Doc Dave

PhD Notes

General Accelerator Physics

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Chapter 1

Introduction to Particle Accelerators

1.1 Applications

The uses of particles accelerators span many areas of society, including manufacturing and industry, medicine, security, and research.

1.2 Basic Concepts

1.2.1 Electric Fields and Particles

Electrostatic Acceleration

The rate of change of the potential (voltage) between two plates is known as the electric field. An electron in an electric field created by applying a voltage across two plates will experience a force

$$\mathbf{F} = m\mathbf{a}.$$

The force will accelerate the particle to faster velocities and higher energies. The energy change of an electron leaving the accelerating region (in eV) will be equal to the voltage between the plates (times the charge of the electron). Electrostatic fields are limited to a few MV. The **Kilpatrick Criterion** describes the breakdown voltage for electrostatic accelerators.

Radio Frequency (RF) Acceleration

By switching the charges on the plates in phase with the particle motion it is possible to cause the particle to always see an acceleration. In this case it is sufficient to alter only the voltage signs instead of requiring an ever-increasing voltage over the particle motion. Using this method gradients of 20-100 $\mathrm{MV\,m^{-1}}$ are possible.

Linacs

Linear accelerators or "linacs" started out as drift tubes; beamlines comprised of hollow cylinders. The static fields previously utilised are replaced by time-varying fields by only exposing the bunches to the field wave at certain selected points. Long drift tubes shield the electric field for at least half of the RF cycle. The gaps increase in length with distance.

Cavity Linacs

At high relative speed, β, it is more spatially efficient to use cavities instead of drift tubes. Since the system is modular, each cavity can have its phase set individually.

1.3 Synchronous Acceleration

Cyclotron

Synchrotron

1.3.1 Longitudinal Focussing

Longitudinal focussing occurs if late particles see a high acceleration and hence gain a higher velocity. Early particles must then see less acceleration, creating particles who are off-momentum or phase-oscillating around the stable particle. Particles with energies outside the energy acceptance drop out of the RF bucket.

1.3.2 Momentum Compaction

A particle which arrives too late or too early will receieve a different acceleration than a synchronous particle. At low energies, the more energy a particle has the faster it travels, however at high energies the speed is approximately constant as it converges on the speed of light. As such, the path around the ring will be longer as the Larmour radius increases.

1.4 Magnets

1.4.1 Dipoles ($n = 1$)

Dipole magnets have a constant vertical B field, causing the beam trajectory to bend in the horizontal plane.

1.4.2 Quadrupoles ($n = 2$)

A quadrupole magnet focusses in one plane and defocusses in the other. The force experienced is proportional to the particle offset.

FODO Cell

As the quadrupoles only focus in one plane then we must alternate the magnets. One popular configuation is the FoDo cell, which gives an overall focussing effect.

1.4.3 Sextupoles ($n = 3$)

Sextupole magnets are used to correct for chromaticity, which is when the path taken by each particle varies with its energies. This mostly affects offset (hence off-momentum) particles. The sextupole magnet gives the lattice a constant focal length as a function of energy over a finite energy range.

1.5 Radiation Emission

Any charge that is accelerated emits radiation, so this applies to accelerated beams of charged particles in a ring (synchrotron), hence it is known as synchrotron radiation. This radiation emission results in severe losses and energy restrictions.

Synchrotron radiation is a quantum process, but it is averaged over a large number of particles (usually 10^{10} per bunch). The radiation spectrum typically ranges from infrared to X-rays and is emitted as a pencil of light in the direction of the beam trajectory.

1.6 Energy Frontier

Accelerators have their own version of Moore's law, known as a Livingston plot, in which the energy of accelerators increase by a factor of 10 every 10 years.

1.6.1 LHC

The Large Hadron Collider (LHC) is currently the world's most powerful particle accelerator, with a 27 km circumference and 120 MW power usage. The radius of a machine is inversely proportional to the magnetic flux density:

$$r = \frac{\gamma m v}{eB}.$$

The solution to increasing the energy (effectively γ), either the radius must also increase or larger magnets must be utilised. Superconducting cables allow stronger electromagnets to be maintained as high currents can flow without losses.

1.6.2 Thermodynamic Critical Field

When electrons condense into Cooper pairs the superconducting state becomes more ordered than the normal conducting state and hence the free energy is lower. When an external magnetic field is applied to a superconductor, supercurrents flow to cancel the field and hence the free energy increases. When the external field rises to such a level, H_c, that the superconducting states and normal conducting state have an equal amount of free energy the states are in equilibrium. When the external field reaches this limit, all the flux enters the superconductor. This is known as the thermodynamic critical field, which is around 200 mT for Nb. This also leads to a critical current density.

1.6.3 Gas Breakdown

If we apply a high voltage across a gap we can ionise the molecules in the intervening gas. At high pressures the mean free path is too low to gain enough momentum however at low pressures there are not enough molecules to ionise. We do not know whether this means that we do not get breakdown in a vacuum.

1.6.4 Kilpatrick Limits

A rough empirical formula for the peak surface electric field is

$$E_{max} \approx 195 \text{ MV m}^{-1} \left[\nu \ \text{(GHz)}\right]^{\frac{1}{2}} .$$

It has also been noted that the breakdown is mitigated slightly by going to lower group velocity structures. The maximum field strength also varies with pulse length as $t^{-0.25}$, though this is only true for a limited number of pulse lengths. As a superconducting radio frequency (SCRF) cavity would quench long before breakdown, we only see breakdown in normal conducting structures.

1.6.5 Novel or Advanced Accelerators

Laser-Plasma Acceleration

Laser-plasma-based electron and hadron accelerators are driven by lasers. Multi-GeV electron beams, suitable energies for applications, have been achieved so now the question is how to best use these beams. Laser-plasma accelerators used limited interaction lengths due to phase slippage between the laser and the beam, limiting the energy per stage. Shot-to-shot stability is of the percent level on energy, charge and direction. Efficiency is at least one or two orders of magnitude less than conventional sources (which are around 1%, if that). For a 1 TeV laser-plasma collider at CERN, the power required would dwarf the rest of Geneva and would potentially require several new dedicated power stations. Rep-rate is also limited by material heating to sub-1 Hz, which would limit luminosity. However, laser efficiency and rep-rate could be increased by future laser technologies by using optical amplification or locking millions of laser fibres. Reaching higher energies requires bigger lasers than are currently available by staging. Staging is difficult due to the variation in beam properties and difficulties in injecting both beam and laser.

Laser-Dielectric Acceleration

Instead of using plasma as the accelerating medium, lasers could be used with dielectrics to overcome the issues with stability and reach gradients up to 1 $\mathrm{GV\,m^{-1}}$. Using THz lasers with vacuum tubes, there would be a significant increase in beam quality over shorter wavelength sources however efficiency would remain an issue.

Beam-Driven Plasma Acceleration

Instead of using lasers, a plasma could be driven using a proton or electron beam. The drive beam could be a highly efficient high current beam which would be far more efficient and stable than a laser-driven plasma. This will likely be a viable option for a novel multi-TeV collider, however the luminosity is very low.

1.7 Brightness Frontier

Brightness of a beam is defined as

$$\text{brightness} = \frac{\text{flux}}{\text{emittance}},$$

where emittance, $\mathcal{E}$, is the area in phase space:

$$\mathcal{E} = k\frac{E^2}{N_{cell}^3}.$$

1.7.1 Issues

There are a number of problems with using storage rings as light sources, including:

- Equilibrium beam dimensions set by radiation emission
- Beam lifetime limiting bunch density

- Demanding ultra-high vacuum (UHV) conditions
- Undulators restricted by cell structure and apertures
- Most issues are worse at low energies

1.7.2 Free Electron Lasers

Free space radiation has transverse fields, i.e. fields that are perpendicular to the direction of motion. In order to coherently amplify signals we need the beam to travel with the wave and in the direction of the field. A periodic set of magnets causes the beam to undulate, generating undulator radiation. As electrons are decelerated by the wave they form bunches, which radiate coherently when decelerated. The principle of a free electron laser is to pass a relativistic electron beam through a periodic magnetic field, causing radiation. A mirror feeds spontaneous emission back into the beam and spontaneous emission is enhanced by stimulated emissions.

High Gain FELs - Single Pass Amplifier

Self-amplified spontaneous emission (SASE) FELs using incoherent radiation-emitting electrons. The radiation is emitted from the tail of the bunch, which interacts with those nearer the front, causing the electrons to bunch on the scale of the radiation wavelength. Due to the bunching, the electrons emit more coherently, hence more radiation leads to more bunching leads to more radiation etc. The radiation power grows exponentially.

Challenges

To go to shorter wavelengths we either needs to use novel FEL concepts using higher harmonics, however these often have less power and can be difficult to implement. Alternatively, higher energy lasers could be used, however these would face the same issues as colliders.

1.8 Intensity Frontier

On the high energy frontier there are high power proton accelerators (HPPAs), which can be used for a large range of applications. Usually these accelerators are of modest energy but they face high beam current issues in supply in control losses, however there are fewer radiation emission effects due to protons being much heavier than electrons. Furthermore, there are major space charge concerns.

1.8.1 Challenges

Challenges include capture and acceleration at low energy, which requires strong focussing magnets and different types of accelerating structures matched to the particle velocity. High duty cycles need superconducting RF to reduce RF losses and high power on targets require liquid metal or high temperatures. Beam losses due to damage and activation are a particular issue. Finally, space charge (repulsion between protons) blows the beam apart so strong focussing is required.

1.8.2 Space Charge Defocussing

Each bunch is comprised of many particles, whose repulsion between one another (space charge) plays an important role. The space charge falls off as $\frac{1}{\gamma^2}$, hence falls off at relativistic velocities. The space charge appears to the first order as a defocussing quadrupole in both planes, hence it can be corrected by using two/three quadrupoles.

1.9 Electromagnetism and Relativity

1.9.1 Special Relativity

1.9.2 Electromagnetism