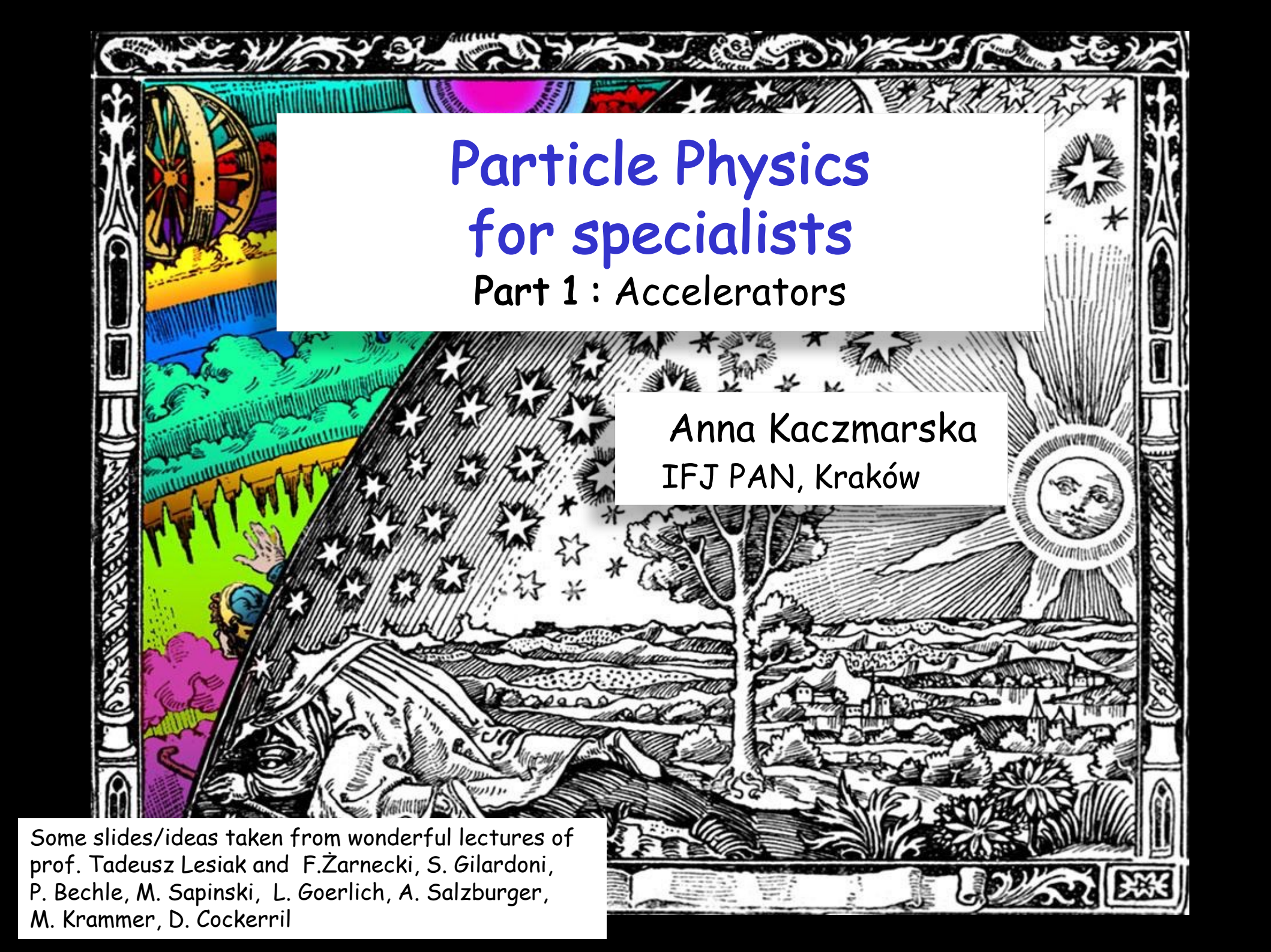




Particle Physics for specialists

Part 1 : Accelerators

Anna Kaczmarska
IFJ PAN, Kraków

Some slides/ideas taken from wonderful lectures of
prof. Tadeusz Lesiak and F. Żarnecki, S. Gilardoni,
P. Bechle, M. Sapinski, L. Goerlich, A. Salzburger,
M. Krammer, D. Cockerril

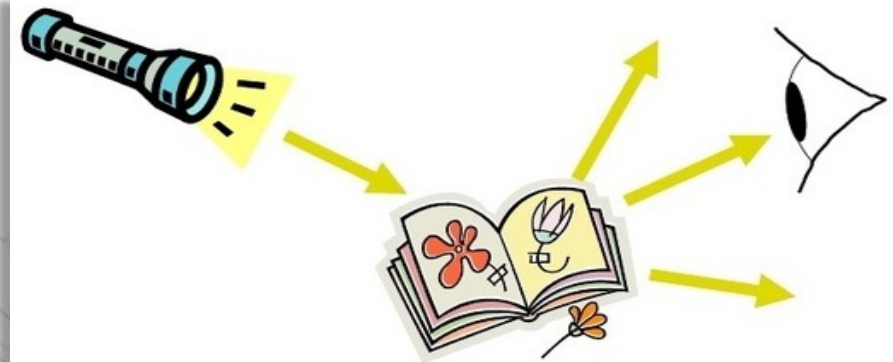
Content of the course

- The Particle Physics **for specialists** course consists of 30h of lectures
 1. Accelerators and Detectors (4h) - Anna Kaczmarska
 2. Standard Model (7h) - Marcin Kucharczyk
 3. Heavy flavour physics (3h) - Andrzej Bożek
 4. Electroweak interactions, Higgs physics and Beyond Standard Model (4h) -Paweł Bruckman
 5. Electron-proton scattering and forward physics (3h) - Rafał Staszewski
 6. Heavy ion physics (3h) - Adam Trzupek
 7. Neutrino physics (3h) - Tomasz Wachała, Grzegorz Żarnecki
 8. Introduction to cosmology, cosmic rays (3h) - Dariusz Góra
- Slides will be available on indico
 - <https://indico.ifj.edu.pl/event/1660/>
- Literature
 - Thomson *Modern Particle Physics (Współczesna Fizyka Cząstek)*
 - Perkins *Introduction to High Energy Physics*
 - Griffiths *Introduction to Elementary Particles*
 - Martin, Shaw *Particle Physics*
 - Halzen & Martin: *Quarks & Leptons: an Introductory Course in Modern Particle Physics*
 - Particle Data Group: "Review of Particle Physics" [<http://pdg.lbl.gov>]

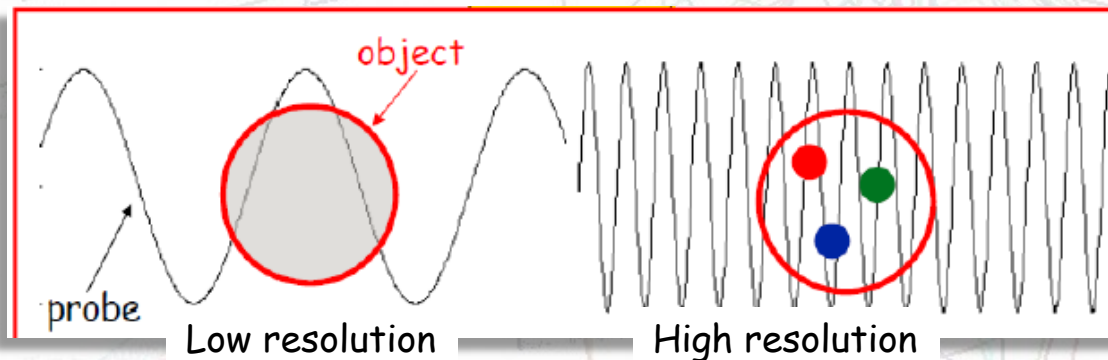
Exam: written, questions randomly selected from the list of questions, the list to be provided at the end of the course

Particle Physics == High Energy Physics

- How do we "see" things?
- We need to send "probe" particles toward target particles and then detect the outcome
- We have to find the right "probe" particles for a given dimension target!



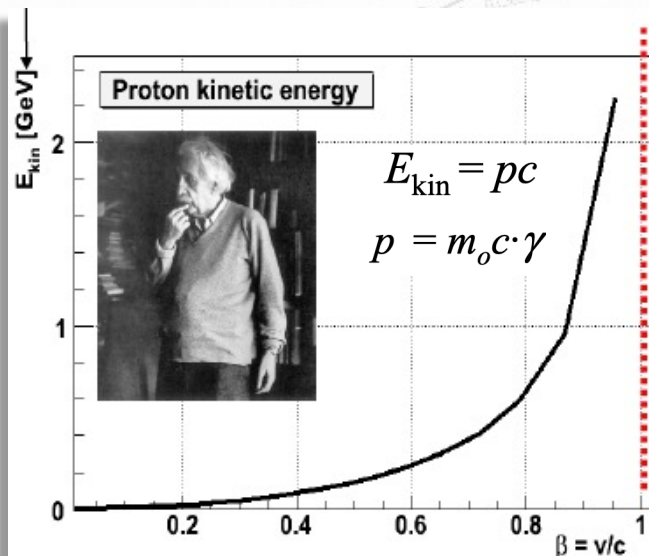
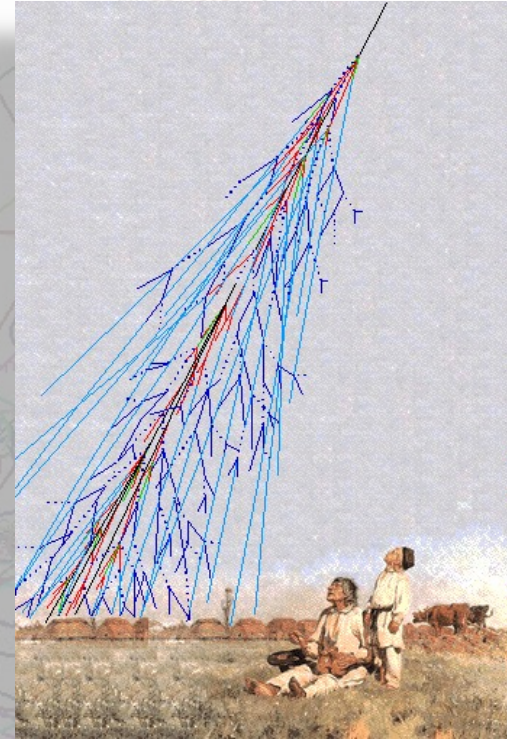
- Energy (of a particle) is connected to de Broglie wavelength $\lambda = h/p = hc/E$
 - the higher the particle energy, the shorter is its wavelength
- To observe an object the wavelength of the probe must be shorter than the size of the object
 - therefore, we probe the smallest things at the **highest possible energies**



- Also, **high energy particles** can have their energy converted into mass ($E = mc^2$), so (heavy) new particles can be created and observed

Why we need accelerators?

- Until the advent of high-energy particle accelerators in the early 1950s only one source of high energy particles
 - Natural/cosmic accelerators => **cosmic rays**
 - see last lectures of this course
- To do an **experiment** we need to produce under **controlled conditions** particle beams:
 - with high intensity
 - at chosen energy
 - of a given particle type } **accelerators!**
- An experiment consists of studying the outcome of collisions, either with a fixed target or between two particle beams.



- In high-energy accelerators, particles normally travel very close to the speed of light
 - under these conditions, as the energy increases, the increase in speed becomes minimal
 - e.g. particles in the LHC move at $0.999997828 \times c$ at injection ($E = 450 \text{ GeV}$) and $0.999999991 \times c$ at top energy ($E = 7000 \text{ GeV}$).
- **Therefore, we generally do not think in terms of speed, but rather in terms of a particle's energy.**

Fixed target vs collider experiments

- The **center-of-mass energy** of a system of particles is the energy measured in the center-of-mass reference frame
 - energy to create new particles or to explore the internal structure of particles
 - $s = E_{CM}^2 = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = m_1^2 + m_2^2 + 2(E_1 E_2 - |\vec{p}_1| |\vec{p}_2| \cos \theta)$

Lorentz-invariant, one of Mandelstam variables

[natural units used]

Fixed target collisions

- $s = m_1^2 + m_2^2 + 2E_1 m_2$
- For $E_1 \gg m_1, m_2$ $s = 2E_1 m_2$
- $\sqrt{s} = \sqrt{2E_1 m_2}$

$$p_1 = (E_1, \vec{p}_1) \quad p_2 = (m_2, 0)$$

- e.g. 450 GeV proton hitting a proton at rest: $\sqrt{s} \sim 30 \text{ GeV}$

Colliding Beams

- For $E_1 \gg m_1, m_2$; $\theta = \pi$, $E_1 = E_2 = E$
- $s = 4E^2 \Rightarrow \sqrt{s} = 2E$

$$p_1 = (E_1, \vec{p}_1) \quad p_2 = (E_2, \vec{p}_2)$$

- e.g. 450 GeV proton colliding with a 450 GeV proton: $\sqrt{s} \sim 900 \text{ GeV}$

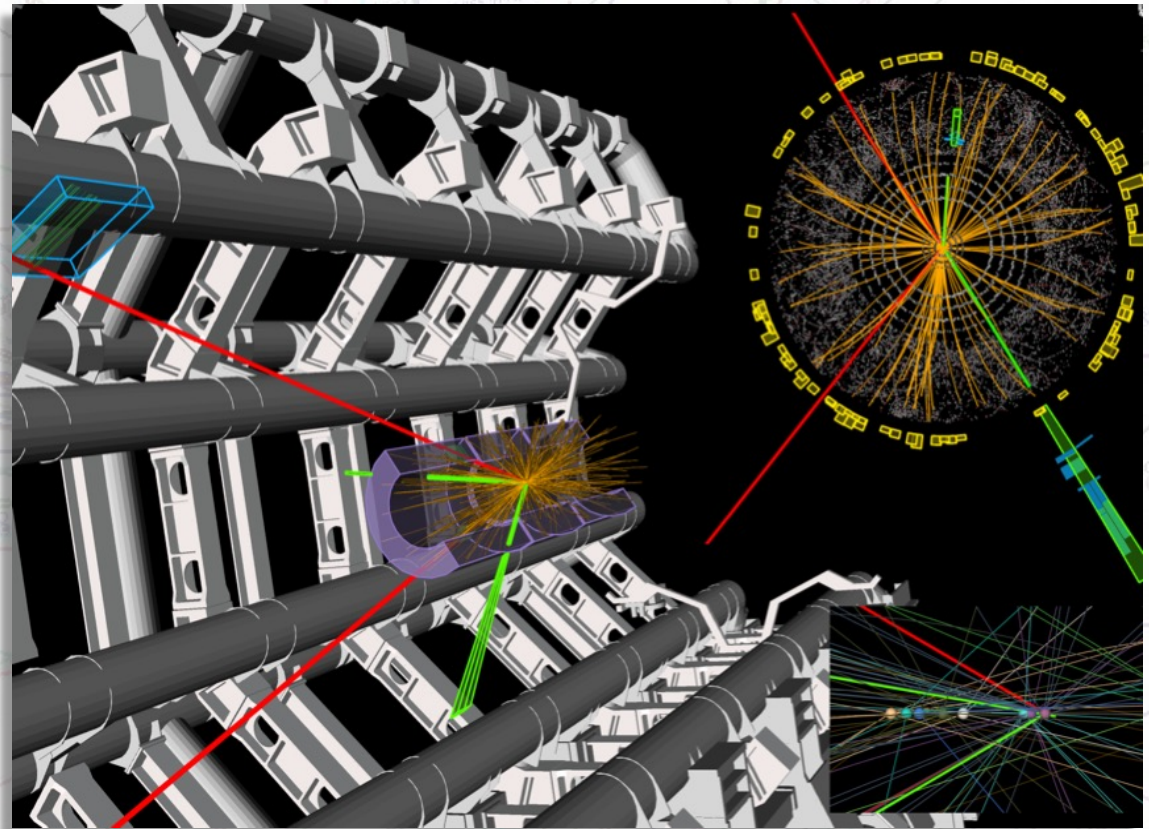
- In a fixed-target experiment, most of the particle energy is used to provide forward momentum to the final-state particles rather than being available to create new particles.
- Pros:** in colliders the total energy of colliding particles is available
- Cons:** frequency of collisions lower! $\rightarrow$ "target", second beam has low density

Accelerators and detectors

Basically, I want to bring you today and next week...



from a bottle of
hydrogen



to this

How does an accelerator work?

- **A particle accelerator** is a machine to accelerate **charged particles** to high energies
- Goal: keep enough particles confined in a well-defined volume to accelerate them
- How ? The Lorentz Force!

$$\overline{F(t)} = q \left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)} \right)$$

Electric field
accelerates particles

Particles with
different velocities
behave differently

Magnetic field keeps
particles on a given
trajectory

Kinetic energy gain $\Delta T =$ work on the particle:

$$\Delta T = W = \int \vec{F} \cdot d\vec{s} = q \underbrace{\int \left(\frac{d\vec{s}}{dt} \times \vec{B} \right) \cdot d\vec{s}}_{=0} + q \underbrace{\int \vec{E} \cdot d\vec{s}}_{=U} \quad \vec{v} = \frac{d\vec{s}}{dt}$$

- Accelerators use electric fields to increase the energy of charged particles

Accelerator parameters

Requirements:

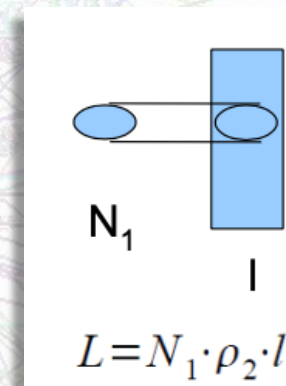
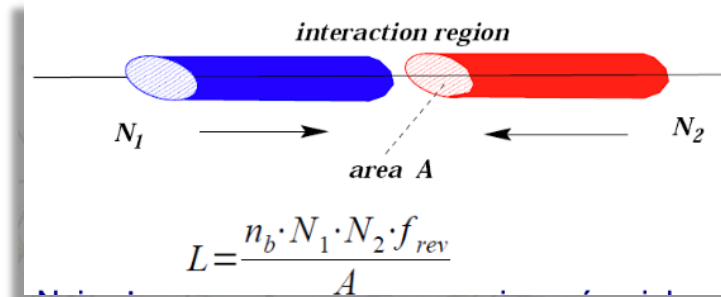
- Highest possible beam energy ($\sqrt{s}$: heavy m_X , small $\lambda \rightarrow$ resolution)
- Highest possible beam intensity: Luminosity, L [$\text{cm}^{-2}\text{s}^{-1}$]
 - R - reaction rate, σ - cross-section

$$R = \sigma \times L$$

- Higher Luminosity $\rightarrow$ rarer processes we can measure!
- Record: $4.65 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ SuperKEKB (2020)
- Collecting data for certain time we integrate luminosity

$$\int \mathcal{L} dt = N \cdot \sigma^{-1} \quad \int \mathcal{L} dt \equiv L \quad \left[\int \mathcal{L} dt \right] = [\text{cm}^{-2}, \text{fb}^{-1}]$$

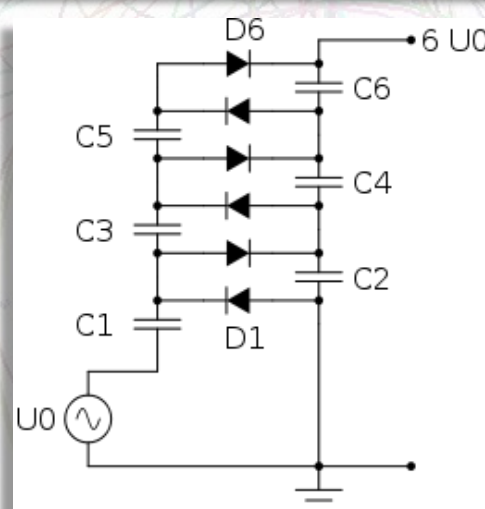
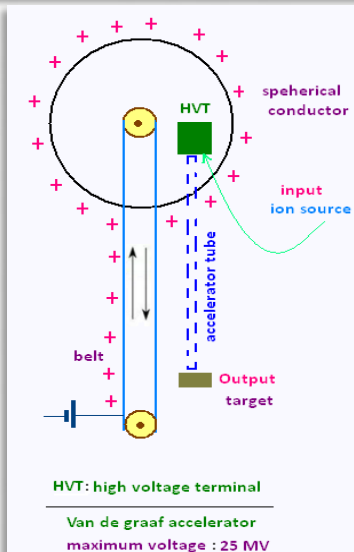
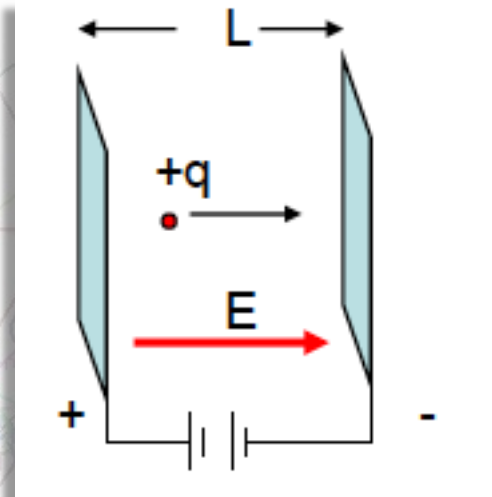
- Best possible beam quality: energy spread, focusing



- Measurement of luminosity mandatory to measure a process cross section
 - from machine parameters
 - from reactions with well known cross sections (f.e. e^+e^- Bhabha scattering)
 - σ can be calculated with high precision, high event rates for low statistical error
 - from optical theorem
 - like the measurement of Bhabha scattering for e^+e^- colliders but uses Coulomb scattering amplitude which can be precisely calculated
 - measurement in forward direction!
 - need special beam conditions and dedicated detectors (roman pots)

Electrostatic accelerators

- These accelerators use a static, direct current DC, potential difference between two electrodes
- Earliest particle accelerators (~1930s)
 - Van de Graaff's belt-charged generator
 - Cockcroft- Walton generator - voltage-multiplier ladder with capacitors and diodes to generate high voltages
- Highest voltage achieved is 24 MV
- It is difficult to establish and maintain a static DC field of 20+ MV
 - High-voltage breakdown; only a few MV are needed to generate lightning
- Particle energies 20+ MeV, too low for us!
- Electrostatic accelerators are still in use in nuclear physics or as initial acceleration

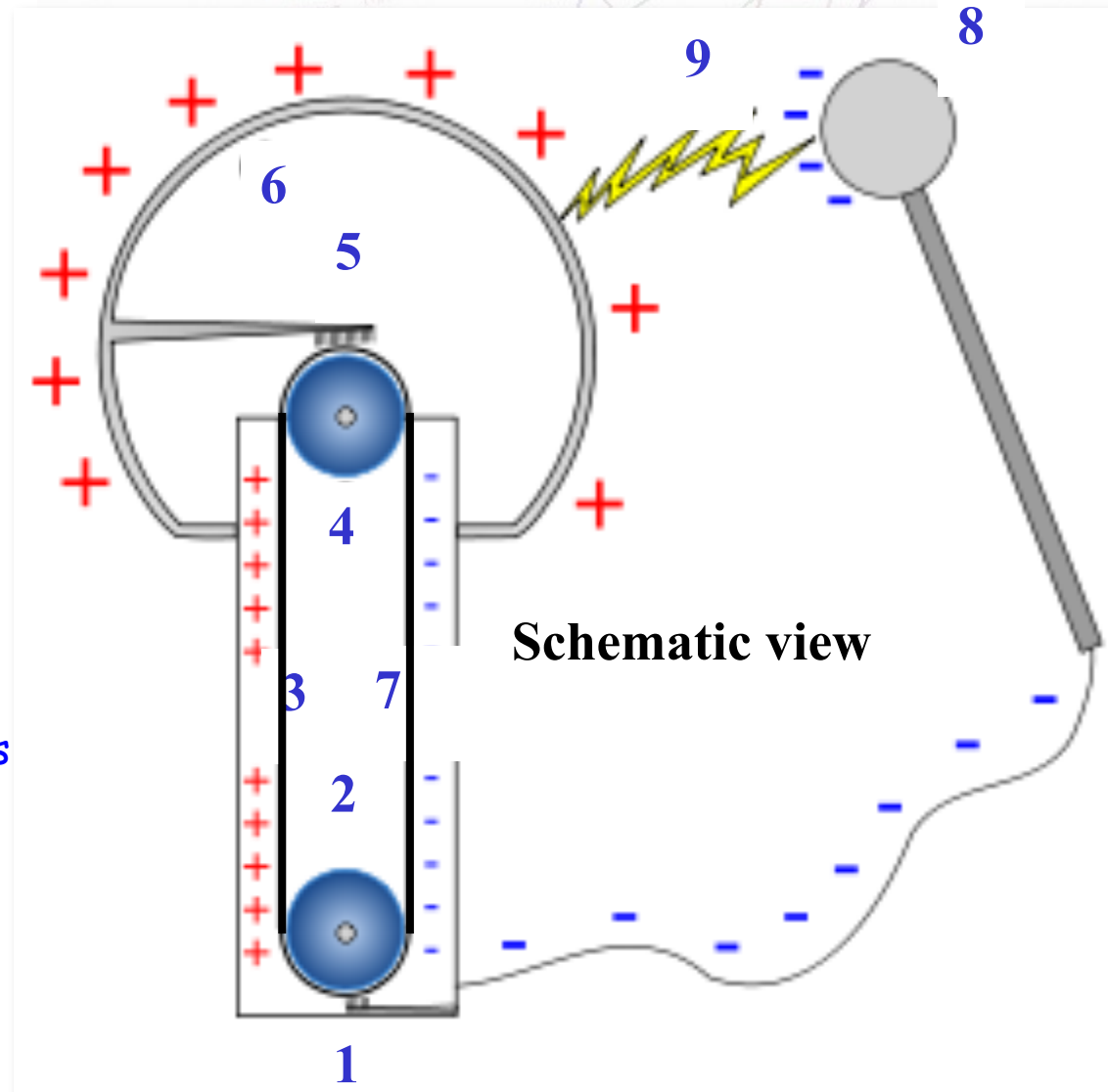


Van de Graaff Generator

A Van de Graaff generator is made by a belt of a flexible **insulating** material, running over two rollers (wheels), one of which is surrounded by a hollow metal ball.

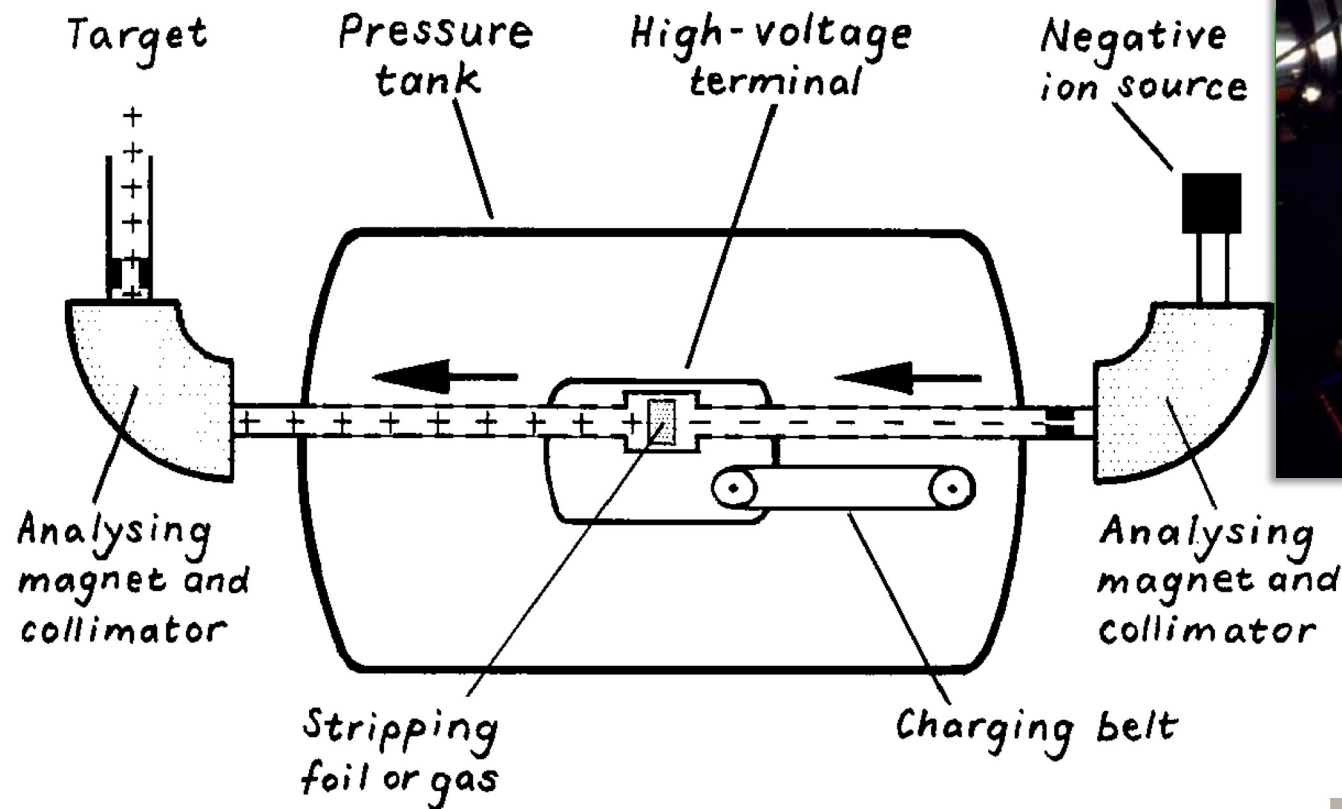
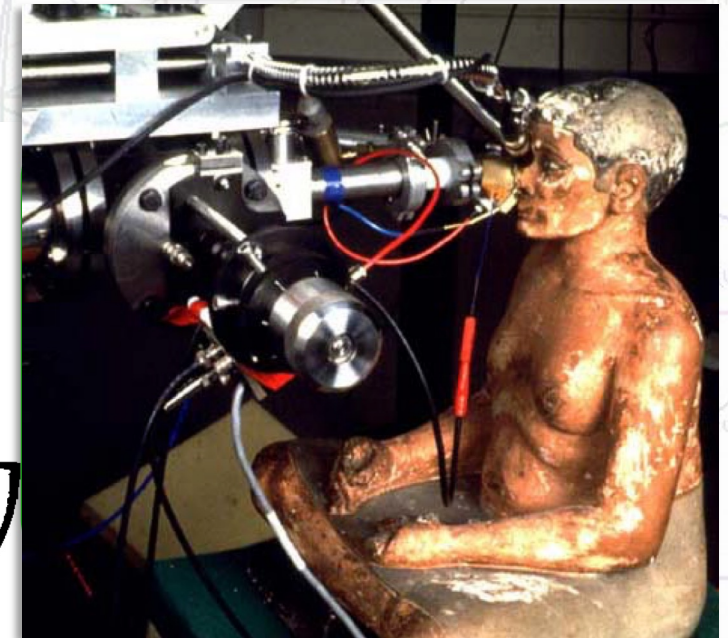
- Power Supply that pulls off electrons (1)
- Rollers (2,4).
- Positively charged belt (lost some electrons) (3)
- Metal comb that drops electrons from the ball onto the belt (5)
- Metal ball that gives up electrons to the belt, then it is charged! (6)
- Negatively charged belt (gained some electrons from the ball) (7).
- Grounding wand, it can give or take electrons to make everything even again (8).
- Discharge: A spark, a flow of electrons through the air (9).

The larger the sphere and the farther it is from ground, the higher will be its peak potential.



Tandem

- Application of Van der Graaf generator
- 2 stages acceleration
 - Accelerate negative ions to HV - dome
 - Pass ions through a foil to remove electrons
 - Accelerate positive ions to ground
 - Everything in a pressurized vacuum tank

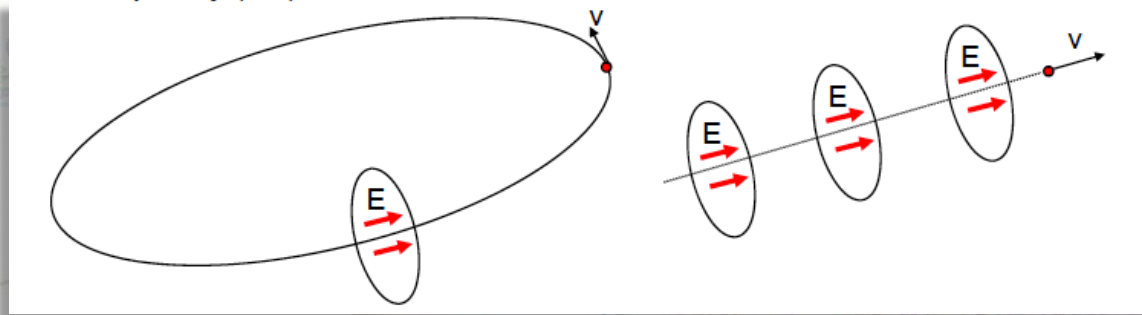


Current applications:

- Low energy injector for ions
 - Brookhaven (US), injector for Cu and Au ions
- Compact system for "other uses"
 - composition of samples at Louvre

Acceleration using Radio-Frequency (RF) generators

- DC accelerators are limited by a maximum size and a maximum break down voltage
- To reach higher particle energies, we would like to reuse the electric fields we generate
 - BUT if the voltage is DC, the particle is accelerated between the plates but decelerated outside them $\rightarrow$ net acceleration = 0!
 - SO, we need a field that can be switched on and off — an Alternating Current, AC, system!
 - We can apply relatively low accelerating voltages at each acceleration step.
- Two approaches for accelerating with time-varying fields



Circular Accelerator

Use one or a small number of radiofrequency accelerating cavities and make use of repeated passage through them

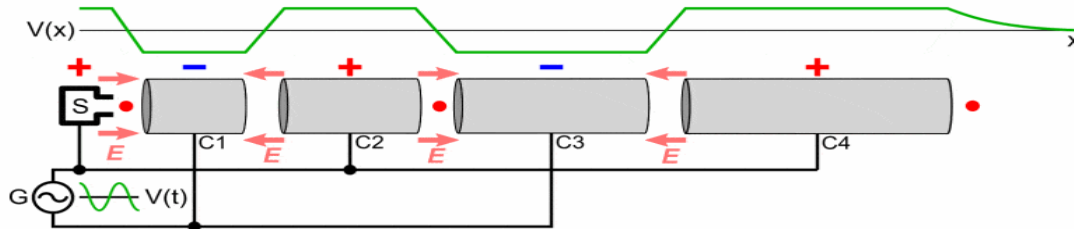
Linear Accelerator

Use many accelerating cavities through which the particle passes only once

Wideroe (1928): the first linear accelerating structure

Ising and Wideroe: application of smaller voltage in a linear accelerator by using time-varying fields

- Subsequent drift tubes are connected to opposite polarities of an alternating voltage source.
- Tubes act as Faraday cages
 - in the tubes particles feel no force
 - outside the tubes they feel the potential difference between successive tubes, they accelerate forward
- Alternating current ensures that the difference always has the correct sign for acceleration (RF, tens of kHz)
- Each time, the same magnitude of voltage is applied and so the energy of the particle $E = n \times q \times V$, is built up in steps without needing to increase the voltage

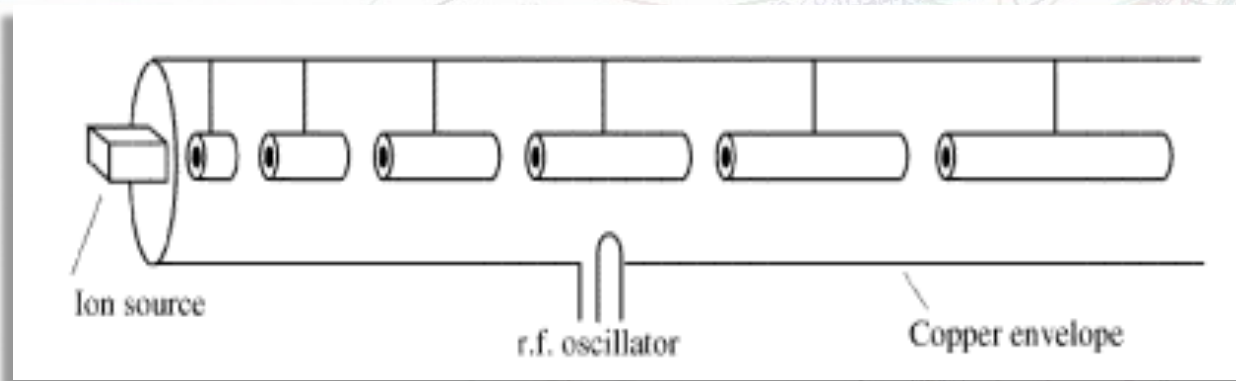


Obs: - the drift tube length has to increase because particles are not yet relativistic (for 500 keV protons at 1 MHz frequency it is ~5 meters!)

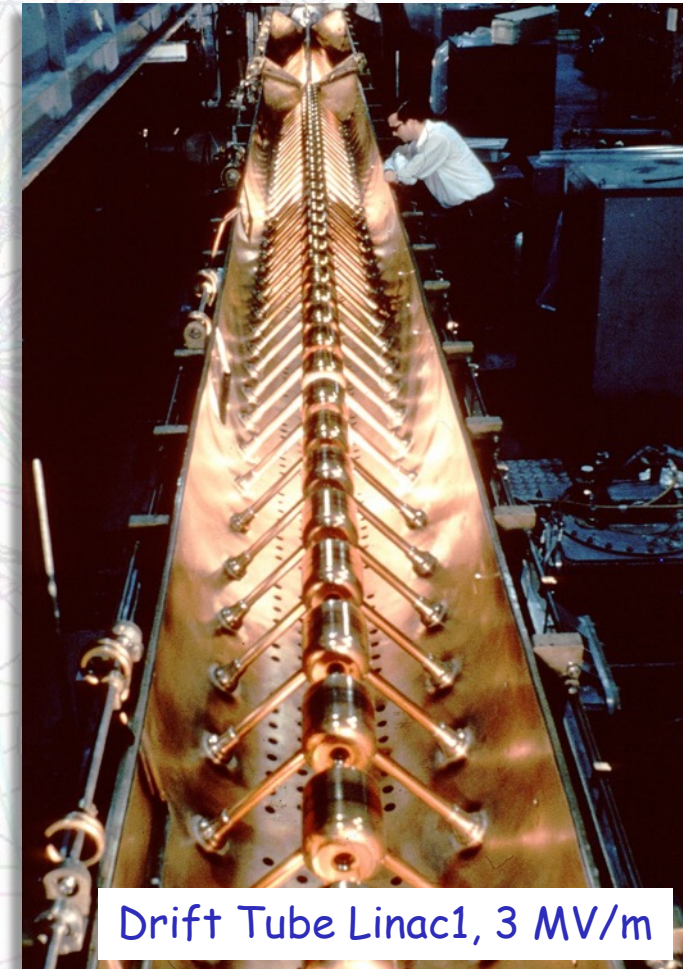
- Main limitation: after a certain energy, the length of the drift tube is too long.
- Way out -> RF frequency has to increase to ~10 MHz, need to enclose the structure in a resonator to avoid field losses - the system is a big emitting antenna

Alvarez (1946): the first serious proton linac

- By this time suitable high-power, high-frequency generators (klystrons) become available to meet the needs of war-time radar development
- Enclose everything in a RESONANT CAVITY, such that resonant frequency is equal to the one needed for acceleration
- In such cavity a standing wave is created with electric field in the direction of particle movement
- As in Wideroe's linac, particles gain energy from the accelerating potential differences between the ends of the drift tube, but the phase shift between drift tube gaps is now 360°
- Field frequency can go up to 200 MHz

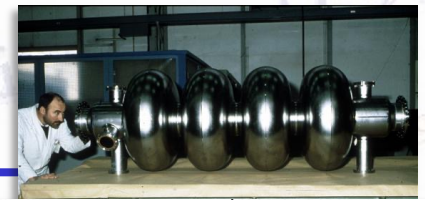


The Alvarez structure is still used for non-relativistic proton and ion beams (CERN Linacs, input to Proton Synchrotron)

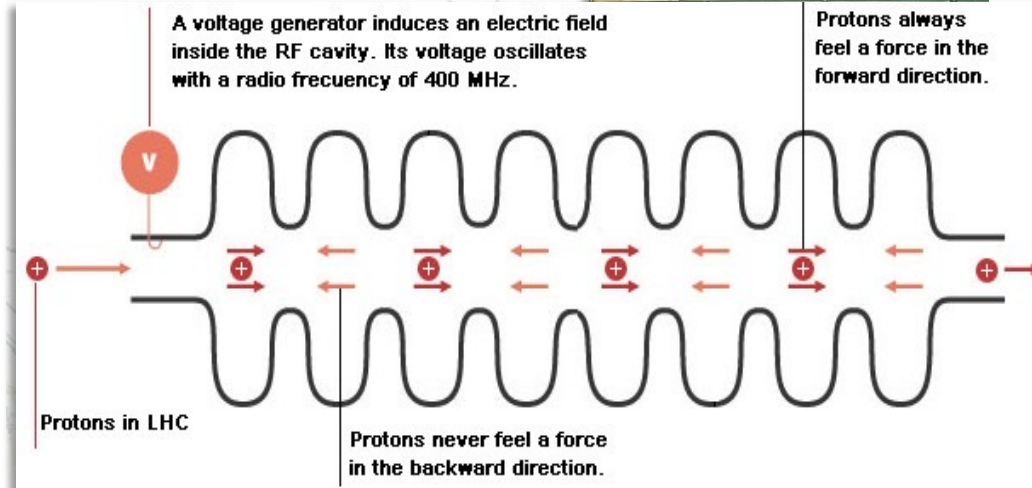


Drift Tube Linac1, 3 MV/m

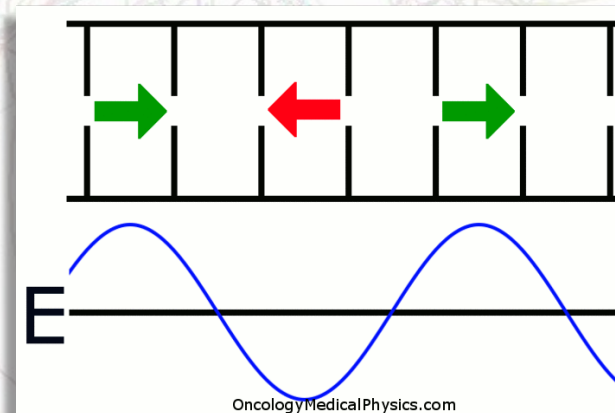
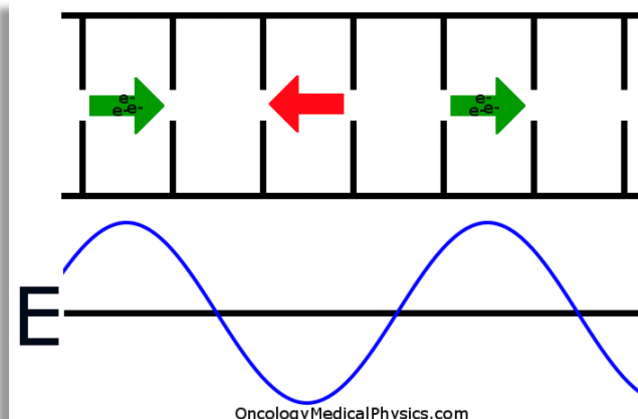
Modern accelerators



- To accelerate relativistic particles we use electromagnetic wave
- Drift tubes typically no longer used and have been generally replaced by cavity structures
- For relativistic particles (e - few MeV, p - few GeV) velocities are close to light speed - when accelerated their velocity remaining almost constant
 - cavity structures of same size
=> relatively simple design
- Resonant cavities reduce RF power consumption, increase gradient ($f \sim 1\text{GHz}$)
- RF cavities for particle acceleration can be operated in standing wave or traveling wave modes (two ways to drive the particles)

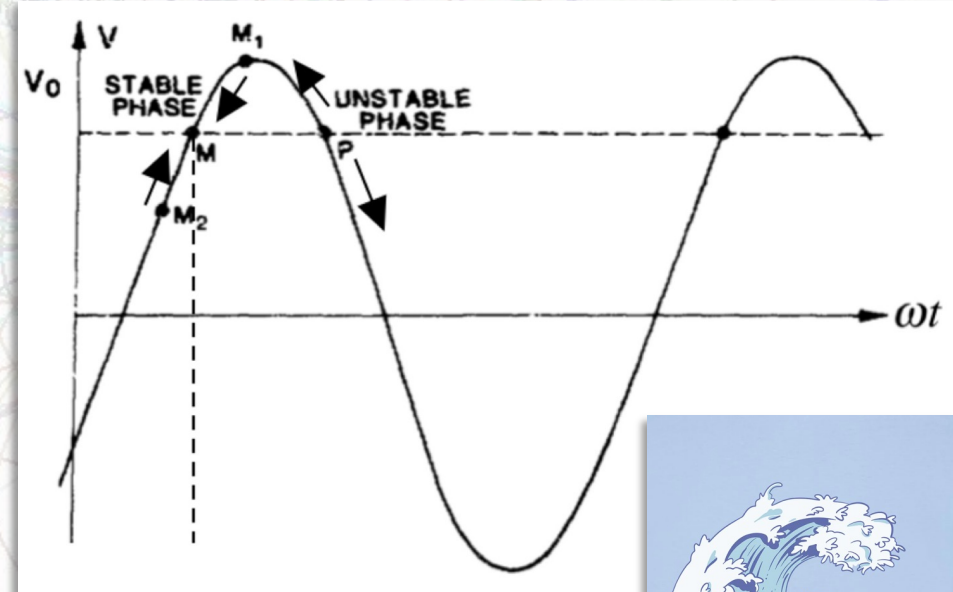


The geometry of the resonant structure is designed to provide the appropriate RF phase and electric-field distribution along the beam path.



Phase stability

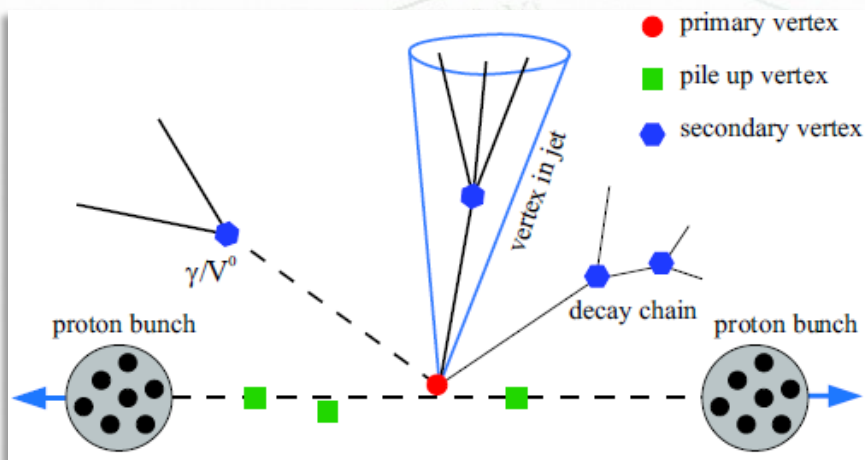
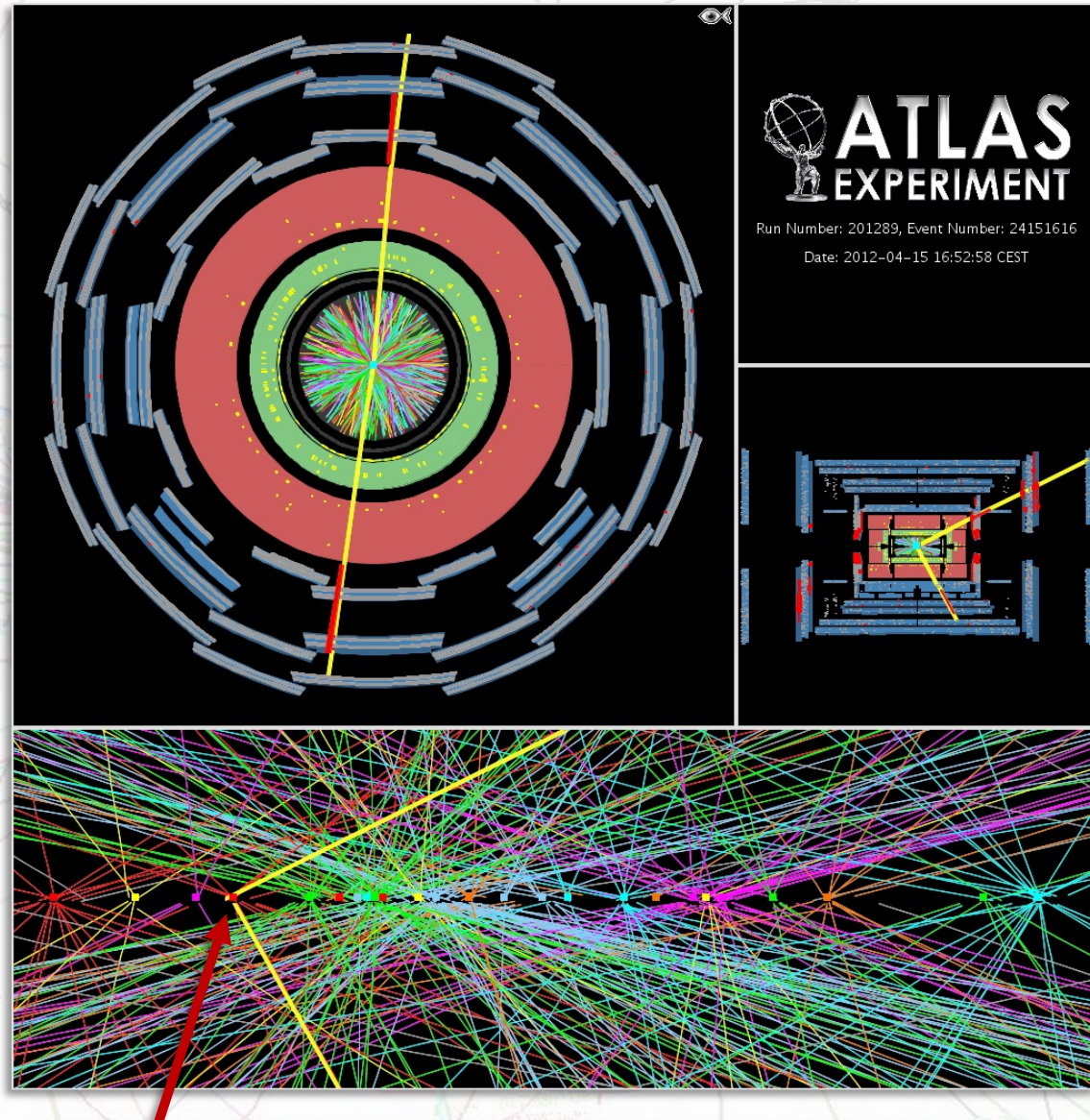
- To maintain effective acceleration, precise synchronization between the particle beam and the RF field is necessary
 - The electric field within the cavity oscillates sinusoidally, and particles must enter the cavity at the correct phase of this oscillation to gain energy
- A particle exactly synchronised with the RF frequency is called **synchronous particle**
 - RF phase of synchronous particle is selected to be when the field is increasing in time (not in maximum!)
- Earlier particle receive smaller energy kick than the synchronous one and will be slowing down with respect to synchronous particle.
- Particles, which arrive later to accelerating gap, receive larger energy gain, and will run down the synchronous particle.
- This continuous restoring mechanism creates stable longitudinal oscillations (**synchrotron oscillations**) around the reference synchronous particle while steadily increasing the beam's overall energy



This means that instead of being spread uniformly in beam, the particles get "clumped" around the synchronous particle in a **BUNCH**

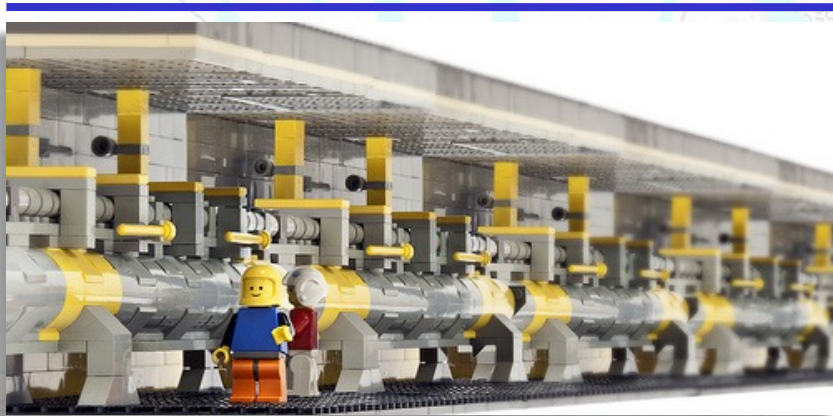
LHC: pile-up

- We are colliding bunches of particles not single particles
- At the LHC a bunch consists of $\sim 10^{11}$ protons
- In a single bunch crossing multiple proton-proton collisions can occur at the same time
- Pile-up** refers to collisions that lead to overlapping detector signals in addition to the primary collision of interest
 - In detector we can see many (almost) simultaneous collisions (vertices)
 - Problem for detector occupancy and particle identification
- During LHC Run 3, experiments experience an average of around 60 simultaneous proton-proton interactions (pile-up) per bunch crossing at collision energy of 13.6 TeV



We are interested only in this one! (hard-scatter event)

Example: SLAC electron linac



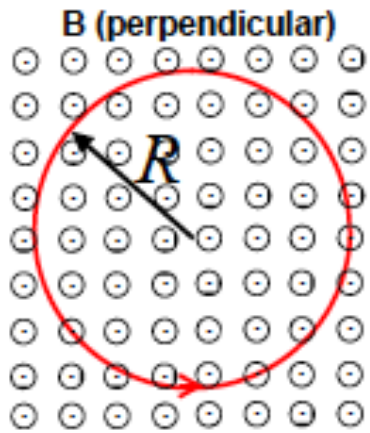
- The world's longest electron linac is the 3.2 km machine at the Stanford (University) Linear Accelerator Center, SLAC, U.S.
- It can accelerate electrons to 50 GeV
- In operation since 1966

Research at SLAC has produced three Nobel Prizes in Physics

- 1976: The charm quark—see J/ψ meson
- 1990: Quark structure inside protons and neutrons
- 1995: The tau lepton



Digression: Movement of the charged particle in magnetic field



Lorentz Force

$$\vec{F} = \frac{d\vec{p}}{dt} = q \vec{v} \times \vec{B}$$

momentum
charge
velocity

of the particle

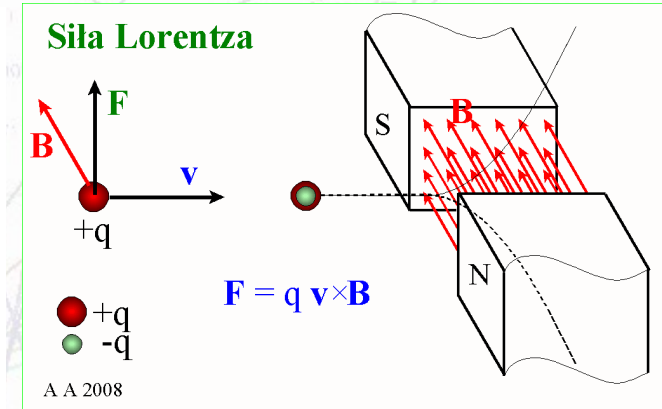
magnetic field

circular motion:

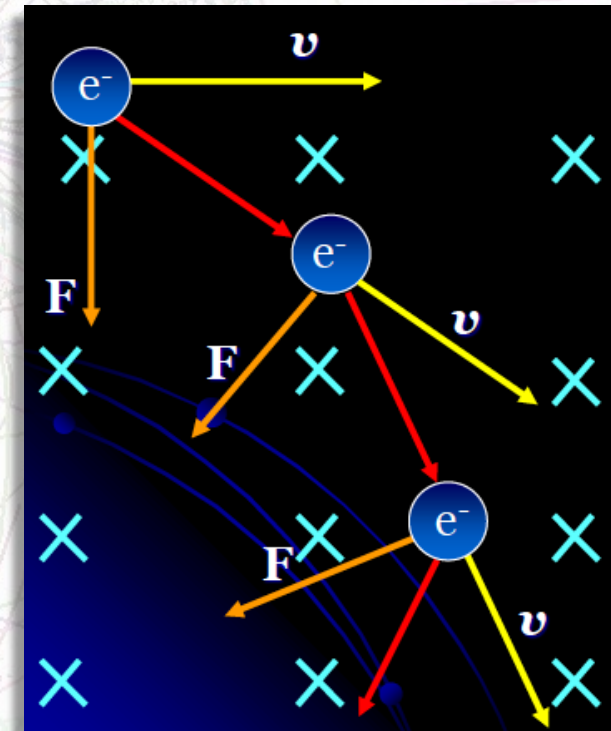
$$\vec{B} \perp \vec{v} \rightarrow F = q v B = m \frac{v^2}{R} \Rightarrow R = \frac{m v}{q B}$$

time for one revolution: $T = \frac{2\pi R}{v} = 2\pi \frac{m}{q B} = \text{const.}$

For field of magnetic flux density B , perpendicular to the direction of travel, the Bqv force provides the centripetal force.

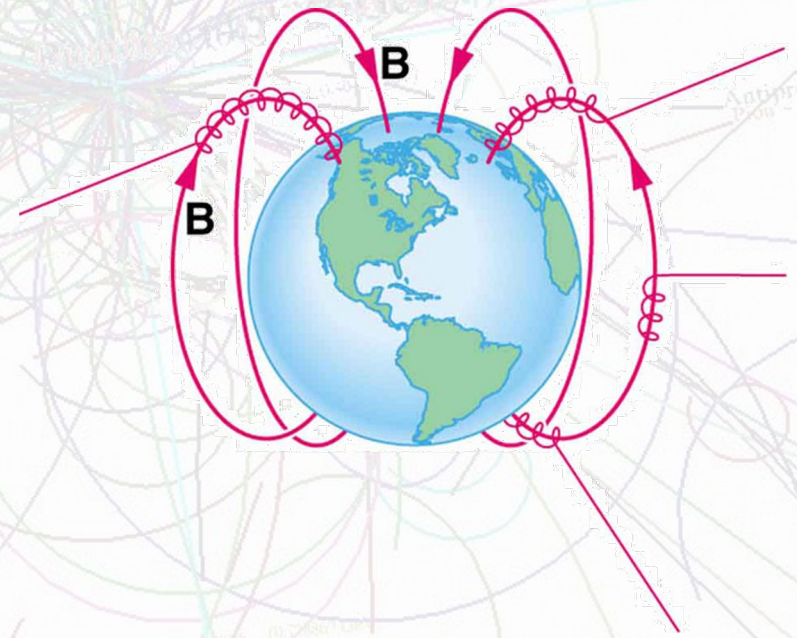


http://www.if.pw.edu.pl/~anadam/WykladyFO/FoWWW_35.html

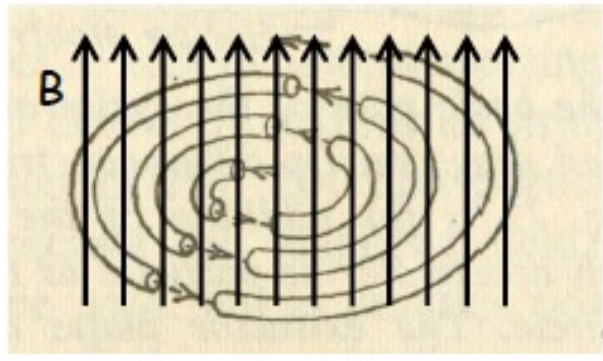


Digression: Aurora Borealis

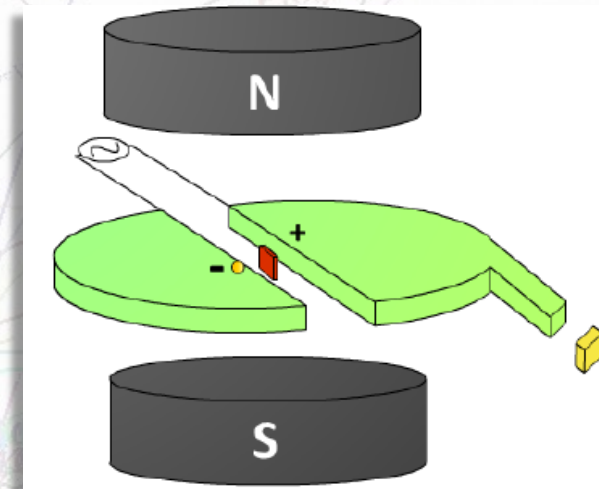
- Aurora Borealis is caused by charged particles from solar wind (streams of charged particles expelled from the Sun) being caught in the Earth's magnetic field and colliding with particles in the Earth's upper atmosphere
- A charged particle in a magnetic field experiences a force, and this force provides the centripetal force.
- This causes the particles to spiral along the earth's magnetic field lines



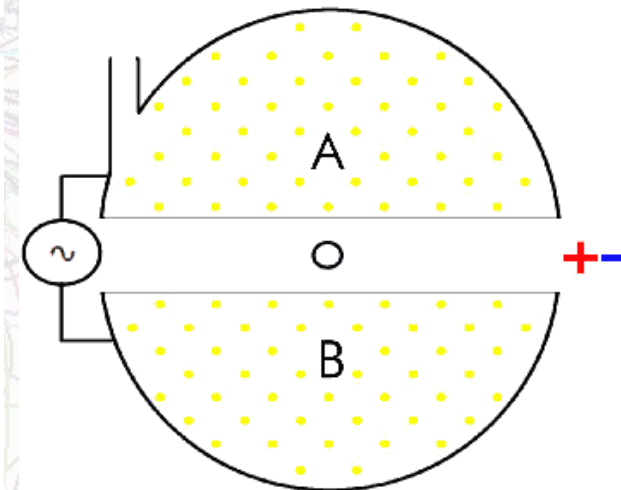
Cyclotron - first circular accelerator



- first concept of the 'cyclotron' (1929) (from E. Lawrence but also Widroe!)
- drift-tube linac "rolled up"
- Lawrence, Nobel 1939



- Cyclotron uses a magnetic field to bend charged particles into a circular path so that they can be repeatedly accelerated by the same electric field
- Proton leaving the center is attracted to the negative D-shaped electrode and magnetic field bends it into a semi-circle
- While the proton is travelling this semi-circular path **in dee** the polarity of the electrodes reverses. When the proton reaches the gap, the electric field accelerates the proton forwards (because it is oppositely charged)
- Crossing gap many times they gain more kinetic energy
- The radius of the proton's path increases $R = mv/Bq$, since it travels faster



Revolution period

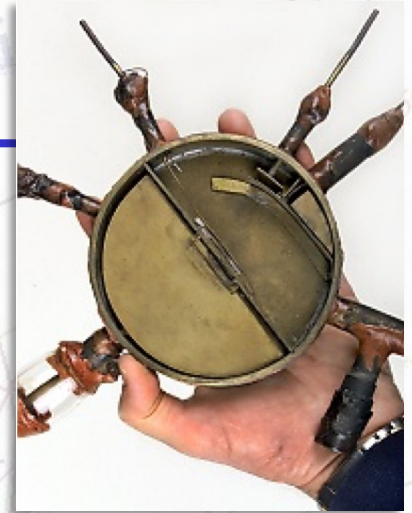
$$T = 2\pi \cdot r / v = 2\pi \cdot m / qB$$

- But despite travelling faster, it takes the same time to travel each semi-circle, so the alternating voltage can stay at the same frequency

Cyclotron

The Advantages of a Cyclotron

- Particles go round many times getting multiple kicks of energy
- Smaller size - E. Lawrence achieved $E(p)$ of 80 keV using a cyclotron with a diameter of 11cm!



The Disadvantages of a Cyclotron

- For larger energy, the magnet diameter increasing, at constant B
- Special relativity: as objects get faster, they get heavier. As $R = mv/Bq$, an increase in mass, will cause a larger R , making it out of step with the field

Modern cyclotrons in use for basic science and medical applications incorporate:

- superconductivity, to obtain much higher magnetic fields for a given R
- Correction for increasing mass by:
 - **Synchrocyclotrons:** $B = \text{const}$, accelerating RF frequency adjusted in time
 - **Isochronous cyclotrons:** shaping of magnetic field, $RF = \text{const}$

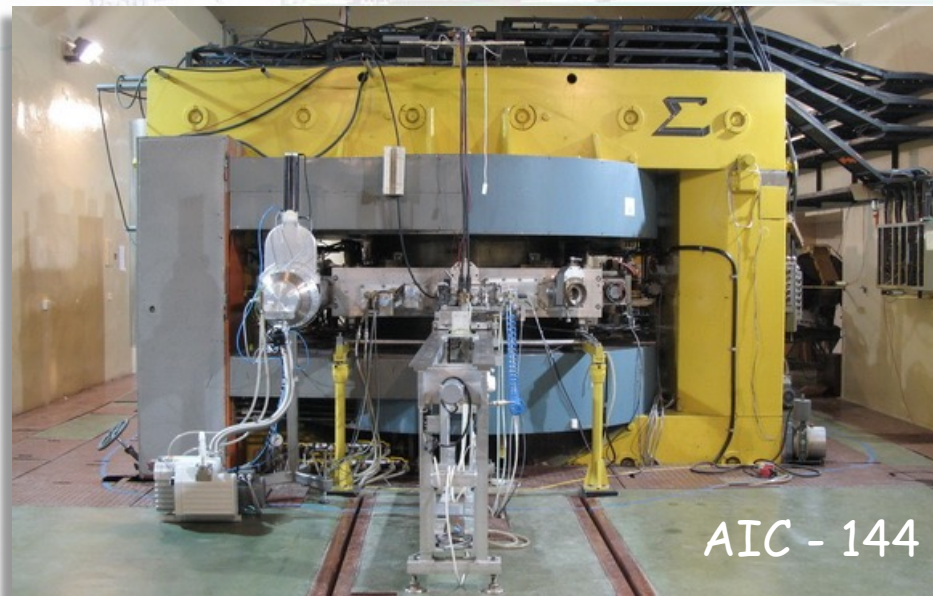


The largest cyclotron in TRIUMF (Canada): 18-meter diameter

- The protons inside this cyclotron travel 45 km as they spiral outwards
- Reaching max energy of 520 MeV
- In operation since 1974.

Cyclotrons at the INP PAN in Kraków

- First cyclotron in Poland C-48 installed in IFJ, 48 cm (1955)
- Soviet built classical cyclotron U-120 (opened 1958, stopped 1994) - 12 MeV deuterons
- Cyclotron isochronic AIC - 144 (from 1995) developed at IFJ PAN, 60 MeV protons
- **Proteus C-235 (isochronic) -> 70 - 230 MeV (in operation from 2012)**



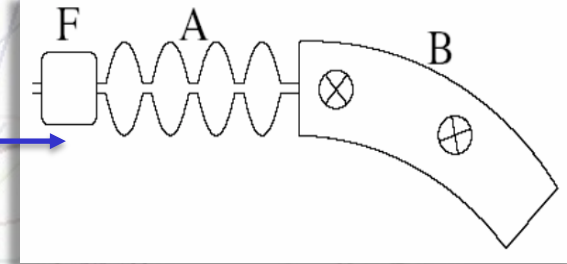
Synchrotron

The principle - Vladimir Veksler (1944)

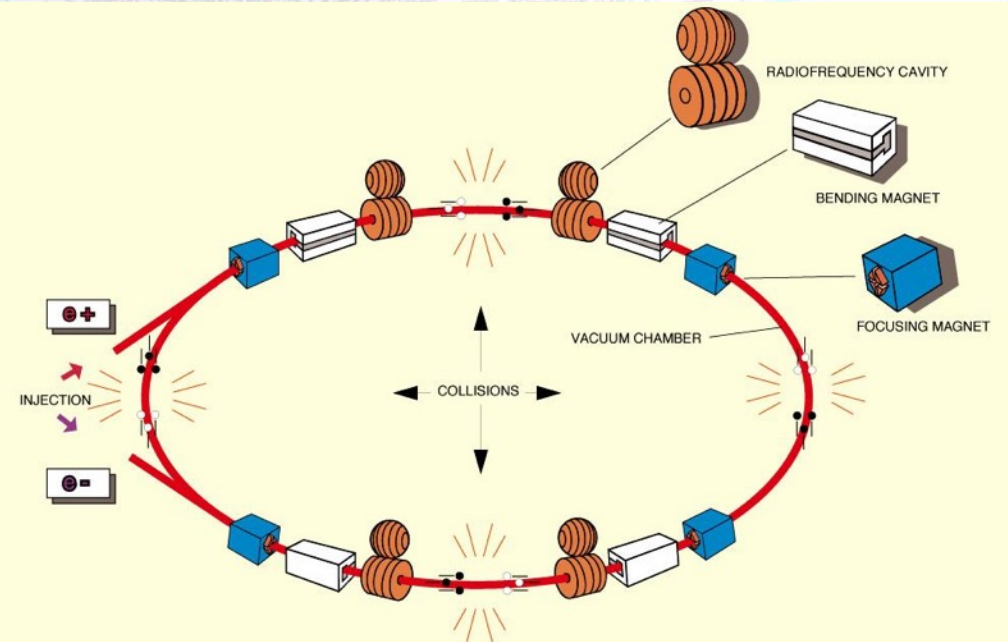
The first electron synchrotron - Edwin McMillan (1945)

The first proton synchrotron Sir Marcus Oliphant (1952)

- Instead of changing the orbit of the particles, the magnetic field increases (synchronously with particle energy)
- For particles not close to c , the frequency of the applied electric field may also change to follow their non-constant circulation time
- Series of accelerating cavities (A) dipole (bending) (B) and quadrupole (focusing) magnets (F)
- $p = qBR$ so for high momentum beams need high B field and/or large radius
- Synchrotrons can be used as colliders or storage rings
 - accumulate and store beam for long time



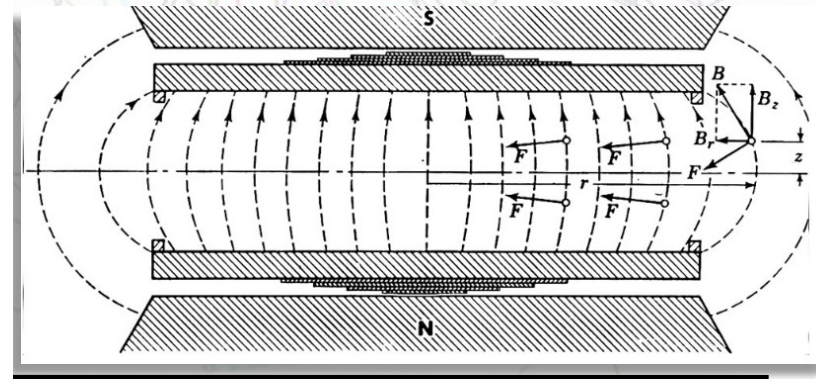
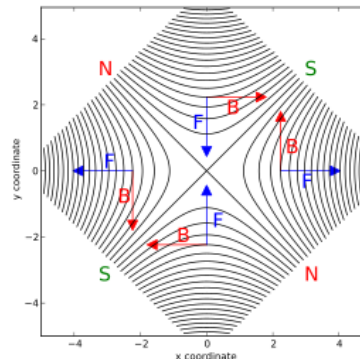
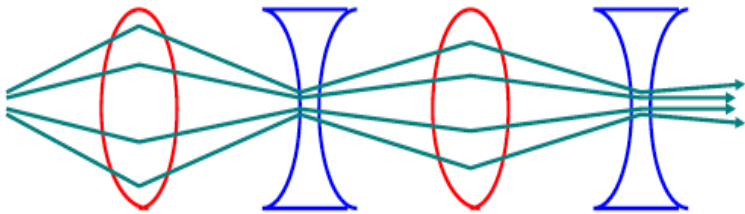
The largest synchrotron in the world - the LHC



CERN AC - E509

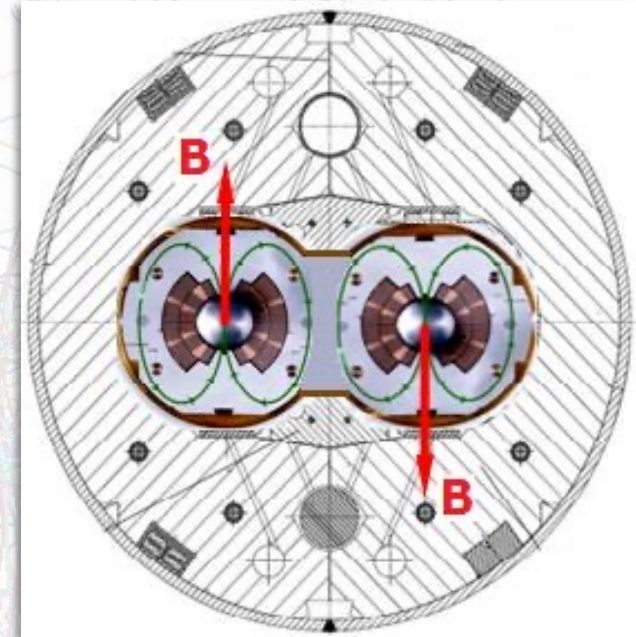
Bending and Focusing

- As particles move around the accelerator, we need to use other electromagnets to bend and focus them
- **Bending:**
 - **Dipoles** (vertical field) bend beam horizontal direction
- **Perfect synchrotron needs only dipoles**
 - but the world is not perfect - beam particles suffer from: gravity, radiative energy losses, interactions between particles, interactions with accelerator etc. $\Rightarrow$ as a result beam is defocused
- **Focusing:**
 - **Weak:** bending magnets also focus the beam by magnetic field shaping
 - **Strong:** sequence of elements that are either strongly focusing or defocusing $\Rightarrow$ net effect is focusing! Invented in 50's.
 - **Quadrupoles** defocuses in one plane focuses in the other
 - With this system **alternate focusing and defocusing quadrupoles the beam dimension is kept small** (even few μm^2).



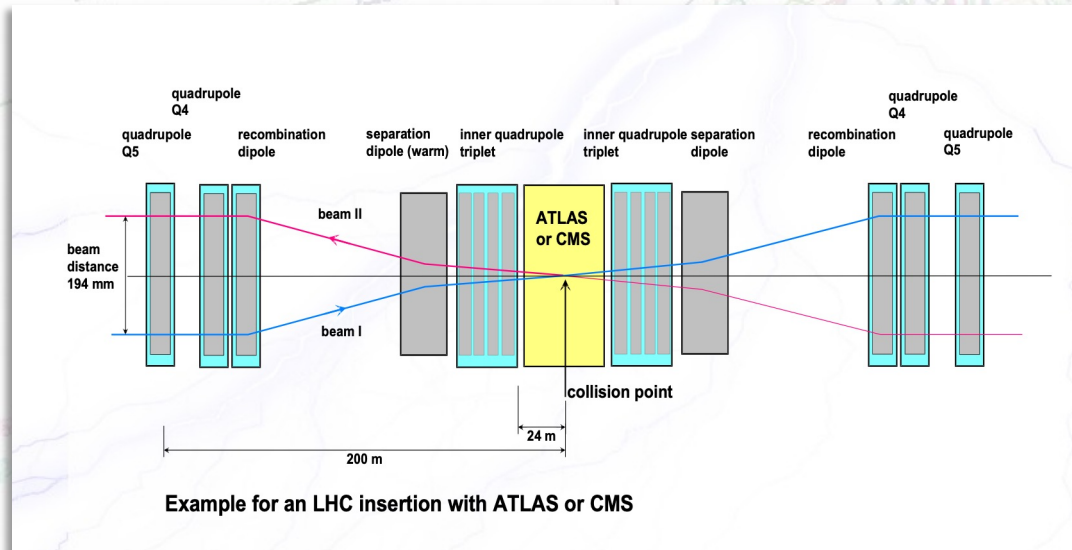
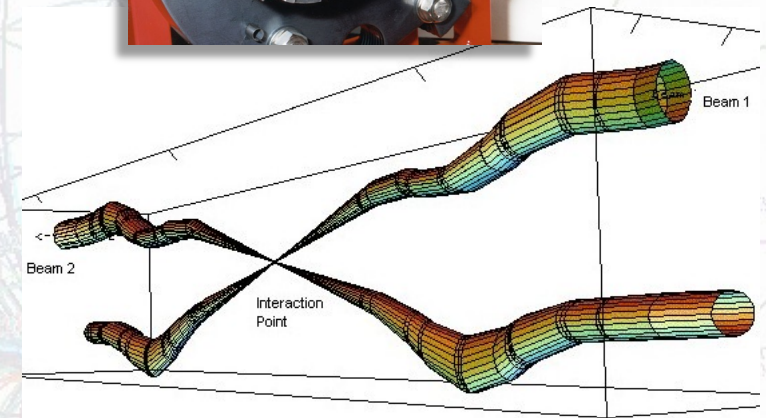
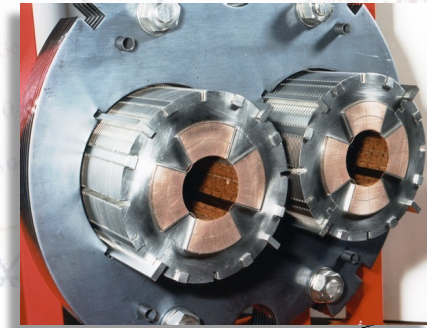
Example: LHC magnets (1)

- The LHC operating at the energy of 6.8 TeV per proton beam
- More than 50 types of magnets are used
- Dipole superconducting magnets are one of the most complex parts of the LHC
 - generate 8.3T magnetic fields
 - 1232 main dipoles, each 14.3 m long and weighs 35 tons
 - If the LHC had been made of conventional magnets, it would have needed to be 120 km long to achieve the same energies and its electricity consumption would have been phenomenal.
 - The magnetic field in every dipole generates a vector B on each pipe opposite in direction to that of the other pipe $\Rightarrow$ 2-in-1 configuration



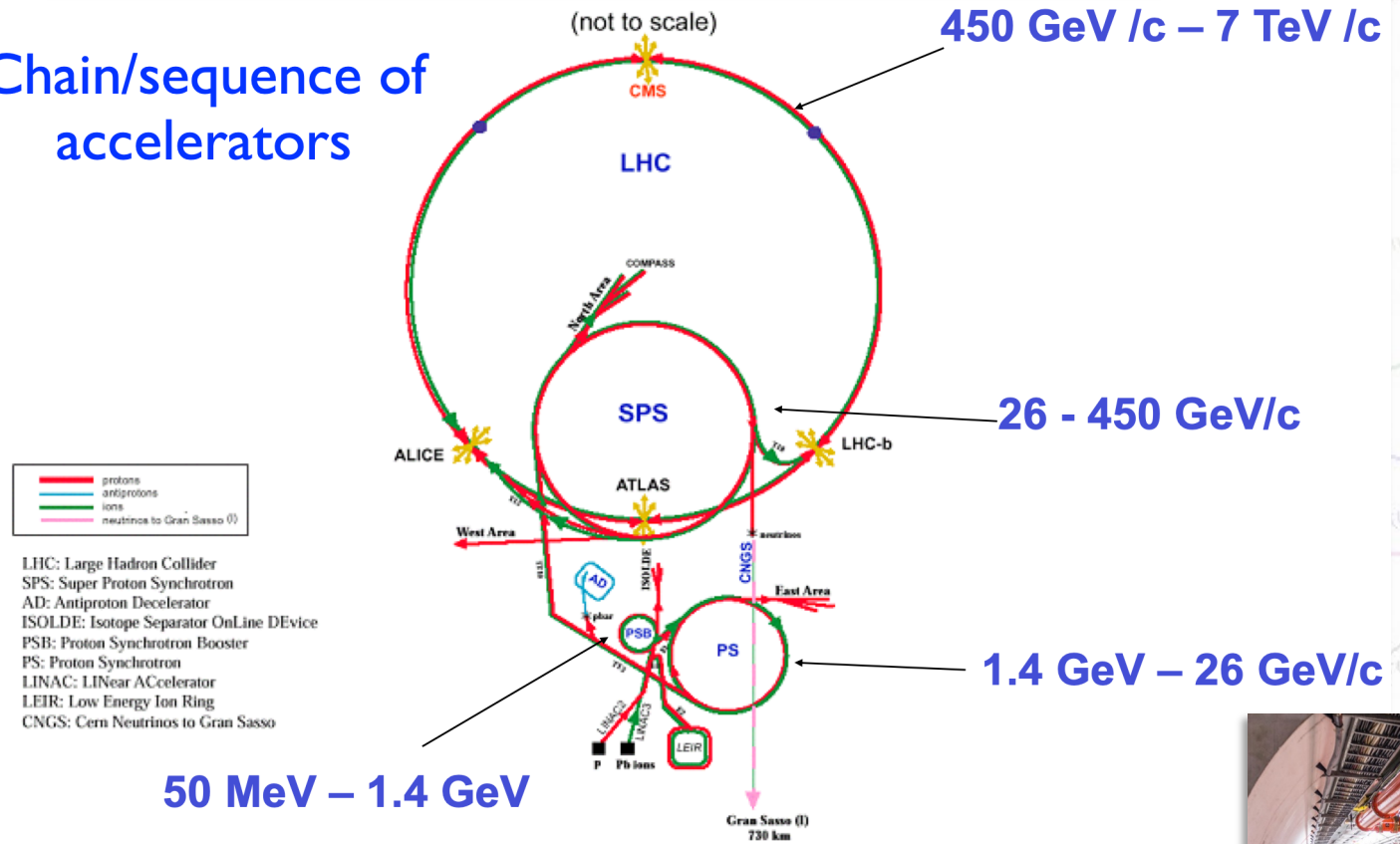
Example: LHC magnets (2)

- 858 quadrupoles keep protons in a tight beam
- Dipoles are also equipped with sextupole, octupole and decapole magnets, which correct for small imperfections in the magnetic field
- There are, in addition, eight sets of so called "inner triplet" magnets in the LHC. Their job is to focus the particle beams into the four areas where particles will collide.
 - The size of bunches passes from 0.2 mm to $16\ \mu\text{m}$ at the Interaction Points
- ~120 tons of liquid helium is needed to keep the magnets at their operating temp. 1.9 K, colder than the 2.7 K (-270.5°C) of outer space.



CERN accelerator complex

Chain/sequence of accelerators



Hydrogen bottle + H^- ion source

Produces H^- ions

Output: H^- ions at $\sim 45\text{keV}$
0.2ng/day



"Linac 4"

Output: H^- 160 MeV
 H^- injection allows new particles to be put into the same orbit as particles already circulating in the PS Booster

Proton Synchrotron Booster

(since 1972)
Output: 2 GeV p



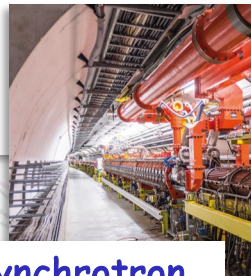
Proton Synchrotron

(since 1959)
Output: 26 GeV p



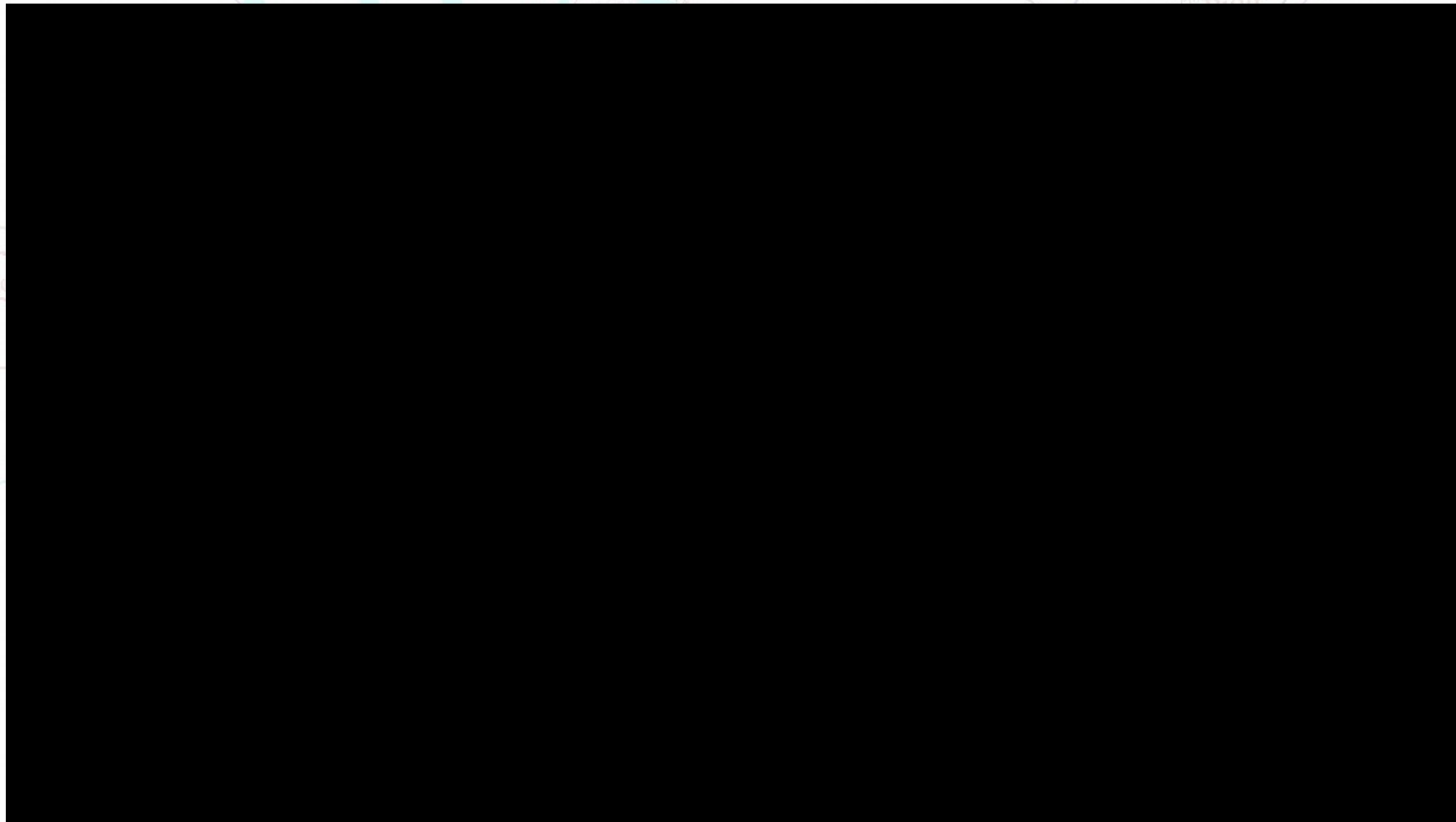
Super Proton Synchrotron

(since 1976)
Output: 450 GeV p



Carlo Rubbia and Simon van der Meer
- discovery W and Z (UA1, UA2) - Nobel Prize in Physics 1984
- direct CP breaking in NA48

LHC accelerator complex

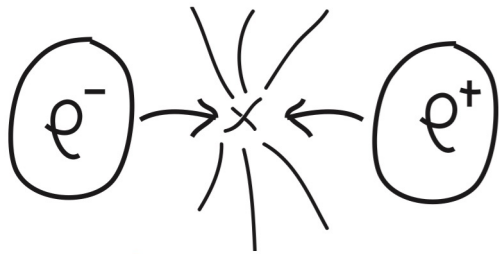


<https://www.youtube.com/watch?v=RDdPuL-uQQc>

<https://videos.cern.ch/record/1610170>

The proper particle for the proper scope

Accelerators can be also classified based on particles used: electrons vs protons (ions)

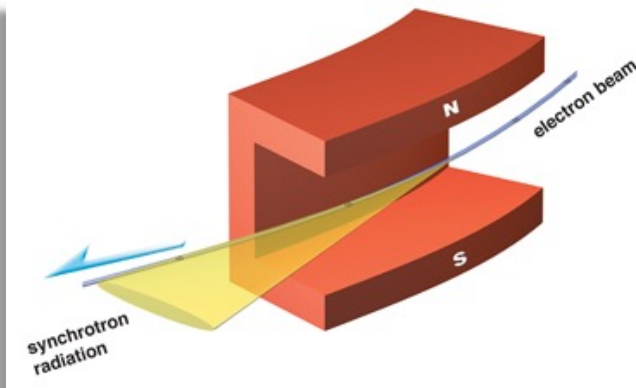


- Electrons (and positrons) are (so far) point like particles: no internal structure
- The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision
- **Pros:** the energy can be precisely tuned to scan for example, a mass region
 - **Precision machine** (LEP)
- **Cons:** above a certain energy is no more convenient to use electrons because of too high synchrotron radiation

- Protons (and antiprotons) are formed by quarks (uud) kept together by gluons
- The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent
- **Pros:** with a single energy possible to scan different processes at different energies.
 - **Discovery machine** (LHC)
- **Cons:** the energy available for the collision is lower than the accelerator energy

Synchrotron Radiation

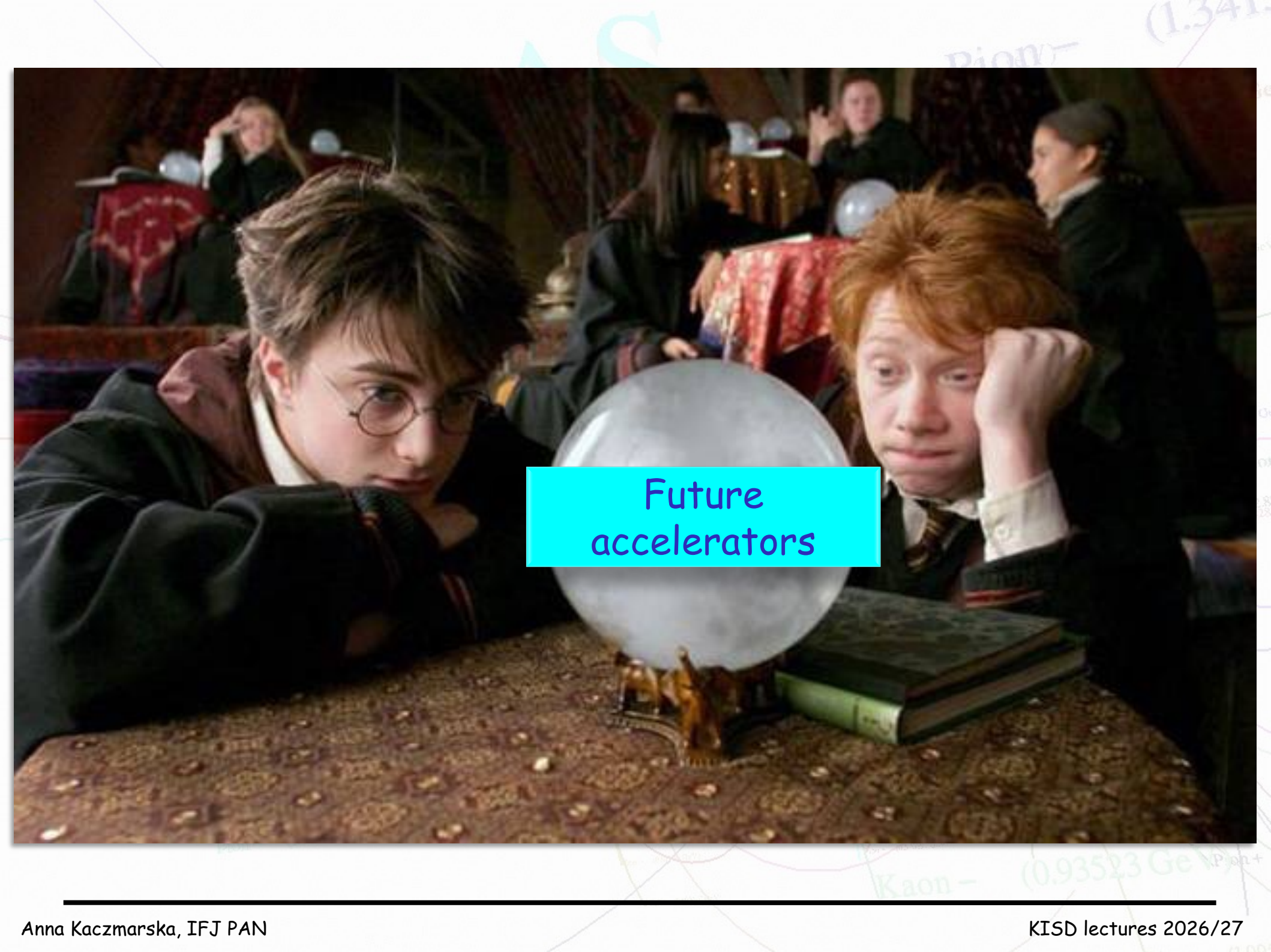
- A charge that is accelerated emits EM radiation
- Examples you may be familiar with
 - an antenna: time-varying current runs up and down the antenna, and in the process emits radio waves
 - Bremsstrahlung: deceleration of a charged particle when deflected by another charged particle. The moving particle loses kinetic energy, which is converted into EM radiation.
- **Synchrotron radiation** is EM radiation emitted when charged particles are radially accelerated (moved on a circular paths)
- The universe creates relativistic electrons and traps them in magnetic fields in a variety of different environments. The objects that emit the high energy electrons tend to be rather exotic and interesting, so understanding the nature of synchrotron radiation is of basic value to modern astrophysics
- **But in accelerators synchrotron radiation is not welcome. As charged particles travel in a curved orbit, they lose energy.**
 - Energy lost per turn $\sim (E/m)^4 1/R$
 - Thus, even with large rings it has to be compensated



SOLARIS

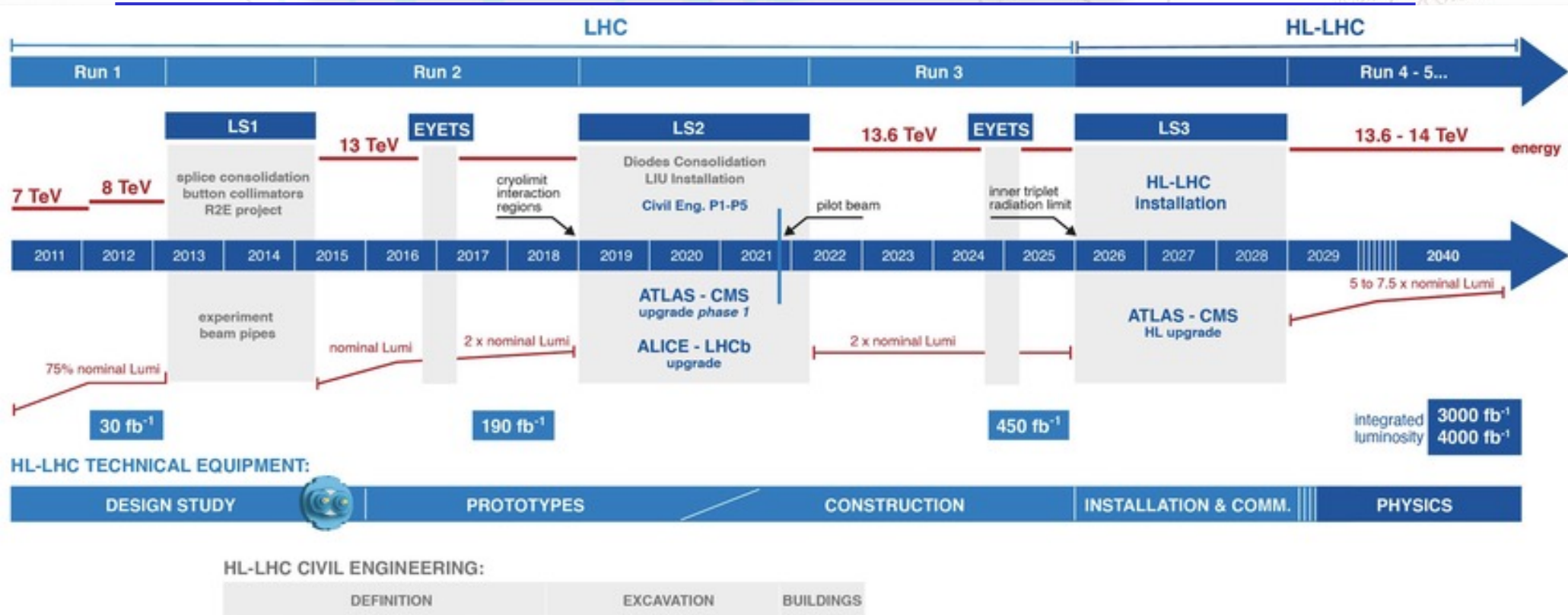
NARODOWE CENTRUM
PROMIENIOWANIA
SYNCHROTRONOWEGO

Synchrotron radiation can be used to study matter and this kind of research can be applied in such fields of science as physics, chemistry, biology, materials science, medicine, pharmacology, geology and crystallography.

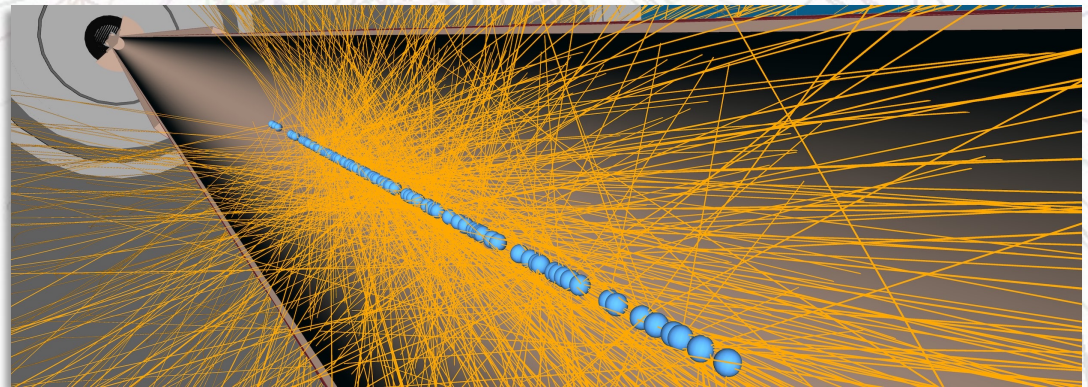
A still from the Harry Potter movie "Prisoner of Azkaban" showing Harry Potter and Sirius Black in the Great Hall. They are both looking intently at a crystal ball resting on a small stand on a table. The crystal ball is glowing with a bright, ethereal light. In the background, other students in their school uniforms are seated at tables, some looking towards the crystal ball. The scene is set in a grand, dimly lit hall with high ceilings and ornate decorations.

Future
accelerators

Future accelerators - HL-LHC (1)



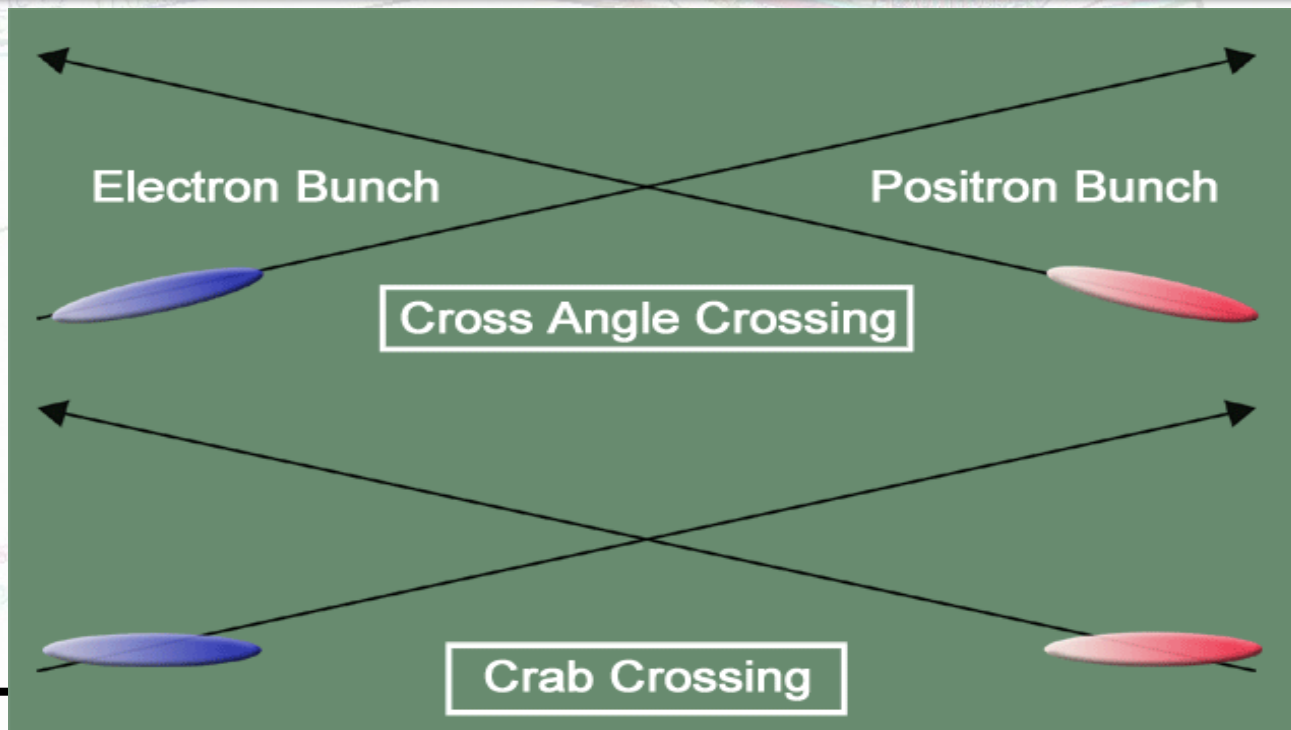
- Increasing the luminosity=> increasing the number of collisions
- The aim is to produce 200 collisions each time as opposed to 60 at Run 3



Future accelerators - HL-LHC (2)

To achieve high luminosity, the beam will be more intense and more concentrated

- New, more powerful quadrupole magnets for the final focusing of the beams before collisions
 - innovative technology providing magnetic fields of up to 12 Tesla, built from a novel superconducting material called niobium-tin (Nb_3Sn), using a unique design that allows the peak magnetic field strength to be increased by around 50% compared with the current LHC magnets
- More particles in beam
- **"Crab" cavities for tilting the beams**
 - Never used before at a hadron collider. The superconducting radio-frequency (RF) "crab" cavities enlarge the overlap area of the incoming proton bunches and thus increase the number of collisions.





The decision making process in particle physics



- Big money → extensive process of planning and decision making
- European particle physics: the CERN Council initiates and oversees the process of updating the European Strategy of Particle Physics (ESPP) together with its final approval
- The last edition: 2024-2026:



More details on ESPP web page: <https://europeanstrategyupdate.web.cern.ch/>

- The **FCC-ee** would deliver the world's **broadest high-precision particle physics programme**
 - Outstanding discovery potential through the Higgs, electroweak, flavour and top sectors, as well as advances in QCD
 - Its technical feasibility is demonstrated via the FCC feasibility study
 - Scope and costs are well defined, plausible funding models exist
- The FCC-ee would maintain **European leadership in high-energy particle physics**, also advancing technology and providing societal benefits
- **FCC-ee** would also **pave the way towards a hadron collider** reusing the tunnel and much of the infrastructure, providing a direct **discovery reach well beyond the 10 TeV parton energy scale**
 - Flagship project at CERN, which will allow Europe to play a leading role in the field



FCC – Future Circular Collider
FCC-ee – Future Circular Collider electron-positron
FCC-hh – Future Circular Collider hadron-hadron



The FCC integrated programme at the popular level

One 91 km tunnel will host two different particle accelerators:

FCC-ee

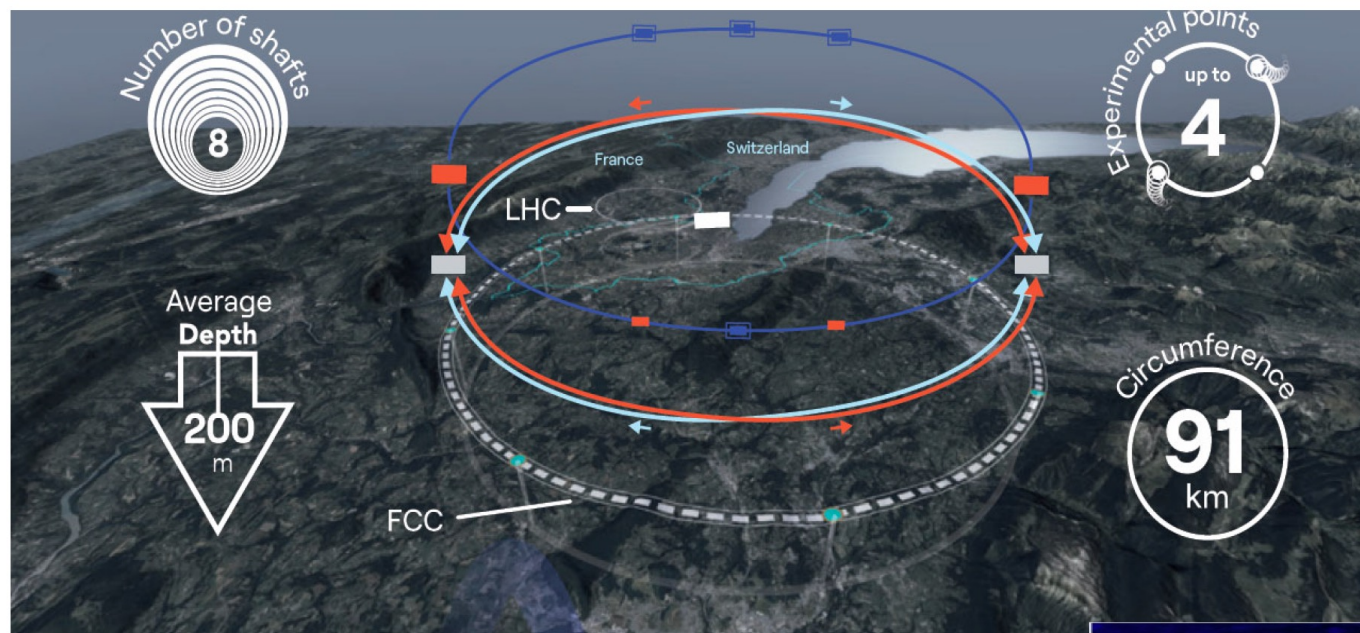


electron-positron
collider

FCC-hh



proton-proton & Heavy-ion
collider



Source: FCC brochure

stage 1: FCC-ee ($Z, W, H, t\bar{t}$) as Higgs factory electroweak & top factory at highest luminosities

stage 2: FCC-hh (~ 100 TeV) as natural continuation at energy frontier, pp & AA collisions, e-h option

Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure

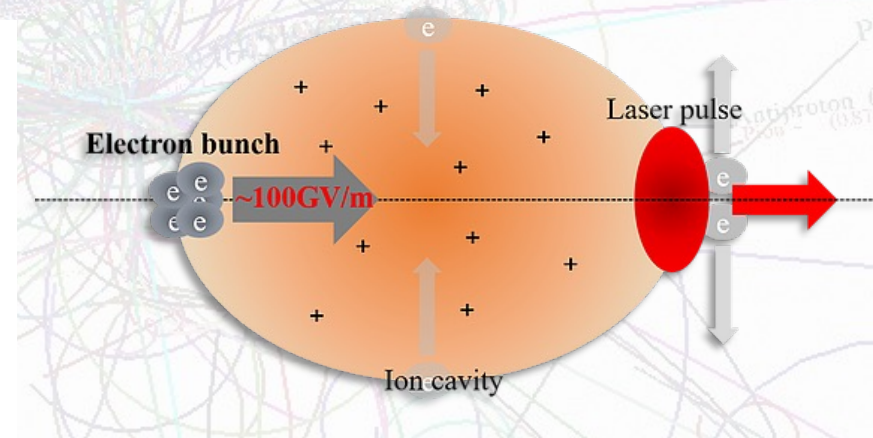
Even more future accelerators



- **Muon collider would be a powerful tool**
 - point particles make full beam energy available for particle production
 - has almost no synchrotron radiation!
- **Muon beam challenges**
 - muons produced as tertiary beam (proton $\rightarrow$ pion $\rightarrow$ muon)
 - low production rate and large energy spread
 - muons have short lifetime
 - fast acceleration needed
 - decay electrons give rise to high background in detector

Plasma Accelerators

- Plasma consists of a fluid of positive and negative charged particles $\Rightarrow$ under normal conditions it is neutral
- Electric field of a laser pulse creates a zone of separation electrons from ions. It looks like a bubble of positive charge (cleared from electrons) moving through plasma at close to the speed of light.
- **When a bunch of particles is placed behind a plasma wake, it accelerates, like a wake surfer, by the charge separation field**



- Reach gradients $\rightarrow$ 100 GV/m!

Laser Wakefield Accelerator (LWFA):

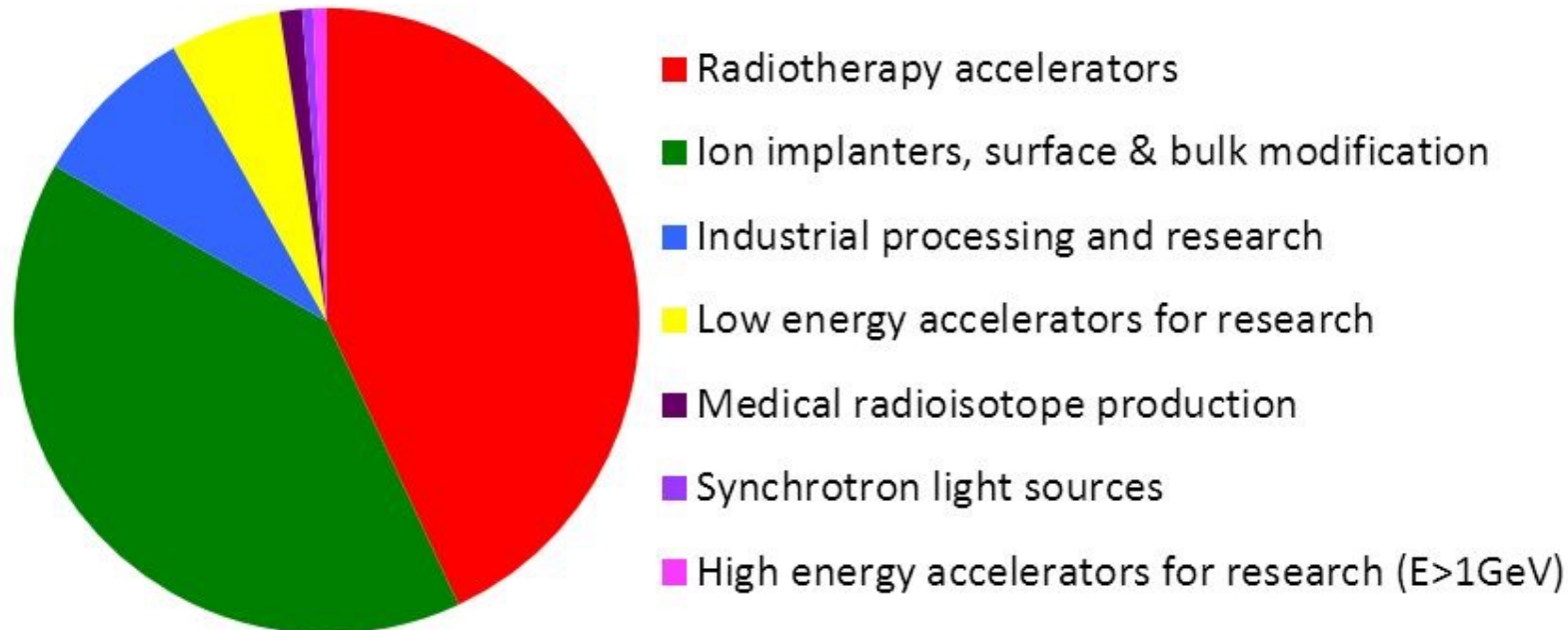
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):

Drive beam = high energy electron or proton beam

Accelerators - from Basic Research to Real-World Applications

~35,000 accelerators in the world



• Medical Applications

- Radio- and proton-/ion- therapy
- Isotope production for PET scans
- Equipment sterilization etc.

• Industrial accelerators

- Ion implantation
- Electron beam processing (production of cables resistive to high temperature)
- Food irradiation etc.
- Cargo scanning

POLSKA SZKOŁA AKCELERATOROWA

SPOTKAJ
EKSPERTÓW
POSZERZ WIEDZĘ
NAWIĄŻ WSPÓŁPRACĘ

NAUKA • TECHNOLOGIA • PRZYSZŁOŚĆ

*Wiedza, która przyspiesza
rozwój nauki i technologii*

ZAPRASZAMY NA

Polską Szkołę Akceleratorową

Inspirujące wykłady i dyskusje
z udziałem wybitnych naukowców i ekspertów
z dziedziny fizyki i technologii akceleratorów.

DATA

19 października 2026 r.

MIEJSCE

Instytut Fizyki Jądrowej PAN
Radzikowskiego 152
31-342 Kraków

DLA KOGO?

Doktoranci, młodzi naukowcy,
studenci, pasjonaci nauki i technologii

W PROGRAMIE M.I.N.:

- wykłady i zajęcia praktyczne
- nowoczesne technologie akceleratorowe
- spotkania z ekspertami z kraju i zagranicy
- możliwości współpracy i rozwoju kariery naukowej

Dołącz
do nas!

Program i rejestracja



ORGANIZATOR



Minister Nauki
i Szkolnictwa Wyższego



Ministerstwo Nauki
i Szkolnictwa Wyższego



INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK

Zadanie pn. „Research and Innovation in Poland - organizacja w latach 2026-2029 w Polsce cyklu dziesięciu warsztatów specjalistycznych”
finansowane ze środków Ministra Nauki i Szkolnictwa Wyższego.

THE END



A
WARNER BROS. —
FIRST NATIONAL PICTURE



Additional slides for curious kids



Recall: momentum & energy

Momentum

- $p = m \cdot v = m_o c \cdot \beta \gamma$
- non-relativistic $p = m_o v$
- high relativistic $p = m_o c \cdot \gamma = E/c$

norm. velocity $\beta = v / c$

Lorentz factor $\gamma = E / m_o c^2$

rest energy $E_o = m_o c^2$

Total energy

- $E = mc^2 = m_o c^2 \gamma = \sqrt{(m_o c^2)^2 + (pc)^2} = E_{kin} + m_o c^2$

Kinetic energy

- $E_{kin} = m_o c^2 (\gamma - 1) = q \cdot U = \text{charge} \times \text{voltage}.$
- E_{kin} in units of eV is equivalent to the accelerating voltage for a particle with charge $q = 1e$ (p, e^+ , Na^+ , μ^+ ...)
- non-relativistic $E_{kin} = \frac{1}{2} m_o v^2$
- high relativistic $E_{kin} = pc$

useful relations:

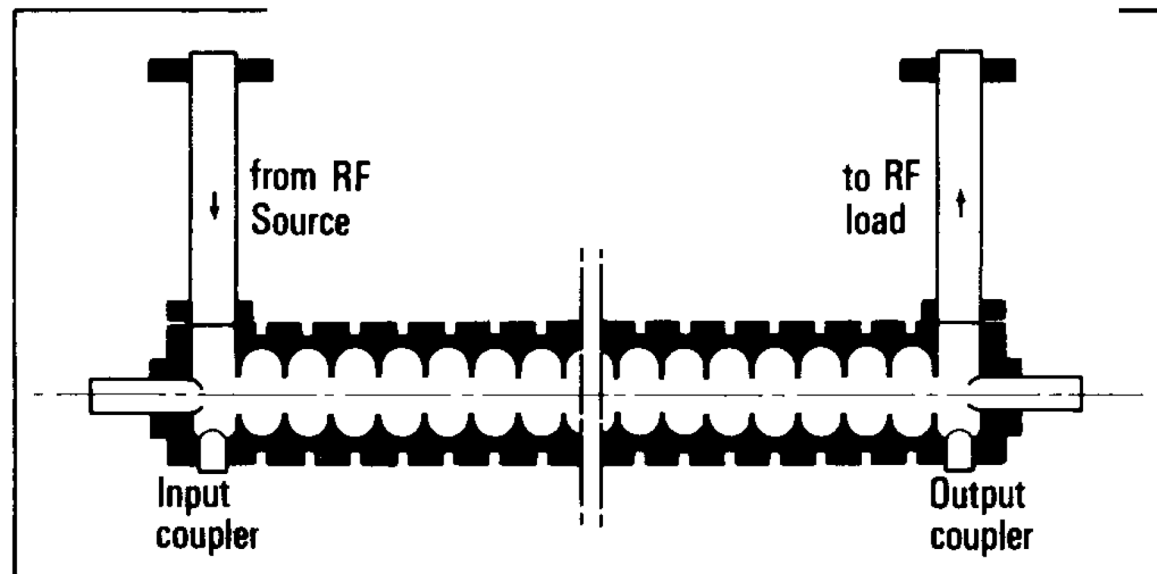
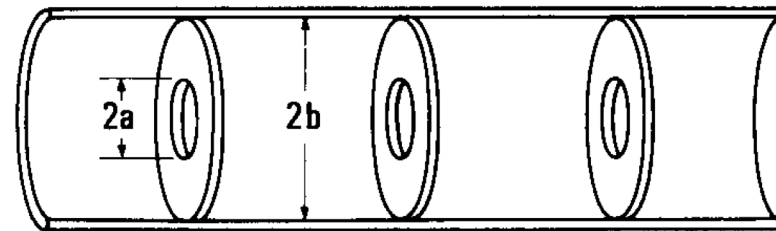
$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \beta\gamma = \sqrt{\gamma^2 - 1}$$

RF accelerating structures

The wave velocity and the particle velocity have to be equal hence we need a disk loaded structure to slow down the phase velocity of the electric field

To achieve synchronism $v_p < c$

Slow down wave using irises



For electrons, which quickly become relativistic, each cell in the structure is the same

Conseil Européen pour la Recherche Nucléaire European Organization for Nuclear Research



CERN:

- created: 29 September 1954 (decided in 1952),
- the biggest lab in the world devoted for fundamental research,
- ~2600 employees and ~13000 users (scientists and engineers) from all over the world (~300 from Poland),
- Poland @ CERN: observer since 1964 r., member since 1 July 1991,
- side 'technologies': www, touch screen, ...

Scientific equipment (of our interest¹):

- accelerator LHC – Large Hadron Collider
- detectors: **ATLAS**, CMS, ALICE, LHCb, TOTEM, LHCf, MoEDAL.

¹At CERN we have about 60 other experiments: e.g. COMPASS, NA61/SHINE, ...



More generally...



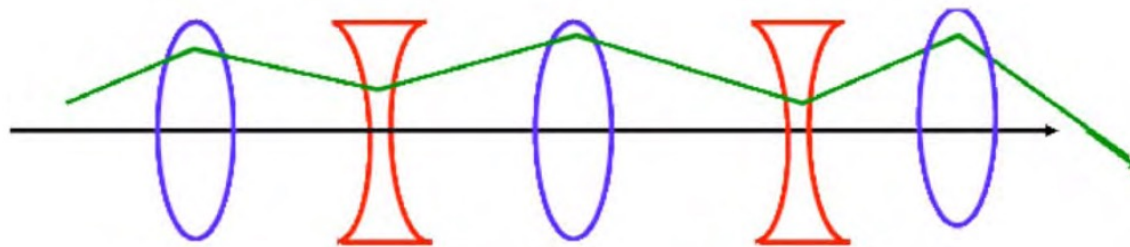
From optics we know that a combination of two lenses, with focal lengths f_1 and f_2 separated by a distance d , has

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

If $f_1 = -f_2$, the net effect is focusing!

$\therefore$ A quadrupole doublet is focusing in both planes!

=> Strong focusing by sets of quadrupole doublets with alternating gradient



N.B. This is only valid in thin lens approximation

The LHC - Guinness records

- The largest and the most powerful accelerator in the world

- Circumference ~ 27 km with ~ 9300 magnets inside
- 2808 bunches of protons, 25 ns apart
- Each bunch $\sim 1.15 \cdot 10^{11}$ protons, ~ 1 cm long, ~ 1 mm across
- $E_{\text{beam}} = 362$ MJ, equivalent of to 120 elephants charging 120 elephants at full attack speed
- Each pp collision has energy of two mosquitos flying into each other but in a very small area!



- The fastest racetrack on the planet

- Protons race around the LHC 11 245 times a second, travelling at $99.9999991\% \cdot c$, colliding 600 million/s

- The emptiest space in the Solar System

- The beams travel in an ultra-high vacuum - as empty as interplanetary space

- The hottest spots in the galaxy, but even colder than outer space

- Collisions of lead ions generate temperatures more than 100 000 times hotter than the heart of the Sun
- By contrast, the cryogenic system with superfluid helium, keeps the LHC at a super cool temperature of -271.3°C (1.9 K) - even colder than outer space!

- The biggest and most sophisticated detectors ever built

- The most powerful supercomputer system in the world

How high energy cosmic rays are generated?

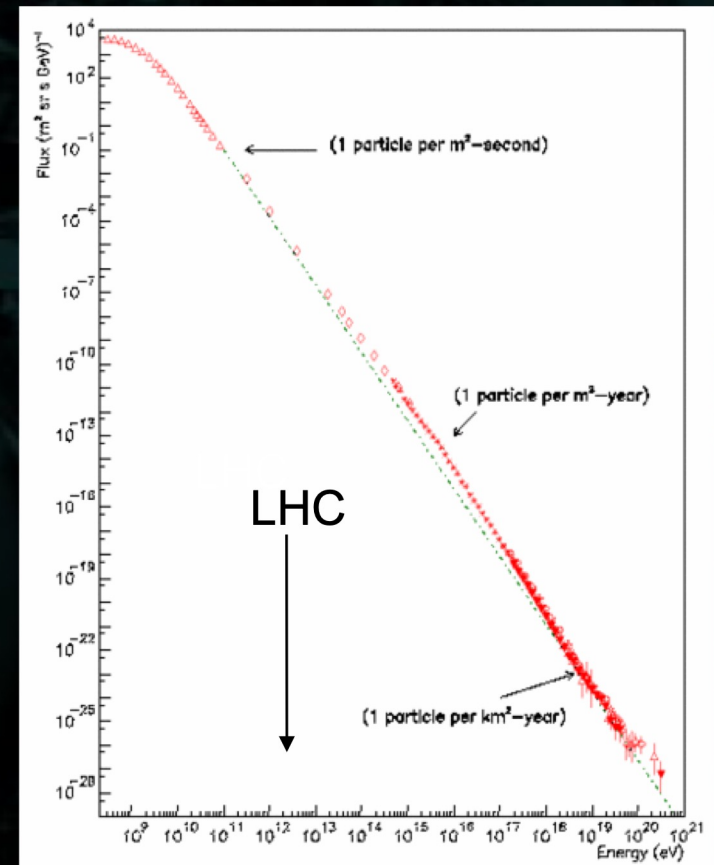
- Ultra-high energies: 10^{20} eV, LHC: $7 \cdot 10^{12}$ eV

(Oh-my-God particle: 50 joules!)

- Ultra-high energy cosmic rays are produced via **Fermi acceleration**: magnetic shock wave after supernova explosion

Not useful for us:

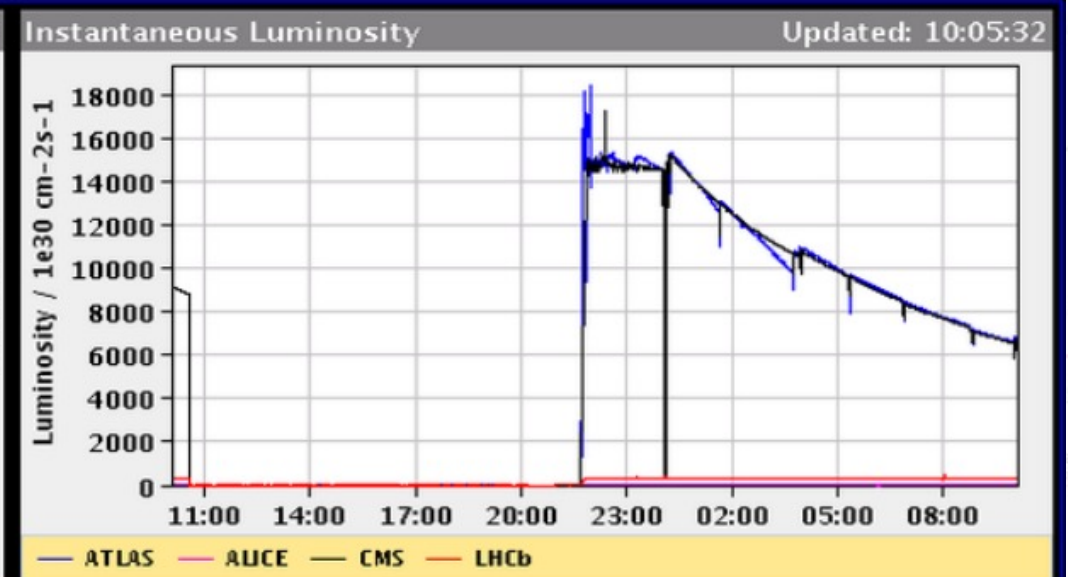
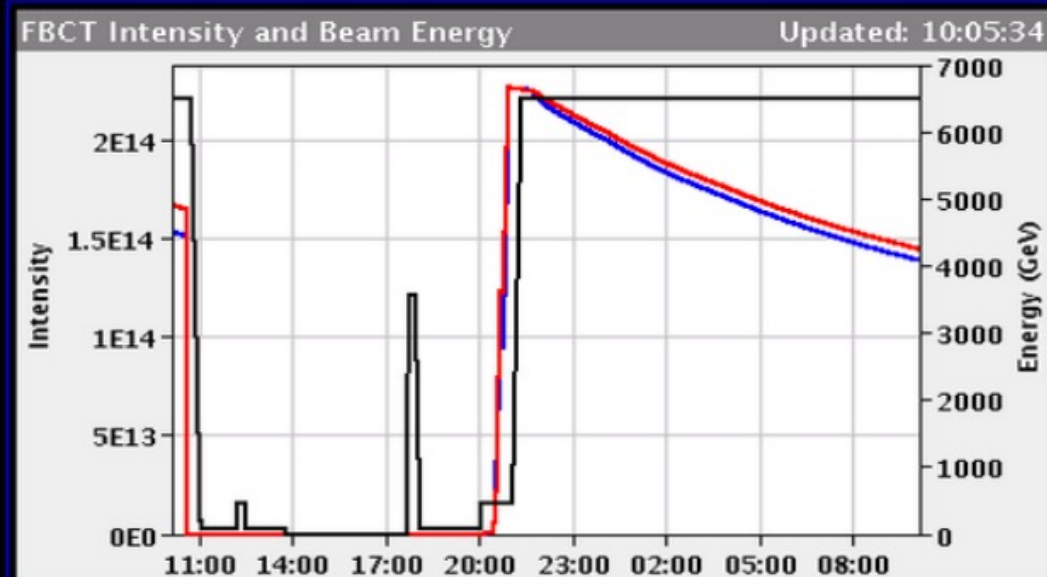
- large space required,
- acceleration is isotropic



PROTON PHYSICS: STABLE BEAMS

Energy: 6499 GeV I(B1): 1.39e+14 I(B2): 1.44e+14

Inst. Lumi [(ub.s)⁻¹] IP1: 6765.69 IP2: 8.12 IP5: 6682.46 IP8: 330.49



10-Oct-2017 10:05:36 Fill #: 6287 Energy: 6499 GeV I(B1): 1.39e+14 I(B2): 1.44e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s) ⁻¹]	6765.407	8.146	6681.323	330.977
BRAN Luminosity [(ub.s) ⁻¹]	6774.6	0.4	5733.8	373.9
Fill Luminosity (nb) ⁻¹	479496.688	353.281	476006.313	14687.383
Beam 1 BKGD	0.752	0.528	1.679	0.000
Beam 2 BKGD	2.579	0.020	1.601	0.001