Particle Acceleration

- Charged particles are accelerated to high momenta using electromagnetic fields: $e^+$, $e^-$, $p$, $\bar{p}$, $Au$, $Pb$, $Cu$ nuclei, $\mu^+$

- Why accelerate particles?
  - High beam energies $\Rightarrow$ high $E_{\text{COM}}$ $\Rightarrow$ more energy to create new particles
  - Higher energies probe shorter physics at shorter distances
  - De-Broglie wavelength: $\lambda = \frac{hc}{p} \approx \frac{197 \text{ MeV fm}}{p \text{ [MeV/c]}}$
    - e.g. 20 GeV/c probes a distance of 0.01 fm.

- An accelerator complex usually uses a variety of particle acceleration techniques to reach the final energy.
Particle Physics Colliders around the World

<table>
<thead>
<tr>
<th>Location</th>
<th>Collider</th>
<th>Interaction</th>
<th>Energy</th>
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<tr>
<td>SLAC, California</td>
<td>SLC</td>
<td>e⁻ e⁺</td>
<td>50 GeV e⁻ and 50 GeV e⁺</td>
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<tr>
<td></td>
<td>PEP II</td>
<td>e⁻ e⁺</td>
<td>9.0 GeV e⁻ and 3.1 GeV e⁺</td>
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<tr>
<td>Fermilab, near Chicago</td>
<td>Tevatron</td>
<td>p ¯p</td>
<td>980 GeV p and 980 GeV ¯p</td>
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<tr>
<td>CERN, Geneva</td>
<td>LEP</td>
<td>e⁻ e⁺</td>
<td>E_{\text{Com}}: 89 to 206 GeV</td>
</tr>
<tr>
<td></td>
<td>LHC</td>
<td>p p</td>
<td>E_{\text{Com}}: 14 TeV</td>
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<tr>
<td>DESY, Hamburg</td>
<td>HERA</td>
<td>e⁻ p</td>
<td>920 GeV e⁻ and 30 GeV e⁺</td>
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<td>KEK, near Toyko</td>
<td>KEKB</td>
<td>e⁻ e⁺</td>
<td>8.0 GeV e⁻ and 3.5 GeV e⁺</td>
</tr>
<tr>
<td>Brookhaven National Lab, Long Island</td>
<td>RHIC</td>
<td>AuAu, CuCu</td>
<td>200 GeV/nucleon</td>
</tr>
</tbody>
</table>

The Tevatron Complex

- As an example, we’ll follow the chain of the Tevatron accelerator.

Proton source: 7 litre bottle of hydrogen.
Cost US$200. 1 bottle lasts about a year

Cockroft-Walton Accelerator
DC Voltage accelerates particles through steps to about 1MV
Linac

• After Cockcroft-Wolton is the linac: linear accelerator.
• Charged particles in vacuum tubes accelerated by an alternating current, with a very high frequency, “Radio Frequency” (RF)
• frequencies typically a few 100 MHz
• Field strengths - few MV/m requires specialised power sources: klystrons

- The tubes act as Faraday cages: when the particles are in the tubes they feel no force
- Outside of the tubes they feel the potential difference between successive tubes, they accelerate forward
- Alternating current ensures that the difference always has the correct sign for acceleration.

Linac Animation

150 m long, accelerates protons to 400 MeV
Cyclotrons and Synchrotrons

• **The Cyclotron** - invented by Ernest Lawrence
  - Two D-shaped electrodes - perpendicular magnetic field
    - Constant frequency AC current applied to each electrode
    - Can to accelerate particles to ~10 MeV
    - At higher energies relativistic effects take over, circular path cannot be maintained need...

  \[ \vec{F} = q\vec{v} \times \vec{B} \]

• Synchrotron accelerators use variable B-field strength and radio frequency E-field, synchronised with particle speed to accelerate charged particles to relativistic energies.

  - Series of bending and focussing magnets
  - Beams have a constant radius in a synchrotron.
  - Synchrotrons used as **storage rings** and **colliders**.

Synchrotrons at the Tevatron

• Many synchrotrons used at the Tevatron:
  - **Booster**: proton energy from 400 MeV to 8 GeV
  - **Accumulator**: stores antiprotons at 8 GeV
  - **Main Injector**: 8 GeV to 120 GeV
  - **Tevatron**: 120 GeV to 980 GeV

  **Storage ring**: once particles have desired energy, they can be stored. Typically 8-24h.

  The Tevatron stores both the proton and anti-proton beam travelling in opposite directions.

  **Collider**: two beams are steered to collide at two points in the (CDF and DØ experiments).
Antiproton Production

- Protons from the main injector are fired onto a nickel target.
- 1 million protons produces 20-30 8 GeV antiprotons.
- Magnetic field used to separate p from $\bar{p}$.
- Stored in the accumulator synchrotron for several hours to several days - until required for collision in Tevatron.
- At the end of a ‘store’ in the Tevatron any remaining antiprotons are stored in the recycler synchrotron.

Two collision points in the Tevatron: CDF and DØ

We’ll see the CDF detector in a moment...

Synchrotron Radiation

- In a synchrotron the accelerated charged particles emit photons: synchrotron radiation.

- The energy lost every turn depends on the energy and mass of the particle ($y = E/m$) and the radius of the orbit, $\rho$:

$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\epsilon_0 \rho}$$

- Synchrotrons are used as high-energy photon sources
- In a storage ring, the energy lost due to synchrotron radiation must be returned to the beam to keep the collision energy constant.
Interactions with Matter

- At an experiment we have to be able to detect all the particles that live long enough to interact with the detector.
- Detector is generally a few centimetres from the interaction point.
- Length travelled before decay is $L = \beta \gamma c t$, anything with $\tau > 10^{-10}$ s might appear in detector
  - $e^+, \mu^+, \pi^+, K^0, p, n, \gamma, \nu$
- Use series of different detection techniques to identify these particles.
- Infer the existence of shorter-lived particles from the decay produces.

Charged Particle Energy Loss

- Energy loss of charged particle through matter is described by Coulomb scattering. Moving charged particles scatter off atomic electrons causing ionisation.
- Energy loss of charged particles by ionisation is given by Bethe-Bloch formula:
  \[
  \frac{dE}{dx} = -4\pi N_A Z^2 e^2 \frac{Z}{A} \left( 1 + \frac{2m_e \gamma^2 \beta^2 e^2 T_{\text{max}}}{I^2} \right) \log \left( \frac{2m_e \gamma^2 \beta^2 e^2 T_{\text{max}}}{I^2} \right) - \beta^2 \frac{\delta}{2}
  \]

- $N_A$: Avogadro’s number
- $Z$, $A$ atomic and mass number of medium
- $r_e = 2.82$ fm (classical radius of electron)
- $T_{\text{max}}$ - maximum kinetic energy of particle
- $I$ - excitation energy
- $x = pd$ density times distance
- $dE/dx$ - energy lost per $x$ [MeVg$^{-1}$cm$^2$]
Interactions of Photons

• Photons are neutral, Bethe-Bloch formula does not apply.
• Photons can create charged particles (e.g. $\gamma \rightarrow e^+e^-$) or transfer energy to charged particles:
  - low energies (<100 keV): Photoelectric effect
    \[ \gamma + \text{atom} \rightarrow \text{atom}^+ + e^- \]
  - medium energies (~1 MeV): Compton scattering
  - high energies (> 10 MeV): $e^+e^-$ pair production in electric field of nucleus
    \[ \gamma + \text{nucleus} \rightarrow e^+e^- + \text{nucleus} \]
• Intensity of photon energy decreases over distance:
  \[ I_\gamma = I_0 \exp(-\mu x) \]
  \[ \mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}} \]
  \[ \mu_i = \frac{N_A}{A} \sigma_i \quad [\text{cm}^2/\text{g}] \]

Interactions of electrons and positrons

• Response of electrons, positrons and photons are inter-linked.
• In addition to ionisation energy loss, electrons lose energy by Bremsstrahlung: $e^- \rightarrow e^-\gamma$
• Positrons annihilate with electrons in matter making pairs of photons: $e^+e^- \rightarrow \gamma\gamma$
• For $e^+$, $e^-$, $\gamma$: end result is an electromagnetic shower. Total energy transferred to detector is related to initial energy of the particle.
A Modern Collider Detector

- Use CDF at the Tevatron as an example.
- Most collider detectors are quite similar - same components blocks: different implementations

- From inside to out:
  1. Silicon tracker
  2. Gaseous tracker
  3. 1.4 T Solenoid Magnet

- Use CDF at the Tevatron as an example.
- Most collider detectors are quite similar - same components blocks: different implementations

  - 4. Electromagnetic Calorimeter
  - 5. Hadronic Calorimeter
  - 6. Muon detectors

Charged Particle Tracking

- Charged particle trajectories are curved in magnetic fields.
- Measure the momentum transverse to the field.
  \[ p_T[GeV/c] = 0.3 \times B[T] \times \rho[m] \]
- **Old method**: use a homogenous substance to trace out the entire motion.
- **Modern method**: take several position measurements as charged particle passes. Reconstruct a ‘track’
- **Silicon detector**: charged particle ionises silicon semiconductor. Six very accurate position measurements.
- **Drift chamber**: large volume filled with argonne-ethane-CF₄ mixture. Gas is ionised and drifts towards cathode and anode wires. 96 position measurements per track.
Electromagnetic and Hadronic Calorimeters

- Electrons, positrons and photons produce **electromagnetic showers**
- Hadrons: \((\pi^\pm, K^\pm, K^0, p, n)\) produce **hadronic showers**
- Calorimeters measure the energy deposited.
- CDF uses a **sampling calorimeter**: sample parts of the shower. Extrapolate to obtain the full amount of energy.
  - CDF electromagnetic calorimeter: Lead + light sensitive scintillator.
  - CDF hadronic calorimeter: Iron + light sensitive scintillator.

- Better energy measurements may be made using a **homogeneous calorimeter** - measures all deposited energy e.g. scintillating crystals (NaJ, CsI, BGO, ...) or cryogenic liquids (argon, krypton, xenon).

Particle Identification

- **All charged particles**: Hits in the tracking detectors are linked together to reconstruct the ‘tracks’.
- **Electrons**: A track and a narrow cluster of energy in the electromagnetic calorimeter.
- **Muons**: Tracks matching to hits in the muon detector.
- **Photons**: A narrow cluster of energy in the electromagnetic calorimeter, and no track.
- **Neutrinos**: Inferred from their absence, using an energy balance technique.
- **Pions/Kaons/protons**: Track and calorimeter energy. Energy loss \(dE/dx\) can be used to separate \(p, \pi\) and \(K\).
- **Neutrons** energy in electromagnetic and hadronic calorimeter.

- Use information from all detector subsystems to identify which particle was seen.
Neutrino Identification at Colliders

- **Neutrinos**: Neutrinos are not charged, very small cross section ⇒ they do not interact at all in the detector.
  - Incoming momentum of the collision is along beam direction. Momentum in the detector should balance perpendicular to beam.
  - We infer neutrinos for absence of momentum seen in a particular direction.

![Direction of momentum carried away by neutrino](image)

Summary

- We accelerate particles to obtain more $E_{\text{CoM}}$ to produce new particles.
- Probes very short distance scales, very short lived particles.
- Linacs and Synchrotrons are main accelerating structures.
- Synchrotron radiation: energy loss due to photon emission:
  - energy need to be added back to beam at a collider
  - can be exploited produce high frequency light
- Particle detectors strive to reconstruct all long-lived particles.
- System of complex subdetector systems used to reconstruct position, momentum, energy and particle type.