Lecture 1a

Introduction to Accelerators

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What are accelerators used for?

- Particle accelerators are devices that produce energetic beams of particles which are used for
  - Understanding the fundamental building blocks of nature and the forces that act upon them (nuclear and particle physics)
  - Understanding the structure and dynamics of materials and their properties (physics, chemistry, biology, medicine)
  - Medical treatment of tumors and cancers
  - Production of medical isotopes
  - Sterilization
  - Ion Implantation to modify the surfaces of materials
  - National Security: cargo inspection, …

- There is active, ongoing work to utilize particle accelerators for
  - Transmutation of nuclear waste
  - Generating power more safely in sub-critical nuclear reactors

Accelerators by the Numbers

<table>
<tr><td colspan="2">World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)</td></tr>
<tr><th>Category</th><th>Number</th></tr>
<tr><td>Ion implanters and surface modifications</td><td>7,000</td></tr>
<tr><td>Accelerators in industry</td><td>1,500</td></tr>
<tr><td>Accelerators in non-nuclear research</td><td>1,000</td></tr>
<tr><td>Radiotherapy</td><td>5,000</td></tr>
<tr><td>Medical isotopes production</td><td>200</td></tr>
<tr><td>Hadron therapy</td><td>20</td></tr>
<tr><td>Synchrotron radiation sources</td><td>70</td></tr>
<tr><td>Nuclear and particle physics research</td><td>110</td></tr>
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Nuclear and Particle Physics

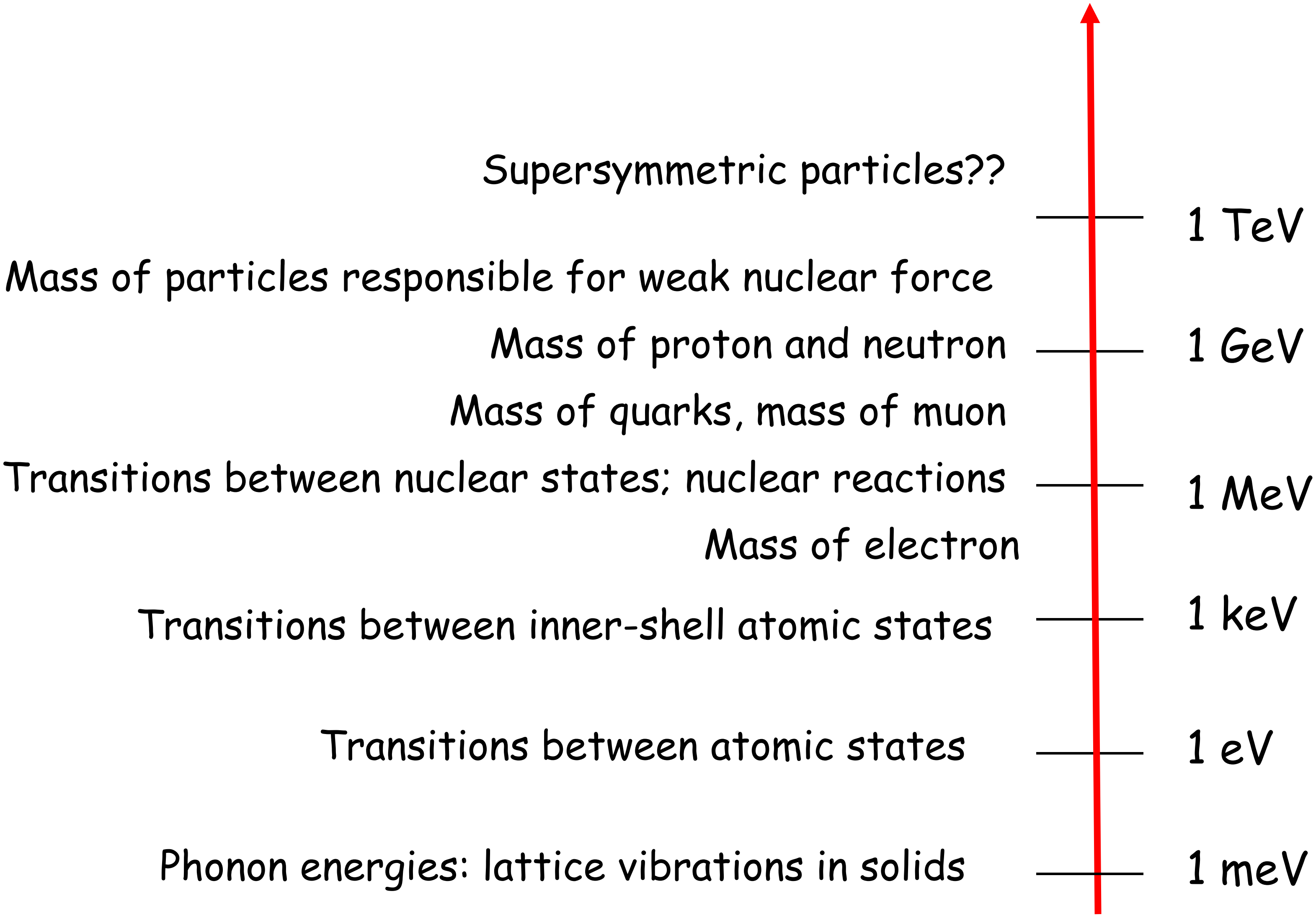
- Much of what we know about the subatomic world is from experiments enabled by particle accelerators
- The first “high-energy” accelerator, made by Cockroft and Walton, was immediately used to understand the atomic nucleus. They made the first artificially produced nuclear reaction:

$$p + Li \rightarrow 2\,He$$

- Early accelerator developments were driven by the quest for higher and higher particle energies, which in turn was driven by developments in nuclear physics (through the 1960s) and then elementary particle physics (1960s-onward)
- The largest accelerator is beginning operation at CERN. It will collide two proton beams of energy 7 TeV each

Energies in the atomic and subatomic world

- Energies are measured in **electron-volts (eV)**



Supersymmetric particles??

1 TeV

Mass of particles responsible for weak nuclear force

Mass of proton and neutron

1 GeV

Mass of quarks, mass of muon

Transitions between nuclear states; nuclear reactions

1 MeV

Mass of electron

Transitions between inner-shell atomic states

1 keV

Transitions between atomic states

1 eV

Phonon energies: lattice vibrations in solids

1 meV

Creation of new particles

- Einstein's famous equation: $E=mc^2$ puts mass and energy on an equal footing.
- An energetic particle has total relativistic energy

  $E = T + m_0c^2$
- One particle colliding with its antimatter partner can annihilate and produces pairs of other particles. Example:

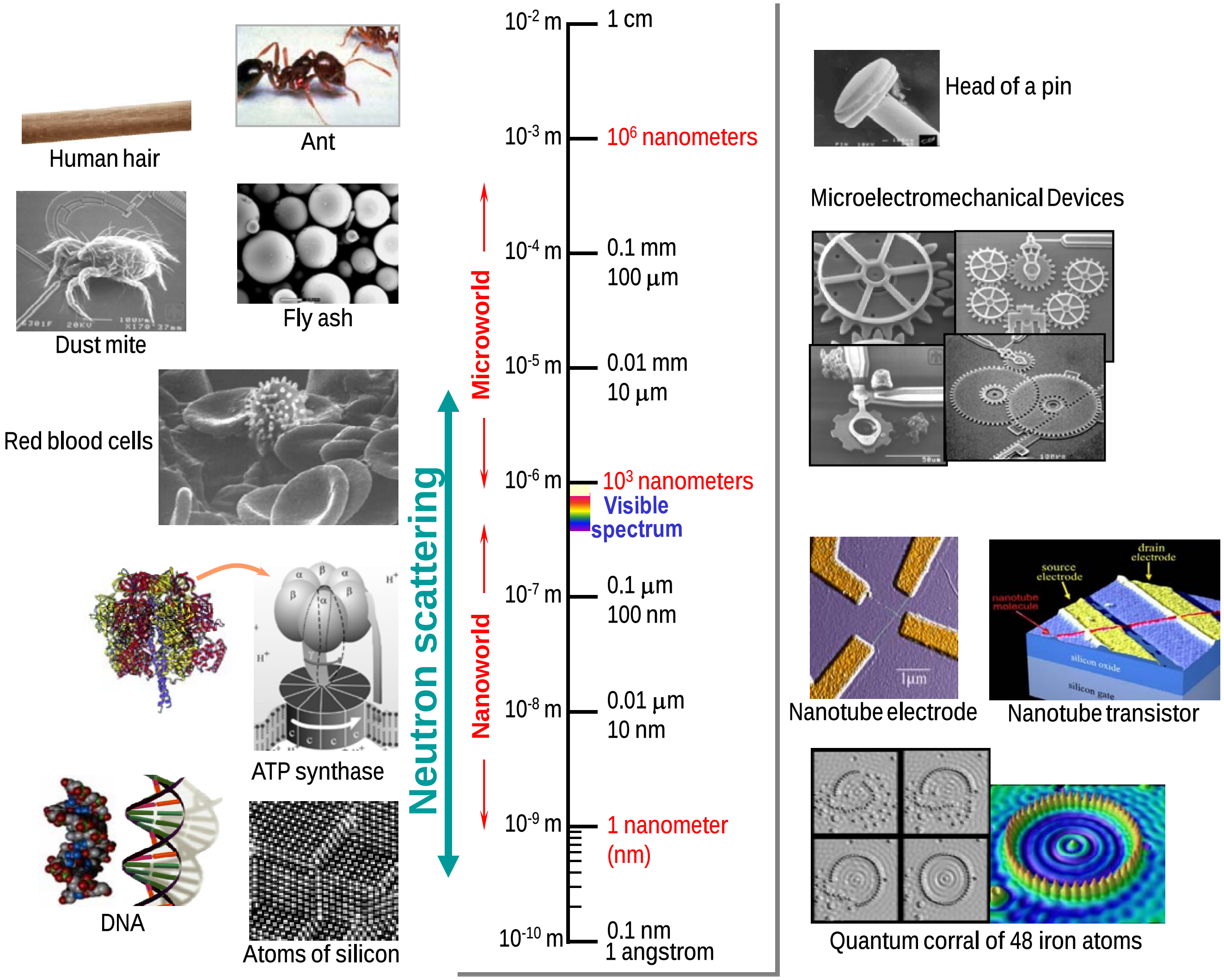
$$e^- + e^+ \rightarrow B^+ B^-$$

	Rest Mass Energy [MeV]	Kinetic Energy [MeV]
e^+, e^-	0.511	5290
B^+, B^-	5279	11.5

Secondary Particle Beams

- Beams of accelerated particles can be used to produce beams of secondary particles:
  - Photons (x-rays, gamma-rays, visible light) are generated from beams of electrons (light sources)
  - Neutrons are generated from beams of protons (spallation neutron sources)
- These secondary particle beams are in turn used to study materials and their properties, through their use as *probes*

Probing a broad range of length scales



Human hair

Ant

Dust mite

Fly ash

Red blood cells

ATP synthase

DNA

Atoms of silicon

Neutron scattering

Microworld

Nanoworld

10^{-2} m — 1 cm

10^{-3} m — 10^{6} nanometers

10^{-4} m — 0.1 mm, 100 µm

10^{-5} m — 0.01 mm, 10 µm

10^{-6} m — 10^{3} nanometers

Visible spectrum

10^{-7} m — 0.1 µm, 100 nm

10^{-8} m — 0.01 µm, 10 nm

10^{-9} m — 1 nanometer (nm)

10^{-10} m — 0.1 nm, 1 angstrom

Head of a pin

Microelectromechanical Devices

Nanotube electrode

Nanotube transistor

Quantum corral of 48 iron atoms

Timeline

- 1895: Roentgen discovers x-rays
- 1897: J.J. Thomson discovers the electron
- 1905: Einstein’s theory of relativity, Einstein’s theory of light quanta
- 1907: Schott develops first theory of synchrotron radiation
- 1911: Rutherford discovers atomic nucleus using alpha particles
- 1920: Greinacher builds first cascade generator of about 100 kV
- 1924: Ising proposes first concept for acceleration by repeated application of voltage kicks
- 1927: Wideroe makes first linear accelerator; accelerates Na and K ions
- 1928: Dirac predicts existence of antimatter (positrons)
- 1931: Van de Graaff builds first high-voltage generator
- 1932: Cockroft and Walton construct first “high-energy” accelerator, produce first artificially generated nuclear reaction: p + Li -> 2 He
- 1932: Lawrence and Livingston construct first cyclotron, accelerating 1.2 MeV protons

Timeline

- 1932: positrons and neutrons are discovered
- 1939: Hansen and Varian brothers invent the klystron
- 1941: Kerst and Serber build first betatron
- 1941: Touschek and Wideroe invent concept of a particle storage ring
- 1943: Oliphant invents concept of synchrotron
- 1947: First direct observation of synchrotron radiation at General Electric
- 1947: Alvarez builds first proton linear accelerator
- 1947: Ginzton builds first electron linear accelerator
- 1950-1952: Concept of strong-focusing is invented
- 1954: R.R. Wilson et. al. builds first strong-focusing synchrotron at Cornell University
- 1956: Hartmann uses synchrotron radiation for first spectroscopy experiments
- 1960: First electron-positron collider: ADA at Frascati
- 1972: First proton-proton collider: ISR at CERN
- 1981: First proton-antiproton collider: SPS at CERN

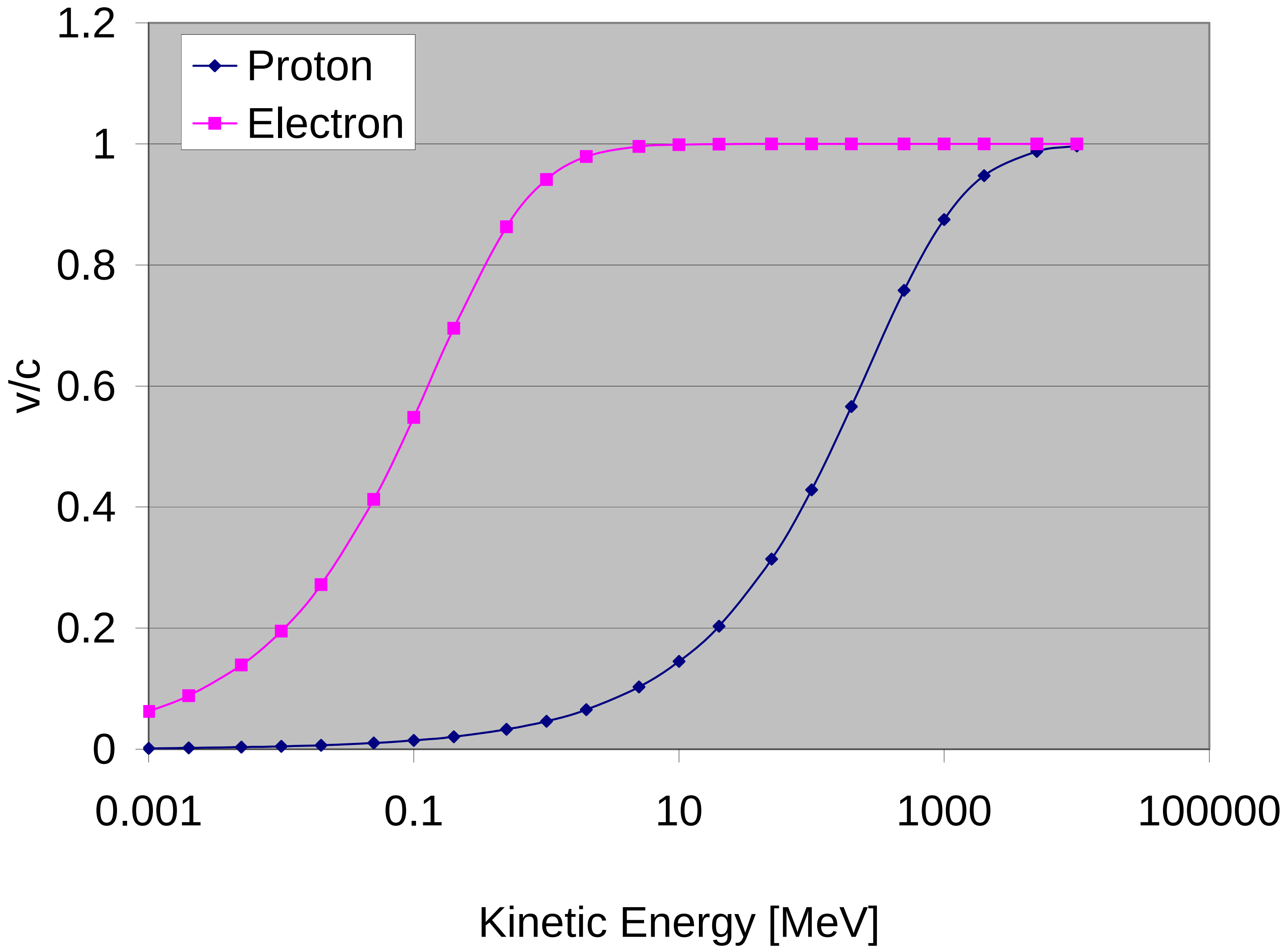
Types of particle accelerators

- A wide variety of particle accelerators is in use today.
- The types of machines are distinguished by the velocity of particles that are accelerated and by the mass of particle accelerated
- We will see that accelerators for electrons generally “look” different from accelerators for protons or heavy ions

Example:

- A typical method for generating electrons utilizes a thermionic gun at a potential of about 100 kV. This gives a beam of 100 keV electrons
- Compare velocities of particles generated at 100 keV kinetic energy:
  - Electrons: $v/c = 0.55$
  - Protons: $v/c= 0.015$
  - Au^{1+}: $v/c= 0.001$
- This has important implications for the type of acceleration scheme that is appropriate, as we will see throughout this course

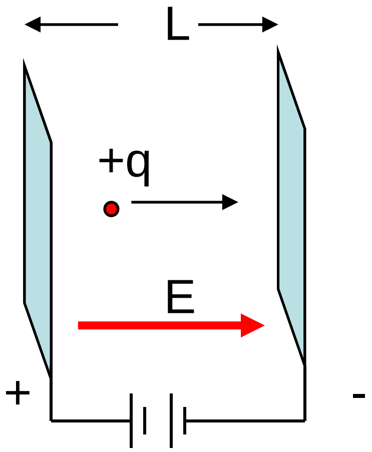
Proton and Electron Velocities vs. Kinetic Energy



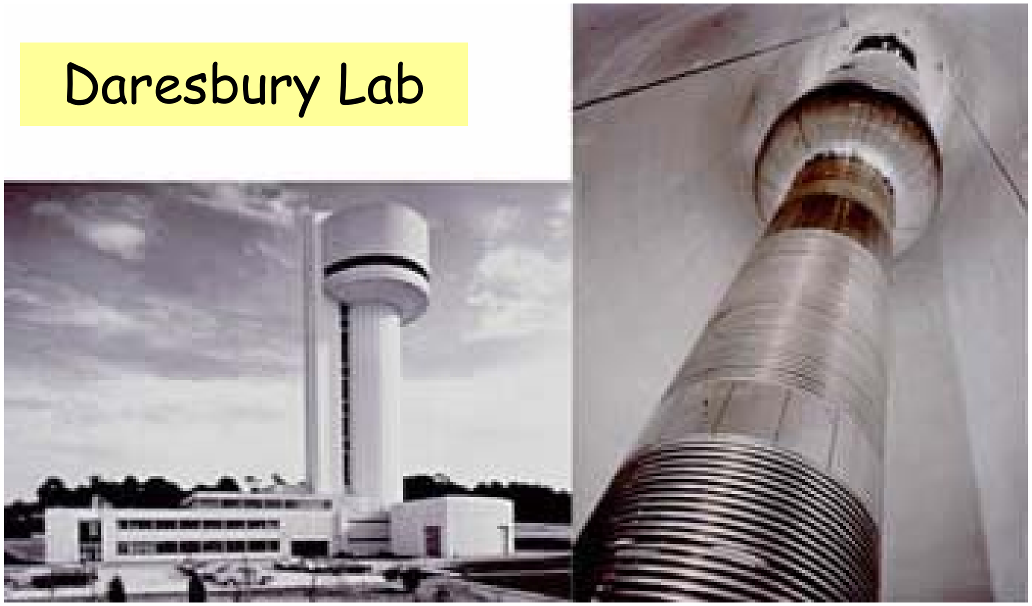
Potential-Drop Accelerators

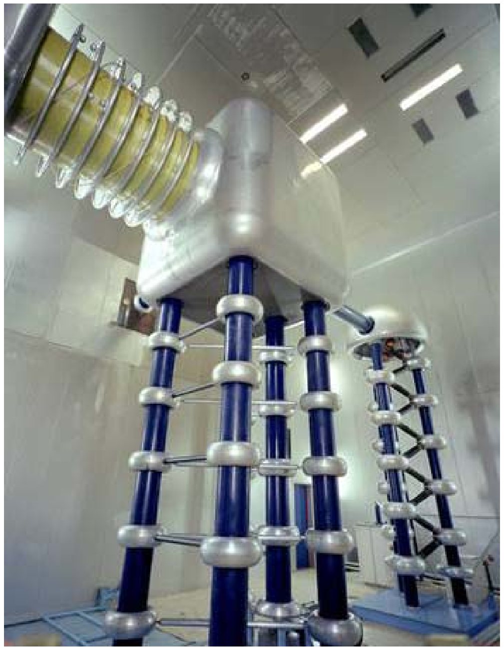
- These accelerators use a static, DC, potential difference between two conductors to impart a kinetic energy

$$\Delta W = qV_0$$



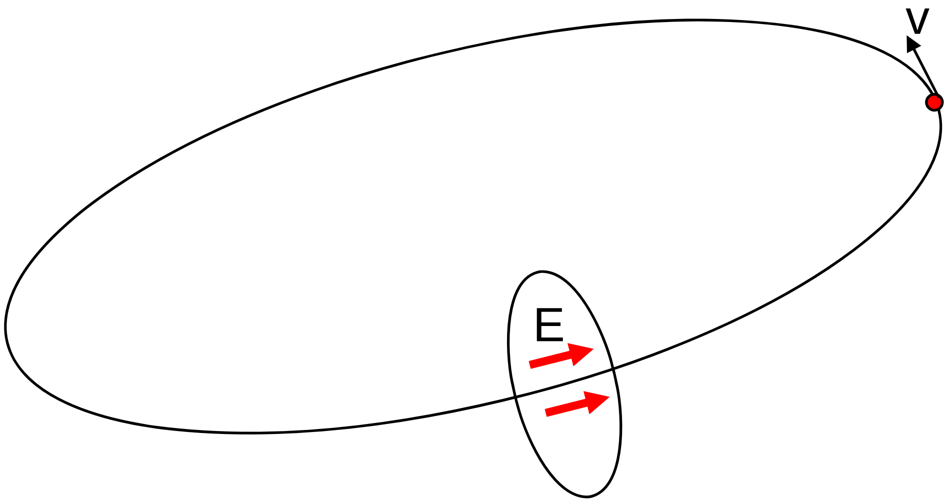
- Earliest particle accelerators were the Cockcroft-Walton generator and the Van de Graaff generator
- Highest voltage achieved is 24 MV
- It is difficult to establish and maintain a static DC field of 20+ MV

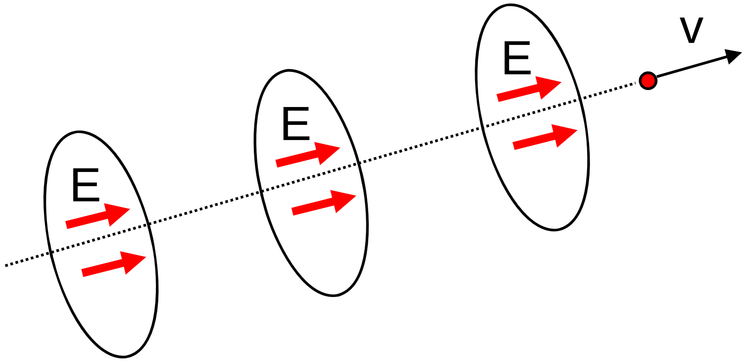




Acceleration by repeated application of time-varying accelerating fields

- Two approaches for accelerating with time-varying fields
- Make an electric field along the direction of particle motion with Radio-Frequency (RF) Cavities





Circular Accelerators

Use one or a small number of Radio-frequency accelerating cavities and make use of repeated passage through them.

This approach leads to circular accelerators: Cyclotrons, synchrotrons, and their variants.

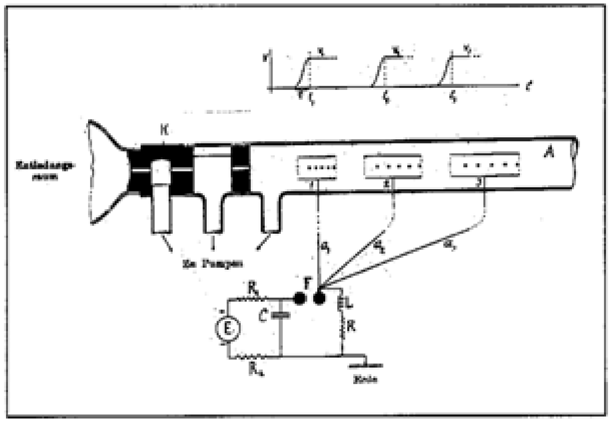
Linear Accelerators

Use many accelerating cavities through which the particle passes only once:

These are linear accelerators.

Acceleration by Repeated Application of Time-Varying Fields

- Ising and Wideroe suggested the repeated application of a much smaller voltage in a linear accelerator by using time-varying fields
- In this way, a high particle beam energy could be attained by repeatedly applying voltage “kicks”



Ising's idea

R. Wideroe

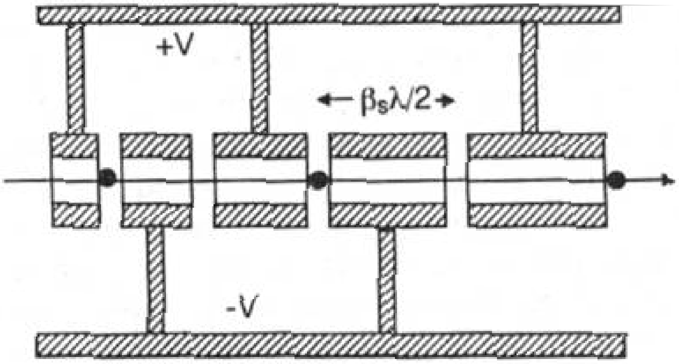
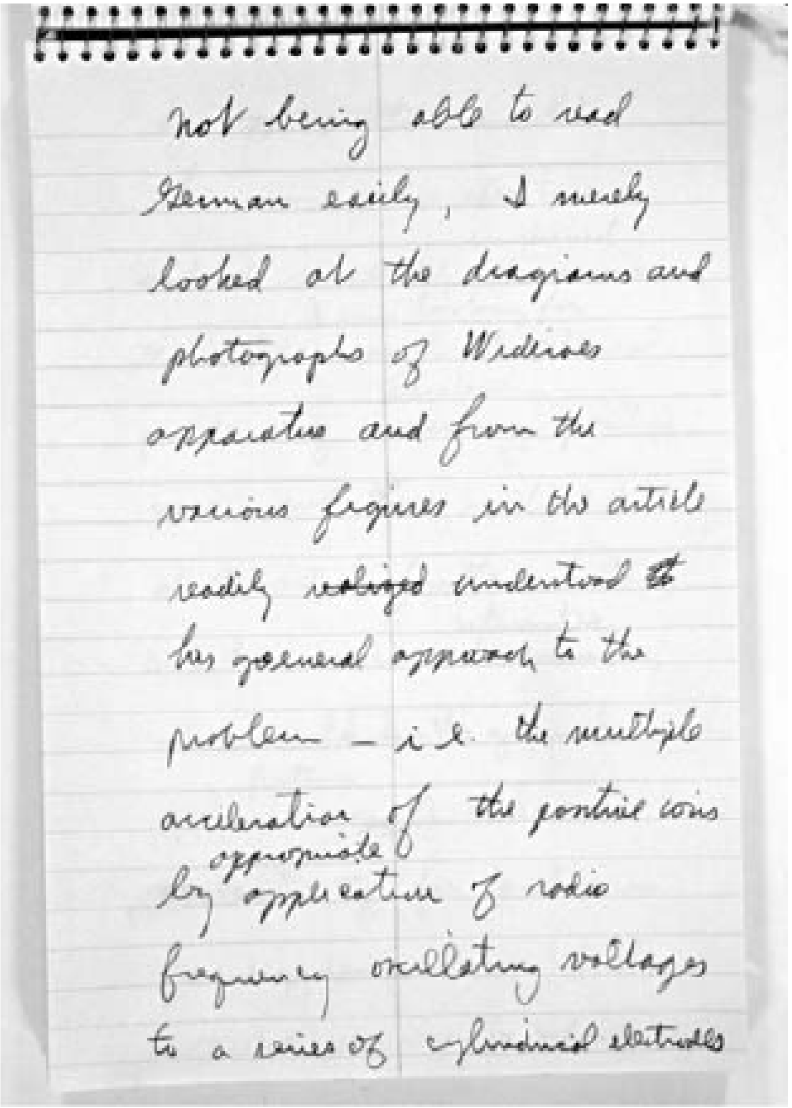


Figure 4.4 Wideröe or Sloan–Lawrence or interdigital structure.

Lawrence's Application of Wideroe's Idea: The Cyclotron



not being able to read
German easily, I merely
looked at the diagrams and
photographs of Wideroes
apparatus and from the
various figures in the article
readily ~~realized~~ understood ~~th~~
his general approach to the
problem – i.e. the multiple
acceleration of the positive ions
by appropriate application of radio
frequency oscillating voltages
to a series of cylindrical electrodes

Lawrence's notes on Wideroes idea

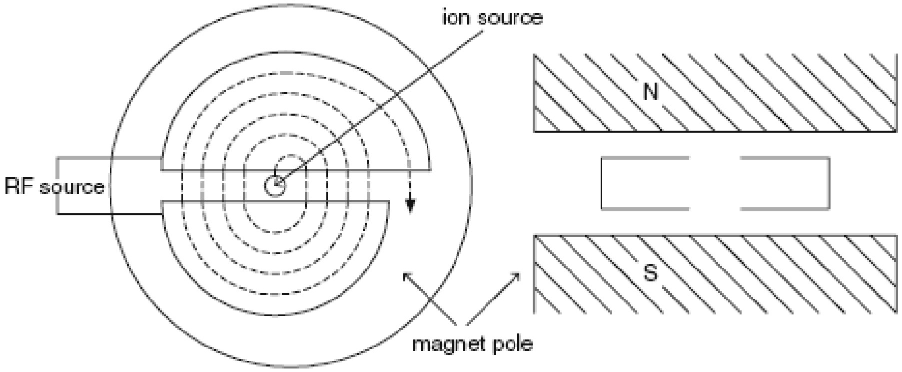


Fig. 1.10. Ernest Lawrence at the controls of the 37 inch cyclotron in about 1938 (Reprinted with permission from LBL)

E. O. Lawrence: Nobel Prize, 1939

Cyclotron Principle

- Uniform circular motion is maintained via centripetal acceleration:

$$\frac{mv^2}{r} = qvB$$

- The radius is

$$\boxed{r = \frac{mv}{qB}}$$

The first cyclotron 4.5” diameter (1929).

- The revolution period and frequency are independent of particle velocity:

$$\boxed{T = \frac{2\pi m}{qB} \qquad \omega = \frac{qB}{m}}$$

- Therefore, a particle in resonance with a time varying field applied to the Dees with frequency given as above will be accelerated. The particle is in *synchronism* with the time-varying field.
- Such cylcotrons can accelerate proton energies up to 20-30 MeV
- The situation becomes more complicated at higher energies due to the increase in relativistic mass
  - The frequency decreases and particles get out of synchronism

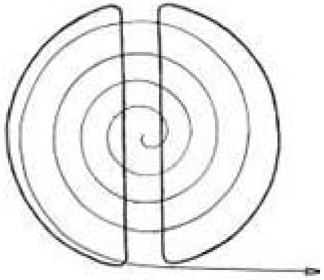
Accounting for Relativistic Mass: The Synchro-Cyclotron

- Veksler and McMillan showed, independently, that by adjusting the frequency of the applied voltage to the decreasing frequency of the rotating protons, it was possible to accelerate the protons to several hundred MeV.
- Whereas the cyclotron can accelerate a stream of particles, the synchro-cyclotron can only accelerate a single ‘bunch’ of particles
- The first synchro-cyclotron was built at Berkeley. It produced 350 MeV protons and was used for the study of π mesons.
- Alternatively, one could vary the magnetic field to keep the revolution frequency constant. This is an isochronous cyclotron.

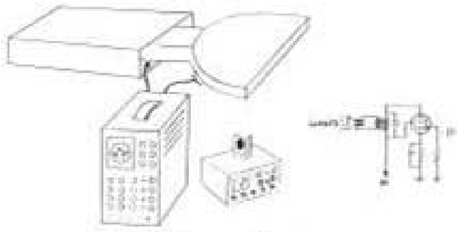
The largest synchrocyclotron still in use is located in Gatchina outside St Petersburg and it accelerates protons to a kinetic energy of 1,000 MeV. The iron poles are 6 meters in diameter and the whole accelerator weighs 10,000 tons, a weight comparable to that of the Eiffel Tower.

The Cyclotron: Different Points of View

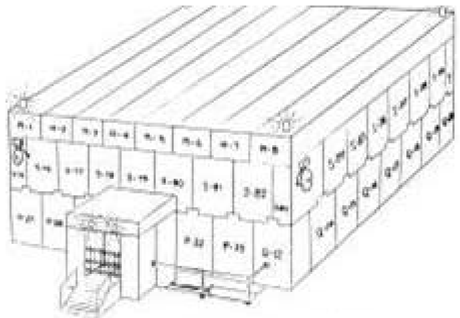
The cyclotron, as seen by...



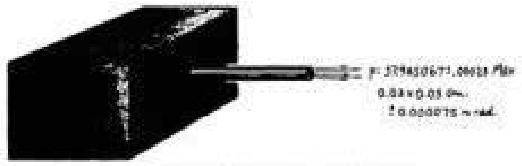
. . . the inventor



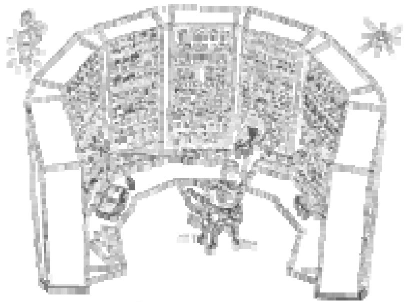
. . . the electrical engineer



. . . the health physicist



. . . the experimental physicist



…the operator

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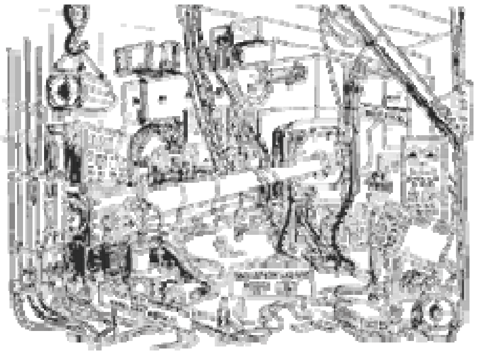
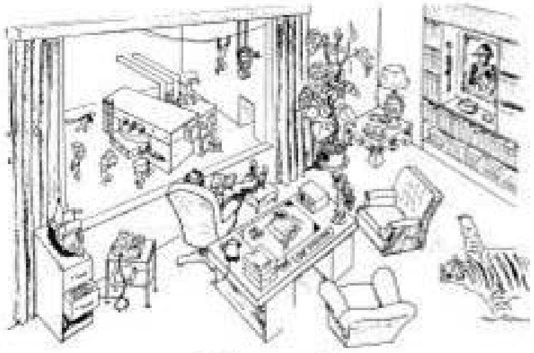
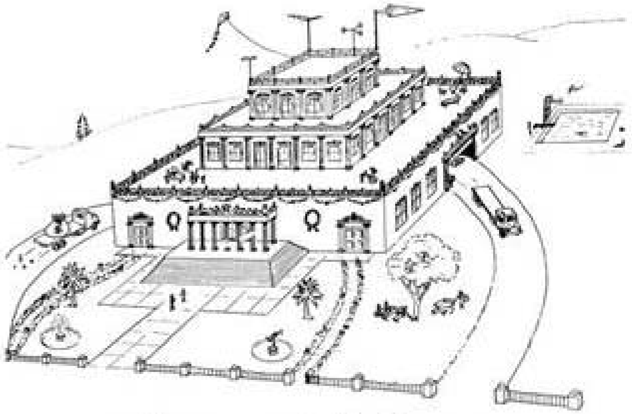
By Dave Judd and Ronn MacKenzie



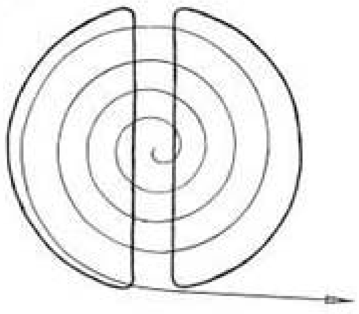
...the visitor



. . . the laboratory director



. . . the governmental funding agency



. . . the student

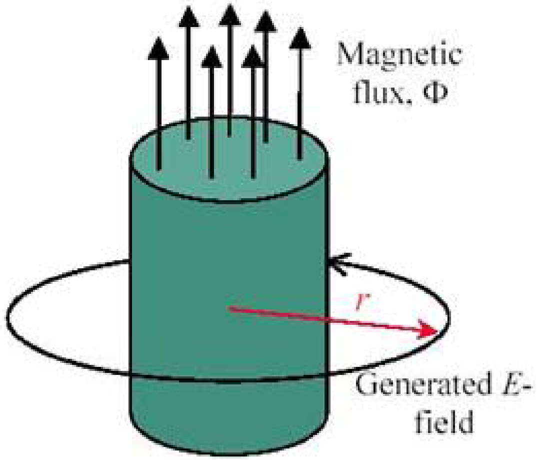
The first circular electron accelerator: The Betatron

- Principle investigated by **Wideröe** (1928) , **Steenbeck** (1935) and first one built by **Kernst** (1940) (energy of 20 MeV)
- Beta particles (=electrons) accelerated by rotational electric field generated by induction from time varying magnetic field $\mathbf{B}(t) = \mathbf{B_0}\sin(\omega t)$
- The magnetic flux $\Phi = \iint_A \mathbf{B}(r)\cdot d\mathbf{s} = \langle \mathbf{B} \rangle \pi r^2$
- From Faraday law of induction

$$2\pi r|E| = \oint \mathbf{E}\cdot d\mathbf{r} = -\iint_A \dot{\mathbf{B}}(r)\cdot d\mathbf{s} = \dot{\Phi} = -\pi r^2 \frac{d}{dt}\langle \dot{\mathbf{B}} \rangle$$

- Motion in uniform magnetic field imposes $|\mathbf{p}| = e\ r|\mathbf{B}|$
- Assuming a constant radius, the accelerating part of the Lorentz force $|\mathbf{F}| = -e|\mathbf{E}| = |\dot{\mathbf{p}}| = e\ r|\dot{\mathbf{B}}|$
- Equating the last equation with the one from Faraday's law we get **Wideröe's betatron condition**

$$\boxed{|\mathbf{B}(t)| = \frac{1}{2}\langle |\mathbf{B}(t)| \rangle + |\mathbf{B}_0|}$$



The Synchrotron

- **In synchrotrons, the particles are accelerated along a closed, circular orbit and the magnetic field which bends the particles increases with time so that a <u>constant orbit is maintained during acceleration.</u>**

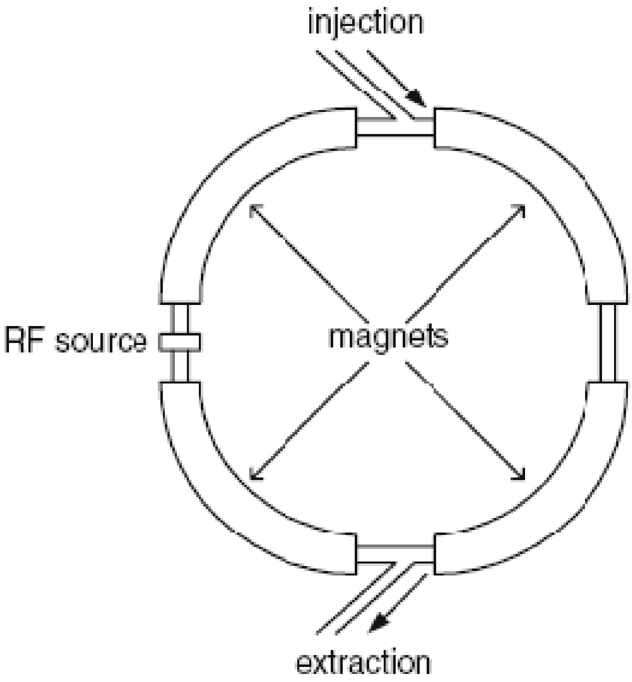


Fig. 1.12. Principle of a synchrotron

The synchrotron concept was first proposed in 1943 by the Australian physicist <u>Mark Oliphant.</u>

The Synchrotron

- The bending field changes with particle beam energy to maintain a constant radius:

$$\frac{1}{\rho[m]} = 0.3\frac{B[T]}{\beta E[GeV]} = 0.3\frac{B[T]}{cp[GeV]}$$

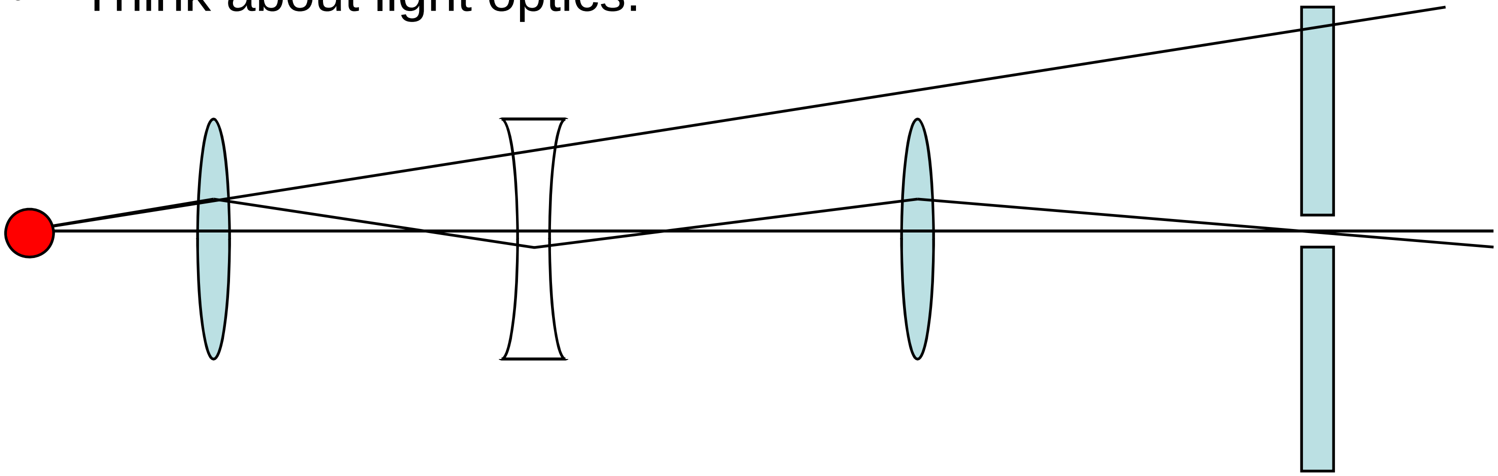
- So B ramps in proportion to the momentum. The revolution frequency also changes with momentum.
- The synchronicity condition, including the relativistic mass, is:

$$\omega = \frac{qB}{m\gamma}$$

- For an electron synchrotron, the injected beam is already relativistic, so only the magnetic field changes with beam energy.
- For a proton synchrotron, the injected beam is not yet relativistic, so the RF accelerating frequency and the magnetic field both ramp with energy.

Particle Beam Focusing

- Suppose two particles start the acceleration process. One has exactly the correct energy, position and angle, so that it is properly accelerated. The accompanying particle has slightly different starting parameters. We need some way of ensuring that non-perfect particles are also accelerated.
- Think about light optics:



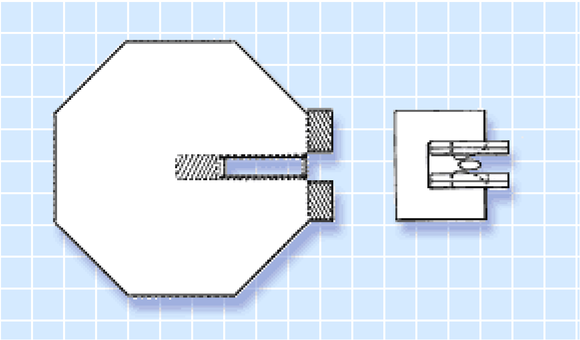
- This concept was first applied to particle accelerators by Courant, Livingston, and Snyder.
- It is known as “Strong Focusing” or “Alternating Gradient Focusing”.
- “Optical” magnetic elements provide focusing (later….).

Strong-focusing Synchrotrons

- In the original scheme, the bending magnets are made to also focus the beam by a built-in field gradient.
- Arrays of magnets with alternating focusing give stability for “non-ideal” particles
- Thanks to strong focusing, the magnet apertures can be made smaller and therefore much less iron is needed than for a weak-focusing synchrotron of comparable energy.
- The first alternating-gradient synchrotron accelerated electrons to 1.5 GeV. It was built at Cornell University, Ithaca, N.Y. and was completed in 1954.
- Most modern applications use seperated-function magnets, including sequences of dipole magnets (bending) and quadrupole magnets (focusing).

Christofilos

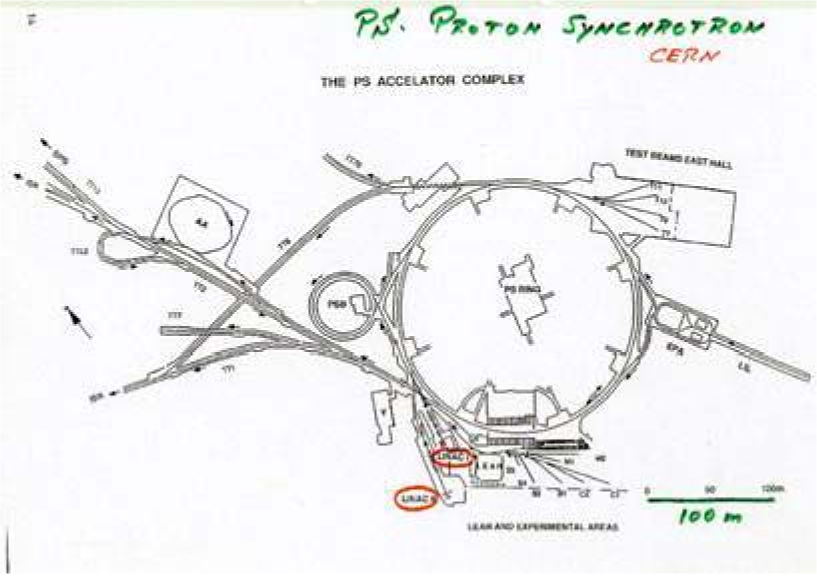
Courant Livingston Snyder



Size comparison between the Cosmotron's weak-focusing magnet (L) and the AGS alternating gradient focusing magnets

Strong-focusing Synchrotrons

Soon after the invention of the principle of alternating-gradient focusing, the construction of two nearly identical very large synchrotrons, which are <u>still in operation</u>, started at the European CERN laboratory in Geneva and the Brookhaven National Laboratory on Long Island. <u>At CERN protons are accelerated to 28 GeV and at Brookhaven to 33 GeV</u>. The CERN proton synchrotron (PS) started operation in 1959 and the Brookhaven Alternating Gradient Synchrotron (AGS) in 1960.

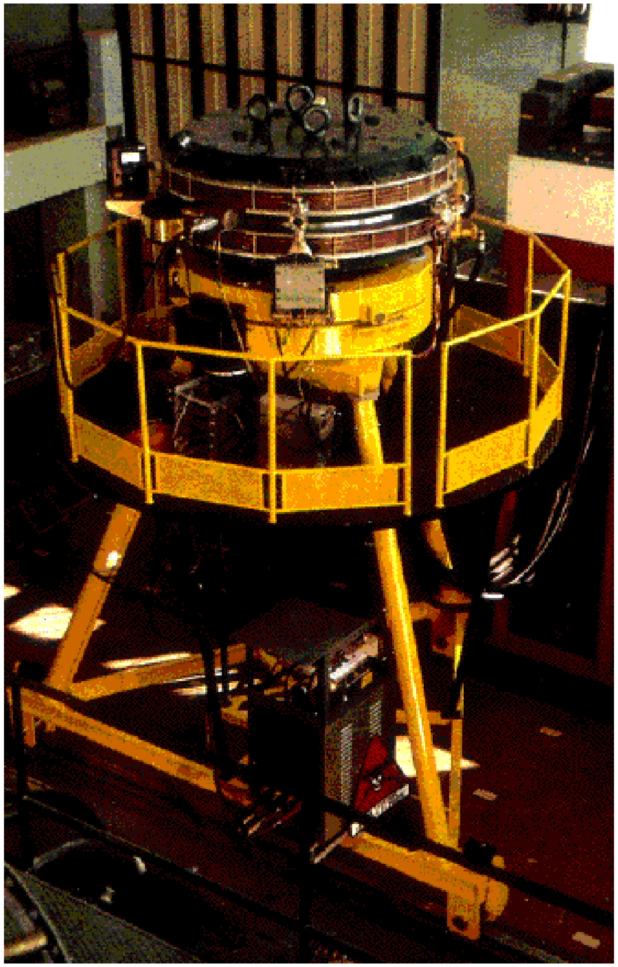


CERN PS

Brookhaven AGS

Colliders

- A collider can be thought of as a fixed-energy synchrotron.
- Beams of matter and antimatter particles counter-rotate, sharing the same beam pipe and are made to collide.



Bruno Touschek built the first successful electron-positron collider, ADA, at Frascati, Italy (1960).

Eventually reached 3 GeV energy

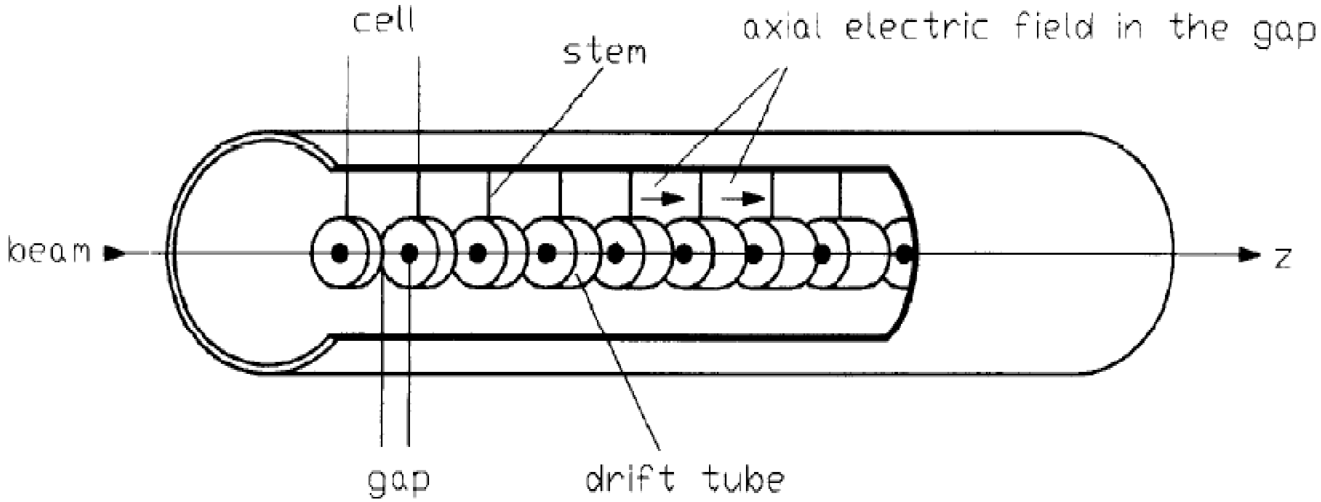
The Large Hadron Collider at CERN

Aerial view of the CERN laboratory, situated between Geneva airport and the Jura mountains. The circles indicate the locations of the SPS (6.9km) and LEP tunnel (27 km). The Large Hadron Collider (LHC) is currently beginning operation in the LEP tunnel.
Photo: CERN

The LHC Tunnel, showing superconducting bending magnets

Linear Accelerators

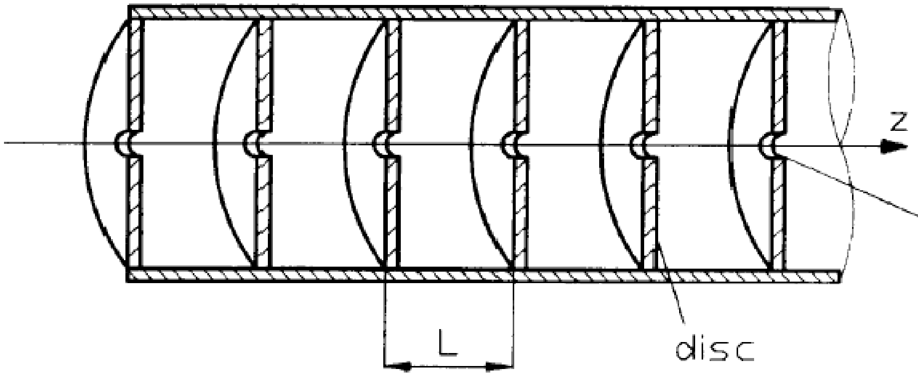
- Whereas a circular accelerator can make use of one or a small number of RF accelerating cavities, a linear accelerator utilizes many (hundreds to thousands) individual accelerating cells.
- Again, accelerators for protons or ions “look” quite different from those that accelerate electrons, because electron beams are already relativistic at low energy.
- Modern proton linear accelerators are based on the Alvarez Drift-Tube Linac. Alvarez was awarded the 1968 Nobel Prize in Physics for his contributions to elementary particle physics.
- The two largest proton linear accelerators are the LANSCE linac at Los Alamos (800 MeV) and the Spallation Neutron Source Linac at ORNL (1000 MeV).



Alvarez Drift tube linac (DTL)

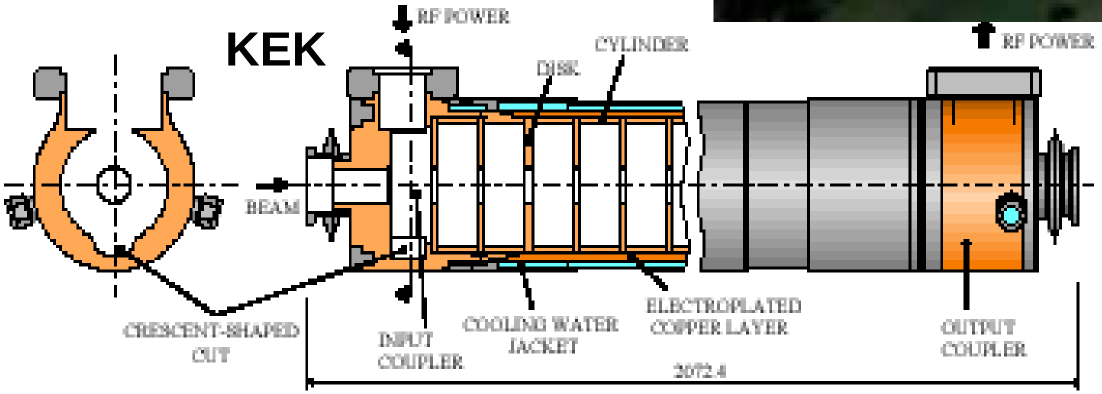
Linear Accelerators for Electrons

- Most electron linacs utilize a structure known as the Disk-Loaded Waveguide.
- Geometry looks somewhat different from that used for protons since electrons quickly become relativistic (more later...).

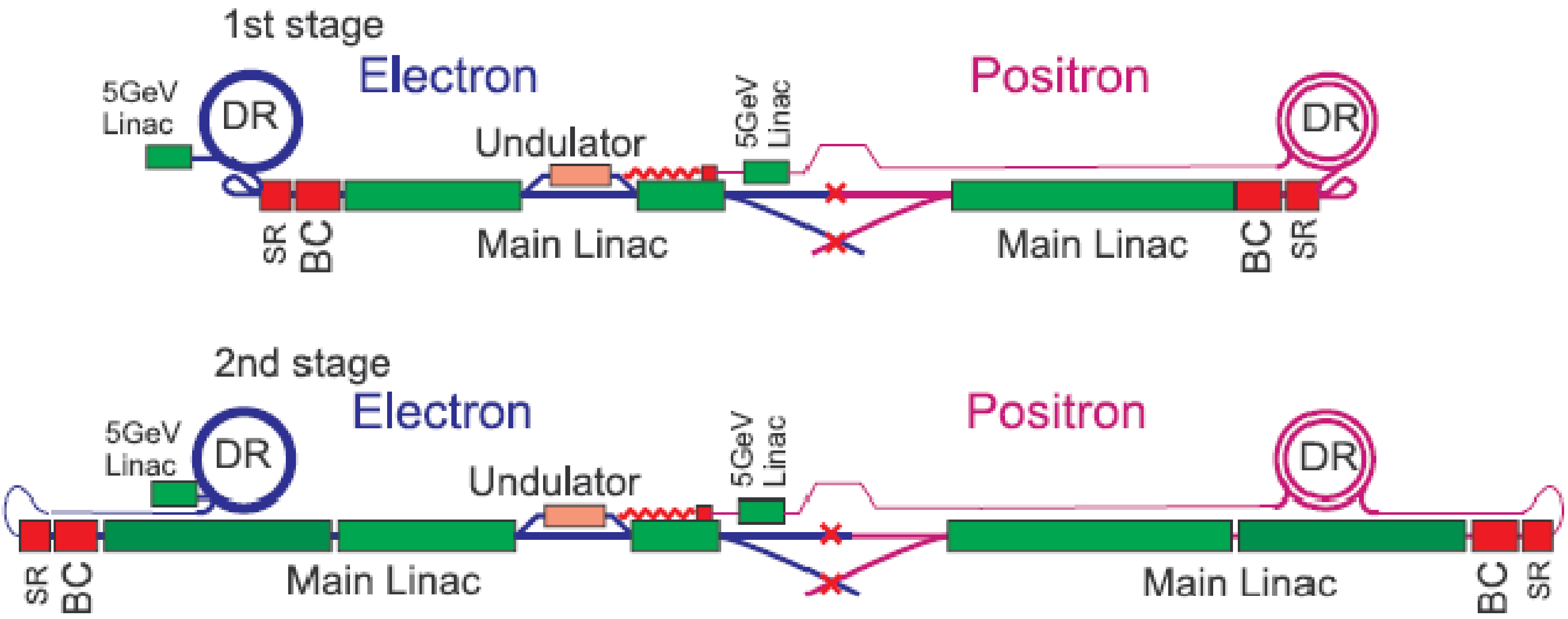



Stanford Linear Accelerator

KEK



International Linear Collider Baseline Configuration



- Configuration for 500 GeV machine with expandability to 1 TeV
- Some details – locations of low energy acceleration; crossing angles are not indicated in this cartoon.

Example of an Accelerator Complex: Fermilab

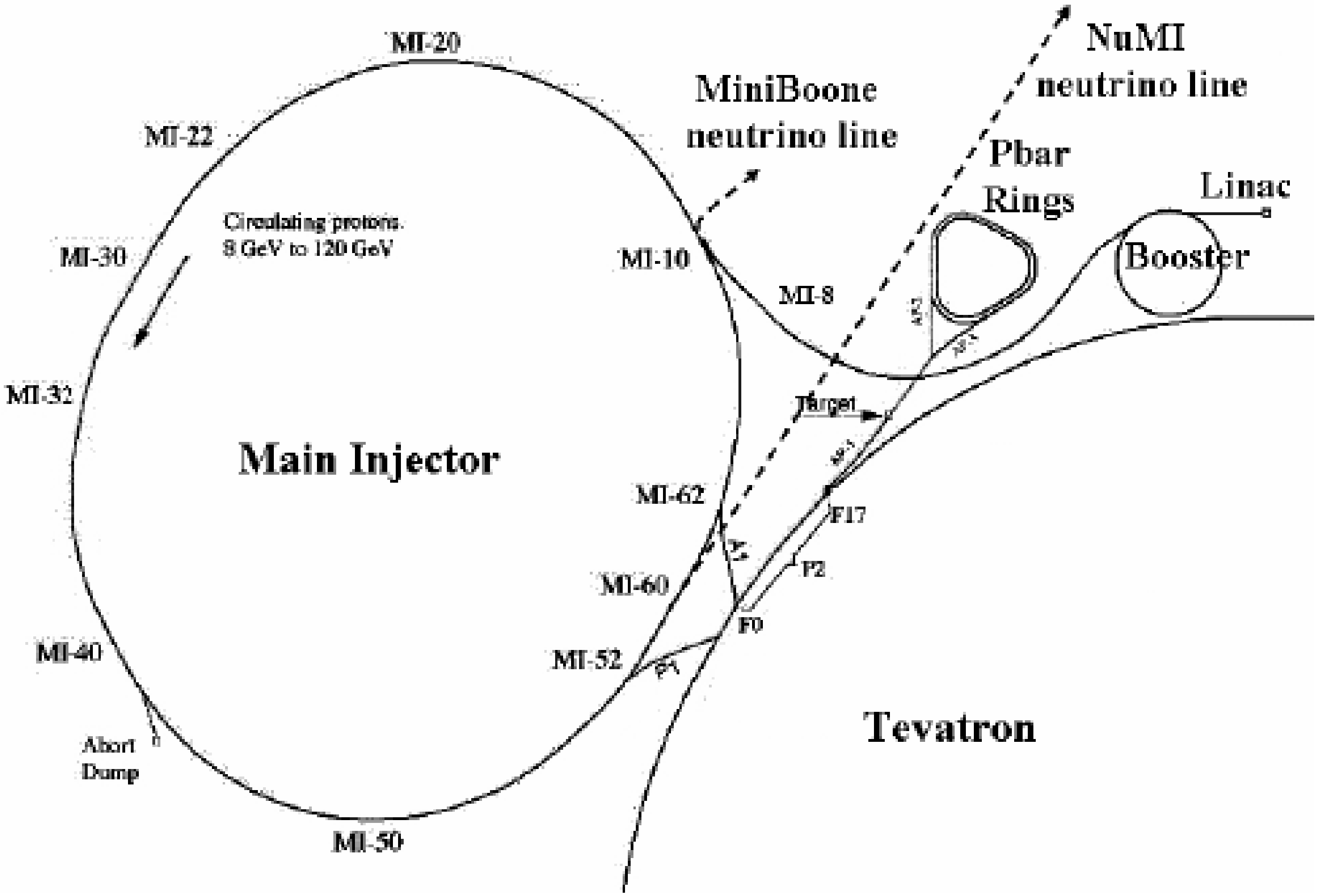
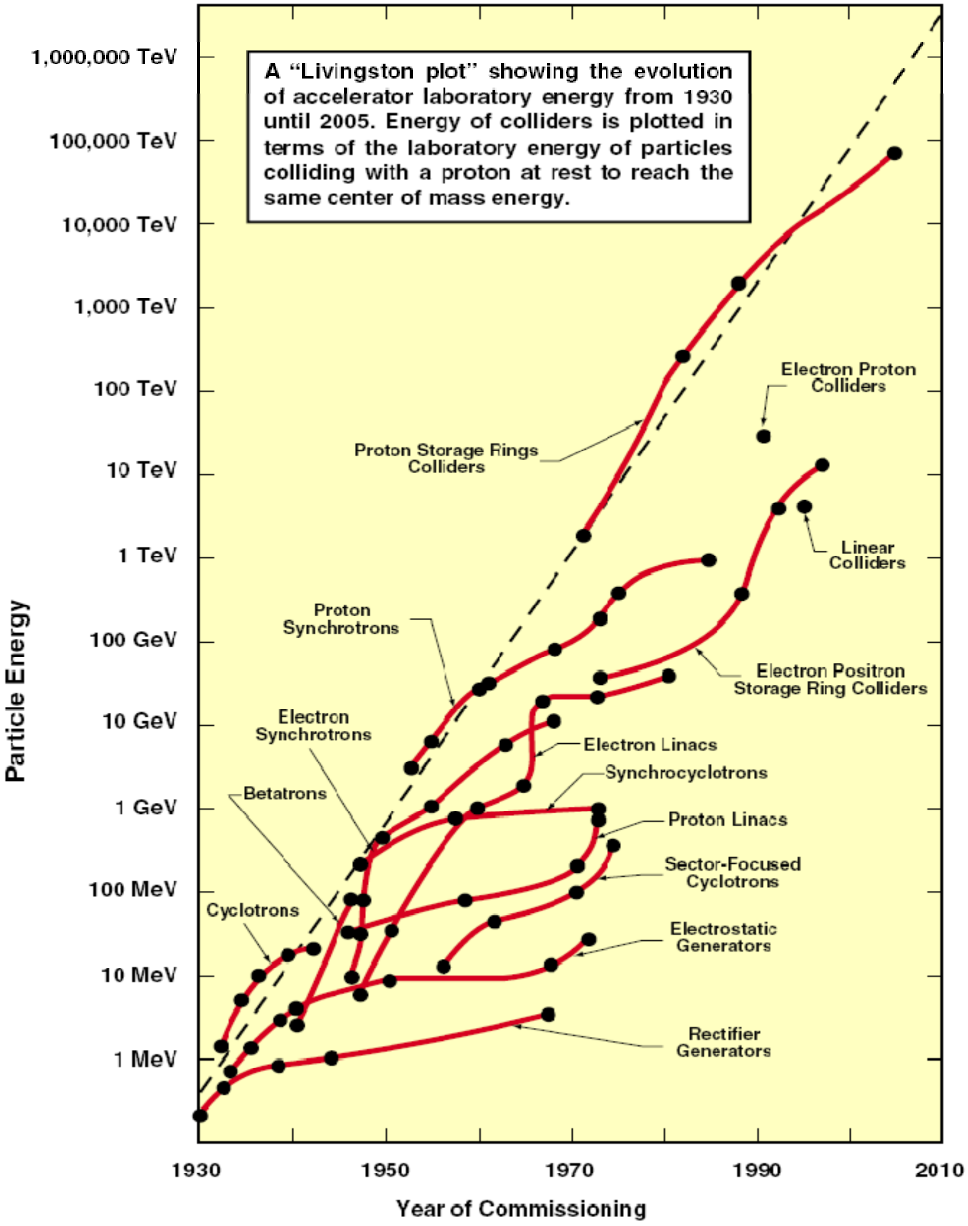


Figure 1: The Fermilab accelerator complex.

Energy Evolution

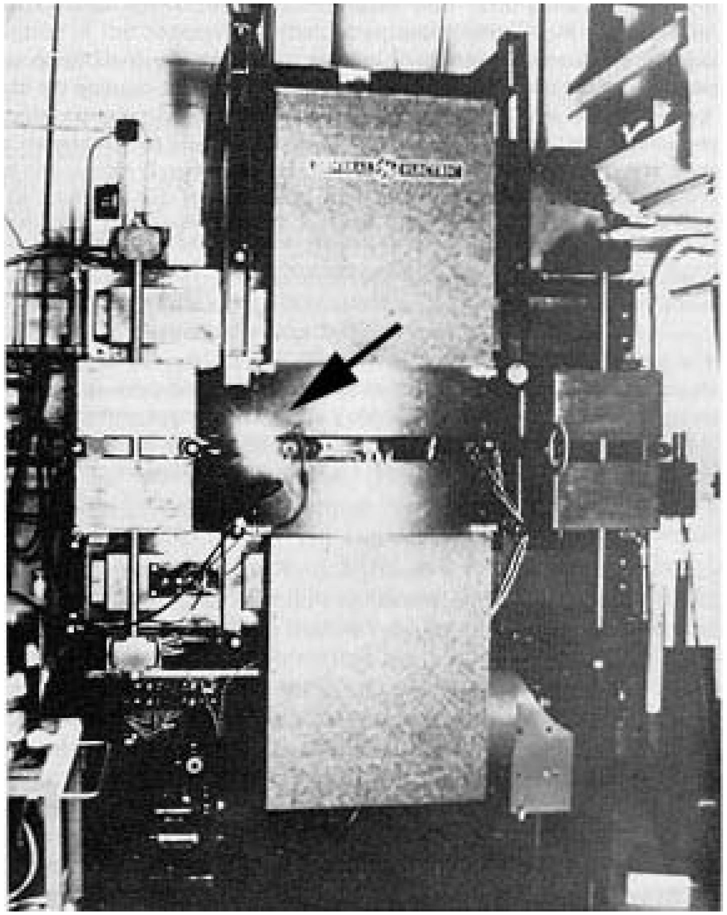


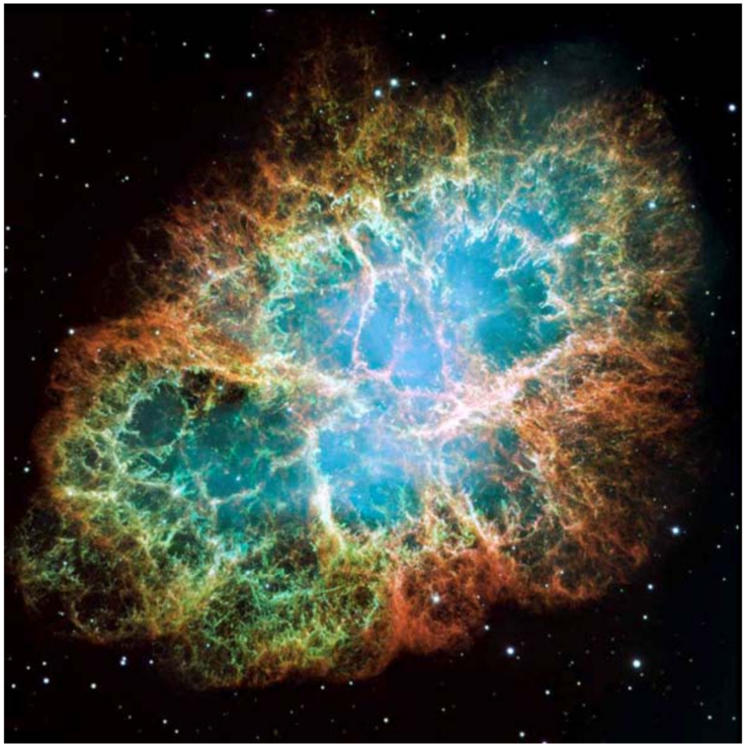
A “Livingston plot” showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

- Exponential growth of energy with time
- Increase of the energy by an order of magnitude every 6-10 years
- Each generation replaces previous one to get even higher energies.
- The process continues…
- Energy is not the only interesting parameter.
  - Intensity
  - Size of the beam

Discovery of Synchrotron Radiation

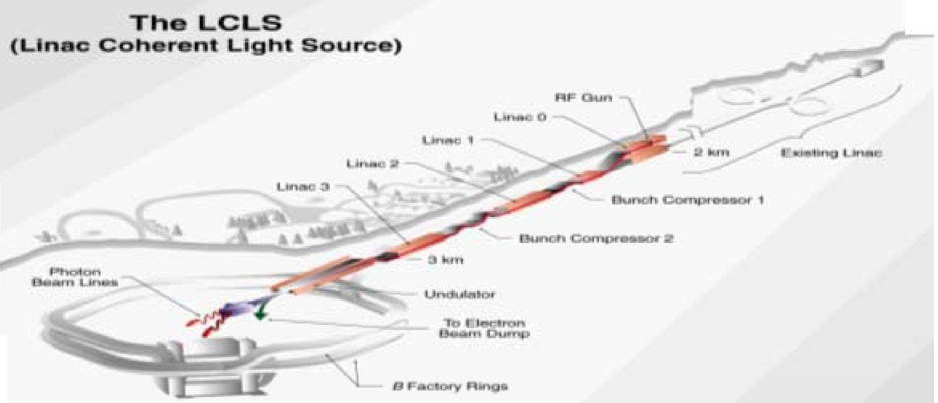
- Synchrotron Radiation is light that is emitted when electrons are bent (accelerated transversely)
- 70 MeV electron synchrotron at General Electric, Schnectady, NY, 1947

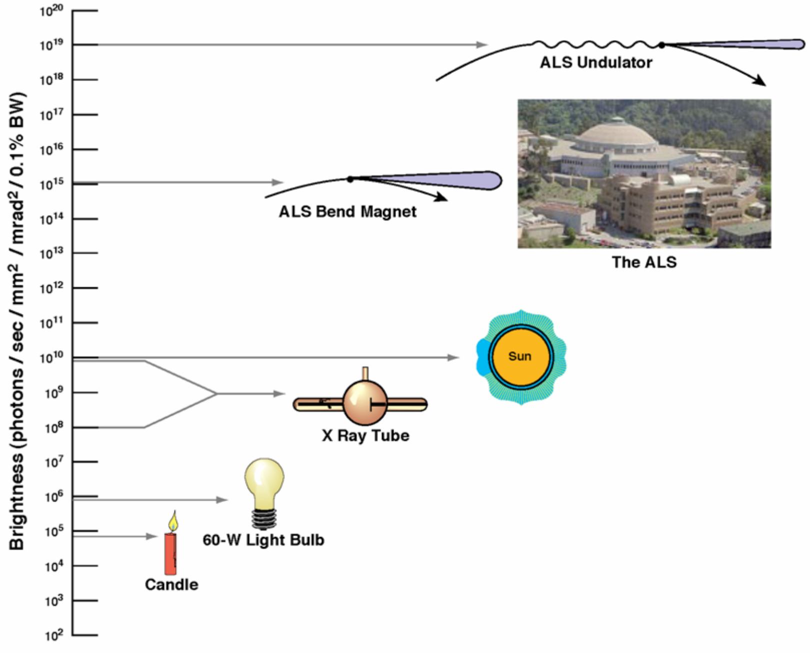




- We now know that some of the luminosity of the Crab Nebula is due to Synchrotron Radiation

Accelerator–Based Light Sources

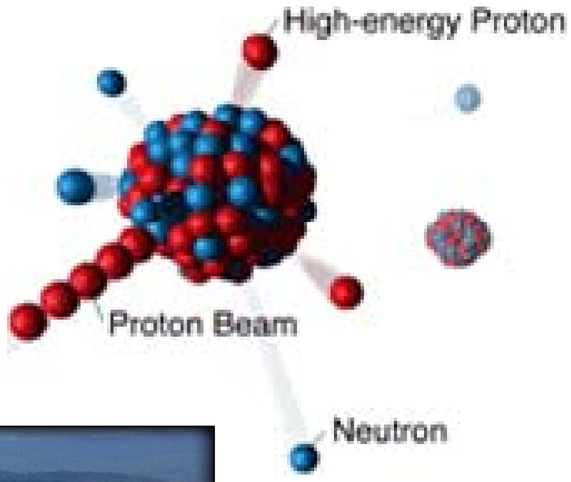




Modern synchrotron light sources are accelerators optimized for the production of synchrotron radiation.

Accelerator-Based Neutron Sources

- High-energy protons are used to generate neutrons from a heavy metal target via the spallation process.
- Several labs, ISIS(UK), LANSCE (Los Alamos), SNS (ORNL), J-PARC (Japan) operate or are building these types of machines.
- They use ~1 GeV protons accelerated by linacs or synchrotrons.

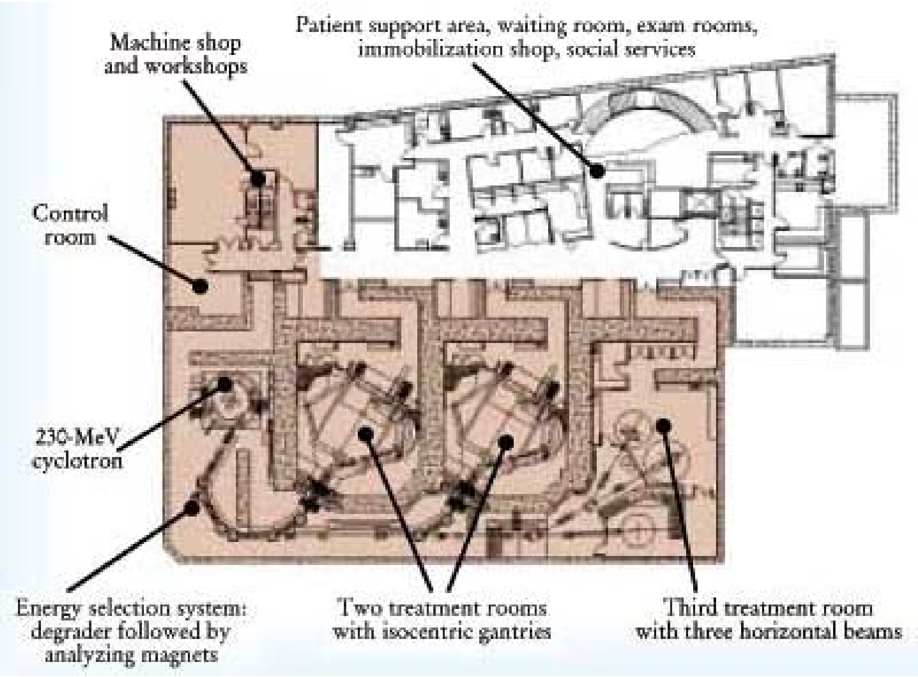


Spallation Neutron Source, Oak Ridge

Medical Accelerators

X-ray therapy based on electron accelerator

Proton Therapy Facility at Mass General Hospital (Boston)



Conclusion

- Accelerators have and continue to progress along several paths:
  - increasing beam energy
  - Increasing beam intensity
  - Increasing beam parameters, such as beam size (brightness) and particle collision frequency (luminosity)

- Accelerator science is a field that makes use of a broad range of physics and engineering.

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