Tentative outline of accelerator lecture

- **A History of Particle Accelerators**
  - cathode rays are particles
  - Rutherford scattering
  - natural particle acceleration
  - electrostatic accelerators:
    - Cockroft Walton multiplier
    - Van de Graaff accelerator
    - Tandem accelerator

- **Cyclotron**
  - motion in E- and B-fields
  - cyclotron frequency and K-value
  - sector focusing cyclotron

- **Radio-frequency accelerator**
  - Wideroe structure
  - Alvarez structure
  - synchrotron

- **Accelerator facility at GSI**
  - heavy ion source
  - charge stripper to increase the efficiency
  - UNILAC, SIS-18

- **Radioactive Ion Beams**
  - projectile fragmentation
  - fragment separator at GSI
  - target fragmentation
  - isotope separation on line
  - ISOLDE at CERN

- **Storage Rings**
  - beam emittance
  - stochastic cooling
  - electron cooling
  - laser cooling
  - experimental storage ring at GSI

- **Large Hadron Collider**
  - electron vs. proton machine
  - fixed target vs. colliding beam experiment
  - LHC layout and experiments

- **Magnets**
  - dipole, quadrupole, n-pole magnets

- **Accelerator light source**
  - Bremsstrahlung
  - Synchrotron radiation
  - Inverse Compton scattering

- **Application**
  - Medical application
  - Ion implantation
  - Spallation target
  - Scanning
  - Transmutation
  - Radiocarbon dating

- **Wakefield Accelerator**
  - Three orders of magnitude higher field gradient
Literature

- Recommended Textbook
- Recommended e-book

Additional material:
What are accelerators used for?

- **High Energy Physics & Nuclear Physics**
  - Understand the fundamental building blocks of nature and the force that act upon them
  - Understanding the structure and dynamics of nuclear matter
  - In short search for answer of the most fundamental questions

- **Chemistry, Biology, Medicine, Material Sciences**
  - Find the structure of molecules, proteins, cells … with ultimate goal of determining structure of a single organic molecule as complex as a protein!
  - Determine structure of material and their properties (physics, chemistry, biology, medicine)
  - Resolve structural changes in a natural (femto-sec and atto-sec) time scales

- **Civil, Industrial and Military Applications**
  - Medical treatment of tumors and cancers
  - Production of medical isotopes
  - Ion implantation to modify the surfaces of materials
  - National security: cargo inspections, …

This list will never be complete …
Accelerator allow us to discover the entire zoo of elementary particles and their combinations (states)
What do we accelerate?

- We can accelerate charged particles:
  - electrons (e-) and positrons (e+)
  - protons (p) and antiprotons ($\bar{p}$)
  - ions (e.g. H$^1\text{-}$, Ne$^{2+}$, Au$^{79+}$, …)

- Few accelerators use positrons or antiprotons
  - which are created by smashing accelerated electrons or protons onto a target

- These particles are typically “born” at low-energy
  - e$: emission from thermionic gun at $\sim$100 kV
  - p/ions: sources at $\sim$50 kV

- A few dedicated facilities accelerate unstable ions
  - radioactive ion facilities

- Finally, there is a discussion and developments towards a more exotic collider using unstable muon beams
  - with 2 microsecond lifetime in the rest frame
Units of energy: Electron Volts

- An “electron-volt” is the energy gained by a particle of unit charge is accelerated over 1V potential
- It is really small
  - $1 \text{ eV} = 1.6 \cdot 10^{-19} (=0.00000000000000000016) \text{ Joules}$
  - our usual unit of energy.
  - A 1 kg weight dropped 1m would have $6 \cdot 10^{18} \text{ eV}$ of energy!

- On the other hand, it’s a very useful unit when talking about individual particles
  - If we accelerate a proton using an electrical potential, we know exactly what the energy is.
  - It’s also useful when thinking about mass/energy equivalence

\[
(proton \text{ mass}) \cdot c^2 = 938\,000\,000 \text{ eV} \approx 1 \text{ billion eV} = 1 \text{ GeV}
\]

\[
(electron \text{ mass}) \cdot c^2 = 511\,000 \text{ eV} \approx \frac{1}{2} \text{ MeV}
\]

speed of light (c): $2.99792 \cdot 10^8 \text{ m/s}$
# Few numbers and units

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
<th>Charge, C</th>
<th>Rest mass, kg</th>
<th>Rest mass, eV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron, e⁻</td>
<td>-e</td>
<td>-1.6⋅10⁻¹⁹</td>
<td>9.11⋅10⁻³¹</td>
<td>0.511⋅10⁶</td>
</tr>
<tr>
<td>Positron, e⁺</td>
<td>+e</td>
<td>+1.6⋅10⁻¹⁹</td>
<td>9.11⋅10⁻³¹</td>
<td>0.511⋅10⁶</td>
</tr>
<tr>
<td>Proton, p</td>
<td>+e</td>
<td>+1.6⋅10⁻¹⁹</td>
<td>1.67⋅10⁻²⁷</td>
<td>938.3⋅10⁶</td>
</tr>
<tr>
<td>Antiproton</td>
<td>-e</td>
<td>-1.6⋅10⁻¹⁹</td>
<td>1.67⋅10⁻²⁷</td>
<td>938.3⋅10⁶</td>
</tr>
<tr>
<td>Ion, ( \frac{A}{Z} X )</td>
<td>Ze</td>
<td>+Z⋅1.6⋅10⁻¹⁹</td>
<td>~A⋅u</td>
<td>~A⋅u</td>
</tr>
<tr>
<td>Atomic mass unit, u</td>
<td></td>
<td></td>
<td>1.66⋅10⁻²⁷</td>
<td>931.5⋅10⁶</td>
</tr>
</tbody>
</table>
Understanding Energy

- High Energy Physics is based on Einstein’s equivalence of mass and energy
  \[ E = m \cdot c^2 \]

- All reactions involve some mass changing either to or from energy

- 0.00000005 % of mass converted to energy
- ~ 0.1 % (of just Hydrogen!) converted

- If we could convert a kilogram of mass entirely to energy, it would supply all the electricity in the United States for almost a day.
Kinetic Energy

- A body in motion will have a total energy given by
  \[ E = \frac{m_0c^2}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \equiv \gamma \cdot m_0c^2 \]

- The difference between this and \( m_0c^2 \) is called the \textit{kinetic energy}
  \[ T_{\text{kin}} = m_0c^2 \cdot (\gamma - 1) \]

\( c = \text{(speed of light)} = 300,000 \text{ km/s!} \)

\( \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \)

For \( v \ll c \) (speed of light), Kinetic energy \( \sim \frac{1}{2}mv^2 \)
Proton and electron velocities vs. kinetic energy
The relevant formulae are calculated if $A_1, Z_1$ and $A_2, Z_2$ are the mass number (amu) and charge number of the projectile and target nucleus, respectively, and $T_{lab}$ is the kinetic energy (MeV) in the laboratory system.

\[
E = T_{lab} + m_0 \cdot c^2
\]

\[
m \cdot c^2 = T_{lab} + m_0 \cdot c^2
\]

\[
\frac{m_0 \cdot c^2}{\sqrt{1 - \beta^2}} = T_{lab} + m_0 \cdot c^2
\]

beam velocity:

\[
\beta = \sqrt{\frac{T_{lab}^2 + 1863 \cdot A_1 \cdot T_{lab}}{931.5 \cdot A_1 + T_{lab}}}
\]

Lorentz contraction factor:

\[
\gamma = (1 - \beta^2)^{-1/2}
\]

\[
\gamma = \frac{931.5 \cdot A_1 + T_{lab}}{931.5 \cdot A_1}
\]

\[
\beta \cdot \gamma = \sqrt{\frac{T_{lab}^2 + 1863 \cdot A_1 \cdot T_{lab}}{931.5 \cdot A_1}}
\]
Relativity and Units

➢ Basic Relativity

- total energy: \( E = \gamma \cdot m_0c^2 \)
- kinetic energy: \( T_{lab} = E - m_0c^2 = m_0c^2 \cdot (\gamma - 1) \)
- momentum: \( p = \gamma \cdot m_0v = \gamma \cdot \beta \cdot m_0c = m_0c \cdot \sqrt{\gamma^2 - 1} \)
  
  \[ E = \sqrt{(m_0c^2)^2 + (pc)^2} \]
  
  \[ p = \sqrt{(\gamma \cdot m_0c)^2 - m_0^2c^2} \]

➢ Units

- For the most part, we will use SI units, except
  - Energy: eV (keV, MeV, etc.) \([1 \, \text{eV} = 1.6 \cdot 10^{-19} \, \text{J}]\)
  - Mass: eV/c² \([\text{proton} = 1.67 \cdot 10^{-27} \, \text{kg} = 938.3 \, \text{MeV}/c^2]\)
  - Momentum: eV/c \([\text{proton} @ \beta = 0.9, \rightarrow 1.94 \, \text{GeV}/c]\)
Another way to look at energy

- Quantum mechanics tells us all particles have a wavelength
  \[
  \lambda = \frac{h}{p} \approx \frac{\text{(size of a proton)}}{\text{Energy \ [GeV]}}
  \]

- So going to high energy allows us to probe smaller and smaller scales

- If we put the high equivalent mass and the small scales together, we have …
Different accelerators

- Source
- Condenser lenses
- Condenser aperture
- Sample
- Objective lens
- Objective aperture
- Intermediate lens
- Projector lens
- Main screen

LHC at CERN

4.3 km
Accelerator facility

- **Ion Sources**: all elements
- **Linear-Accelerator**: 20% speed of light
- **Ring-Accelerator**: 90% speed of light
- **Experimental Areas**

**Diagram Details**:
- **SIS**
- **FRS**
- **ESR**
- **UNILAC**

Scale: 0 - 50 m
Accelerator facility
How do we see an object?

A light bulb shines on a hand and the different reflections make the fine structure visible. With a magnifying glass or microscope more details can be seen, but there is a fundamental limit: The wavelength of the light (1/1000 mm) determines the size of the resolvable objects.

available wavelength

→ electromagnetic waves $E = \frac{hc}{\lambda}$

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW</td>
<td>3000 m</td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td>300 m</td>
<td></td>
</tr>
<tr>
<td>KW</td>
<td>30 m</td>
<td></td>
</tr>
<tr>
<td>UKW</td>
<td>3 m</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>0.3 m</td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td>10^{-6} m</td>
<td></td>
</tr>
<tr>
<td>light</td>
<td>5·10^{-7} m</td>
<td>2 eV</td>
</tr>
<tr>
<td>UV</td>
<td>10^{-7} m</td>
<td>10 eV</td>
</tr>
<tr>
<td>X-ray</td>
<td>10^{-10} m</td>
<td>10^4 eV</td>
</tr>
<tr>
<td>γ-ray</td>
<td>10^{-12} m</td>
<td>10^6 eV</td>
</tr>
</tbody>
</table>

light bulb
magnifying glass or microscope → accelerator
detector
What means visibility?
visibility = capability to create an image

- Projectiles → Target → Detector

- One needs:
  1. size of projectile « size of object
  2. target accuracy « size of object
How do we detect what’s happening?

- Projectile: glow-in-the-dark basketballs
How do we detect what’s happening?

- Projectile: glow-in-the-dark tennis balls
How do we detect what’s happening?

- Projectile: glow-in-the-dark marbles

...let's get out of here!
Energy, wavelength and resolution

Small objects (smaller than $\lambda$) do not disturb the wave
→ small object is not visible
Large objects disturb the wave
→ large object is visible

**all particles have wave properties:**

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E_{kin} \cdot (E_{kin} + 2m_0c^2)}}$$

de Broglie wavelength

$\hbar \cdot c = 1239.84$ [MeV fm]
Wave properties of atoms

- excited Helium is easier to detect
- wavelength (i.e. velocity) has a resolution of 5%
- slits!!

He* incoherent
\( \lambda_{dB} = 0.47 \text{ Å} \)

Carnal&Mlynek, PRL 66,2689)1991
Graphik: Kurtsiefer&Pfau
For the investigation of small dimensions ($10^{-15}$ m) high photon energies are needed:

$$E_\gamma = h \cdot \nu = \frac{hc}{\lambda} = 2 \cdot 10^{-10} [J]$$

In case of Bremsstrahlung, the electron energy is given by

$$E_e > E_\gamma \quad \text{with} \quad E_e = e \cdot U$$

An extremely high voltage is needed

$$U = \frac{E_e}{e} = 1.2 \cdot 10^9 [V]$$