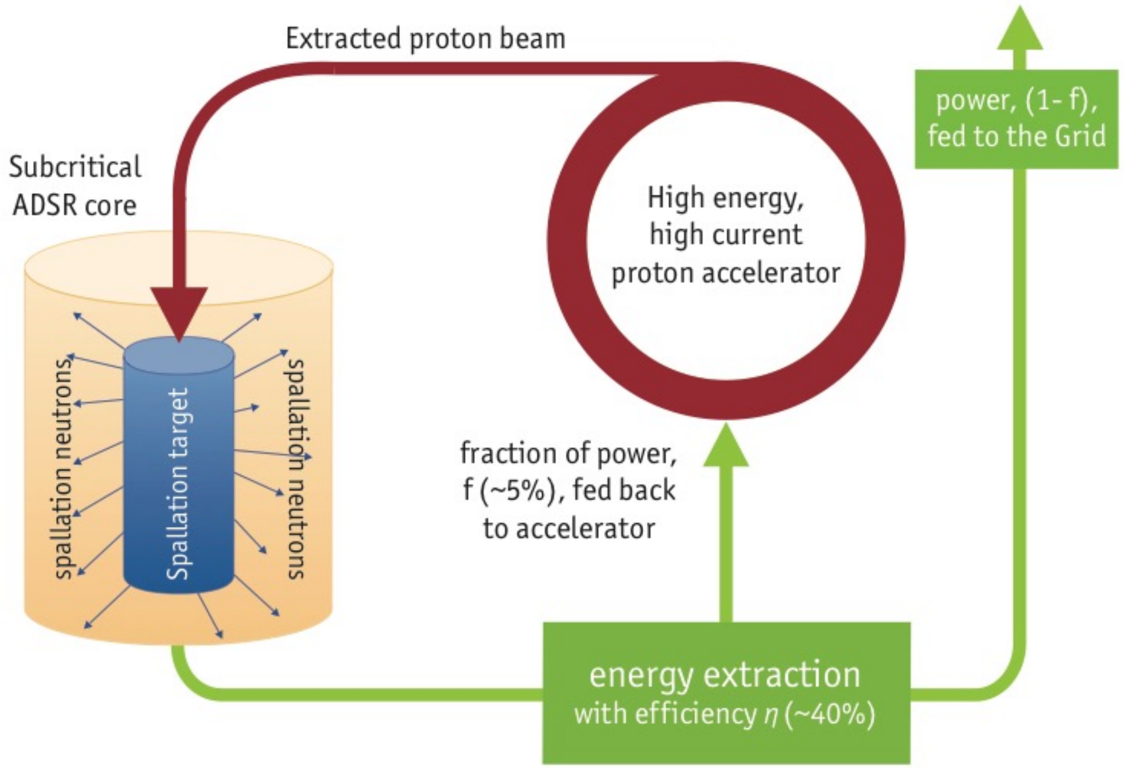



Image Sources:
APAE report, ‘Applications of particle accelerators in Europe’, http://apae.ific.uv.es/apae/
Dr. Suzie Sheehy, Applications of accelerators, CAS 2014, Prague

Application - Energy

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.

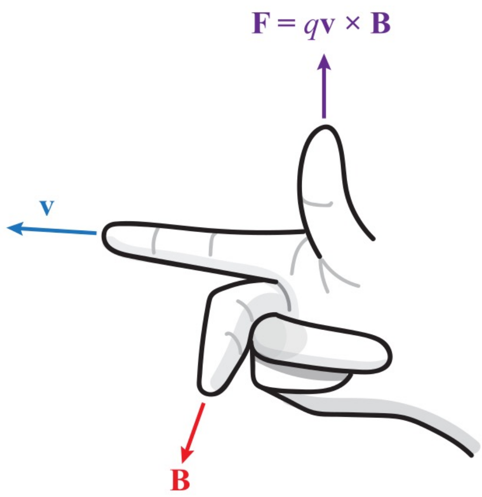
Major challenges for accelerator technology: beam power (>10MW) and reliability.

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

How can we control particles?

A *charged* particles that travels through an electro-magnetic field feel 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:
$v = c$,
$B = 1\text{T}$

$E = v\,B = 3\text{x}10^8\ \text{m/s x 1T}$
$\boldsymbol{E = 300\ \text{MV/m}}$

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

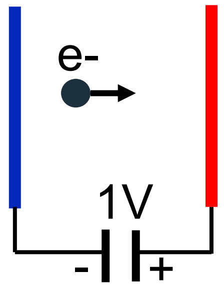
How can we increase the energy of a particle?

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

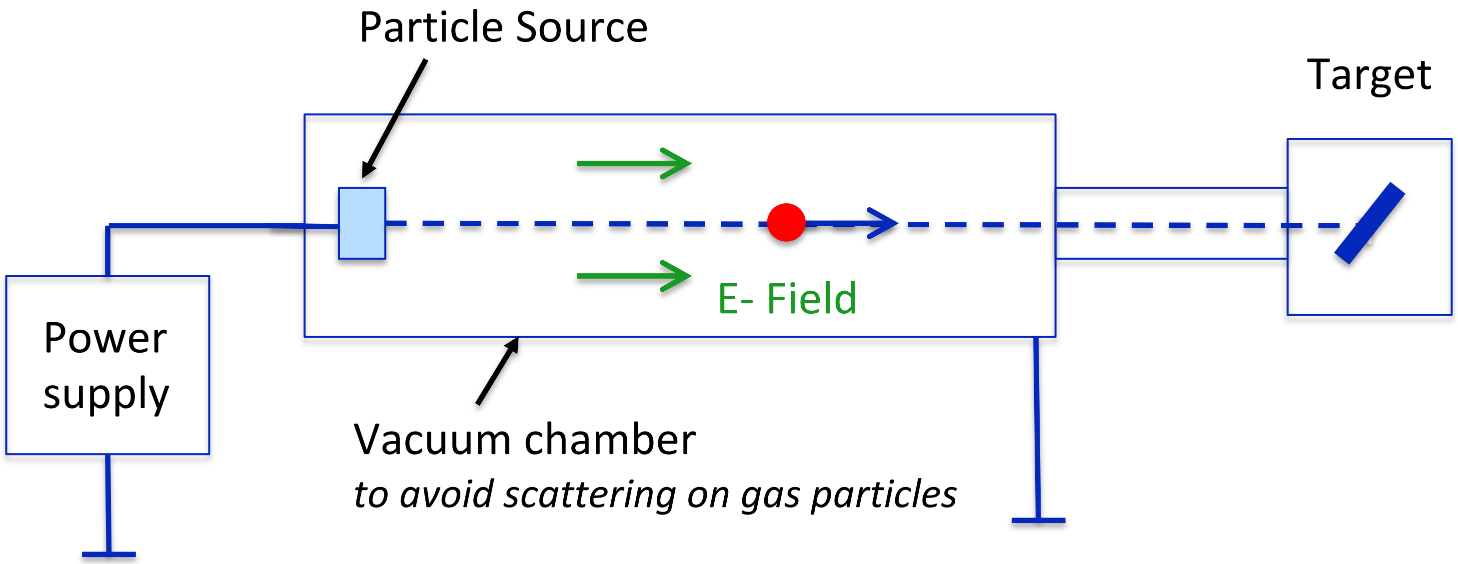
With $E = mc^2$ unit of mass *m* is **eV/c²**

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

Definition of Units

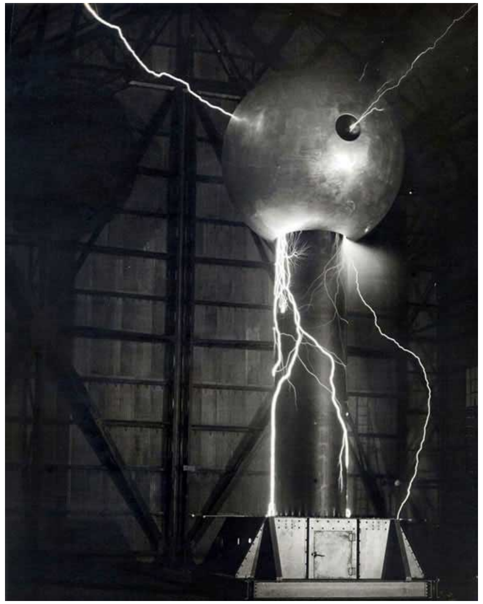
The most Basic: Electro-static Accelerator

A charged particle travels through a fixed high voltage *U* and gains an energy of $\Delta E = eU$



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

Electrostatic Accelerator Limitation

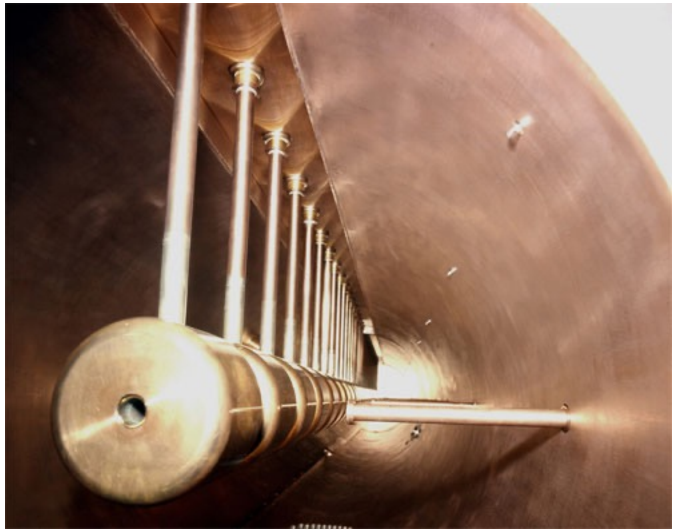


Electrostatic

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

Acceleration over one stage or gap.

Radio Frequency

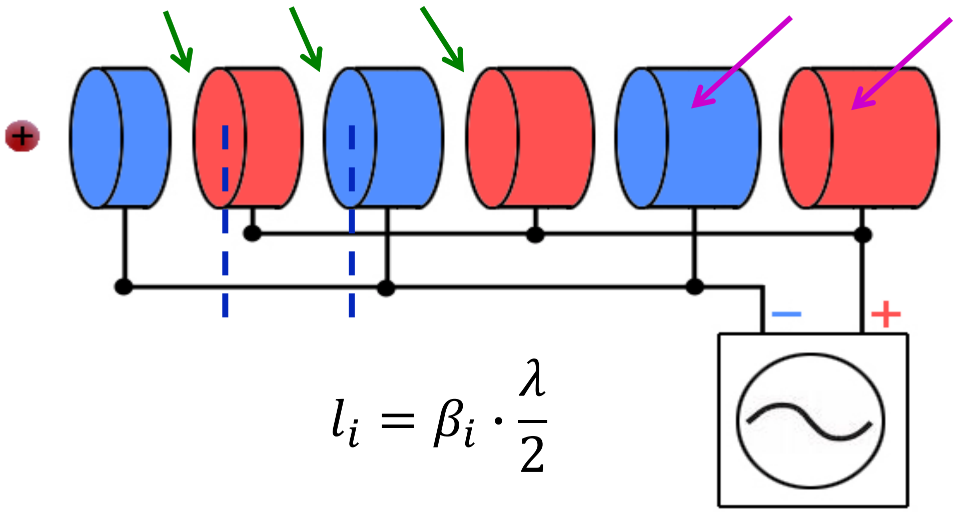


Solution:
Use alternating (RF) voltages and pass the particles through many acceleration gaps of the same voltage.

1925 idea by Ising
1928 first working RF accelerator by Wideroe

LINear ACcelerator (LINAC)

Chain of accelerating gaps provided by an alternating high frequency RF field



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

Energy gain after n gaps:

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

$\boldsymbol{n}$ No. of acceleration gaps
$\boldsymbol{q}$ Charge of the particle
$\boldsymbol{V_{RF}}$ Peak voltage of RF System
$\boldsymbol{\phi_s}$ synchronous phase w.r.t. 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 during the reversed polarity.
BUT: The more energy the particle gains, the faster it becomes (non-relativistic regime)
→ Drifts have to increase in length.

Solutions are in the back up slides

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

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

LINear ACcelerator (LINAC)

Particle should only feel the field when the field direction is synchronized

Arrival time must be synchronised to the field.

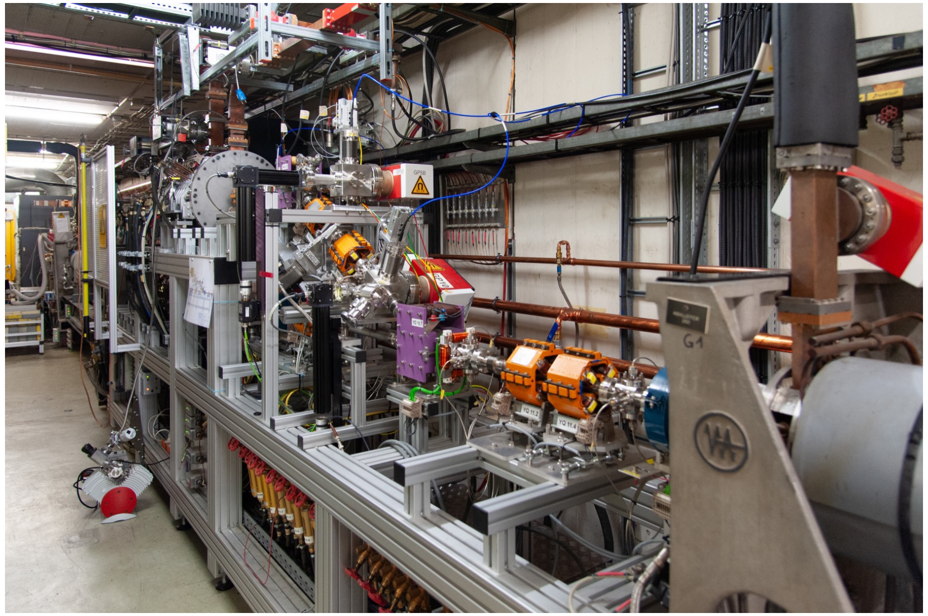
Particles need to cluster in bunches and move together.

Credit: Bild Schaukel von hermandesign2015 auf Freepik
Photo: https://kuk.verdi.de/darstellende-kunst/juedisches-leben-eine-stadt-in-aktion-585/

A LINAC is the most common pre-accelerator for high energy

LINAC II generates Electrons for the PETRA III Complex at DESY

Electron beam



Electron gun (source)
at the beginning
of the PETRA III injector chain

LINAC II **cavity** (acceleration) section

FODO channel (beam focusing)

LINAC: Particle Energy is limited by Length

… Make it a circle

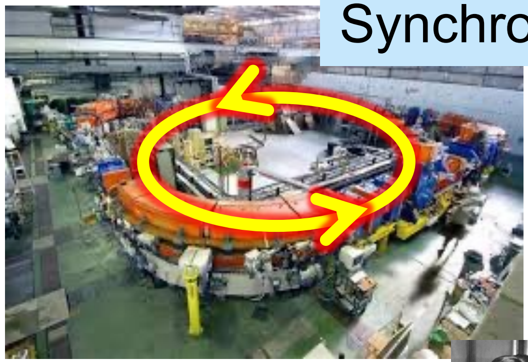
Linear

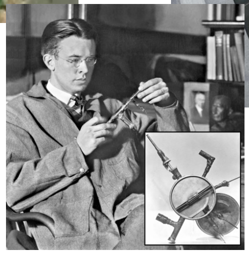
Consists of a chain of many accelerating gaps placed on a straight line.

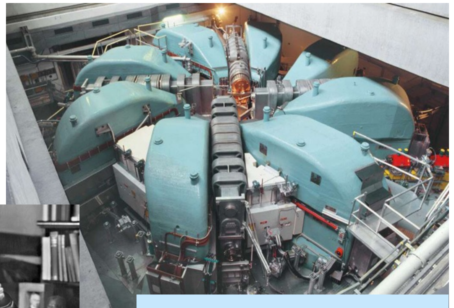
Particles pass the accelerator only ONCE.

The final energy is limited by length.

Circular





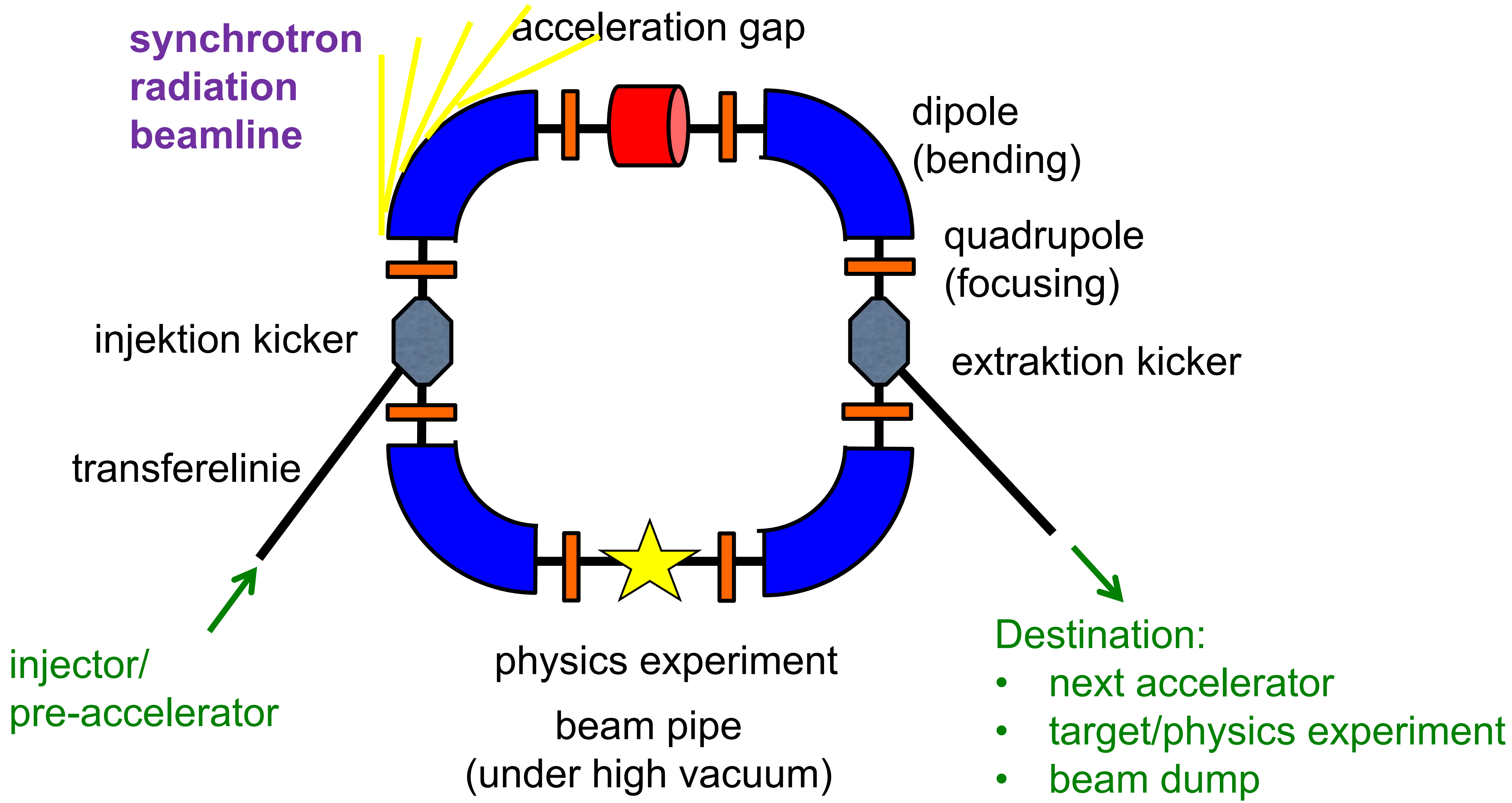


Use magnets that bend particles on a circular orbit.

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

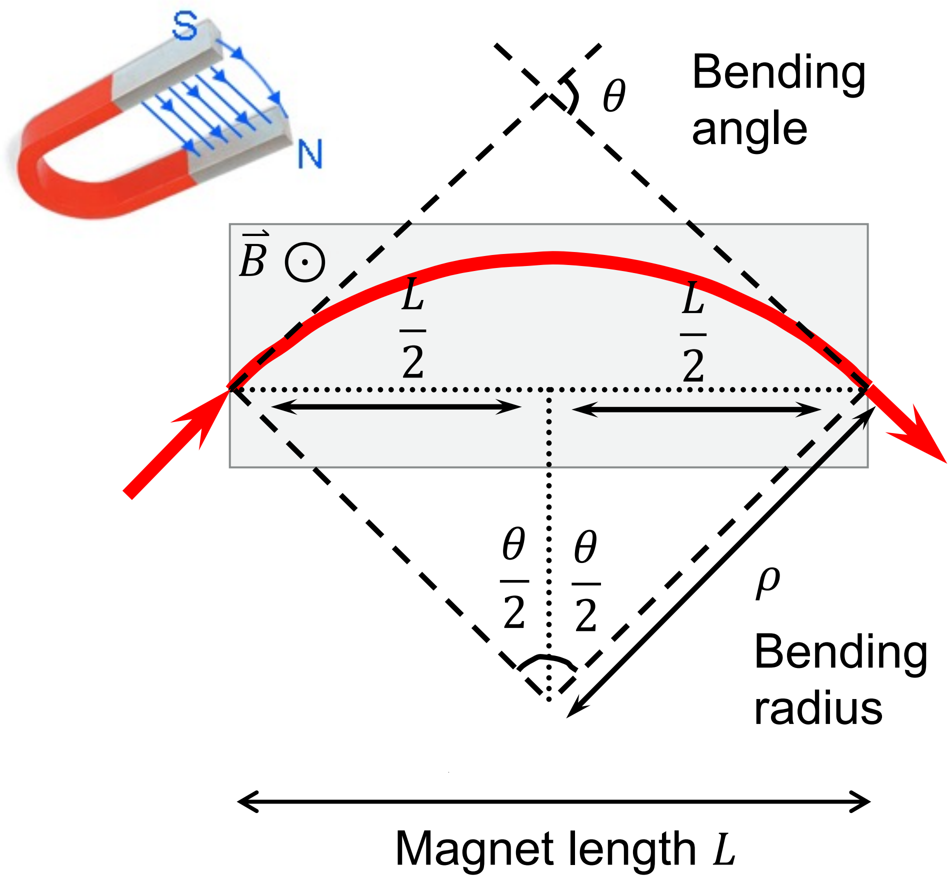
Synchrotron

THE accelerator to reach highest particle energies and able to store the beam over many hours



Charged Particles are Deflected in a Magnetic Field

With a bending radius proportional to its momentum



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

The ideal circular orbit

Lorentz Force $\quad F_L = q\, v\, B$

Centrifugal Force $\quad F_{centr} = \dfrac{\gamma\, m_0\, v^2}{\rho}$

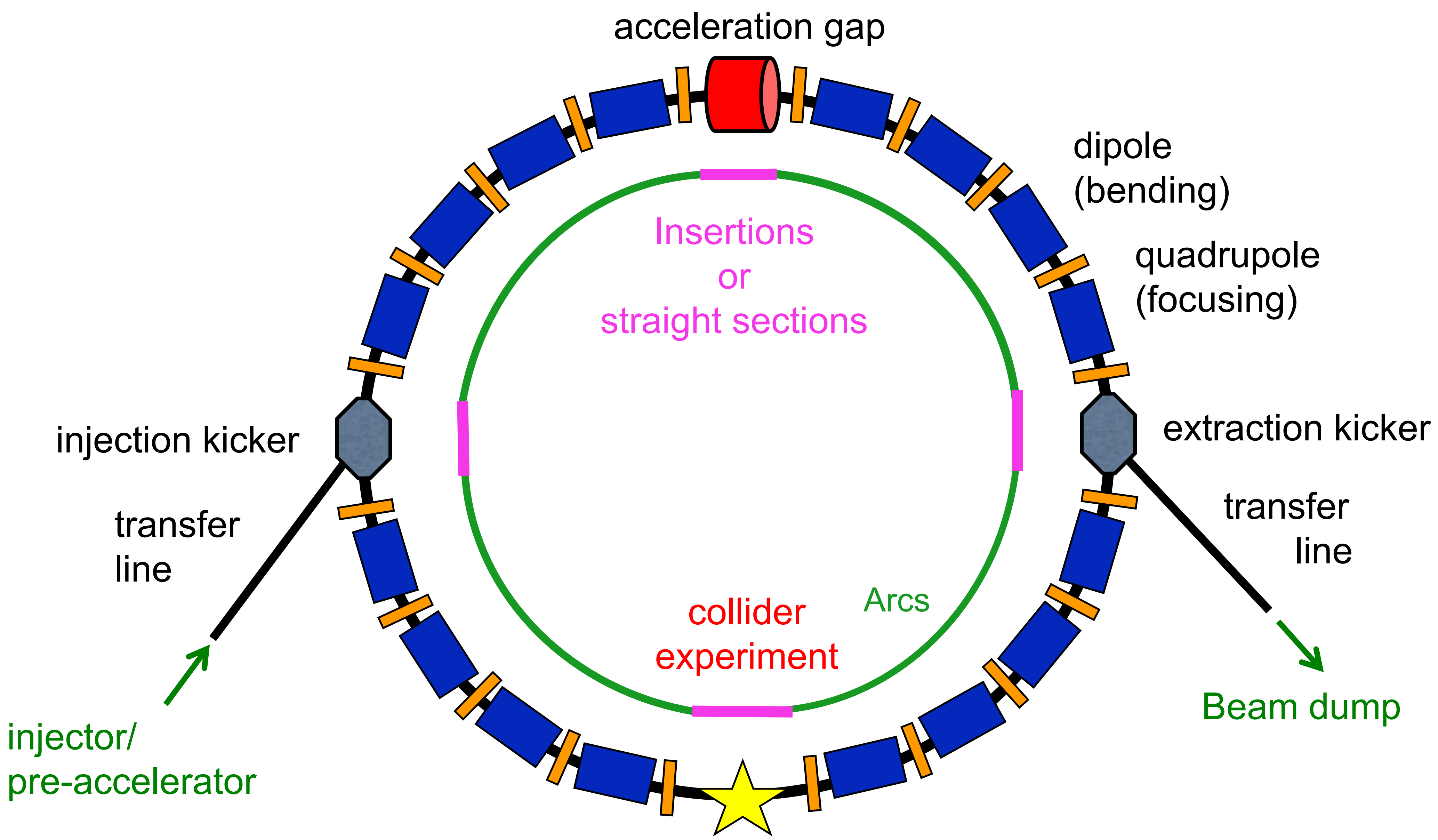
$$F_L = F_{centr}$$

$$\frac{p}{q} = B\,\rho$$

$B\,\rho$ = **Beam rigidity**

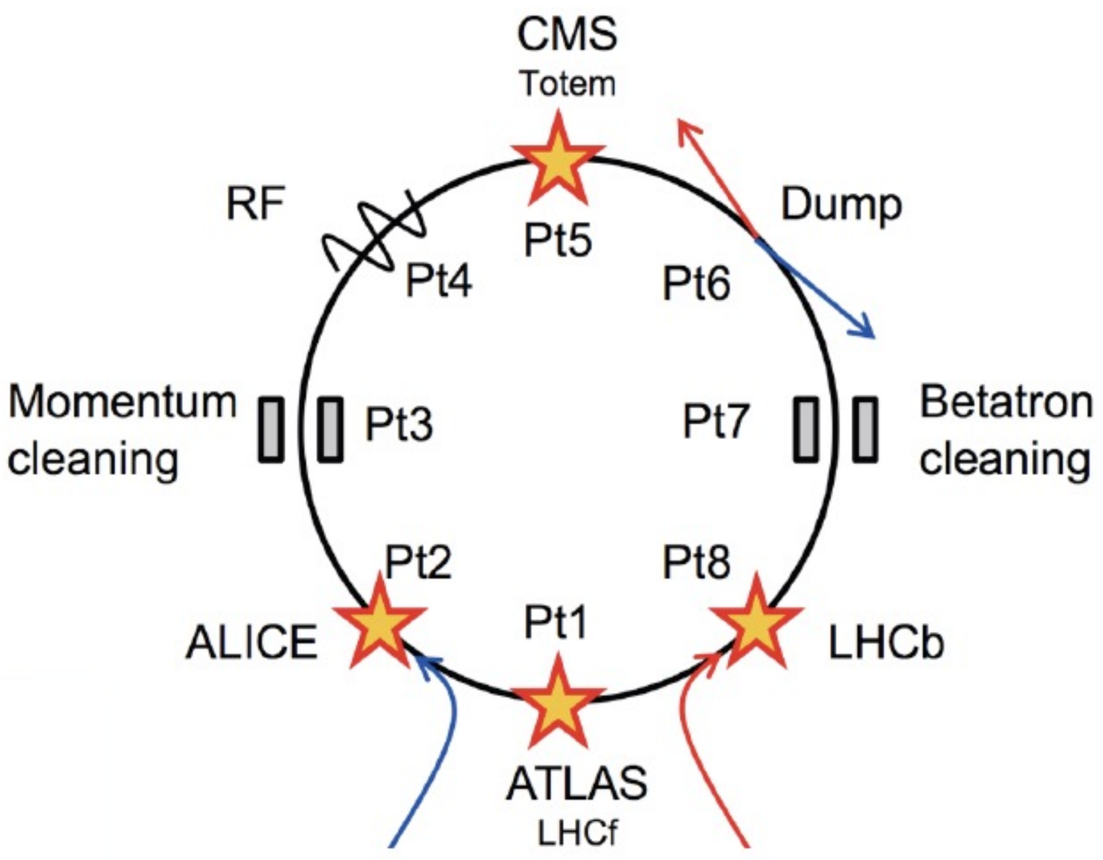
q charge
$p = \gamma\, m_0 v^2$ momentum
B magn. field strength
ρ bending radius

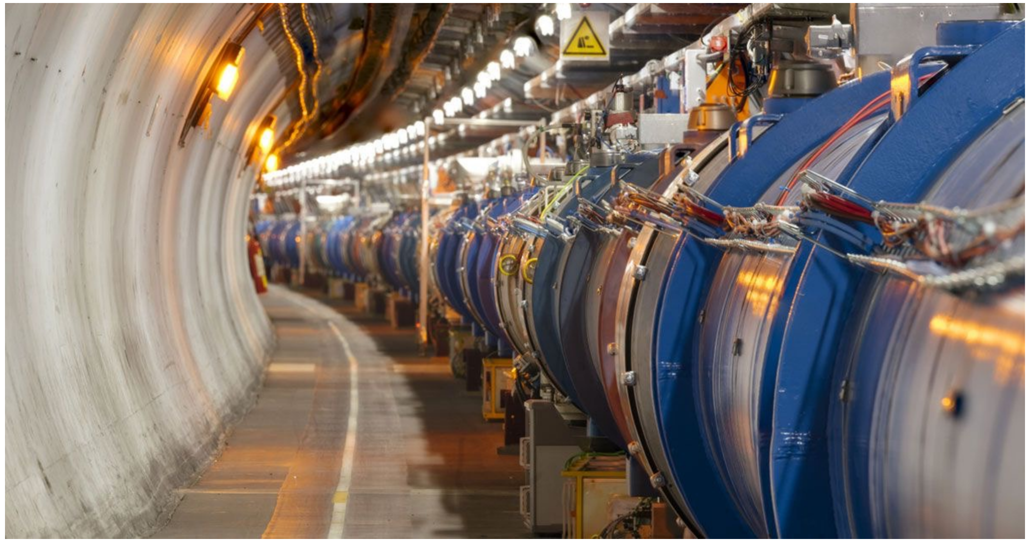
Collider


acceleration gap
dipole
(bending)
quadrupole
(focusing)
Insertions
or
straight sections
injection kicker
extraction kicker
transfer
line
transfer
line
collider
experiment
Arcs
Beam dump
injector/
pre-accelerator

LHC - Most Famous Example

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



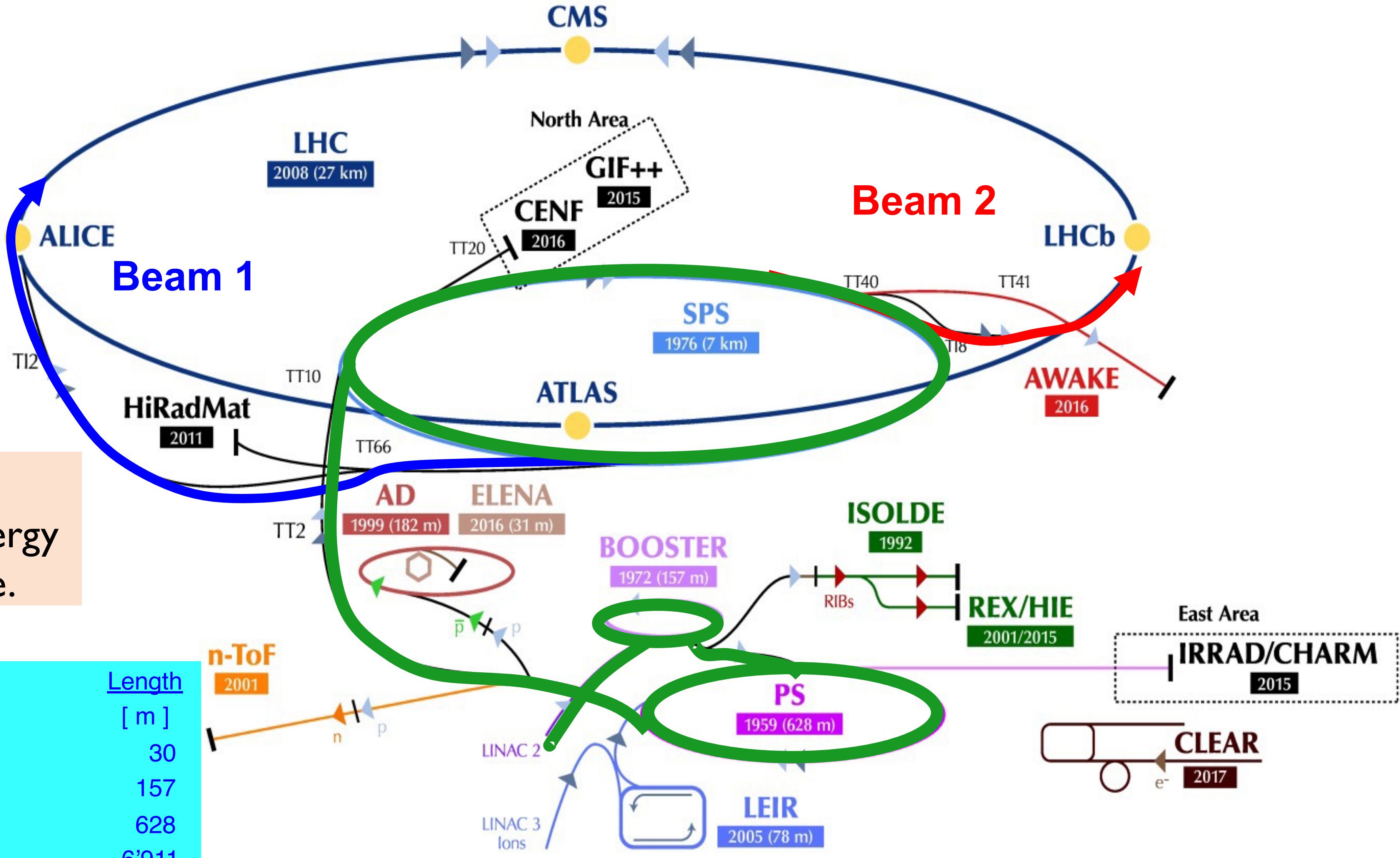


27 km circumference
100m underground

Accelerates protons and heavy-ions to E = 6.8 Z TeV (2025).

Collides 2 counter-rotating beams in 4 physics experiments.

Getting protons 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

Required Magnetic Field Strength

Full circle: $\alpha = \int \frac{dl}{\rho} = \int \frac{Bdl}{B\rho} = 2\pi$ $\xrightarrow[\int B\,dl \approx N\,l\,B]{\frac{p}{e} = B\rho}$ $B = 2\pi p / (qNl)$

Example SPS:

- Particle:
  - p = 450 GeV/c
  - q = +1e (proton)
- Dipole magnets:
  - l = 6.2m
  - ρ = 735m
  - N = 744

$$B \approx \frac{2\pi \times 450\ GeV}{744 \times\ 6.2\,m \times 3 \times 10^8 \frac{m}{s} \times\ e} = 2.0\,T$$

normal conducting magnet

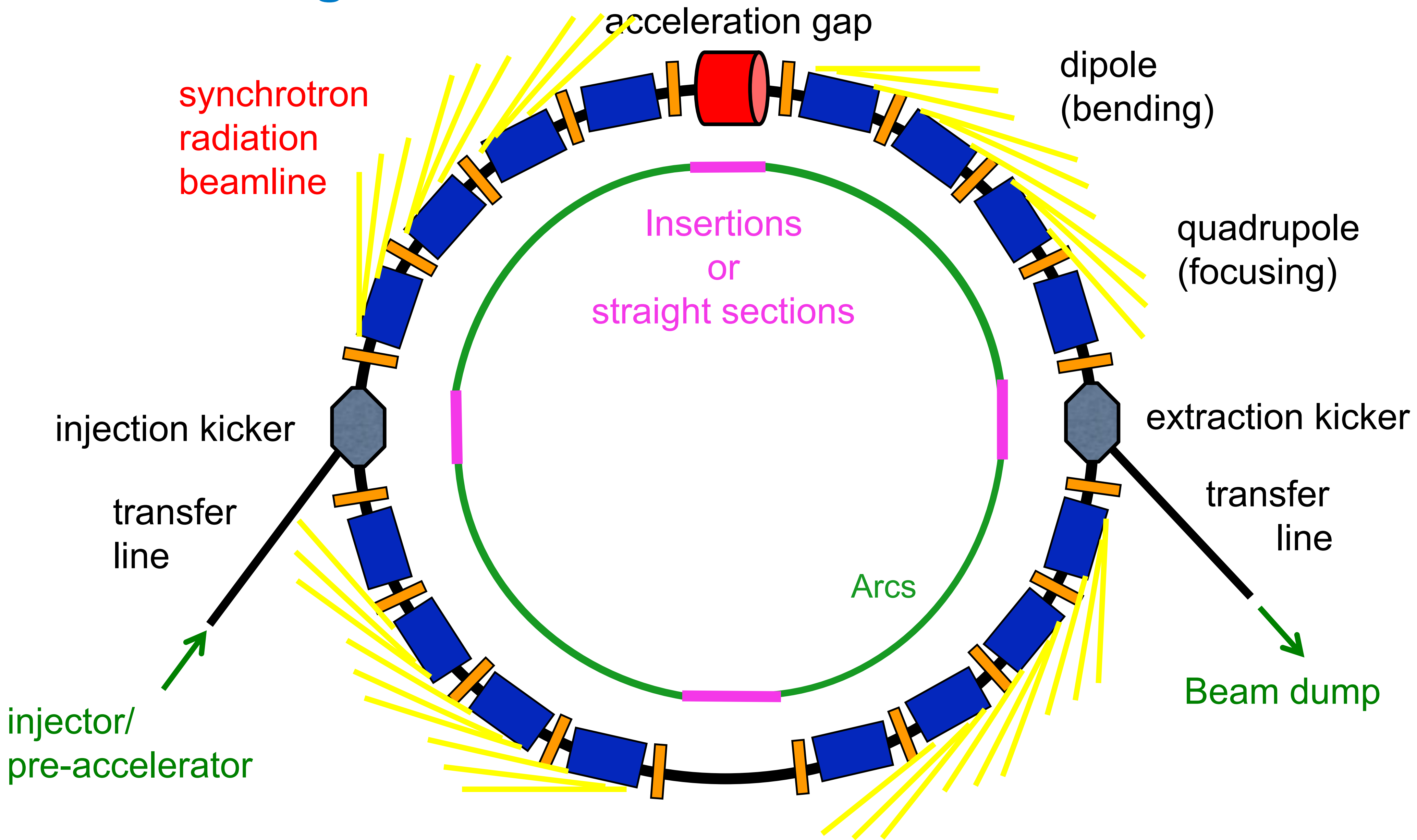
Example LHC:

- Particle:
  - p = 7000 GeV/c
  - q = +1e (proton)
- Dipole magnets:
  - l = 15m
  - ρ = 2803m
  - N = 1232

$$B \approx \frac{2\pi \times 7000\ GeV}{1232 \times\ 15\,m \times 3 \times 10^8 \frac{m}{s} \times\ e} = 8.3\,T$$

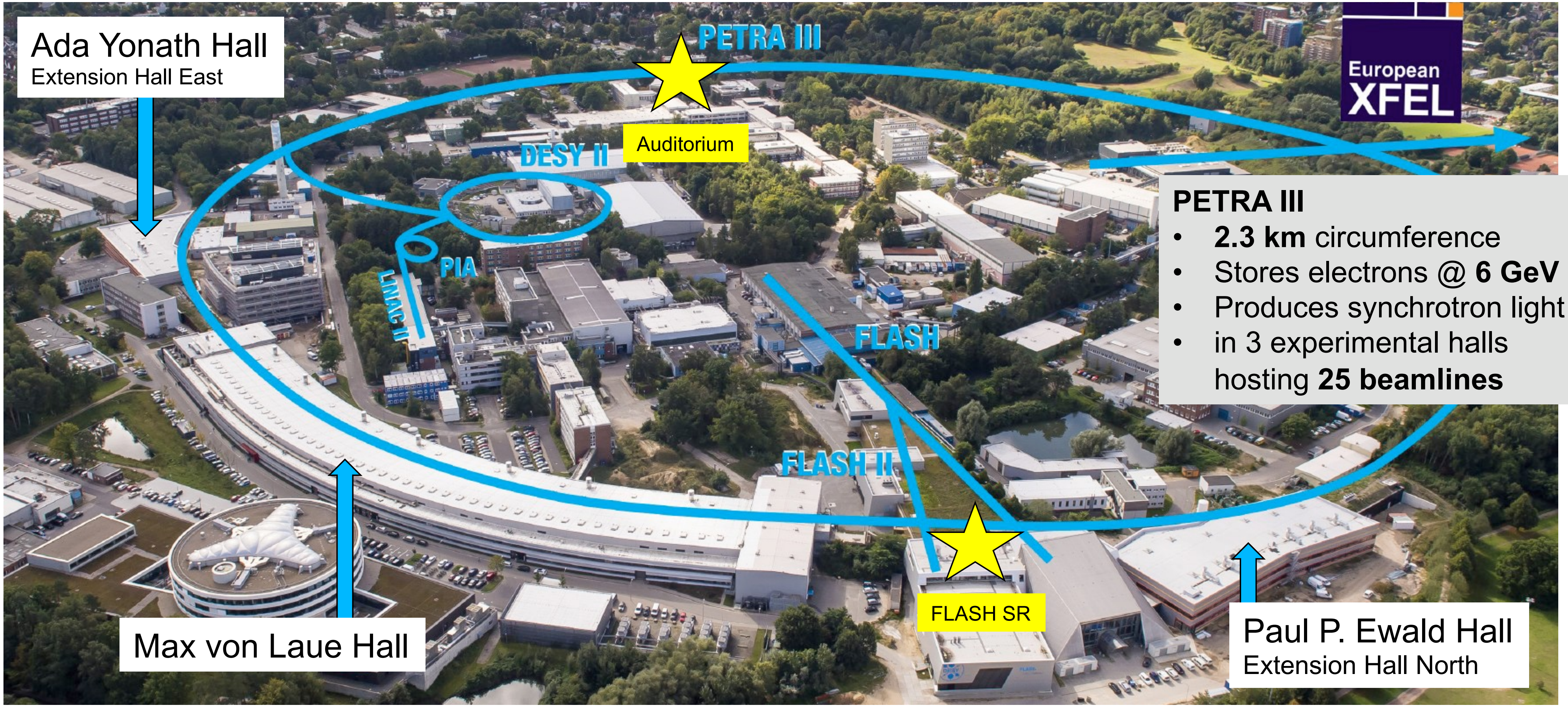
superconducting magnet

Synchrotron Light Source



Accelerators @ DESY generate Synchrotron Radiation

PETRA III ist the world's biggest and one of the most brilliant storage ring light source



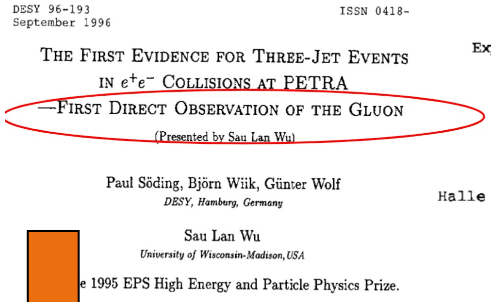
PETRA III

- **2.3 km** circumference
- Stores electrons @ **6 GeV**
- Produces synchrotron light
- in 3 experimental halls hosting **25 beamlines**

PETRA - Collider becomes Synchrotron Light Source

From e+/e- collider over e-/p injector for HERA towards synchrotron light source

PETRA I
1978-1986:
She observed as an e+/e- collider the gluon for the first time.


DESY 96-193 ISSN 0418-
September 1996

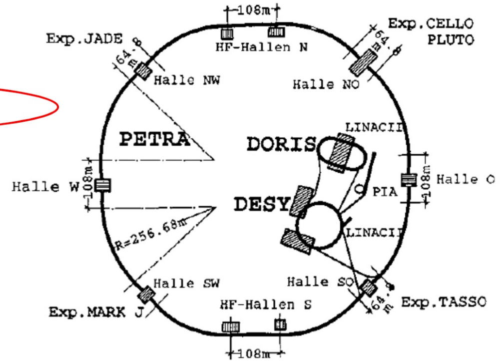
THE FIRST EVIDENCE FOR THREE-JET EVENTS IN e^+e^- COLLISIONS AT PETRA
—FIRST DIRECT OBSERVATION OF THE GLUON

(Presented by Sau Lan Wu)

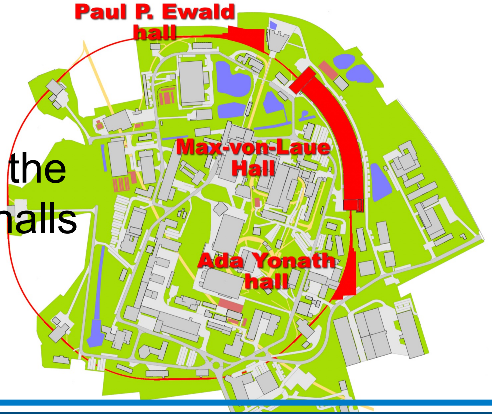
Paul Söding, Björn Wiik, Günter Wolf
DESY, Hamburg, Germany

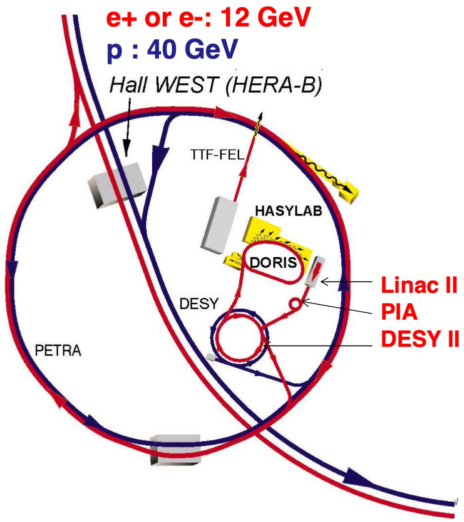
Sau Lan Wu
University of Wisconsin-Madison, USA

e 1995 EPS High Energy and Particle Physics Prize.

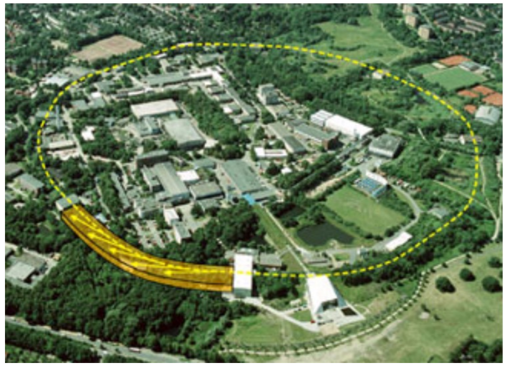


2015:
construction of the two extension halls



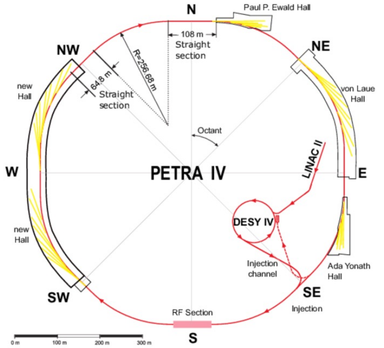


PETRA II
1988-2007:
She provided e+/e-/p to HERA.



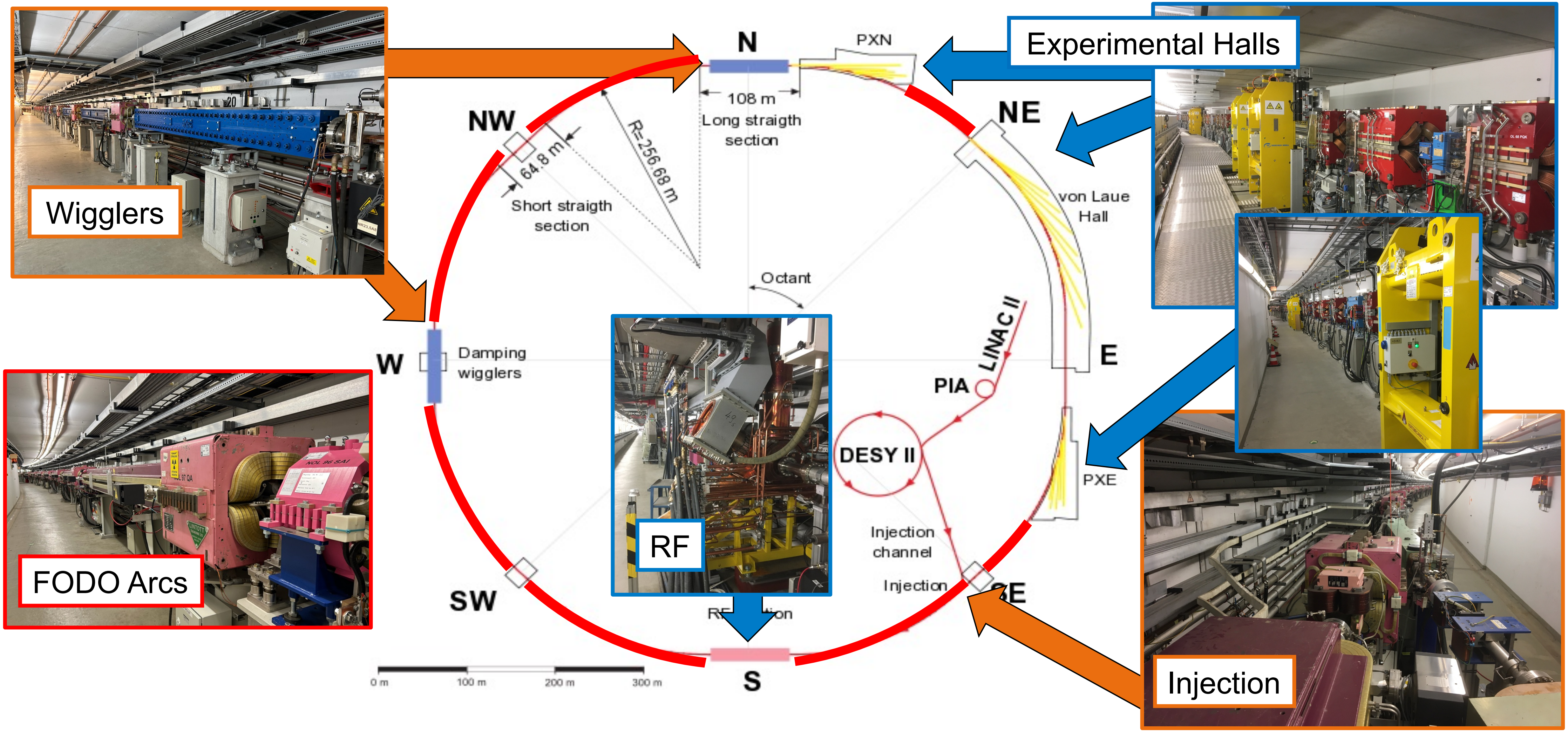
PETRA III
Since 2009:
She radiates as the worldwide biggest storage ring light source

From 2030:
Upgrade to PETRA IV



PETRA III Layout with 3 Experimental Halls

Visit to the PETRA Tunnel
1.8.2025 13:30



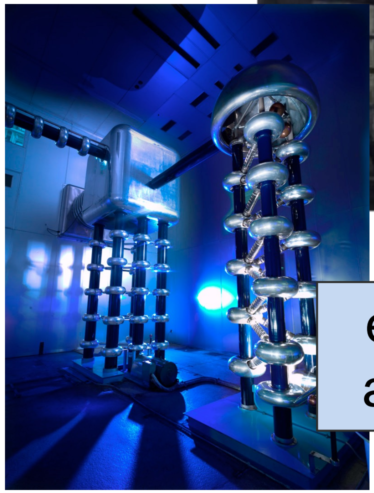
Accelerators come in different shapes and sizes

Each having different limits for scientific, industrial and medical applications

Linear

Limited by length

LINAC

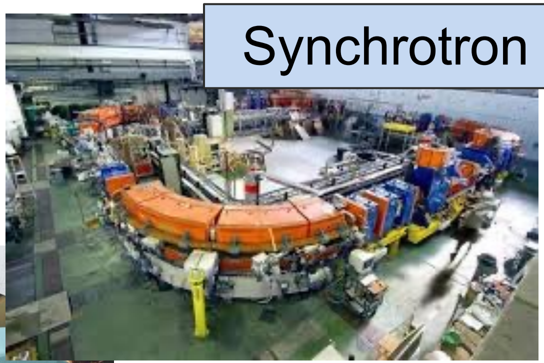


electrostatic accelerators

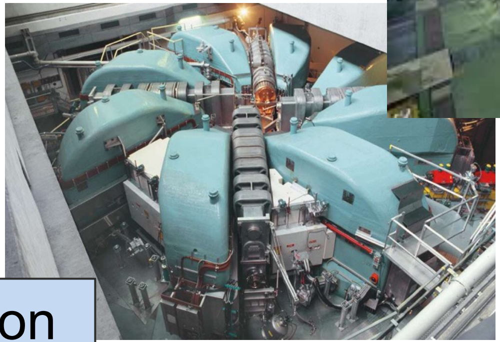
Limited by high voltage discharge

Circular

Limited by max. B-field & radius



Synchrotron

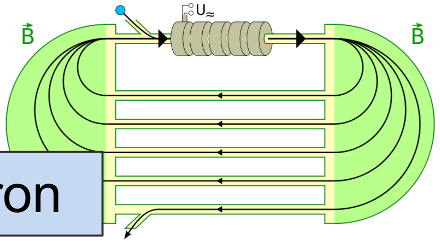


Cyclotron

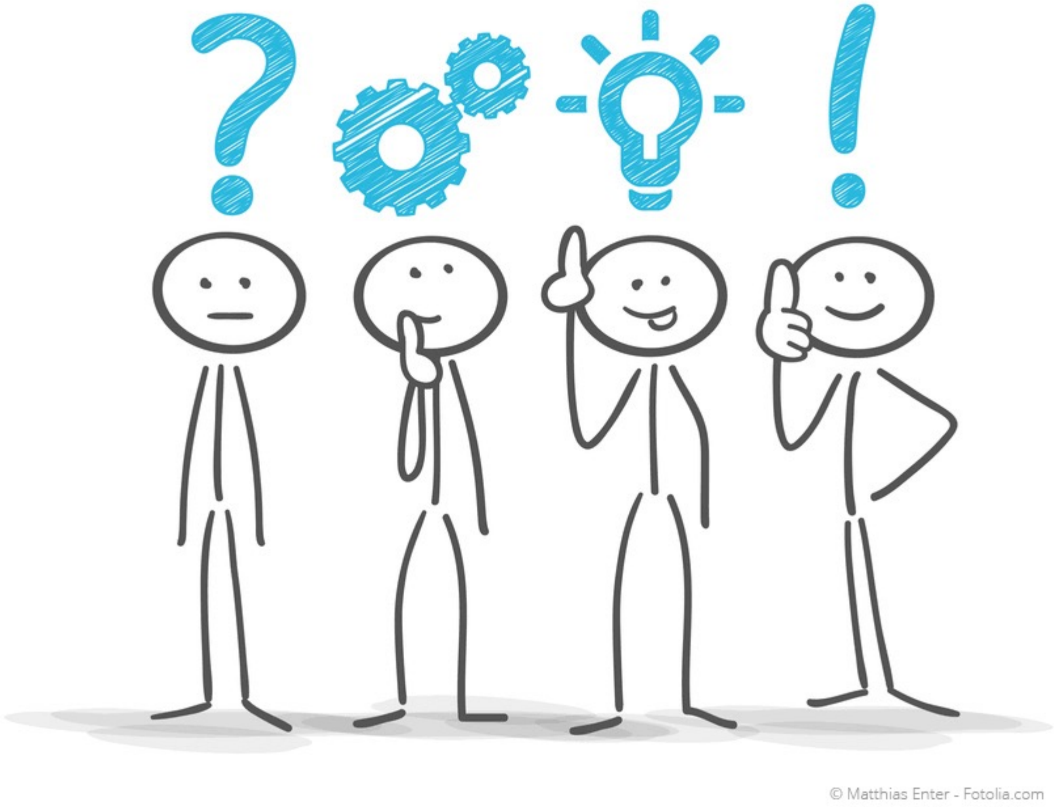
Limited by const. mass & size

Other types of circular accelerators (not discussed here)

Betatron



Microtron



Everything clear! Hmm ….

EPACE

European Compact accelerators, Applications, Entrepreneurship

MARIE CURIE ACTIONS

- 15 PhD in plasma acceleration in Europe, combined with training in innovation & entrepreneurship
- Funded as an MSCA Doctoral Network, Start in Sept. 2025
- Contact: lisa.crinon@desy.de
- **visit our website for current opportunities!** **www.epace.eu**

Research projects:

- kHz laser-wakefield acceleration
- Snapshot tomography of laser-plasma acceleration
- Machine-Learning-Enhanced Laser Plasma Accelerators
- Tailored plasma targets for Laser Wakefield Acceleration
- Production of high-density spin-polarized hydrogen-atom target
- Spin polarisation in plasma accelerators
- Very high energy electrons (VHEE) radiotherapy with beams from a wakefield accelerator
- Compact muon and electron source combined with the GScan detector system: the radiological system for medical applications
- Advancing radiotherapy with laser-plasma accelerators
- ICS soft x-ray source for semiconductor wafer metrology
- Inverse Compton Scattering (ICS) x-ray source from a high repetition rate laser wakefield accelerator
- Controlling plasma sources on hydrodynamic time scales to better plasma accelerators
- Theoretical study of superluminal laser-plasma acceleration
- Plasma Mirrors: towards extreme intensity light sources and high-quality compact electron accelerators
- Better beam quality in plasma accelerators through high-performance computing

Acknowledgments

These lectures are based on lectures given at

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

Mainly by

- **Pedro Garcia Castro**
- **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)

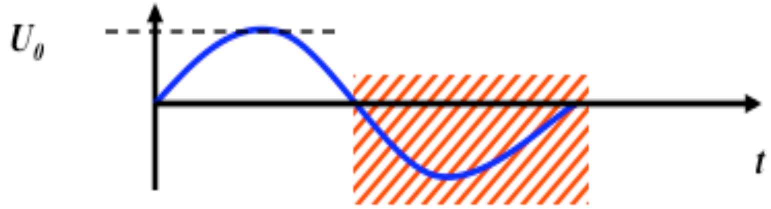
Solutions to Exercises

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: $l_i = v_i * \frac{\tau_{rf}}{2}$

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

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

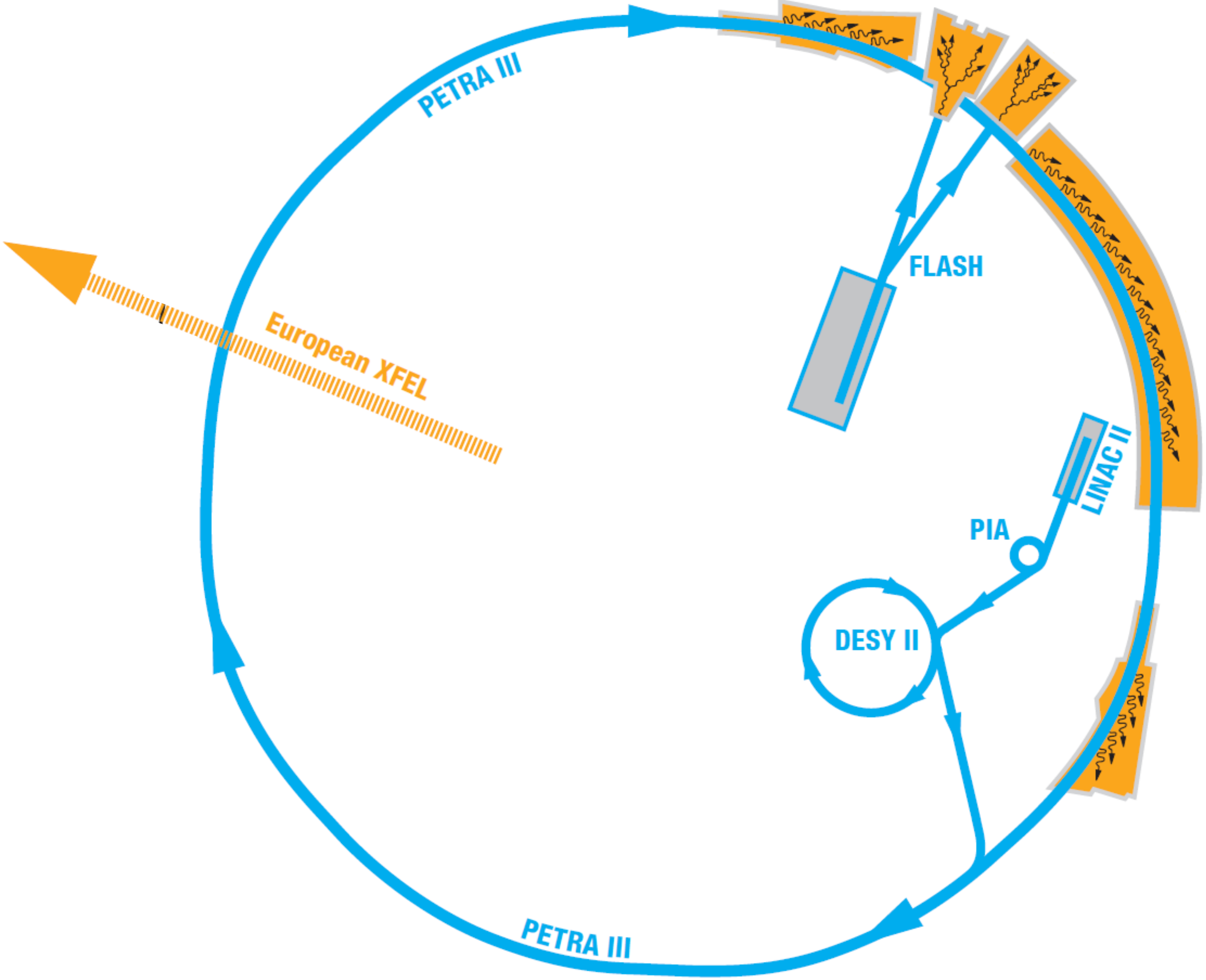
$$l_i = \frac{1}{f_{RF}} \sqrt{\frac{i\ q\ V_{RF}\ \sin\phi_s}{2m}}$$

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*.

Back up

Accelerators @ DESY generate Synchrotron Radiation



PETRA III Komplex

- **Linac II** 1970
  450 MeV e+/e-
- **PIA** 1970
  450 MeV e+/e-
- **DESY II** 1990
  6 GeV e+/e-
- **PETRA III** 2009
  6 GeV e-

FELs

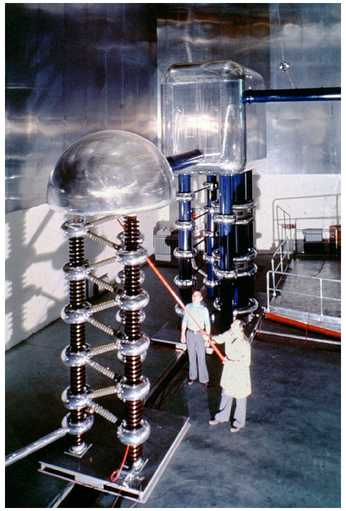
- **FLASH** 2003
  1 GeV e-
- **XFEL** 2016
  20 GeV e-

Electrostatic Accelerators – 1930s

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

Cockcroft-Walton cascade generator

1928



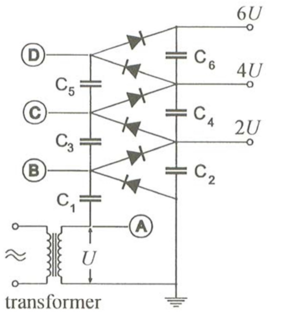


Image Credit: K. Wille

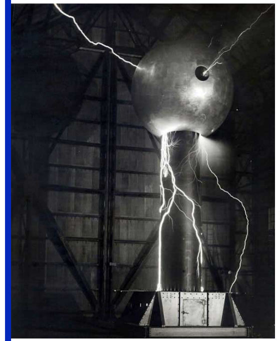
Concept:
rectifier circuit, built of capacitors and diodes (Greinacker circuit)

Limitation:
Electrical discharge in air
(Paschen Law)

Max. Voltage ~ 1 MV

Van de Graaff accelerator

1930



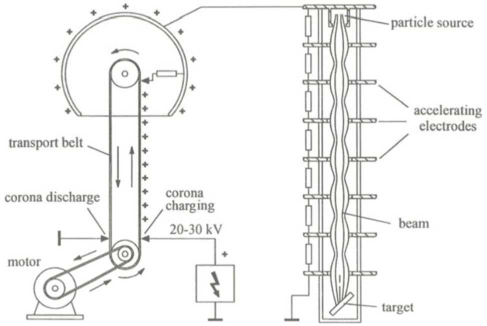


Image Credit: K. Wille

Concept:
mechanical transport of charges via rotating belt

Electrode in high pressure gas to suppress discharge (SF_6)

Max. Voltage ~ 1- 10 MV

Tandem Van de Graaff accelerator

1936

at MPI Heidelberg

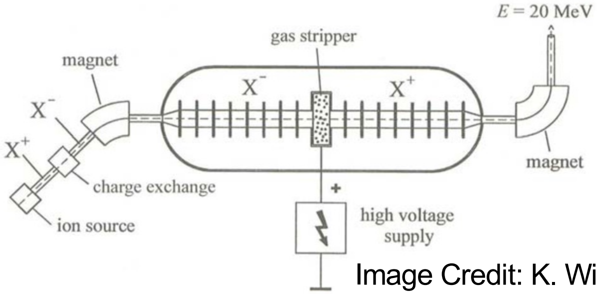


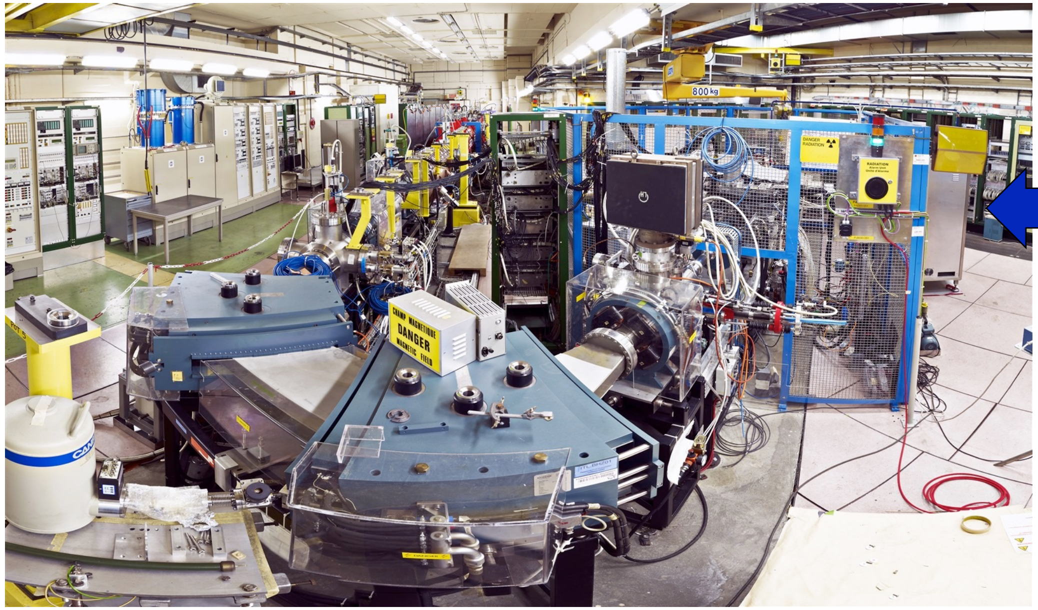
Image Credit: K. Wille

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

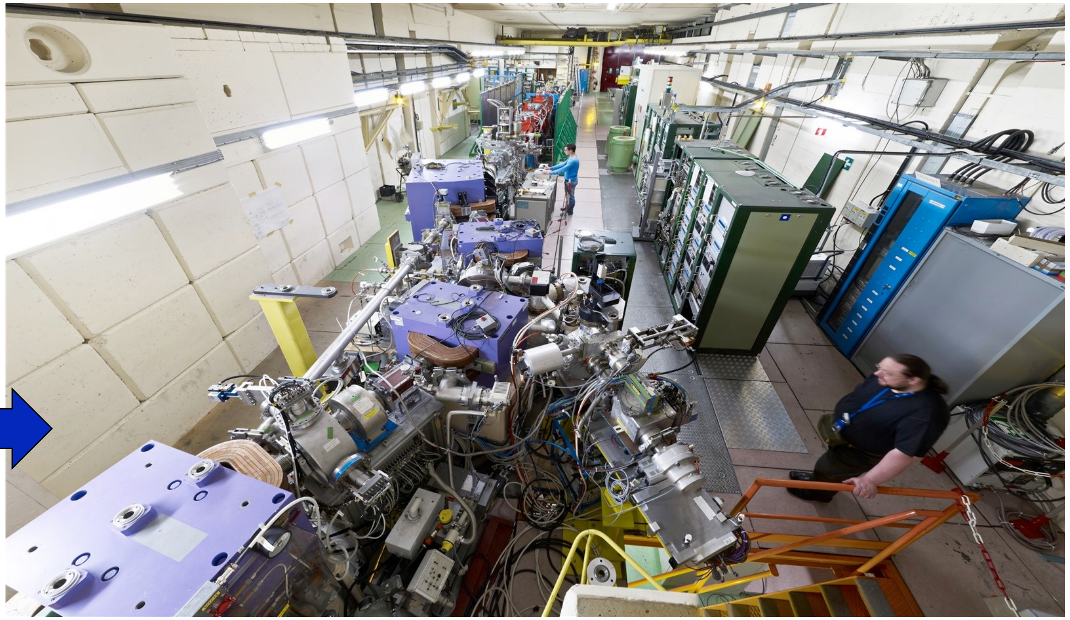
Max. Voltage ~ 25 MV

Additional Example of a LINAC

CERN's LINAC 3 brings different ion species to LEIR (Low Energy Ion Ring)



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

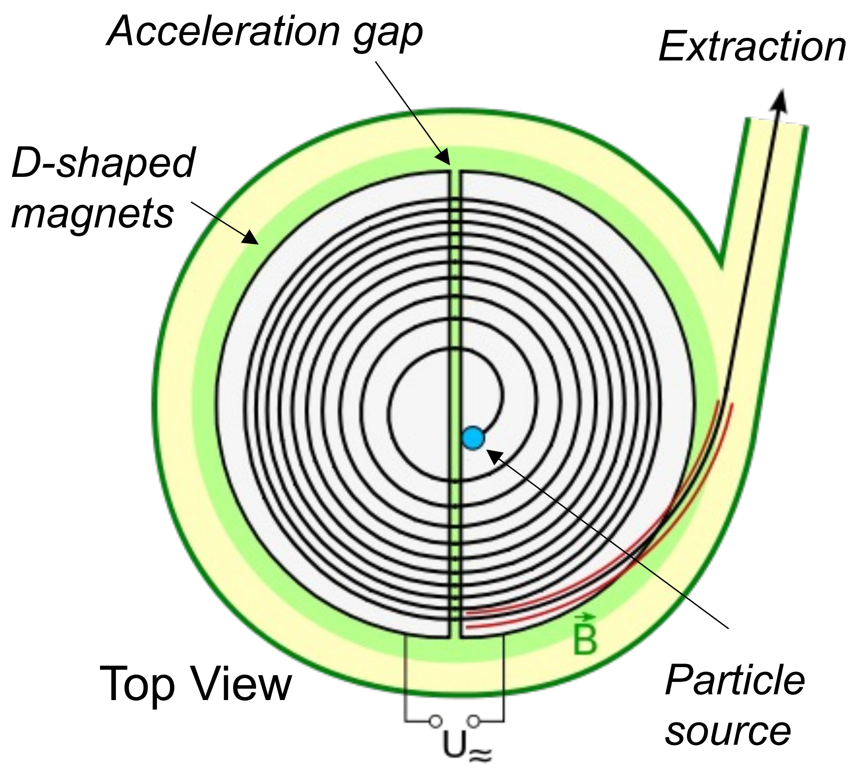


Downstream part of LINAC 3:
Transfer and diagnostics (front)
Accelerating structures (back)

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: NOT for Electrons

Revolution frequency changes with particle energy

Constant revolution frequency for constant mass: $$\omega = \frac{v}{r} = \frac{Bq}{m} = \frac{Bq}{m(E)}$$

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

f_{RF} (E)
B (E) or B = const.

Isochronous cyclotron

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.

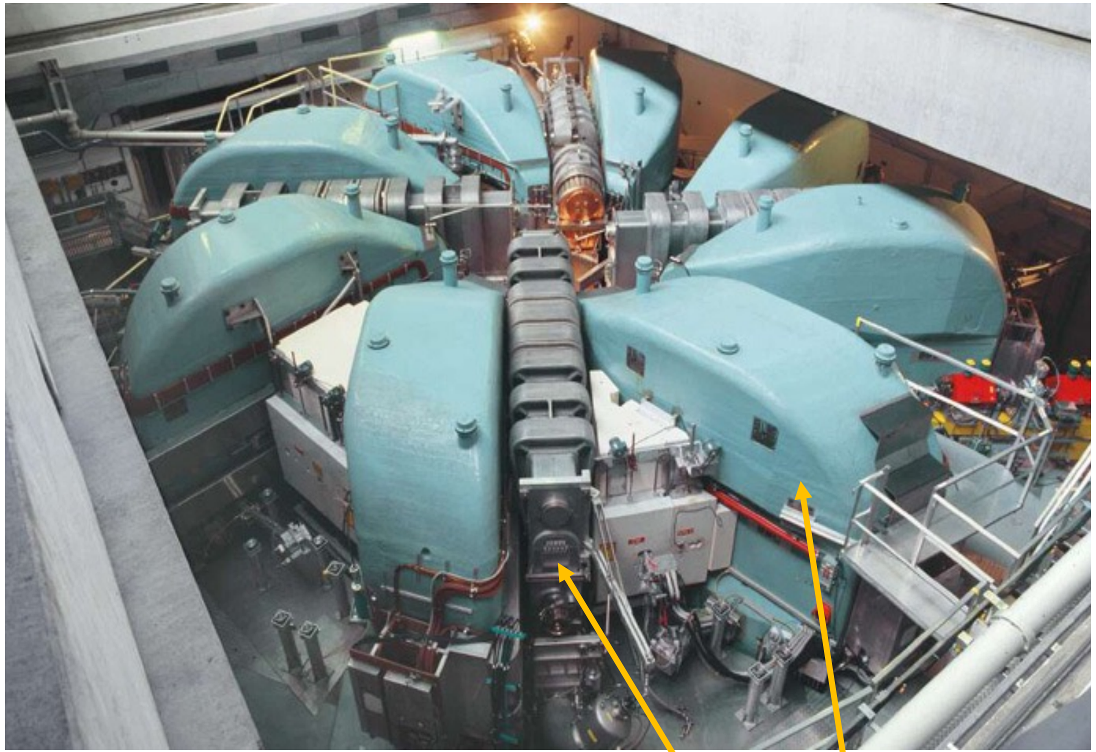
Modern cyclotrons can reach > 500 MeV (PSI, TRIUMF, RIKEN)

PSI Cyclotron

1974

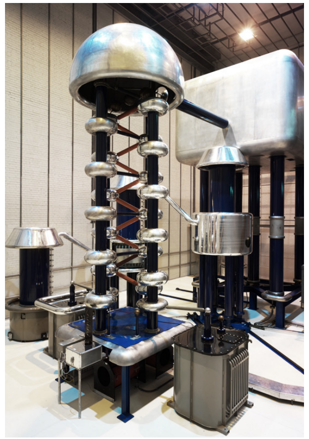
- Diameter ~15m
- Injection energy 72 MeV
- Accelerates protons
  to E = 590 MeV (i.e. 0.8c) in 186 revolutions

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



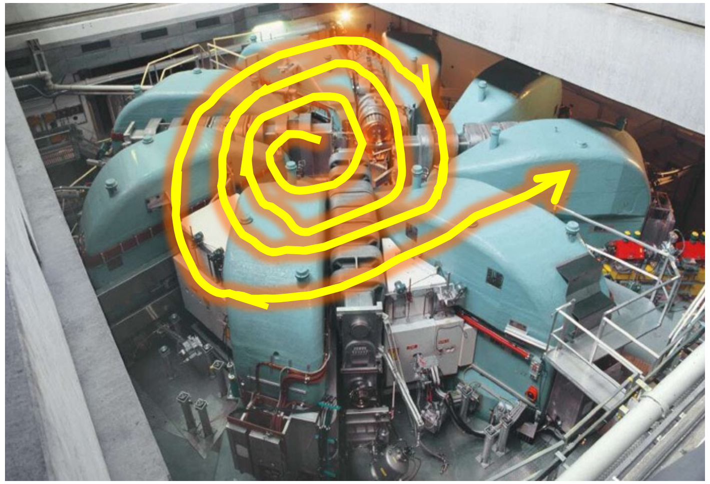
8 sector magnets

4 acceleration cavities



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).

Contact

Deutsches Elektronen-
Synchrotron DESY

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