Accelerate, Collide and give a Hit

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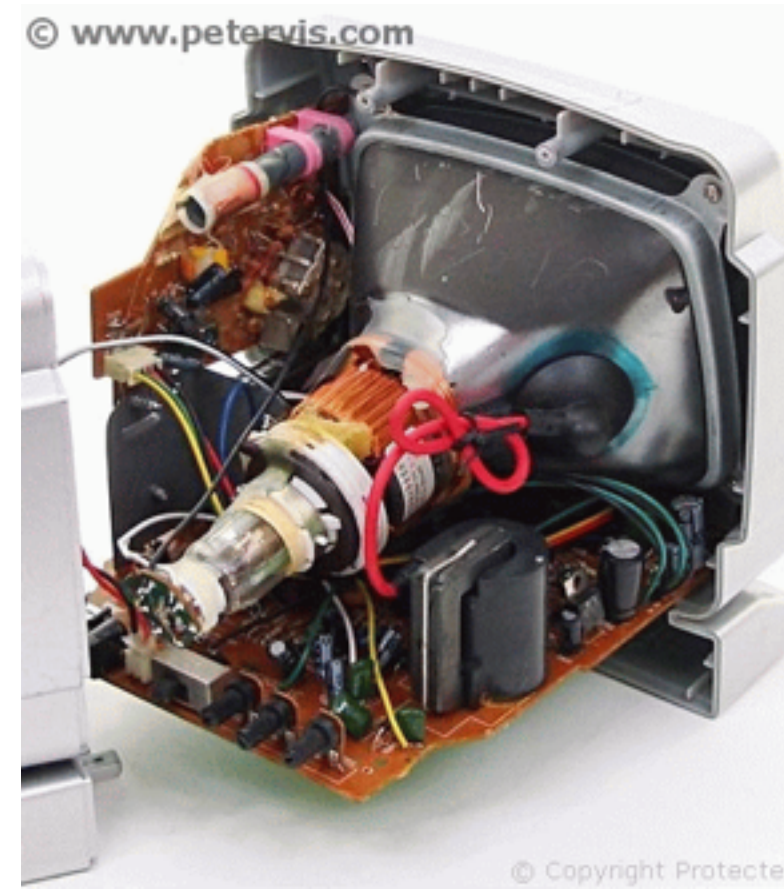
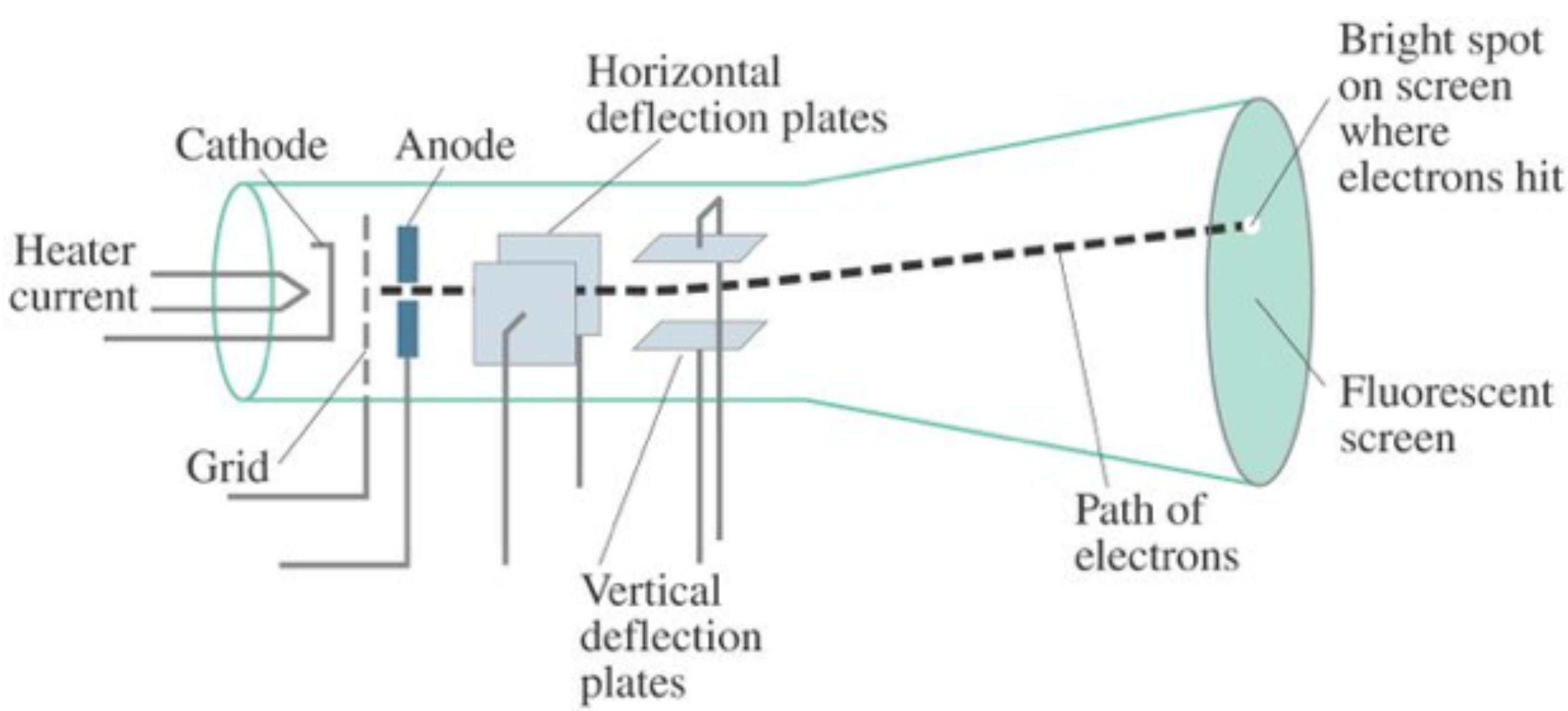
Lecture on Heavy ion and particle colliders

Eotvos University, Spring semester 2021

Particle Accelerator

A particle accelerator is a machine that accelerates elementary particles (or ions) to very high energies.





Build your own particle accelerator:
https://core.ac.uk/download/pdf/327368343.pdf

Classifications:

static field accelerators (or electrostatic accelerators or potential-Drop Accelerators): electric fields that do not change with time.

e.g.:
Cockcroft-Walton accelerator
Van de Graaff accelerator,
cathode ray tube (old televisions)

oscillating field accelerators (or electrodynamic or electromagnetic): electric fields that periodically change with time.

e.g.:
Linac
Cyclotrons, synchrotrons

PS:
Although electrostatic accelerators accelerate particles along a straight line, the term linear accelerator is more often used for accelerators that employ oscillating rather than static electric fields.

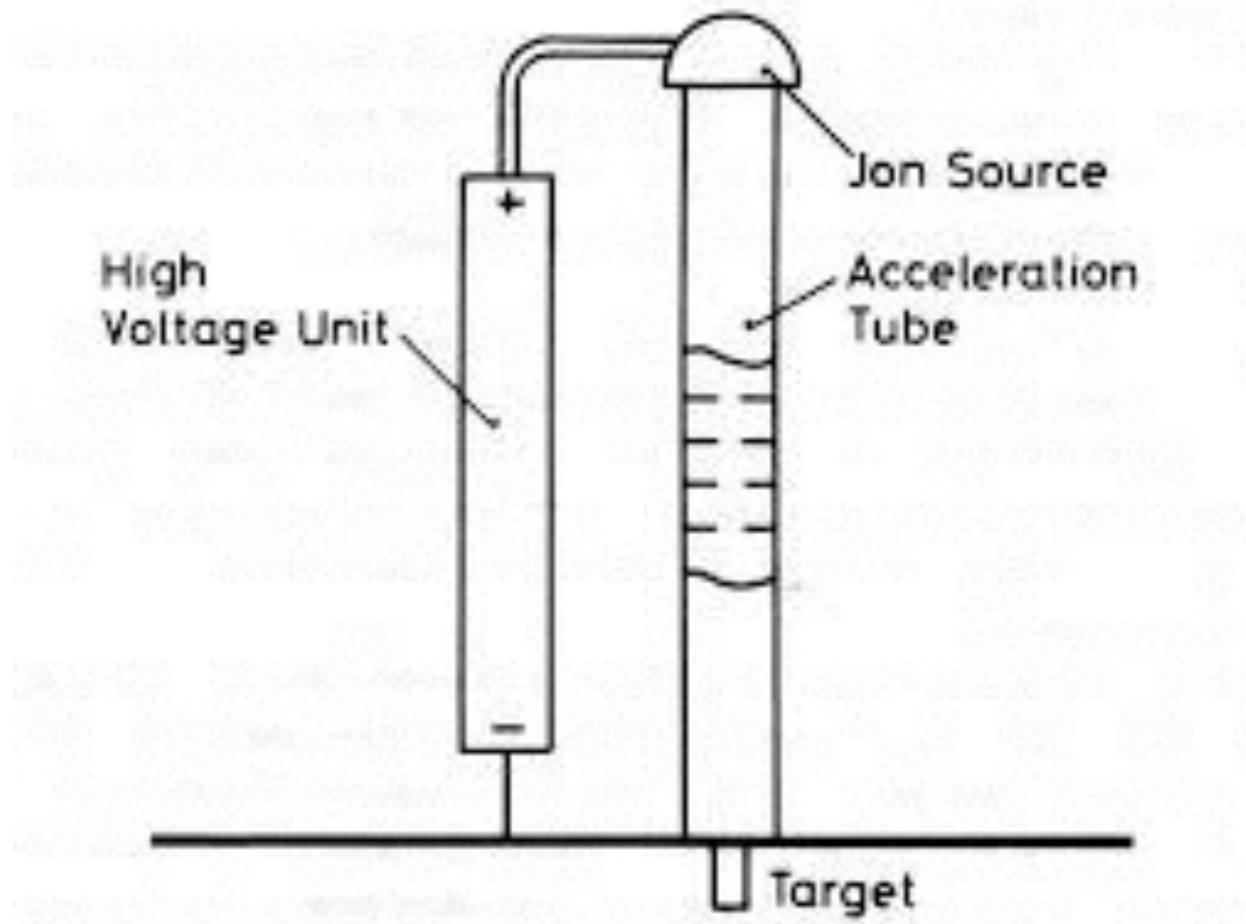
Working of electrostatic particle accelerator

- accelerating charged particles through a constant potential difference.

- voltage from a high voltage generator connected to accelerating tube, and particles are accelerated (in one step) through the tube,

- accelerating tube is constructed as along drift tube with a number of electrodes along the axis

=>giving uniform field distribution for acceleration



$$E_{Kin} = \frac{mv^2}{2} = qV$$

E_{Kin} is gain in Kinetic energy, for particle having mass m & charge q, moving through a potential difference V

example -1: Cockcroft-Walton accelerator

Inventor:
John Cockcroft and Ernest Walton
Cavendish Laboratory, Cambridge
early 1930's
Noble award, 1971

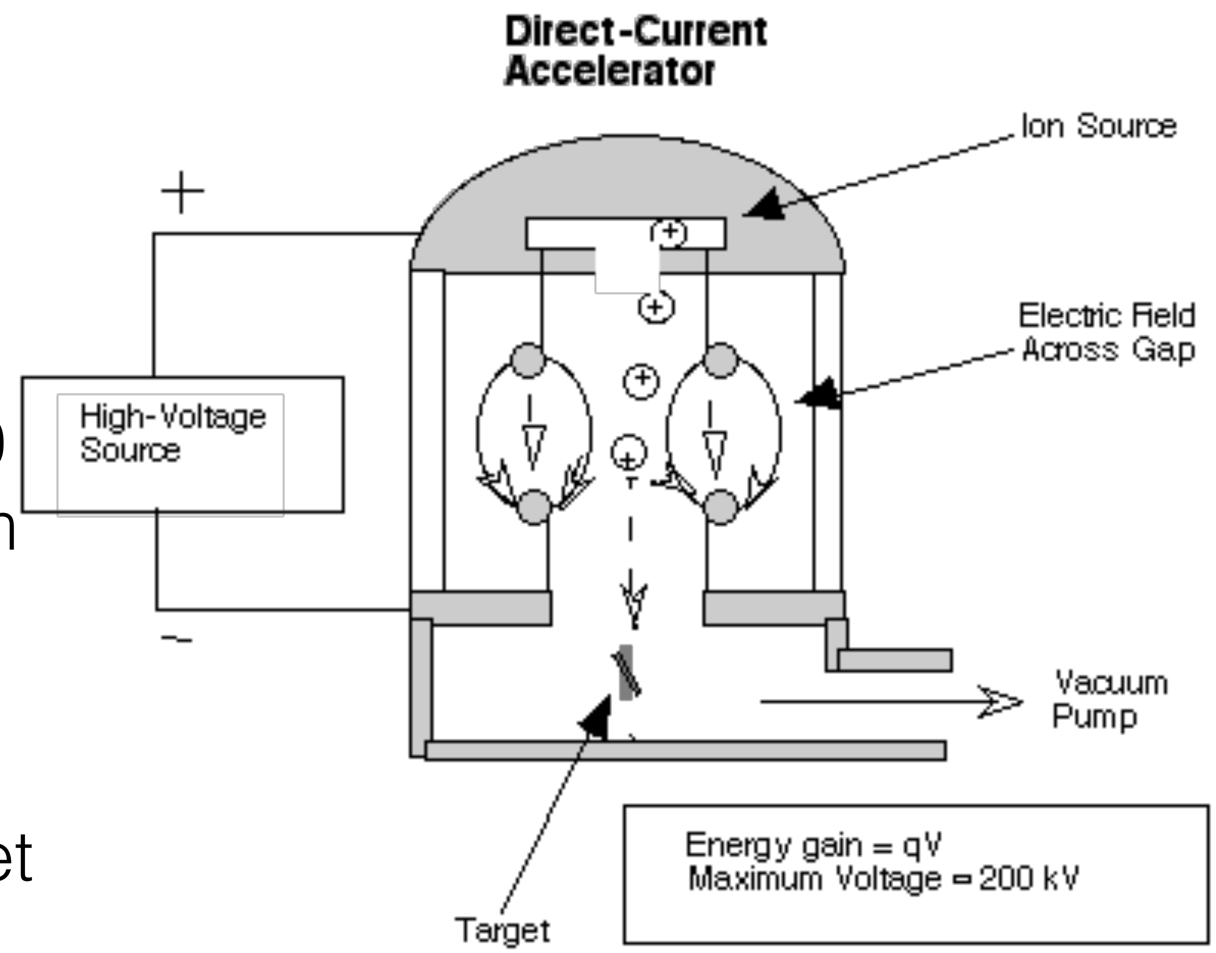
- most straightforward type of accelerator, results from application of a potential difference between two terminals.

- To obtain accelerating voltage >200 kV, it is necessary to use one or more stages of voltage-doubling circuits.

https://www.nms.ac.uk/explore-our-collections/stories/science-and-technology/cockcroft-walton-generator/

example -1: Cockcroft-Walton accelerator

- ☑ hydrogen gas is ionized to create negative ions, each consisting of two electrons and one proton.
- ☑ ions are accelerated by a positive voltage and reach an energy of 750,000 electron volts (750 keV) [~30 times the energy of the electron beam in a television's picture tube].
- ☑ They travel 8 foot vacuum tube, where they collided with Lithium target [first artificial nuclear disintegration in history, p+Li -> 2He]



https://www2.lbl.gov/abc/wallchart/chapters/11/1.html

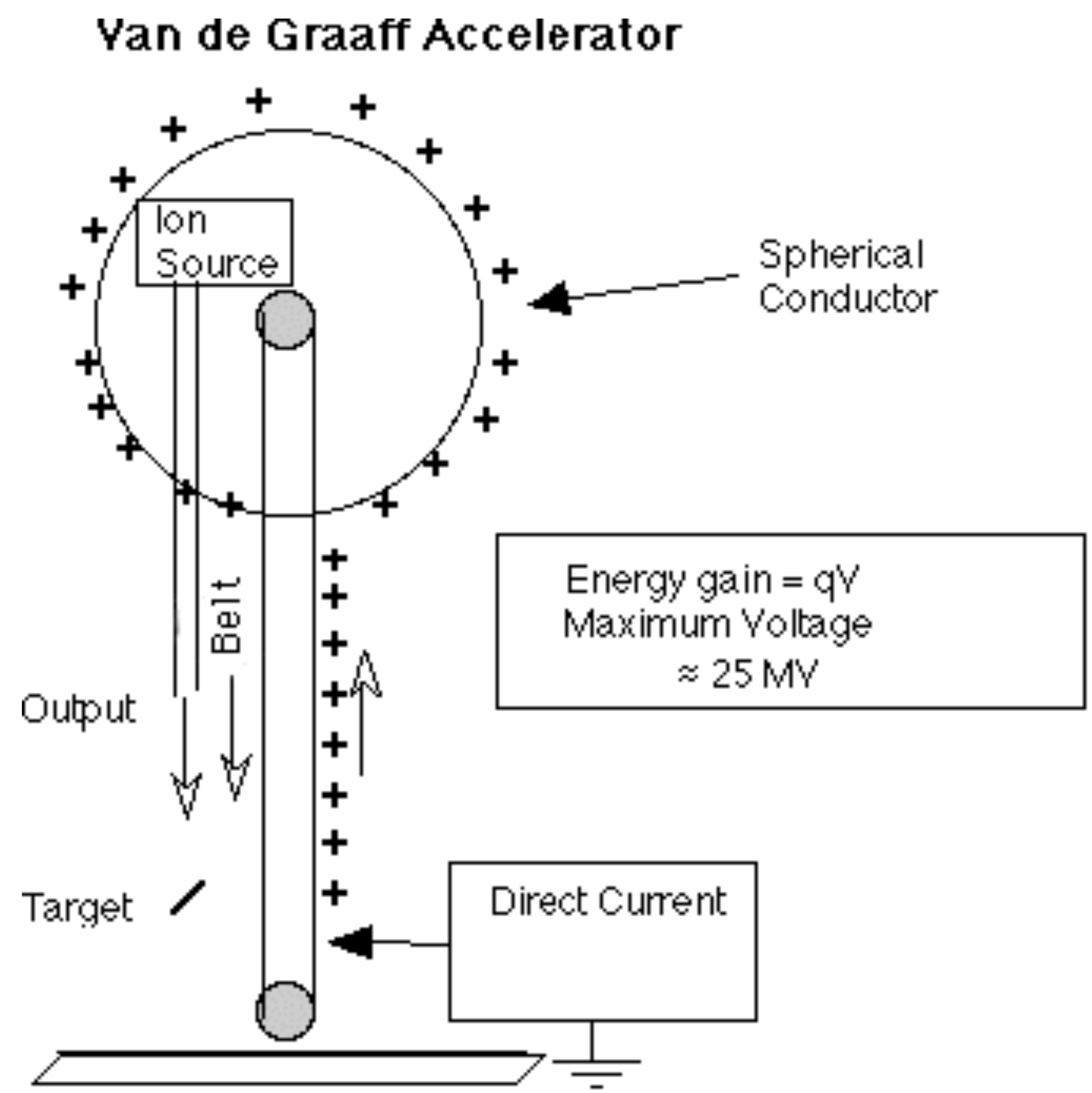
example -2:
Van de Graaff accelerator

Inventor
Robert Van de Graaff
post-doctorate, Princeton
1929

- ☑ Upper limit of Cockroft-Walton Accelerators was about 1 MeV; here it achieved energies of about 10 MeV.
- ☑ A Van de Graaff accelerator is a very big Van de Graaff generator with an accelerator tube contained within it.
- ☑ By 1933 a Van de Graaff accelerator was in operation that could accelerate hydrogen ions to an energy of 0.6MeV (600,000eV).

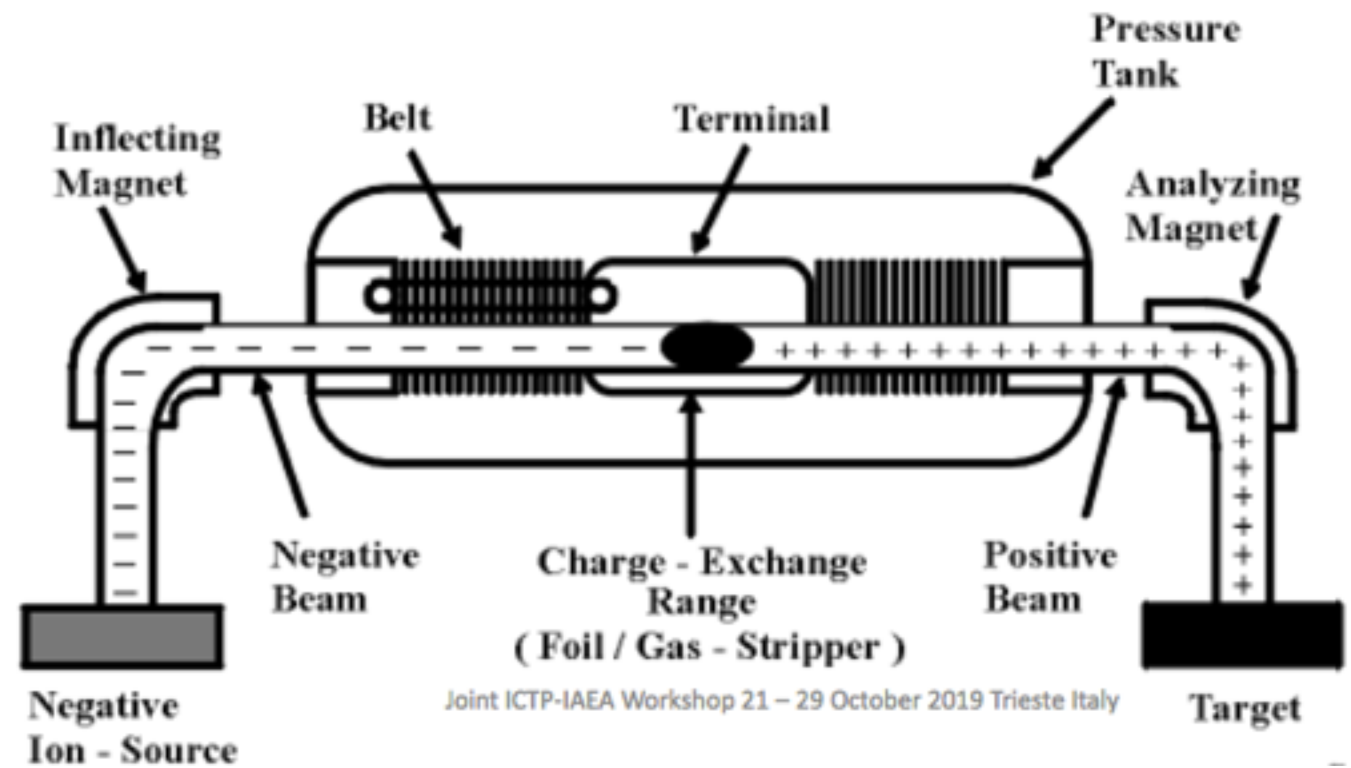
example -2:
Van de Graaff accelerator

- A high potential difference is built up and maintained on a smooth conducting surface by the continuous transfer of positive static charges from a moving belt to the surface.
- When used as a particle accelerator, an ion source is located inside the high-voltage terminal.
- Ions are accelerated from the source to the target by the electric voltage between the high-voltage supply and ground.



tandem Van de Graaff accelerator (dual-use of the same high voltage)

- Negative ions are first accelerated towards a positive high-voltage terminal in the center of a pressure tank.
- Inside the terminal the negative ions pass through either a foil or gas "stripper" and are stripped of electrons, producing a positive-ion beam.
- This beam is then accelerated a second time away from the high-voltage terminal.



http://indico.ictp.it/event/8728/session/2/contribution/2/material/slides/0.pdf

$E_{Kin} = eU + qU$
where e = absolute value of singly charged negative ion,
q = charge of positive ion

Limitations
of electrostatic particle accelerator

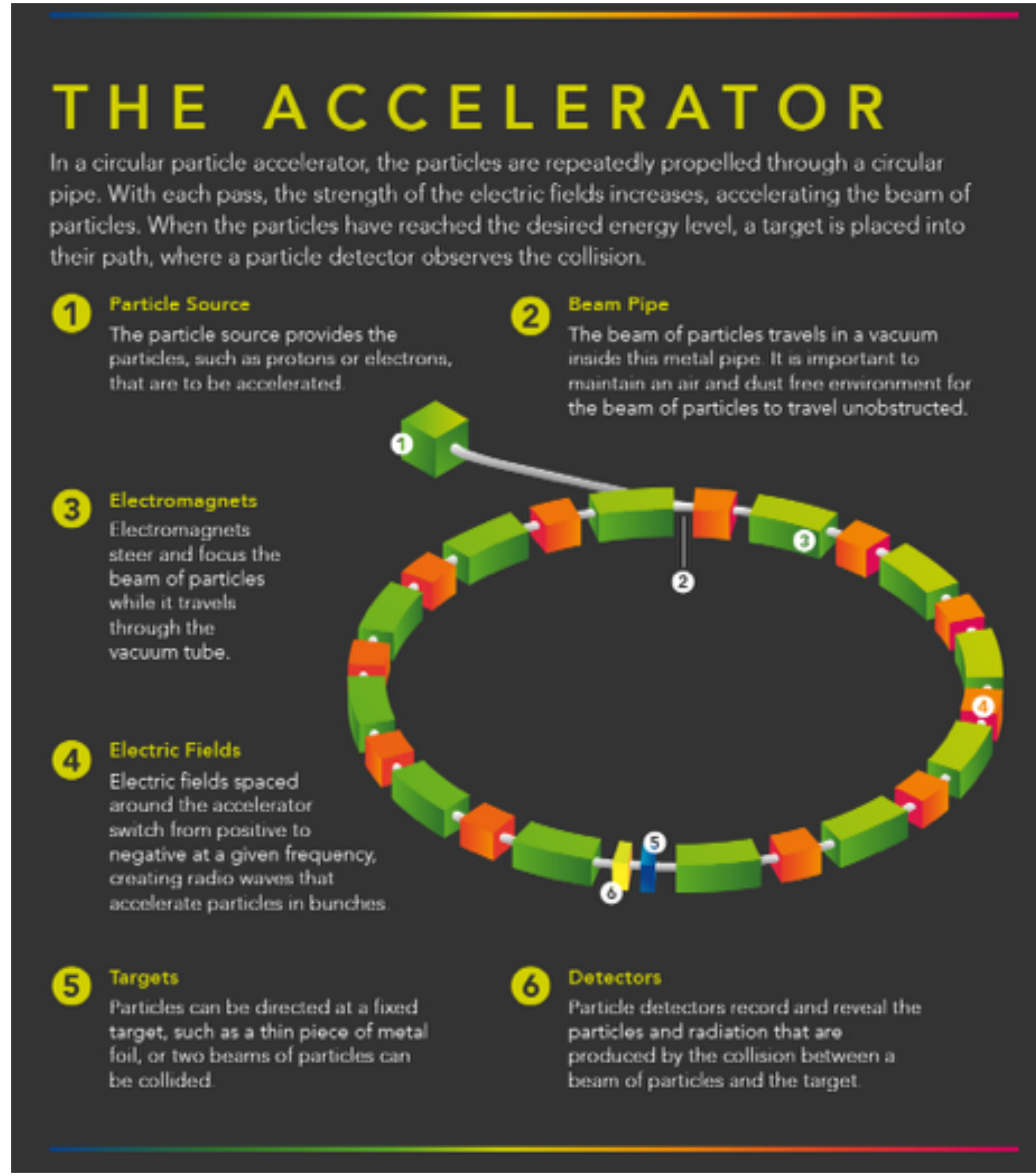
- ☑ Increasing the energy means increasing the length of the accelerator.

- ☑ The maximum particle energy is limited by the accelerating voltage on the machine, which is limited by insulation breakdown to a few megavolts.

Working of
oscillating field particle accelerator

- ☑ To accelerate particles, the accelerators are fitted with metallic chambers containing an electromagnetic field known as radiofrequency (RF) cavities.

- ☑ Charged particles injected into this field receive an electrical impulse that accelerates them.



https://www.energy.gov/articles/how-particle-accelerators-work

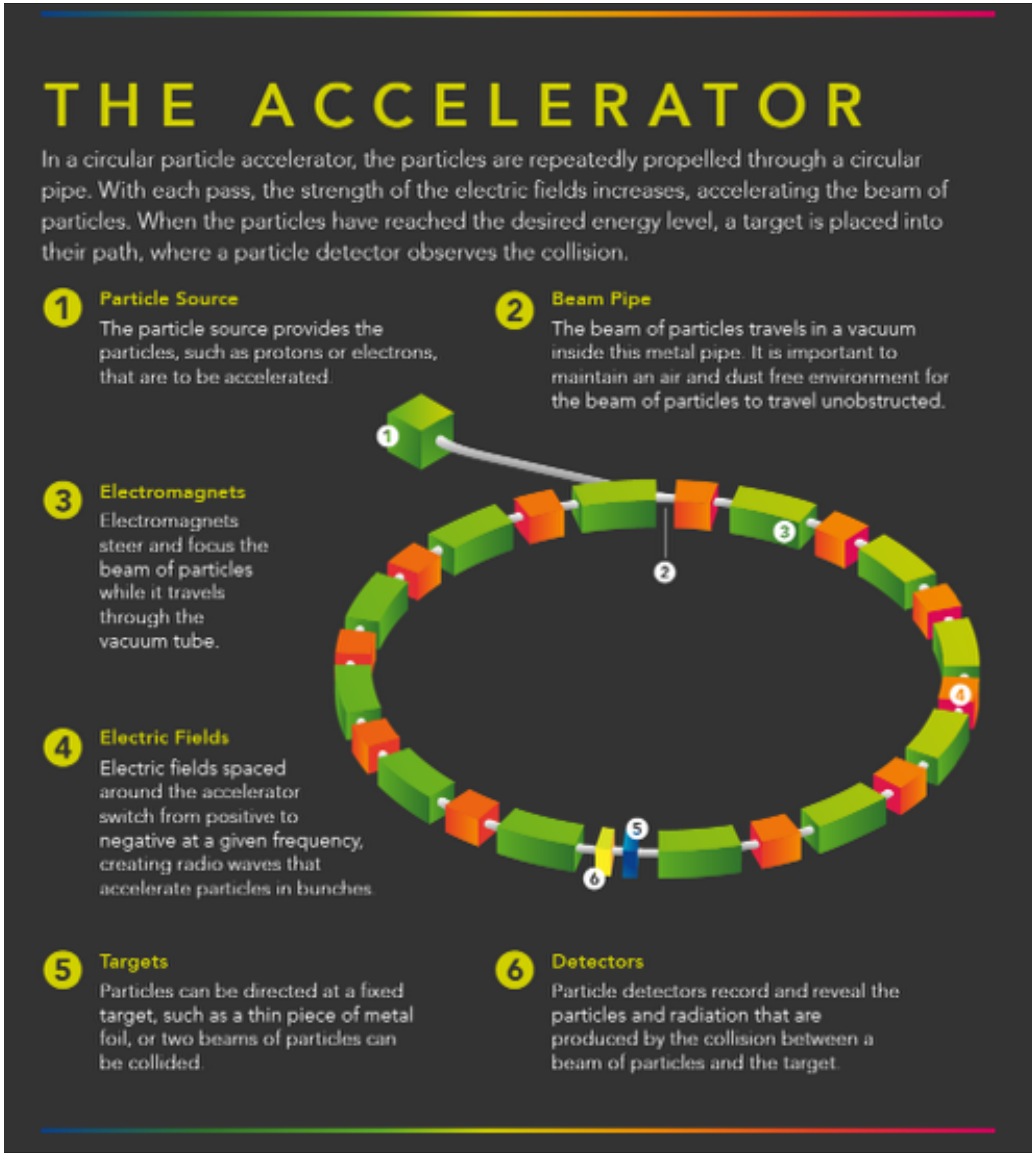
Working of oscillating field particle accelerator

- field in an RF cavity is made to oscillate (switch direction) at a given frequency, so timing the arrival of particles is important.

- When the beam has reached the required energy,

=>an ideally timed proton with exactly the right energy will not be accelerated.
=>protons with slightly different energies arriving earlier or later will be accelerated or decelerated so that they stay close to the desired energy.

- In this way, the particle beam is sorted into packs of protons called "bunches".



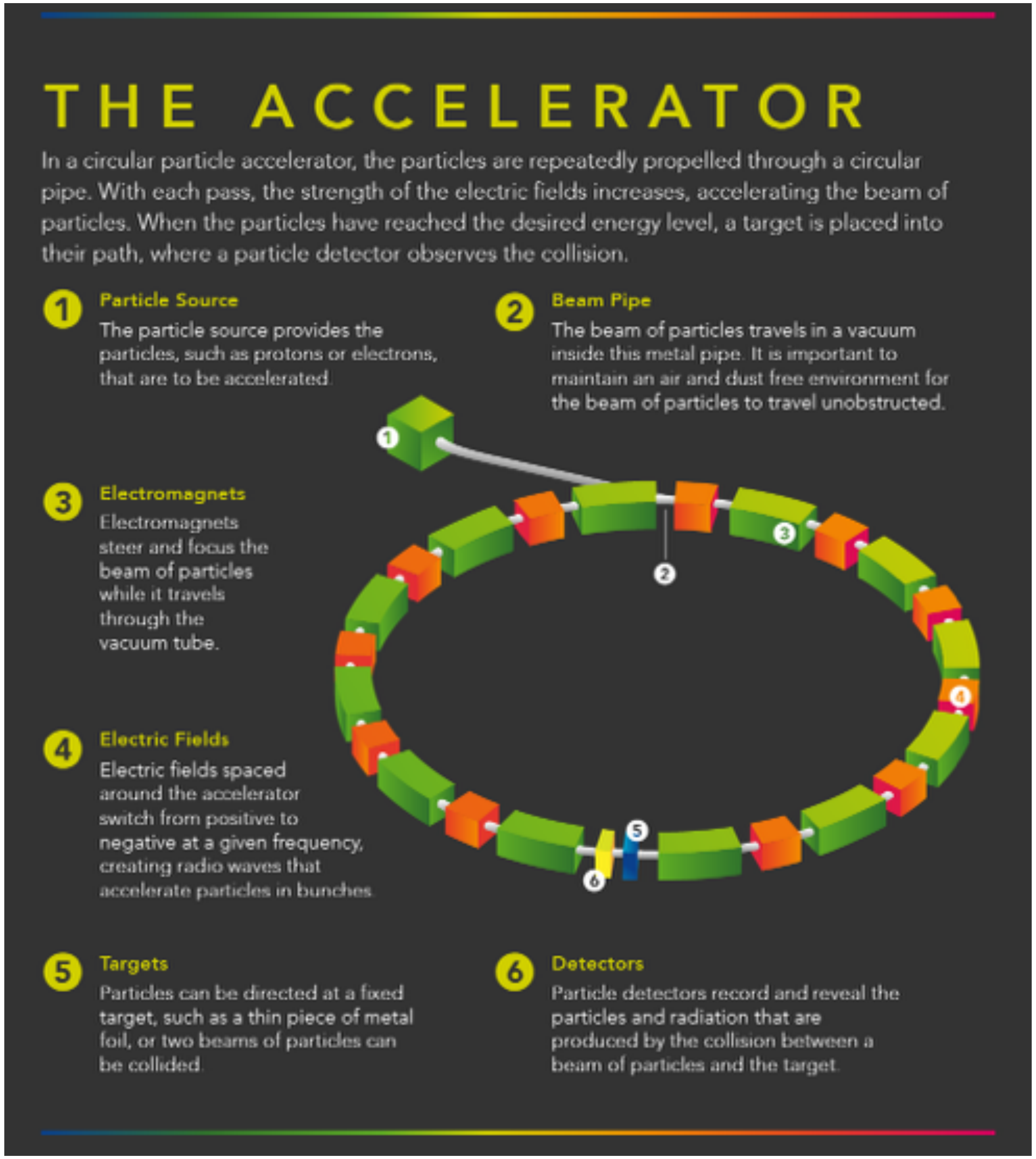
https://www.energy.gov/articles/how-particle-accelerators-work

Working of
oscillating field particle accelerator

- ☑ Radiofrequency cavities boost the particle beams, while magnets focus the beams and bend their trajectory.

- ☑ In a circular accelerator, the particles repeat the same circuit for as long as necessary, getting an energy boost at each turn.

- ☑ A linear accelerator is exclusively formed of accelerating structures, since the particles do not need to be deflected, but they only benefit from a single acceleration pass.



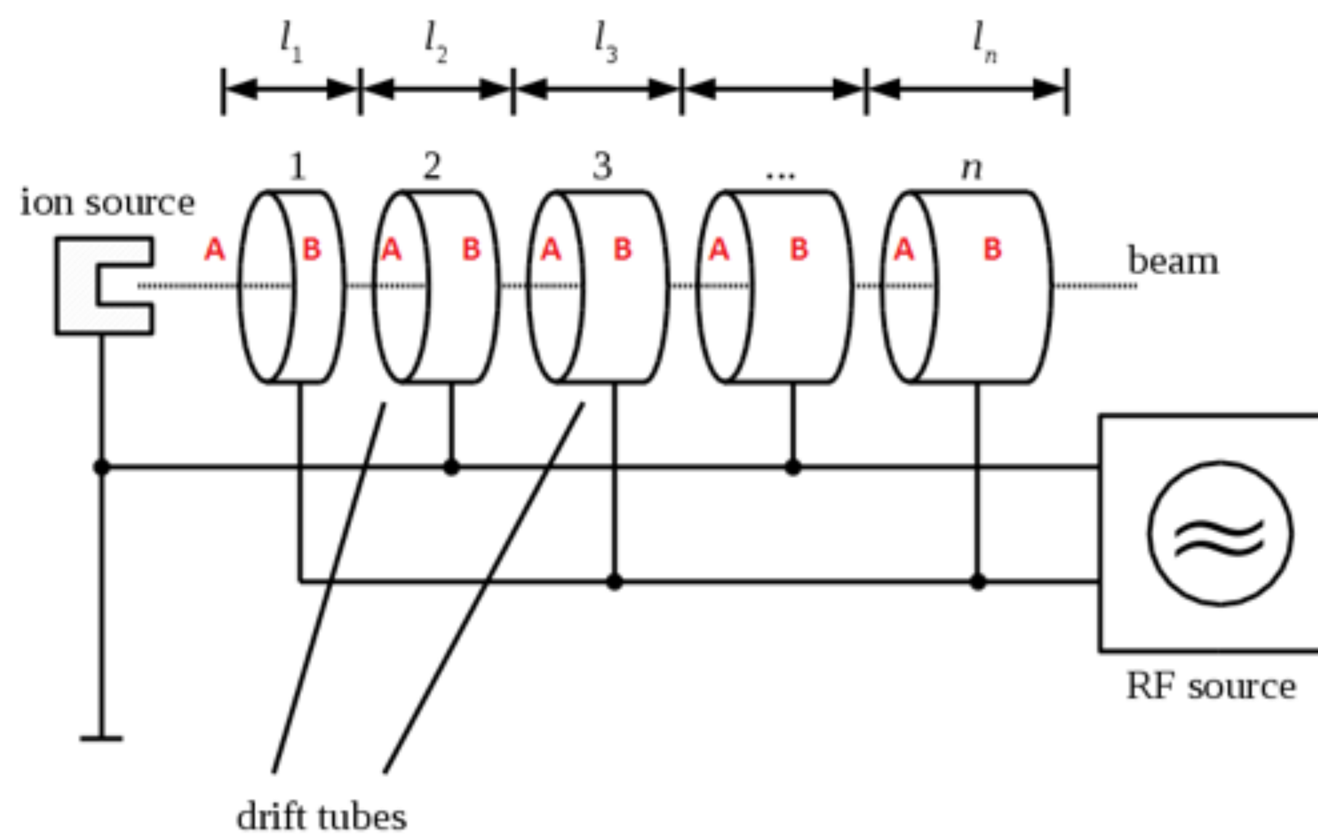
https://www.energy.gov/articles/how-particle-accelerators-work

example -1:
The Linear Accelerator (Linac)

Inventor:
Rolf Widerøe
1927

His professor refused any further work because it was "sure to fail."
Published his idea in Archivfur Electrotechnic.

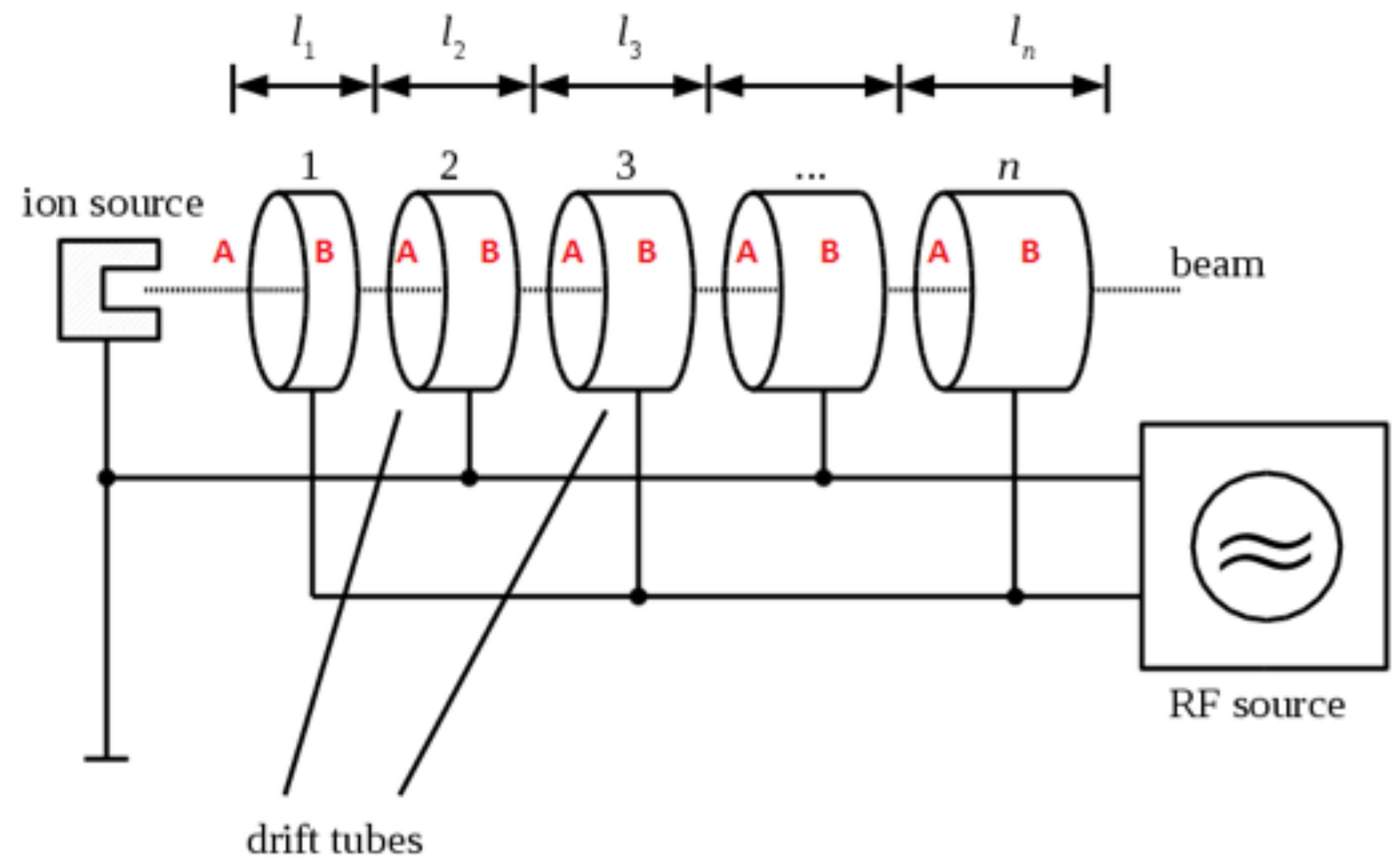
https://ec.europa.eu/programmes/erasmus-plus/project-result-content/ac05b07f-7433-4058-8317-47bf89e0104e/Particle%20Generators%20Accelerators.pdf



example -1:
The Linear Accelerator (Linac)

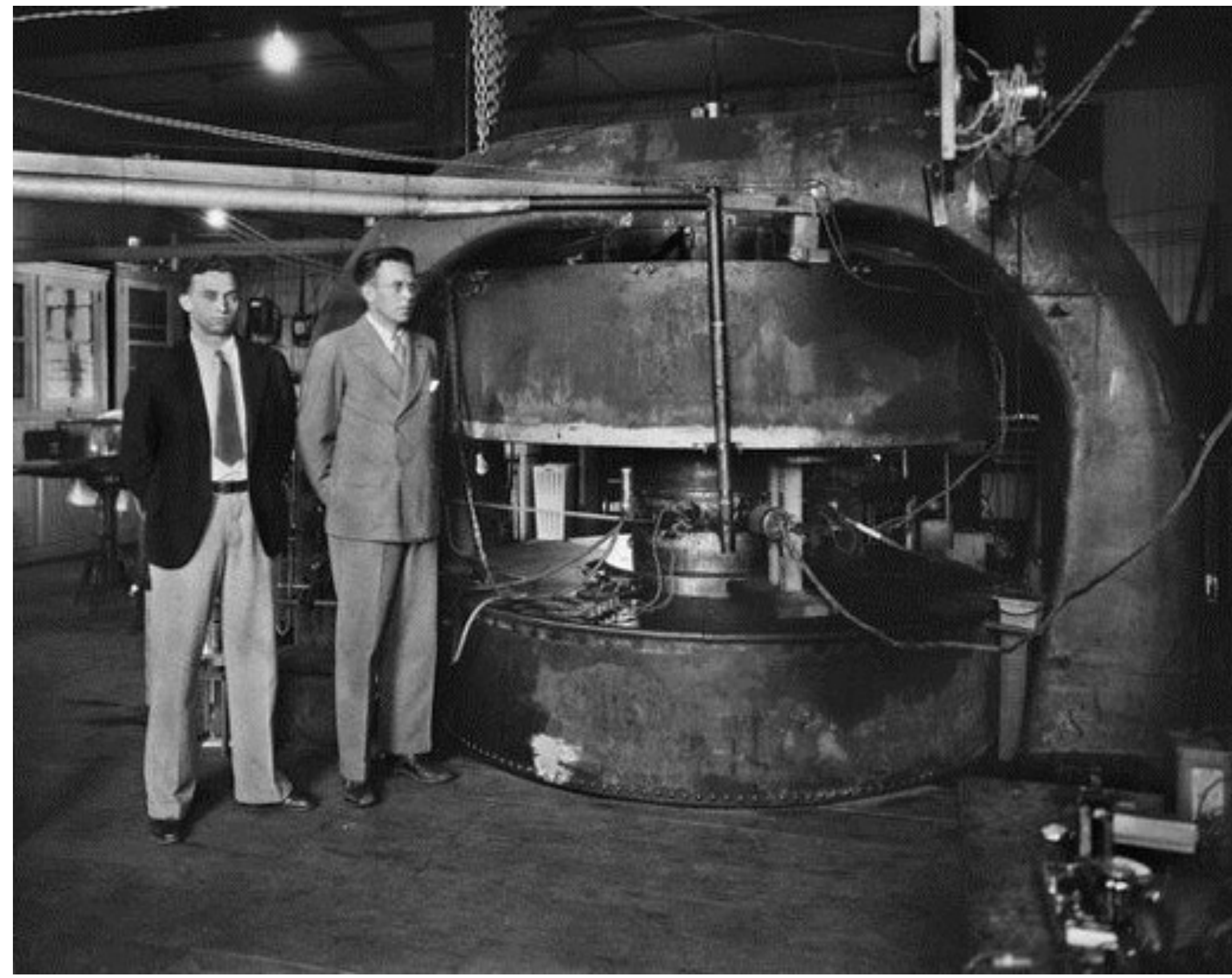
- In an AC, the flow of electric charge is periodically reversed, the flow of electric charge can be thought of as a series of peaks and anti-peaks of voltage.

- A charged particle acted on by an AC voltage would be accelerated from point X to point Y, during a peak, then when the current is reversed would be accelerated back from point Y to point X, during an anti-peak.



example -2: The Cyclotron

Inventor
Ernest Lawrence,
associate professor of physics
University of California,1928
1939,Nobel prize in physics

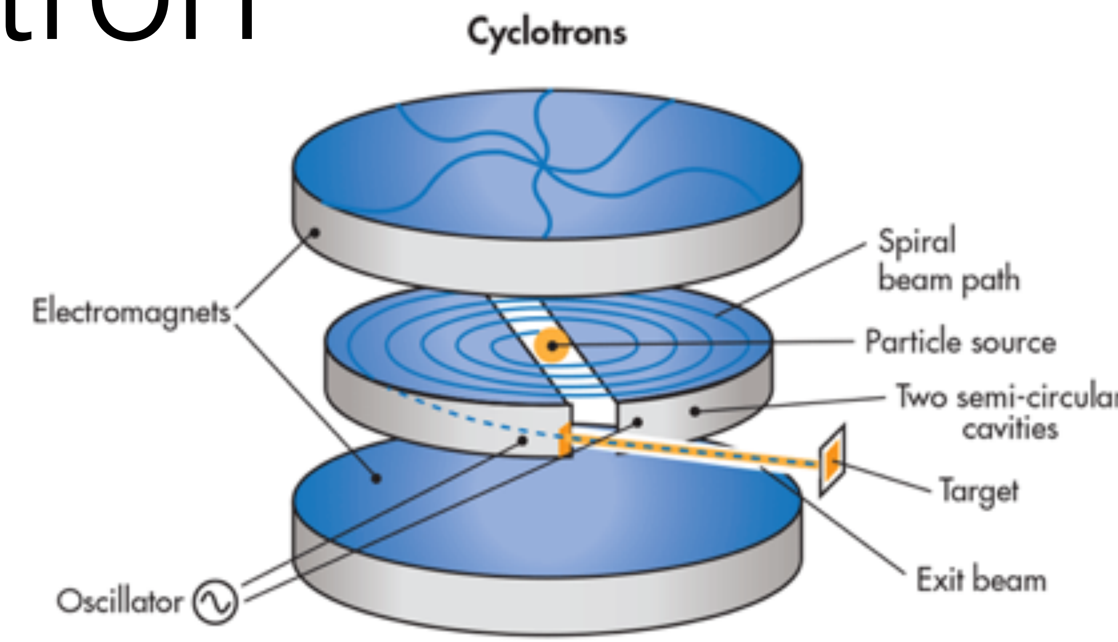


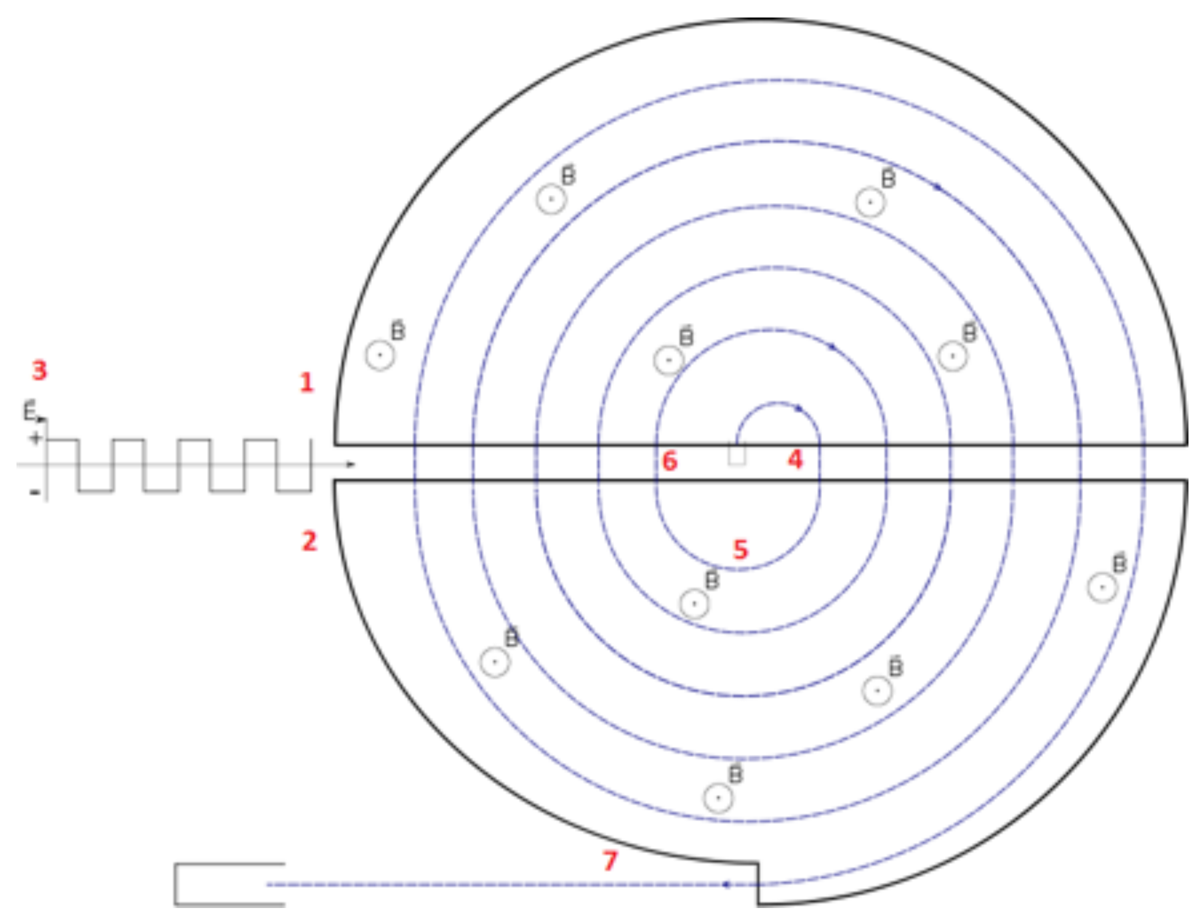
frequency of a charged particle, moving perpendicular to the direction of a uniform magnetic field B (constant magnitude and direction):

$$f = \frac{w}{2\pi} = \frac{qB}{2\pi m}$$

example -2: The Cyclotron

- (1 & 2) : two hollow D-shaped electrodes alternatively charged to a voltage by an (3) oscillator. The electrodes were separated by a small gap.
- When one of the electrodes is charged, a particle is accelerated across the gap into the other (4), under the influence of a magnetic field, it moves in a semi-circular path back to the surface of the electrode (5).
- Just as the voltage has charged the other electrode, the particle is again accelerated across the gap (6).
- As the speed of the particle increases, the radius of the semi-circular motion of the particle increases until the particles are eventually focused out of the Cyclotron as a high energy beam (7).



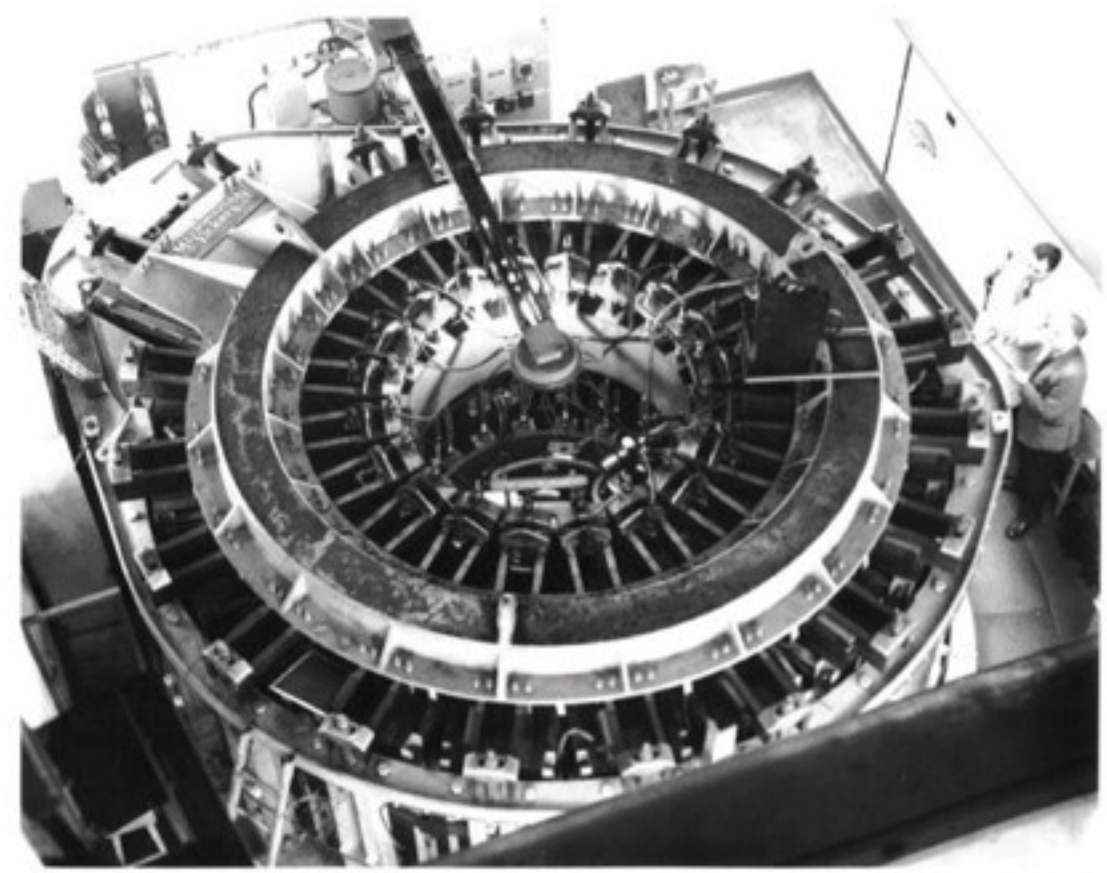


example -3: The Synchrotron

Inventor:
Frank Goward and D. Barnes.

- The basic principle of the Synchrotron is to maintain the accelerated particles at a constant orbital radius.

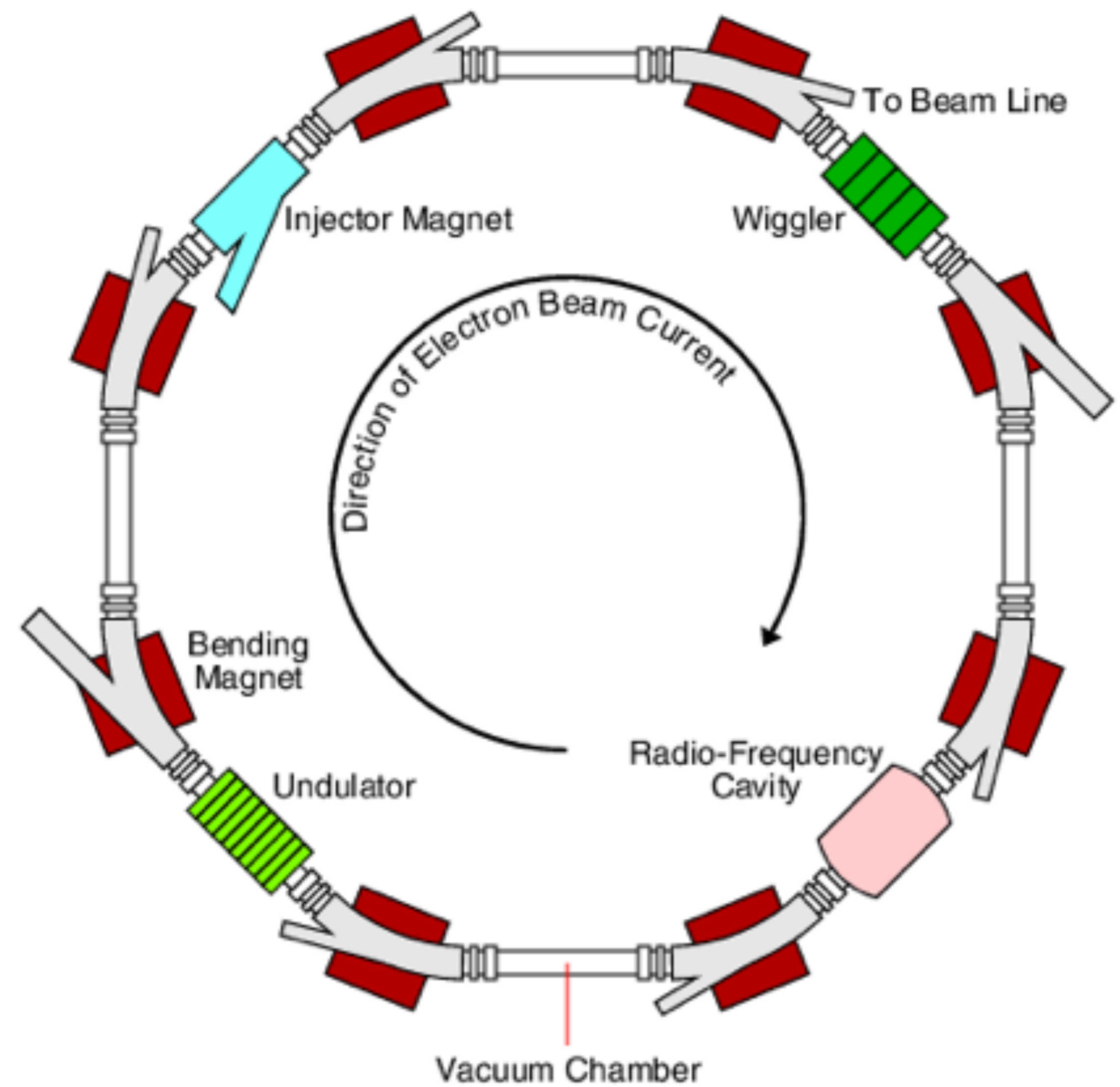
- This is achieved by synchronizing the magnetic field strength with the energy of the accelerated particles. So, as the particles are accelerated and gain energy, the magnetic field is increased, keeping the particles orbit constant.



example -3:
The Synchrotron

synchrotron's loop is not a spiral.
In fact, since the various tasks a synchrotron must accomplish :

focusing, bending, and accelerating the particles into a beam inside a vacuum pipe -
can be accomplished by different assemblies and at different times, the path can be a circle, oval or a polygon with rounded corners.



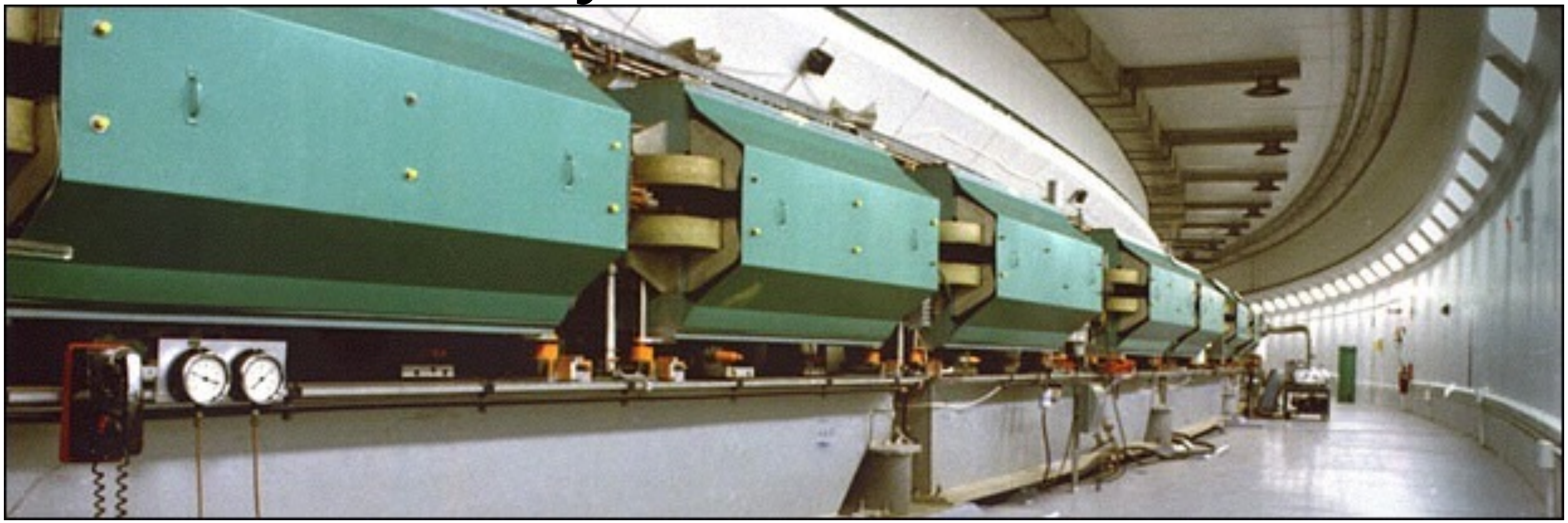
https://users.aber.ac.uk/ruw/teach/334/ring.gif

Super proton synchrotron

John Adams,
1976
director-general,Laboratory II.

- ☑ It takes particles from the Proton Synchrotron and accelerates them to provide beams for other experiments (LHC/ NA61/SHINE/NA62)
- ☑ operates at up to 450 GeV
- ☑ handle many different kinds of particles: sulphur and oxygen nuclei, electrons, positrons, protons and antiprotons.

Alternating gradient synchrotron



https://www.bnl.gov/rhic/AGS.asp

- ☑ AGS name is derived from the concept of alternating gradient focusing
- ☑ field gradients of the accelerator's 240 magnets are successively alternated inward and outward, permitting particles to be focused in both the horizontal and vertical plane at the same time
- ☑ AGS receives protons and other ions from the AGS Booster and delivers them to the Relativistic Heavy Ion Collider after acceleration.

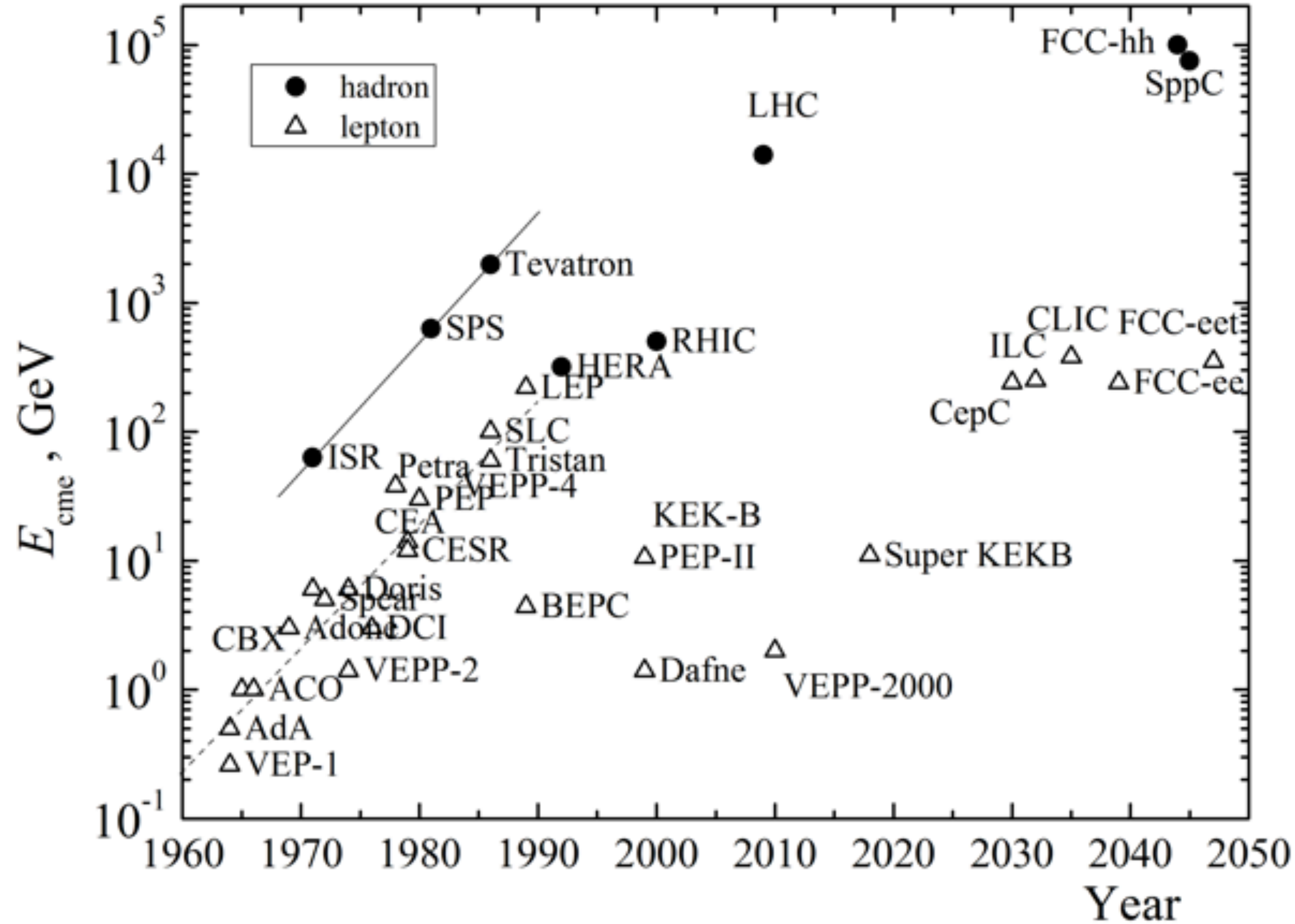
Limitations of oscillating field particle accelerator

- ☑ The more energy the particles have, the more powerful the magnetic fields have to be to keep them in their circular orbit.

- ☑ a particle traveling in a circle is always accelerating towards the center of the circle, it continuously radiates towards the tangent of the circle. This radiation is called synchrotron radiation.

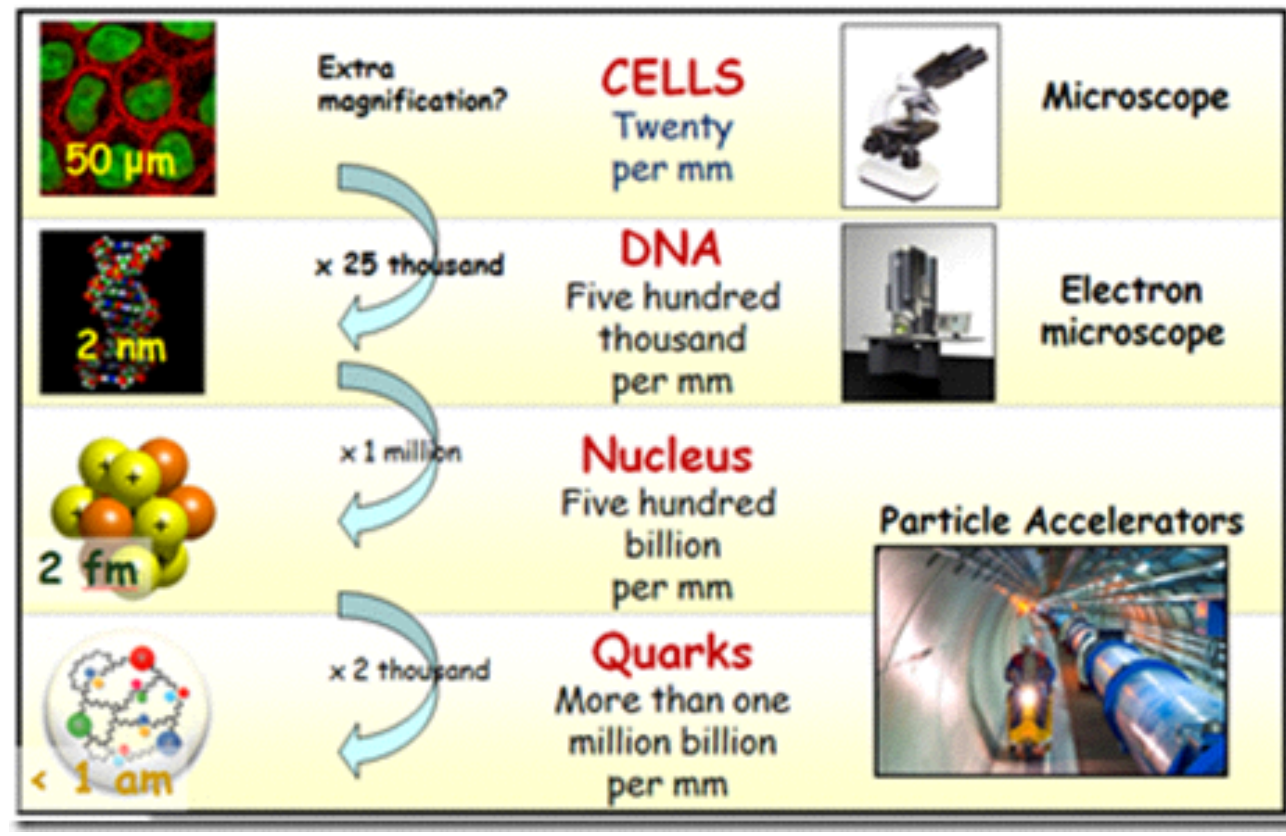
Particle Collider

Colliders are a type of particle accelerators that generate head-on collisions between particles.



To probe into small distance, you need large energy !

Louis de Broglie
PhD thesis, 1924
https://tel.archives-ouvertes.fr/tel-00006807/document
Nobel Prize for Physics in 1929



$$\lambda = h/p$$

$$or \lambda/2\pi = \hbar c/pc$$

$$or \lambda/2\pi = 197 MeV\, fm/p[MeV/c]$$

eg.
20 GeV/c => probes a distance of 0.01 fm
at 1 TeV (the average collision energy of a quark–quark interaction) we can resolve 10–18 m, scale

charge radius of a proton: 0.84–0.87 fm (or 0.84 to 0.87×10^{-15} m).
quarks are at the level of 5×10^{-20} m.

Large energy:
Fixed target or collider ?

For two particle system:

$$m_0^2 = (E_1 + E_2)^2 - [\overrightarrow{p_1} + \overrightarrow{p_2}]^2$$

Let's say particle 1 is at rest, so E_1 is rest mass energy m_1c^2 and p_1 is 0; while particle 2 is moving with energy E_2 and momentum $\overrightarrow{p_2}$.

$$\begin{aligned} s &= \left(m_1c^2 + E_2\right)^2 - (0 + \overrightarrow{p_2})^2 \\ &= m_1^2c^4 + E_2^2 + 2m_1c^2E_2 - \overrightarrow{p_2}^2 \\ &= m_1^2c^4 + 2m_1c^2E_2 + m_2^2c^4 \ [\because E_2^2 - \overrightarrow{p_2}^2 = m_2^2c^4] \end{aligned}$$

For $E >> m^2$ and $m_1 = m_2$;

$$\sqrt{s} = \sqrt{2mc^2E^2}$$

e.g.
for E=100 GeV protons
hitting stationary protons
mc^2 ~1 GeV;
E_{FXT} ~ 14 GeV energy.

For many decades, the only arrangement of accelerator experiments was a fixed target setup where a beam of particles accelerated with a particle accelerator hit a stationary target set into the path of the beam

Large energy:
Fixed target or collider ?

In the centre-of-mass frame:

$$
\begin{aligned}
s &= (E_1 + E_2)^2 - (\overrightarrow{p_1} + \overrightarrow{p_2})^2 \\
&= E_1^2 + E_2^2 + 2E_1E_2 - \left(\overrightarrow{p_1}^2 + \overrightarrow{p_2}^2 + 2\overrightarrow{p_1}\overrightarrow{p_2}cos(\theta)\right) \\
&= \left(E_1^2 - \overrightarrow{p_1}^2\right) + \left(E_2^2 - \overrightarrow{p_2}^2\right) + 2E_1E_2 + 2\overrightarrow{p_1}\overrightarrow{p_2} \; [\because \theta = 180] \\
&= \left(m_1^2 + m_2^2\right)c^4 + 2E_1E_2 + 2\sqrt{E_1^2 - m_1^2c^4}\sqrt{E_2^2 - m_2^2c^4}
\end{aligned}
$$

For $E >> m^2$ and $E_1 = E_2$;

$$\sqrt{s} = 2E$$

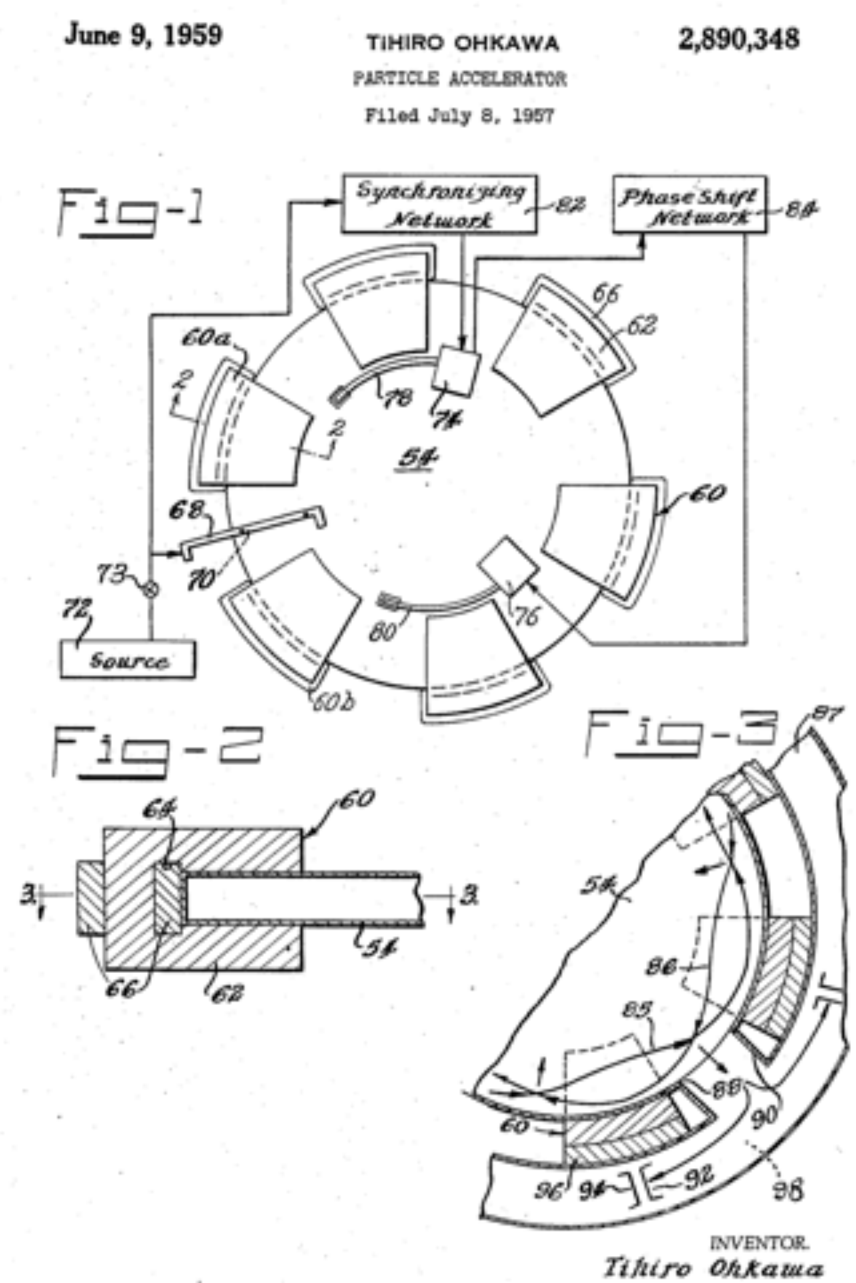
e.g.
for E=100 GeV protons
hitting another proton with
E=100 GeV;
Ecoll ~200 GeV

Such an obvious advantage led to the first practical proposals of colliding-beam storage rings in the late 1950's

Fixed-Field alternating gradient Accelerator (FFA)

Inventor
Tihiro Ohkawa
MURA,1961

- ☑ time-independent magnetic fields (fixed-field, like in a cyclotron) and the use of strong focusing (alternating gradient, like in a synchrotron).
- ☑ could accelerate two counterrotating particle beams within a single ring of magnets
- ☑ third FFAG prototype built by the MURA group was a 50 MeV electron machine



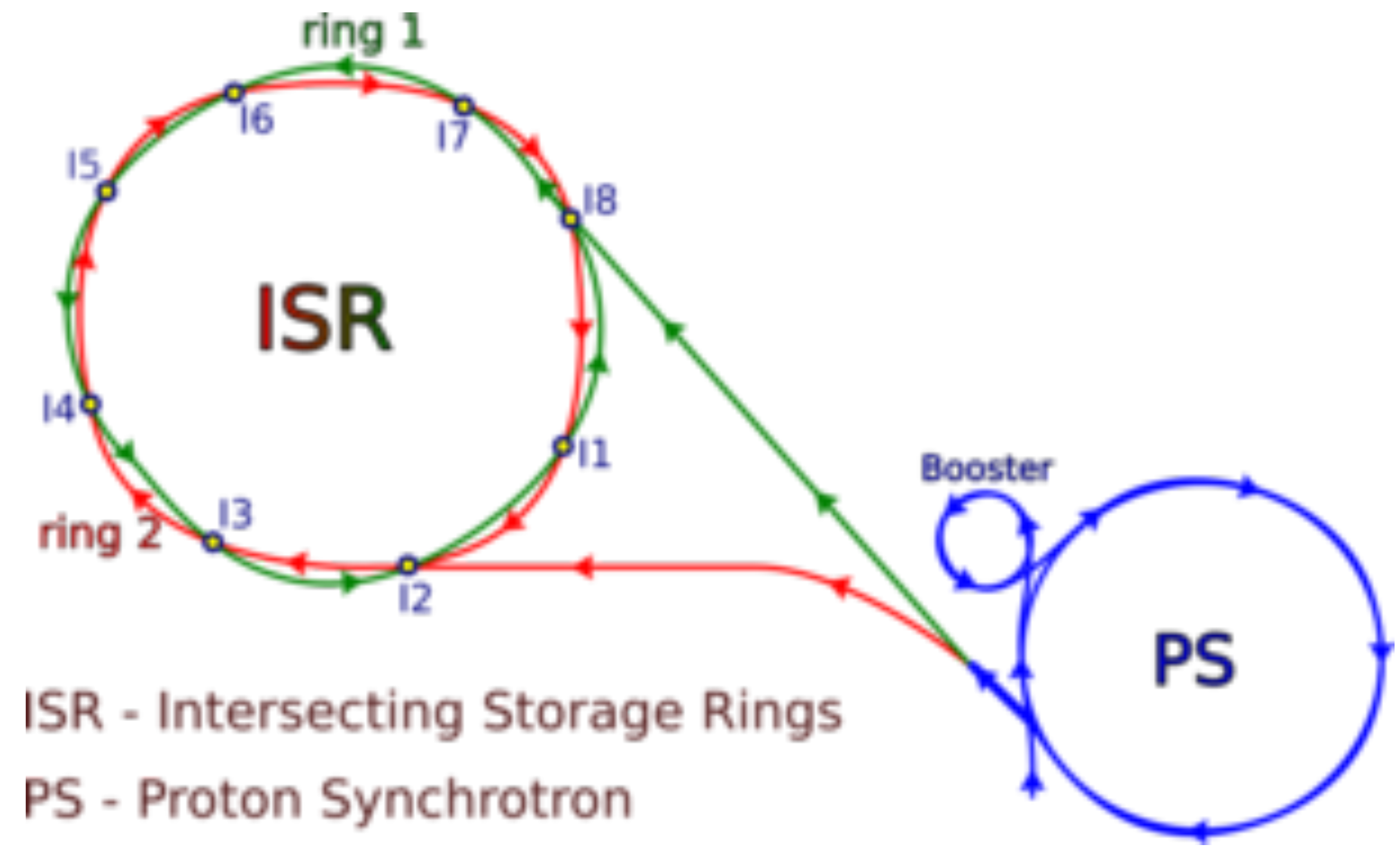
https://patents.google.com/patent/US2890348

Storage Ring Colliders

Inventor
Gerard K. O'Neill,
faculty, Princeton
1956

A storage ring is a type of synchrotron.

- ☑ a conventional synchrotron serves to accelerate particles from a low to a high energy state with the aid of radio-frequency accelerating cavities,
- ☑ a storage ring keeps particles stored at a constant energy and radio-frequency cavities are only used to replace energy lost through synchrotron radiation and other processes.

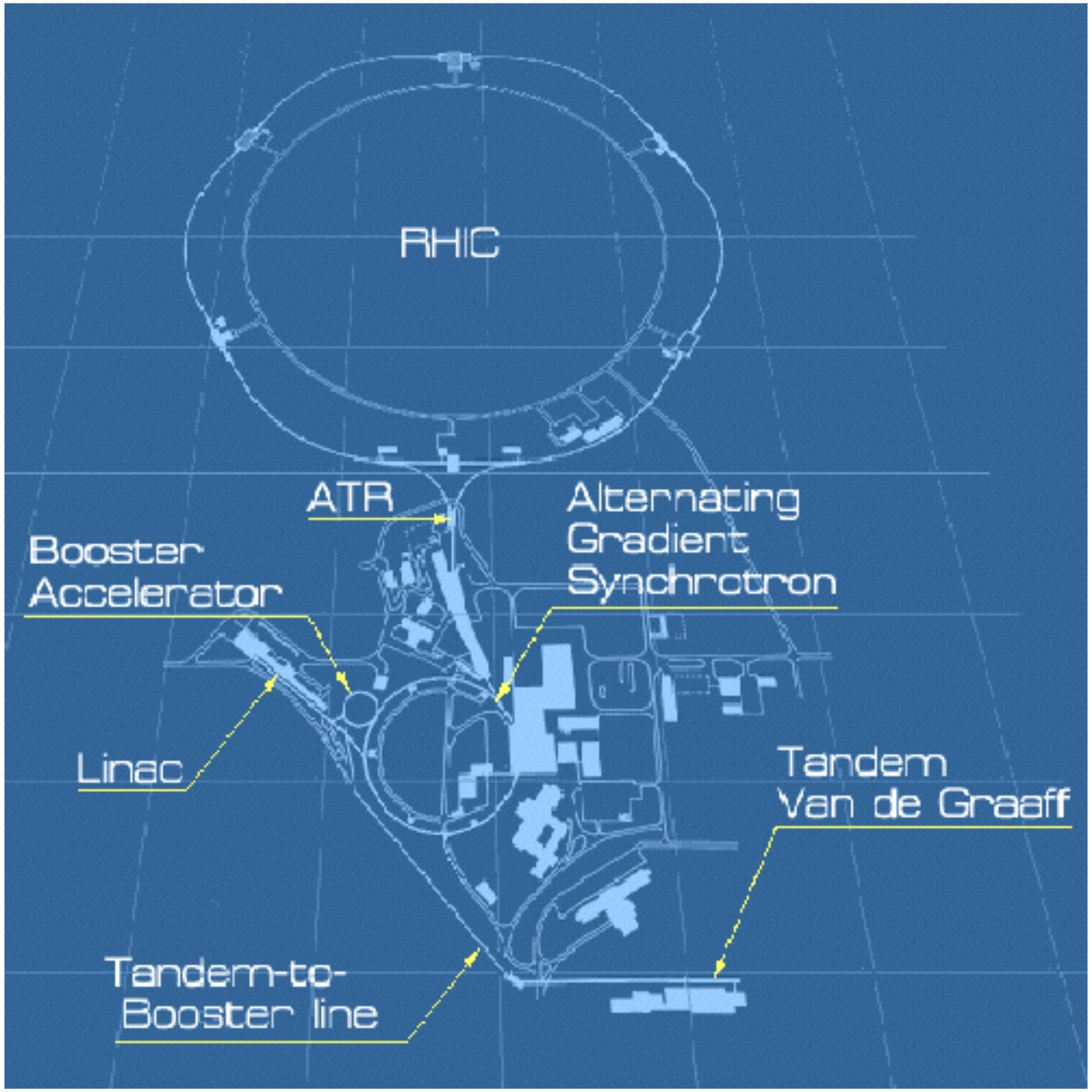


e.g.
LHC, LEP, PEP-II, KEKB, RHIC, Tevatron and HERA.

eg-1:
Relativistic Heavy Ion Collider

Conceptualize:
1983, NSAC meeting
First collision:
2000

- ☑ first heavy-ion colliders
- ☑ only spin-polarized proton collider
- ☑ STAR (one of expt.) is composed of 68 institutions from 14 countries, with a total of 742 collaborators
- ☑ superconducting magnets down to the operating temperature of -268.6°C (4.5K)



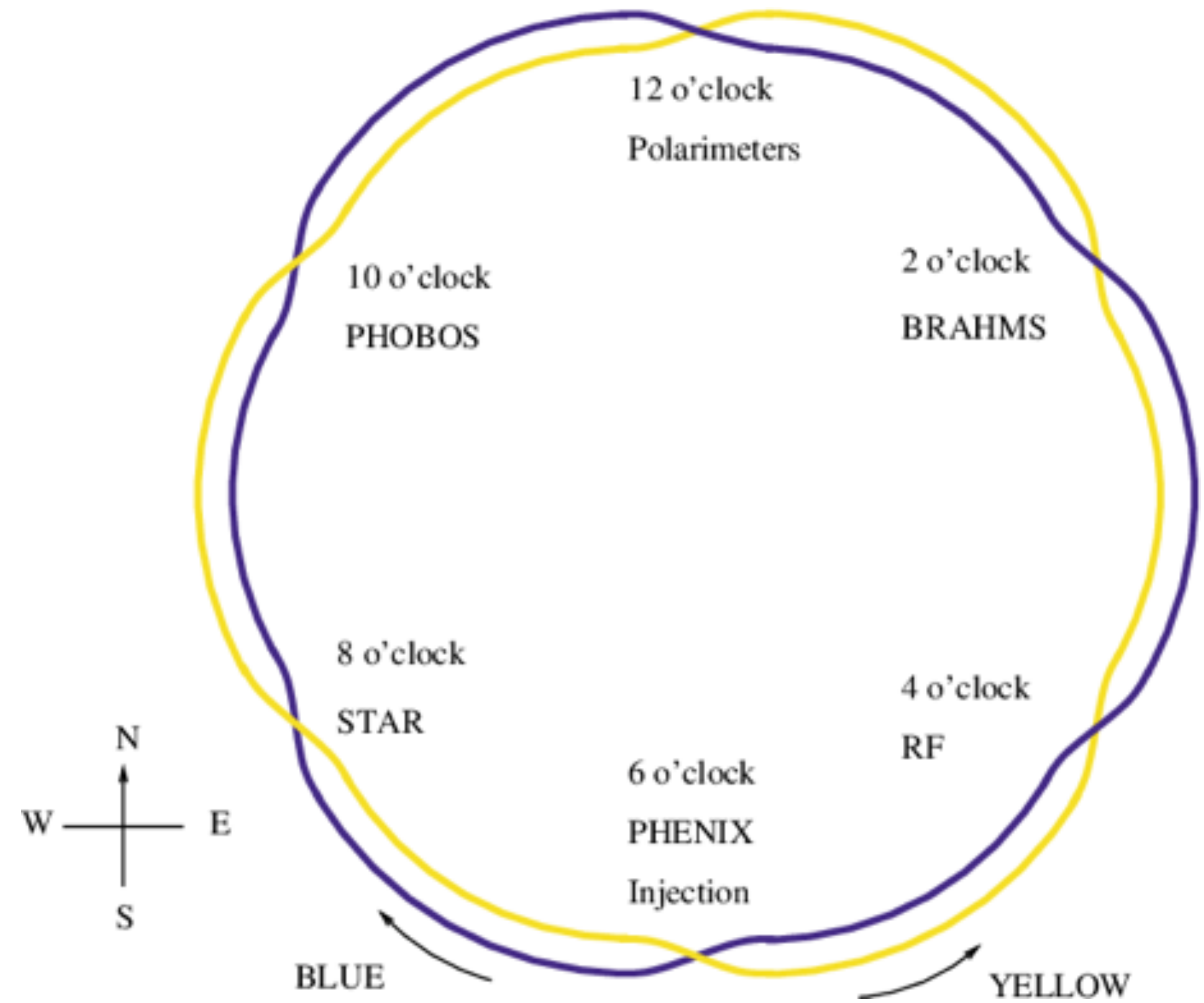
http://www.bnl.gov/RHIC/images/RHIC-complex-w2.gif

eg-1: Relativistic Heavy Ion Collider

Accelerator name	Incoming P speed	Outgoing P speed
OPPIS		750KeV
Linac	750KeV	200MeV
Booster	200MeV	2.35GeV
AGS	2.35	24.3GeV
RHIC Ring	24.3GeV	

Accelerator name	Incoming Ion		Outgoing Ion	
	charge	speed	charge	speed
EBIS			+32	2MeV
Booster Synchrotron	+32	2MeV	+77	100MeV
AGS	+77	100MeV	+79	8.86GeV
RHIC storage ring	+79	8.86GeV		

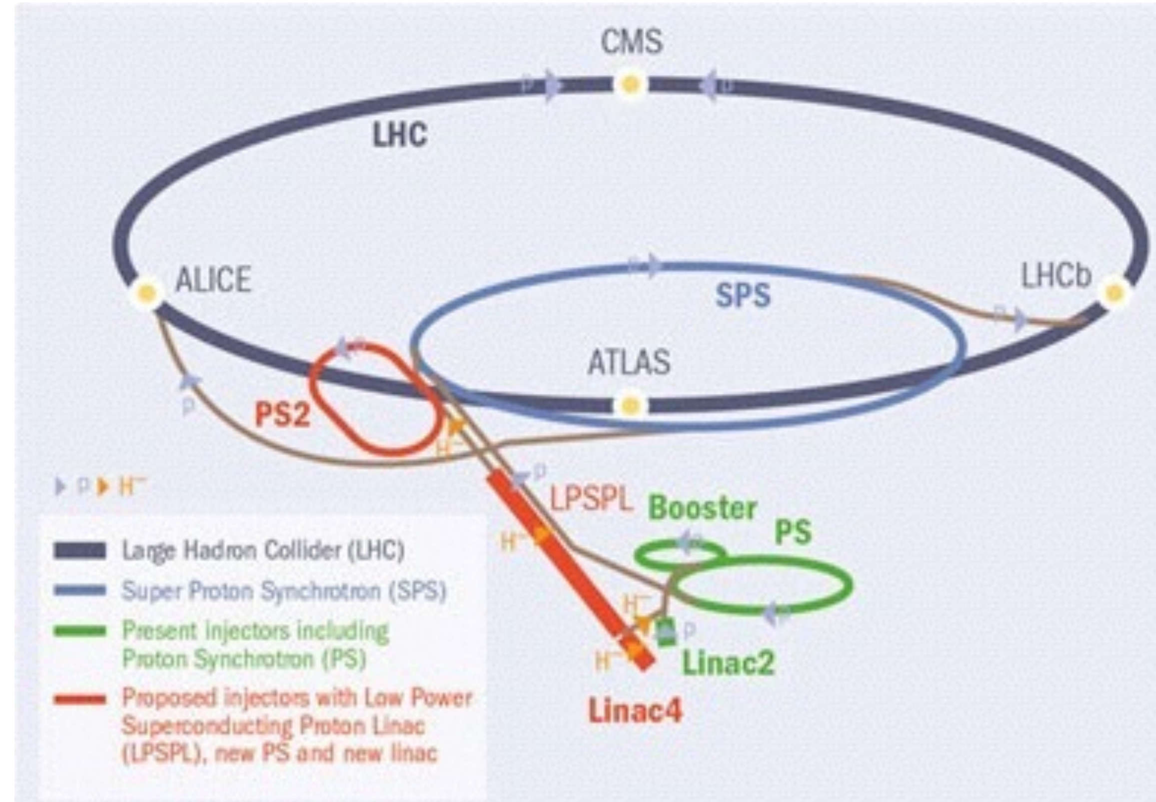
☑ double storage ring, hexagonally shaped and has a circumference of 3834 m,

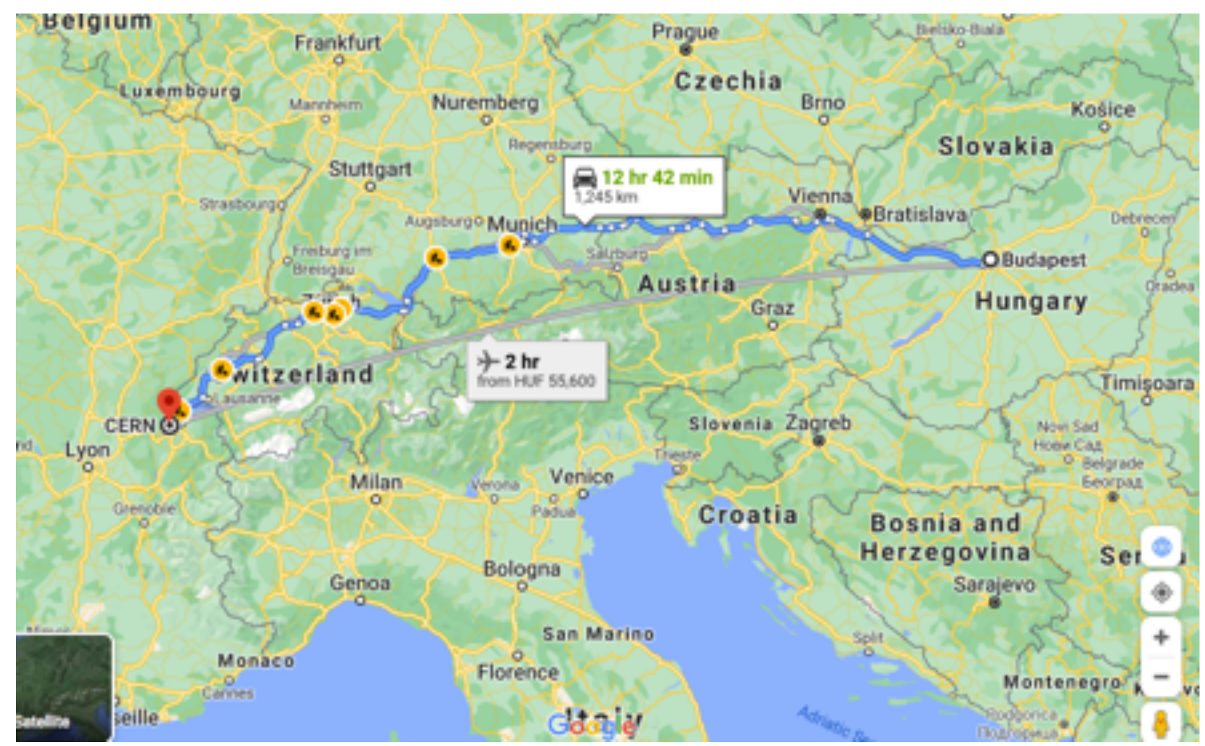


eg-2:
Large Hadron Collider

Conceptualize:
1983
First collision:
2010

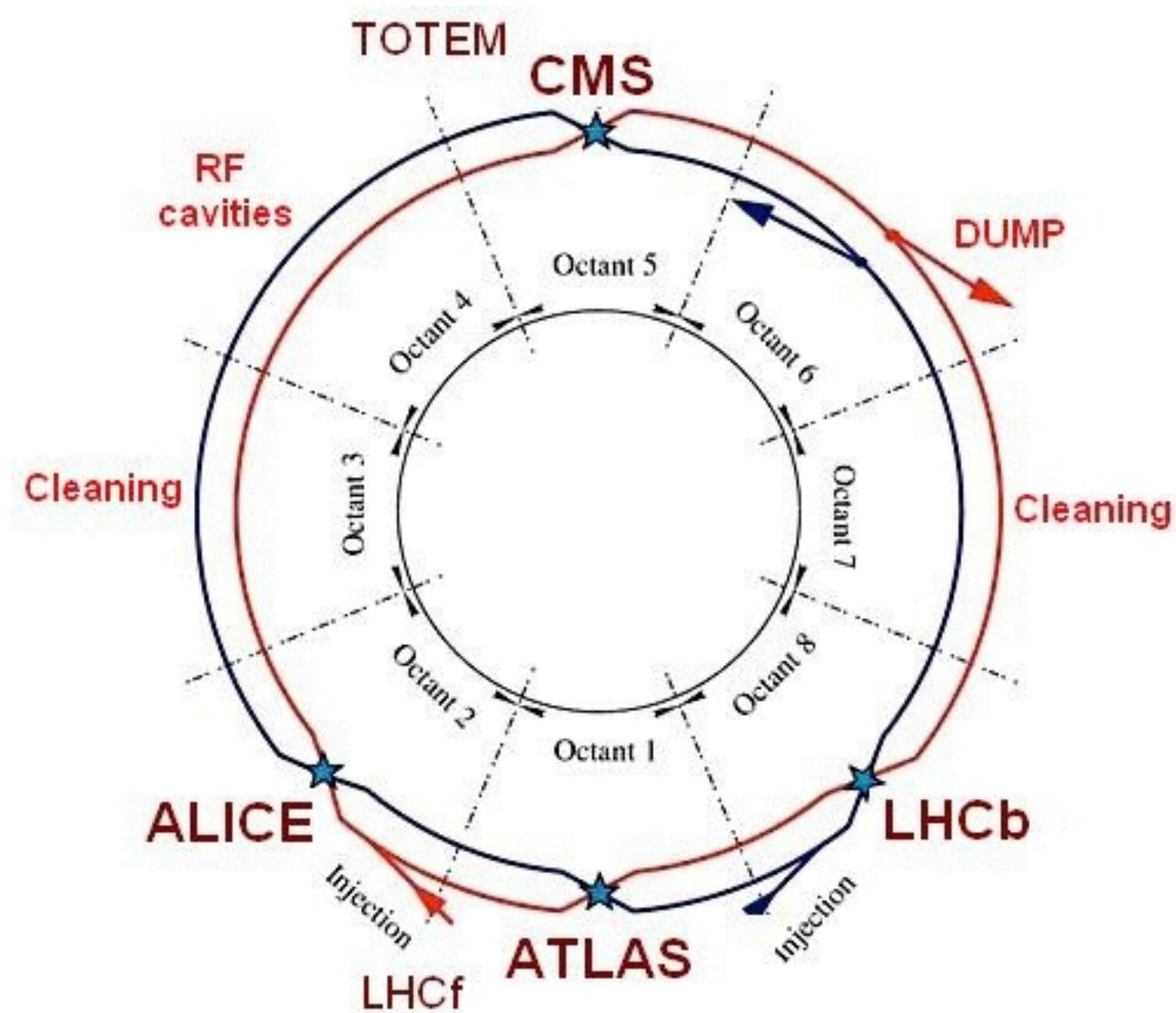
- ☑ world's largest and highest-energy particle collider
- ☑ 10,000 scientists and hundreds of universities and laboratories, as well as more than 100 countries.
- ☑ The electromagnets in the LHC are chilled to -271.3°C (1.9K)
- ☑ Number of collisions per second ~1 billion





eg-2:
Large Hadron Collider

- ☑ approximately 27km (26 659 m) in circumference
- ☑ not a perfect circle,eight 2.45-km-long arcs, and eight 545-m-long straight sections



https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lhc_layout

Particle detector

A particle detector, also known as
a radiation detector,
is a device used to detect, track,
and/or identify ionizing particles.

Detectors
based on Image analysis

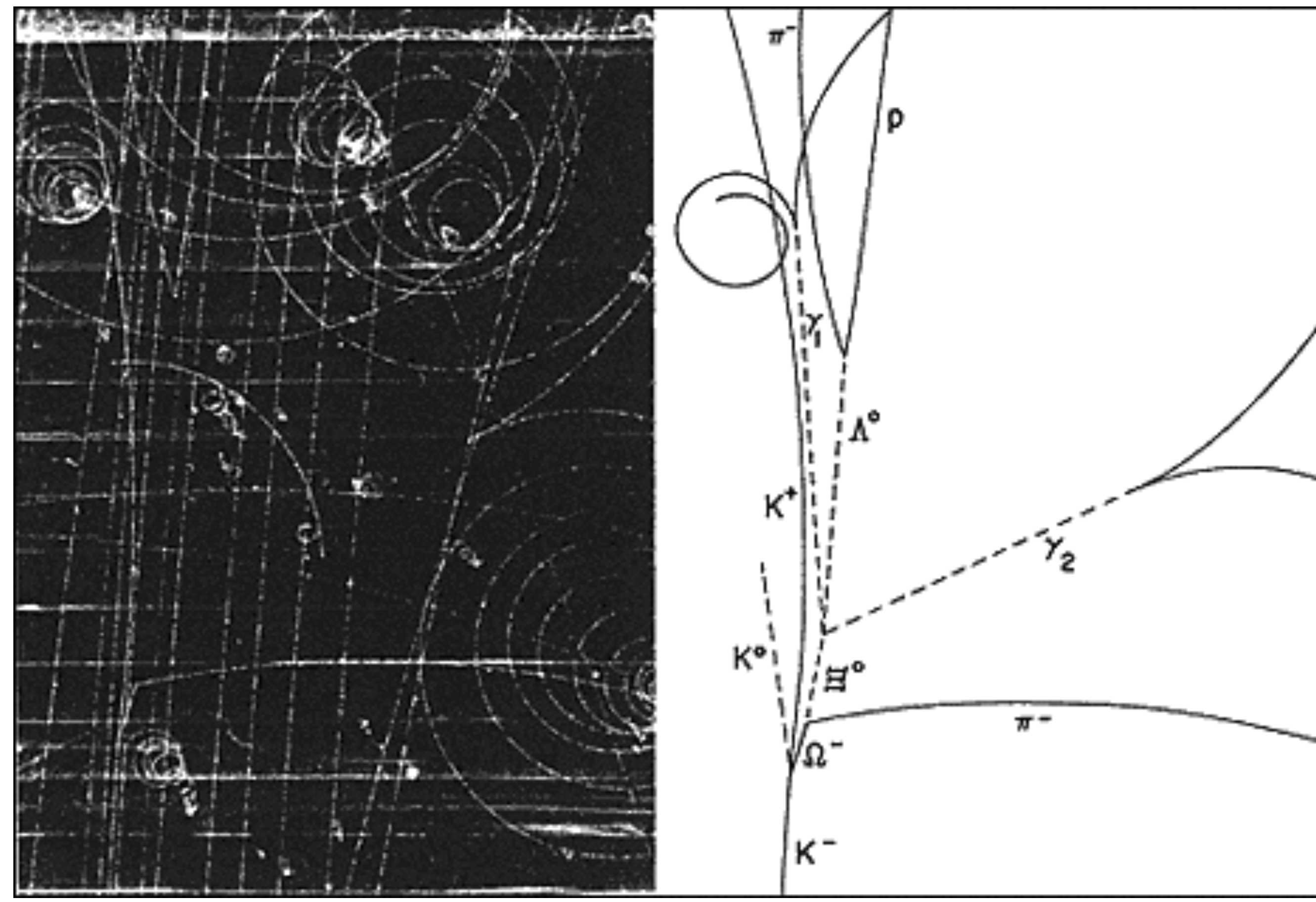
- Cloud chambers:

supersaturated gas, condensation, tracks visible

- Bubble chambers:

overheated fluid, bubble creation image reveals particle tracks

- Nuclear emulsions



http://www.hep.fsu.edu/~wahl/satmorn/history/Omega-minus.asp.htm

Discoveries from these detectors:

7 Cloud Chamber:

e^+
μ^+, μ^-
K^0
Λ^0
Ξ^-
Σ^-

6 Nuclear Emulsion:

π^+, π^-
anti-Λ^0
Σ^+
K^+, K^-

2 Bubble Chamber:

Ξ^0
Σ^0

3 with Electronic techniques:

anti-n
anti-p
π^0

eg-1:
Cloud chambers

inventor
Charles Thomson Rees Wilson
1911
Scottish physicist

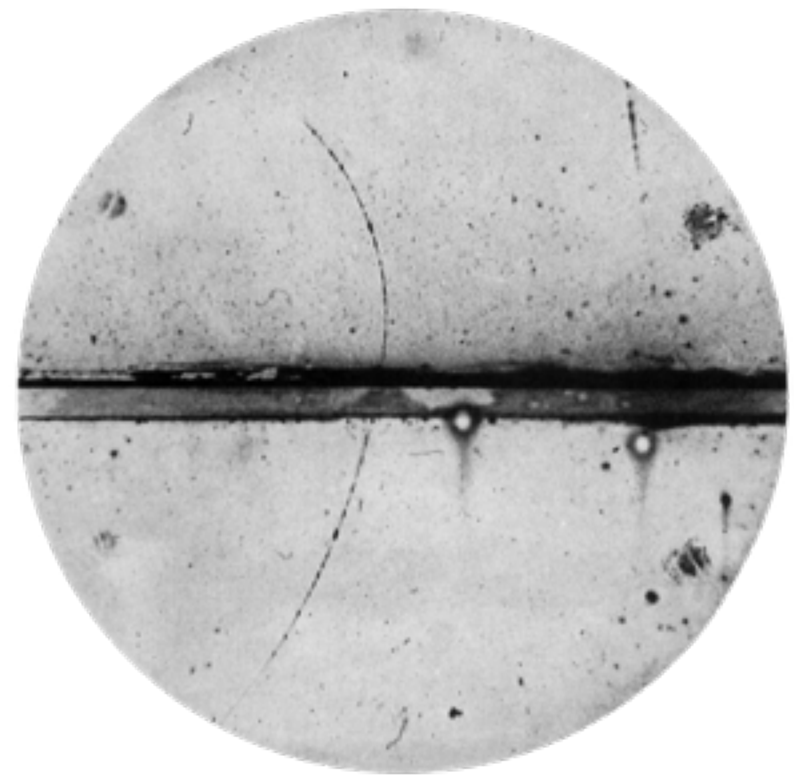
- ☑ A cloud chamber consists of a sealed environment containing a supersaturated vapor of water or alcohol.
- ☑ A charged particle interacts with the gaseous mixture by knocking electrons off gas molecules via electrostatic forces during collisions, resulting in a trail of ionized gas particles.

https://www.researchgate.net/figure/Wilson-Cloud-Chamber_fig2_317060457

eg-1: Cloud chambers

- resulting ions act as condensation centers around which a mist-like trail of small droplets form if the gas mixture is at the point of condensation.

- These droplets are visible as a "cloud" track that persists for several seconds while the droplets fall through the vapor



existence of the positron. Observed by C. Anderson

Issues

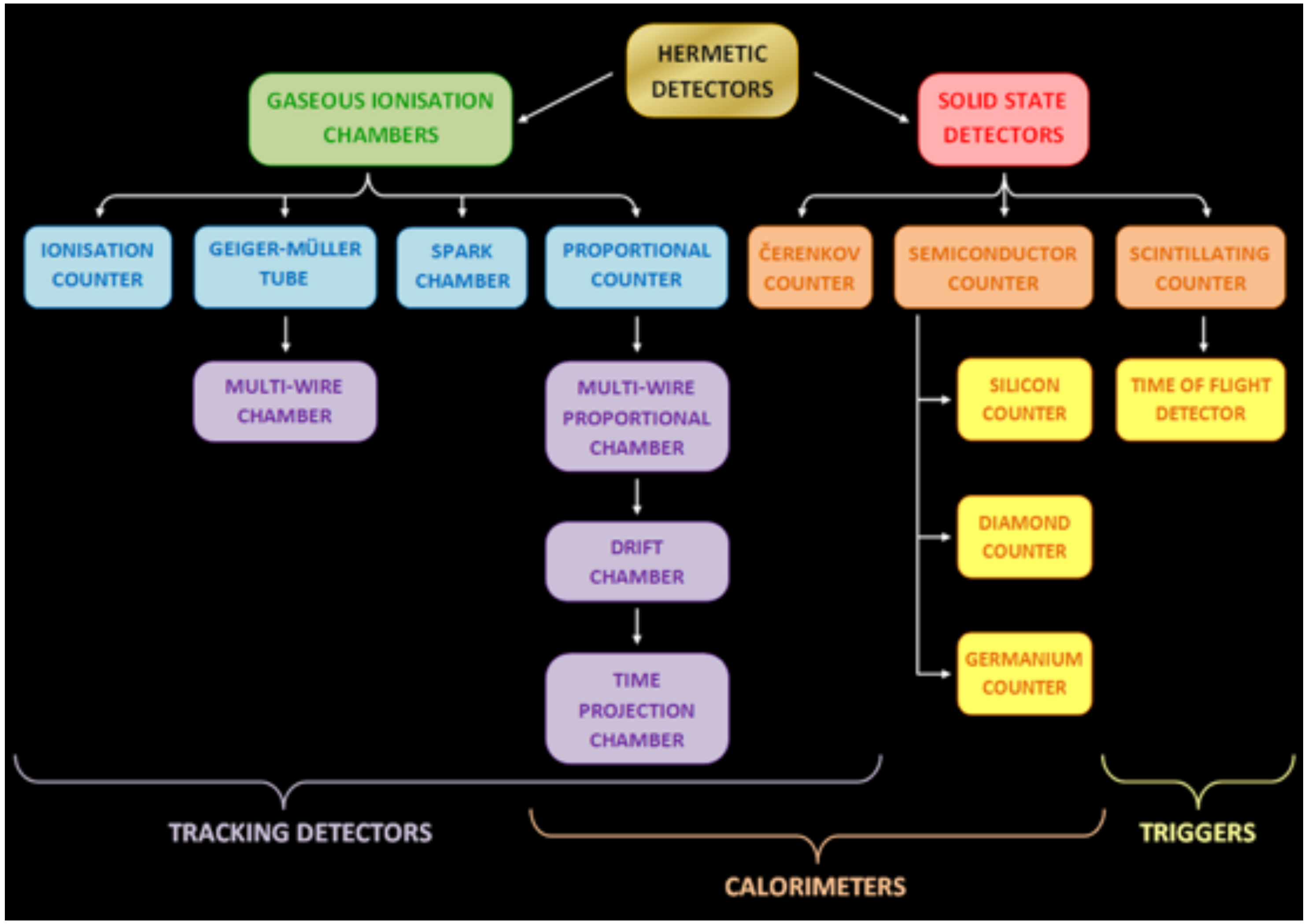
- ☑ Bubble chambers position resolution ~5um
- ☑ low rate capability ~ few tens / second
- ☑ Imaging detectors can not be triggered selectively, every event must be photographed and anslyszed.

Detectors
based on electronic signals:

- Based on the principle to transfer radiation energy to detector mass.

- Charged particles are transferring their energy through collisions to atomic electrons leading to excitation and ionisation.

- In most cases, neutral particles have to produce charged particles first inside the detector volume which in turn are transferring their energy by excitation or ionisation to the detector.

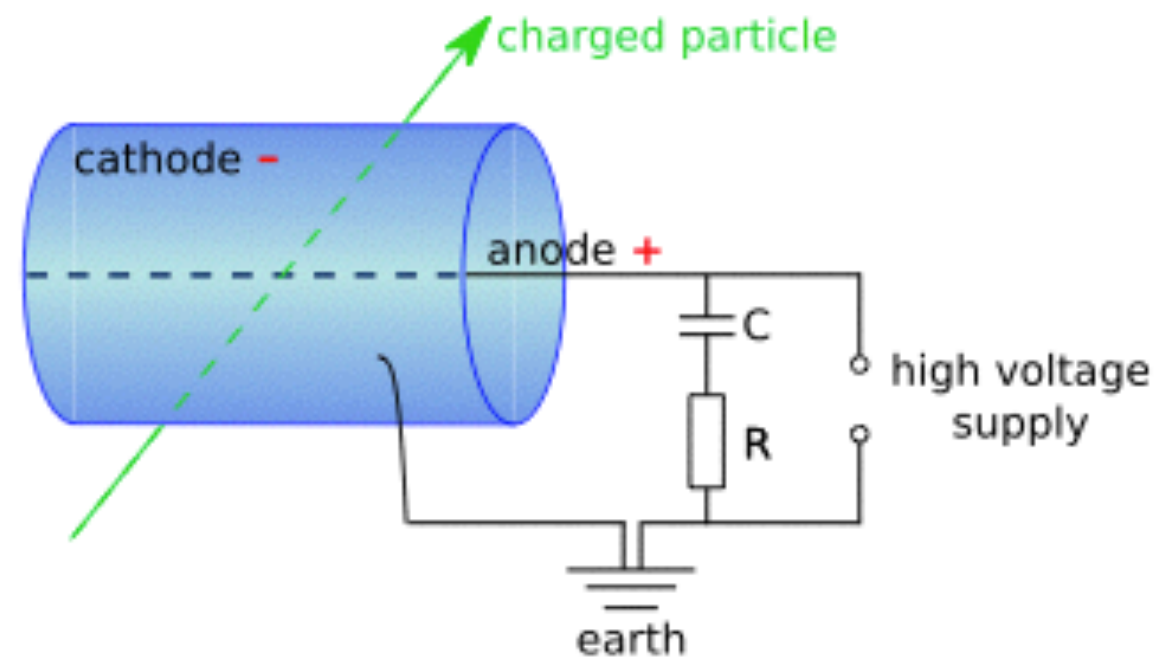


Gaseous ionisation detectors: Principle of operation

A voltage is applied to the

central anode (positive) and the chamber walls / cathode (negative)

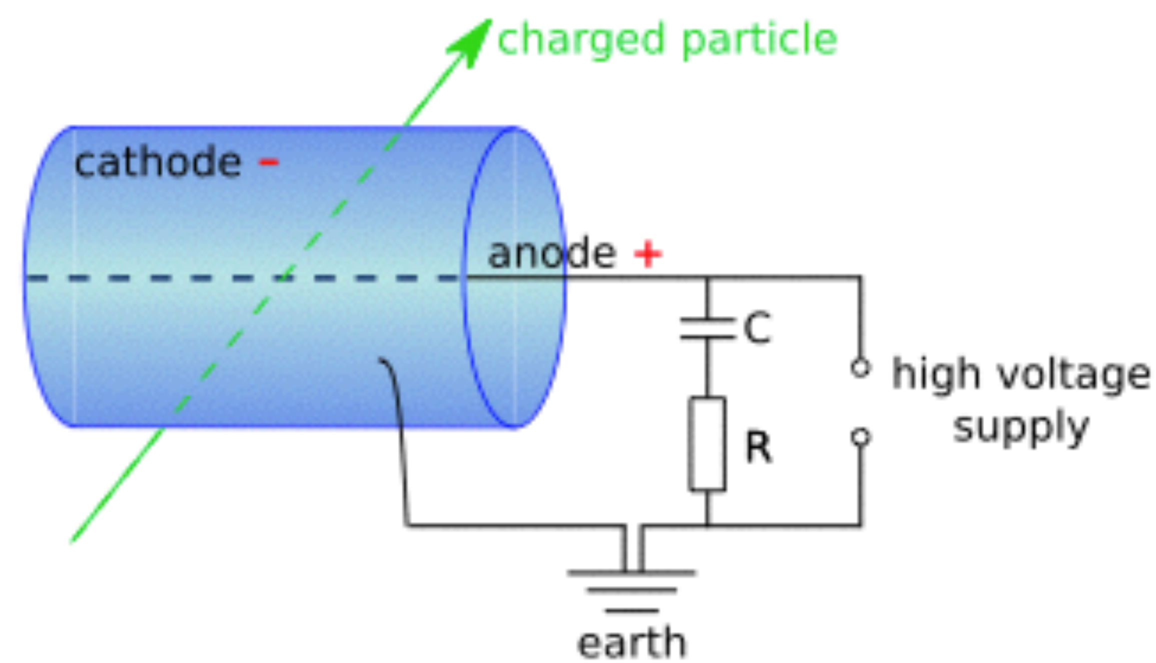
to create an electric field between them.



Pulse height = A *n *e/C
where A = gas amplification factor
n = number of ionizing events
e = charge of electrons
C =Capacitance of capacitor

Gaseous ionisation detectors: Principle of operation

- charged particle passing through the chamber, ionises the gas molecules inside, along the path it takes, creating negative electrons (anions) and positive ions (cations).
- collection of these charged particles reduces the voltage across the capacitor - this in turn increases the voltage across the resistor.
- This 'pulse' across the resistor is recorded electronically, registering a hit.



Pulse height = A *n *e/C
where A = gas amplification factor
n = number of ionizing events
e = charge of electrons
C =Capacitance of capacitor

Gaseous ionisation detectors: Applied detector voltage

- ☑ Ionization region: operate at a low electric field strength, selected such that no gas multiplication takes place.

- ☑ Proportional region: operate at slightly higher voltage, selected such that discrete avalanches are generated.

- ☑ Geiger-Müller region: operates at higher voltage, selected such that each ion pair creates an avalanche

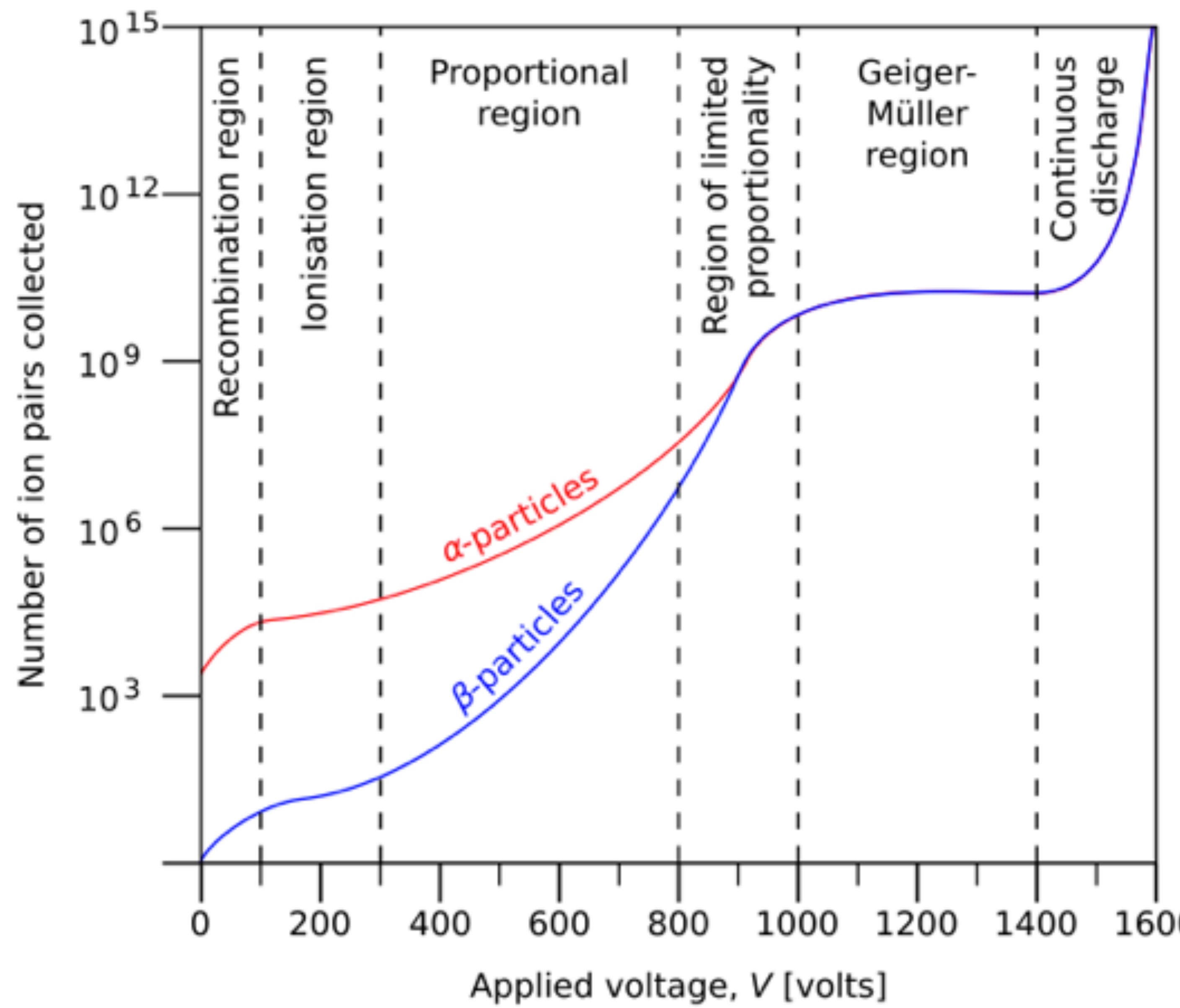


Figure 3: Number of ion pairs collected versus applied voltage in a gaseous ionisation chamber.

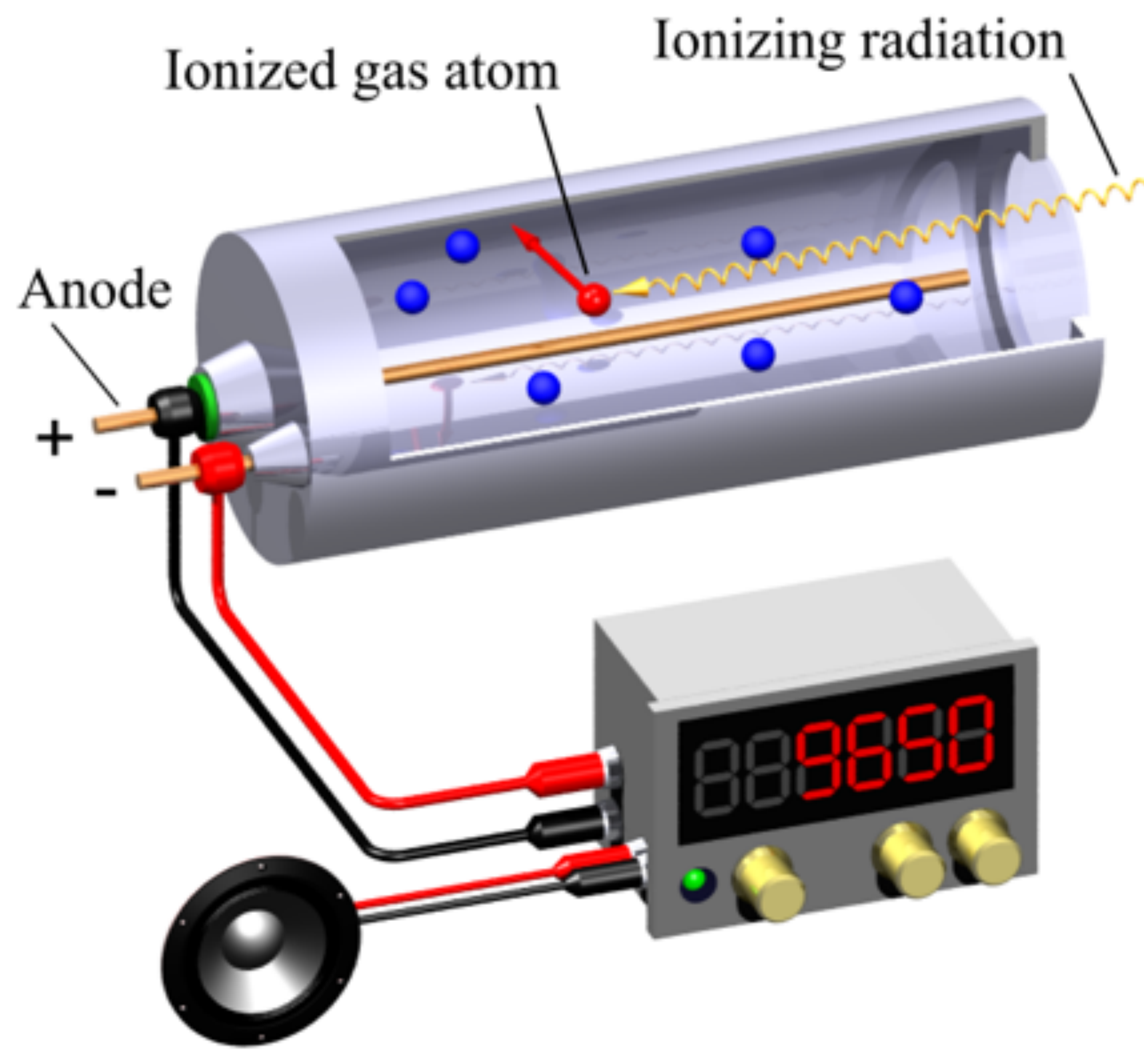
eg-1: Geiger-Muller tubes

Inventor
Hans Geiger,
Walther Müller,
University of Kiel,1928

- ☑ For any given detector working in the Geiger-Muller region, all particles have the same Geiger plateau.
- ☑ Therefore the same number of ions are collected irrespective of the charged particle passing through the tube.

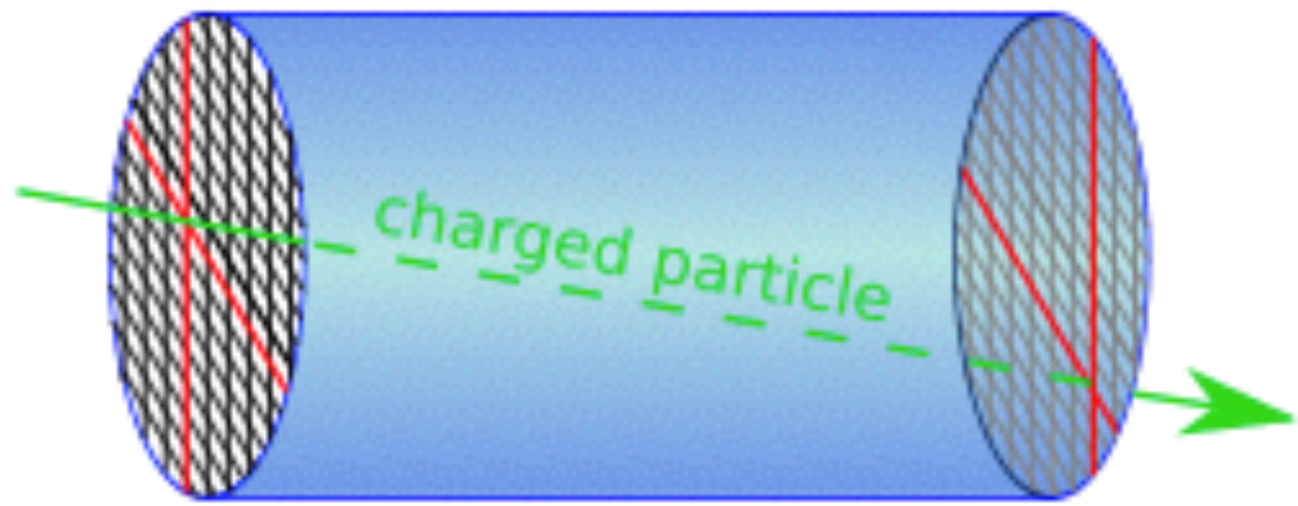
=> means the voltage pulse is the same height for all particles

=> making particle identification impossible.



eg-2:
Time projection chambers (TPCs)

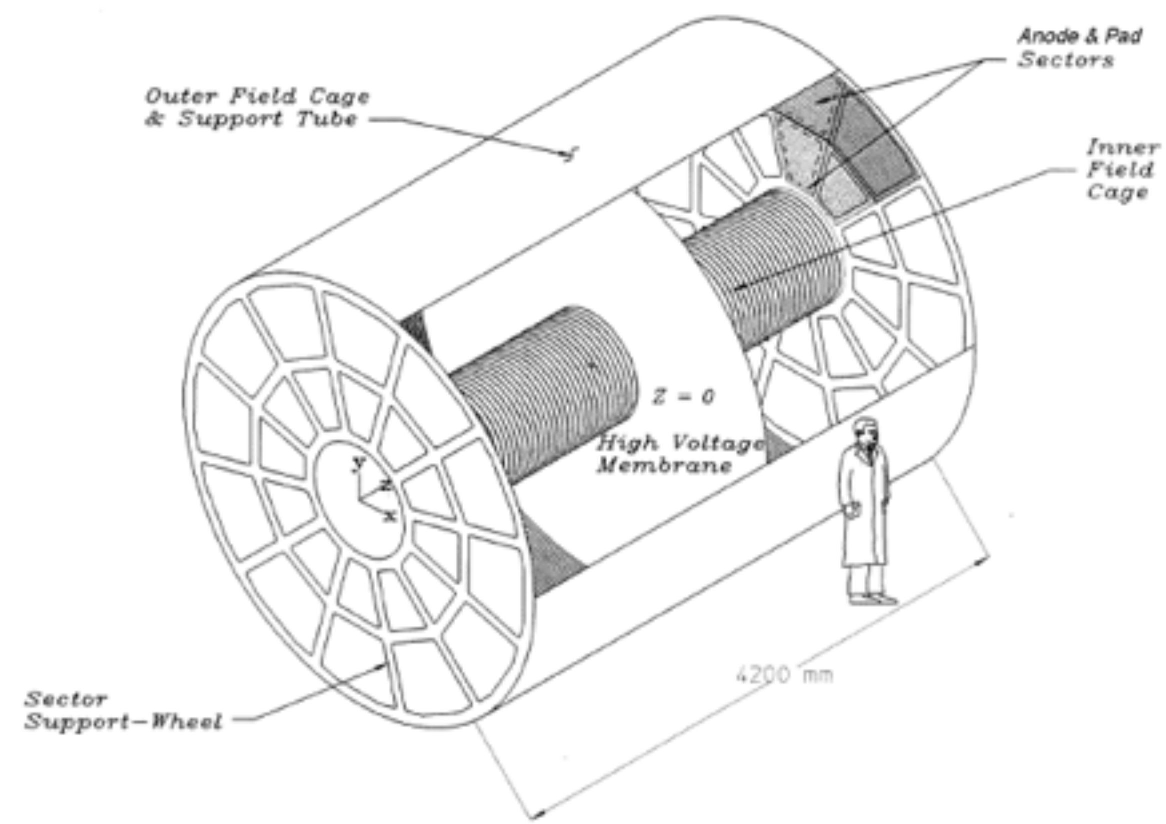
- placing a high-voltage cathode disc at centre of the chamber, an electric-field can be established between the disc and the end-plates.
- electrons that result from ionisation events in the chamber, will drift to the multi-wire end-plates
- arrival times of the electrons at the end-plates determine how far they have travelled and hence the axial (z) coordinate of the charged particle



eg-2:
Time projection chambers (TPCs)

- ☑ velocity of the particle can be found, if the two end-plates are used to trigger a timing device that records the time taken for the particle (distance of travel =length of the chamber).

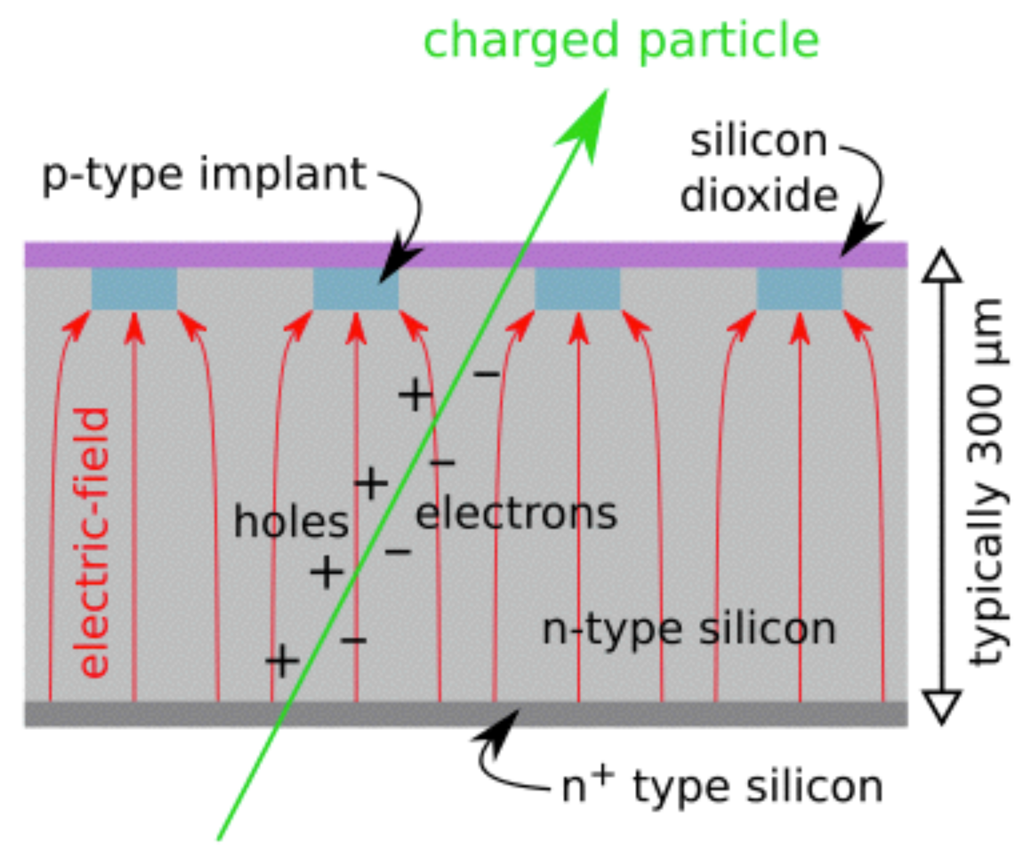
For this reason such detectors are called time projection chambers or TPCs.



STAR TPC layout

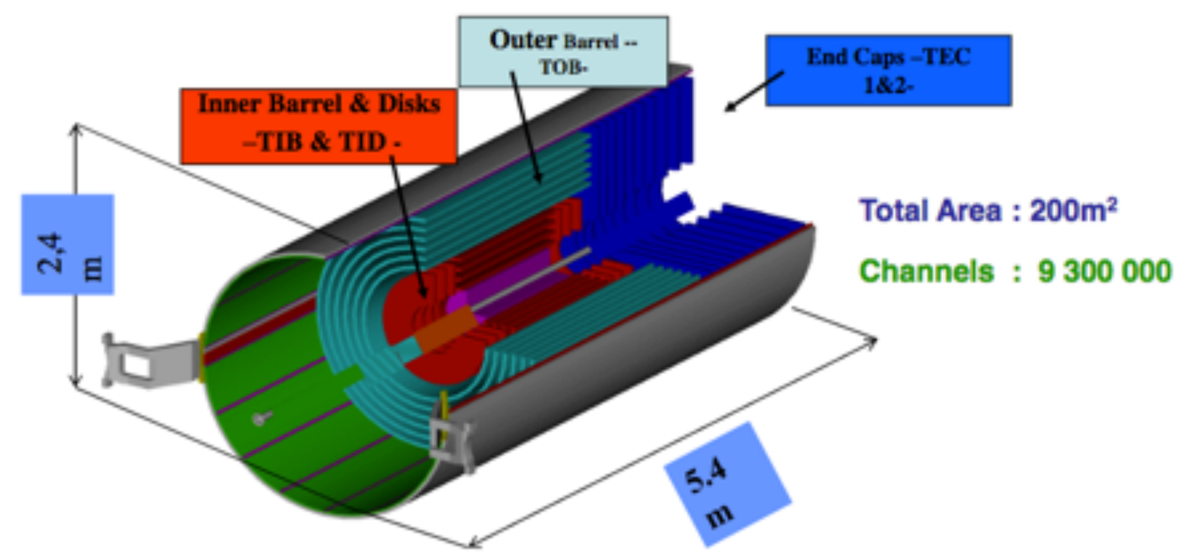
Solid state detectors (Silicon semiconductor): Principle of operation

- An individual detector module comprises silicon that has been doped, to form a diode.
- When the module is reverse-biased, a depletion region is set up with an electric-field that sweeps charge-carriers to the electrodes.



Solid state detectors (Silicon semiconductor): Principle of operation

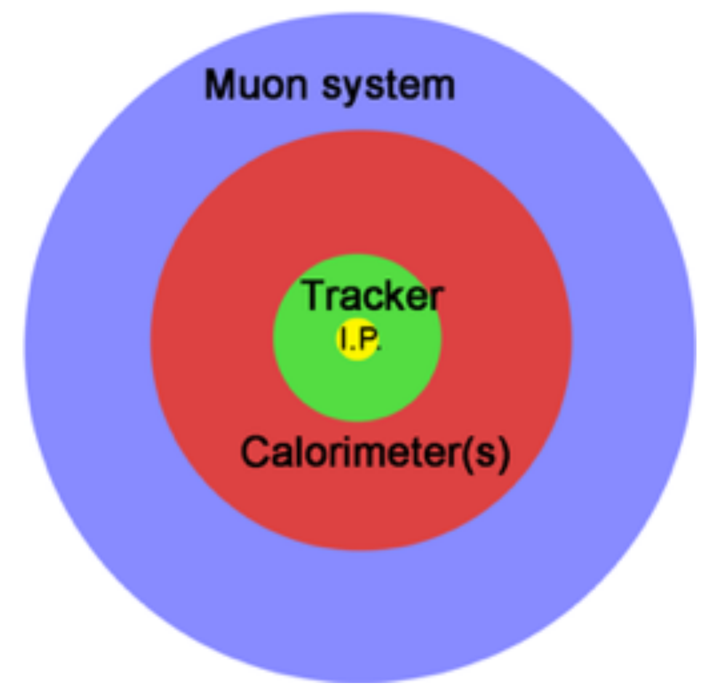
- ☑ Charged particles passing across the silicon strip, will liberate electrons from their atom => create electron-hole pairs.
- ☑ Electric filed in depletion region => sweeps the new electron-hole pair to the electrode, where they are collected.
- ☑ That particular module records a hit.



CMS Tracker Layout

Hermetic detector/4π detector

- ☑ cover nearly all of the 4π steradians of solid angle around the interaction point
- ☑ Typically roughly cylindrical, with different types of detectors wrapped around each other in concentric layers

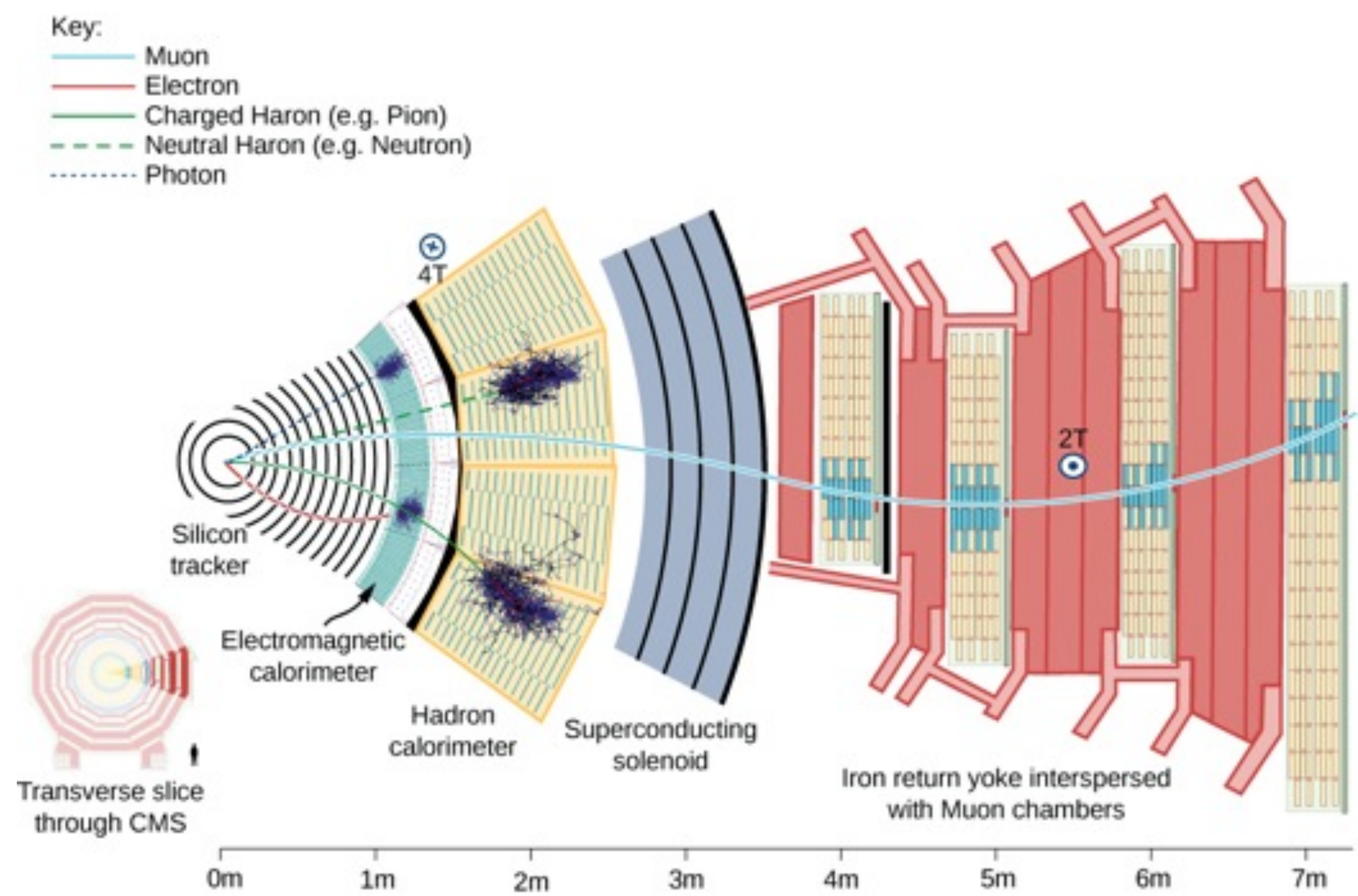


eg-1:
CMS detectors at CERN's LHC

☑ Tracker:
measures the momentum of charged particles as they curve in a magnetic field.

☑ calorimeters:
measure the energy of most charged and neutral particles by absorbing them in dense material

☑ muon system:
measures the one type of particle that is not stopped through the calorimeters and can still be detected



24 Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

Who knows, you may be next !!