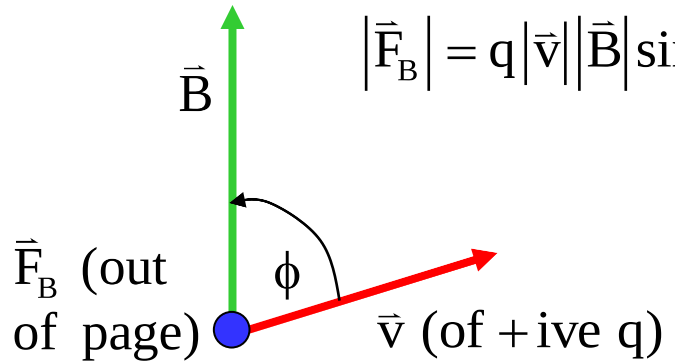
Lecture 12

- In this lecture we will look at:
  - Magnetic fields.
  - Force on a charged particle in a magnetic field.
  - Magnetic field lines.
  - Circulating charged particles.
  - Magnets in particle physics.
  - The Aurora Australis and the Aurora Borealis.

- After this lecture, you should be able to answer the following questions:
- How does a magnetic field influence a) a stationary charged particle and b) a moving charged particle?
- Use field lines to illustrate the field due to a bar magnet.
- Explain how the mechanism that gives rise to the Aurora Borealis.

Magnetic Fields

- As soon as we start considering moving electric charges, we are faced with a new phenomenon: magnetism.
- Two comments:
  - Not really new phenomenon! (See "Relativity and Magnetism" in Lecture 14.)
  - Fields due to magnets – i.e. magnetic materials – are result of electric currents in the materials, e.g. electrons orbiting nuclei.
- The strength and direction of an electric field was defined in terms of the force it caused on a test charge:
  $\vec{F}_E = q\vec{E}.$
- No magnetic monopoles, so cannot quite do same for magnetic field.
- Magnetic fields have no effect on stationary electric charges, but do cause force on moving charges.
- Magnitude and direction of magnetic force found to depend on velocity of charge (speed and direction!).



$$\left|\vec{F}_B\right| = q\left|\vec{v}\right|\left|\vec{B}\right|\sin\phi.$$

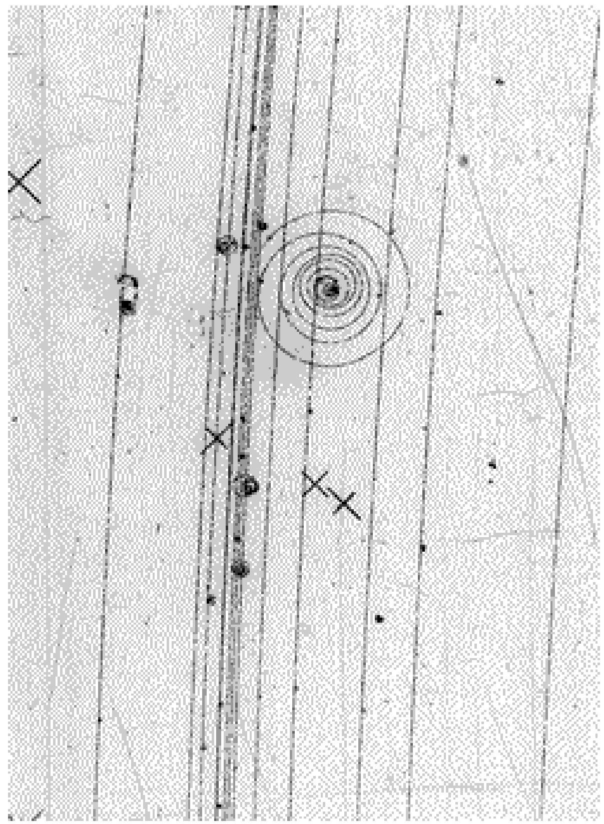
- See is cross product:
  $$\vec{F}_B = q\vec{v}\times\vec{B} \qquad [12.1]$$

Force on a Charged Particle in a Magnetic Field

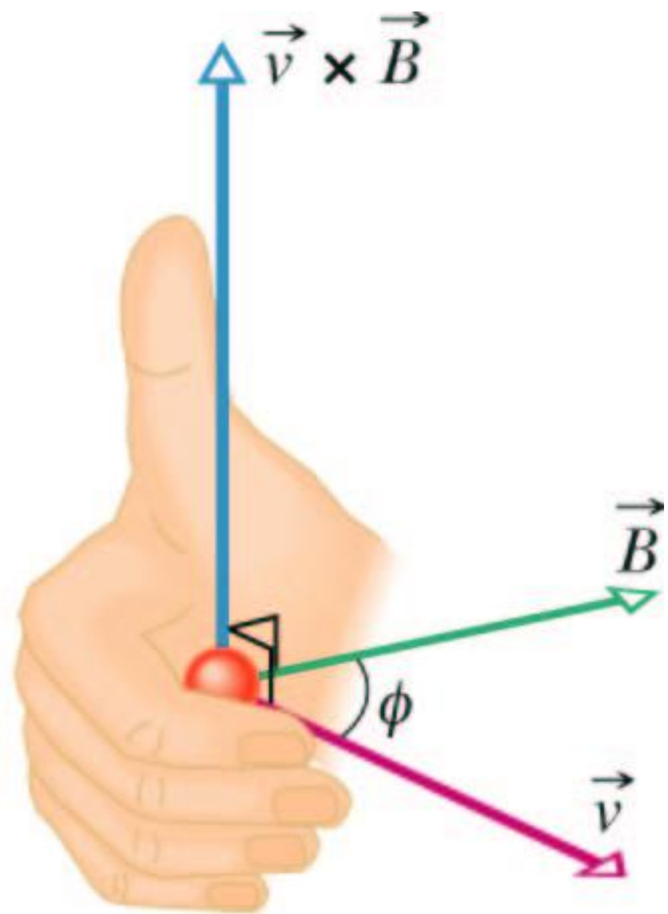
- This defines strength and direction of the magnetic ("B") field.
- More descriptively, the direction of the B field is that in which the charged particle experiences no force.
- The strength of the B field is

$$\left|\vec{B}\right| = \frac{F_B}{|q|\,v}, \text{ when } \vec{v} \perp \vec{B}.$$

- Sense (which way along direction vector) from right hand rule:
  - 1st finger: velocity (+ive charge).
  - 2nd finger: B field.
  - Thumb: motion (i.e. force).
- Work out the direction of the B field in this bubble chamber photograph, assuming that the spiralling track is that of an electron:



Force on a Charged Particle in a Magnetic Field



- Another way of thinking of the RH rule:
  - Hold your right hand so your extended fingers point along the +ive particle's velocity.
  - Turn your hand so that when you curl your fingers they move towards the direction of the B field.
  - Your thumb is then pointing in the direction of the force.
- And another...
  - Rotate a RH screw from the direction of the velocity towards that of the B field.
  - The screw moves in the direction of the force.

Force on a Charged Particle: Typical Magnetic Fields

- Some comments:
  - Force is proportional to charge, force on –ive particle opposite to that on +ive particle.
  - Force always perpendicular to both particle's velocity and direction of the B field.
  - The force doesn't change the speed (and hence kinetic energy) of the particle.
- The unit of magnetic field strength is the Tesla:

$$1\,\mathrm{T} = 1\frac{\mathrm{N}}{\mathrm{C\,m\,s^{-1}}} = 1\frac{\mathrm{N}}{\mathrm{C\,s^{-1}\,m}} = 1\frac{\mathrm{N}}{\mathrm{A\,m}}.$$

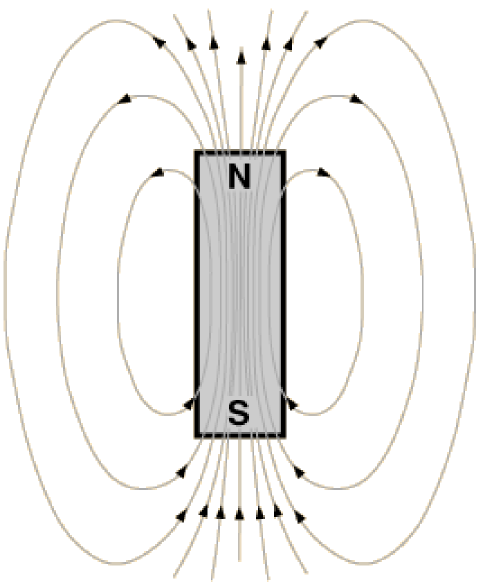
- Older unit, the gauss, 1 T = 10 kG.

- Some typical magnetic field values:

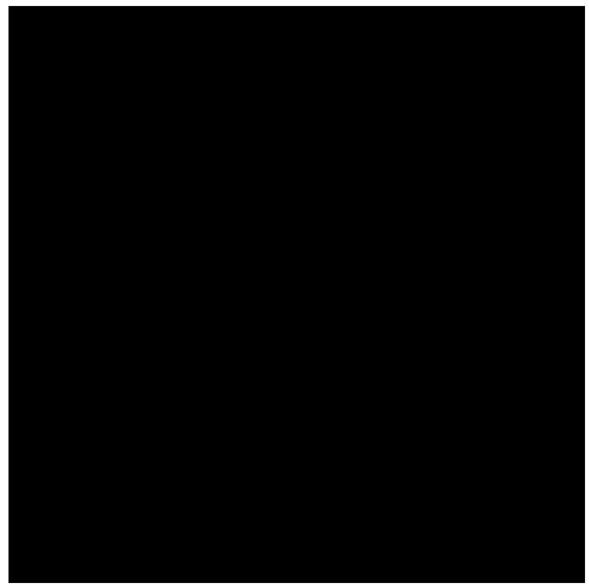
Surface of neutron star	10^{8} T
Superconducting magnet	10 T
Small bar magnet	10^{-2} T
At earth's surface	10^{-4} T = 1 G
Interstellar space	10^{-10} T
Magnetically shielded room	10^{-14} T

Magnetic Field Lines

- Represent magnetic field using field lines.
- Direction of the field line gives the direction of the B field.
- Density of the lines represents the magnitude of the field: the closer the lines the stronger the field.



- Video of simulation of one of periodic flips of earth's B field direction (flip takes ~ 1000 years!).
- Earth's magnetic field represented using field lines, blue = inward, yellow = outward lines.



Circulating Charged Particle

- If project beam of particles, into magnetic field with $\vec{v} \perp \vec{B}$, magnetic force causes particles to follow circular path, radius r.
- Magnetic force $F_B = qvB$.
- Centripetal force:

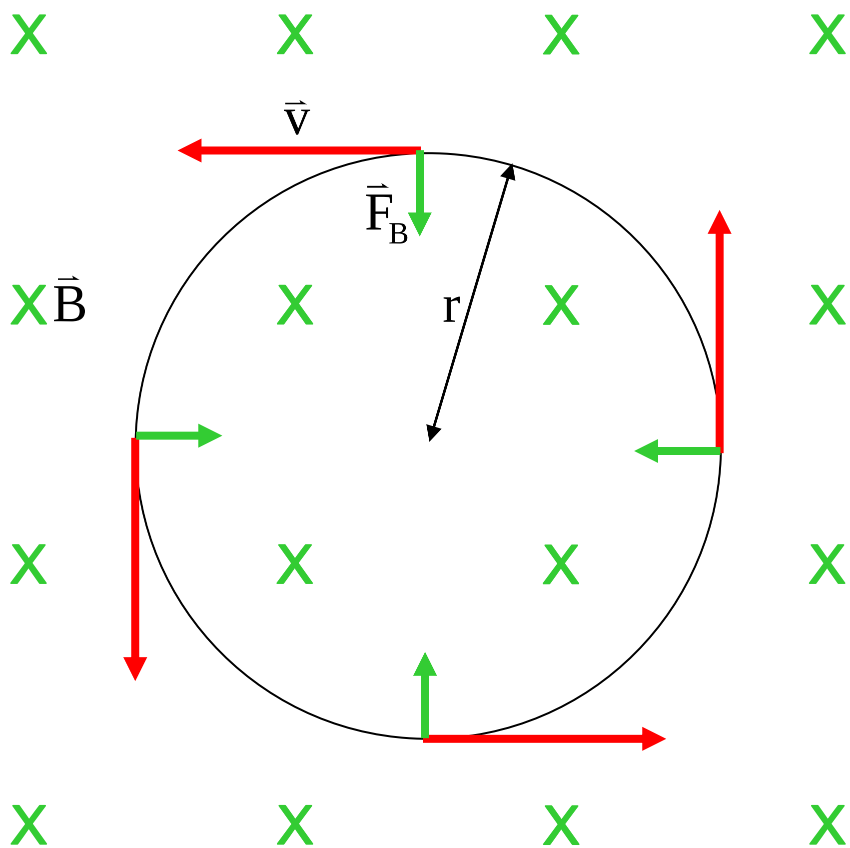
$$F = mr\omega^2 = m\frac{v^2}{r}.$$

- Equating these:

$$qvB = m\frac{v^2}{r}$$

$$\Rightarrow r = \frac{mv}{qB} = \frac{p}{qB} \qquad [12.2]$$

- B field directed into transparency.



Circulating Charged Particle

- The period (time for one revolution) is given by speed/distance, i.e.

$$T = \frac{2\pi r}{v} = \frac{2\pi}{v}\frac{mv}{qB} = \frac{2\pi m}{qB}.$$

- Frequency given by:

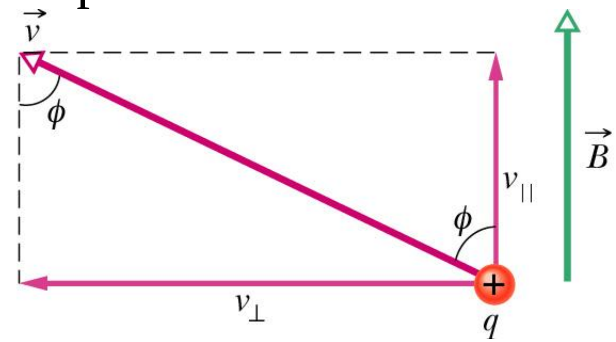
$$f = \frac{1}{T} = \frac{qB}{2\pi m}.$$

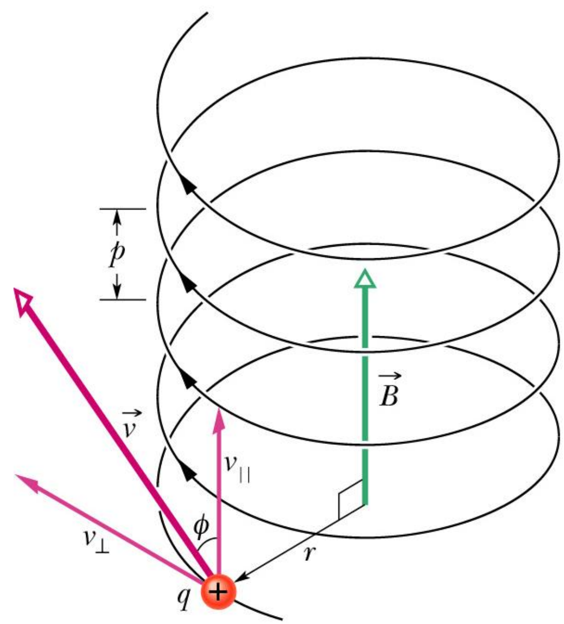
- Angular frequency:

$$\omega = 2\pi f = \frac{qB}{m} \qquad [12.3]$$

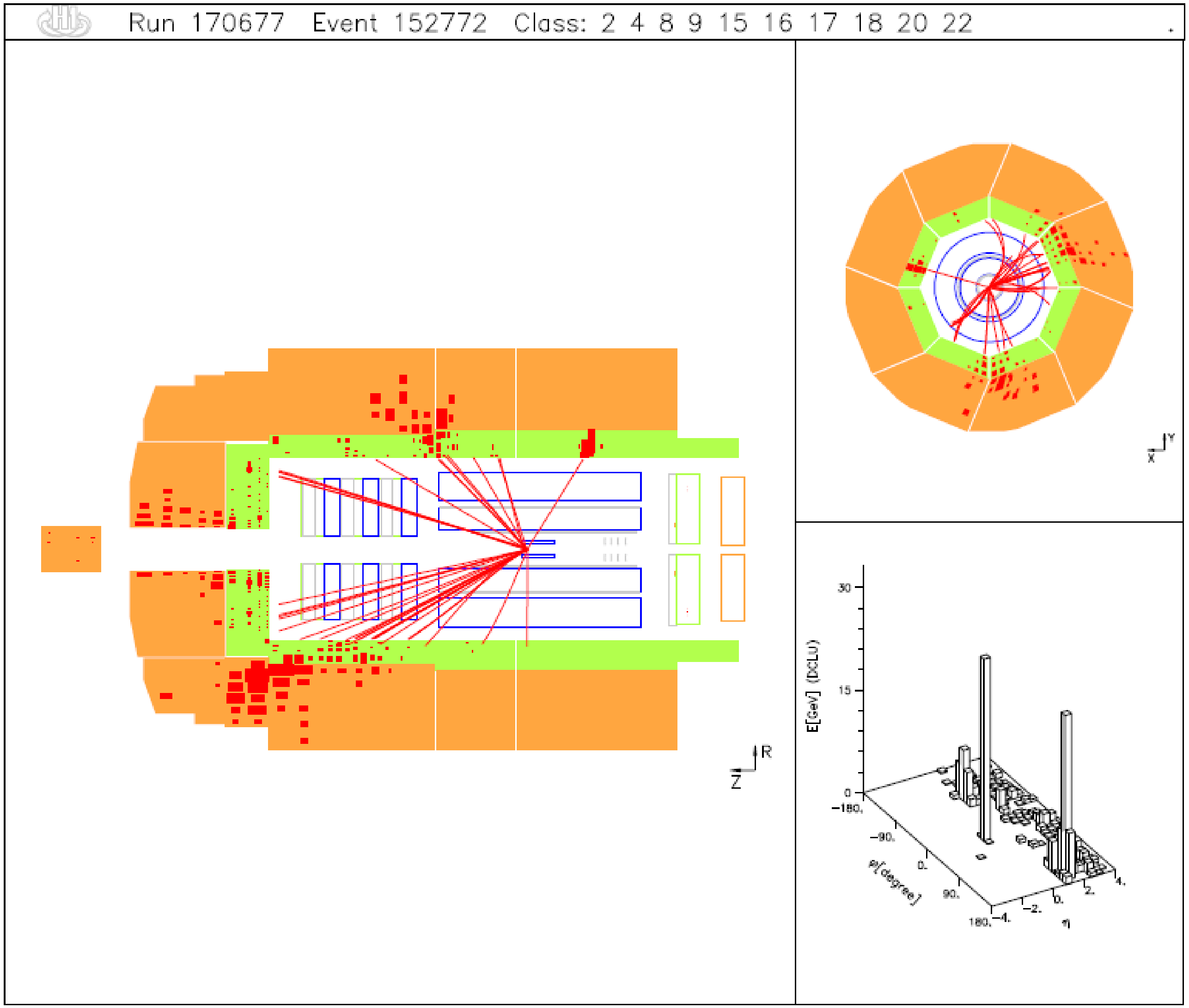
- If there is a component of particle's velocity, v_L, along direction of B field, particles follow helical path.
- Radius of helix given by v_T, transverse component of velocity, pitch by v_L.

- Helical path:



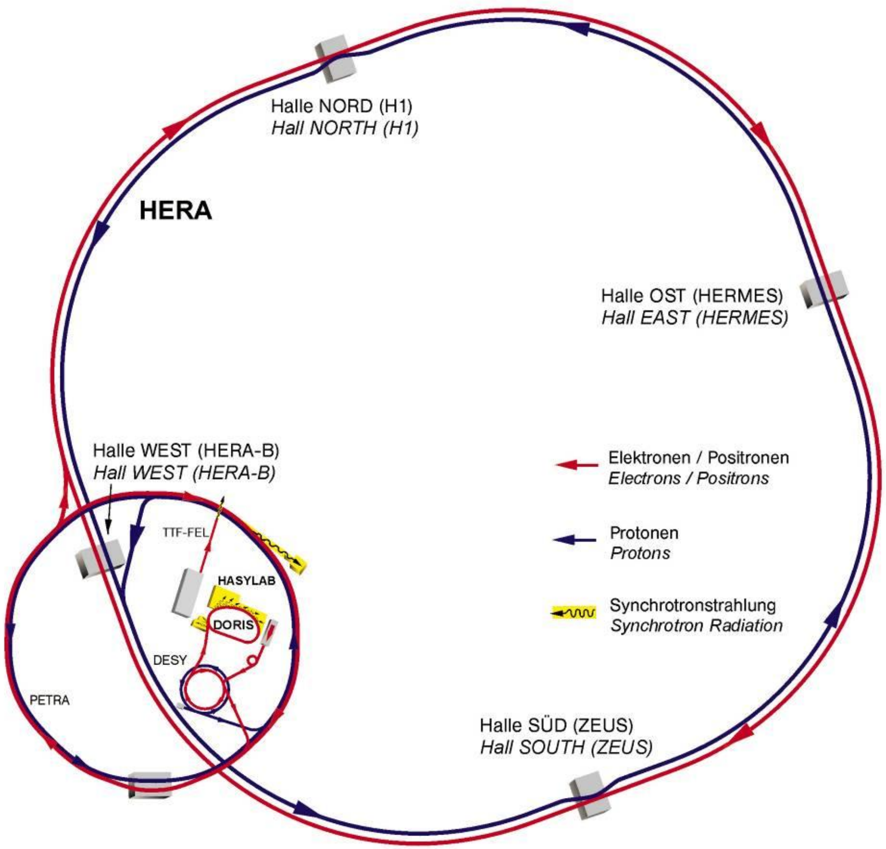


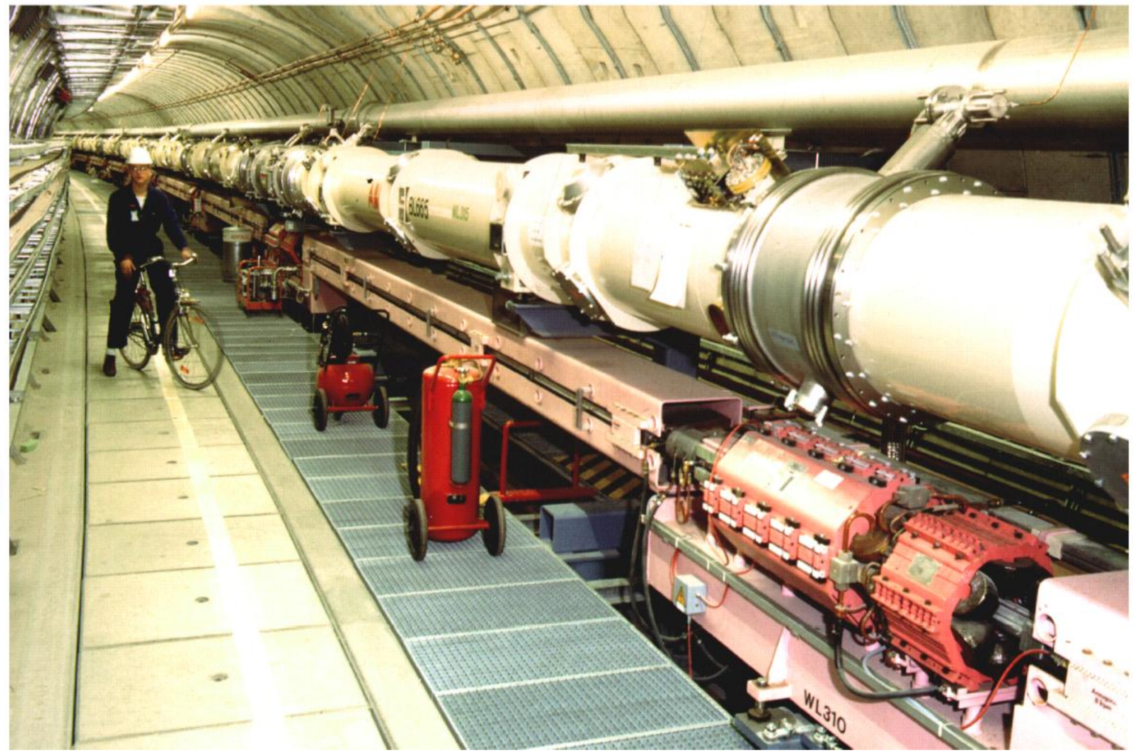
Magnets in Particle Physics Detectors



Magnets in Particle Accelerators

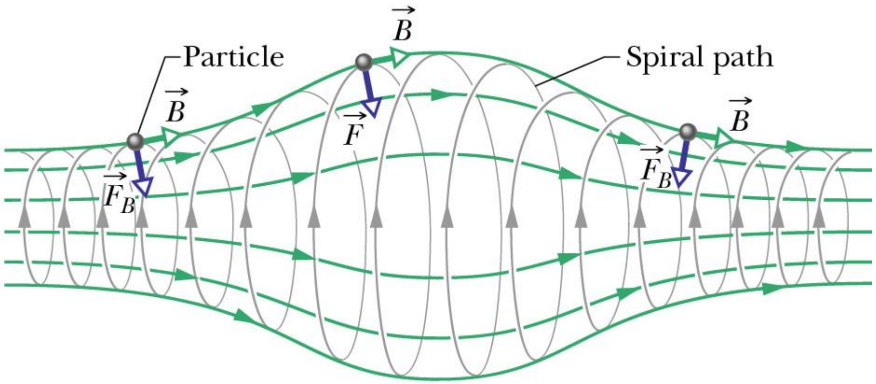
- Dipole magnets steer particles around accelerators and quadrupole magnets provide focussing.



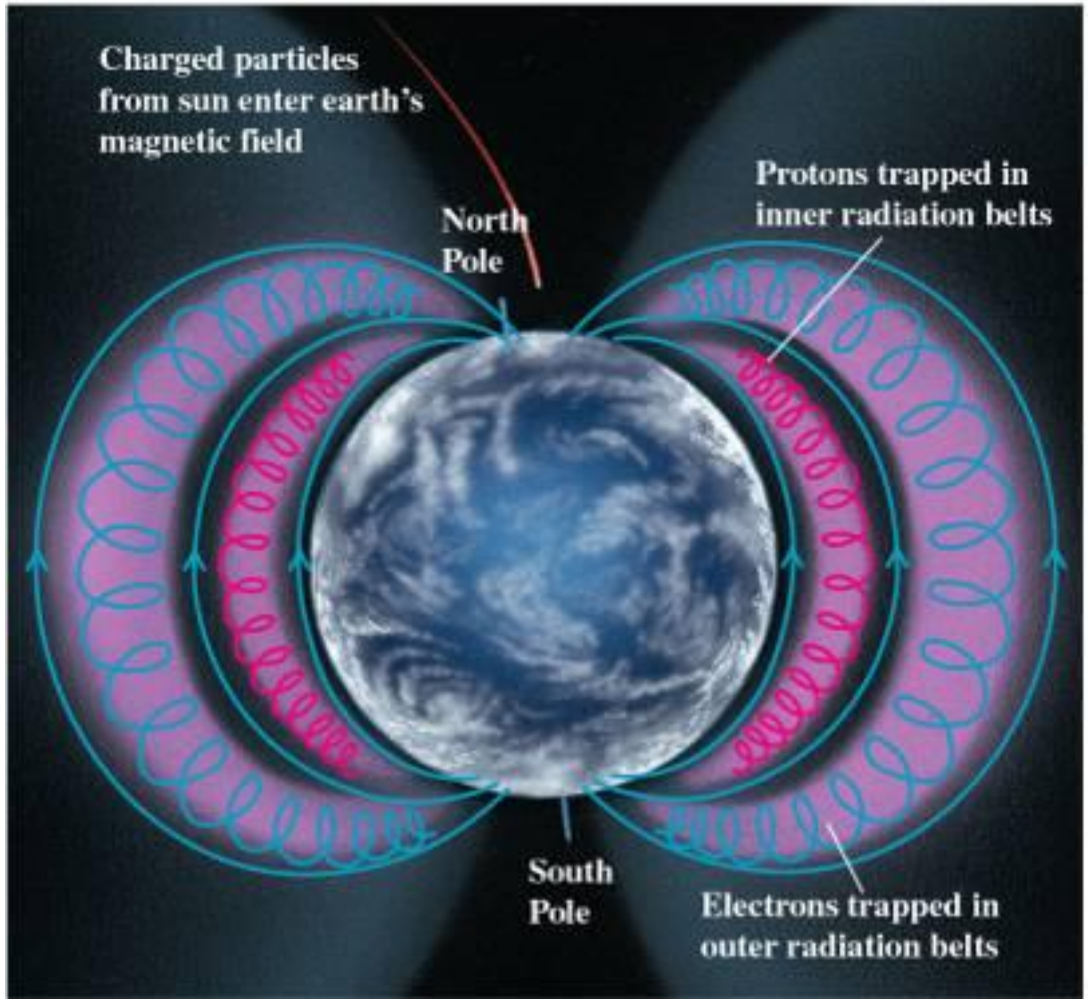


Magnetic Bottle

- Charged particle can become trapped in non-uniform B field:



- This happens in the magnetic field of the earth, gives rise to Van Allen Radiation Belts (right), Aurora Australis and Aurora Borealis (next slides) .



Aurora Australis, Photo from Discovery

Aurora Borealis

Photo: Pekka Parviainen

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Aurora Borealis

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Aurora Borealis

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