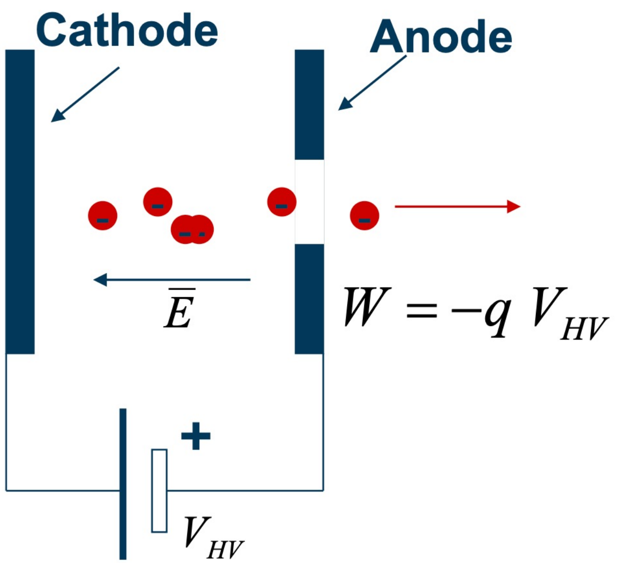
Gli acceleratori di particelle e la nascita della "BigScience"

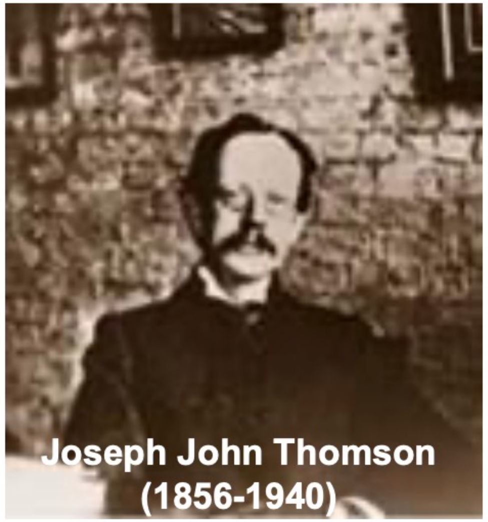
1927: Rutherford in a famous speech at the Royal Society asks for "a copious supply of particles at higher energy than radioactive sources", to disintegrate heavier nuclei and study their structure.

"*it has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the alpha- and beta-particles from radioactive bodies*"

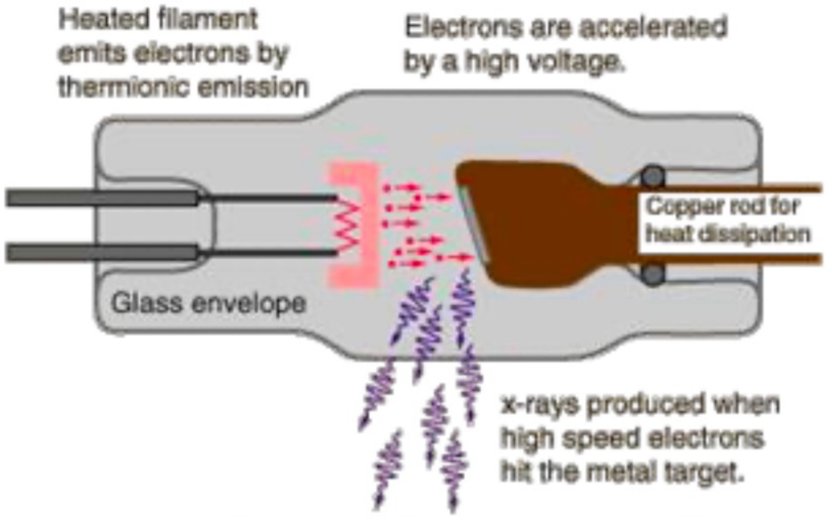
Electrostatic Accelerators



In 1895 Röntgen, using a cathode ray tube discovered the x-rays.
(1901 Nobel Prize)



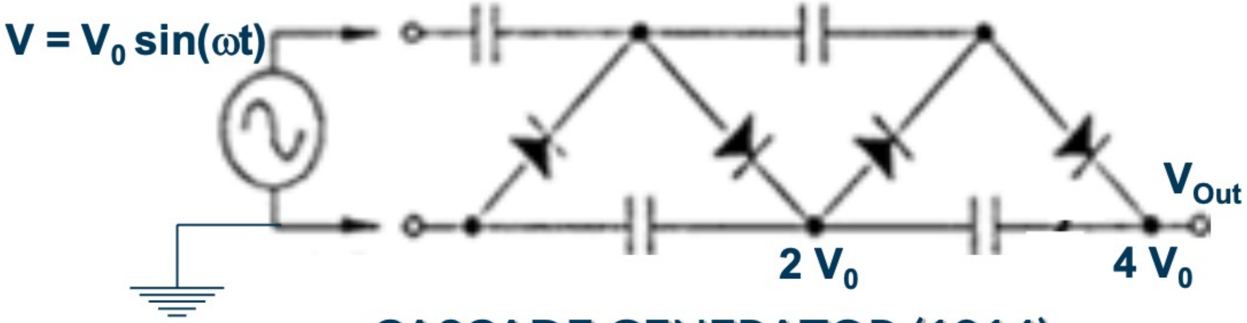
But it was only in 1897 that Thomson discovered the electron, showing that the cathode rays were these small negative charged particles being accelerated in the tube.
(1906 Nobel Prize)



From: hyperphysics.phy-astr.gsu.edu

Electrostatic Accelerators. The Cockcroft-Walton Scheme

$V_{Out} = 2\,V_0\,N_{CELLS}$

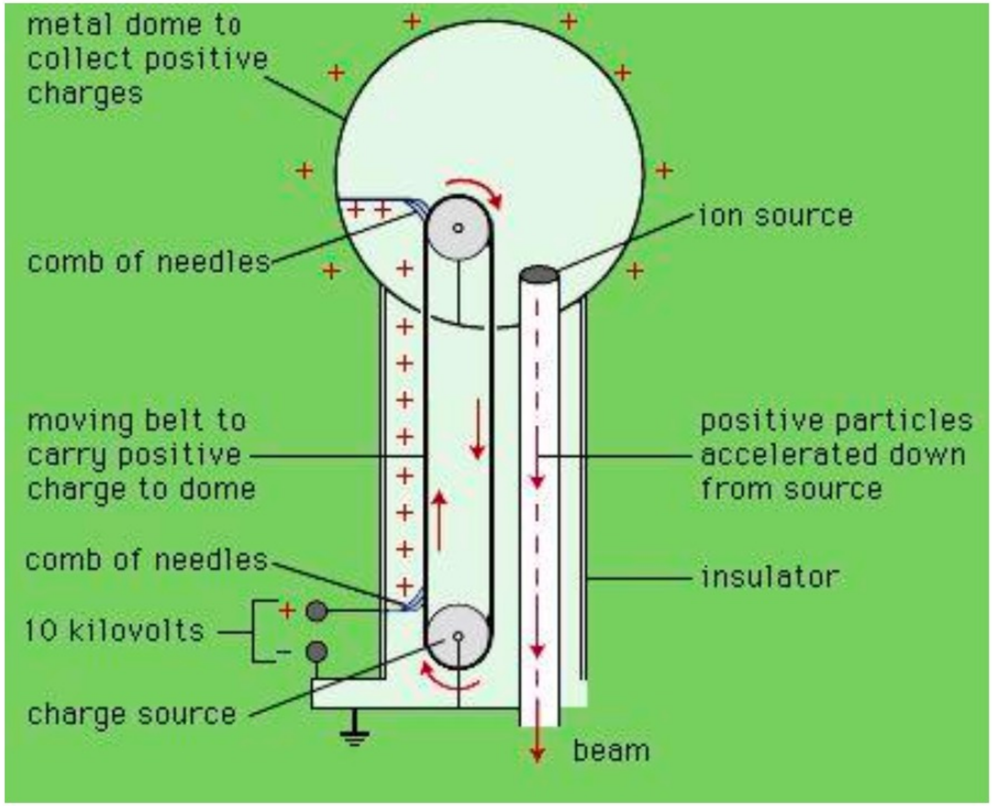


CASCADE GENERATOR (1914)

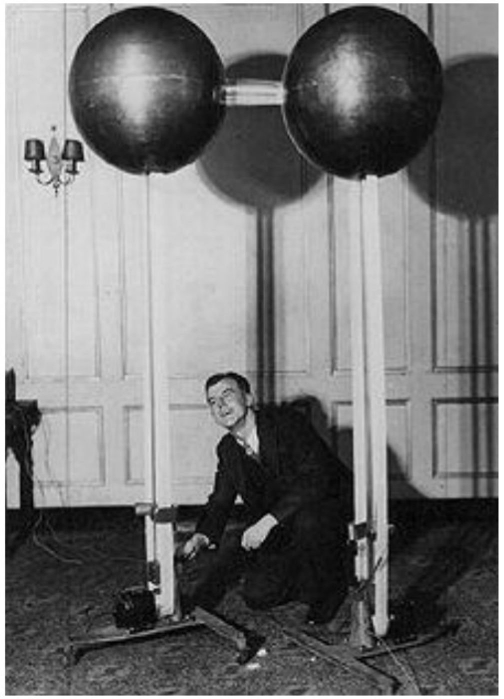
James Cockcroft and Ernest Walton in 1932 accelerated protons to 800 keV and produced fission of Lithium in Helium
(Nobel Prize 1951)

$$p + Li \rightarrow 2He$$

Electrostatic Accelerators: The Van de Graaff



- The needle transmits the charge to the belt by glow discharge and/or field emission
- The electric field inside the sphere is zero permitting the passage of the charge from the belt to the sphere



- The maximum voltage is limited by voltage breakdown. Inert gasses (Freon, SF6) help.

7MV in 1933

~ 20 MV nowadays

A fruitful marriage: radio waves and accelerators

Rolf Widerøe

Electrostatic accelerators were soon showing their limits in terms of maximum achievable electric field due to voltage breakdown.

Inspired by a 1924 paper by G. Ising, a Swedish professor (acceleration of particles using “voltage pulses” between tubes), in 1928 he put together for his thesis a device to demonstrate the acceleration of particles by RF fields:

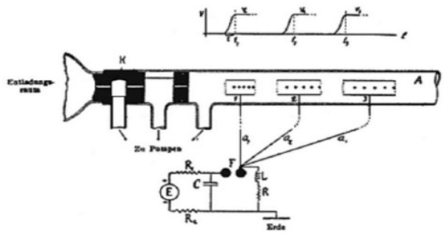


Fig. 2.13
Ising's proposal for a linear particle accelerator. The high-frequency field is supplied by a discharge across the spark gap F; K is the cathode; a_1, a_2, a_3, connections to the drift tubes. Ising, *Kosmos, 11* (1933), 171.

The apparatus that he made for his thesis was the first modern accelerator:

1. use of a triode and of radio technology (at the time limited to 1-2 MHz) → marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of synchronous RF accelerators.
3. complete accelerator: ion source, RF accelerator, detector, in vacuum

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration in a 88 cm long glass tube) “at a cost of four to five hundred marks”, less than 2’000 € today!

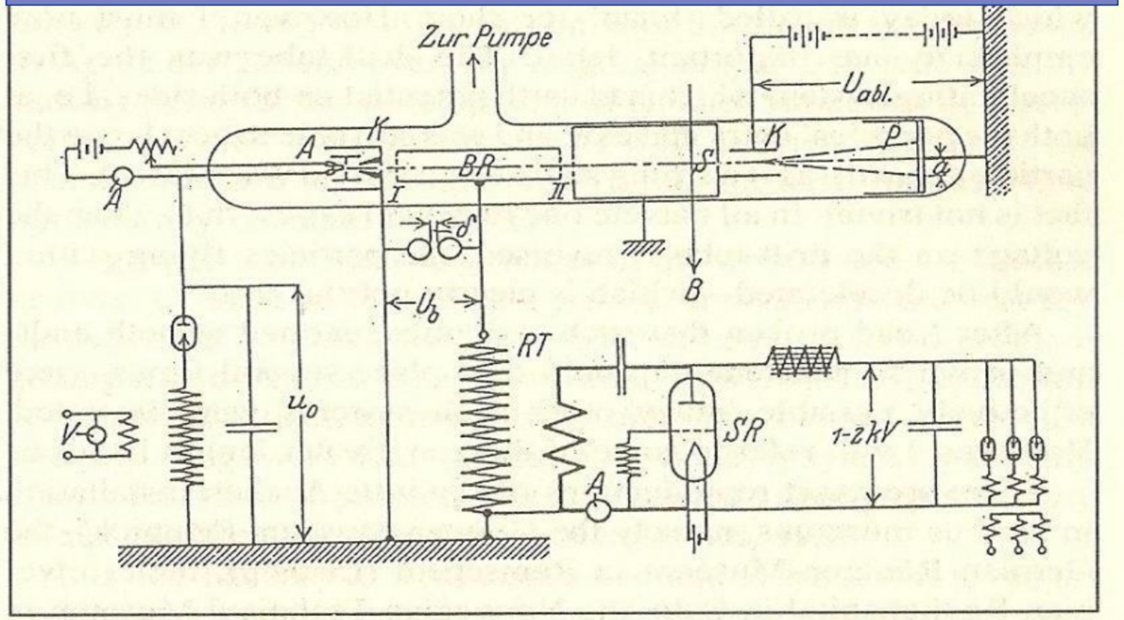
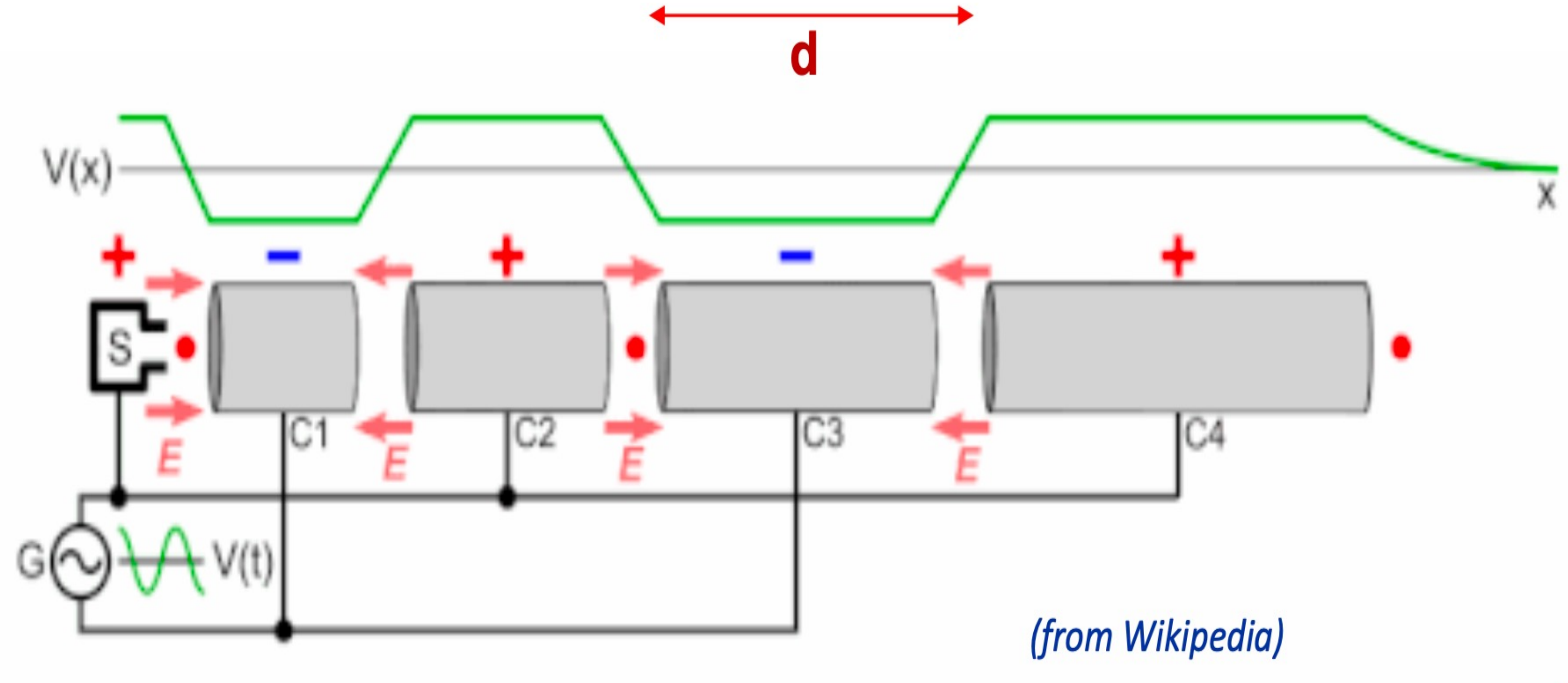


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

Higher energies in a Widerøe linac

The Widerøe structure can be used to reach higher energies, if the "**drift tubes**" are made longer and longer as the energy and velocity of the particle increase



(from Wikipedia)

Synchronicity condition:

$T/2 = d/v_{particles}$

or

$f_{RF} = v_p/2d$

or

$\mathbf{d = v_p/2f_{RF}}$

$$d = \frac{\beta c}{2c/\lambda} = \frac{\beta\lambda}{2}$$

with $\beta = v/c$, relativistic particle velocity

The limits of the Widerøe linac – a first stop

Limitation of the Widerøe device:
for light particles (protons) and high energy, requires high frequencies:

($d=\beta\lambda/2$, → taking tubes with d ≈ 10 cm, W=500 keV → f≈50 MHz)

☞ But a) higher frequency were not possible with the tubes of the time;
b) losses from the RF circuit become too large at high frequency.

→ after the PhD, Rolf Widerøe goes to AEG to build HV circuit breakers and his thesis, published in the "Archiv für Elektrotechnik", remains unnoticed.

... But the topic was hot!

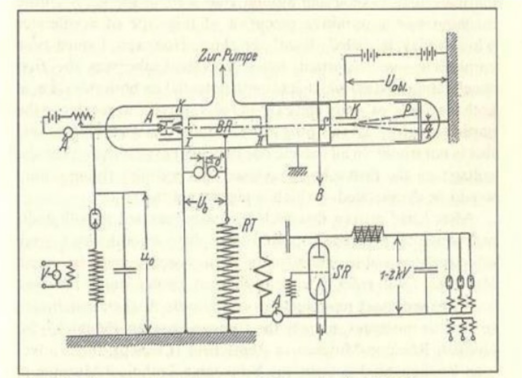


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

"Ueber Ein Neues Prinzip Zur Herstellung Hoher Spannungen," Von Rolf Wideroee, Archiv Fuer Elektrotechnik, Band XXI, Heft 4, Dezember 17, 1928

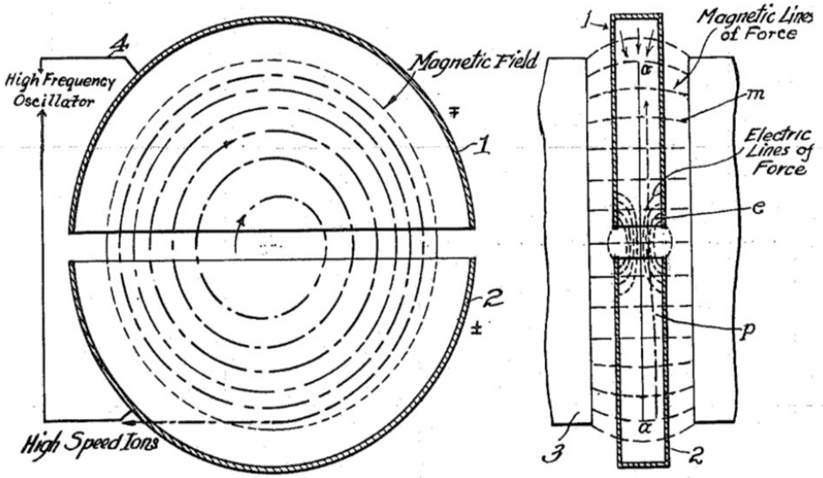
Ideas travel: from Aachen to Berkeley…

In the 1920's, Ernest O. Lawrence (born 1901), young professor of physics at Berkeley, wants to join the "energy race", and is looking for new ideas…

In 1929, during a conference, he goes to the university library and finds Widerøe' s thesis in the 1928 "Archiv für Elektrotechnik" (but he did not speak German…).

Immediately, he realised the potential of the idea of Radio-Frequency acceleration, and starts working with his PhD students on 2 parallel activities:

1. A Widerøe "linear accelerator" (linac) with several drift tubes, to accelerate heavy ions (D. Sloan) → not much progress.
2. A "cyclic" accelerator, bending the particles on a circular path around Wideröe's drift tube (S. Livingston) → the **cyclotron**.



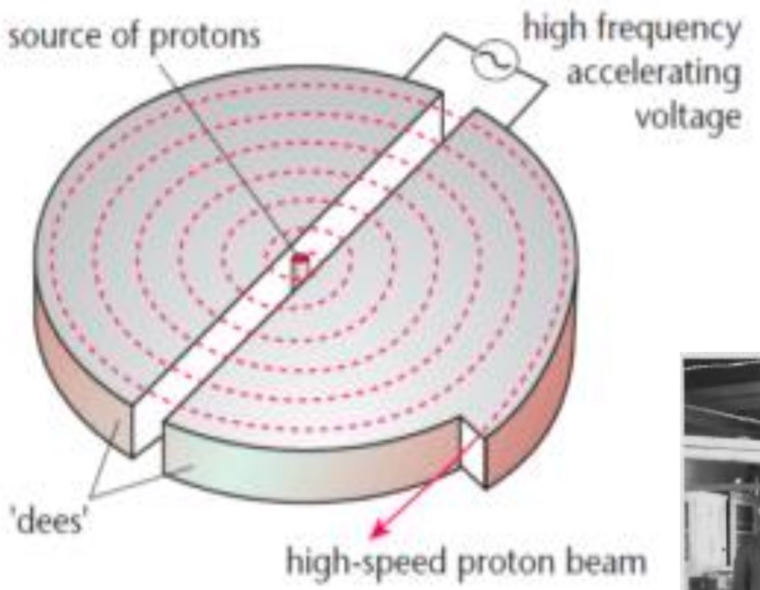
A compact low-energy accelerator: the cyclotron

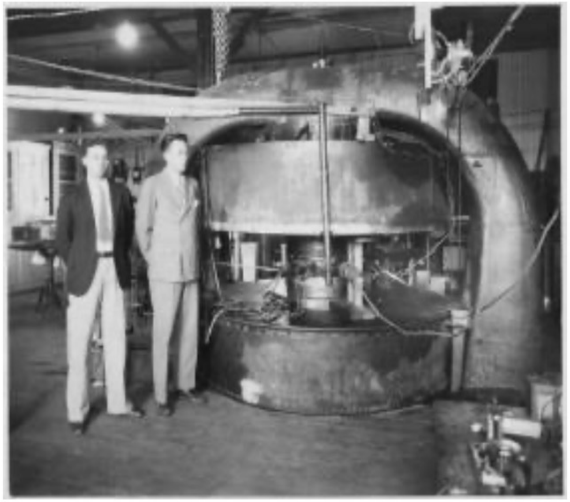
The idea: insert a Widerøe's sequence of RF gaps into a transverse magnetic field, to keep particles in a closed circular orbit.

Basic principle: Use RF **electric field** to accelerate, **magnetic field** to keep particle in a circular orbit: the 2nd ingredient of modern accelerators!

1. **Technology**: The drift tubes are replaced by two "D" (a slotted cylinder), the RF is applied between the D's and particles are accelerated in the gap → long path of the particles in the D, low frequencies can be used (3.5 MHz, 1st Berkeley cyclotron). The D's are placed inside a large electromagnet that generate a transverse magnetic field.

2. **Acceleration**: An ion source is placed in the centre. Particles gain energy and they are deflected by the magnetic field, to "spiral" in the cyclotron. Since the revolution frequency does not depend on beam energy, they arrive on the gaps at the accelerating field (synchronicity!).





f is the "revolution frequency"
independent on energy or velocity!

$$\frac{mv^2}{r} = evB \quad f = \frac{1}{\tau} = \frac{2\pi r}{v} = \frac{2\pi r m}{eBr} = \frac{2\pi m}{eB}$$

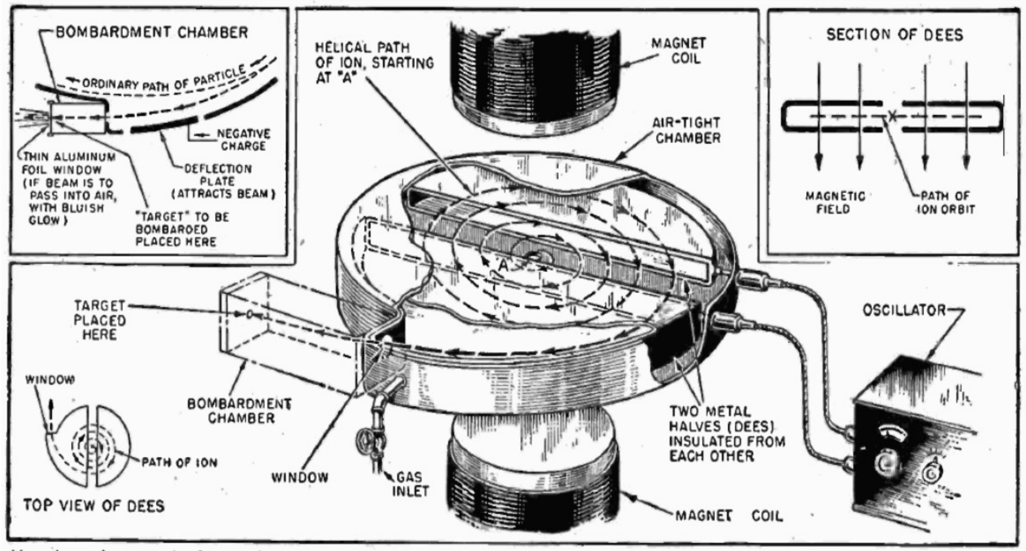
Cyclotrons give a boost to nuclear physics

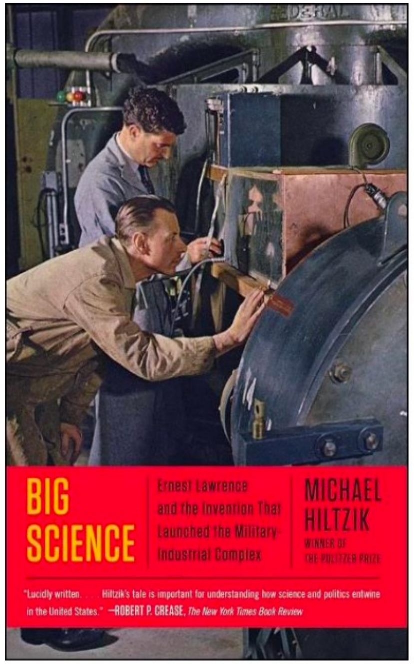
1931: the Berkeley cyclotron reaches 1.2 MeV with protons. First atom disintegrations in 1932.

1934: 5 MeV reached on a new larger machine accelerating protons and deuterons , used to produce neutrons, discovered in 1932. Start of a cancer therapy programme with neutrons, parallel to nuclear physics.

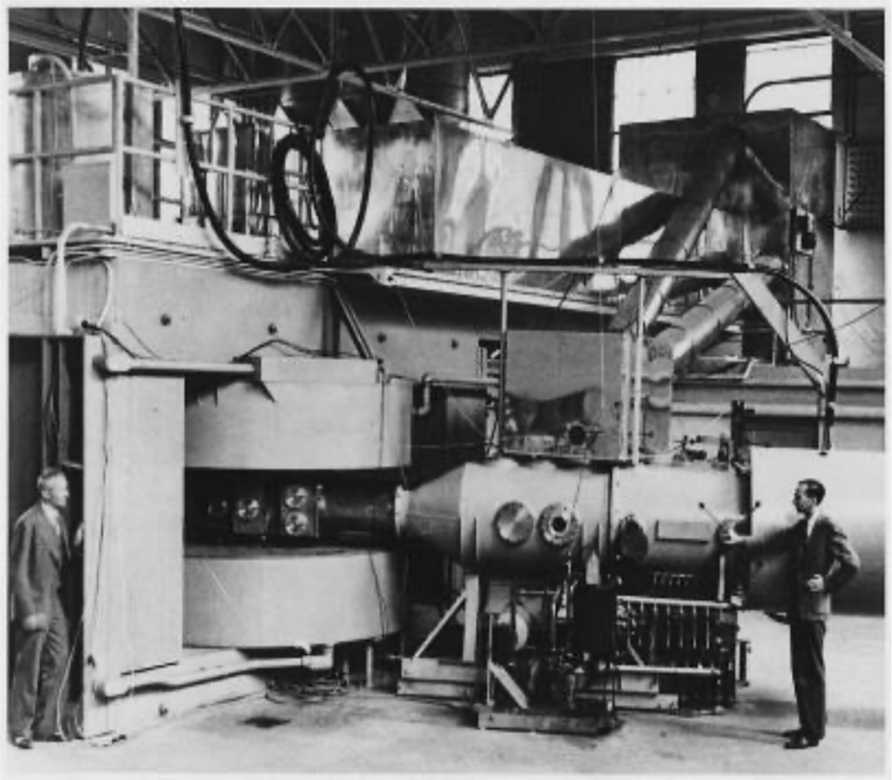
Many institutes worldwide start the construction of cyclotrons. This technology makes artificial production of heavy elements possible and leads to discoveries in nuclear physics providing the background for the US (and URSS) nuclear programmes.

Lawrence is not only the inventor of **Big Science**, associating industry and political/social support, but also the first promoter of **Open Science**, freely sharing his technology and his results.





For further reading, an excellent book (12$ on Amazon)



The difficult road to higher energies: basic limitations of cyclotron and Widerøe linac

Limitation to cyclotrons: relativity

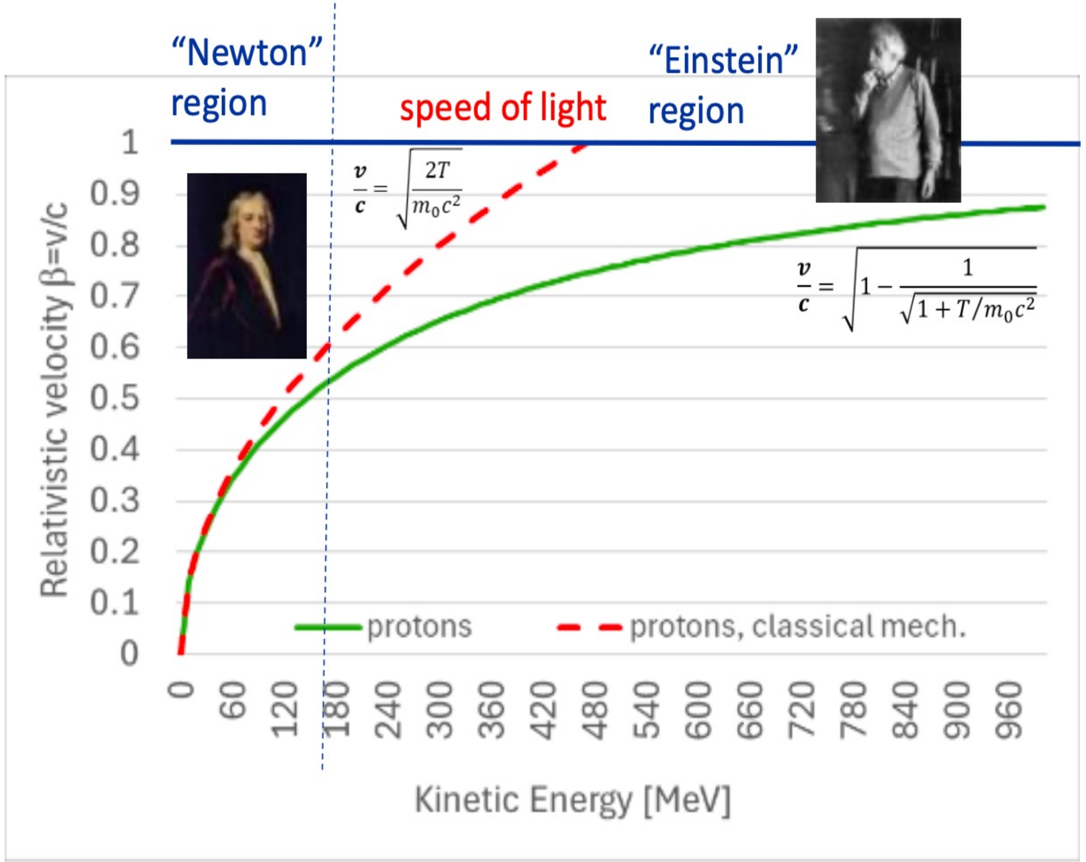
The cyclotron formula is valid only for non-relativistic particles: When the mass start to increase accordingly to $m = \gamma m_0$, the revolution frequency increases, and the particles are no longer in phase with the RF frequency.

Some corrections (modulation of the excitation frequency or shaping of the magnet field) can be applied, but conventional cyclotrons are limited in energy to ≈70 MeV. Special "synchrocyclotrons" can go higher (≈500 MeV) but with high complexity and cost.

Limitation to Widerøe linacs: frequency

As velocity increases, to keep a reasonable distance between gaps the RF excitation frequency must increase ($f_{RF} = v_p / 2d$) but frequencies above a few MHz are not possible with the technology of the 30's.

$$f = \frac{1}{\tau} = \frac{2\pi r}{v} = \frac{2\pi r m}{eBr} = \frac{2\pi m}{eB}$$



β=v/c of protons as function of kinetic energy T

2^{nd} technology leap: going round again, the synchrotron

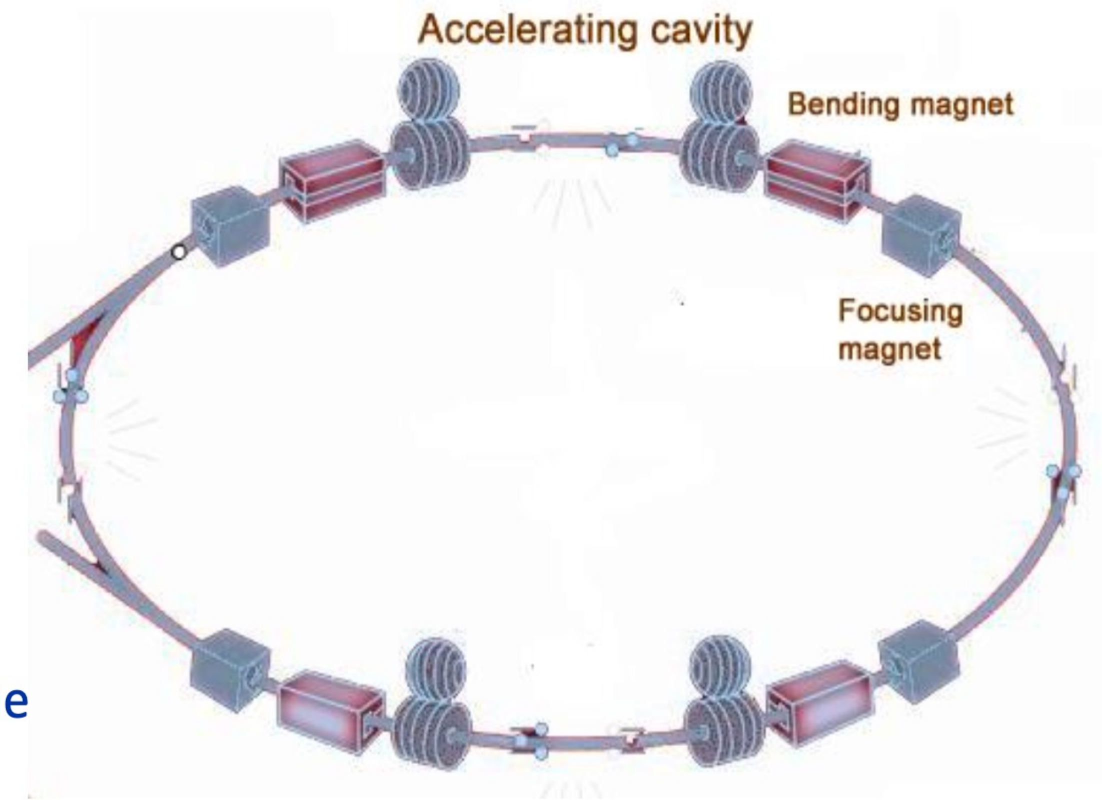
Higher frequencies have allowed increasing the energy of linacs, but how can we extend the reach of circular (cyclic) accelerators to the relativistic region?

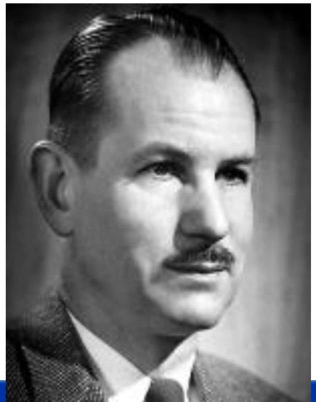
The idea of a "**synchrotron**" slowly matured in the 40's: M. Oliphant, UK/US, 1943; V. Veksler, URSS, 1944; E. McMillan, US, 1945. Last 2 building on their "phase stability" concept.

- 1^{st} electron synchrotron: McMillan, USA, 1945.
- 1^{st} proton synchrotron: Oliphant, UK, 1952.

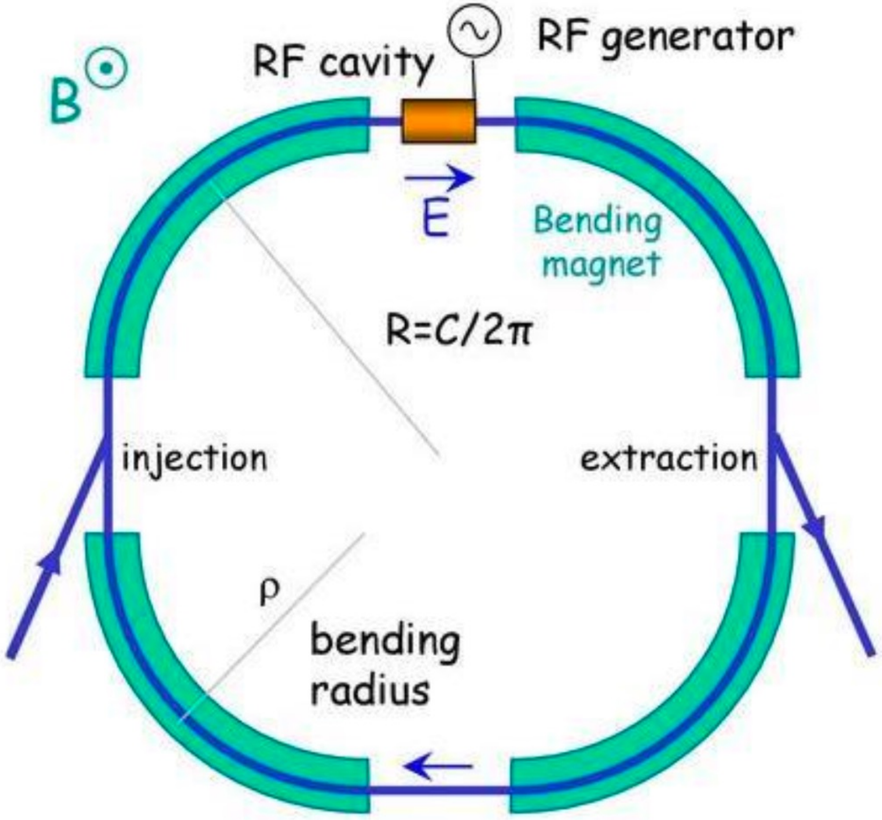
Basic idea: With respect to the cyclotron, instead of letting the orbit change with energy, keep the orbit constant by: 1) increasing the magnetic field; 2) increasing the RF frequency (synchronise!) during acceleration. And replace the "gaps" with localized accelerating cavities (short sequences of gaps).

The particles gain energy at every turn; the process can go on (almost) forever → acceleration at (almost) zero cost!





A synchrotron looks simple, but…



1. For synchronicity, particles must cross the gap at the same phase for every turn → RF frequency must increase with velocity: $f=1/T_{rev}=v/2\pi R$ → *need of variable frequency accelerating cavities.*

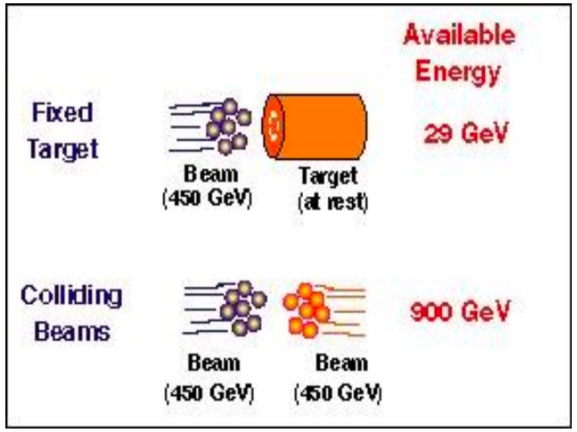
2. to keep the particles on the closed orbit, B must also increase, proportionally to the particle momentum p : $pc = eB\rho$ → *need of variable magnetic field in the magnets.* → requires operation in *pulsed mode.*

3. A synchrotron cannot start with particles at zero velocity (f=0!) → *need of an injector linac.*

4. When many particles are accelerated over many turns, they can be easily lost in the longitudinal (out of synchronicity!) plane, or in the transverse plane → *need of accurate beam optics, combining phase stability (Veksler and McMillan) and transverse focusing*.

1. A synchrotron can in principle go up to any energy, limited only by its rigidity $B\rho$ (peak magnetic field x curvature radius).
2. A synchrotron is the ideal accelerator for protons and heavy ions at high energy (relativistic region: when v≈const, also f≈const)

One more step: colliders!



Example: CERN SPS collisions

What counts for physics is the "centre of mass" energy developed in the collision. But because of **relativity**, the energy available at centre of mass in fixed target collisions is much lower than the energy of the particle beam.

Instead, for heads-on collisions of two beams traveling in opposite directions, the available energy is exactly twice the energy of the particle beams.

$$E_{cm} = 2E$$

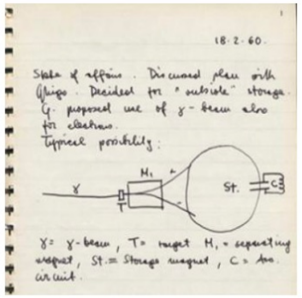
head-on collision of 2 identical particles with same energy E

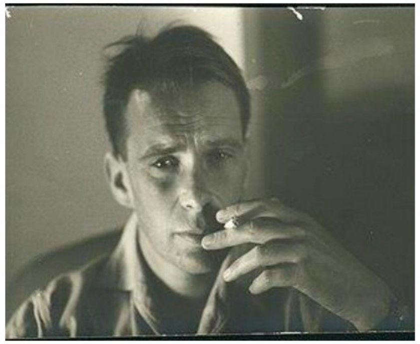
$$E_{cm} \approx \sqrt{2E}$$

collision of a particle at energy E with same type of particle at rest.

The first collider

- Collider idea patented by R. Widerøe during WWII (but considered "trivial" by B. Touschek).
- Touschek moved to Frascati (I) after the war and in **1961** together with a team of Italian scientists built AdA (Anello di Accumulazione), a small e+e– storage ring and the first collider of the world





Diameter 1.6 m
Electrons 200 MeV

The next innovation: superconductivity

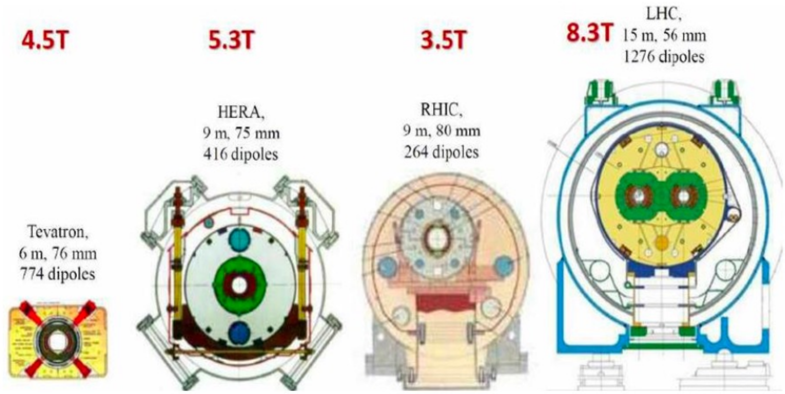
Discovered in 1911, explained in 1958, started to be used for accelerators in the 1970's.
Allows to build magnets that can stand higher electric currents and higher fields and accelerating RF cavities that reach higher gradients and have higher electrical efficiency (although power is dissipated in the cryogenic system).

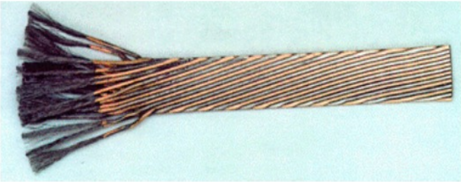
THE TEVATRON ENERGY DOUBLER:
A Superconducting Accelerator

Helen T. Edwards

Fermi National Accelerator Laboratory,[1] Batavia, Illinois 60510

The upgrade of Tevatron to 800 GeV (double energy), was the 1st large project to use SC magnets (1983).
Tevatron discovered the top-quark in 1995.
Next SC collider: LHC (7 TeV, 2008) discovery Higgs boson.





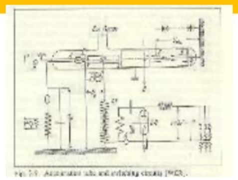
The LHC magnet superconducting cable (Nb-Ti)

One of the 8 compressor units of the 4.5 K refrigerator for LHC

Clean room assembly of superconducting RF cavities

Major developments of SC RF cavities: JLAB (1990), LEP200 (1996/97), DESY (TTF, 1997/2005 and XFEL, 2016).

Particle accelerators: 100 years of innovation

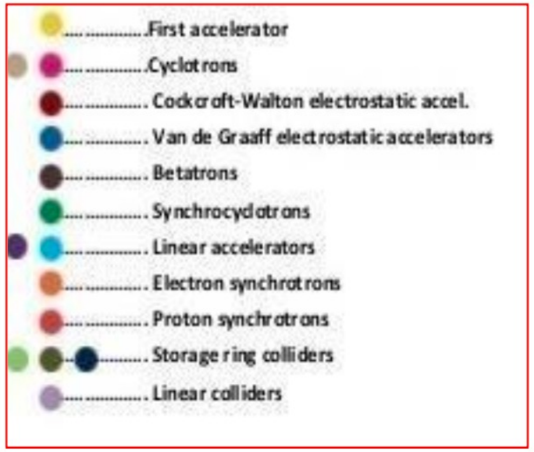


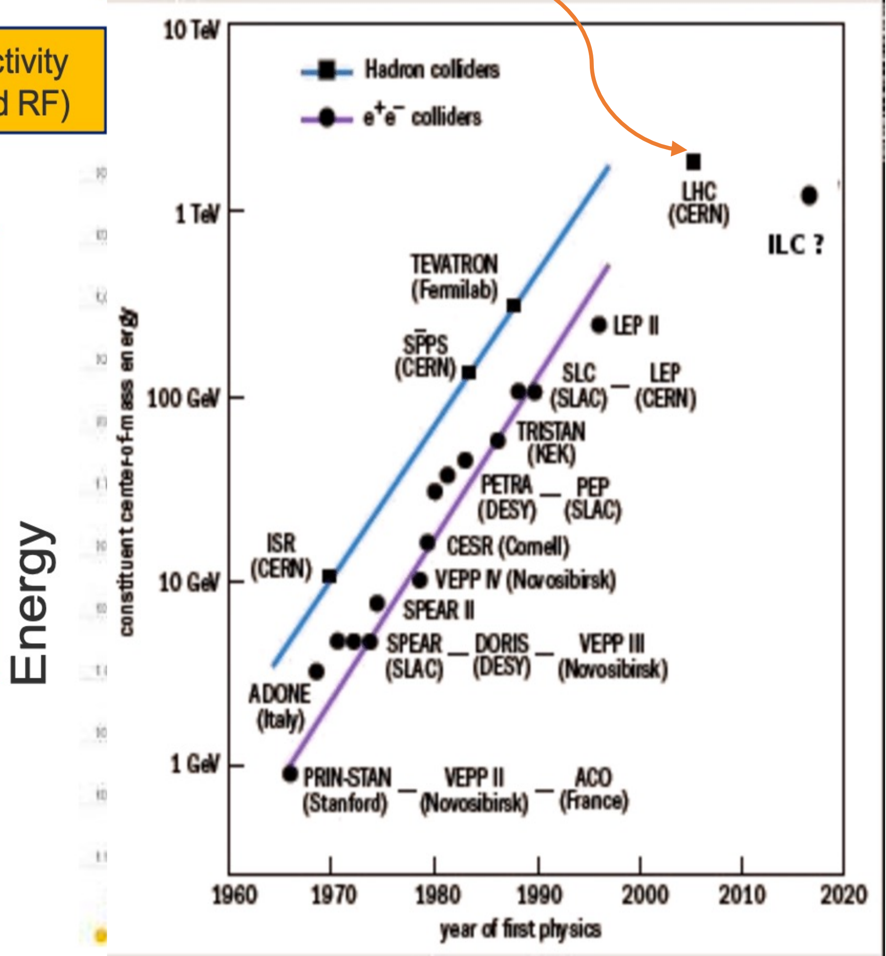
1927…………1945/48….1950… 1960…..1970….1990

XXI century ?

- Electrostatic acceleration
- Widerøe linac: RF acceleration
- Cyclotron: cyclic acceleration with magnets
- RF linacs using radar technology
- Synchrotrons
- Strong focusing
- Colliders
- Superconductivity (magnets and RF)

Succession of enabling technologies (technology leaps)





S. Livingston, 1959: **Livingstone's plot**

Top energy of particle accelerators increased exponentially in the period 1965-1995, by a factor of 10 every 6 years *(Moore's law of accelerators).*