

PARTICLE ACCELERATORS

Prehistory:

- **α -particles**
- **cosmic rays**

Early ideas:

- **Cockcroft-Walton**
- **Van de Graaff**
- **Linear accelerator**
- **Cyclotrons**

Synchrotrons:

- **Proton synchrotrons with weak focusing**
- **Proton synchrotrons with strong focusing**
- **Secondary beams from proton accelerators**
- **Electron accelerators**

Colliders

Prehistory: α -particles as the first projectiles.

There are three types of radioactive decays of nuclei: α , β , γ . The classification is based on the charge of emitted particles, which can be positive (α -particles), negative (β -particles), and neutral (γ -particles). A typical energy released in nuclear decays is of the order of 1 MeV, a few MeV at most.

In β -decay, a neutron decays to proton, electron, and anti-neutrino. As a result, the original element (Z,A) becomes ($Z+1,A$), while electron and neutrino are emitted (neutrino escapes undetected). A newly formed nucleus (eg as a result of a β -decay) is not necessarily at its ground energy state, i.e. it may be excited. There are two typical ways how such excitation can be released: via emitting a high energy photon (γ -ray) or by shedding a nucleus of helium (two protons and two neutrons form a very strongly bound system and therefore get emitted in such a combination).

1900s Rutherford figured out that α -particles were He nuclei.

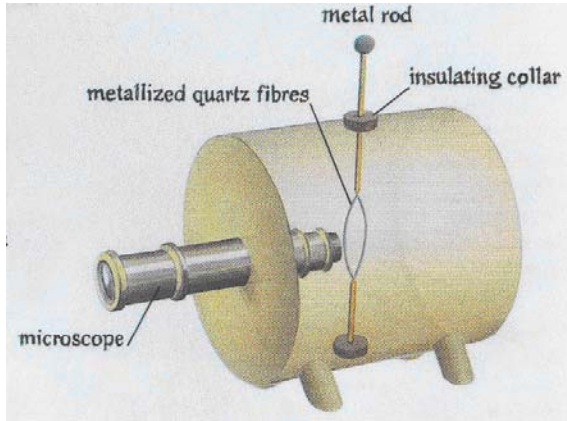
1910 Rutherford and Madsen were the first to use α -particles to bombard atoms with the goal to gain insights in the atom structure from α -particle scattering patterns. They did detect the presence of a **nucleus**.

1910s Rutherford and Madsen kicked out **protons** from various elements by bombarding them with α -particles.

1930s Bothe and Becker, Joliot-Curie family, Chadwick knocked out neutrons by bombarding Be nuclei with α -particles: $\alpha + \text{Be}^9 \rightarrow \text{C}^{13} + \text{n}$. Chadwick convincingly showed that the emerging particles were **neutrons**.

Prehistory: Cosmic Rays

1900s Physicists were looking for radioactivity using electroscopes and electrometers, devices that allowed sensing the level of ionization. They started seeing that there was some radiation present even when all radioactive sources were removed far away from the apparatus.



1910 Father **Theodore Wulf** climbed up at the top of the Eiffel tower and saw a somewhat increased level of radiation. He speculated that the radiation might have an extraterrestrial origin and suggested doing similar measurements at higher altitudes.

1911-12 **Victor Hess** made 10 balloon ascends reaching altitudes of 5000 m and indeed observed the level of radiation increasing by a factor of 3-5 in comparison to the sea level. In 1936, he received the Nobel Prize “for his discovery of cosmic radiation”

Important note: the “cosmic rays” we see at the sea level are not really cosmic. The primary cosmic rays, when they hit upper layers of the atmosphere, produce showers of particles some of which reach the sea level. The highest energy primary cosmic rays that we have seen so far are of the order of $\sim 10^{20}$ eV (!!!)



1932 Anderson discovered **positron**, e^+

1937 Anderson and Neddermeyer discovered **muons**, μ^\pm

1947 Lattes, Occhialini, Powell discovered charged **pions** π^\pm (hadrons made of $\bar{u}d$ and $\bar{d}u$ quark pairs)

1940s Discoveries of the first **strange particles**: K^\pm , K^0 , Λ , Σ^+ (hadrons with one strange quark)

The difficulty of this path was that one had no control over the projectiles and their rate was rather scarce... Once the accelerators reached the energy sufficient for creating new particles, the experimentalists happily changed from hunters to farmers.

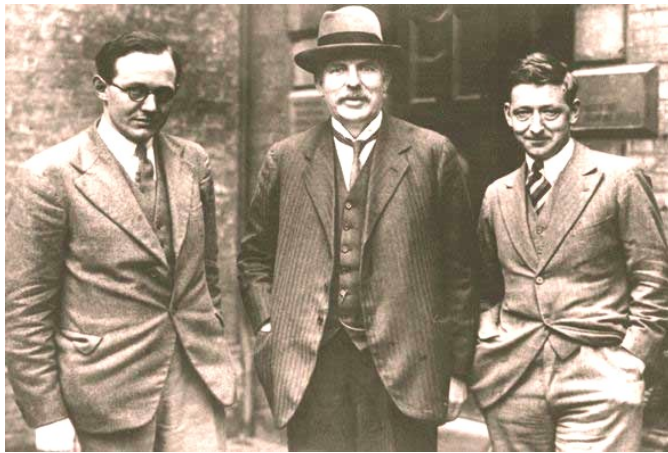
Early Ideas (1): Cockcroft-Walton

1928-1932

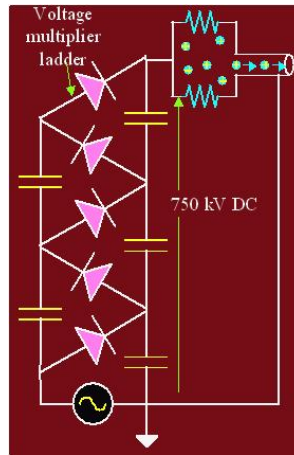
D. Cockcroft and T. Walton (Rutherford's Lab in Cambridge) invented/applied a combination of large transformer combined with a rectifier to accelerate protons to ~1 MeV. The main idea is to charge a capacitor to a large potential and accelerate particles in its field. It is very hard to go above ~1 MV due to discharges through air and along material surfaces. The energy is just comparable to that of α -particles, but one can reach much higher and more focused intensity.

Cockcroft and Walton observed and fully reconstructed the first artificial transmutation: $p+Li \rightarrow 2 He$. In 1951, they shared the Nobel Prize "for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"

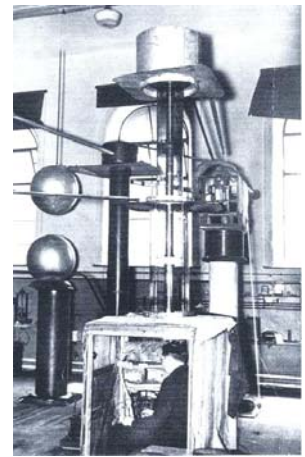
Cockcroft-Walton accelerator is the first elements in most contemporary accelerators:



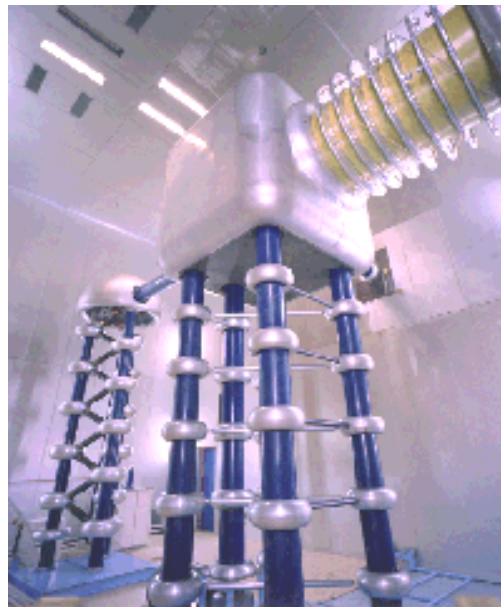
Cockcroft and Walton with Rutherford in the center



Concept



First Accelerator



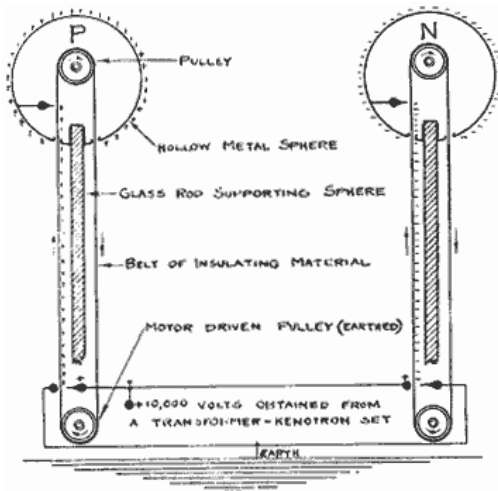
Cockcroft-Walton Accelerator at Tevatron, Fermilab

Early Ideas (2): Van de Graaff

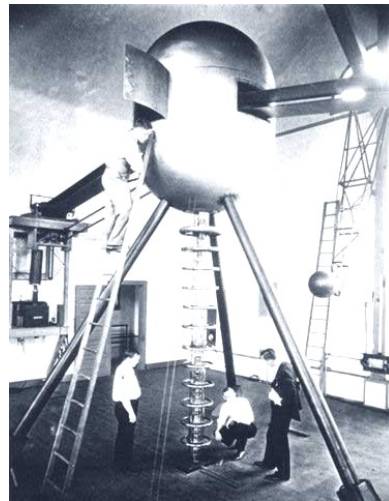
- 1929 **Robert J. Van de Graaff** (postdoc at Princeton) invents a high voltage generator and builds the first 80 kV model
- 1931 Two-sphere generator of -0.75 MV and $+0.75$ MV, to give total 1.5 MV
- 1933 Generator of 7 MV is built at MIT.



Van de Graaff accelerators cannot go much beyond of 10-20 MV. They are still in use for nuclear physics and material science studies. They are known for very smooth operation. To double the energy, one can do a trick by first accelerating negatively charged ions towards the positively charged Van de Graaff sphere, stripping off electrons from the ions as they pass through the center of the globe, and, thus, accelerating them again away from the sphere. Such a scheme is called a tandem Van de Graaff accelerator. One of the biggest tandem accelerators was used for many years at Daresbury in the United Kingdom. Its acceleration tube, placed vertically, was 42 meters long and the centre terminal could hold a potential of up to 20 MV. It was not used for elementary particle physics research.



Concept of Van de Graaff Accelerator



Early Van de Graaff Generator

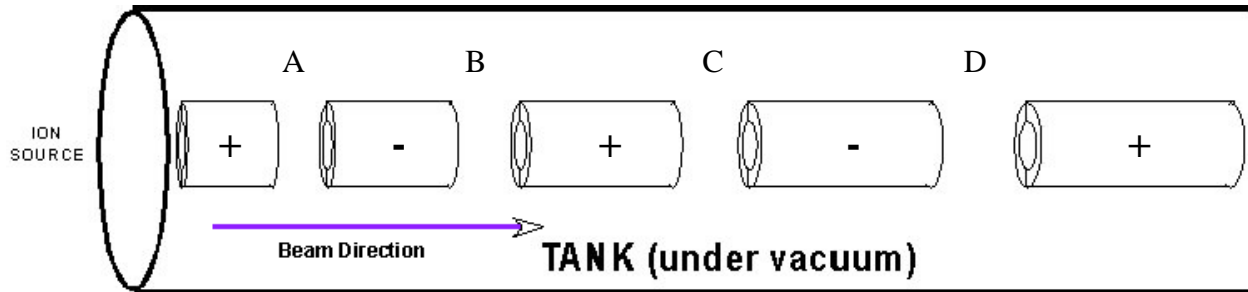


Early Ideas (3): Linear Accelerator

The Cockcroft-Walton and Van de Graaff accelerators are machines with static field. Therefore, the acceleration of particles happens in one step. The linear accelerator employs the idea of kicking charged particle a few times (multi-stage acceleration), which requires quick alternation of potentials. Beam of particles necessarily becomes bunched.

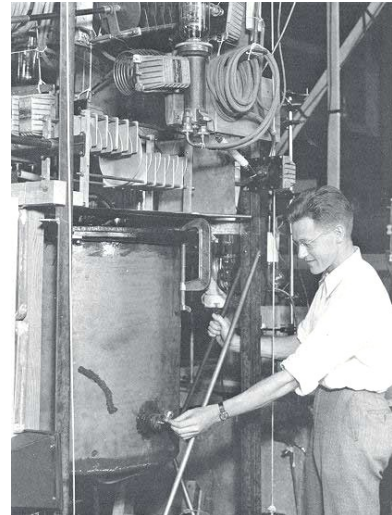


1929 **Wideroe** invented a multi-gap drift lineal accelerator (LINAC) and built a small 3-stage prototype.



Concept:

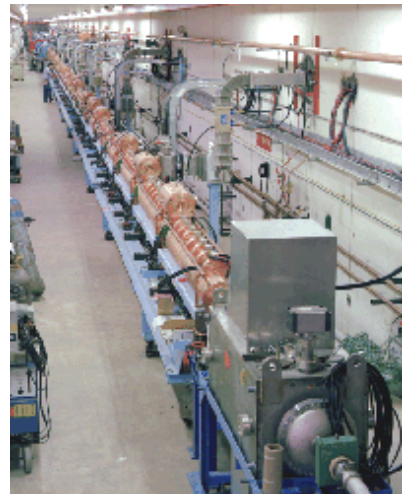
- charged particles (e.g., electrons) travel through hollow conducting cylinders placed in the vacuum pipe;
- alternative potentials $V(t)=V_0\cos(\omega t)$ and $V(t)=V_0\cos(\omega t+\pi)$ are applied to odd/even numbered cylinders;
- therefore, at any moment only half of the gaps have field in accelerating direction and particles should go through these gaps at that time; let's assume that a bunch of electrons at time $t=0$ crosses gap B—the electrons will be accelerated and gain energy eV_0 .
- when signs of potentials are getting reversed, the particles travel through the cylinders and do not see any electric field
- by the time when particles emerge in the next gap C, it must have its field reversed, i.e. the field in that gap will again point in the accelerating direction and the electrons will gain another energy increment eV_0 .
- since the frequency of potential alterations is constant, the length of cylinders is tuned to match the accelerating speed of particles so that cross the gaps at right moments.



D. Sloan and his 1 MeV LINAC

1931 **D. Sloan** (UC-Berkeley, Lawrence group) built a LINAC that could accelerate Hg ions up to 1 MeV. However, further research in this direction was set aside. It did not look economical to escalate the number of accelerating gaps in comparison to the new idea of cyclotrons also being developed at Berkeley when particles were brought back to the same accelerating gaps by turning them around in magnetic field.

The idea will be revived again later. E.g., linear accelerators nowadays are a standard element of all modern accelerators. Also, there are some linear accelerators where the LINAC is the main thing: 45 GeV electron-positron LINAC at Stanford and 800 MeV proton LINAC at Los Alamos National Lab. These two are the largest in the world for electron and proton beams, respectively. Furthermore, a future electron-positron collider now under serious consideration can be built based only on the linear accelerator technology (to be discussed further below).



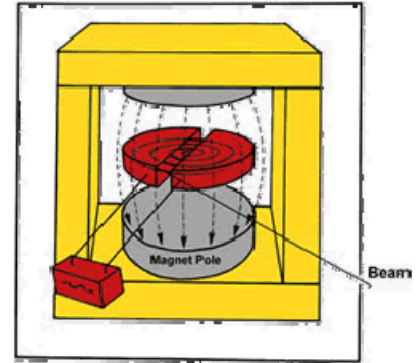
400 MeV LINAC at Fermilab

Early Ideas (4): Cyclotrons

1930 **Ernest O. Lawrence** (UC-Berkley) invents a Cyclotron

Concept:

- Non-relativistic particle rotates in magnetic field with a period independent of its velocity: $T=2\pi m/eB$
- Make a conducting drum and cut it along the diameter line
- Apply an alternating potential of correct frequency $\nu=(eB/2\pi m)$; for protons and about 1 T field it would be ~ 20 MHz—challenge at the time...
- Inject charged particles in the center; as they accelerate in the gap between drum halves (dees), their radius increases, but they always get into the gap at right phase
- Maximum kinetic energy will depend on the maximum radius available, i.e. the size of a cyclotron: $KE=0.5\pi^2 v^2 R^2 m$, which for protons and 1 T field is $\sim 50R^2$ MeV (where R should be expressed in meters);
- Slightly bulging outward magnetic field automatically keeps particles in the mid-plane of the dees (do the Lorentz force right hand rule to see it!).



1931-39 5" model: 80 keV H⁺, 11" model; 27" Cyclotron (5 MeV deuterium), 37" Cyclotron (8 MeV d, 16 MeV α), then in 1939 60" Cyclotron, 220 ton magnet: $E_{\max} \sim 10$ MeV

1938 *first artificial element Technetium (Z=43)* (via X-ray spectroscopic analysis of irradiated metal scraps)

1939 **Ernest O. Lawrence** received Nobel Prize "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

Further progress is hindered by the onset of relativistic kinematics. Speed of particles starts saturating so that it takes them longer and longer to turn at larger radii and they finally fall out of synch with the cyclotron frequency—one would need to adjust the frequency as particles accelerate. It was not clear how this can be done in sync with the accelerating process itself.

1945 **V. I. Veksler** and, independently, **E. M. McMillan** introduced the idea of "phase stability" that actually allowed one to overcome the relativistic limitations of a classical cyclotron.

1948 184" Synchrocyclotron at Berkley, 4,000 tons, 350 MeV protons (this energy now is sufficient to start producing pions, ~ 140 MeV particles)

1950 *Observation/discovery of π^0 , the first man-made hadron, in 1950 at the 350 MeV Berkley Cyclotron*

1952 *Observation of Δ -resonance in 1952 (Chicago University cyclotron)*

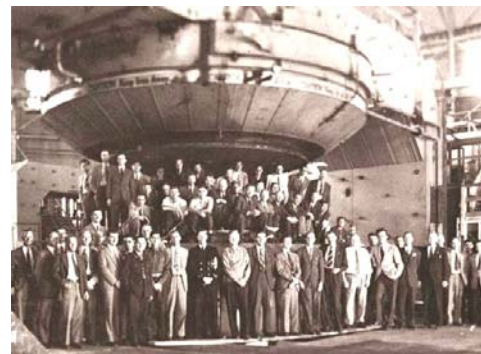
Higher energy cyclotrons would require larger and larger magnets and further advances in increasing the energy of protons were becoming cost prohibitive. Luckily, the idea of synchrotrons came to replace cyclotrons. Nevertheless, cyclotrons are still being used in many research areas where moderate energy beams of very high intensity are needed. For example, the PSI cyclotron in Switzerland, built in 1974, provides a 2 mA beam of 590 MeV protons.



E. O. Lawrence



The first 5" Cyclotron (80 keV H⁺)



350 MeV 184" Synchrocyclotron at Berkeley

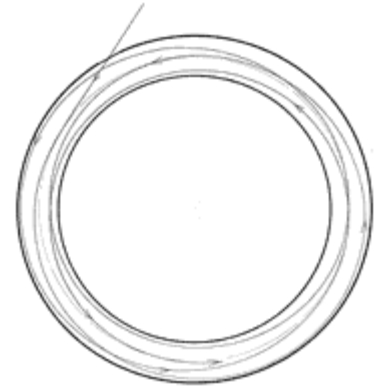
Large Accelerators: Synchrotrons with weak focusing

The key idea is to keep particles at the same radius and adjust B-field as they accelerate (of course, one will need to synchronize frequency of high voltage applied to accelerating elements, and even more so than in the case of synchrocyclotrons). However, the advantage is obvious: there would be no need to fill in the inner area of the ring with magnetic field—tremendous savings for large energy accelerators!

Stability for particle orbits during time of a an acceleration cycle of 1 s or so was made possible by taking advantage of the discovery of phase stability (discussed earlier) and week focusing principle.

Weak focusing requires the magnetic field

- a) bulge outward (same as in the case of cyclotrons)—this insures vertical stability
- b) become stronger outward—this causes particle going outward bend more and particles going inward bend less; as the result particles stay more or less around the nominal radius orbit. However, the spread is not small and large aperture magnets and vacuum beam lines are needed



Weak focusing accelerator

- 1952 **Cosmotron 3 GeV** (Brookhaven)¹, 75 ft diameter, 8x12 inches aperture
 → *Discovery of many strange particles (earlier a few of them had been found in cosmic rays).*
- 1954 **Bevatron 6.4 GeV** (UC-Berkley), 150 ft across
 → *Discovery of antiproton in 1956*
 → *Discovery of many resonances*

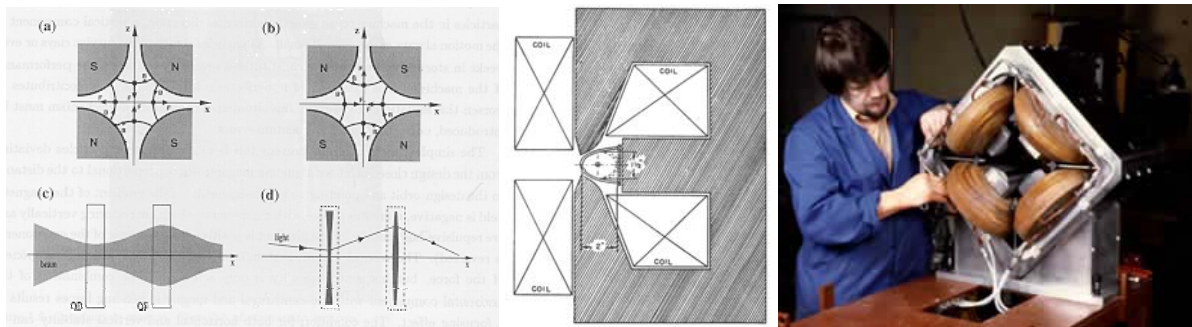


¹ Actually, Cosmotron started out from ~1 GeV and only later reached 3 GeV.

Huge Accelerators: Synchrotrons with strong focusing

1952 **E. D. Courant, M. S. Livingston, H. S. Snyder** put forward an idea of strong focusing, or alternating-gradient. **N. Christofilos** discovered the same principle two years earlier, but the paper was not published

A quadrupole magnet formed by two North and two South poles has zero field along its axis. A charged particle that deviates from the axis will either be focused or defocused depending on whether it moves in x-z plane or in y-z plane. A series of quadrupole magnets with alternating focus/defocus/focus/defocus actions in each plane turn out to have an overall focusing effect. This scheme is called either alternating gradient or strong focusing. This method allows one to keep particles in a beam of sub-mm diameter inside a vacuum chamber of a small aperture, a few cm in diameter (compare to apertures of weak focusing synchrotrons whose beam line chambers are large enough to allow a person to walk inside). Thus, accelerators of much larger diameters become cost-wise feasible.



The shape of accelerators changed one more time. Instead of magnets providing continuous ϕ -angle independent field along a circumference of some radius R , the accelerators now look like a string of magnets, some of which have dipole field and provide overall bending and some have quadrupole field and keep beam tightly squeezed. The accelerators stepped out from experimental halls and their sizes are now measured in kilometers!

- 1959 **28 GeV PS at CERN**
(PS—proton synchrotron)
→ 1973 *Neutral Currents*
- 1960 **33 GeV AGS at Brookhaven**
(AGS—alternating gradient synchrotron)
→ 1962: *discovery of muon neutrinos*
→ 1963: *discovery of CP violation*
→ 1964: *discovery of Ω -particle*
→ 1974: *discovery of J/ψ -particle (c-quark)*
→ 1975: *charmed baryon*
- 1967 **76 GeV U70 at Serpukhov, Russia**
- 1975 **500 GeV machine at Fermilab (upgrade)**
→ 1977: *discovery of Υ -particle (b-quark)*
- 1976 **450 GeV SPS at CERN, $2\pi r=7$ km**
- 1984 **1000 GeV machine at Fermilab, $2\pi r=6$ km:**
(with superconducting magnets)
- Cockcroft-Walton accelerator: 0.75 MeV
 - LINAC: 200 MeV
 - Synchrotron booster: 8 GeV
 - Final Synchrotron: 1 TeV
 - 140,000 revolutions
 - 2.8 MeV per revolution
 - 10 s



Fermilab lab site (aerial view)

Proton accelerators: secondary beams

Secondary beams

- o π beam
- o K beam
- o μ beam
- o ν beam
- o neutrals (γ , K_L , n)

π/K beams:

- collide protons with a target, lots of pions and some Kaons will be produced
- bend charged particles with a magnet;
- use a collimator (a narrow slit) to select particles of desired momentum; focus them into a beam
- guide the beam toward a fixed target experiment

μ beams:

- do everything as above, but instead of guiding the beam to an experiment,
- lead the beam into a long vacuum pipe and let pions decay into muons and neutrinos ($\pi \rightarrow \mu \nu$)
- block away remaining pions with a slab of iron/dirt
- focus muons into a beam

ν beams:

- do everything as above, but at the end sweep away muons with a magnet; what remains are ν 's.

Accelerators: Electron Beams

Earlier electron synchrotrons

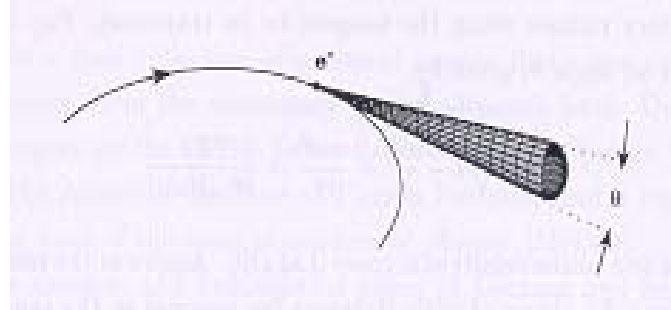
1954	1.5 GeV Cornell
1962	6 GeV Harvard-MIT
1964	7 GeV DESY

Considering the energy per particle, why did electron synchrotrons lag so much behind proton synchrotrons? And they still do.

There is a serious problem with electrons—they have very small mass and therefore experience very large accelerations as compared to protons of the same energy and traveling along the same circles. Energy losses are proportional to the fourth power of acceleration and per one turn are

$$\Delta E \text{ (GeV)} = 6 \cdot 10^{-18} / R(\text{m}) \times (E/\text{m})^4$$

Since electrons are ~2000 times lighter than protons, they radiate 10^{13} times more energy!



There are two ways to beat it: build larger radius circular accelerators or build linear accelerators...

1966 **22 GeV SLAC (Linac)**
 → 1969 discovery of point-like constituents in proton

1989 Upgraded to 45 GeV and made to accelerate electron and positron beams, split them into two arches that would bring the beams in a collision point...

Colliders: idea

To utilize the electron beam more efficiently, people started contemplating beam-beam colliders. This seemed to be a real possibility after the discovering the strong focusing mechanism in 1952. As estimation were showing, beams of feasible intensity and being squeezed to tens of microns would result in meaningful rates of reactions/scatterings...

GAIN: center-of-mass energy: $E_{cm}=2E_{beam}$ vs. $E_{cm}=\sqrt{(2mE_{beam})}$

CHALLENGES:

1) Luminosity L: Rate (reactions/sec) = $L(\text{luminosity, cm}^{-2}\text{s}^{-1}) \times \sigma(\text{cross section, cm}^2)$

For fixed target experiments,

L can be derived as follows:

$$\text{Rate} = J \cdot n \cdot dx \cdot \sigma$$

$$L = J \cdot n \cdot dx$$

For 1 m Liquid Hydrogen target and

for typical beam intensity of 10^{13} protons per spill every 10 s

$L=10^{37} \text{ cm}^{-2}\text{s}^{-1}$, which is many orders of magnitude larger than we can ever hope for in colliders

For colliders,

L will depend on intensity and size of beams as well as frequency of beam bunch collisions:

$$\text{Rate} = L\sigma = J \cdot (n \cdot dx) \cdot \sigma$$

$$L = (fN_1) \cdot (N_2/A) = f \cdot (N_1 \cdot N_2) / A$$

To make colliders meaningful for physics, one needs to push the following aspects of accelerator technology:

(a) high beam intensity (accumulate and store lots of particles, 10^{13})

(b) extremely squeezed beams (microns)

(c) make bunch collisions as often as possible (MHz)

(d) ensure beam stability over much-much longer times (hours!)

2) Electron-Positron colliders: Synchrotron radiation (relevant for electron-positrons)

Electrons/positrons, having very small mass, loose large amount of energy as they turn along their circular orbits. Therefore, one needs to add more and more energy on every turn to compensate for the losses.

$$\Delta E/\text{turn} = (4\pi/3) \cdot e^2/R \cdot \beta^3 \gamma^4$$

$$10 \text{ GeV at } R=1 \text{ km} \quad \rightarrow \quad 1 \text{ MeV per turn}$$

$$50 \text{ GeV at } R=5 \text{ km} \quad \rightarrow \quad 200 \text{ MeV per turn}$$

$$100 \text{ GeV at } R=5 \text{ km} \quad \rightarrow \quad 3.8 \text{ GeV per turn}$$

(same tunnel as will be used for LHC with 7 TeV beams of protons)

3) Proton-antiproton colliders: making a neat beam of antiprotons.

Antiprotons are produced in hadron collisions with very large spread of momenta and directions. They need to be squeezed into thin highly collinear beams. In 1970 Simon van der Meer from CERN showed that by so-called *stochastic cooling* one can substantially reduce the transverse momentum spread of antiprotons—this was the key for embarking on $\bar{p}p$ colliders at CERN and Fermilab. The basis of the idea is to detect an average transverse deflection of an antiproton bunch and give it a correcting kick. After so many rotations, the dispersion of transverse momenta of antiprotons gets reduced by a factor of 10^4 . Only after achieved that, the luminosity of proton-antiproton colliders would have a chance to become meaningful.

Major Colliders

Year	e^+e^- colliders			hadron colliders			Major Discoveries
	Name/Place	\sqrt{s} , GeV	$L, \text{cm}^{-2}\text{s}^{-1}$	Name/Place	\sqrt{s} , GeV	$L, \text{cm}^{-2}\text{s}^{-1}$	
1972	SPEAR/Stanford	8	10^{32}				ψ , τ , quark jets
1973				ISR/CERN	pp 62	$2 \cdot 10^{32}$	
1974	DORIS/DESY	10	10^{32}				
1979	CESR/Cornell	16	$9 \cdot 10^{31}$				
1979	PETRA	46	10^{31}				gluon jets
1980	PEP/Stanford	30	$8 \cdot 10^{31}$				
1981				SppS/CERN	$\bar{p}p$ 630	$3 \cdot 10^{30}$	W, Z
1987	TRISTAN/KEK	60	10^{31}				
1987				Tevatron I	$\bar{p}p$ 1800	$2 \cdot 10^{31}$	t-quark
1989	SLC/Stanford	92	10^{28}				N_ν
1989	LEP/CERN	92	$6 \cdot 10^{30}$				N_ν , Precision SM
1995-	LEP-II/CERN	200	$2 \cdot 10^{31}$				Precision SM
2001				Tevatron II	$\bar{p}p$ 2000	$2 \cdot 10^{32}$	
(2007)				LHC/CERN	$\bar{p}p$ 14000	10^{34}	(Higgs? SUSY?)
Special purpose machines							
1991	HERA/DESY	$(30 e^\pm) \times (820 p)$	$2 \cdot 10^{31}$	electron-proton collider			
1999	PEP-II/SLAC	e^+e^- 11	$6 \cdot 10^{33}$	B-factory for studies of CP violation			
1999	KEK-B/KEK	e^+e^- 11	10^{34}	B-factory for studies of CP violation			
1999	DAFNE/Italy	e^+e^- 1	$5 \cdot 10^{31}$	ϕ -factory: rear K meson decays			
2000	RHIC/BNL	$(100/N) \times (100/N)$		Heavy ions: Quark Gluon Plasma			

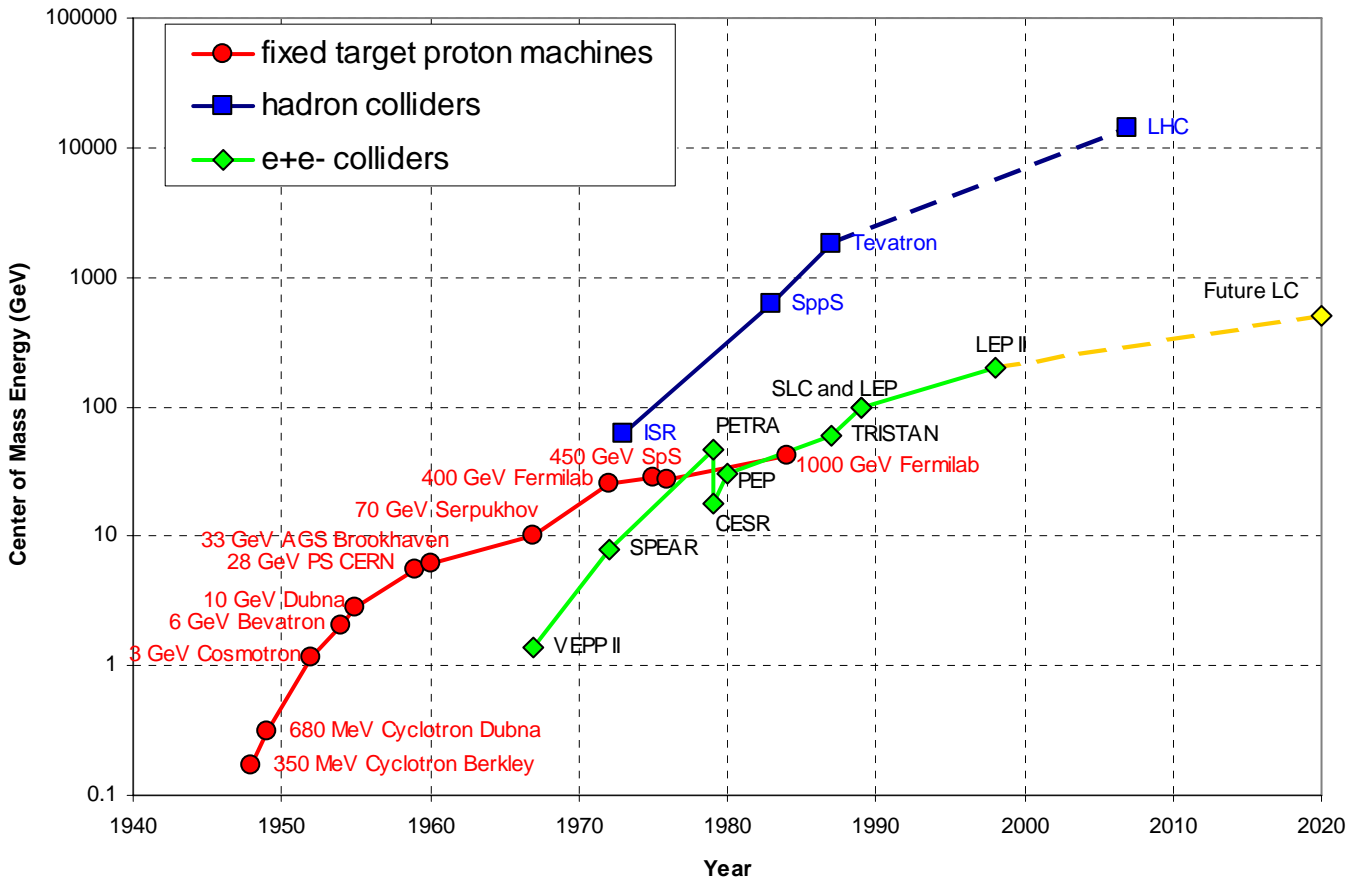


Important jargon: Integrated Luminosity $L_{\text{int}} = \int L dt$

Measured in inverse units of cross section, pb^{-1} , fb^{-1}

For example, the current integrated luminosity of Tevatron (integrated since its start in 2001) is $\sim 2 \text{ fb}^{-1}$
 LHC at its full instantaneous luminosity will deliver $\sim 100 \text{ fb}^{-1}$ per year

Accelerators and Colliders: Summary



World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wieszczycka (See U. Amaldi Europhysics News, June 31, 2000)

Category	Number
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110