Particle Accelerators

Kalanand Mishra
Dept of Physics, University of Cincinnati

Abstract:

Physicists learned most of what they know about the fundamental forces of nature by using larger and larger accelerators to smash subatomic particles together. The science of particle accelerators and the results obtained from them are at the cutting edge of physics. A particle accelerator is a device that accelerates a charged particle beam to a desired kinetic energy to perform certain experiments. The basic scheme involves speeding a particle using electromagnetic fields and smashing it into a target or other particles. Surrounding the collision point are a series of detectors that record the many pieces of the event. The entire setup works in several steps from creation of beam of particles to identification and detection of product particles. In this paper, I have tried to mainly focus on the physics of particle accelerators and how different types of particle accelerators work.

1. Introduction

1.1 Historical Overview:

To break atoms and nuclei into their smallest bits, physicists have always sought to blast them with the fastest-moving particles they could get their hands on. During the 1920s (soon after Rutherford succeeded in splitting the atom in 1919) several physicists used scaled-up versions of this process to generate protons of about a million electron-volts. But these methods were unwieldy, and going to higher energies presented new problems.

The era of the modern particle accelerator began in 1932, when Ernest O. Lawrence and M. Stanley Livingston of the University of California at Berkeley published their design in the *Physical Review*. Their machine, the cyclotron, revs up protons by giving them repeated boosts as they travel around on a spiral path. The basic cyclotron concept remains even in the largest accelerator on earth, the 27-kilometer-circumference machine currently under construction at CERN outside Geneva.

Lawrence and Livingston, his graduate student, had the idea of pushing particles to higher energies by making them travel in circles. They mounted two flat, semicircular metal chambers between the faces of a powerful electromagnet. The chambers were shaped like the two halves of a cookie sliced down the middle and became known as "dees" because of the letter they resembled. The team applied opposite and alternating voltages to the dees, so that whenever one was positive, the other was negative. The voltage difference pulls a charged particle into one of the dees, where the magnetic field forces it onto a curved path that slings it back to the other dee, by which time the voltages have reversed. In this way, particles loop back and forth, gaining energy at each passage. The faster they move, the larger the arc they follow through each dee. Luckily, the time they spend in each semicircle remains the same, so that Lawrence and Livingston could use a fixed frequency for the oscillating voltage without getting "out of step" with the particles. Crucial to the device's success was another stroke of luck. The electric and magnetic fields inside the cyclotron tend to "focus" any straying particles back toward the central plane of the device, keeping them in a tight beam. In a cyclotron 28 centimeters across, Lawrence and Livingston got protons to circulate more than 300 times by applying an oscillating 4,000 volts; the protons emerged with better than a million electron-volts of energy, according to the 1932 paper. The principle of the cyclotron fails as particles accelerate close to the speed of light. Relativity theory comes into play, and the time a particle would spend in each dee as it accelerates is no longer fixed. The 1940s invention of the synchrotron solved this problem by continually adjusting the frequency. But the cyclotron was "the first major workhorse" of particle physics and its central principle of getting large energies from modest voltages survives in all modern synchrotrons to this date.

1.2 What is a Particle Accelerator?

Quite simply, accelerators give high energy to subatomic particles, which then collide with targets. Out of this interaction come many other subatomic particles that pass into detectors. From the information gathered in the detectors, physicists can determine properties of the particles and their interactions. The higher the energy of the accelerated particles, the more closely we can probe the structure of matter. For that reason a major goal of researchers is to produce higher and higher particle energies.

Types of Accelerators

Linear Accelerators (LINAC)

The linear accelerator is the simplest type of accelerator. Fundamentally it is a long line of coils (or drift tubes) through which charged particles are accelerated. However, there are two types of linear accelerators. One type of accelerator is the standing- wave linear accelerator; particles travel along a cylindrical vacuum tank through a series of drift tubes, separated by gaps. As the particles cross the gaps, electromagnetic waves, called standing waves, accelerate them. (Or, more simply put, as the particle passes through the drift tube, the current through it is swapped. If the current was kept it would pull the particle back towards the tube when it leaves. Changing the current repels the particle from the end of the tube.) The waves provide an electric field that speeds up the particles by acting on their electric charges. This type of accelerator can only manage to accelerate particles to 200 MeV. Physicists mainly use them as a primary accelerator that feeds into a synchrotron. In industry and medicine, they are used as powerful X-ray machines.

The other type of linear accelerator is the traveling- wave linear accelerator. This speeds particles through a single long pipe by an electromagnetic wave that travels with the particle. This high- frequency wave is called a traveling wave. As long as the wave speed matches the particles' speed, the particles will continue to gain energy. This type of accelerator can accelerate particles to 30 GeV; this is the Stanford Linear Collider, the longest accelerator in the world at 3.2km. The SLC is used to smash electrons and positrons into each other at 50 GeV

Cyclotrons

The more advanced type of particle accelerator is the cyclotron. The idea behind these accelerators relies on the understanding of the effects of fields on charged particles. A cyclotron is made of two magnets and two D-shaped electrodes, which physicists like to call 'Dees'.

The particles are forced into a circular path by the magnetic field; the electrodes are subjected to an alternating current that attracts and repels the particle, thus accelerating the particle. This type of accelerator is much easier to make than a few miles of linear accelerator. However, it is not perfect. As the electrodes accelerate, the particles they increase the radius of their path. In order to produce faster moving particles, the radius of the cyclotron has to be larger. This is not really a problem for the electrodes but it is a huge problem for the magnets!

Synchrotrons

With most complicated problems, it is often the simplest solution that works best. The linear accelerator is very simple, and does not require a huge magnet. The problem is it has to be very long. How could there be a simple way of making it shorter and more useful? This can be resolved by forcing the electrons into a circular path using magnets. However, unlike having a single magnet providing the force to push the particle into a circular path, this system requires a series of magnets positioned so as to deflect its path into a circle.

This type of accelerator again suffers the same problem as the cyclotron, yet its problems are more easily overcome. As the particle travels faster the mass increases, and so the force needed to pull it around in a circle increases. In the synchrotron, this is done by increasing the strength of electromagnets used to turn the particle. As soon as the particle is accelerated, it requires a greater applied force. In this case the energy required to keep the particle in a circular path instantly becomes too much for any conventional system. This is the main reason that CERN is 27 kilometers long.

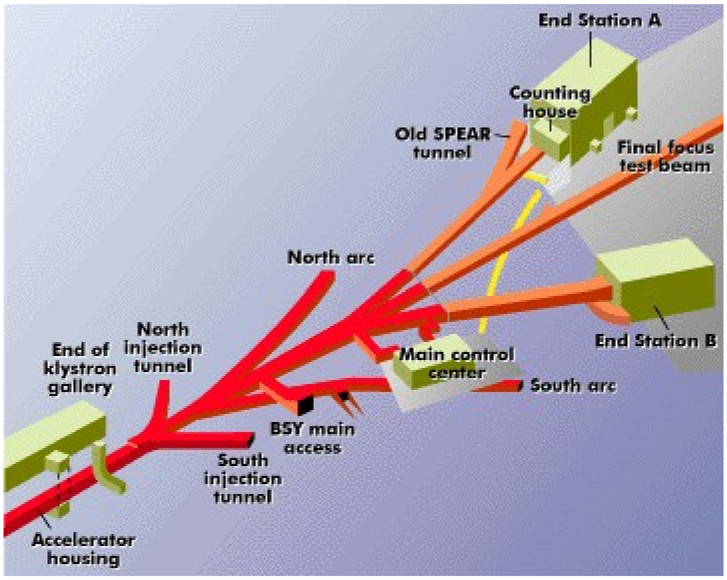
Ironically, the largest particle accelerator in the world is not the most powerful. CERN can produce particles of 50GeV, which is fairly impressive but not as impressive as the Fermi National Accelerator Laboratory (Fermi Lab). Fermi Lab is home to the Tevatron, a particle accelerator capable of producing 1TeV. This is mainly due to the fact that all the magnets used in the accelerator are superconductive, meaning no loss of energy and interesting magnetic properties! The accelerator is also a storage ring collider accelerator. Two sets of particles rotate in opposite directions around the ring, then collide. This effectively means a collision of at least 2TeV will occur when two particles collide.

2. LINEAR ACCELERATORS (with SLAC as example):

Accelerator Components

- Beam Production
- Bunching
- Acceleration (Electron Gun)
- Beam Focusing
- Colliding & Detecting

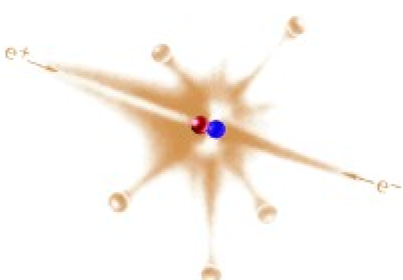
Beam Production



Primarily, in a particle accelerator, beams of electrons or protons are created. They are the most stable charged particles. Other particles are created by colliding them to some appropriate target. However, many experiments today require collisions of electrons and positrons, thus necessitating positron beams.

The electrons are created by thermionic emission. This involves liberating free electrons from the surface of the metal by external energy transferred to the electron (through heating). Proton beams are created by ionizing hydrogen. Glow discharge technique is used in ionization process. Hydrogen gas is put in a strong electric field inside a glow discharge tube so that the protons and the electrons are separated out and move in opposite directions, thus creating a stream of protons.

Positron Beam



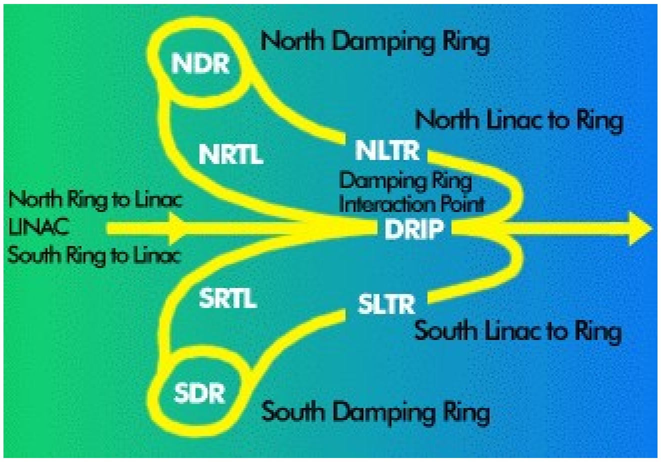
If we want to perform an experiment where electrons and positrons collide, how do we produce the positrons? These are antimatter particles. There are none around -- we really have to make them!

Positrons are produced by diverting some of the electrons from the accelerator and colliding them with a large piece of tungsten. This collision produces large numbers of electron- positron pairs. The positrons are collected and sent back along a separate line to the start of the linac, where magnets turn them around. They are then fed back into the linac and accelerated in the same manner as the electrons.

When the electrons and positrons reach the end of the linac and enter the Beam Switch Yard (BSY), they are diverted in different directions by a powerful dipole magnet and travel into storage rings, such as Stanford Positron Electron Accelerating Ring (SPEAR), Positron Electron Project (PEP), or into other experimental facilities, such as Final Focus Test Beam (FFTB) or the arcs of SLC -- the SLAC Linear Collider.

Bunching

After the first ten feet of the linac, the electrons are traveling in bunches with an energy of approximately 10 MeV. This means the electrons have reached 99.9% the speed of light. These bunches have a tendency to spread out in the directions perpendicular to their travel.

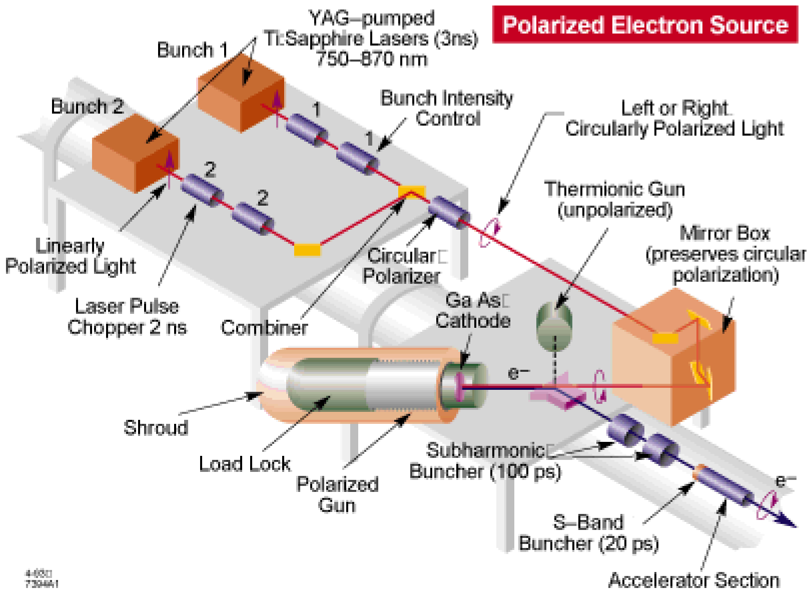


Because a spread out beam gives fewer collisions than a narrowly focused one, the electron and positron bunches are sent into damping rings (electrons to north, positrons to south).

There are small storage rings located on either side of the main accelerator. As the bunches circulate in the damping ring, they lose energy by synchrotron radiation and are re-accelerated each time they pass through a cavity fed with electric and magnetic fields. The synchrotron radiation decreases the motion in any direction, while the cavity re-accelerates only those in the desired direction. Thus, the bunch of electrons or positrons becomes more and more parallel in motion as the radiation "damps out" motion in the unwanted directions. The bunches are then returned to the accelerator to gain more energy as they travel along it.

Electron Gun

At the end of the two mile tunnel that houses the beam line is the electron gun, which produces the electrons to be accelerated. When a filament is heated by an electrical current flowing through it, a few electrons are released into the space around it. A strong electric field is then applied to pull more electrons out of the hot filament. The electric field accelerates the electrons towards the beginning of the accelerator structure. This is also the way our TV or computer monitor produces its electron beams.



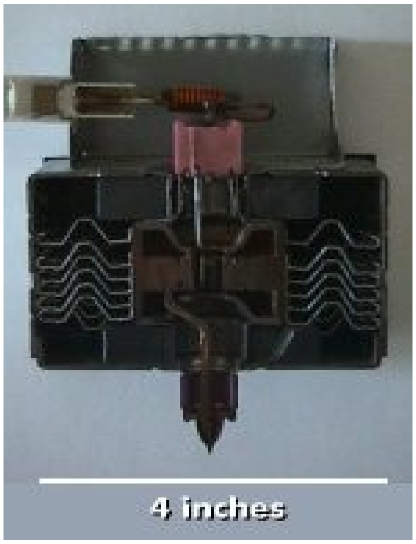
SLC Polarized Electron Gun

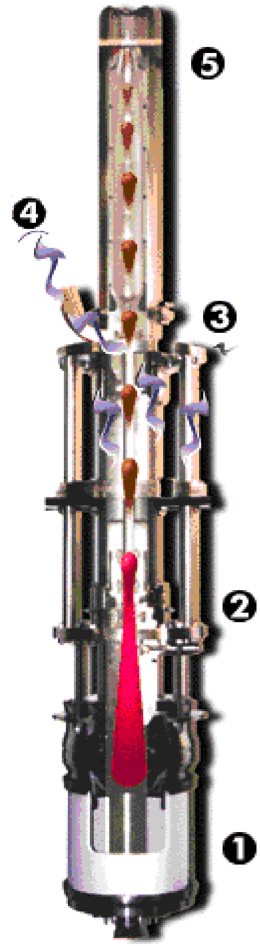
In the polarized electron gun, polarized laser light knocks electrons off the surface of a semiconductor and an electric field accelerates them toward the end of the accelerator pipe.

Beam Focusing: Role of Klystron

Klystron is a Microwave Generator

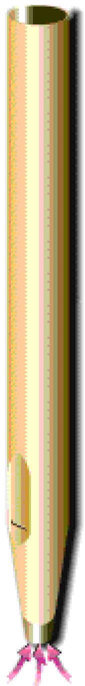
Compare SLAC's large, high- power microwave generator (klystron – Figure 2) with this much smaller one (magnetron – Figure 1) from a typical microwave oven**.**





Above: Microwave magnetron
Right: Klystron

A klystron looks and works something like an organ pipe.



In an organ pipe:

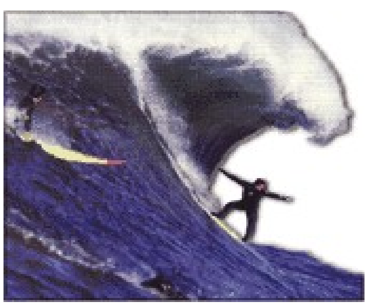
- Blowing into the organ pipe produces a flow of air.
- Flowing air excites vibrations in the cavity of the whistle.
- The vibrations flow into the surrounding air as sound waves.

Sequence of Events in a Klystron (Above):

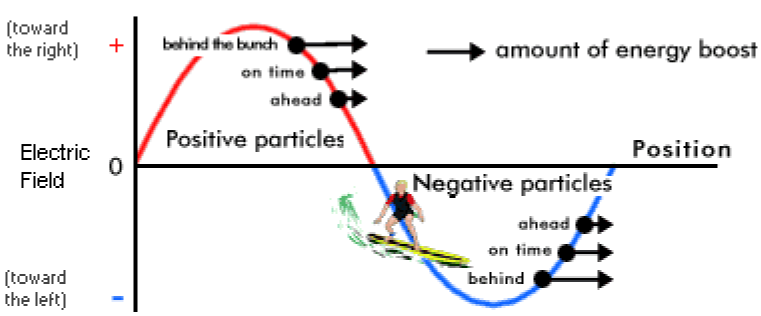
- The electron gun ❶ produces a flow of electrons
- The bunching cavities ❷regulate the speed of the electrons so that they arrive in bunches at the output cavity.
- The bunches of electrons excite microwaves in the output cavity ❸of the klystron.
- The microwaves flow into the waveguide ❹, which transports them to the accelerator.

Overall Operation of LINAC

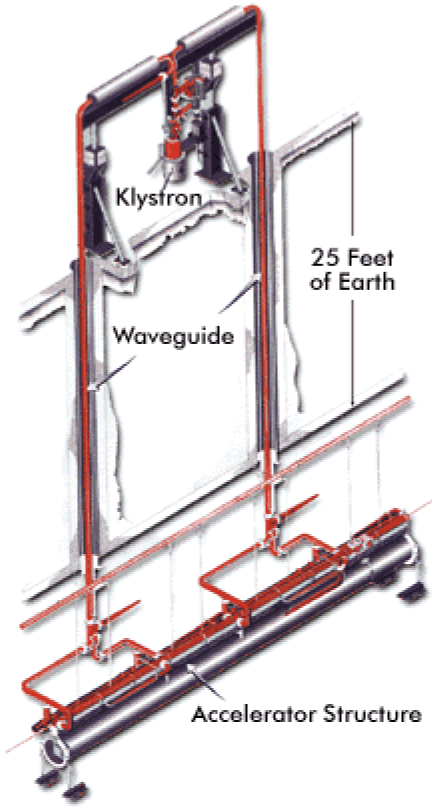
Electrons are Accelerated in a Copper Structure



Bunches of electrons are accelerated in the copper structure of the linac in much the same way as a surfer is pushed along by a wave



In the linac, the wave is electromagnetic. That means it is made up of changing magnetic and electric fields.

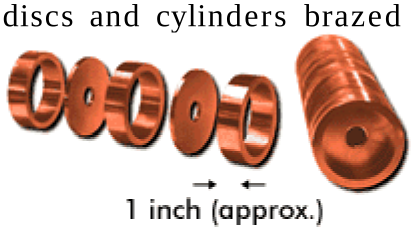


The electromagnetic waves that push the electrons in the linac are created by higher energy versions of the microwaves used in the microwave oven in our kitchen.

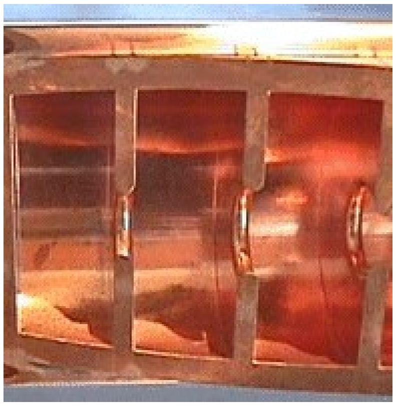
The microwaves from the klystrons in the Klystron Gallery are fed into the accelerator structure via the waveguides.

This creates a pattern of electric and magnetic fields, which form an electromagnetic wave traveling down the accelerator.

The 2-mile SLAC linear accelerator (linac) is made from over 80,000 copper discs and cylinders brazed together.



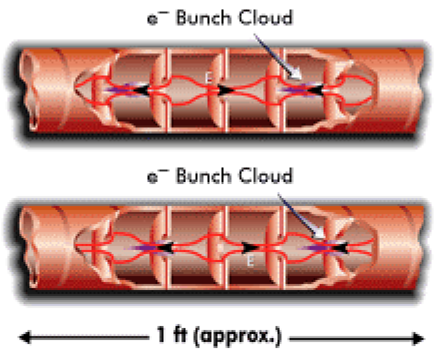
Inside the accelerator structure, the microwaves from the klystrons set up currents in the copper that cause oscillating electric fields pointing along the accelerator as well as oscillating magnetic fields in a circle around the interior of the accelerator pipe. The trick is to have the electrons or positrons arrive in each cell or cavity of the accelerator just at the right time to get maximum push from the electric field in the cavity. Of course, since positrons have opposite charge from electrons, they must arrive when the field is pointing the opposite way to be pushed in the same direction.



Photograph of accelerator structure, cut open for viewing.

The size of the cavities in the accelerator is matched to the wavelength of the microwaves so that the electric and magnetic field patterns repeat every three cavities along the accelerator. This means, in principle, there could be electron bunches following one another three cavities apart, and positron bunches half way in between. Usually the spacing between the bunches is kept somewhat larger (though always in multiples of three cavities for the same sign particles).

Notice how far the bunches have moved after just 1/20,000,000,000 of a second!

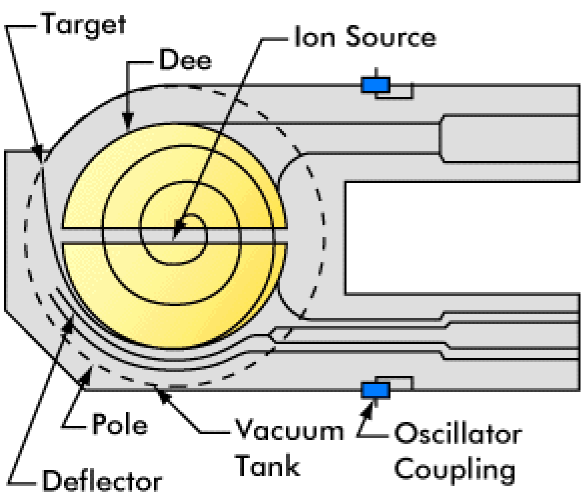


3. Circular Accelerators

- Cyclotron
- Synchrotron
- Storage Ring

Cyclotron

The cyclotron is a particle accelerator conceived by Ernest O. Lawrence in 1929, and developed with his colleagues and students at the University of California in the 1930s.



A cyclotron consists of two large dipole magnets designed to produce a semi-circular region of uniform magnetic field, pointing uniformly downward.

These were called D’s because of their D-shape. The two D's were placed back-to-back with their straight sides parallel but slightly separated.

An oscillating voltage was applied to produce an electric field across this gap. Particles injected into the magnetic field region of a D trace out a semicircular path until they reach the gap. The electric field in the gap then accelerates the particles as they pass across it.

The particles now have higher energy so they follow a semi-circular path in the next D with larger radius and so reach the gap again. The electric field frequency must be just right so that the direction of the field has reversed by their time of arrival at the gap. The field in the gap accelerates them and they enter the first D again. Thus the particles gain energy as they spiral around. The key is as they speed up, they trace a larger arc, so that they always take the same time to reach the gap. In this manner, a constant frequency electric field continues to accelerate them across the gap. The maximum energy that can be reached in such a device depends on the size of the magnets that form the D's and the strength of their magnetic fields.

Once the synchrotron principle was developed (see below), it was found to be a much cheaper way to create high energy particles than the cyclotron, making the original cyclotron method obsolete.

The maximum speed a proton could have in a dee of radius R and strength B is given by (ignoring relativistic effects.)

$$v_m = BeR / m_p$$

Synchrotron

A synchrotron (sometimes called a synchro- cyclotron) is a circular accelerator which has an electromagnetic resonant cavity (or perhaps a few placed at regular intervals around the ring) to accelerate the particles.

There are several circular accelerators at Fermi National Accelerator Laboratory. Particles pass through each cavity many times as they circulate around the ring, each time receiving a small acceleration, or increase in energy. When either the energy or the field strength changes, so does the radius of the path of the particles.

Thus, as the particles' energy increases, the strength of the magnetic field used to steer them must be changed with each turn to keep them moving in the same ring. The change in magnetic field must be carefully synchronized to the change in energy or the beam will be lost; hence the name "synchrotron". The range of energies over which particles can be accelerated in a single ring is determined by the range of field strength available with high precision from a particular set of magnets. To reach high energies, physicists sometimes use a sequence of different size synchrotrons, each one feeding the next bigger one. Particles are often pre-accelerated before entering the first ring, using a small linear accelerator or other device.

The radius of curvature of the path of particles of momentum p and charge q in a synchrotron is given by the formula R = p / q B where B is the field strength.

If a synchrotron of radius R has 4 straight sections of length L each and the period of the radio frequency oscillator corresponds to the time of one revolution then

(a) The speed of the particles must be

$$v = (2pR + 4L)\, f$$

(b) By considering the relativistic momentum of particles of mass M, the magnetic field strength of the synchrotron is given by

$$B = \frac{M}{eR}(2\pi R + 4L) f \left[1 - \frac{(2\pi R + 4L)^2 f^2}{c^2}\right]^{-1/2}$$

Where f = frequency of the oscillator.

Synchrotron Radiation

Synchrotron radiation is the name given to the electromagnetic radiation emitted by the charged particles circulating in a synchrotron. This is due to the charged particles being accelerated (deflected) by the magnetic field from the dipole magnets to make the beam travel around the ring. Any accelerated charged particle produces some electromagnetic radiation.

The wavelength and intensity of the synchrotron radiation depends on the energy and type of the emitting particle. Meanwhile, storing a high energy beam in this configuration is problematic. The energy lost from the beam by this radiation effect must be restored by introducing accelerating cavities at one or more places in the ring, to give the particles a kick in energy every time they pass. The amount and energy of the radiation depends on the speed of the radiating particles and the magnetic field strength. As the particle approaches the speed of light, the effect increases rapidly. The energy loss for a given electron energy is proportional to $(\gamma)^3$, where the factor gamma (γ) is the ratio of the energy of the particle to its rest mass-energy, mc^2.

Dependence on Particle Type

For a 1.5 GeV electron in the SPEAR storage ring, gamma is approximately 3000. For a 50 GeV electron in the SLC arcs, gamma is approximately 100,000. Because a proton is so much more massive than an electron, a proton with 1 TeV = 1,000 GeV energy has a gamma factor of only 1,000. (1 TeV is the energy produced by the synchrotron at Fermi lab). Thus synchrotron radiation is much greater for electrons than for equal energy protons. This allows for much higher energy synchrotrons for protons than for electrons.

SSRL

At SPEAR, the synchrotron radiation has wavelengths ranging from ultraviolet to x-ray, making it a useful scale to probe the atomic and molecular structure of matter. The Stanford Synchrotron Radiation Laboratory at SLAC is devoted to studies using this powerful tool.

Storage Ring

A storage ring is the similar to a synchrotron, except that it is designed to merely keep the particles circulating at a constant energy for as long as possible and not to increase their energy any further. However, the particles must still pass through at least one accelerating cavity each time they circle the ring, to compensate for the energy lost to synchrotron radiation.

Three storage rings have been built at SLAC: SPEAR, a 3 GeV ring completed in the early 70's; PEP, a 9 GeV ring completed in the early 80's; and PEP II completed in the late 90’s (an electron ring with 9GeV and a positron ring with 3.1 GeV).

4. Particle Accelerators Around the World:

Sorted by Location

	Europe
AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherlands
ANKA	Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))
ASTRID	Aarhus Storage Ring in Denmark, ISA, Aarhus, Denmark
BESSY	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany (BESSY I status, BESSY II status)
BINP	Budker Institute for Nuclear Physics, Novosibirsk, Russian Federation (VEPP-2M collider, VEPP-4M collider (status))
CERN	Centre Europeen de Recherche Nucleaire, Geneva, Suisse (LEP & SPS Status, LHC, CLIC, PS-Division, SL-Division)
COSY	Cooler Synchrotron, IKP, FZ Jülich, Germany (COSY Status)
CYCLONE	Cyclotron of Louvain la Neuve, Louvain-la-Neuve, Belgium
DELTA	Dortmund Electron Test Accelerator, U of Dortmund, Germany (DELTA Status)
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (HERA, PETRA and DORIS status, TESLA)
ELBE	ELectron source with high Brilliance and low Emittance, FZ Rossendorf, Germany
ELETTRA	Trieste, Italy (ELETTRA status)
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France (ESRF status)
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
HISKP	Helmholtz-Institut für Strahlen- und Kernphysik, Bonn, Germany (Isochron Cyclotron)
IHEP	Institute for High Energy Physics, Protvino, Moscow region, Russian Federation
INFN	Istituto Nazionale di Fisica Nucleare, Italy, LNF - Laboratori Nazionali di Frascati (DAFNE, other accelerators), LNL - Laboratori Nazionali di Legnaro (Tandem, CN Van de Graaff, AN 2000 Van de Graaff),

	LNS - Laboratori Nazionali del Sud, Catania, (Superconducting Collider & Van de Graaff Tandem)
ISIS	Rutherford Appleton Laboratory, Oxford, U.K. (ISIS Status)
ISL	IonenStrahlLabor am HMI, Berlin, Germany
JINR	Joint Institute for Nuclear Research, Dubna, Russian Federation (U-200, U-400, U-400M, Storage Ring, LHE Synchrophasotron / Nuclotron)
JYFL	Jyväskylän Yliopiston Fysiikan Laitos, Jyväskylä, Finland
KTH	Kungl Tekniska Högskola (Royal Institute of Technology), Stockholm, Sweden (Alfén Lab electron accelerators)
MLL	Maier-Leibnitz-Laboratorium: Accelerator of LMU and TU Muenchen, Munich, Germany
LURE	Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Orsay, France (DCI, Super-ACO status, CLIO)
MAMI	Mainzer Microtron, Mainz U, Germany
MAX-Lab	Lund University, Sweden
MSL	Manne Siegbahn Laboratory, Stockholm, Sweden (CRYRING)
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge-Energie Fysica, Amsterdam, Netherlands (AmPS *closed!*)
PSI	Paul Scherrer Institut, Villigen, Switzerland (PSI status, SLS *under construction*)
S-DALINAC	Darmstadt University of Technology, Germany (S-DALINAC status)
SRS	Synchrotron Radiation Source, Daresbury Laboratory, Daresbury, U.K. (SRS Status)
TSL	The Svedberg Laboratory, Uppsala University, Sweden (CELSIUS)
TSR	Heavy-Ion Test Storage Ring, Heidelberg, Germany

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS [status], Intense Pulsed Neutron Source IPNS [status], Argonne Tandem Linac Accelerator System ATLAS)
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)
CAMD	Center for Advanced Microstructures and Devices
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CESR	Cornell Electron-positron Storage Ring, Cornell University,

	Ithaca, NY (CESR Status)
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
IAC	Idaho accelerator center, Pocatello, Idaho
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
LAC	Louisiana Accelerator Center, U of Louisiana at Lafayette, Louisiana
LANL	Los Alamos National Laboratory
MIT-Bates	Bates Linear Accelerator Center, Massachusetts Institute of Technology (MIT)
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
ORNL	Oak Ridge National Laboratory (EN Tandem Accelerator), Oak Ridge, Tennessee
PBPL	Particle Beam Physics Lab (Neptune- Laboratory, PEGASUS- Photoelectron Generated Amplified Spontaneous Radition Source)
SBSL	Stony Brook Superconducting Linac, State University of New York (SUNY)
SLAC	Stanford Linear Accelerator Center (Linac, NLC - Next Linear Collider, PEP- Positron Electron Project (finished), PEP-II - asymmetric B Factory (in commissioning), SLC - SLAC Linear electron positron Collider, SPEAR - Stanford Positron Electron Asymmetric Ring (actually SPEAR-II, see SSRL), SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison (Aladdin Status)
SURF II	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TASCC	Tandem Accelerator Superconducting Cyclotron (Canada) *(closed!)*
TRIUMF	TRI-University Meson Facility / National Meson Research Facility, Vancouver, BC (Canada)

South America

LNLS	Laboratorio Nacional de Luz Sincrotron, Campinas SP, Brazil
TANDAR	Tandem Accelerator, Buenos Aires, Argentina

Asia

BEPC	Beijing Electron-Positron Collider, Beijing, China
KEK	National Laboratory for High Energy Physics ("Koh-Ene-Ken"),

	Tsukuba, Japan (KEK-B, PF, JLC)
NSC	Nuclear Science Centre, New Delhi, India (15 UD Pelletron Accelerator)
PLS	Pohang Light Source, Pohang, Korea
RIKEN	Institute of Physical and Chemical Research ("Rikagaku Kenkyusho"), Hirosawa, Wako, Japan
SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East, Jordan (under construction)
SPring-8	Super Photon ring - 8 GeV, Japan
SRRC	Synchrotron Radiation Research Center, Hsinchu, Taiwan (SRRC Status)
UVSOR	Ultraviolet Synchrotron Orbital Radiation Facility, Japan
VECC	Variable Energy Cyclotron, Calcutta, India

Africa

NAC	National Accelerator Centre, Cape Town, South Africa

Sorted by Accelerator Type

Electrons

Stretcher Ring/Continuous Beam facilities

ELSA (Bonn U), JLab, MAMI (Mainz U), MAX-Lab, MIT-Bates, PSR (SAL), S-DALINAC (TH Darmstadt), SLAC

Synchrotron Light Sources

ANKA (FZK), ALS (LBL), APS (ANL), ASTRID (ISA), BESSY, CAMD (LSU), CHESS (Cornell Wilson Lab), CLS (U of Saskatchewan), DELTA (U of Dortmund), ELBE (FZ Rossendorf), Elettra, ELSA (Bonn U), ESRF, HASYLAB (DESY), LURE, MAX-Lab, LNLS, NSLS (BNL), PF (KEK), UVSOR (IMS), PLS, S-DALINAC (TH Darmstadt), SESAME, SLS (PSI), SPEAR (SSRL, SLAC), SPring-8, SRC (U of Wisconsin), SRRC, SRS (Daresbury), SURF II (NIST)

Other

Alfén Lab (KTH), IAC, Neptune, PEGASUS

Protons

88" Cyclotron (LBL), CELSIUS (TSL), COSY (FZ Jülich), IPNS (ANL), ISL (HMI), ISIS, IUCF, LHC (CERN), NAC, PS (CERN), PSI, SPS (CERN)

Light and Heavy Ions

88" Cyclotron (LBL), AGOR, ASTRID (ISA), ATLAS (ANL), CELSIUS (TSL), CRYRING (MSL), CYCLONE, EN Tandem (ORNL), GANIL, GSI, HISKP, ISL (HMI), IUCF, JYFL, LAC, LHC (CERN), LHE Synchrophasotron / Nuclotron (JINR), Maier-Leibnitz-Laboratorium, LNL (INFN), LNS (INFN), NAC, NSC, PSI, RHIC (BNL), SBSL, SNS, SPS (CERN), TANDAR, TSR, U-200 / U-400 / U-400M / Storage Ring (JINR), VECC

Collider

BEPC, CESR, DAFNE (LNF), HERA (DESY), LEP (CERN), LHC (CERN), PEP / PEP-II (SLAC), SLC (SLAC), KEK-B (KEK), TESLA (DESY), Tevatron (FNAL), VEPP-2M, VEPP-4M (BINP)

Remark: This is not a list of high-energy physics experiments or laboratories, but a list of particle accelerators and accelerator laboratories.

References:

[1] E. O. Lawrence and M. S. Livingston, "The Production of High Speed Protons Without the Use of High Voltages," Phys. Rev. 38, 834 (1931) is a half-page letter reporting a smaller cyclotron.

[2] The Production of High Speed Light Ions Without the Use of High Voltages Ernest O. Lawrence and M. Stanley Livingston Phys. Rev. 40, 19 (issue of April 1932).

[3] Accelerator Physics at SLAC

http://www-ssrl.slac.stanford.edu/accphy/accphy.html

[4] Operations Accelerator Glossary Index:

http://www-bdnew.fnal.gov/operations/accgloss/gindex.html

[5] CERN Accelerators & Beam Physics Group

http://slap.web.cern.ch/slap/

[6] Helmut Wiedemann, Particle Accelerator Physics: Basic Principles & Linear Beam Dynamics (1993)