Accelerators

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Accelerators

The general aim is to collide two particles at high(est) energy and create new particles from combined energy and quantum numbers or to probe inside one of the particles to see what it is made of.

Only stable charged particles can be accelerated:

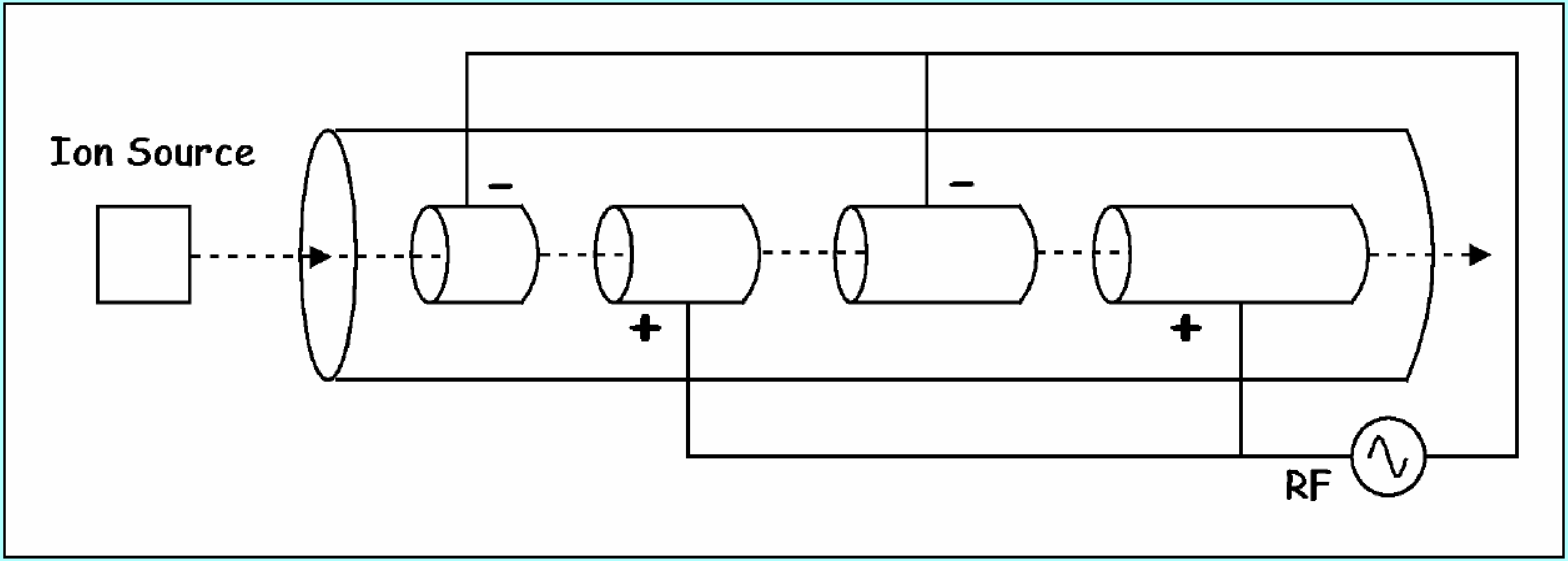
e^-, e^+, p, $\bar{p}$ (+ some ions)

There are two general types of accelerators –

Linear and Circular (Cyclic).

Linear Accelerators

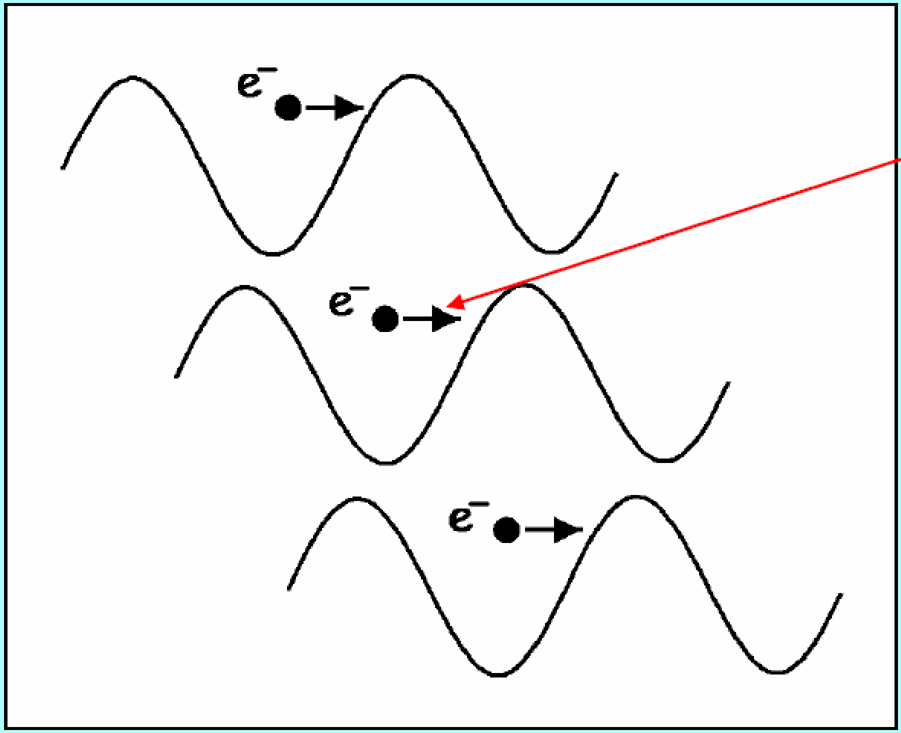
Proton Linear Accelerators (Linacs) use a succession of drift tubes of increasing length (to compensate for increasing velocity).



Particles always travel in vacuum. There is no field inside the drift tubes. External field between ends of tubes changes sign so proton always sees -ve in front and +ve behind. Proton linacs of ~10-70m give energies of 30 to 200 MeV. Usually used as injectors for higher energy machines.

Electron Linacs

Above a few MeV, electrons travel at speed of light, c. The 'tubes' become uniform in length and microwaves provide by Klystrons provide accelerating potential.



Electron is attracted to positive part of waveform

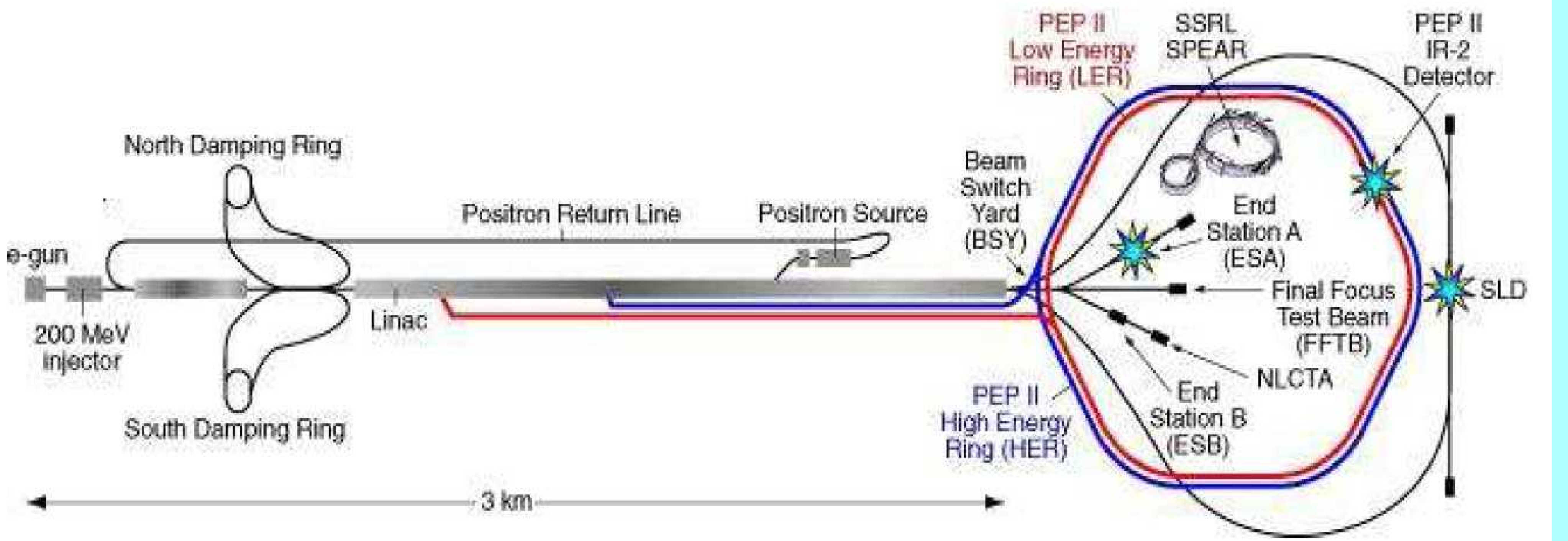
Wave travels down accelerator

Largest Linac is at SLAC (Stanford Linear Accelerator Center). 3Km long → 45 GeV electrons. Linac energies limited by available length. Next generation ~several 100 GeV (Next Linear Collider).

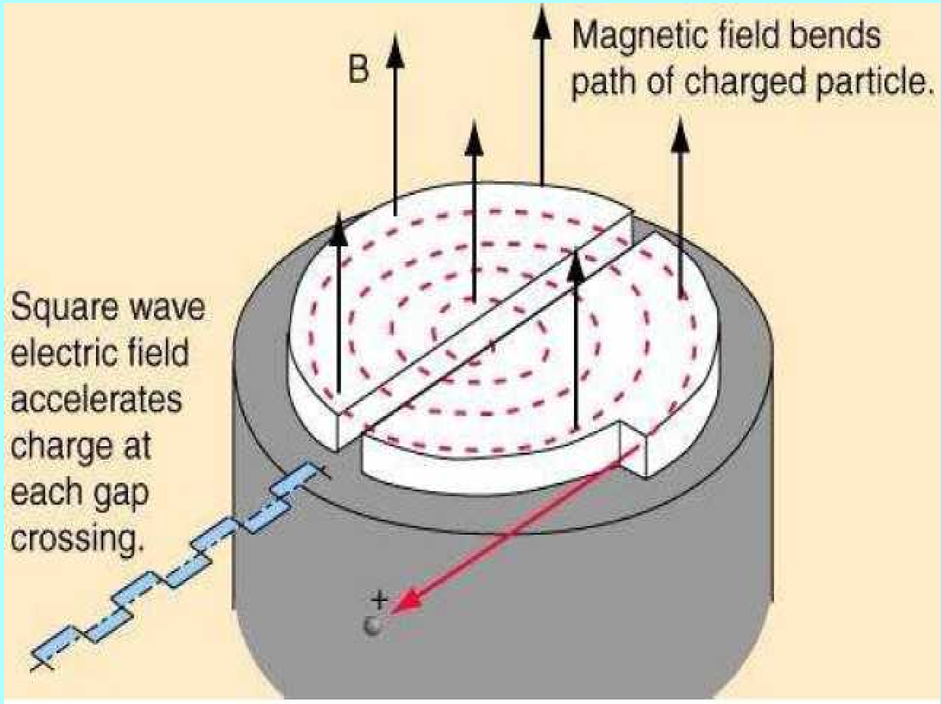
SLAC

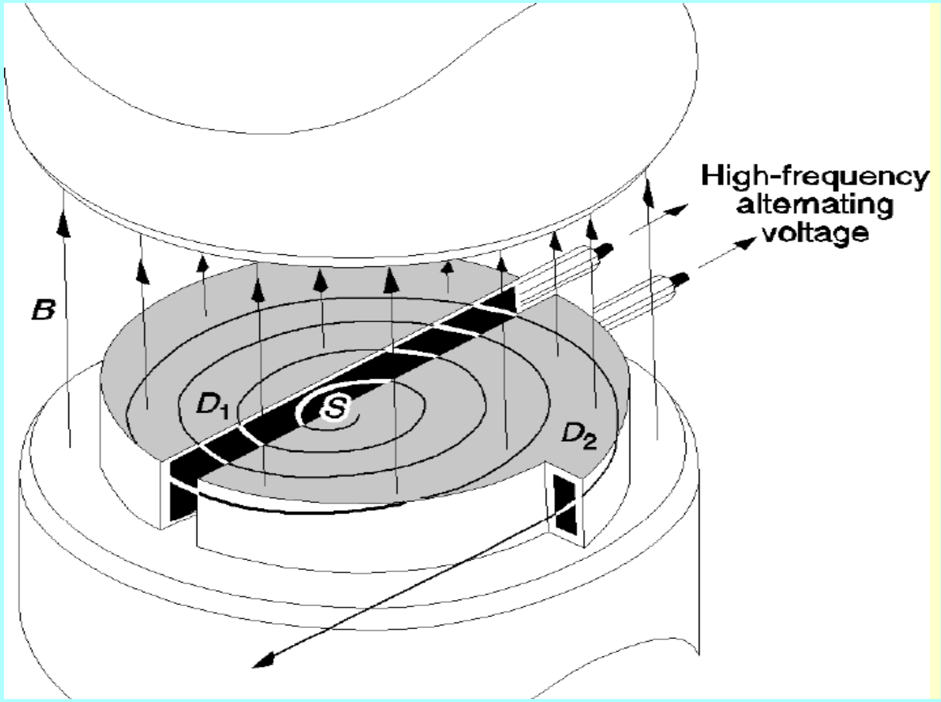
http://www.slac.stanford.edu/

At the end of the tube the electrons and positrons are stored in a storage ring (they go around the storage ring in opposite directions under the influence of the same magnetic field) and there are intersection points where electron-positron scatterings occur.



Cyclotrons





The prototype design for all circular accelerators

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

and

$$F = Bev = m\frac{v^2}{r}.$$

the angular velocity $\omega = v/r$ is constant

Taking relativistic effects into account The angular velocity is

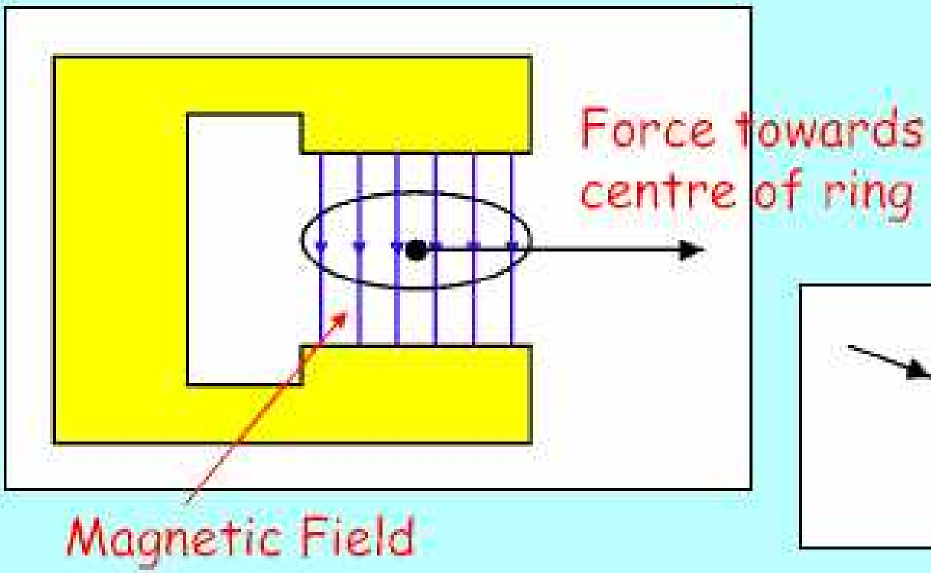
$$\omega = \sqrt{1 - v^2/c^2}\frac{Be}{m}.$$

Synchrotrons

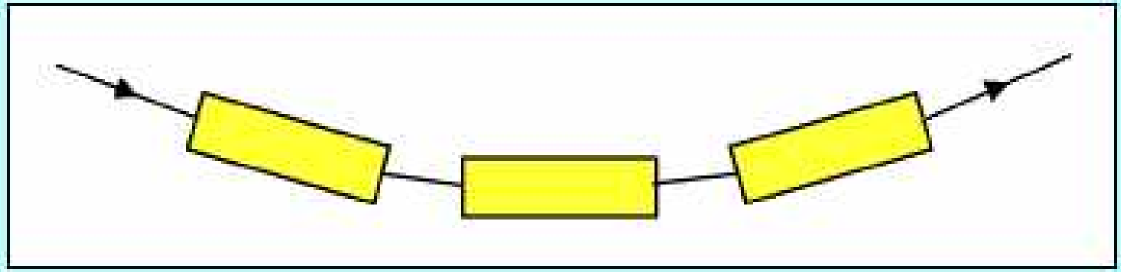
- ***as the particles accelerate, either the frequency of the applied electric field must vary - such machines are called "synchrocyclotrons" - or the applied magnetic field must be varied (or both) - such machines are called "synchrotrons".***

The majority of accelerators (all proton, most electron) are Cyclic accelerators called Synchrotrons. They overcome the length problem by passing the particles through the same accelerator many times.

The vacuum pipe is a torus, a few cm^2 in cross section and hundreds of metres to several Km in circumference. The LEP accelerator at CERN was ~27Km in circumference.



Dipole magnets keep particles in circular orbit using p = 0.3 BR (p in GeV/c, B in Tesla, R in m.



Quadropole magnets used to focus the beam.

Synchrotrons

Since the bending field B is limited then the maximum energy is limited by the size of the ring. The CERN SPS (Super Proton Synchrotron) has a radius R = 1.1Km and a momentum of 450 GeV/c.

Particles are accelerated by RF Cavities as in Linacs. The bending field B is increased with time as the energy (momentum p) increases so as to keep R constant [$p = 0.3\,BR$].

Electron synchrotrons are similar to proton synchrotrons except that the energy losses are greater.

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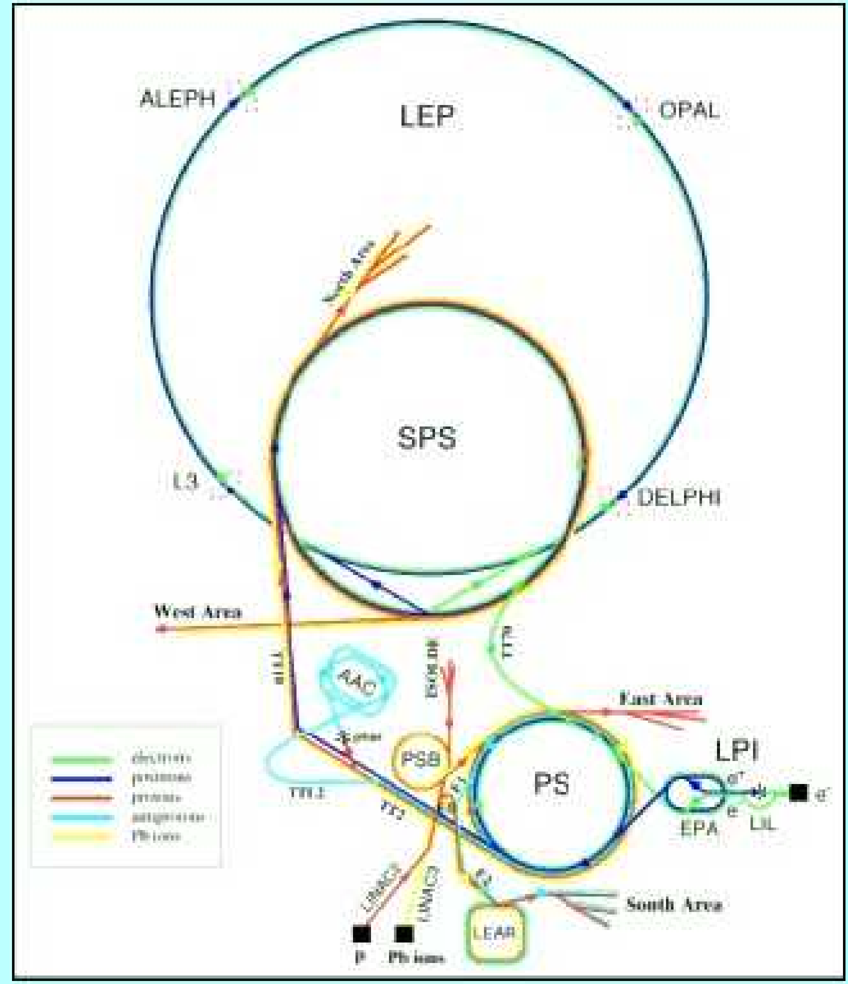

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Synchrotron Radiation

A charged particle moving in a circular orbit is accelerating (even if the speed is constant) and therefore radiates.

The energy radiated per turn per particle is:

$$\Delta E = \frac{4\pi e^2 \beta^2 \gamma^4}{3R}$$

where e is the charge, $\beta = v/c$ and $\gamma = (1-\beta^2)^{-\frac{1}{2}} = E/m$.

i.e $\Delta E \sim m^{-4}$.

For relativistic electrons and protons of the same momentum the ratio of energy losses are very large for electrons, negligible for protons:

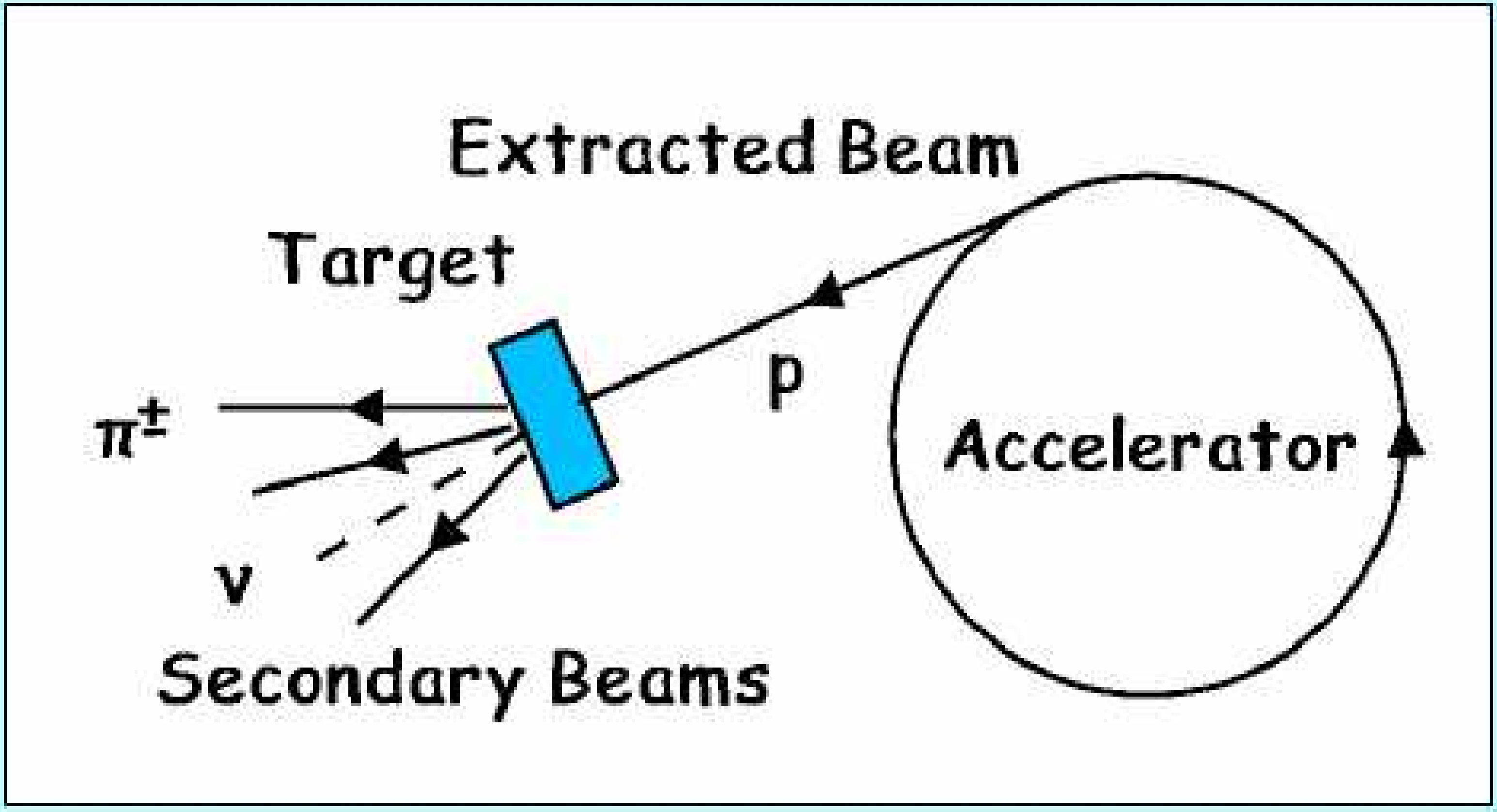
$$\frac{\Delta E_{electron}}{\Delta E_{proton}} = \left(\frac{m_p}{m_e}\right)^4 \simeq 10^{13}$$

LEP at 45 GeV with a 27 Km circumference, 8 bunches of 4×10^{11} particles per bunch loses ~0.5MW of power through synchrotron radiation. For electron machines it is better to have large R, smaller B.

Fixed Target Experiments

These are mostly historical or used for testing. Accelerated particles are extracted from the accelerator and directed onto an external target. This can be the source of secondary particles that need to be stable or long lived but need not be charged.

i.e $\pi^{\pm}, K^{\pm}, K^0, p, \bar{p}, n, \bar{n}, e^{\pm}, \mu^{+}, \nu, \bar{\nu}, \ldots$



Colliding beams

For a single particle $E^2 = \vec{p}^{\,2} + m^2$ where m is the rest mass.

For a collision between two particles A and B, the total Four-momentum squared of the system in the Laboratory Frame is:

$$P^2 = (E_A + E_B)^2 - (\vec{p}_A + \vec{p}_B)^2$$

$$P^2 = E_A{}^2 + E_B{}^2 + 2E_AE_B - p_A{}^2 - p_B{}^2 - 2\,\vec{p}_A\vec{p}_B$$

$$P^2 = m_A{}^2 + m_B{}^2 + 2E_AE_B - 2\,\vec{p}_A\vec{p}_B$$

This (P^2) is Lorentz invariant i.e. the same in all frames.

The Centre of Mass (CM) system has $\Sigma\vec{p} = 0$ by definition. If the total energy in the CM Frame is E^* then

$$P^2 = E^{*2}$$

Since P^2 is the same in the two frames then

Measured in Lab

Measured in CM →

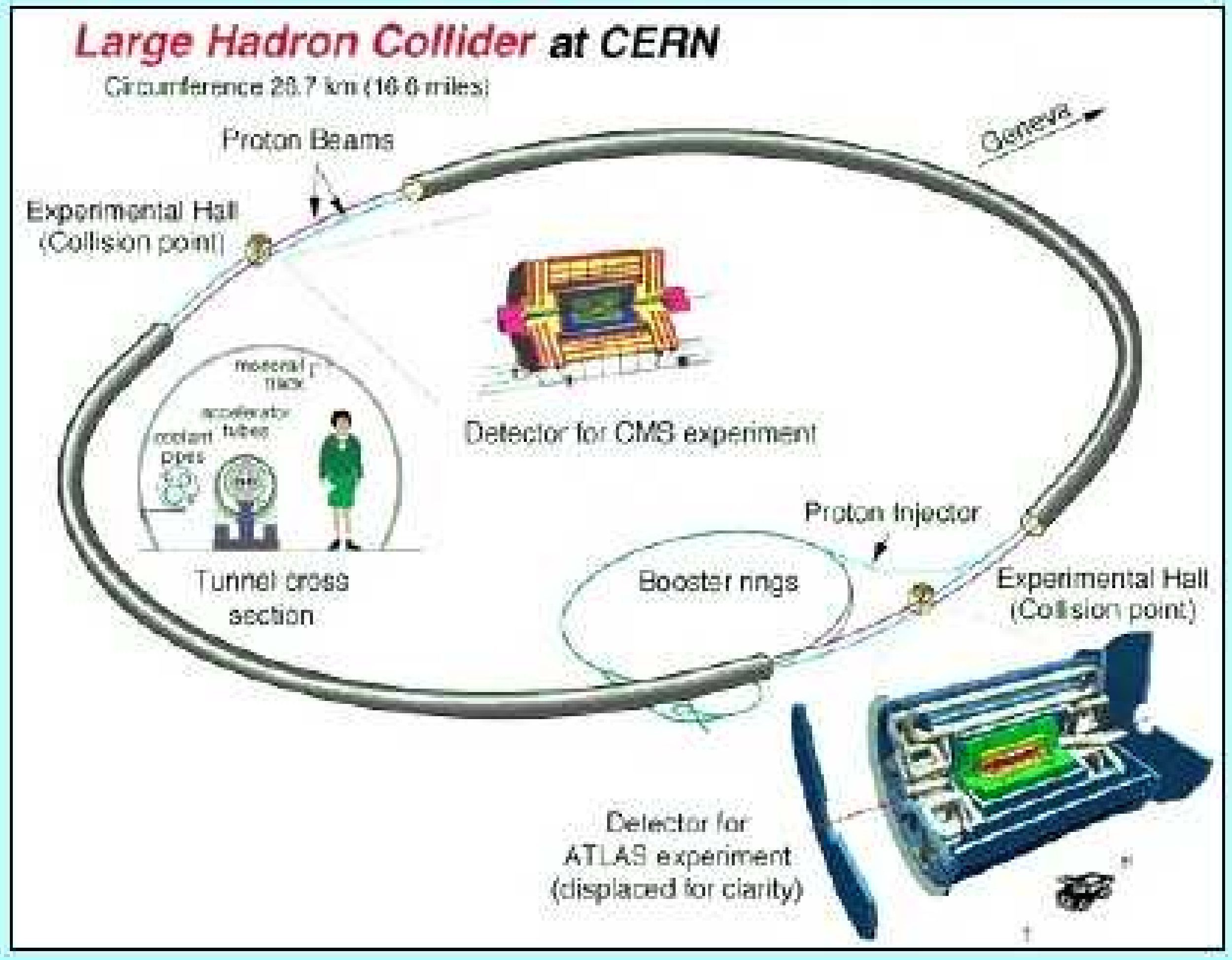
$$E^{*2} = m_A{}^2 + m_B{}^2 + 2E_AE_B - 2\,\vec{p}_A\vec{p}_B$$

Colliding beam machines

For e^+e^- or $p\bar{p}$ machines one ring is sufficient since particles with opposite charges and the same mass can go in opposite directions using the same magnets. For pp or $e^{\pm}p$ two rings are required with different magnets.

The particles collide at a number of Intersection Regions where the experiments are installed.

The disadvantage of colliding beams is the reaction rate is much lower because the 'target' is much smaller.



Luminocity

The Reaction Rate R is given by

$$R = \sigma \times \mathcal{L}$$

Cross section σ (units of area)

Luminosity $\mathcal{L}$ (units of area^{-1} s^{-1})

$$\mathcal{L} = \frac{n\, f\, N_1 N_2}{A}$$

n is the number of 'bunches' of particles in each beam (typically 4-8)
f is the revolution frequency (45kHz - 40 MHz)
N_1, N_2 are the number of particles in each bunch ($\sim 10^{10}$)
A is the area of each beam (~μm)

Electrons vs Protons

Electron Machines	Proton Machines
Clean - no other particles involved than e^+e^-.	Messy - qq or $q\bar{q}$ interact and rest of p or $\bar{p}$ is junk.
Lower energy for same radius (synchrotron radiation). LEP e^+e^- ~ 200 GeV.	Higher energy for same radius. LHC (pp) in LEP tunnel ~14 TeV.
Energy of e^+e^- known.	Energy of qq or $q\bar{q}$ not known.
Fixed energy (for a given set of operating conditions).	Range of qq or $q\bar{q}$ energies for fixed pp or $p\bar{p}$ energy.
Best for detailed study.	Best for discovering new things.

Major accelerators

Name	Particles	Energies	Where	Status
SLC	e^+e^-	50+50GeV	Stanford USA	Ended
LEP	e^+e^-	100+100GeV	CERN Geneva	
Tevatron	$p\bar{p}$	1+1TeV	Fermilab USA	Current
HERA	$e^{\pm}p$	30+820GeV	DESY Hamburg	Ended
PEP II	e^+e^-	9+3.1GeV	Stanford USA	Current
KEKB	e^+e^-	8+3.5GeV	Tsukuba Japan	Current
LHC	pp	3.5+3.5TeV	CERN Geneva	Current