LECTURE 1

<u>Varieties of accelerators</u>

Particle Sources ,Linear Accelerators, Circular Accelerators

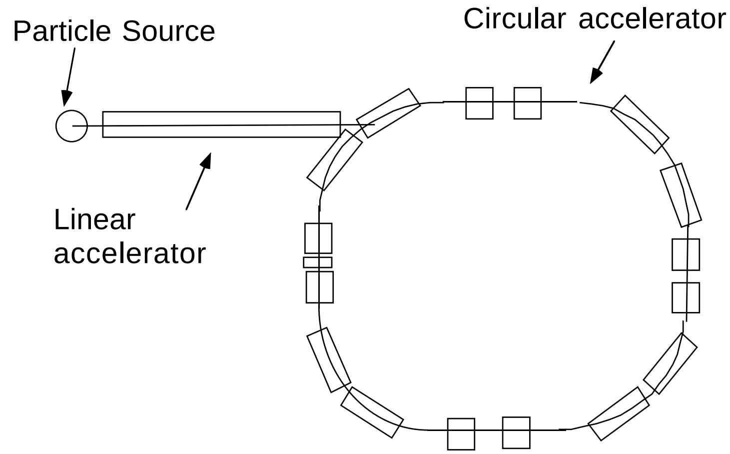
<u>Accelerator Technologies</u>

Magnets, Radiofrequency Systems,Vacuum systems

<u>Applications of Accelerators</u>

Research

Other applications



THE GENERIC ACCELERATOR COMPLEX

<u>Varieties of accelerators:</u>

<u>Particle Sources</u>

<u>Ion sources:</u>

(see N. Augert, “Ion Sources”, Ref. 2, Vol. 2, pp. 619-642)

<u>Positive ion sources:</u> the positive ions are formed from electron bombardment of a gas and extracted from the resulting plasma. Species ranging from H to U (multiply charged) are available

<u>Negative ion sources:</u> Principal interest is in H^-, for charge-exchange injection

Surface sources: In a plasma, H picks up electrons from an activated surface

Volume sources (magnetron, Penning): electron attachment or recombination in H plasma

Polarized ion sources: e.g., optically pumped sources: some penalty in intensity, relatively high (>65%) polarization

<u>Electron sources</u>

DC HV guns: 50-500 keV acceleration

Electron production mechanism:

- thermionic emission (pulse duration controlled by a pulsed grid)
- photocathode irradiation by pulsed laser (laser pulse width determines the pulse duration)

RF guns: cathode forms one wall of an accelerating RF cavity

Rapid acceleration to above 10 MeV in a few cells->mitigates space charge effects, makes for low emittance

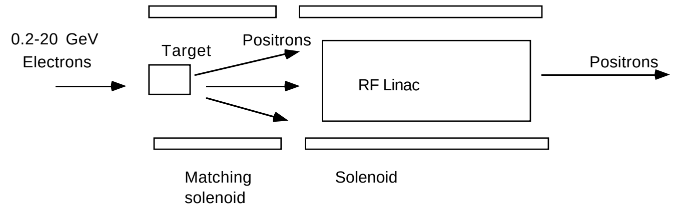
Electron production mechanism:

- thermionic emission (pulse duration controlled RF structure)
- photocathode irradiation by pulsed laser (laser pulse width determines the pulse duration)

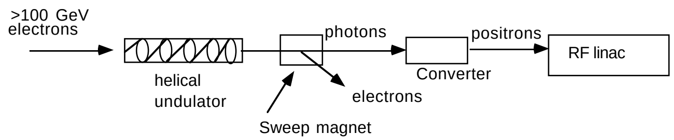
Positron sources

(see R. Chehab, “Positron Sources”, Ref. 2, Vol. 2, pp. 643-678)

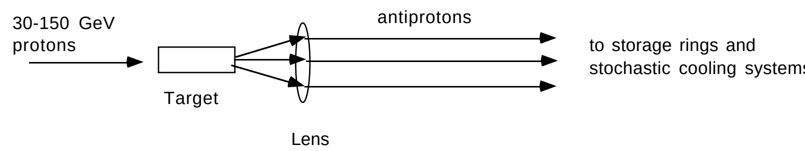
“Conventional” positron source: Can get from 10^{-3} :1 up to ~1:1 positron/electron as electron energy rises from 0.2 to 20 GeV



Positron production by high energy photons



Antiproton sources

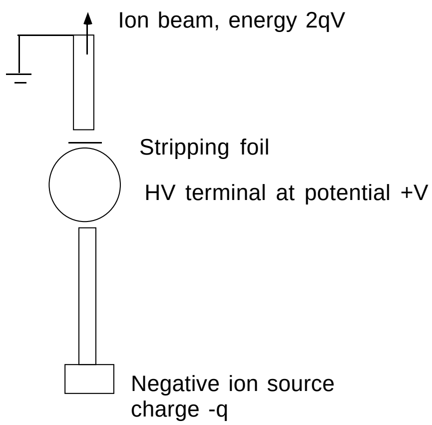


Yield of antiprotons/proton is typically 10^{-5}

Linear Accelerators

Electrostatic Accelerators:

Tandem Van de Graff, Pelletron

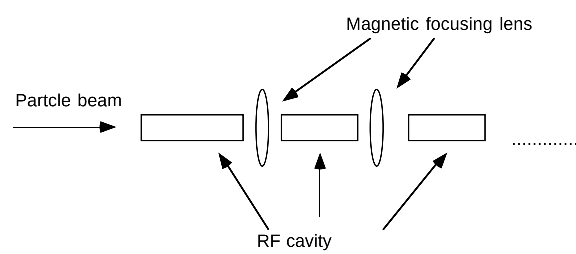


HV terminal is charged mechanically

Energies are limited to 10-20 MeV

RF Linacs

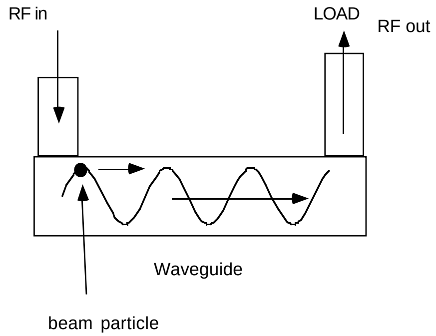
(see M. Weiss, “Introduction to RF linear accelerators”, Ref. 2., Vol 2, pp. 913-954)



Lenses are required for transverse stability (the RF cavities are transversely defocusing)

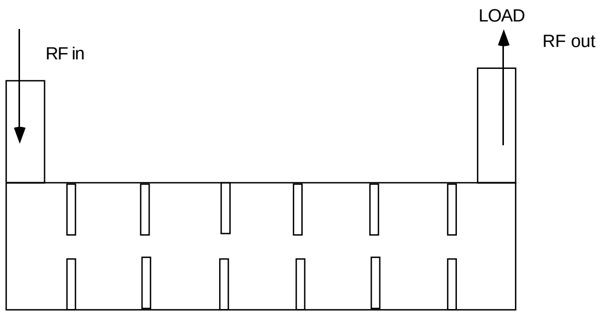
RF cavities may be of two forms: “travelling wave” or “standing wave”

Travelling wave cavity:



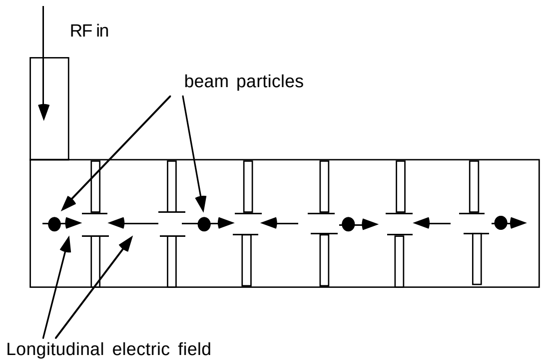
Typically operated in a TM mode: longitudinal electric field provides the acceleration. Beam is bunched, rides at crest of wave

For a uniform waveguide, the phase velocity is greater than *c*, so the particle gets out of sync with the wave very rapidly. The waveguide must be *loaded* with periodic obstacles (disks) , with holes (irises) for the beam



Disk-loaded waveguide

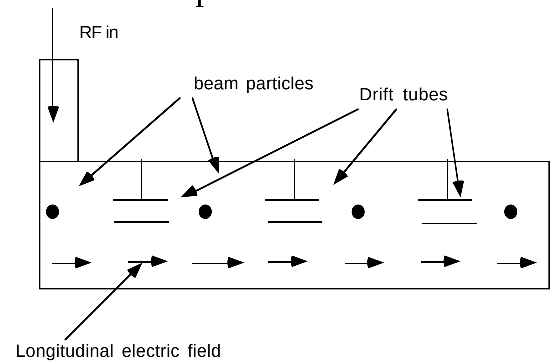
Standing wave cavity:



π mode: fields alternate in adjacent cavities

0 mode: fields are the same in adjacent cavities

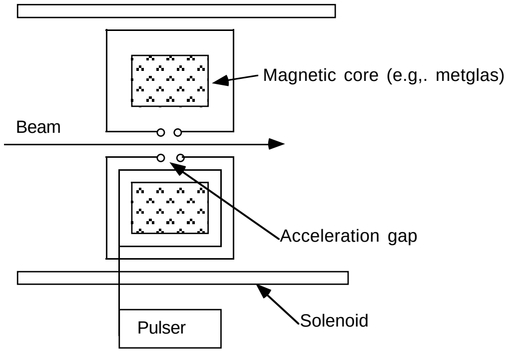
Drift-tube (Alvarez) linac: typically used at the first stage in a proton linac



Beam is shielded from the fields when at the wrong phase by using hollow "drift tubes"

Radio-frequency quadrupole ("RFQ"):
A long electric quadrupole, with a sinusoidally varying voltage on its electrodes. The electrode tips are modulated in the longitudinal direction; this modulation results in a longitudinal field, which accelerates particles. It is a capable of a few MeV of acceleration. Typically used between the ion source and the Alvarez linac in proton RF linacs.

Induction linac:



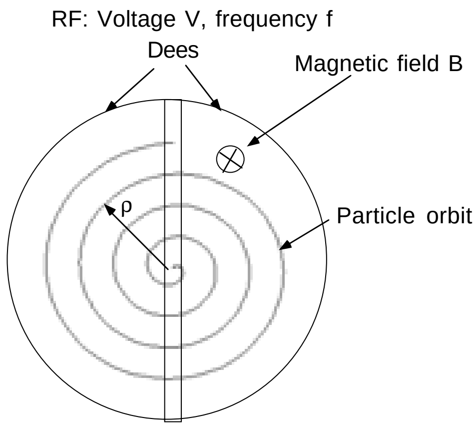
The beam forms the secondary circuit of a high-current pulse transformer
Induction linacs have very low rep rates (a few Hz) and intermediate voltages (30-50 MeV) but very high peak currents (>10 kA) in short (100 ns-1 μs) pulses

Circular Accelerators

Cyclotrons

(see P. Heikken, “Cyclotrons”, in Ref. 2, Vol. 2, pp. 805-818)

Classical cyclotron: Static B field, DC beam



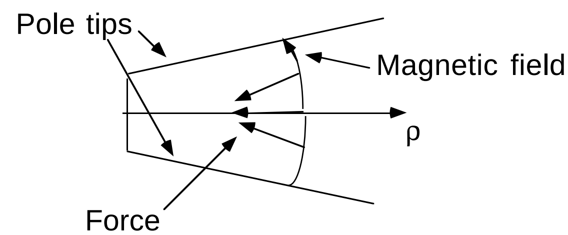
Centripetal force=Lorentz force=$e\left[\vec{E}+\vec{v}\times\vec{B}\right]$

$$\frac{mv^2}{\rho}=evB$$

$$\rho=\frac{mv}{eB}=\frac{p}{eB}$$

$$f=\frac{v}{2\pi\rho}=\frac{eB}{2\pi m}$$

To get vertical focusing, field B must decrease with ρ:



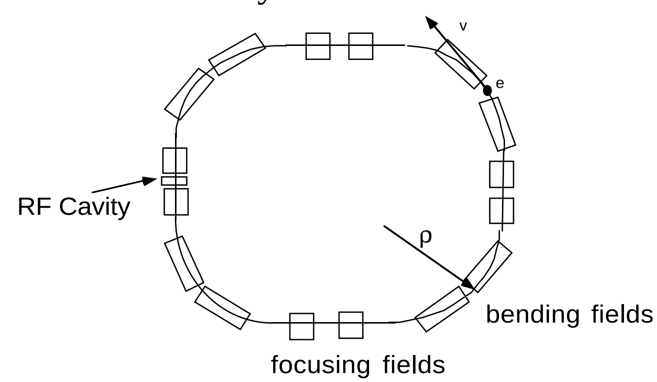
This fact, and the relativistic mass increase with velocity, limits the maximum energy of the classical cyclotron to about 10% of the rest mass energy.

Improvements:

- Isochronous cyclotron: Vary the *B* field azimuthally. This gives vertical focusing (like alternating gradient focusing in a synchrotron) and the *B* field can then increase with ρ to keep f constant as m increases.

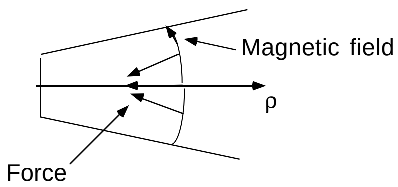
- Synchrocyclotron: Increase the RF frequency on the dees as m increases to maintain synchronism. The beam must then be bunched, as only a limited region in RF phase is stable, and the current is reduced.

Synchrotrons



A ring of magnets at fixed $\rho = \frac{p}{eB}$. As p increases during acceleration, B is increased to keep ρ constant. The RF frequency $f = \frac{v}{2\pi\rho}$ is constant for relativistic particles.

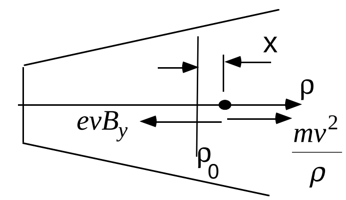
Focusing: to get vertical stability, we could allow the bending field to decrease with ρ, as in the classical cyclotron.



This can be represented as

$$B_y = B_0\left(\frac{\rho_0}{\rho}\right)^n$$

where n, called the **field index**, is > 0. However, n cannot be arbitrarily large, since we must also have radial stability:



For radial stability, the centrifugal force must be less than the Lorentz force for x>0:

$$\frac{mv^2}{\rho} = \frac{mv^2}{\rho_0 + x} \approx \frac{mv^2}{\rho_0}\left(1 - \frac{x}{\rho_0}\right)$$

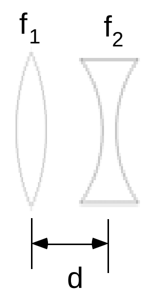
$$\leq evB_y = evB_0\left(\frac{\rho_0}{\rho}\right)^n = evB_0\left(\frac{\rho_0}{\rho_0 + x}\right)^n \approx evB_0\left(1 - n\frac{x}{\rho_0}\right)$$

$$\frac{x}{\rho_0} \geq n\frac{x}{\rho_0} \Rightarrow 1 \geq n$$

Focusing of this kind is called “weak focusing”. In 1952, “strong focusing”, or “alternating gradient focusing”, was invented by Courant and Snyder.

Strong focusing: alternate the focal length of magnetic lenses around the ring

Optical analogy:



$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$ is positive for a large range of focal lengths and d=> net focusing both radially and vertically

If this is done by providing a radially varying field in the bending magnets: the machine is called *combined function*. If this is done by using uniform field dipoles and separate quadrupole magnets, the machine is called *separated function*. Much greater focusing, hence smaller beam sizes, are obtained in a strong focusing machine than in a weak focusing one.

The RF cavities in proton synchrotrons are used primarily to accelerate the particles.

However, in electron synchrotrons of moderate to high energies, the RF cavities must also provide the energy lost by the electrons due to *synchrotron radiation.* (see R. P. Walker, "Synchrotron Radiation", Ref. 2, Vol. 2, pp 437-460)

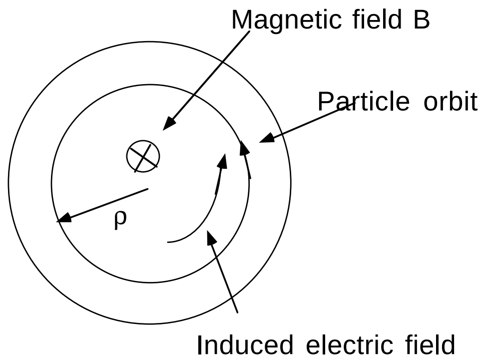
The energy loss per turn is

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\beta^3\gamma^4}{\rho}$$

In practical units $U_0[\mathrm{MeV}] = 0.0885\frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]}$

The radiation spectrum extends from the infrared to the many keV region.

Betatron: The circular analog of the induction linac

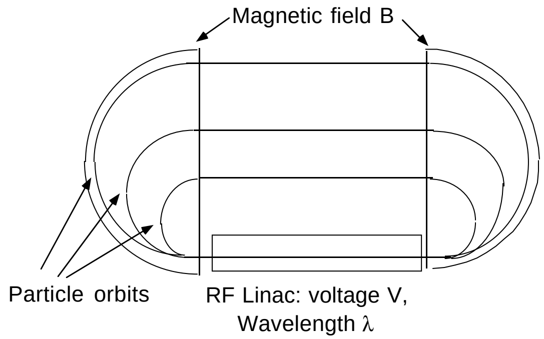


The orbit radius ρ is fixed. The accelerating electric field is provided by the changing magnetic flux within the orbit. The required flux change is $\Delta\phi = 2\pi\rho^2 B_{\max}$. Energies up to 300 MeV have been obtained.

Microtron

(see P. Lidbjork, "Microtrons", Ref. 2, Vol. 2, pp 971-81)

Racetrack microtron:



Resonance condition: $n\lambda B = \frac{2\pi}{c}V\cos\phi$, *n=1,2,…* (for relativistic particles), ϕ=relative particle-RF phase

Accelerator Technology

Magnet Systems

Principal types of magnets used in accelerators:

- Dipoles: provide a "static" transverse uniform field, typically to a few parts in 10^4
- Quadrupoles: provide a "static" uniform transverse field gradient, to the same accuracy
- Sextupoles: provide a "static" quadratic dependence of transverse field on position

- Combined function dipoles: provide a mostly uniform transverse field, with a small field gradient
- Solenoids: Provide a longitudinal uniform field
- The fields are ramped during acceleration in a synchrotron.

Magnet power supplies:

Primarily DC or slowly ramping for ring magnets; currents from 10-10,000 A, current regulation required typically 10-100 parts per million.

Principal magnet technologies:

- Permanent magnets-for fixed-energy rings, dipole fields up to about 1 T. Alnico, ferrite, $SmCo_3$, $Nd_2Fe_{14}B$. Need good temperature regulation for field stability. (See T. Meinander,

"Generation of magnetic fields for accelerators with permanent magnets", Ref. 2, Vol. 2, pp 893-998)

- Resistive electromagnets-the standard solution: excited with copper or aluminum coils, dipole field range up to about 2 T (See N. Marks, "Conventional Magnets", Ref. 2, Vol. 2, pp 867-912)

- Superconducting magnets-reduced power consumption, higher field range, used in large proton synchrotrons. Dipole fields up to 8 T (with NbTi superconductor), to 15 T (with Nb_3Sn superconductor) at 4.2^o K. Require extensive cryogenic systems. (See S. Wolff, "Superconducting Accelerator Magnet Design, Ref. 2, Vol. 2, pp 755-790)
- Pulsed magnets: provide rapidly varying fields, for beam injection, extraction, and fast switching in transport lines

Radiofrequency Systems

• Traveling wave and standing wave cavities are both possible elements in rf linacs or synchrotrons. The principal performance parameters of a cavity are its electric field (voltage gradient) and frequency. Generally, the relation between these is $E_a\lambda \approx$constant: Higher frequency systems can develop larger voltage gains. Systems from 20 MHz up to 11 GHz are in operation.

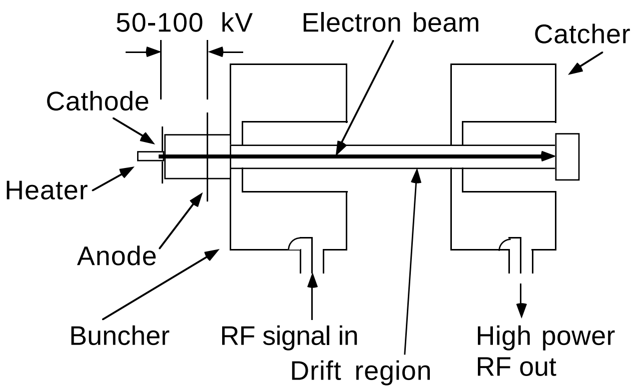
• Normal conducting (NC) cavities are fabricated from OHFC copper.
(See M. Puglisi, "Conventional RF System Design", Ref. 2, Vol.2, p 677-716)

• Superconducting (SC) systems typically use pure Nb cavity surfaces (sometimes plated on copper) at 4.2^{o}K. (See H. Lengeler, "Modern Technologies in RF Superconductivity", Ref. 2, Vol.2, p 791-804)
Higher accelerating fields (at low frequencies) are obtainable with SC systems than with NC systems. Power dissipation is much reduced in SC systems, although a cryogenic system is required.

Radiofrequency power sources:

• Triodes and tetrodes:
high power vacuum tube power generators, useful up to 300 MHz and 100 kW

- Klystrons: Narrow-band, tuned microwave amplifiers--500 MHz to15 GHz



Vacuum Systems

(See A. G. Mathewson, "Vacuum System Design", Ref. 2, Vol. 2, pp 717-730)

Accelerator vacuum systems are the most challenging for *storage rings:* synchrotrons in which the beam is maintained at fixed energy for many hours. Required pressures are typically below 10^{-9} Torr (about 10^{-12} atmospheres).

- Proton storage rings: gas load from thermal outgassing
- Electron storage rings: gas load from thermal outgassing and from photodesorption due to synchrotron radiation.

(Very high energy proton storage rings also have photodesorption issues)

Pumping systems:
Turbomolecular pumps, sputter ion pumps, non-evaporable getter pumps, and titanium sublimation pumps.

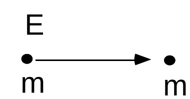
The pumping system can be lumped for proton storage rings, but must be continuously distributed around the ring for rings with high photodesorption gas loads.

Applications of Accelerators: Research

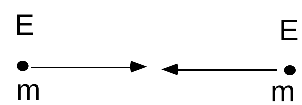
High Energy and Nuclear Physics

History: Livingston Plot

The collider energy advantage:



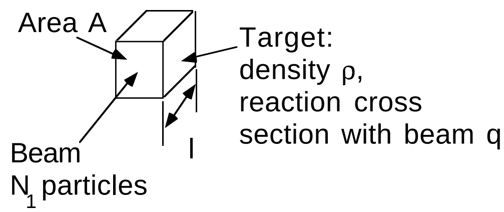
Fixed target (ultrarelativistic): $E_{cm} \approx c\sqrt{2Em}$



Collider: $E_{cm} \approx 2E$

Luminosity: the other figure of merit (besides energy) of a high energy collider

Luminosity (L) = reaction rate per unit cross section



Number of target particles $N_2 = \rho l A$

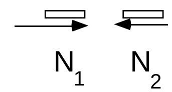
Effective area seen by the beam $A_{eff} = qN_2 = q\rho l A$

Probability of an interaction $P = \frac{A_{eff}}{A} = q\rho l$

Reaction rate $\frac{dR}{dt} = \frac{dN_1}{dt} P = \frac{dN_1}{dt} q\rho l$

Luminosity $L = \frac{1}{q}\frac{dR}{dt} = \frac{dN_1}{dt}\rho l = \frac{dN_1}{dt}\frac{N_2}{A}$

Colliding beams:



$$L = fN_1 \frac{N_2}{A}$$

f is the collision frequency; A is the cross-sectional area of the beams

In differential form:

$$\frac{dL}{dA} = f \frac{dN_1}{dA}\frac{dN_2}{dA}$$

for Gaussian, round beams, of rms size σ:

$$\frac{dN}{dA} = \frac{N}{2\pi\sigma^2}\exp\left[-\frac{r^2}{2\sigma^2}\right]; \text{ then}$$

$$L = f\frac{N_1 N_2}{4\pi\sigma^2}$$

Types of high-energy colliders: operating

Type	*Facility*	*CM energy(GeV)*	*Luminosity(10^{33} cm^{-2} s^{-1})*
e^+-e^-, two rings	DAFNE (Italy)	1.05	0.01
e^+-e^-, single ring	BEPC (China)	3.1	0.05
e^+-e^-, single ring	CESR (US)	10.4	0.8
e^+-e^-, two rings	SLAC PEP-II (US)	10.4	0.6
e^+-e^-, two rings	KEK-B (Japan)	10.4	0.3
e^+-e^-, single ring	CERN LEP (Europe)	200	0.05
Pbar-p, single ring	Fermilab Tevatron (US)	1,800	0.02
e-p, two rings	DESY HERA (Germany)	300	0.02
e^+-e^-, linear collider	SLAC SLC (US)	100	0.002

Types of high energy colliders: under construction or proposed

Type	*Facility*	*CM energy(GeV)*	*Luminosity(10^{33} cm^{-2} s^{-1})*
pp, two rings	CERN LHC	14,000	10
e^+-e^-, linear collider	NLC, JLC, TESLA, CLIC	500-1,500	10
μ^+-μ^-, single ring	Muon collider	100-3,000	0.1-100
pp, two rings	VLHC	100,000	10

Accelerators for nuclear physics (operating)

Type	*Facility*	*CM energy(GeV)*	*Luminosity(10^{33} cm^{-2} s^{-1})*
AuAu, two ring collider	BNL RHIC (US)	100/nucleon	10^{-6}
Electron Microtron	CEBAF (US)	4	---
Electron linac	Bates (US)	0.3-1.1	---
Proton synchrotron	IUCF (US)	0.5	---
Isochronous heavy-ion cyclotron	MSU NSCL (US)	0.5	---
Isochronous cyclotron	TRIUMF(Canada)	0.5	---
Isochronous cyclotron	PSI (Switzerland)	0.5	---

Applications of Accelerators: Research

(See O. Barbarlat, “Applications of particle accelerators”, Ref. 2, Vol. 2, p 841-854)

Field	*Accelerator*	*Topics of study*
Atomic Physics	Low energy ion beams	atomic collision processes, study of excited states, electron-ion collisions, electronic stopping power in solids
Condensed matter physics	Synchrotron radiation sources	X-ray studies of crystal structure
Condensed matter physics	Spallation neutron sources	Neutron scattering studies of metals and crystals, liquids, and amorphous materials
Material science	Ion beams	Proton and X-ray activation analysis of materials; X-ray emission studies; accelerator mass spectrometry
Chemistry and biology	Synchrotron radiation sources	Chemical bonding studies: dynamics and kinetics; protein and virus crystallography; biological dynamics

Other applications of accelerators

- Oil well logging with neutron sources from small linacs
- Archaeological dating with accelerator mass spectrometry
- Medical diagnostics using accelerator-produced radioisotopes
- Radiation therapy for cancer: X-rays from electron linacs, neutron therapy from proton linacs, proton therapy; pion and heavy-ion therapy
- Ion implantation with positive ion beams
- Radiation processing with proton or electron beams: polymerization, vulcanization and curing, sterilization of food, insect sterilization, production of microporous membranes
- X-ray microlithography using synchrotron radiation
- Inertial confinement fusion using heavy-ion beams as the driver
- Muon-catalyzed fusion
- Tritium production, and radioactive waste incineration, using high energy proton beams