# Particle Physics for specialists

## Part 1 : Accelerators

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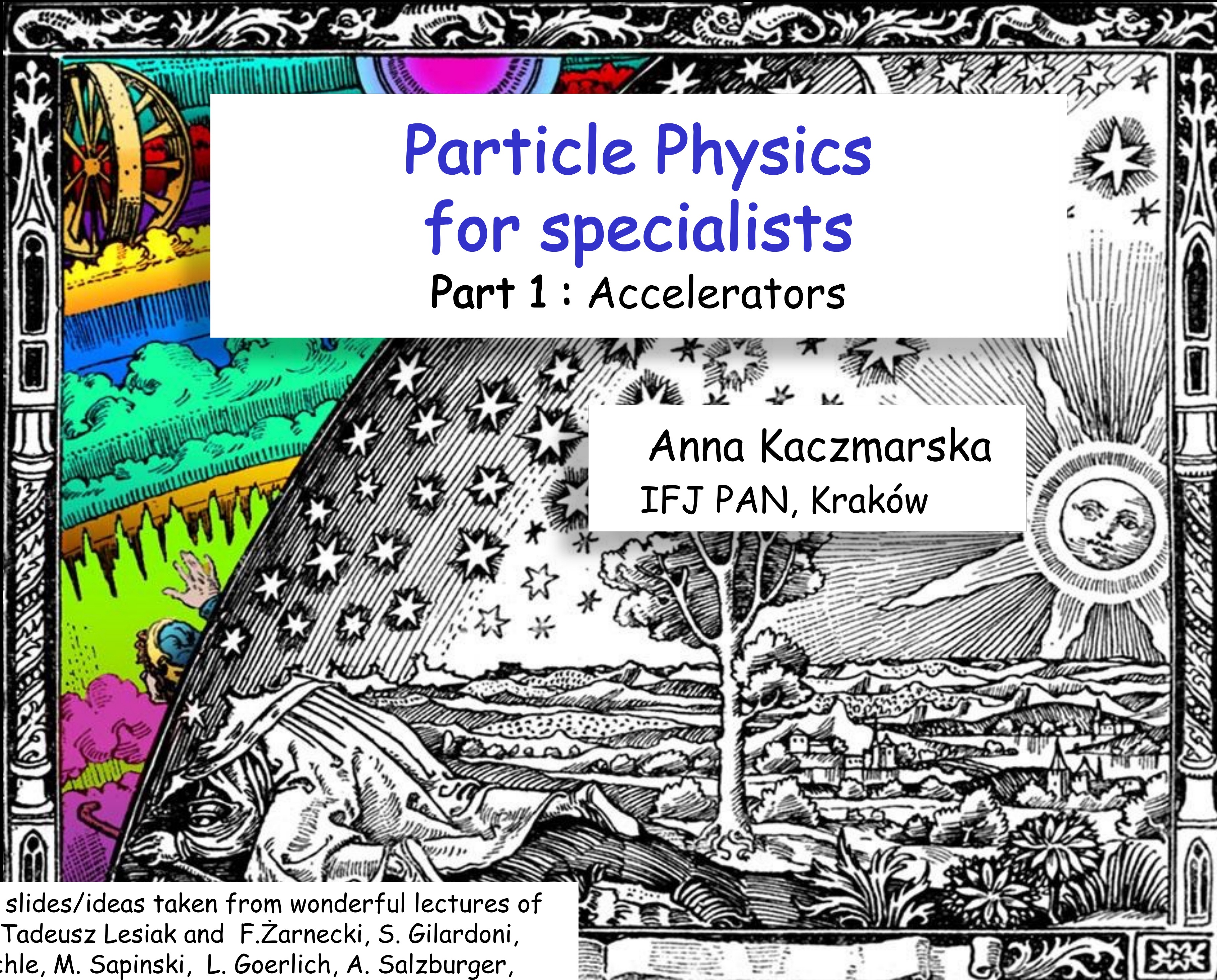


Some slides/ideas taken from wonderful lectures of prof. Tadeusz Lesiak and F.Żarnecki, S. Gilardoni, P. Bechle, M. Sapinski, L. Goerlich, A. Salzburger, M. Krammer, D. Cockerril

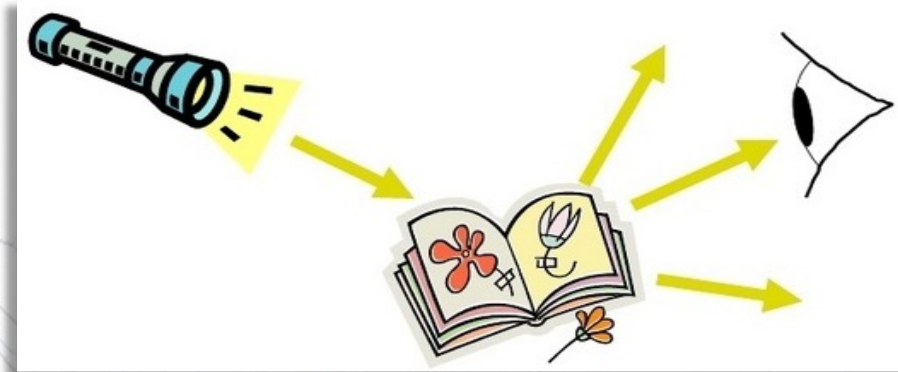
# Content of the course

- **The Particle Physics for specialists course** consists of 30h of lectures
  1. Accelerators and Detectors (4h) – Anna Kaczmarska
  2. Standard Model (7h) – Andrzej Bożek
  3. Heavy flavour physics (3h) – Marcin Kucharczyk
  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 Wąchała
  8. Introduction to cosmology, cosmic rays (3h) - Dariusz Góra

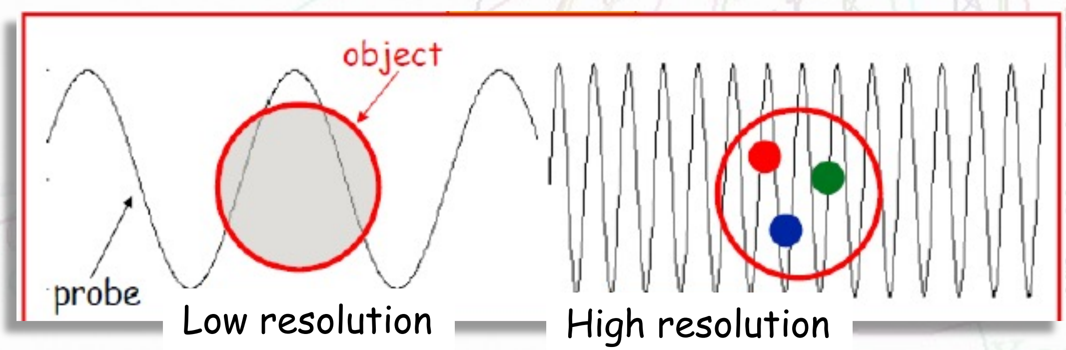
- Slides will be available on indico
  - **https://indico.ifj.edu.pl/event/727/**
- **Literature**
  - Perkins *Introduction to High Energy Physics*
  - Griffits *Introduction to Elementary Particles*
  - Martin, Shaw *Particle Physics*
  - Halzen & Martin: *Quarks & Leptons: an Introductory Course in Modern Particle Physics*
  - Particle Data Group: "Review of Particle Physics" [http://pdg.lbl.gov]
- Exam: essay min. 5 pages, topics to choose will 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 for a given dimension target!

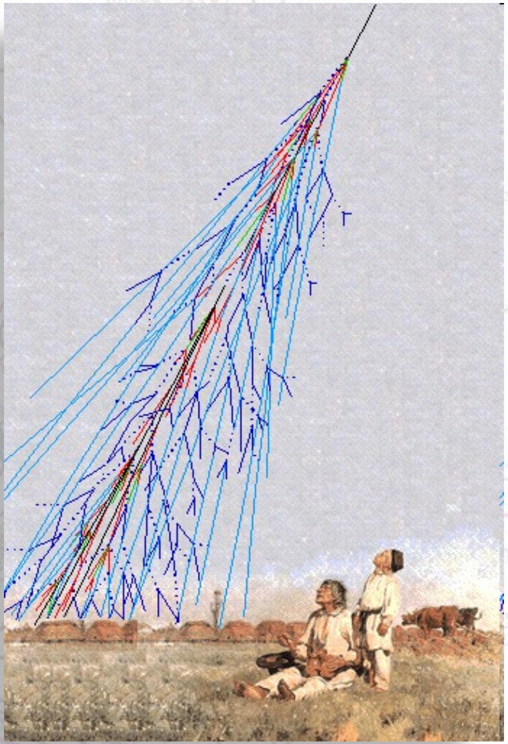


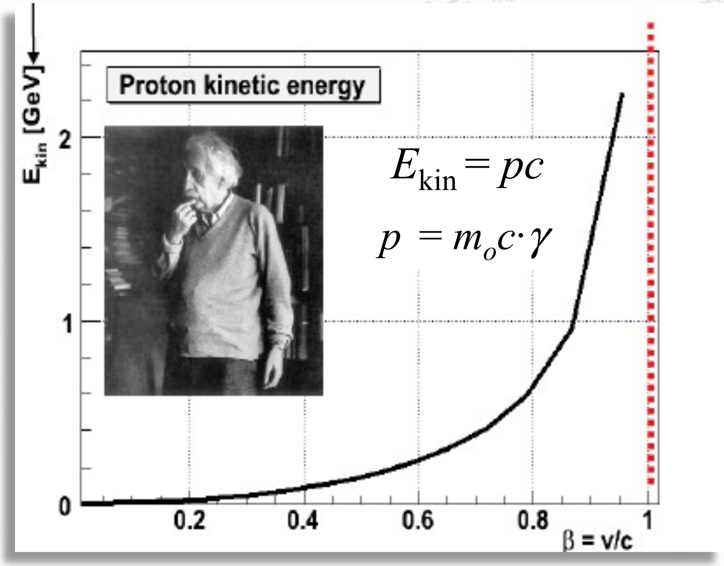
- Energy (of particle) is connected to de Broglie wavelength $\lambda = h/p = hc/E$
  - the higher is the particle energy, the smaller is its wavelength
- To observe object the wavelength of the probe must be shorter than the size of the object
  - therefore, we probe the smallest things at the **highest 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 lecture of this course
- To do **an experiment** we need to produce under **controlled conditions** particle beams:
  - with high intensity
  - at chosen energy
  - of given particle type
- *An experiment consists of studying the results of colliding particles either onto fixed target or with another particle beam*






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

# Fixed target vs colliders

- 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
  - $s = E^2_{CM} = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2 = m^2_1 + m^2_2 + 2(E_1E_2 - |\mathbf{p_1}||\mathbf{p_2}|\cos\theta)$

**Lorentz-invariant**, one of Mandelstam variables [natural units used]

- Fixed target collisions
  - $s = m^2_1 + m^2_2 + 2E_1m_2$
  - For $E_1 \gg m_1, m_2$ $s = 2E_1m_2$
  - $\sqrt{s} = \sqrt{(2E_1m_2)}$
    - e.g. 450 GeV proton hitting a proton at rest: $\sqrt{s} \sim 30$ GeV

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

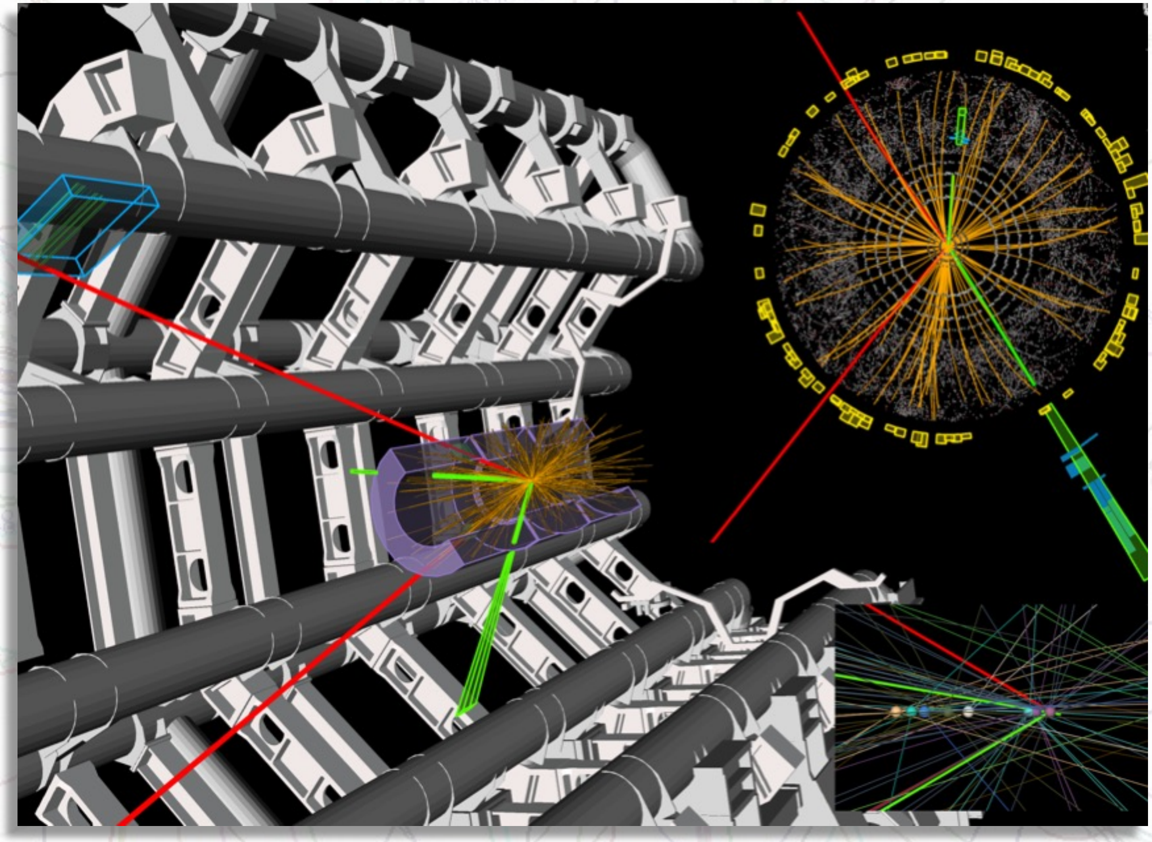
- Colliding Beams
  - For $E_1 \gg m_1, m_2$; $\theta = \pi$, $E_1 = E_2 = E$
  - $s = 4E^2 \Rightarrow \sqrt{s} = 2E$
    - e.g. 450 GeV proton colliding with a 450 GeV proton: $\sqrt{s} \sim 900$ GeV

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

- In a fixed target most of the particle energy is wasted providing forward momentum to the final state particles rather than being available for conversion into interesting particles
- Pros: in colliders the total energy of colliding particles is available
- Cons: frequency of collisions lower! -> "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 an accelerator works ?

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

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

Electric field accelerates particles

Particles of different velocity behave differently

Magnetic field keeps particles on a given trajectory

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

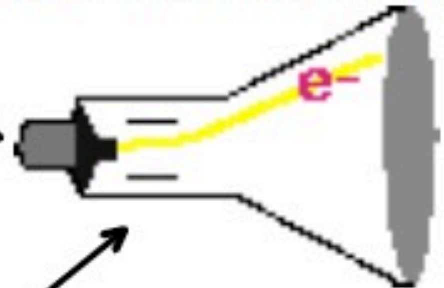
$$\Delta T = W = \int \vec{F}\cdot d\vec{s} = q\underbrace{\int\left(\frac{d\vec{s}}{dt}\times\vec{B}\right)\cdot d\vec{s}}_{=0} + q\underbrace{\int \vec{E}\cdot d\vec{s}}_{=U} \qquad \vec{v} = \frac{d\vec{s}}{dt}$$

- All accelerators are based on the same principle. A charged particle accelerates in a gap between two electrodes when there is a potential difference between them.

# Home Accelerator

- The “classic” television is a **Cathode Ray Tube**

heated *filament*, electron source (*cathode*)




phosphorescent screen which lights up when struck by electrons

electromagentic fields to ***accelerate*** and steer the electron beam (*ray*)

evacuated glass container (*tube*)

**[*CRT*]**

OK, so it’s a *little* more than that… but not much! *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10,000 eV**!

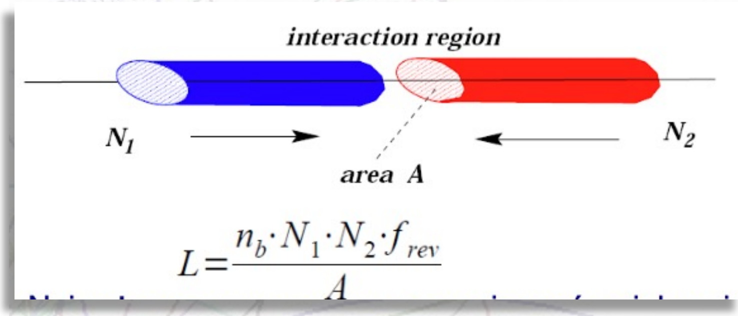
# Accelerator parameters

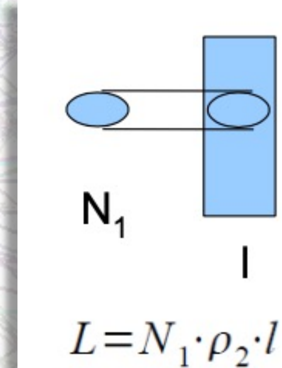
**Requirements:**

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

$$R = \sigma \times L$$

  - Higher Luminosity -> rarer processes we can measure!
  - Record: $2.1 \times 10^{34}$ $cm^{-2}s^{-1}$ KEKB and LHC
  - Collecting data for certain time we integrate luminosity
- $$\int \mathcal{L}\, dt = N \cdot \sigma^{-1} \qquad \int \mathcal{L}\, dt \equiv L \qquad \left[\int \mathcal{L}\, dt\right] = [cm^{-2}, fb^{-1}]$$
- Best possible beam quality: energy spread, focusing



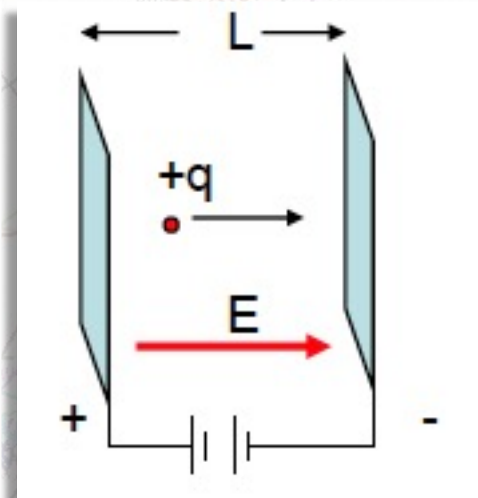

- Measurement of **absolute luminosity** mandatory to measure a process cross section
  - from machine parameters
  - from reactions with well known cross sections (f.e. $e^+e^-$ Bhabha scattering)
    - $\sigma$ can be calculated with high precision, high event rates for low statistical error
  - from 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)

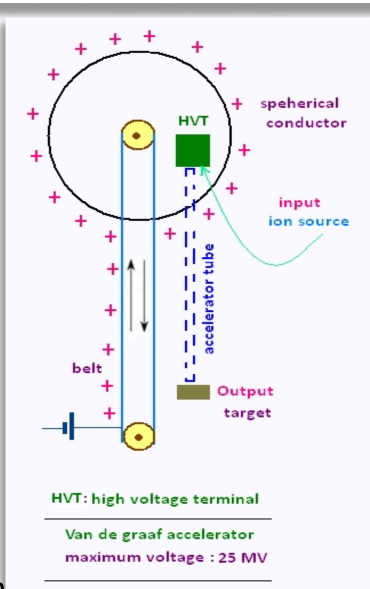
# Acceleration with an electrostatic field

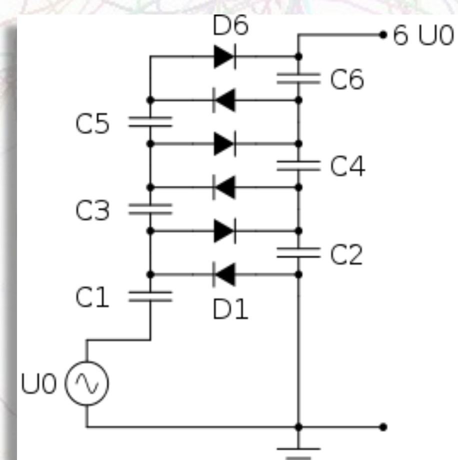
- These accelerators use a static, DC, potential difference between two electrodes

- Earliest particle accelerators (~1930s)
  - Cockcroft- Walton generator - voltage-multiplier ladder with capacitors and diodes to generate high voltages
  - Van de Graaff's belt-charged generator

- Highest voltage achieved is 24 MV
- It is difficult to establish and maintain a static DC field of 20+ MV
  - High voltage break-down, takes only few MV to generate lightning
- Particle energies 20+ MeV, too low for us!
- Electrostatic accelerators are still in use in nuclear physics or as initial acceleration



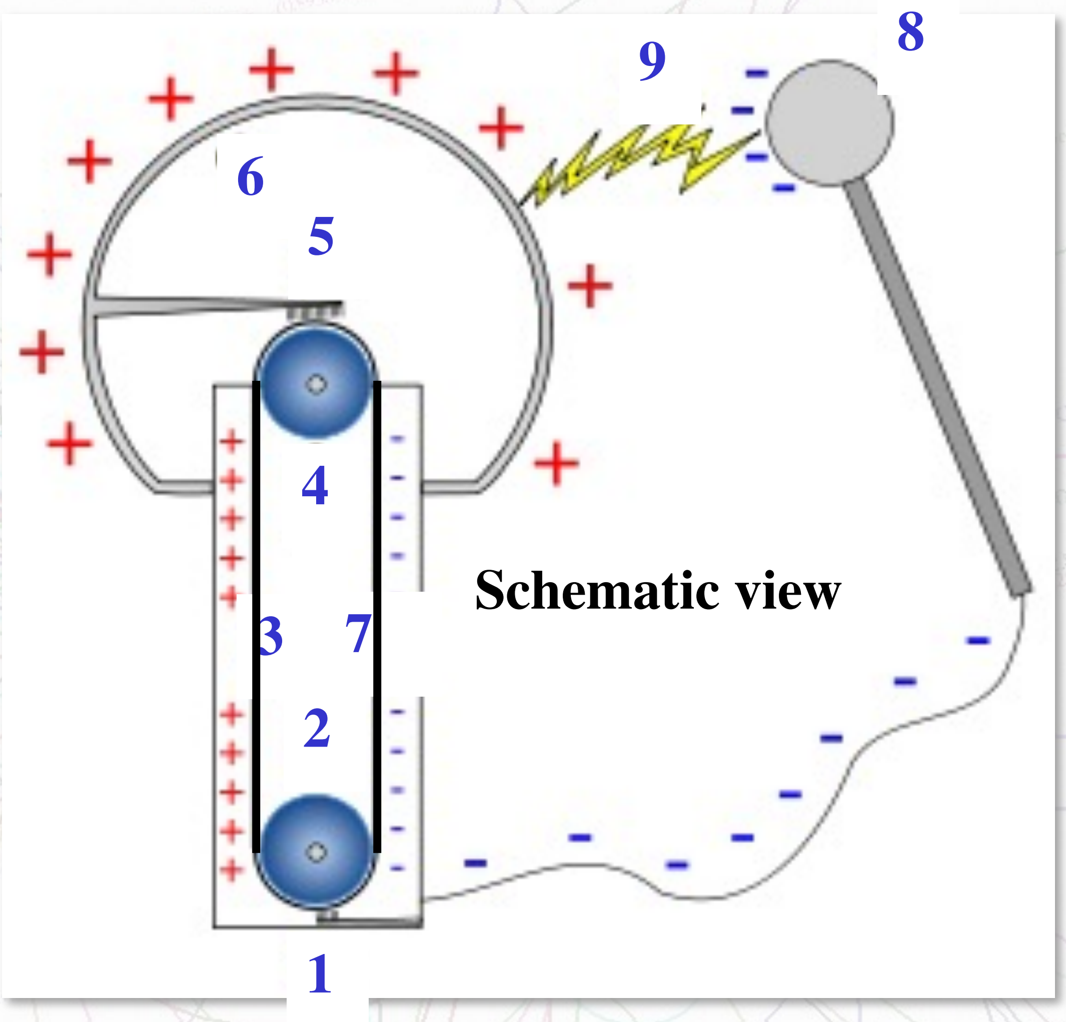




# Van de Graaff Generator

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.

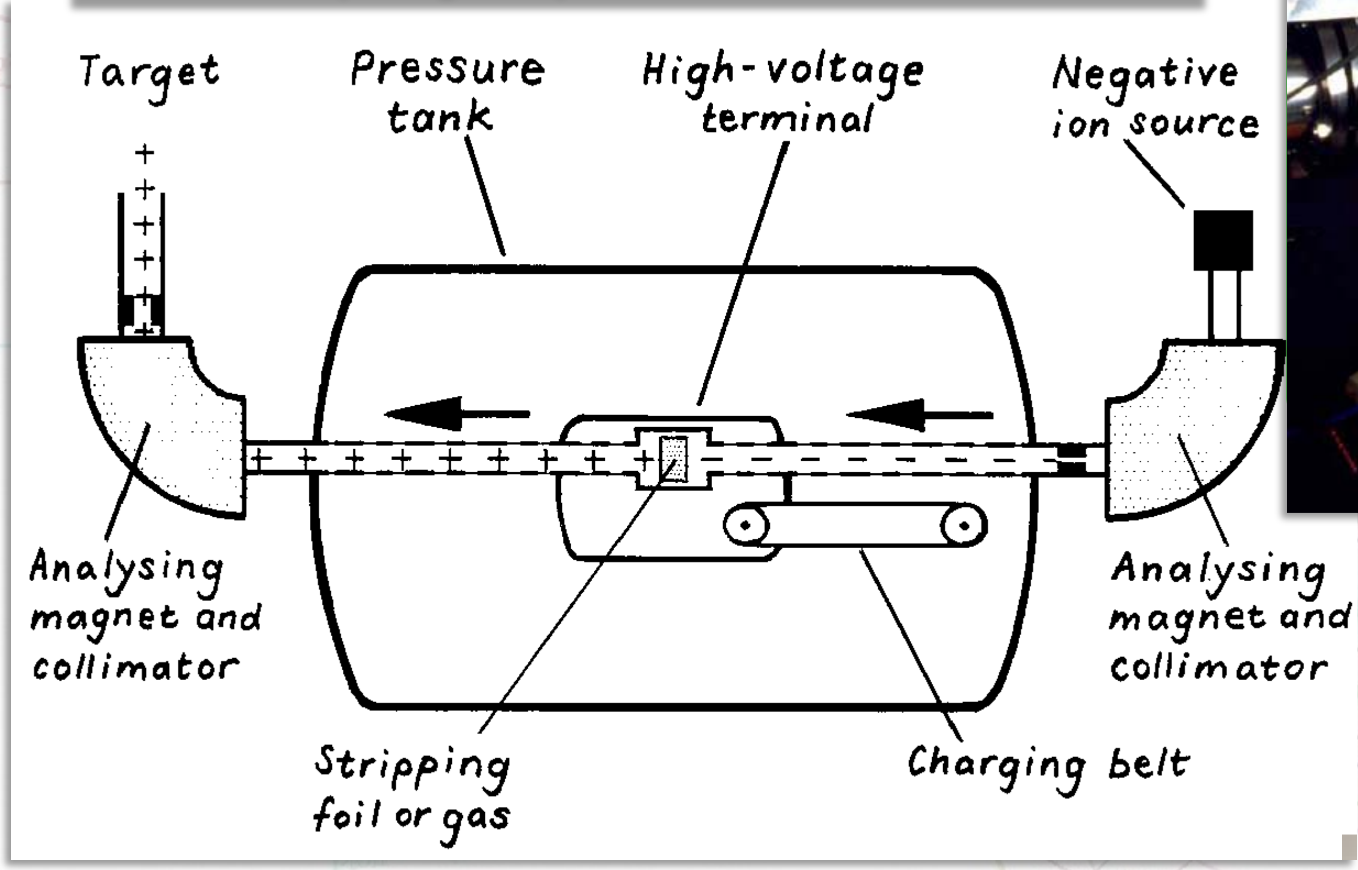
- Power Supply that pulls off electrons (1).
- Rollers (2,4).
- Positively charged belt (lost some electrons) (3)
- Metal comb that drops electrons from the ball onto the belt (5)
- Metal ball that gives up electrons to the belt, then it is charged! (6)
- Negatively charged belt (gained some electrons 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).

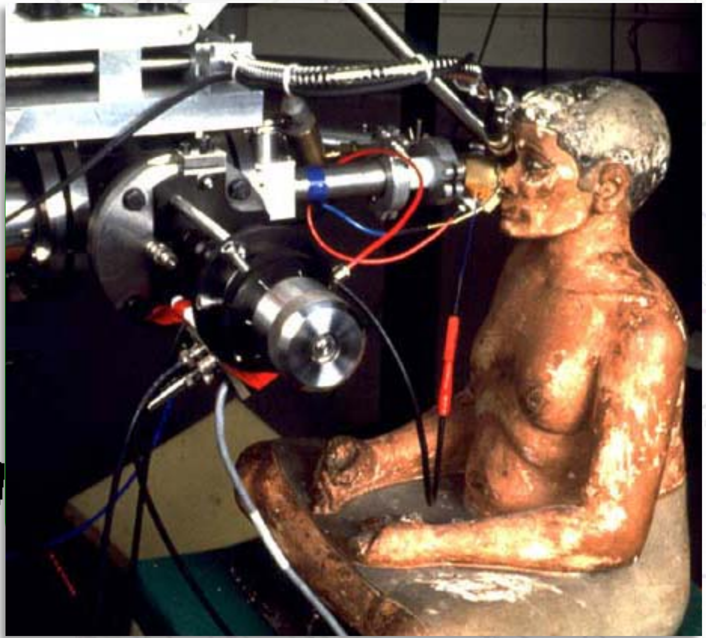



The larger the sphere and the farther it is from ground, the higher will be its peak potential.

# 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

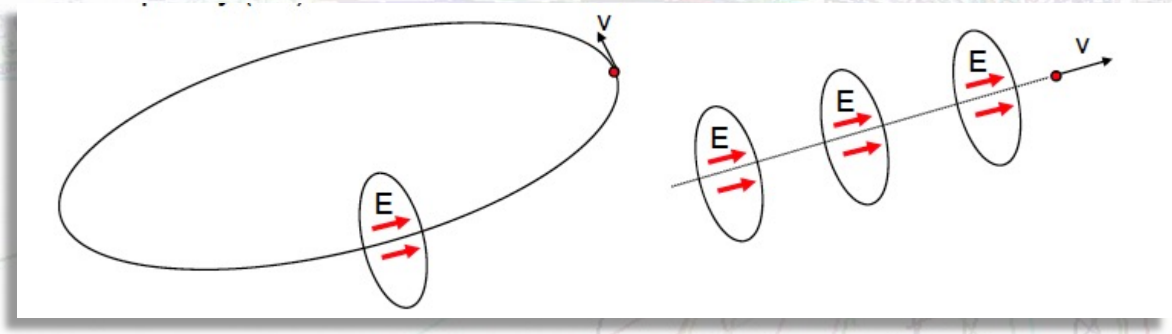


Current applications:
- Low energy injector for ions
  - Brookeven (US), injector for Cu and Au ions
- Compact system for “other uses”
  - compostion of samples at Louvre

# Acceleration using Radio-Frequency (RF) generators

- DC accelerators are limited by a maximum size and a maximum break down voltage
- So, to continue to higher particle energies, would like to re-use the electric fields we generate
  - BUT if the voltage is DC, then though particle is accelerated in between the plates, it will be decelerated while outside the plates! => net acceleration = 0 !
  - SO, need a field which can be switched on and off -- an AC system!
  - one can apply relatively low accelerating voltages at each acceleration step
- Two approaches for accelerating with time-varying fields



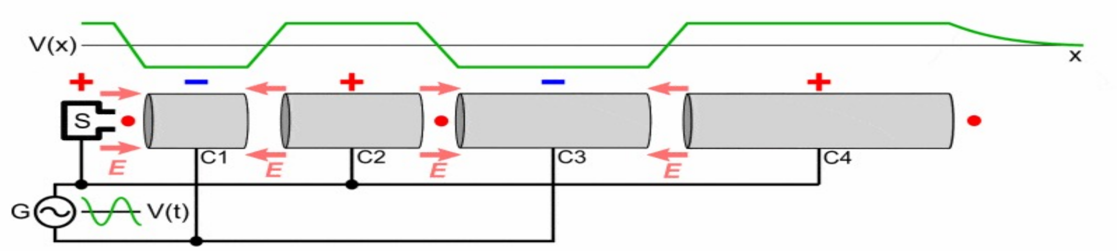

*Circular Accelerator*
Use one or a small number of radiofrequency accelerating cavities and make use of repeated passage through them

*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

- Series of tubular electrodes connected to an alternating voltage
- 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



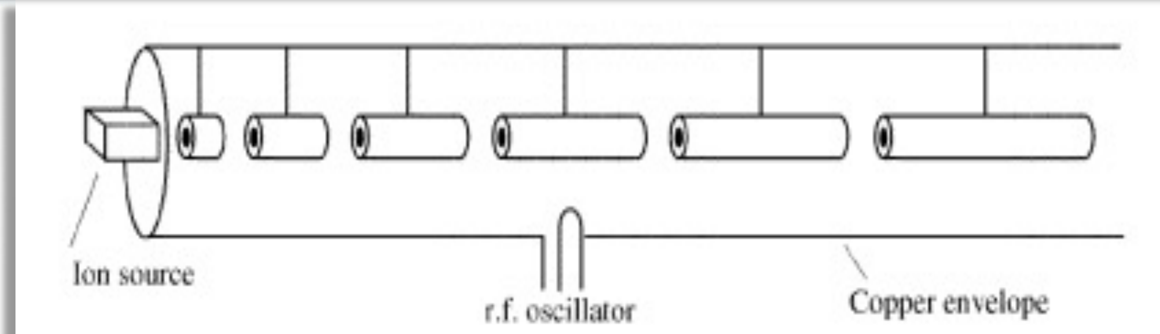

Obs: - the drift tube length has to increase because particles are not yet relativistic
(for 500 keV protons at 1 MHz frequency it is ~5 meters!)

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

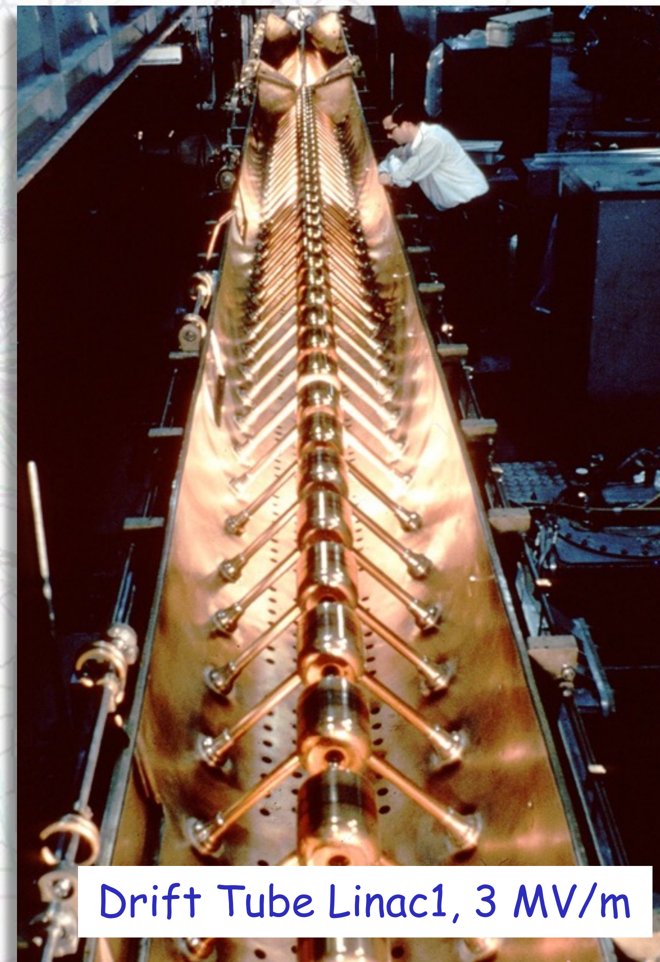
# Alvarez (1946): the first serious proton liniac

- 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 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



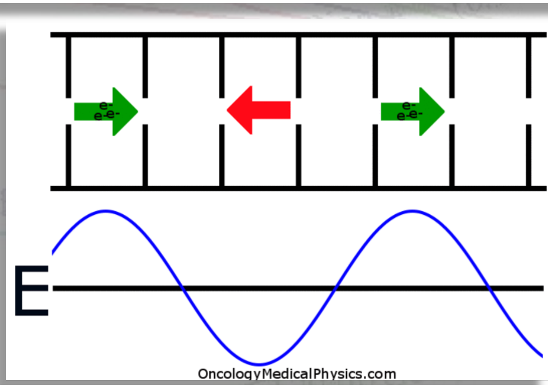

The Alvarez structure is still used for non-relativistic proton and ion beams (CERN Linacs, input to Proton Synchrotron)



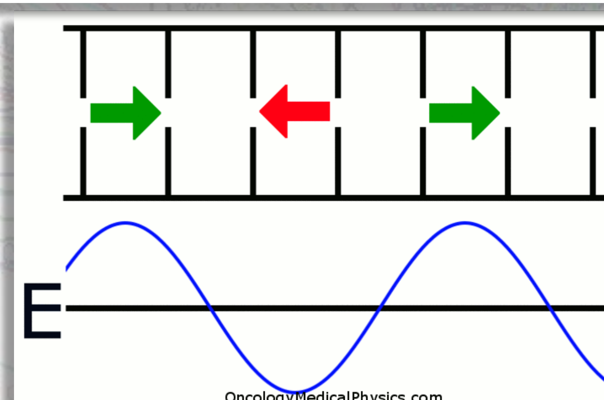
Drift Tube Linac1, 3 MV/m

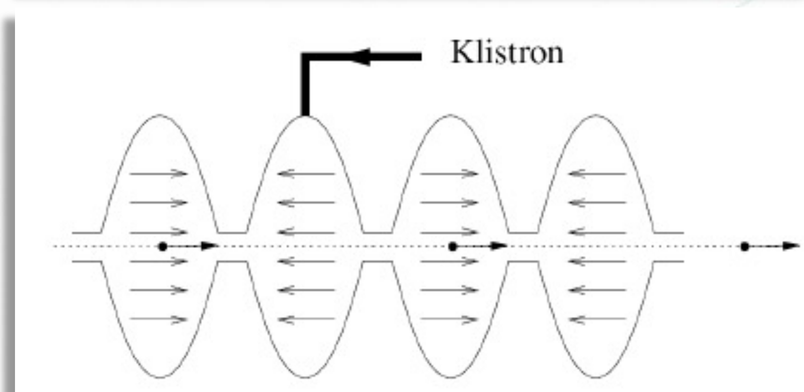
# Modern accelerators

- 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
  - allows cavity structures of same size to be situated along whole length of linac => relatively simple design
- Resonant cavities reduce RF power consumption, increase gradient (f~ 1GHz)
- RF cavities for particle acceleration can be operated in standing wave or traveling wave modes (two ways to drive the particles)

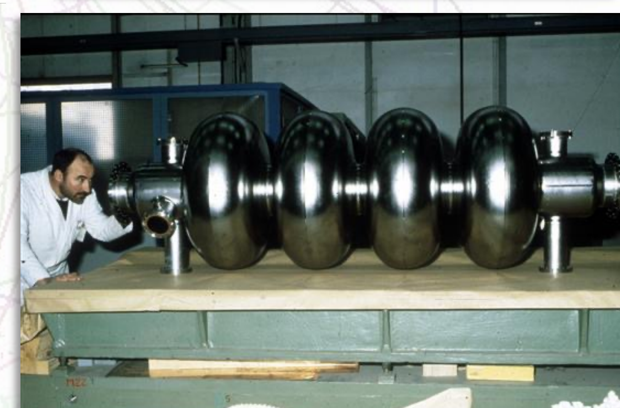



Accelerating gradient: up to 5 MV/m



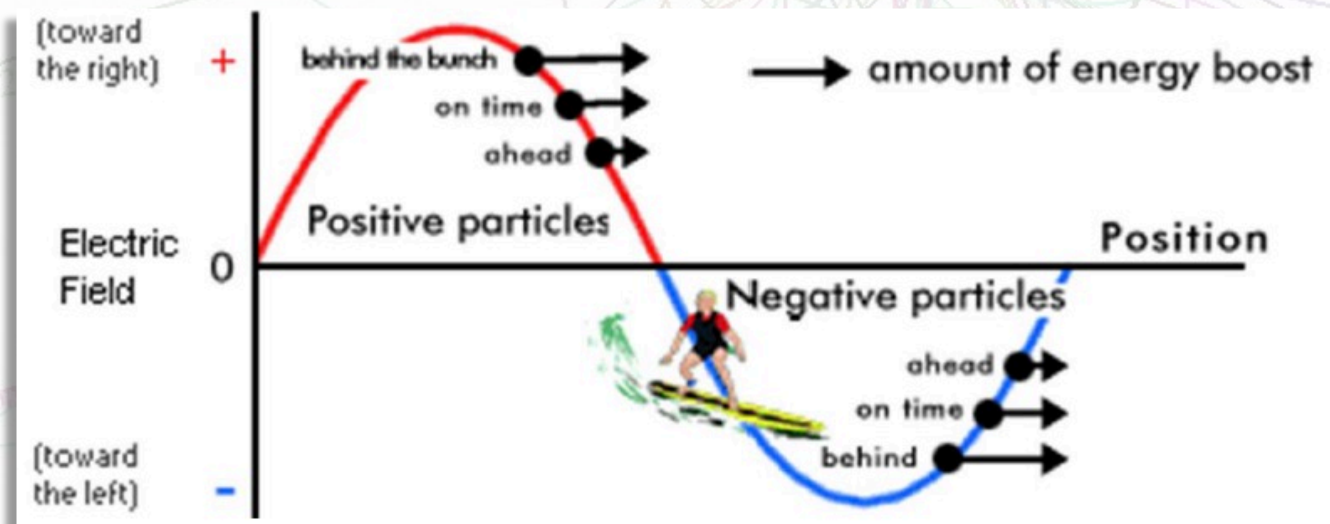




Accelerating gradient up to 20 -30 MV/m (superconducting cavities)
Effect riding the crest of the wave and thus always experiencing an accelerating field



# Phase stability

- Field in an RF cavity is made to oscillate (switch direction) at a given frequency, so timing the arrival of particles is important
- Particles not all in sync with accelerating phase
- Solution: On-time particles should not arrive on the peak:
  - Particle late/slow
    - Larger field , acceleration, catch up with synchronous particle
  - Particle early/fast
    - Smaller field, deceleration, wait for synchronous particle
  - Both of them stay close to the desired energy
- It is this feature that allows us to accelerate simultaneously a group of particles, with a spread in energies and a spread in time
- In this way, the particle beam is sorted into packs of particles called "bunches"



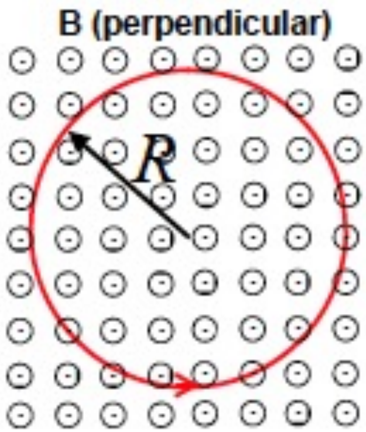
# Example: SLAC electron liniac

- 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

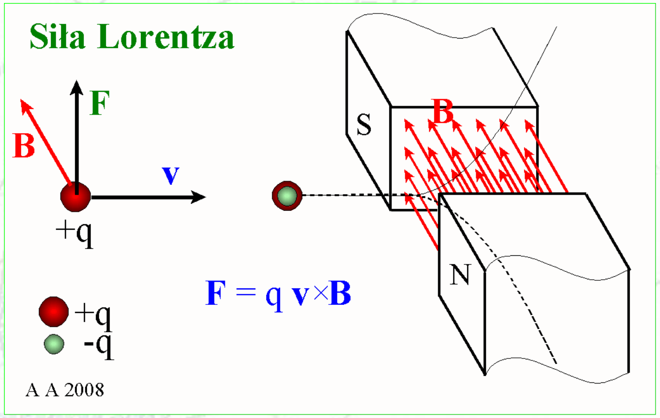
$$\vec{F} = \frac{d\vec{p}}{dt} = q\,\vec{v} \times \vec{B}$$

momentum, charge, velocity — of the particle; magnetic field

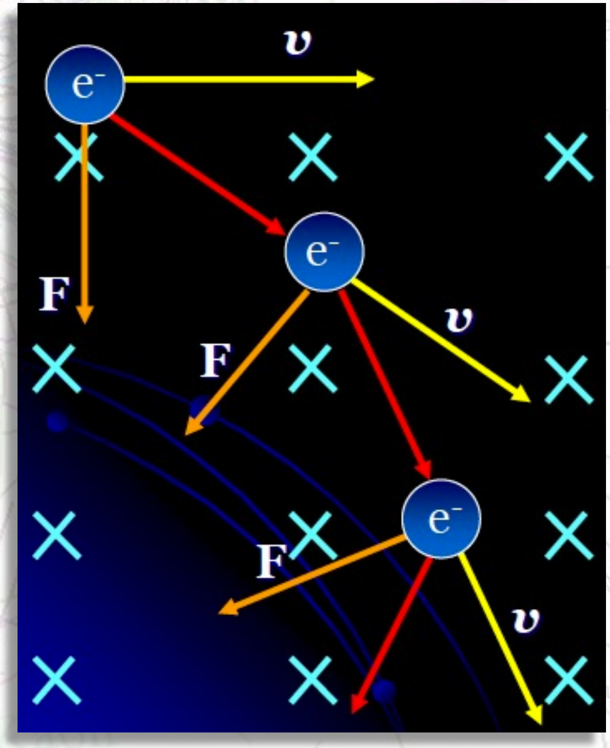
circular motion:

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

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



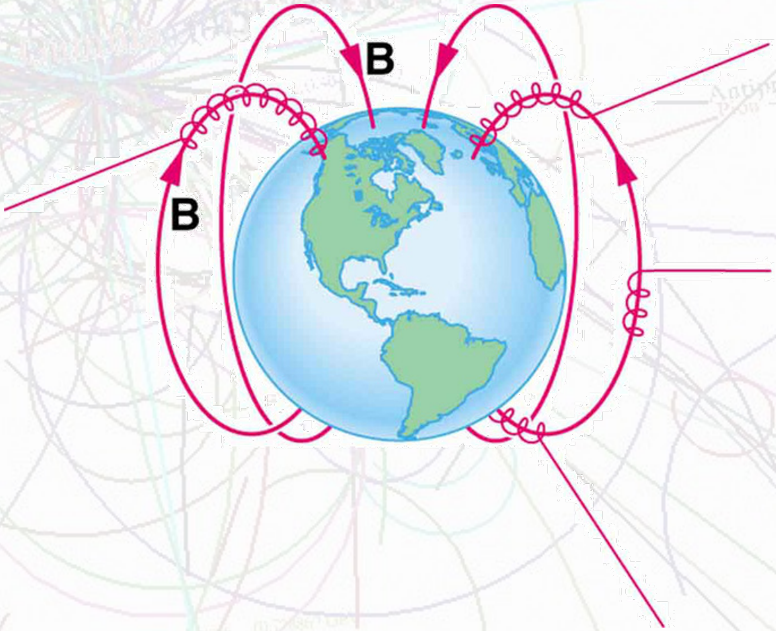

http://www.if.pw.edu.pl/~anadam/WykLadyFO/FoWWW_35.html



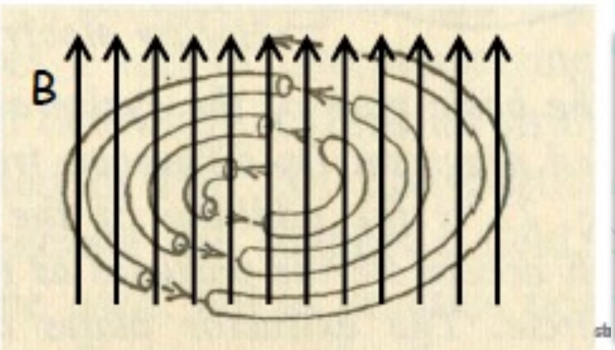

For field of magnetic flux density *B*, perpendicular to the direction of travel, **the Bqv force provides the centripetal force.**

# Digression: Aurora Borealis

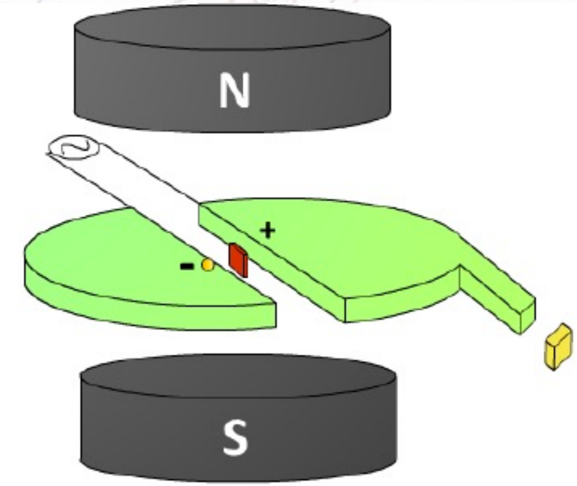
- Aurora Borealis is caused by charged particles from solar wind (streams of charged particles expelled from the Sun) being caught in the Earth's magnetic field and colliding with particles in the Earth's upper atmosphere
- A charged particle in a magnetic field experiences a force, and this force provides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



# Cyclotron - first circular accelerator

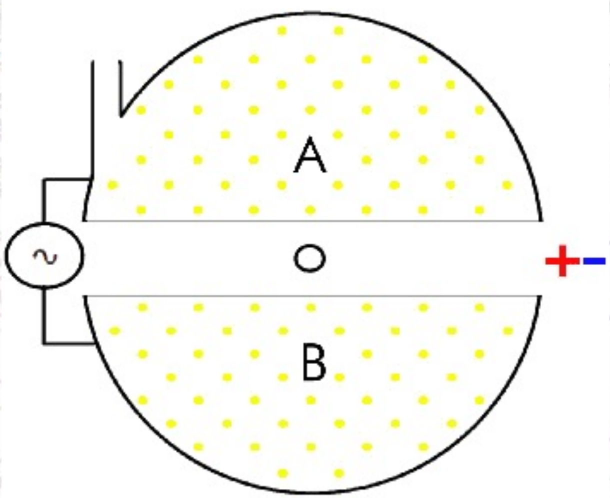



- first concept of the 'cyclotron' (1929) (from E. Lawrence but also Widroe!)
- drift-tube linac "rolled up"
- Lawrence, Nobel 1939




- 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 electrode and magnetic field bends it into a semi-circle
- While the proton is travelling this semi-circular path 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

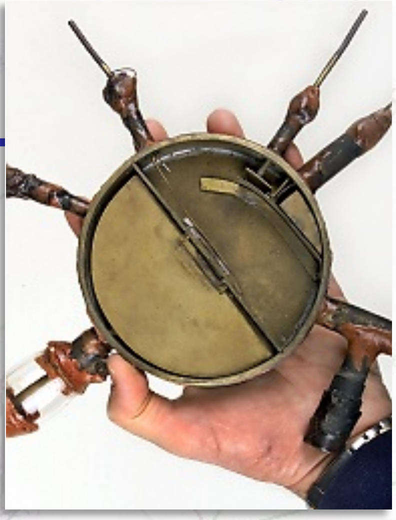



**Revolution period**

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

- 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:

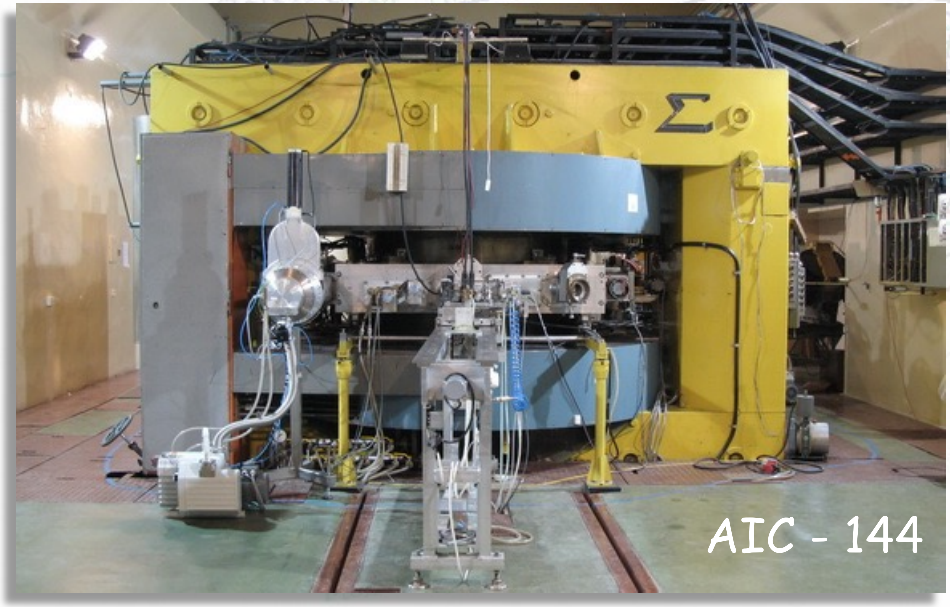
- superconductivity, to obtain much higher magnetic fields for a given R
- Correction for increasing mass by:
  - **Synchrocyclotrons**: B = const, accelerating RF frequency adjusted in time
  - **Isochronous cyclotrons**: shaping of magnetic field, RF = const

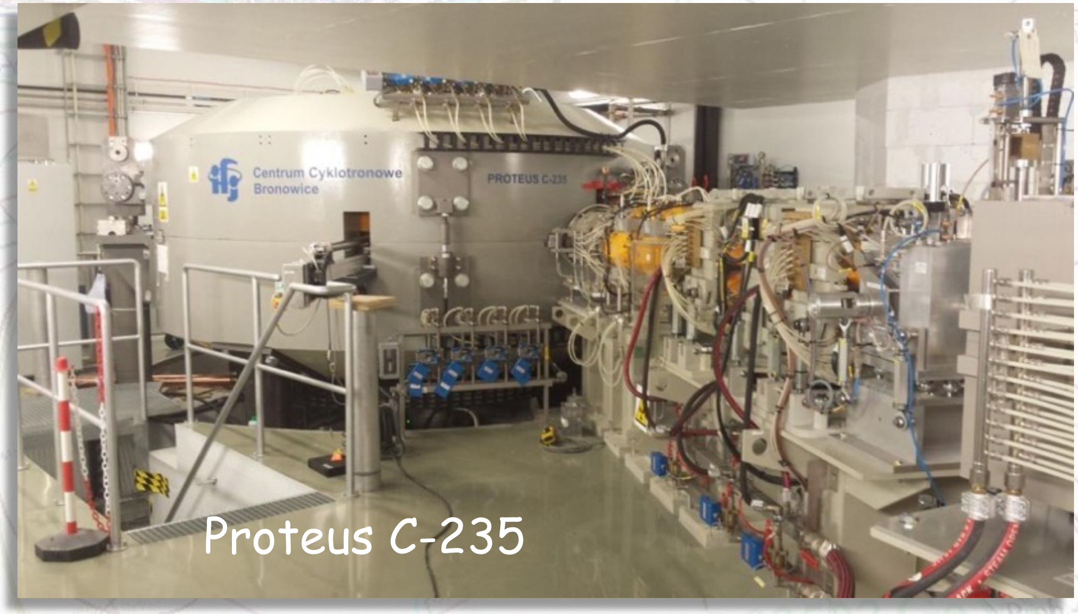
The largest cyclotron in TRIUMF (Canada): 18-meter diameter

- 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 developed by 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 (from 2012)

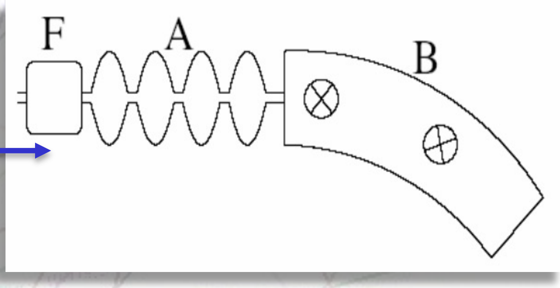



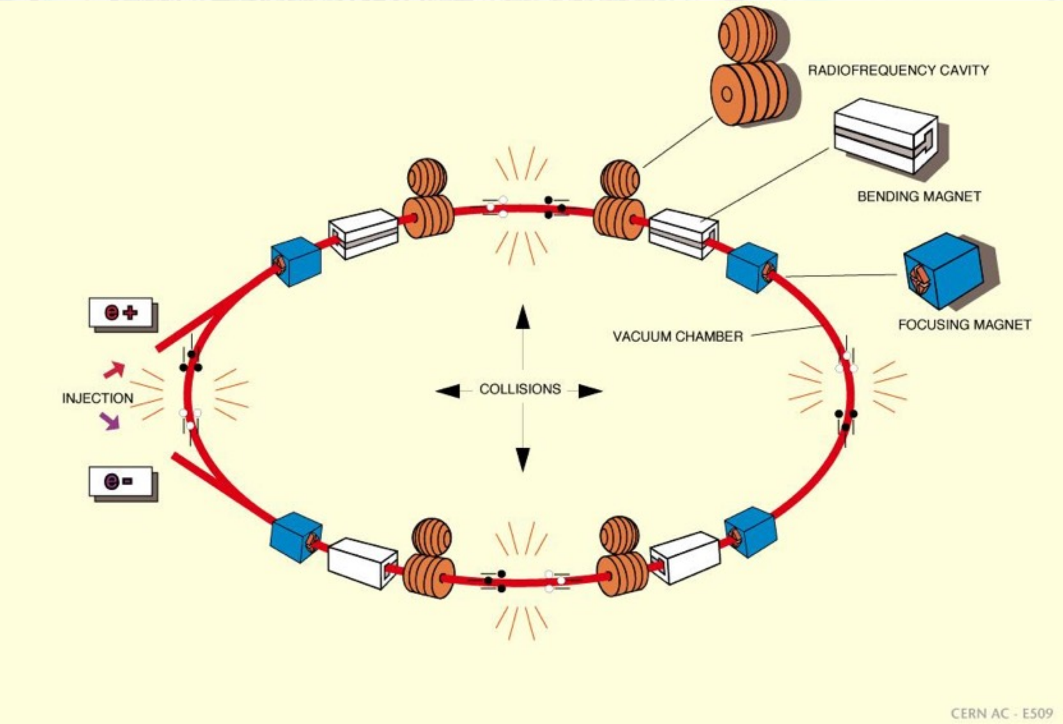
# Synchrotron

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

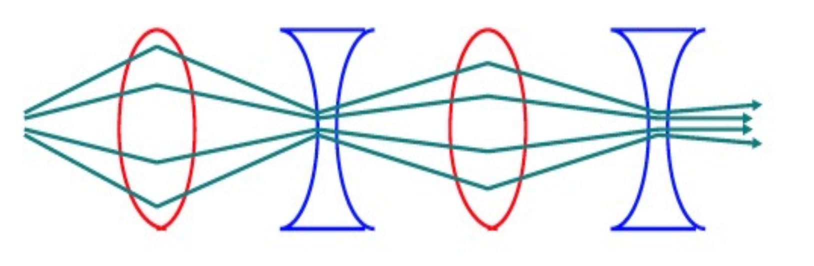


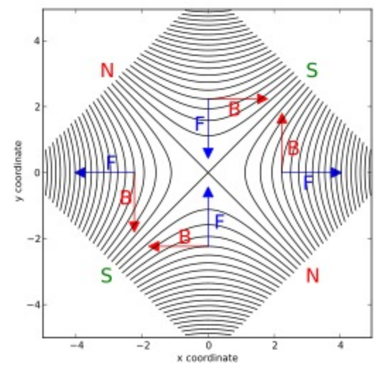

The largest synchrotron in the world – the LHC

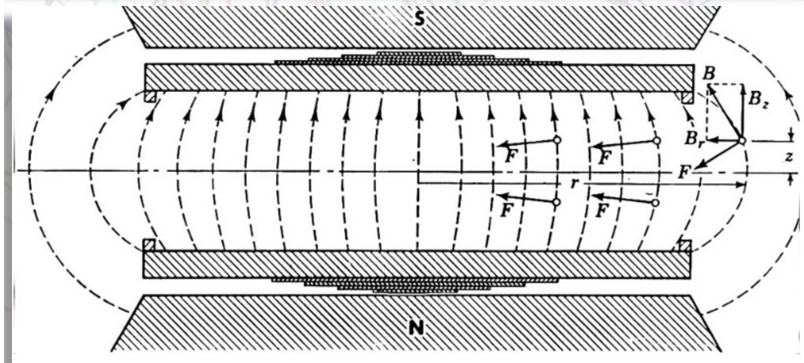


# Bending and Focusing

- 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. => 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 => 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 $\mu m^2$).





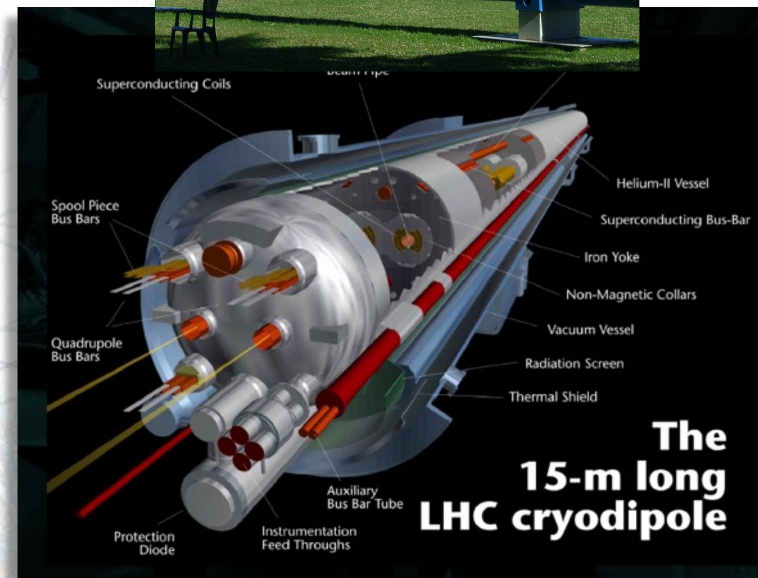



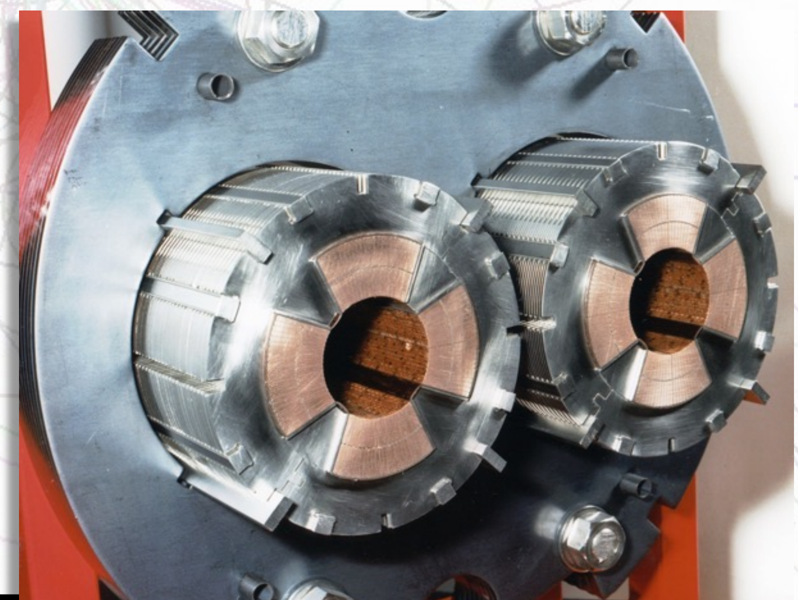
# Example: LHC magnets

- The LHC operating at the energy of 6.5 TeV per proton beam
- More than 50 types of magnets are used

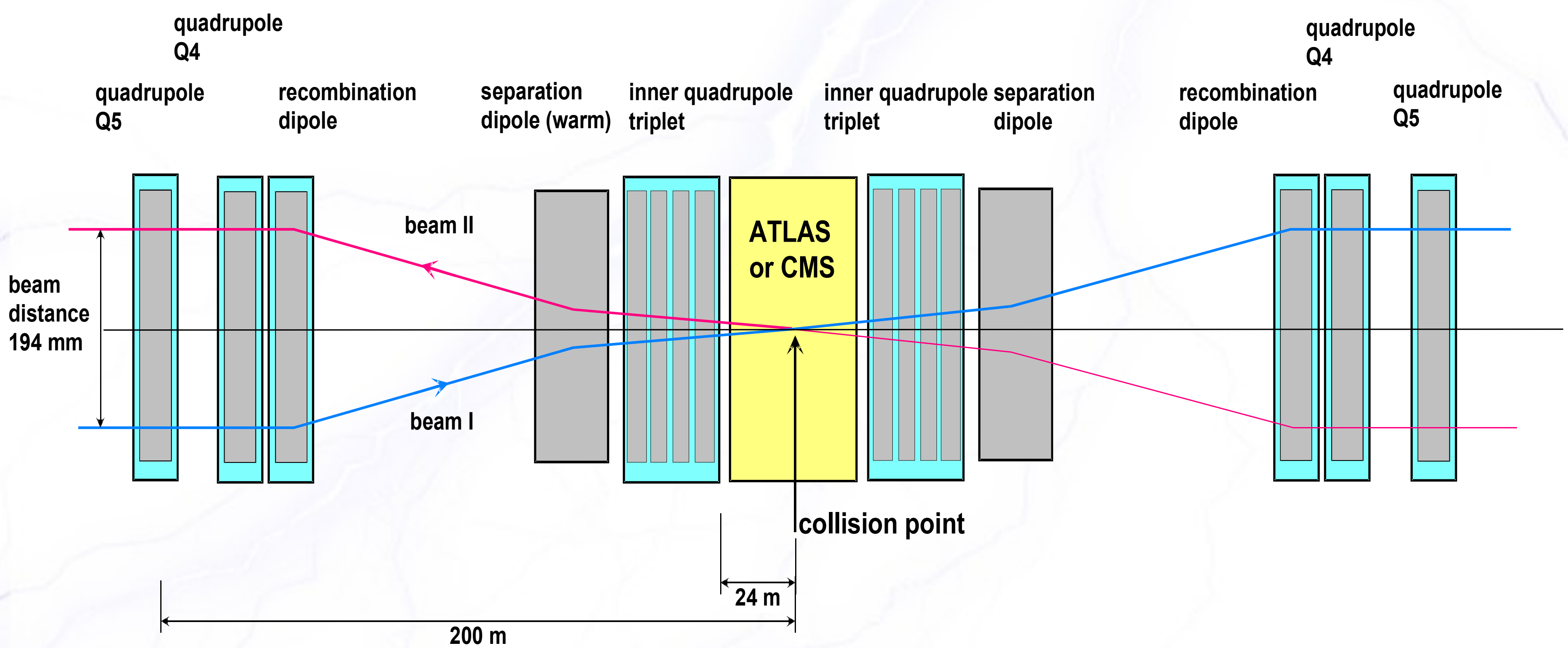
- Dipole superconducting magnets are one of the most complex parts of the LHC
  - generate 8.3T magnetic fields
  - 1232 main dipoles, each 15 m long, 35 tonnes
  - if normal magnets used instead LHC would have 120 and not 27 km!
- 858 quadrupoles keep protons in a tight beam
- Dipoles are also equipped with sextupole, octupole and decapole magnets, which correct for small imperfections in the magnetic field
- Insertion magnets squeezing beams of protons and collide them
  - they tighten the beam, making it 12.5 times narrower – from 0.2 mm down to 16 $\mu$m across

- ~96 tonnes of liquid helium is needed to keep the magnets at their operating temp. 1.9 K, making the LHC the largest cryogenic facility in the word

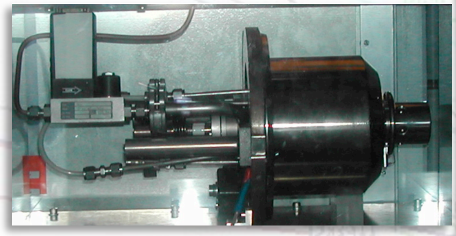



# Optics of LHC interaction point



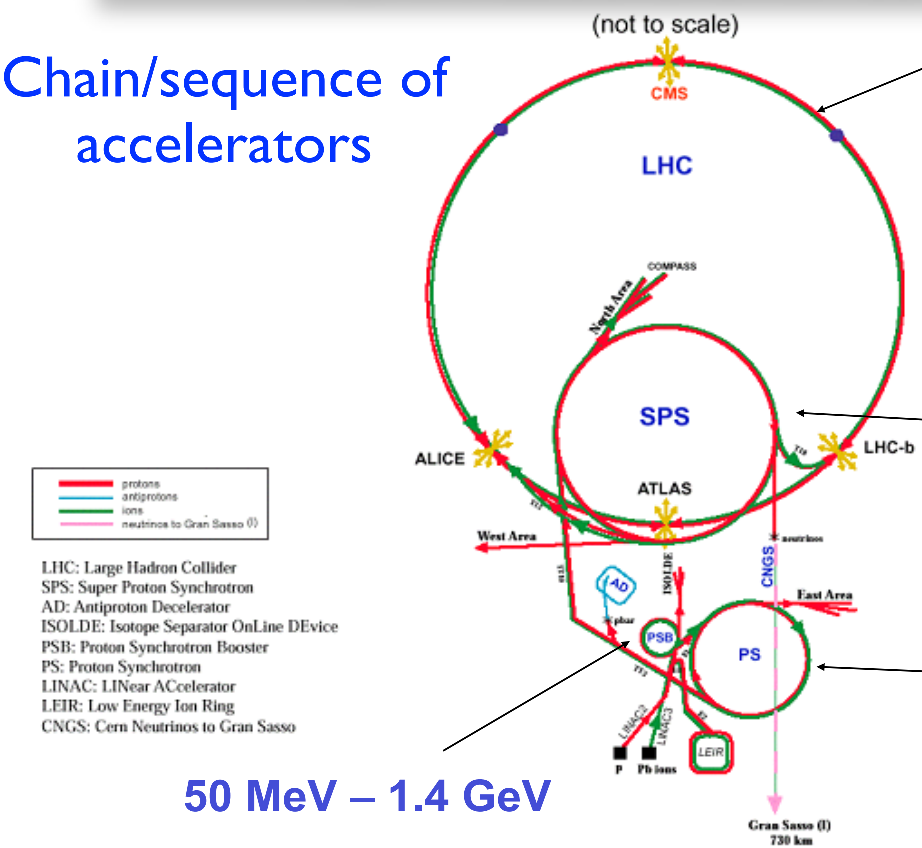

Example for an LHC insertion with ATLAS or CMS

# CERN accelerator complex

**Hydrogen bottle + duo-plazmatron**
(strips electrons from protons)
0.2ng/day
Output: p's ~100keV

## Chain/sequence of accelerators




450 GeV /c – 7 TeV /c

26 - 450 GeV/c

1.4 GeV – 26 GeV/c

50 MeV – 1.4 GeV

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

**Super Proton Synchrotron**
(since 1976)
Output: p's 450 GeV

**"Linac 2"**
Output: p's 50 MeV

**Proton Synchrotron Booster**
(since 1972)
Output: p's 1.4 GeV

**Proton Synchrotron**
(since 1959)
Output: p's 26 GeV

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

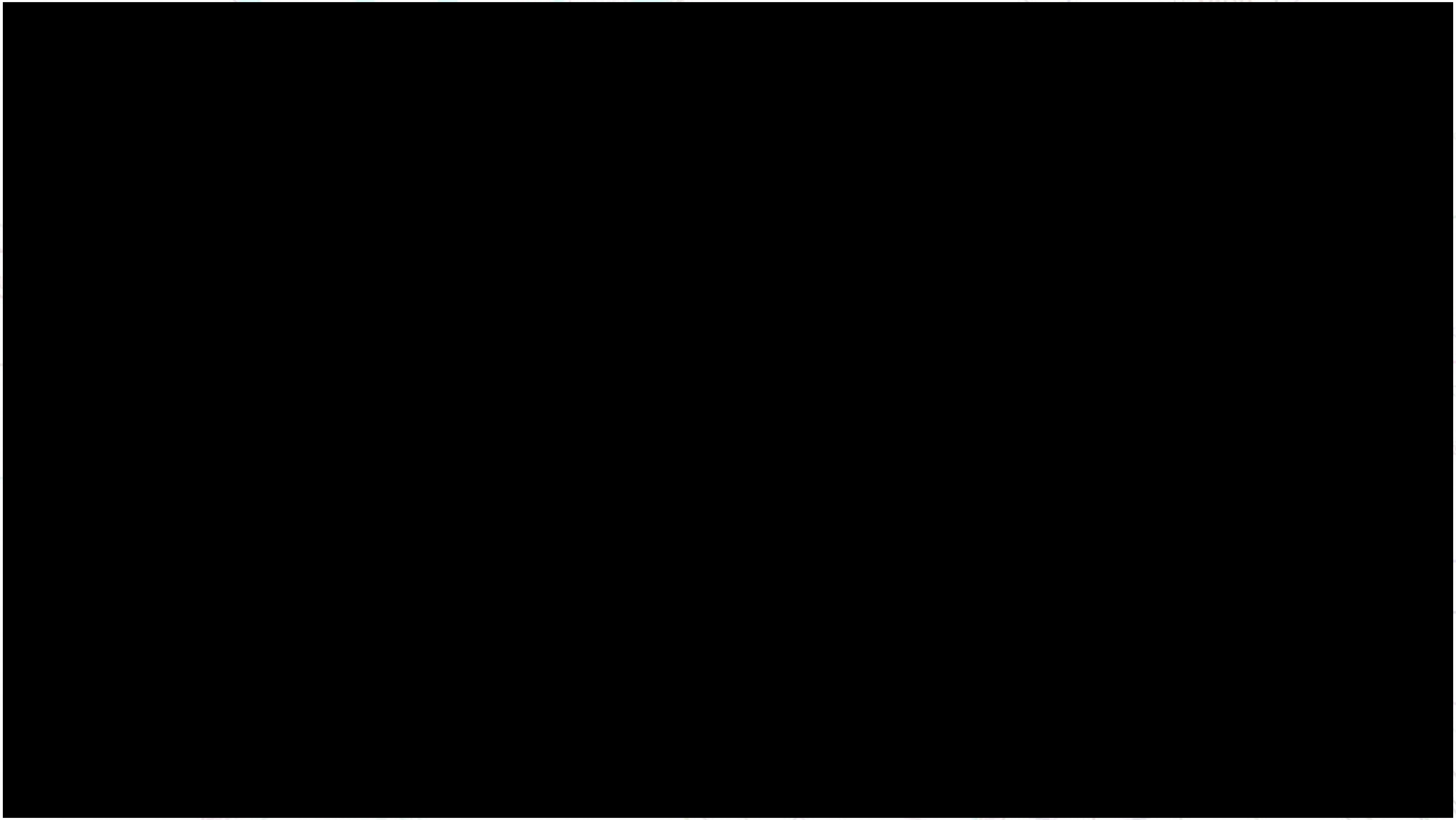
# The LHC – Guinness records

- 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 ~$1.15*10^{11}$ protons, ~1 cm long, ~1 mm across
  - $E_{beam}$= 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!


W WIELKIM ZDERZACZU HADRONÓW

- The fastest racetrack on the planet
  - Protons race around the LHC 11 245 times a second, travelling at 99.9999991%*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

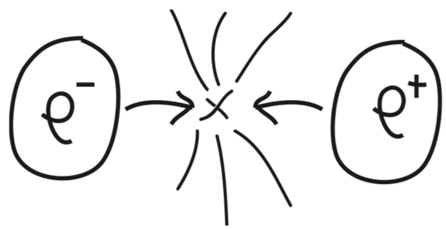
# LHC accelerator complex

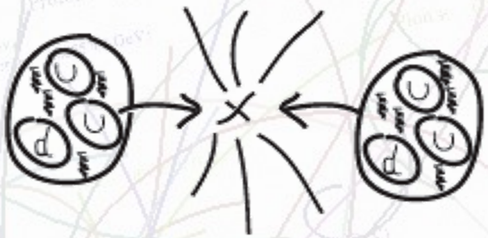


https://www.youtube.com/watch?v=RDdPuL-uOQc
https://videos.cern.ch/record/1610170

# The proper particle for the proper scope

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



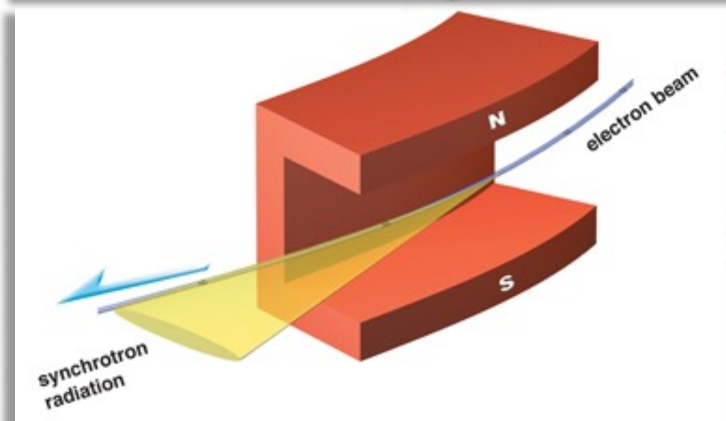



- Electrons (and positrons) are (so far) point like particles: no internal structure
- The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision
- Pros: the energy can be precisely tuned to scan for example, a mass region
  - Precision measurement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

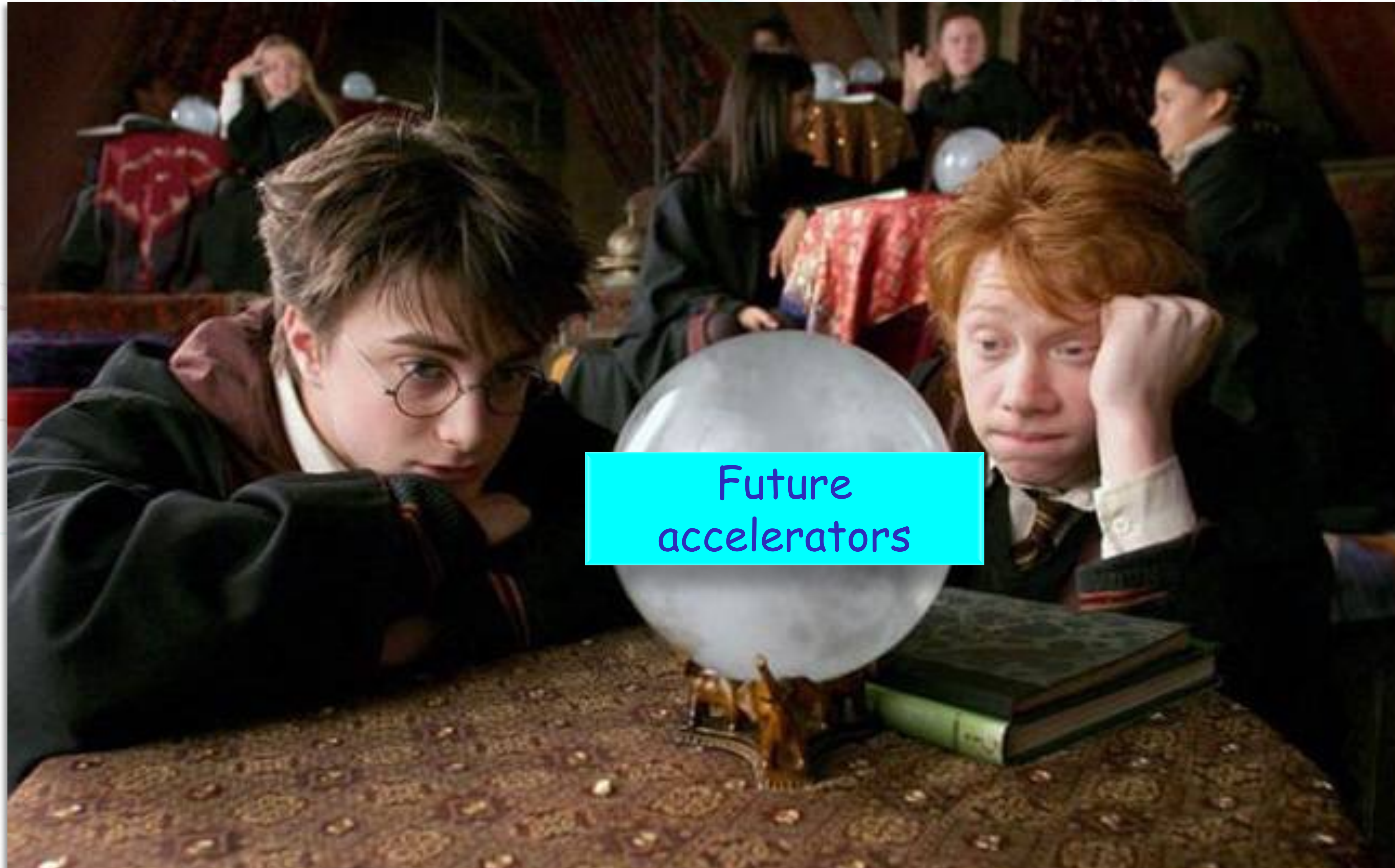
# Synchrotron Radiation

- *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)
  - Energy lost per turn ~ $(E/m)^4$ 1/R
    - Thus, even with large rings it has to be compensated
  - LEP was probably the last (???) circular $e^+e^-$ collider, it is more worth to build linear colliders for high energy electron collisions




Synchrotron radiation is 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.

SOLARIS
NARODOWE CENTRUM PROMIENIOWANIA SYNCHROTRONOWEGO


Future
accelerators

# Future accelerators - HL-LHC

# Future accelerators (circular)

## FCC Future Circular Collider

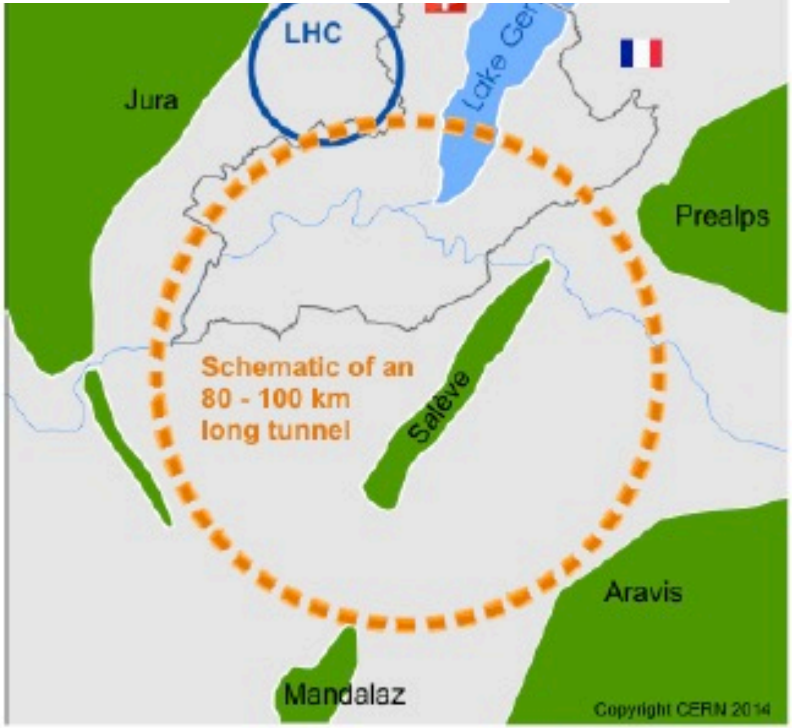
Future Circular Collider

FCC-ee: $e^+e^-$ with $\sqrt{s}$ = 90 - 350 GeV

FCC-hh: pp with $\sqrt{s}$ ~ 100 TeV

Circumference: 80-100 km

- HE-LHC - 27 TeV pp collider relying on the 16 T magnet technology being developed for FCC-hh
- 16 T magnets for pp@100 TeV




## CepC

Circular Electron Positron Collider

CepC: $e^+e^-$ with $\sqrt{s}$ = 240 - 250 GeV

SppC: pp with $\sqrt{s}$ = 70 - 100 TeV

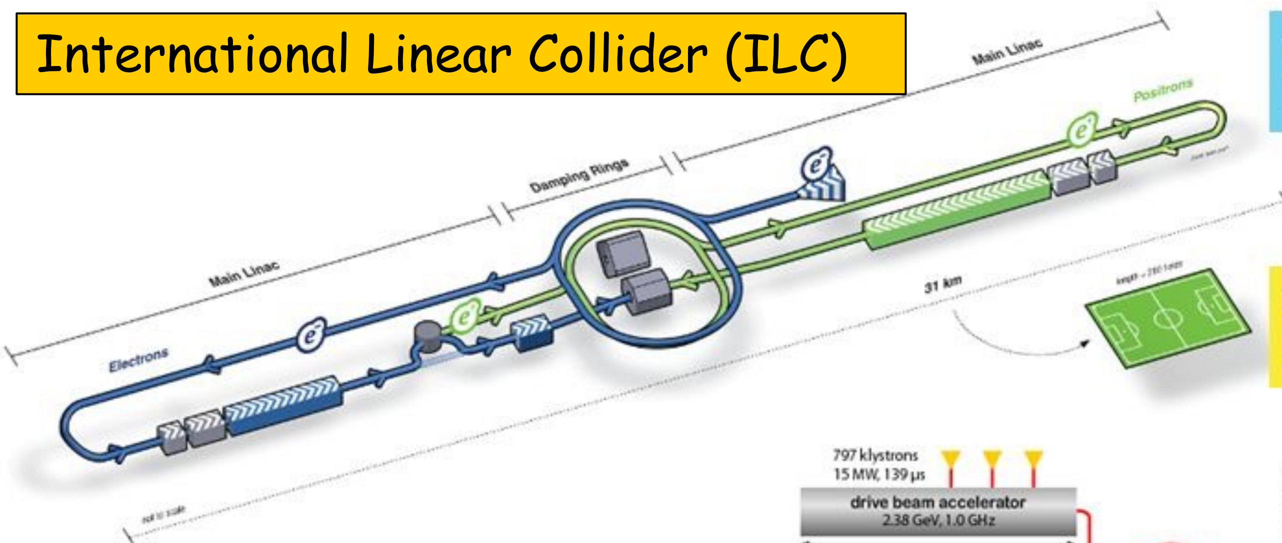
Circumference/Length: 54-100 km

investigated site in China

# Future accelerators (linear)

## ILC and CLIC collimation design

International Linear Collider (ILC)

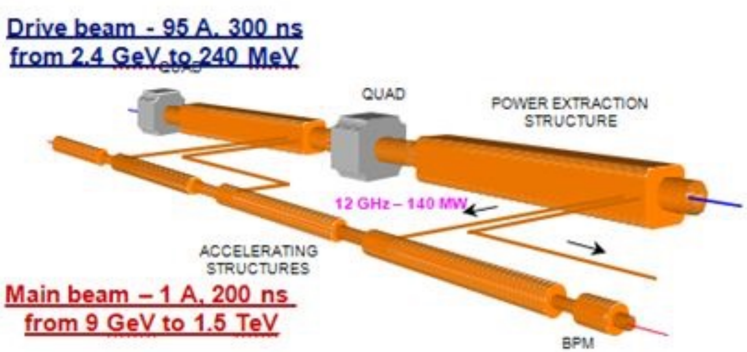


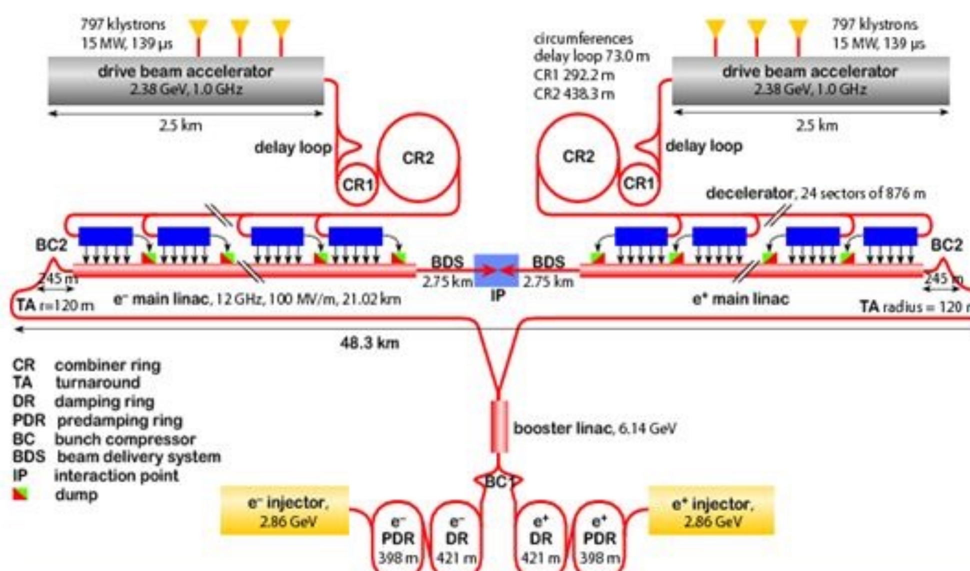

ILC 0.5 TeV – 30 km
ILC 1 TeV – 50 km

- Use high gradient superconducting technology

CLIC 3 TeV: 48 km
CLIC 0.5 TeV: 13 km

- Linear collider with high gradient normal-conducting acceleration
- nano-beams



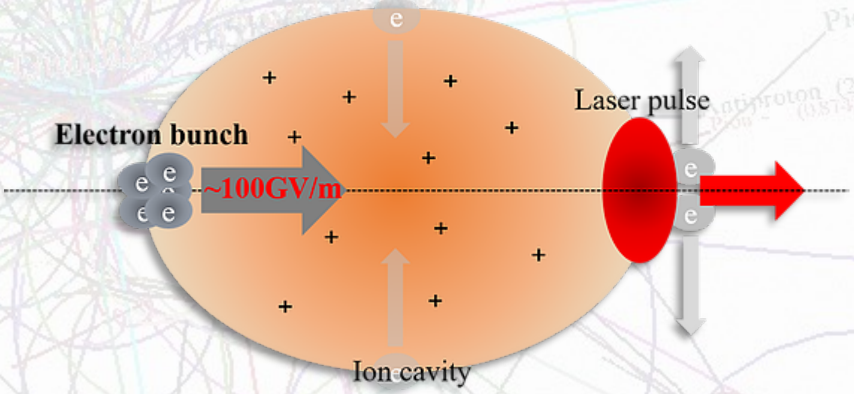

Compact Linear Collider (CLIC)

# 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->pion -> 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 => 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

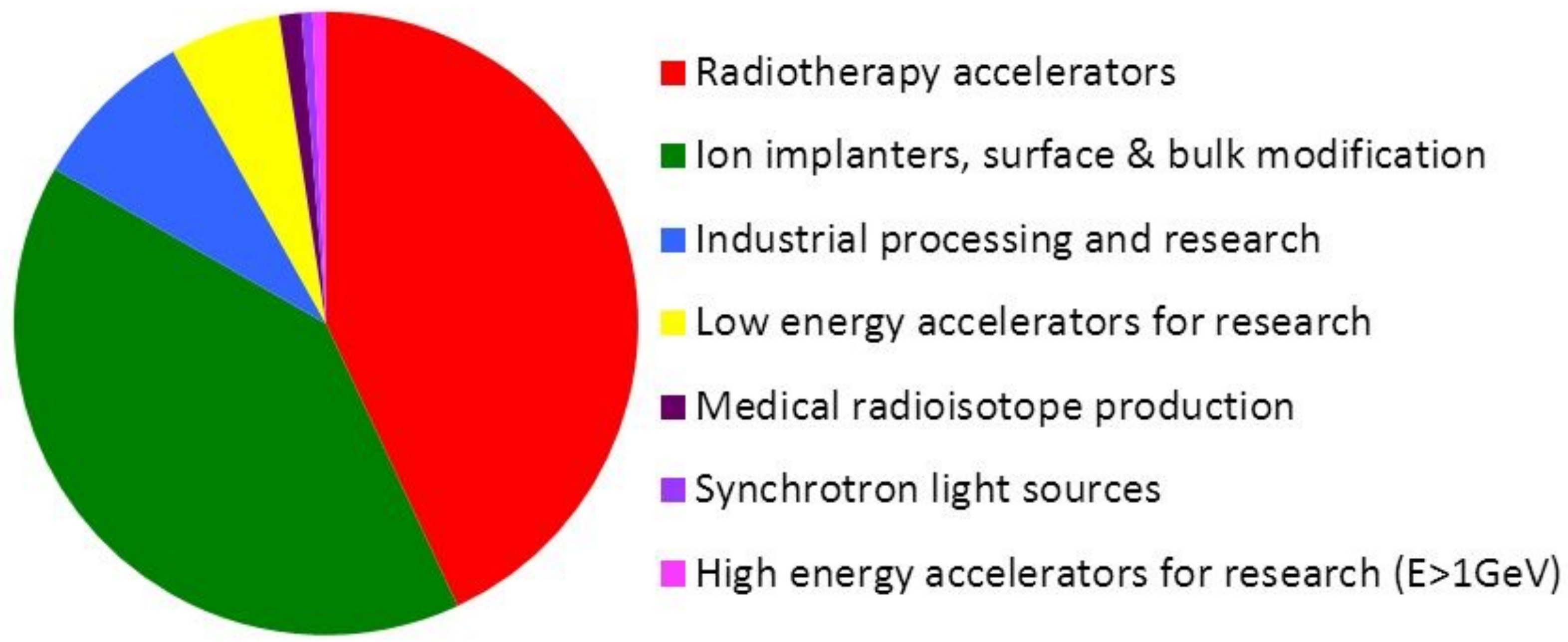



- Reach gradients -> 100 GV/m!

**Laser Wakefield Accelerator (LWFA):**
Drive beam = laser beam
**Plasma WakeField Accelerator (PWFA):**
Drive beam = high energy electron or proton beam

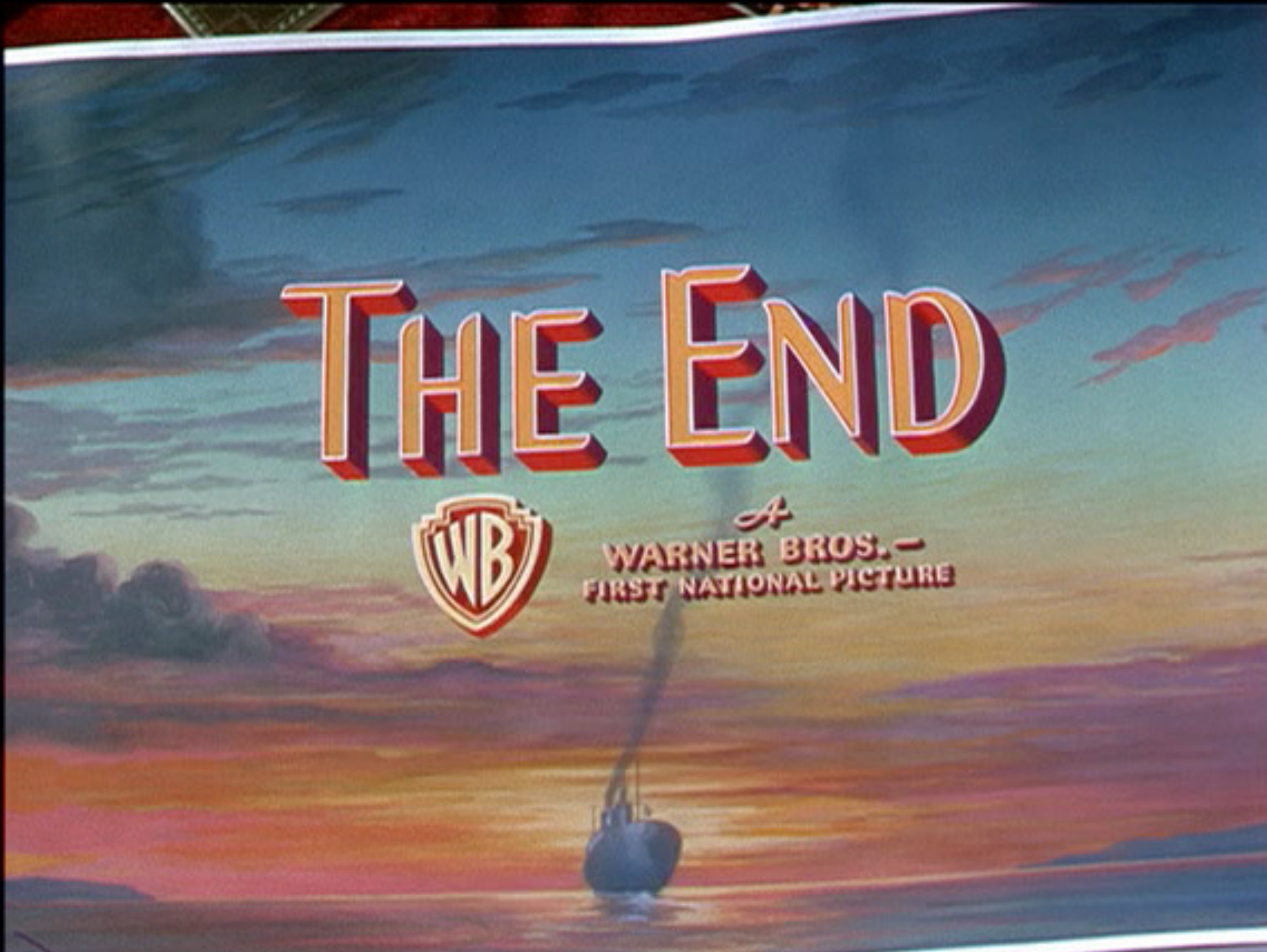
# Applications of Accelerators

~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


THE END
WB
A
WARNER BROS.–
FIRST NATIONAL PICTURE

# Additional slides for curious kids

# Recall: momentum & energy

norm. velocity $\beta = v / c$

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

rest energy $E_o = m_o c^2$

## Momentum

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

## 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

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

useful relations:

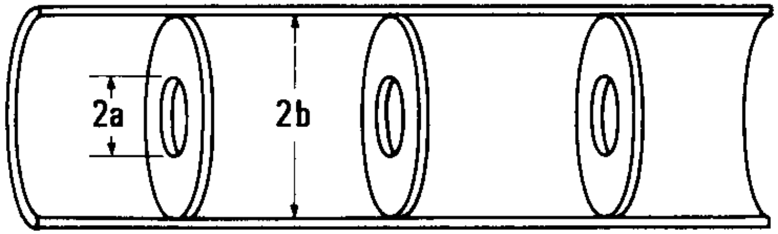
$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \qquad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \qquad \beta\gamma = \sqrt{\gamma^2 - 1}$$

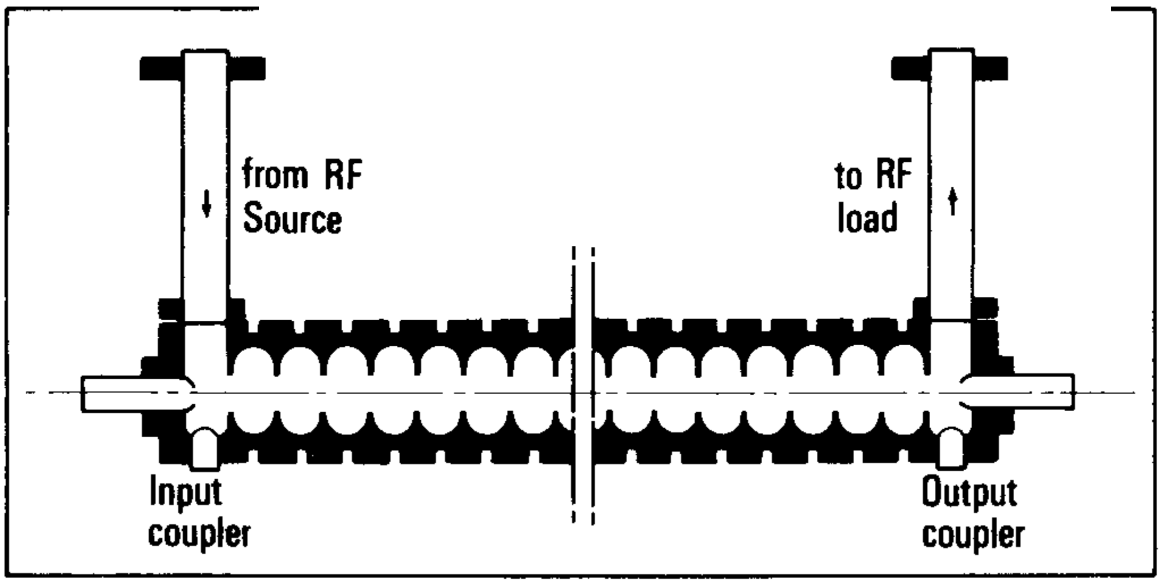
# RF accelerating structures

**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**

**C**onseil **E**uropéen pour la **R**echerche **N**ucléaire
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 interest[1]):

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

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

# More generally…

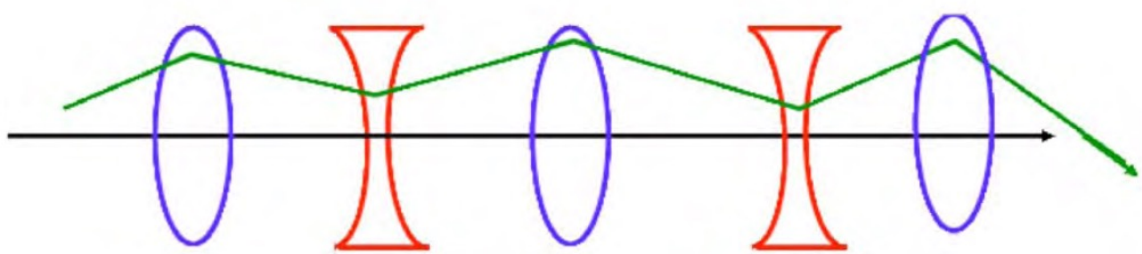
From optics we know that a combination of two lenses, with focal lengths $f_1$ and $f_2$ separated by a distance d, has

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

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

*∴ A quadrupole doublet is focusing in both planes!*

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



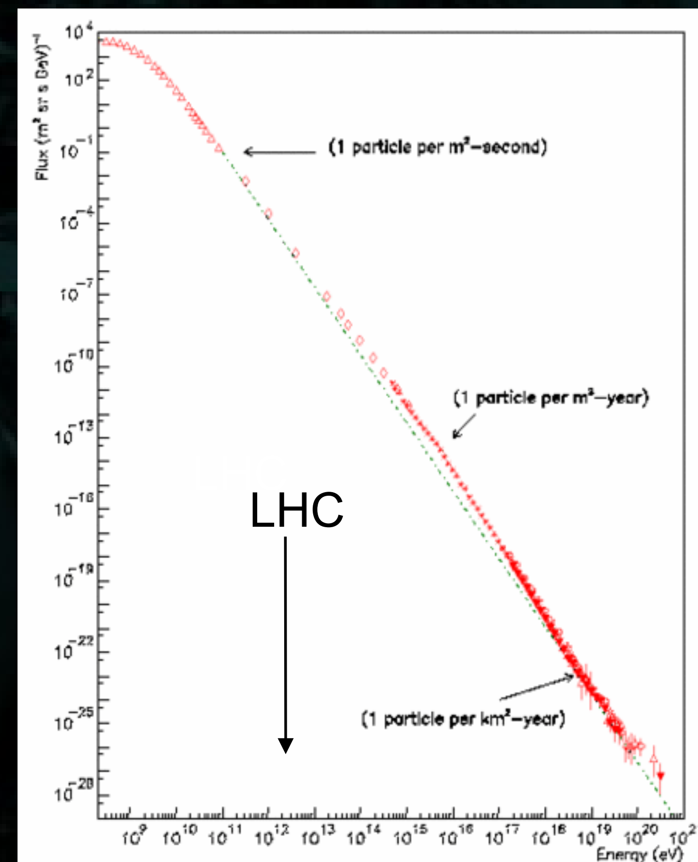
*N.B. This is only valid in thin lens approximation*

# 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

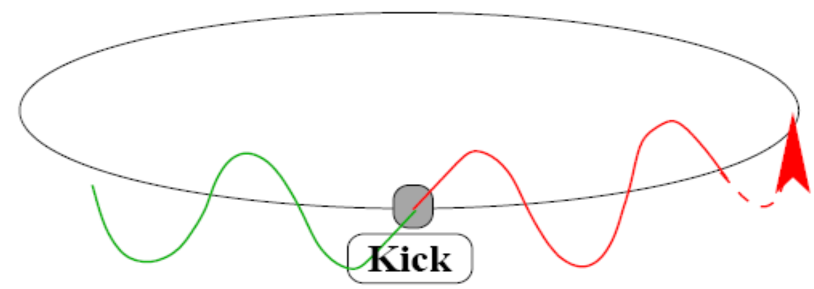



Not useful for us:

- large space required,
- acceleration is isotropic

# Ogniskowanie wiązki

- Cząstki w wiązce oscylują wokół idealnej orbity:



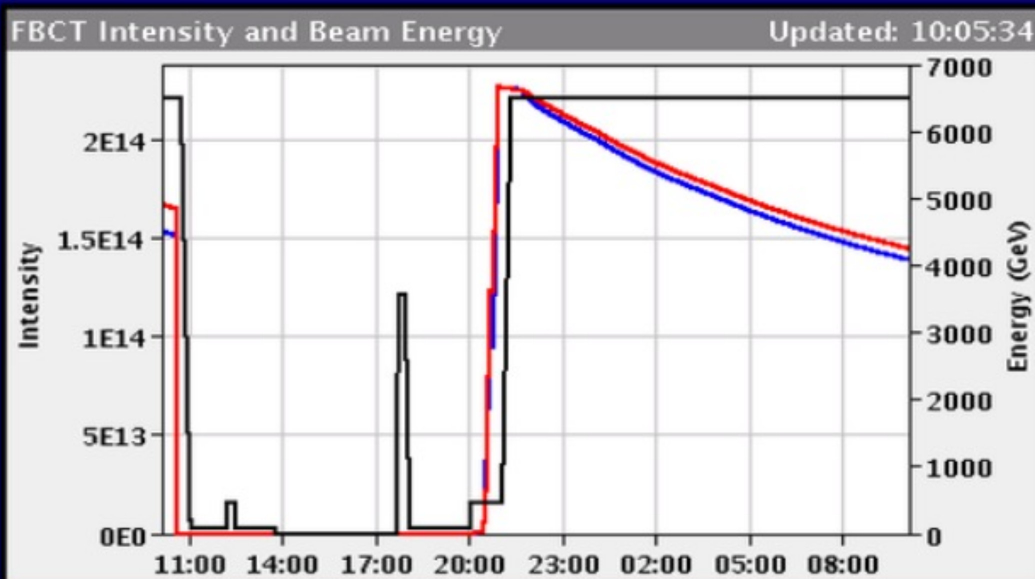

- Emitancja ε= pole przestrzeni fazowej zajmowanej przez wiązkę (amplituda oscylacji * maksymalna prędkość oscylacji)
- Na samym początku wiązka jest produkowana z **emitancją** ε – emitancja nie maleje (chyba że stosujemy tzw. chłodzenie wiązki albo jeśli przyśpieszamy)
- Ewolucję rozmiaru wiązki wzdłuż akceleratora nazywamy funkcją β

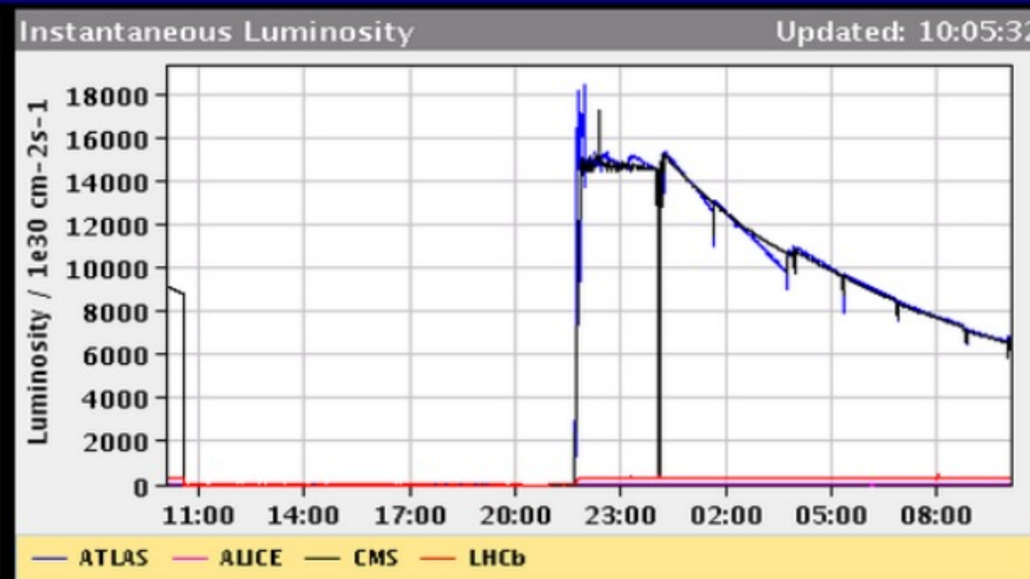
LHC Page1 Fill: 6287 E: 6499 GeV t(SB): 12:13:25 10-10-17 10:05:34

# 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 |