Acceleration of Charged Particles

by

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Why Accelerate Particles?

To probe sub-nuclear world

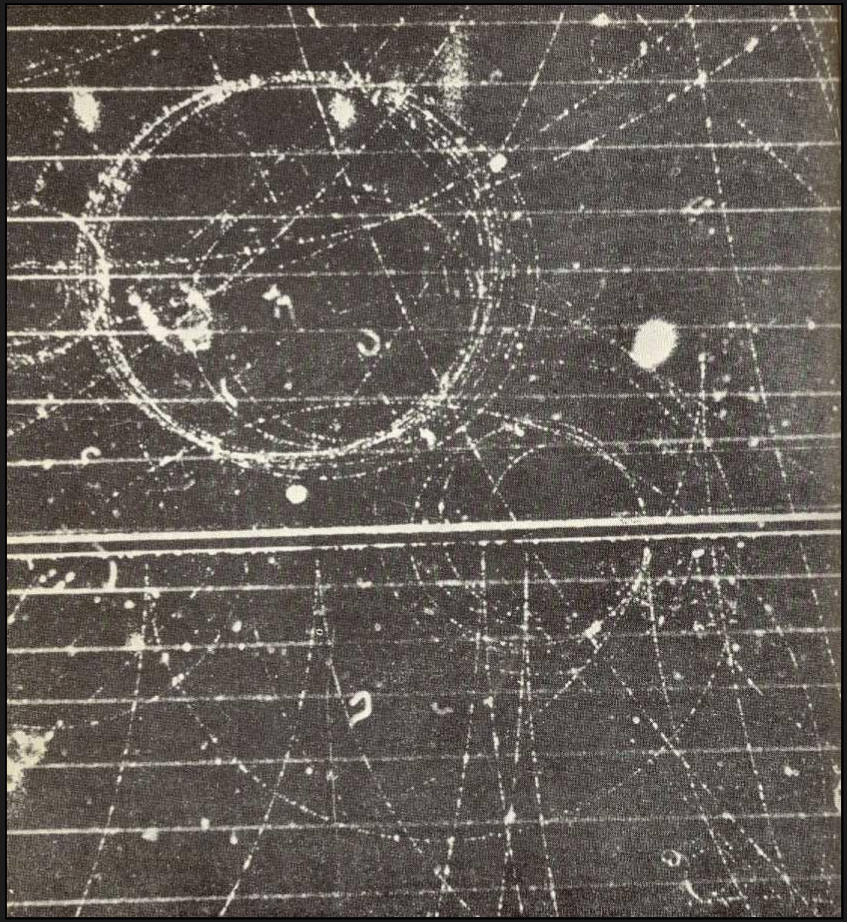
Two-Fold Nature of Particle Accelerators

1. To provide high energy projectiles for:

- Breaking particles into constituents
- Creating new particles according to mass - energy relation $E = mc^2$
  - Pair Production
  - Pair Annihilation

Two-Fold Nature of Particle Accelerators

Pair Production



Rochester, C. D. and J. G. Wilson; *Cloud Chamber Photographs of the Cosmic Radiation*; Pergamon Press, Ltd., 1952.

Two-Fold Nature of Particle Accelerators

2. To serve as a microscope in which projectiles of ultra-short wavelength probe the sub-nuclear world according to the matter - wave relation $\lambda = \mathbf{h/p}$.

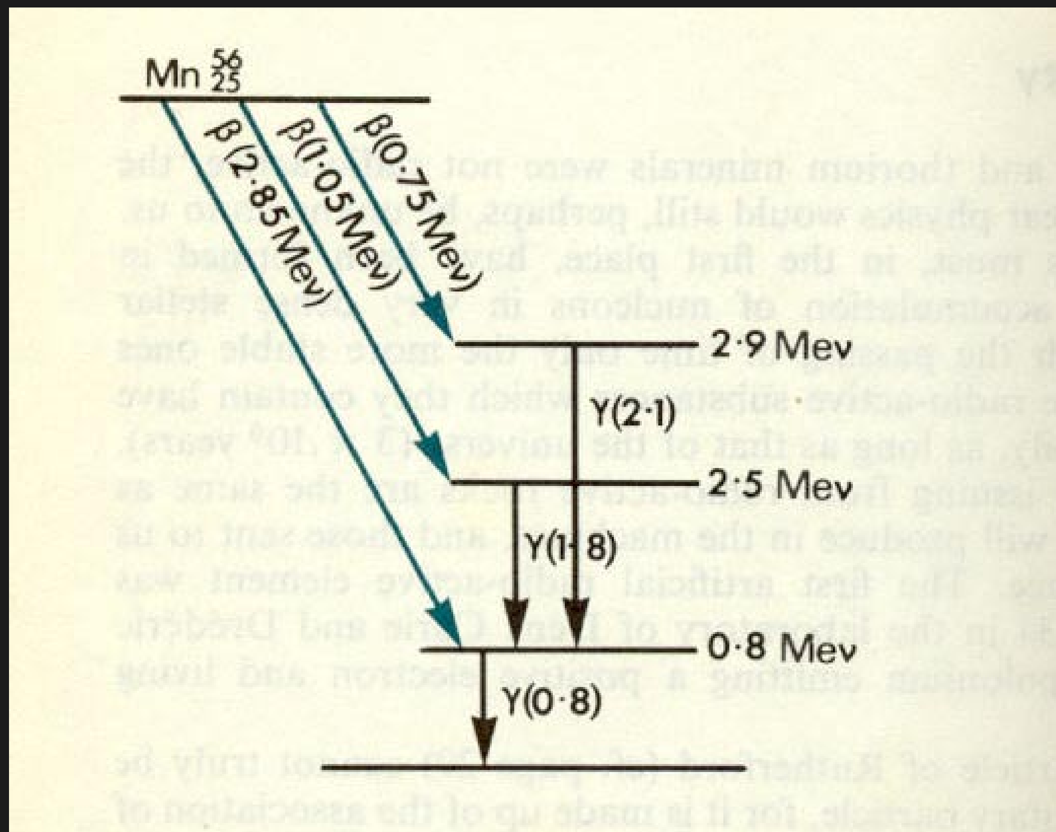
Natural Particle "Accelerators"

- 1. Radioactive Sources
  - Beta Particle Emission

    Mn-56 $\longrightarrow$ Fe-56 + β + γ
  - Alpha Particle Emission

    Ra-226 $\longrightarrow$ Rn-222 + He-4 (α)

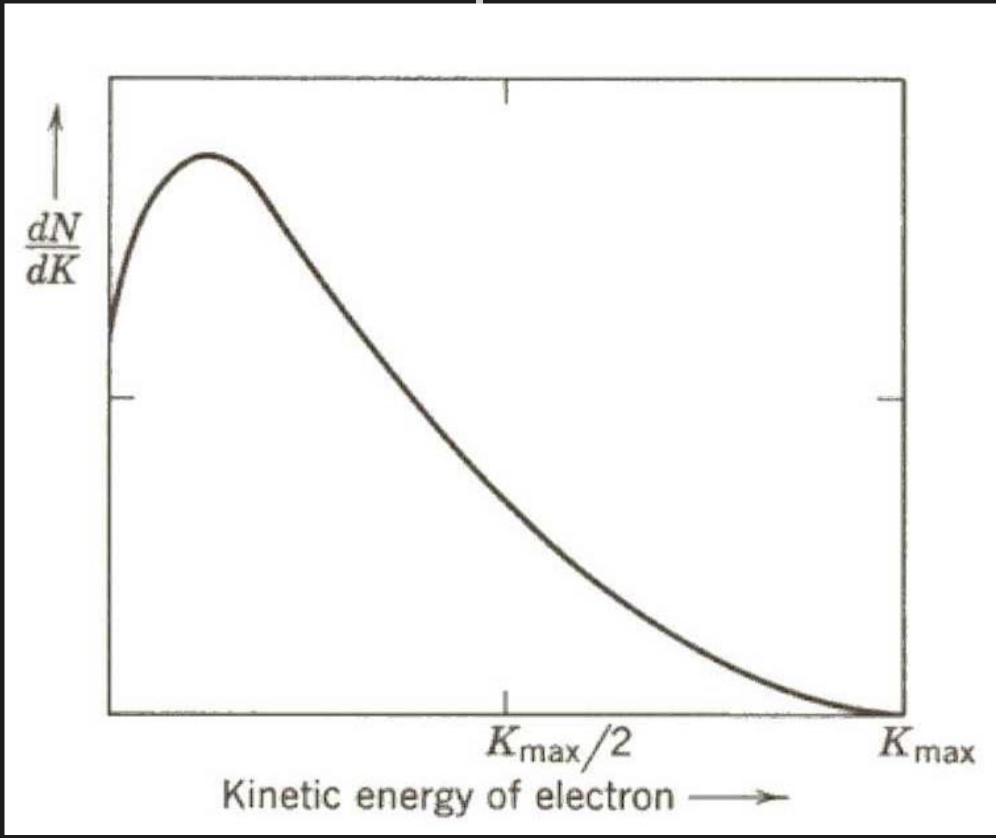
Natural Particle "Accelerators"
Beta Decay



Gouiran, Robert; *Particles and Accelerators*; World University Press; 1967 page178.

Natural Particle "Accelerators"

Beta Spectrum



Spectrum suggested neutrinos

Sproull, Robert L., and W. Andrew Phillips; *Modern Physics The Quantum Physics of Atoms, Solids, and Nuclei*, Third Edition; John Wiley and Sons, 1980; page549.

Natural Particle "Accelerators"

Radioactive Decay Modes

Radioactive sources

Isotope	$t_{1/2}$ (yr)	Decay product	Particle energies (MeV)
^{3}H	12.26	e^-	0.019
^{22}Na	2.602	γ	0.511, 1.275
		e^+	0.54, 1.8
^{55}Fe	2.6	X-rays	0.0057
^{60}Co	5.26	β	0.315
		γ	1.173, 1.332
^{85}Kr	10.76	e^-	0.670
		γ	0.514
^{90}Sr	28.1	e^-	0.546
^{106}Ru	1.01	e^-	0.039
$\rightarrow {}^{106}Rh$	30 sec	e^-	2.0, 2.4, 3.1, 3.53
		γ	0.512, 0.616
^{109}Cd	1.23	γ	0.088
^{133}Ba	7.2	γ	0.081, 0.303, 0.356
^{137}Cs	30.23	γ	0.662
		e^-	0.511, 1.176
^{207}Bi	30.2	γ	0.570, 1.064, 1.770
		β	0.481, 0.554, 0.976, 1.048
^{241}Am	458	γ	0.060
		α	5.486, 5.443, 5.389

Source: CRC Handbook of Chemistry and Physics, 64th ed., Boca Raton: CRC Press, 1983; Radioisotope data chart, Bicron Corp, Newbury, Ohio, 1974.

Fernow, Richard; *Introduction to Experimental Particle Physics*; Cambridge University Press; 1986; page 119.

Natural Particle "Accelerators"

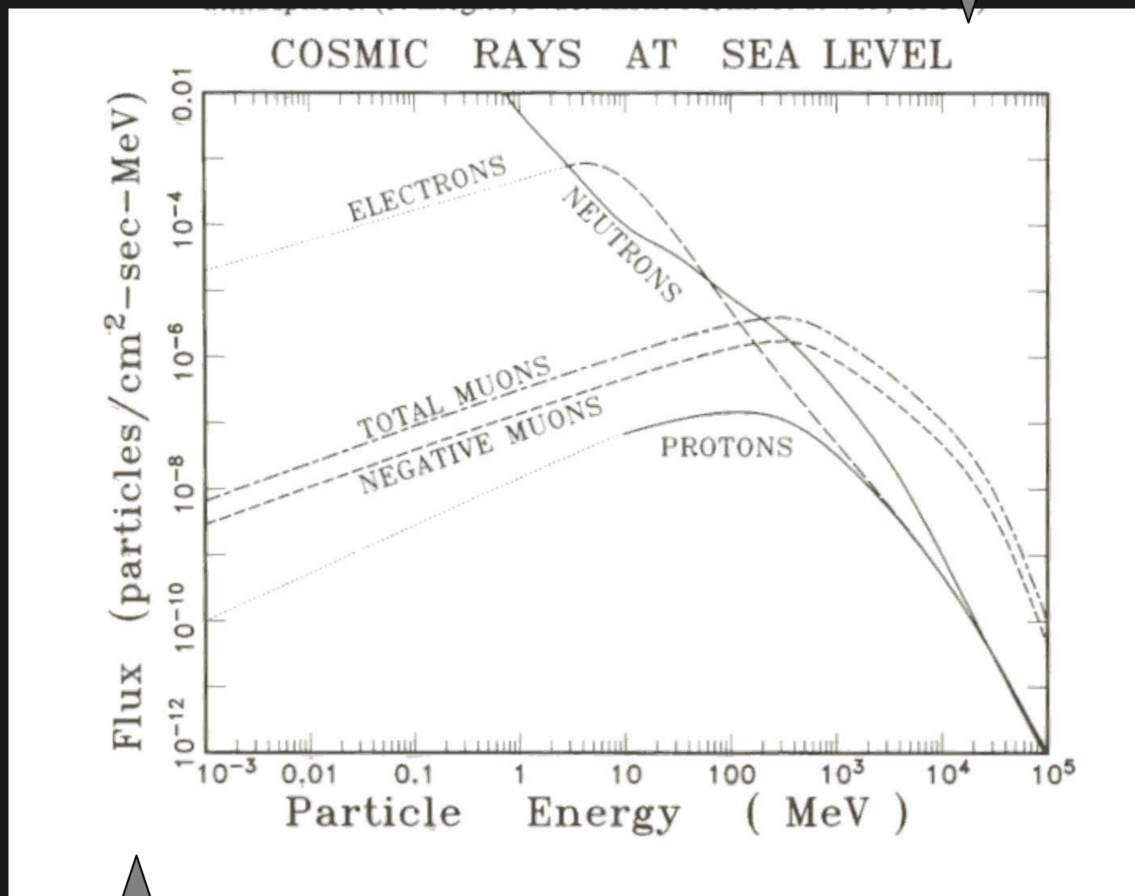
- 2. Cosmic Radiation
  - Primary --- Protons
  - Secondary ---

    Muons

    Electrons

    Neutrons

Cosmic Rays



Fernow, Richard; *Introduction to Experimental Particle Physics*; Cambridge University Press; 1986; page 118.

Natural Particle "Accelerators"

- 3. Disadvantages of Natural Particle "Accelerators"

LACK OF CONTROL OVER PARTICLE:

- Type
- Energy
- Direction
- Flux
- Arrival Time

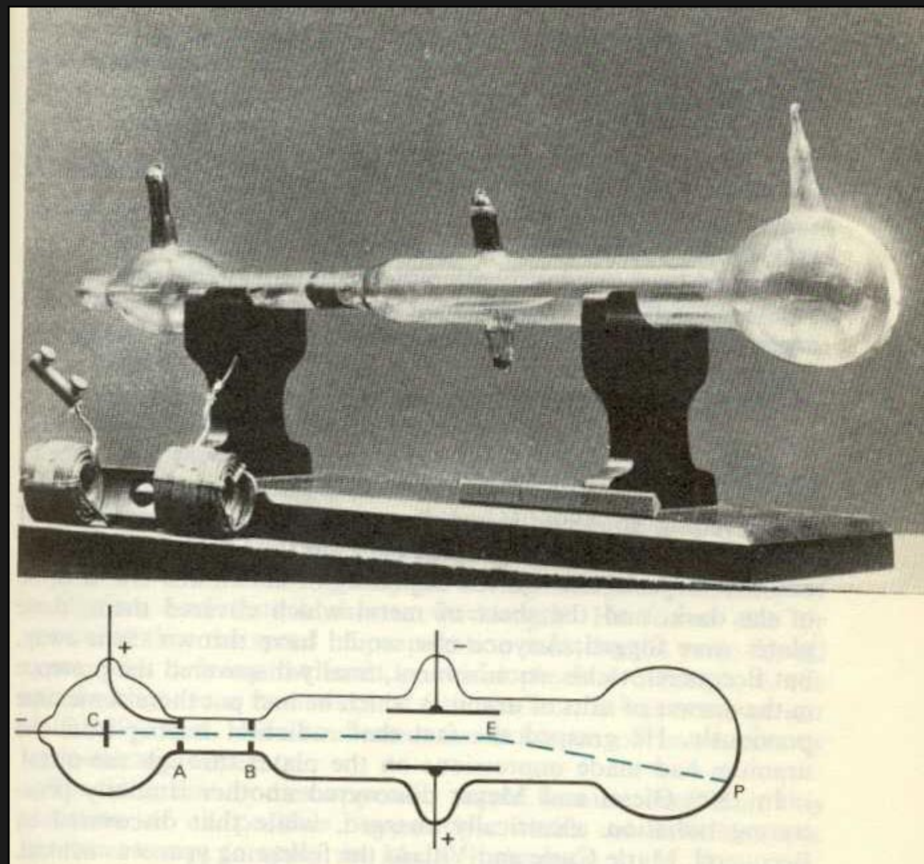
Electrostatic Accelerators

- Crookes's Tube ---1st Research Accelerator

  Used by J.J. Thomson in Measuring e/m of electron

Electrostatic Accelerator

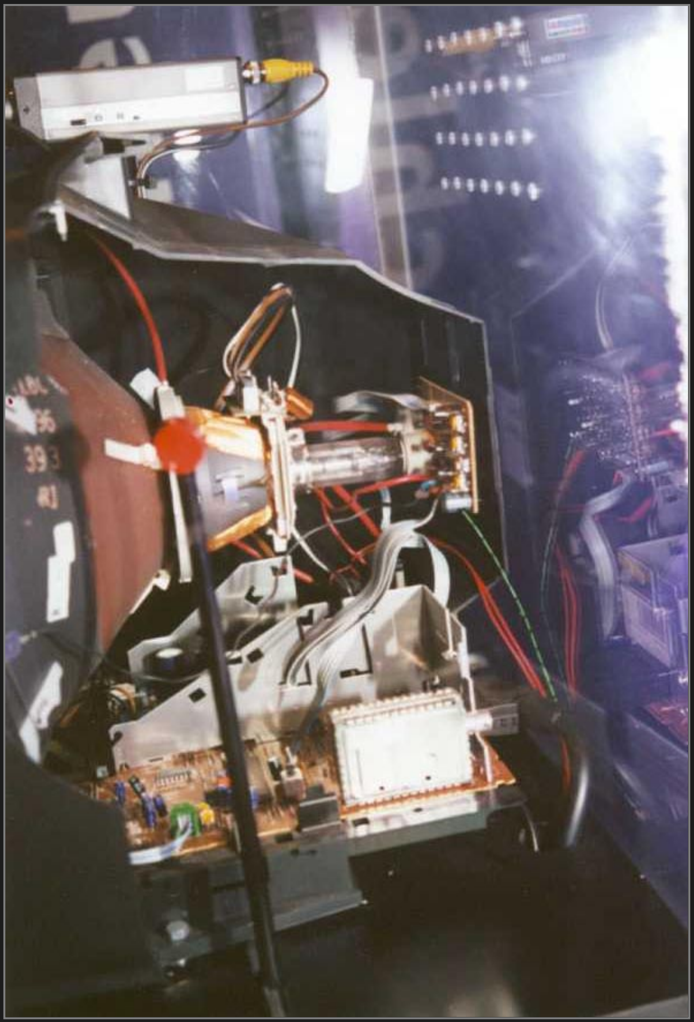
Crookes's Tube



Gouiran, Robert; *Particles and Accelerators*; World University Press; 1967; page 19.

Electrostatic Accelerators

TV Accelerator



Open structure TV set at Microcosm Museum - CERN; Photo by Ken Taylor

Electrostatic Accelerators: Cockcroft-Walton

- Invented at Famous Cavendish Laboratory in 1932
- Used to produce the 1st nuclear disintegration produced by man-made accelerator

$p + Li\text{-}7 \rightarrow \alpha + \alpha + 17\ MeV$

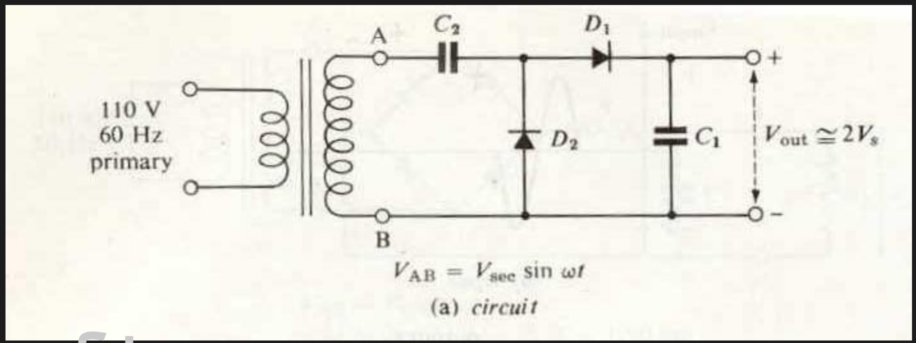
Electrostatic Accelerators: Cockcroft-Walton

- Cascading Voltage Doubler
- Analogous to charging capacitors in parallel and discharging in series

(high impedance, low current voltage source)

Cockroft-Walton

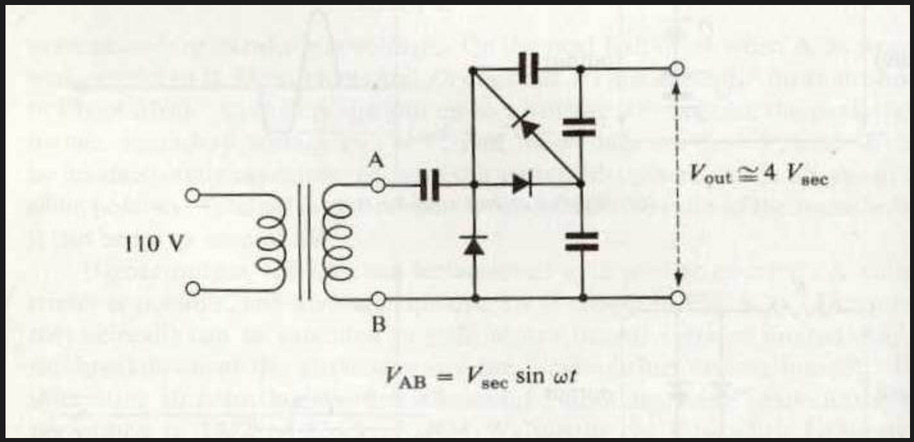
Voltage doubler circuit - unit cell



(a) *circuit*

Cockroft-Walton

Voltage quadrupler circuit



Retired Cockcroft-Walton Accelerator - Microcosm Museum -CERN
Photo by Ken Taylor

Retired Cockcroft-Walton Accelerator - Microcosm Museum -CERN Photo by Ken Taylor

Electrostatic Accelerators: Disadvantages

- Electrostatic Accelerators limited to ≤ 1 MV (Due to arcing discharges)
- All charges accelerated through gaps having electric fields established by potential differences

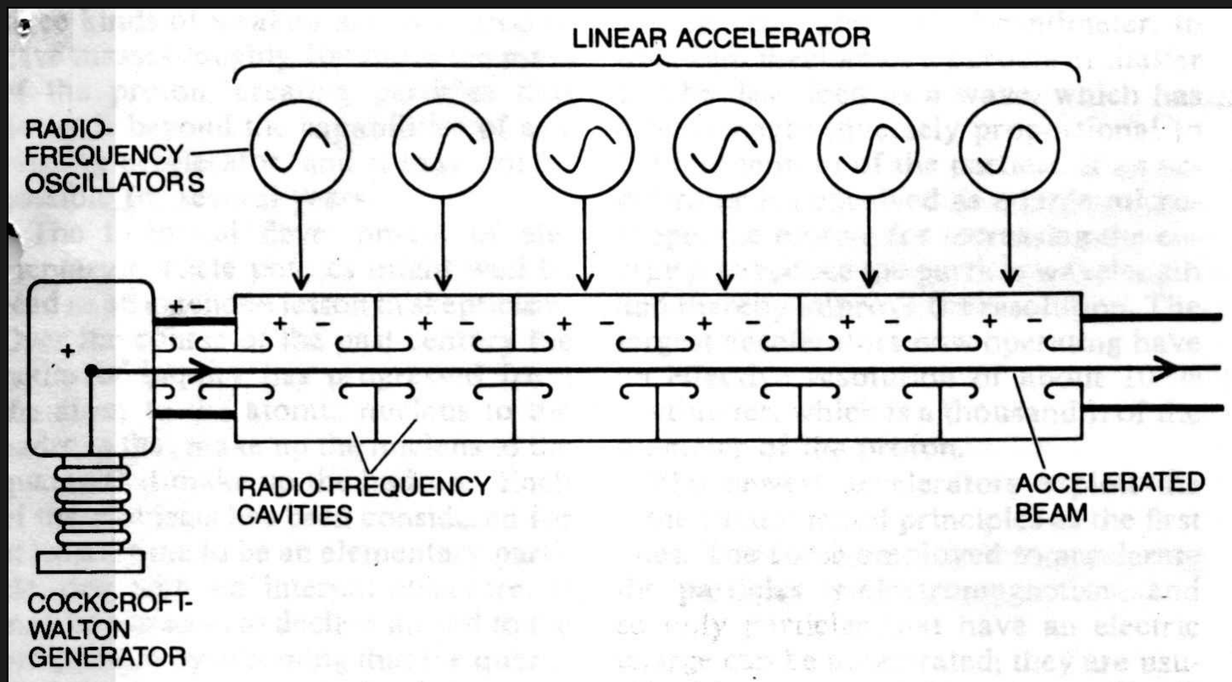
Radio-Frequency Accelerator:

The LINAC

- First constructed by R. Wideroe in 1928 ---

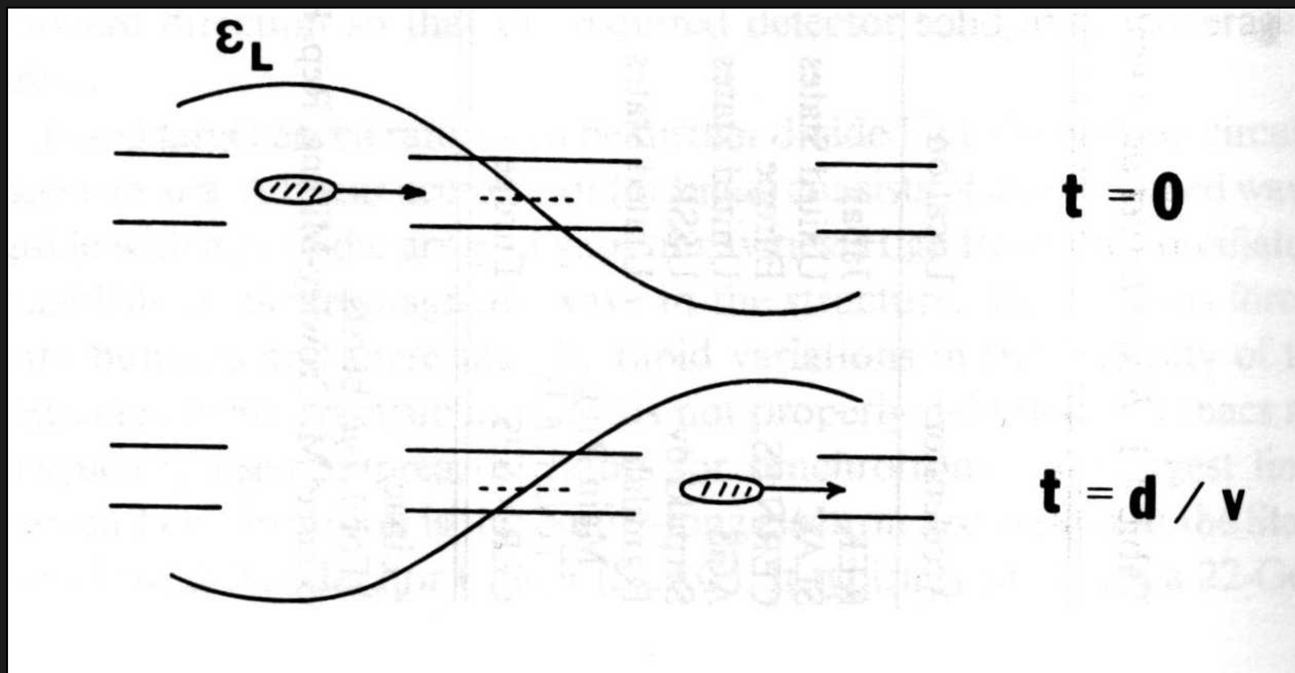
  50 keV
- Idea: replace single wide gap of large potential difference with succession of many smaller gaps having smaller potential differences
- Thus: acceleration takes place across a sequence of a large number of small steps (rather than one large step)

RF Accelerating Cavities



Wilson, Robert R; *Scientific American, The Next Generation of Particle Accelerators*; January, 1980; Volume 242, Number 1

RF Accelerating Wavefront



Fernow, Richard; *Introduction to Experimental Particle Physics*; Cambridge University Press; 1986; page 96.

Klystron RF Generator

Fermilab LINAC Photo by Ken Taylor

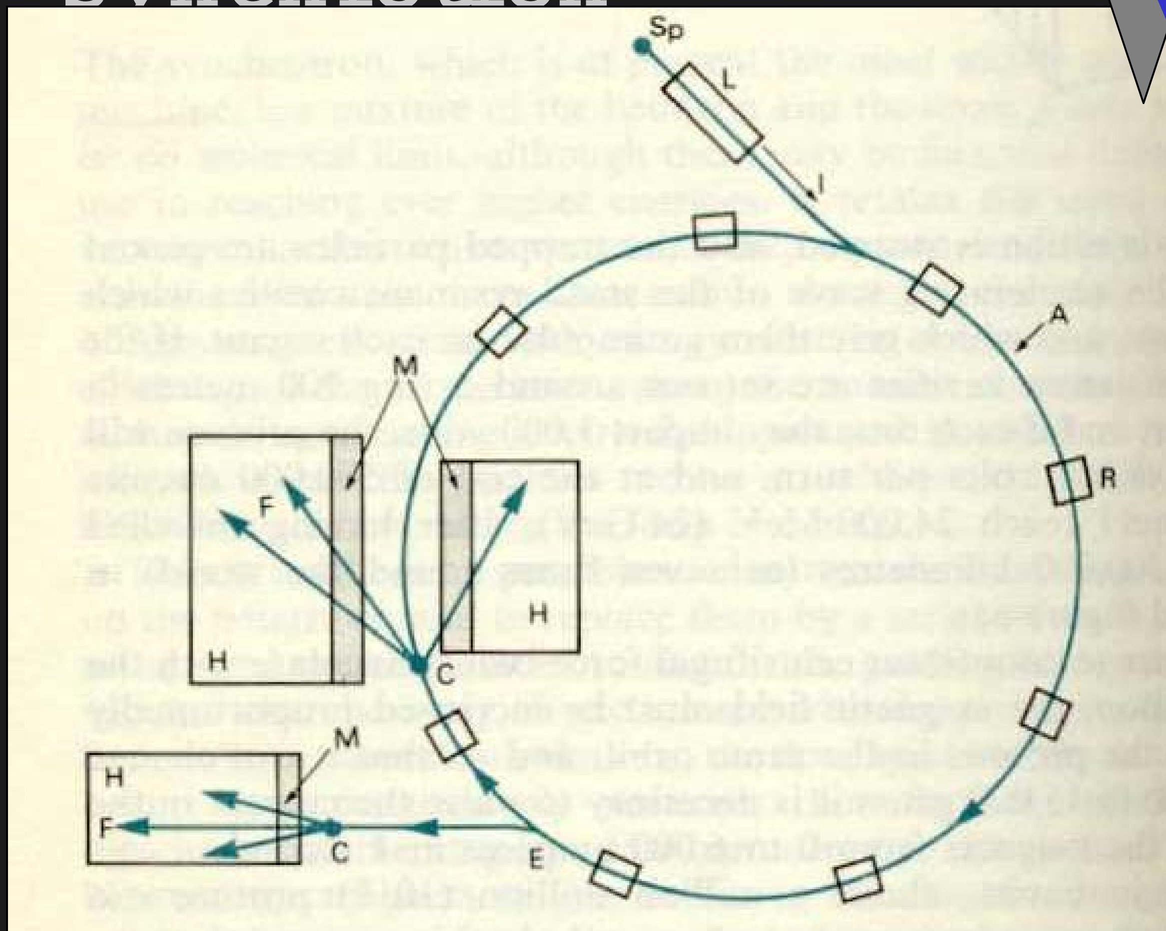
Klystron RF Generator

Fermilab LINAC Photo by Ken Taylor

Circular Accelerators: The Synchrotron

- Idea: Reuse same accelerating structure (RF type --- similar to LINAC) to save space and money
- Circular array of bending magnets (causes particles to circulate again and again and obtain energy boosts during each orbit)
- Magnetic field of magnets increases as particle energy increases in order to maintain constant radius of motion

Macro-view of Synchrotron



Gouiran, Robert; *Particles and Accelerators*; World University Press; 1967; page 208

Synchrotron

- Magnetic force provides required centripetal acceleration of moving charges
- Required force to maintain fixed radius increases due to increase in velocity and mass of charges

Synchrotron

- Maximum magnetic field of bending magnets approximately 8 - 10 Tesla
- Maximum field places limit on energy of accelerator for given radius or accelerator size
- Greater energies thus require greater real estate to reduce required centripetal force (due to larger radius)

Driver Motor

Fermilab Helium Liquifier Plant Photo by Ken Taylor

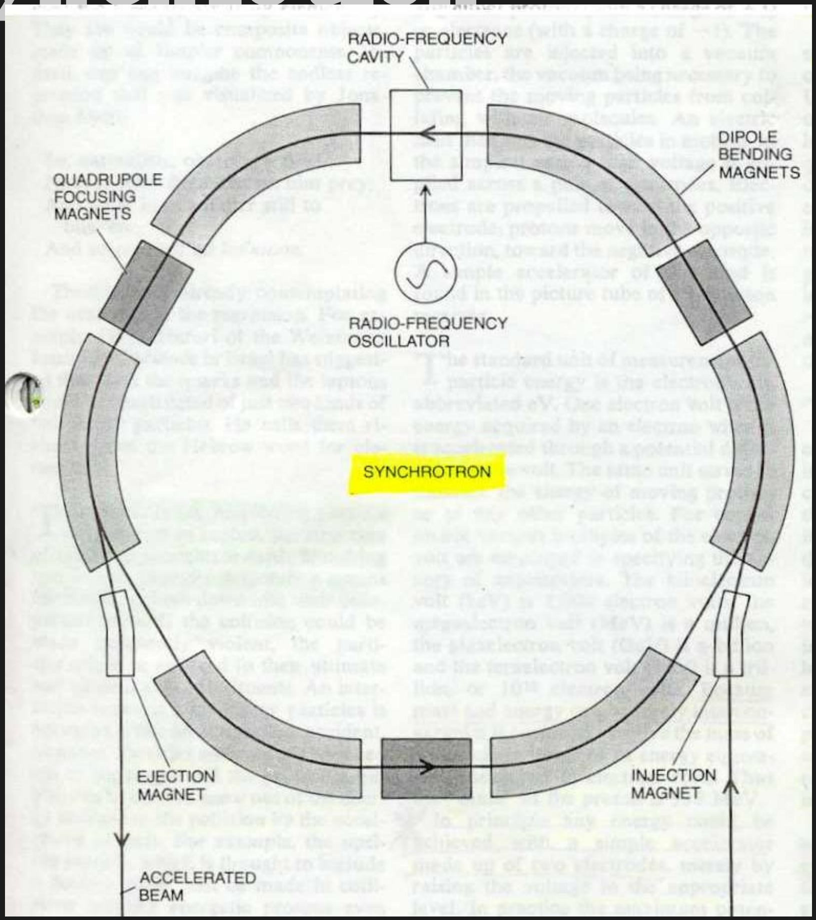
Helium Compressing Facilities

Fermilab Photo by Ken Taylor

Liquid Helium Storage Tank

Fermilab Photo by Ken Taylor

Micro-view of Synchrotron



Wilson, Robert R; *Scientific American, The Next Generation of Particle Accelerators*; January, 1980; Volume 242, Number 1

Synchrotron Radiation

- $\Delta E \ \alpha \ E^4/RM^4$
- Electrons in circular accelerators
- Protons in circular accelerators (all things being equal, protons suffer 10^{13} times less radiative losses than electrons)

Fixed-Target Beams vs Colliders

- Collider beams enjoy much greater collision energies than those for fixed-target experiments
- For colliders --- The collision energy is twice the energy of either beam

Collider Detector at Fermilab

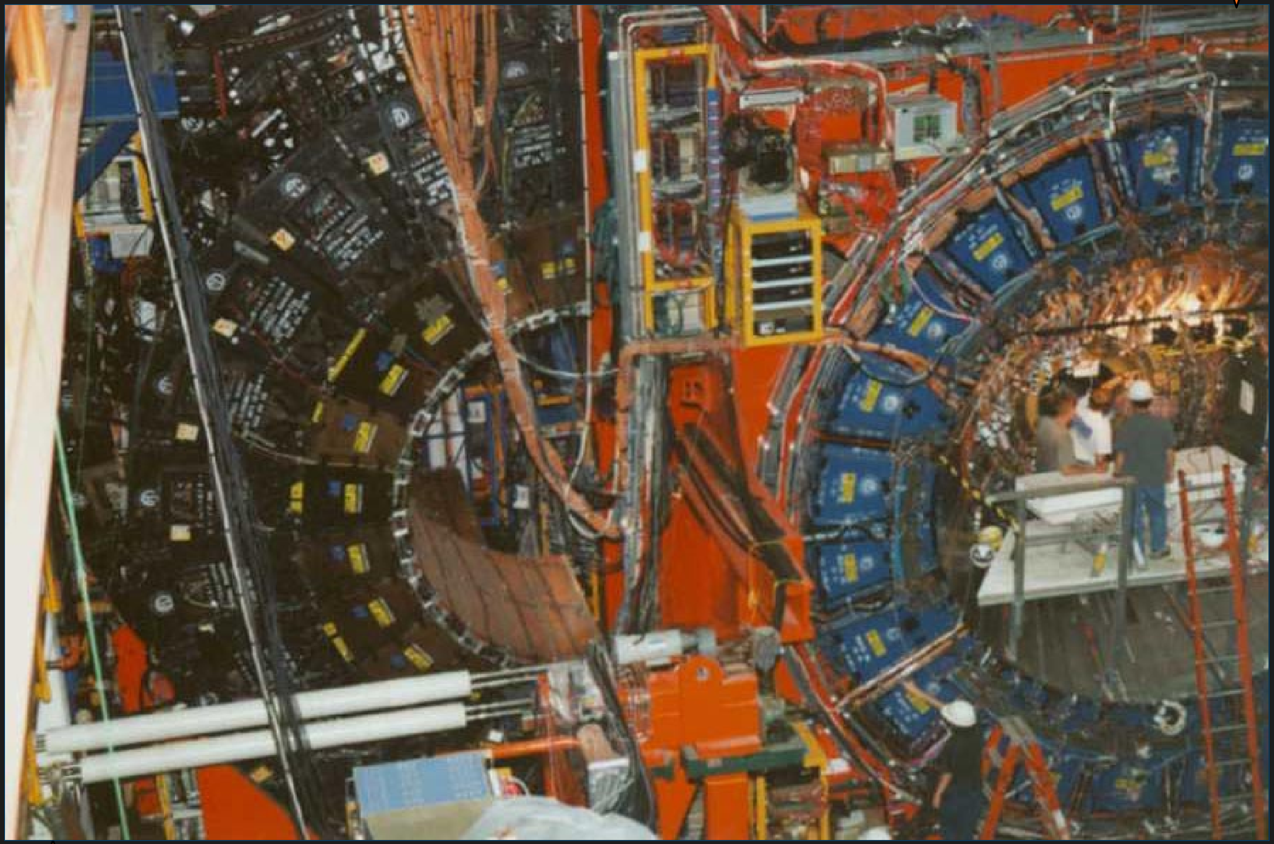
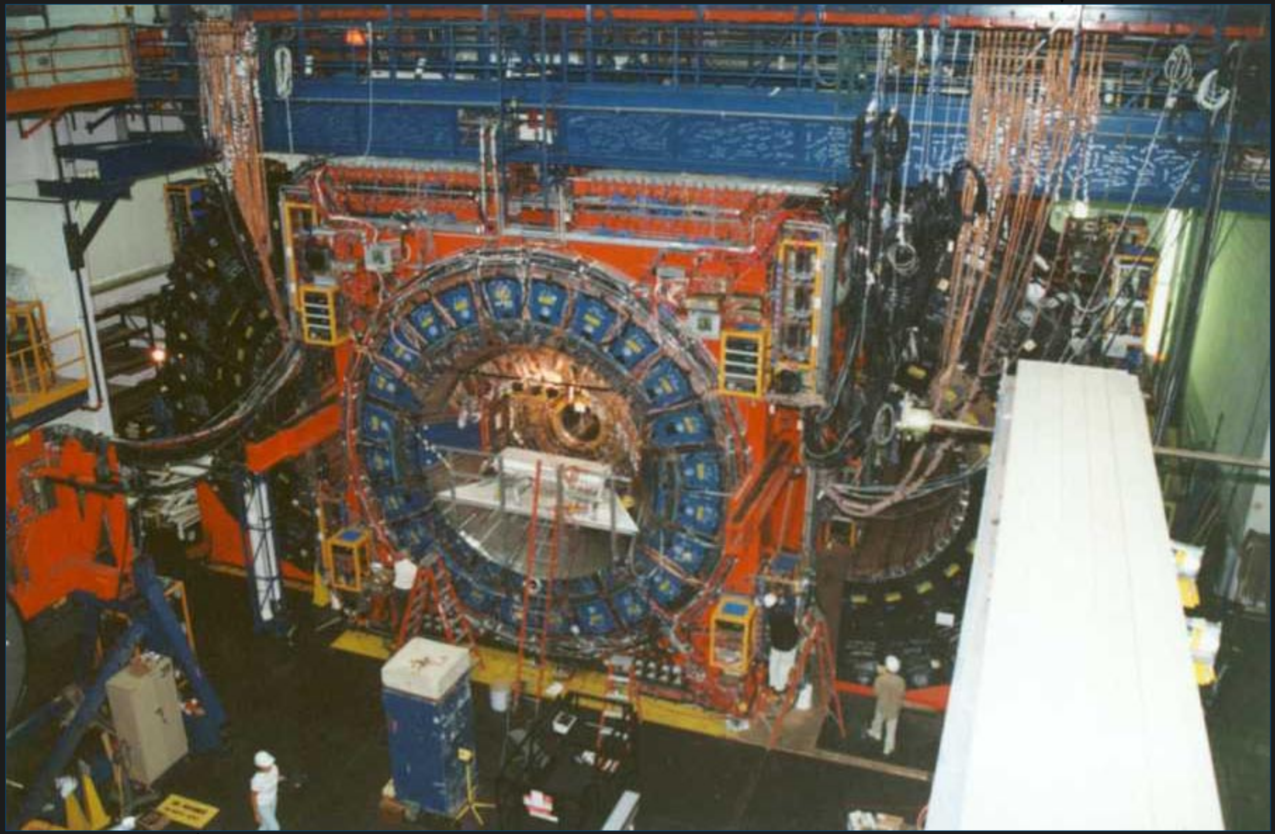


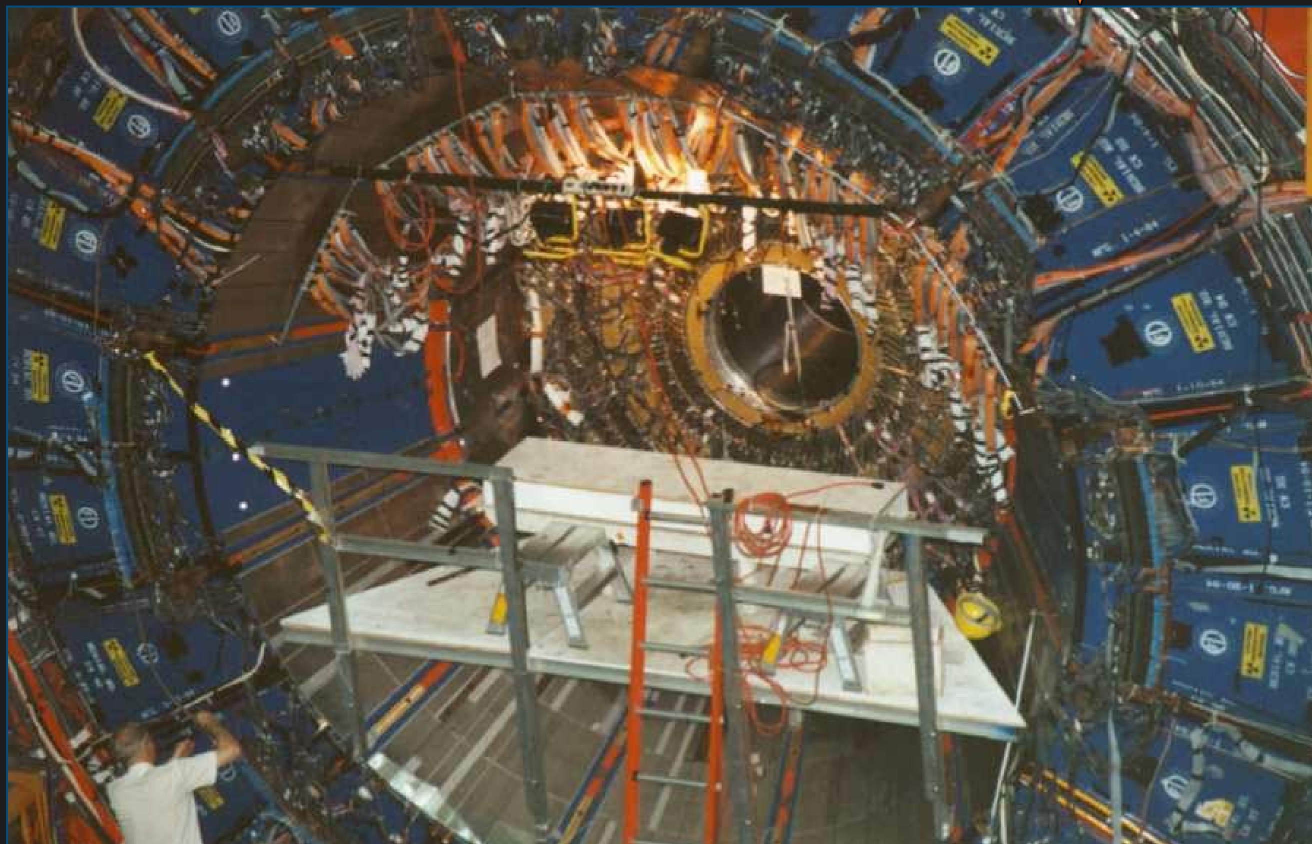
Photo by Ken Taylor

CDF



Fermilab Photo by Ken Taylor

CDF



Fermilab Photo by Ken Taylor

CDF and Assembly Area

Fermilab Photo by Ken Taylor

Aleph Experiment Hall

CERN Photo by Ken Taylor

Tunnel Near Aleph Experiment Hall

CERN - Geneva, Switzerland Photo by Ken Taylor

Atlas Construction Site

CERN Photo by Ken Taylor

Atlas Construction Workers

CERN Photo by Ken Taylor

Atlas Tunnel Excavation (looking down)

CERN Photo by Ken Taylor

Atlas Utility Tunnel (looking down)

CERN Photo by Ken Taylor

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