Introduction to Particle Accelerators & CESR-C

Michael Billing

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What Are the Uses for Particle Accelerators?

- **Medical Accelerators**
  - Create isotopes tracers for Medical Diagnostics & Biological Studies
  - Are sources for Cancer Therapy

  **Physics Principle:**
  Need few to 10’s MeV Electrons or Protons for nuclear activation

- **Synchrotron Light Sources**
  - Source of intense Visible & Ultra-Violet Light and X-rays
  - Used as a research tool for examining the atomic & molecular structure for
    Material Science – e.g. fluorescence, matter at high pressures
    Molecular & Biological Science – e.g. virus crystallography, function of tissue (e.g. tendons)

  **Physics Principle:**
  Use Synchrotron X-rays generated by bending Electrons on a curved path

\[
E_c = \frac{3}{4\pi} \frac{h c}{\rho} \left( \frac{E_b}{m c^2} \right)^3
\]
• High Energy Physics
  – Sub-atomic particle physics
  – Standard model for Quarks and Leptons
  – Mechanisms functioning in the instant after the Big Bang

Physics Principle:

Need few GeV to 100’s of GeV Electrons or
100’s of GeV to 10 TeV Protons for
Sub-atomic particle creation

\[ E_b \geq \sum_{f} m_f c^2 \]
Where Are Particle Accelerators in Physics Picture?

Branches of Physics

**Astronomy & Astrophysics** - Stars, Galaxies, Cosmos

**Classical Physics** - Light, Heat, Motion, Electricity, Magnetism

**Low Temperature Physics** - Superconductivity

**Plasma Physics** - Discharge tubes, Fusion

**Quantum Physics** - Lasers, LED's, Fiber Optics

**Atomic & Solid State Physics** - Transistors, Material Science, Surface Physics

**Relativistic Physics** - Stars, Cosmology, Particle Physics

**Accelerator Physics** - Particle Accelerators, RF Devices, X-ray Sources

**Nuclear Physics** - Nuclei, Fission, Radiation Therapy

**High Energy Physics** - Elementary Particle Physics, Tomography, Catscans
Important Reminders

• Make Use of the Lorentz Force \[ \vec{F} = q \left( \vec{E} + \vec{v} \times \vec{B} \right) \]

  \( \Rightarrow \) Acceleration Requires Charged Particles

• Energy of Particles Measured in eV

  Energy gain of 1 eV
  = Energy of 1 electron Passing through 1V of Potential Difference

• Deflection of Particle Beams

  Uses Magnetic Fields
Tools of the Trade: Particle Sources

• Electron Source

Boil Electrons Off of a Hot Cathode

Television Tube as an Accelerator
Tools of the Trade: Particle Sources

• **Positron Source**

Electron Beam Incident on a Target Can Generate Positrons via Bremsstrahlung and Pair Production

Requires a Fairly High Energy Electron Beam:

Electrons Incident

Then Capture and Accelerate Positrons
Tools of the Trade: Particle Sources

- **Proton Source**

  Use Electrons to Ionize a Hydrogen Gas Target

  Pulse HV after the Electron Beam Passes
Tools of the Trade: Magnets

- **Dipole**

\[ \mathbf{B} = B_0 \hat{y} \]

\[ \mathbf{F} = -q \mathbf{c} B_0 \hat{x} \]

**Purpose:** Bends Beam on “Circular” Path
Tools of the Trade: Magnets

**Quadrupole**

\[ \vec{B} = k_y \hat{x} + k_x \hat{y} \]

- Linear Restoring Force for \( x \)
  – Similar to a Spring

\[ \vec{F} = q_c k \left( -x \hat{x} + y \hat{y} \right) \]

- Purpose – Focus/Defocus Beam (Lens)

- Net Effect of Alternating Focus/Defocus Lenses is to Focus the Beam – “Principle of Strong Focusing”
Tools of the Trade: Accelerator Structures

• “RF” Accelerator Structures

Use Radio Frequency Structures to Develop a Large Oscillating Electric Field  ->  Time-Varying Potential

\[ V(t) = V_0 \cos \omega t \]

• Can Generate 10’s MV/m Accelerating Electric Fields
Introduction to CESR-C

- Create electrons/positrons
- Accelerate to 99.9999995% of the speed of light
- Store large numbers of particles
- Collide beams in CLEO (Interaction Point)
CESR-C Continued

• **Transfer Line** – takes beam from Synchrotron to CESR

• **Final Focusing Quad**
  Focuses beams going into CLEO
Fast History of Accelerators

1895: Roentgen discovers x-rays with cathode ray

1919: Rutherford produces first nuclear reactions with natural alpha particles,
\[ ^{4}\text{He} + ^{14}\text{N} \rightarrow ^{17}\text{O} + ^{4}\text{He} \]

Cyclotron

1932: Lawrence and Livingston use a cyclotron for 1.25MeV protons

Low Energy Accelerator Develops RF Voltage Between the Two DEEs

\[ \omega = \frac{e B_0}{m} \]
\[ \text{Radius} = \frac{m v}{e B_0} \]
1939: Lawrence uses 60” cyclotron for 9 MeV protons, 19 MeV deuterons, and 35MeV $^4$He.

First tests of tumor therapy with neutrons
• **LINear ACcelerator**
  Single Pass Accelerator

Highest Energy (Electron) LINAC is SLAC LINAC
=> 50+ GeV Beam Energy

1928: Wideroe builds the first drift tube linear accelerator for Na<sup>+</sup> and K<sup>+</sup>
Examples of Simple Accelerators

• Circular Accelerator, e.g. Synchrotron
  Multi-turn Accelerator
  – Energy Ramps Up
  Multiple Passes through Same RF Cavities

1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
1946: Goward and Barnes build the first synchrotron
1949: Wilson et al. at Cornell are first to store beam in a synchrotron
Highest Energy Accelerator is Tevatron $E_b = 1$ TeV
Storage Ring
Footprint Same as Synchrotron, BUT

Ring Accelerator Maintains Constant Energy – “Stores the Beam” for Long Times

Can be used for “Head-On” Collisions:

1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV

1972: SPEAR electron-positron collider at 4 GeV. Discovery of the J/Psi at 3.097 GeV by Richter (SPEAR) and Ting (AGS) starts the November revolution and was essential for the quark model and chromodynamics.
1979: 5GeV electron positron collider CESR at Cornell U. (designed for 8 GeV)

1987: Start of the super-conducting TEVATRON at FNAL

1989: Start of the 27 km long LEP electron-positron collider

1990: Start of the first asymmetric collider, electron (27.5 GeV) proton (920 GeV) in HERA at DESY
1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II

Today: 27km, 7 TeV proton collider LHC being build at CERN
Energy Available for Collisions vs Time for Hadron and Electron Accelerators
Synchrotron Light Sources

1947: First detection of synchrotron light at General Electric.
1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.

1st Generation (1970s): Many HEP rings are parasitically used for X-ray production
2nd Generation (1980s): Many dedicated X-ray sources (light sources)
3rd Generation (1990s): Several rings with dedicated radiation devices (wigglers and undulators)

Today (4th Generation): Construction of Free Electron Lasers (FELs) driven by LINACs
Future Accelerators

SASE Free Electron Lasers

Energy Recovery Linacs

Linear Collider
Large Hadron Collider – CERN

7 TeV Protons on 7 TeV Protons

26 km Ring of Superconducting Magnets

Soon to begin operation in Switzerland and France
Compact Beam From Linac Accelerated in Superconducting RF cavities
Beam goes once around the accelerator
Then is Decelerated in RF Cavities – Returning Energy back to the Cavities
Produces a very compact X-ray source
SASE FEL: Self Amplified Spontaneous Emission Free Electron Laser

**Undulator**
Causes bunch to wiggle back-and-forth quickly
Synchrotron photons given off in the undulation react back on the electrons and modulate the distribution of particles -> makes more photons
Then pass these through a second undulator to amplify the modulation of the bunch
Makes a very intense source of light of 1 – 100 nm wavelengths
Linear Electron Positron Collider

33 Km Long

350 GeV Electron-Positron Collider

One Possibility is TESLA:

Two Linacs Pointed at each other

Two Damping rings to compress the transverse beam sizes

Uses Superconducting RF Accelerator Structures
References


“Accelerators Around the World”, http://www-elsa.physik.uni-bonn.de/Informationen/accelerator_list.html


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Reflection: Not All Accelerator Physics is Physics Alone

Some is Art

Artist:
Robert R Wilson, Cornell & FNAL