Accelerator Physics and Technologies for Linear Colliders
University of Chicago, Physics 575

Lecture 1: S. D. Holmes, An Introduction to Accelerators for High Energy Physics

I. Introduction to the Course

An **electron-positron linear collider** has been identified by the world high energy physics community as the preferred next forefront facility following the completion of the Large Hadron Collider at CERN. Such a facility would produce electron-positron collisions at unprecedented

Energy	**500-1000 GeV**
Luminosity	**$>10^{34}$ cm^{-2}sec^{-1}**
Size	**30 km**

The realization of such a facility will require significant achievements in the technical, political, and organizational realms. This course is designed to examine the first of these.

Two technologies are believed capable of forming the basis of a linear collider—superconducting or room temperature. Both technologies are striving to establish performance, as measured in accelerating gradients, well beyond (factors of 3-6) current experience.

The goal of the course is to provide an introduction to the technologies and the physical principles that form the basis for operations of a large linear collider. This course was organized by Professor Kwang-Je Kim. He has managed to convince many of the leaders of the effort to develop, design, build, and operate a linear collider to participate in the presentation of materials in this course. The hope of the instructors is that at the completion of the course you will have a good understanding of how these machines work and the technical challenges that need to be overcome, and that you might even feel inspired to join the effort.

II. Motivations: Why Build Particle Accelerators?

The goal of elementary particle physics is to identify the most fundamental building blocks of nature and the forces that bind them together. The tool that has been used almost exclusively for this purpose for the last seventy is the particle accelerator.

Particle accelerators provide a source of high energy elementary particles with fluxes much larger than those normally encountered in nature. For this reason the terms elementary particle physics and high energy physics are often used interchangeably.

High energy is useful in probing the structure of matter for two reasons:

- Conversion of energy into mass:

$$\boxed{E = mc^2}$$

(proton = 938 MeV)
(electron = 511 KeV)

- Probing structures at shorter distances:

$$\boxed{l = \frac{h}{p}}$$

($h=1.2\times10^{-10}$ MeV/c-cm)

Fermilab operations provide proton-antiproton collisions at 2.0 TeV ($2\text{x}10^{12}$ eV, measured in the center-or-mass). Within these collisions particles can be created with masses several hundred times the mass of a proton, and structure can be probed at the levels down to 10^{-19} cm.
(A note on units: we will use as the unit of energy the "electron volt", eV and the unit of momentum, eV/c. One electron volt represents the energy gained by a particle with charge e being accelerated through a potential difference of 1 Volt.)

$$\boxed{1eV = 1.6\times10^{-19}\ Joules}$$

All accelerators constructed to date accelerate protons or electrons, or their antiparticles. The reason is that these are the only stable, charged particles, and the technology does not yet exist to accelerate particles with lifetimes measured in milliseconds.

Accelerators come in two configurations:

- Fixed target
  - Primary beams
  - Secondary beams

$$\boxed{E_{CM} = \sqrt{M_b^2c^4 + M_t^2c^4 + 2E_bM_tc^2}}$$

- Colliders

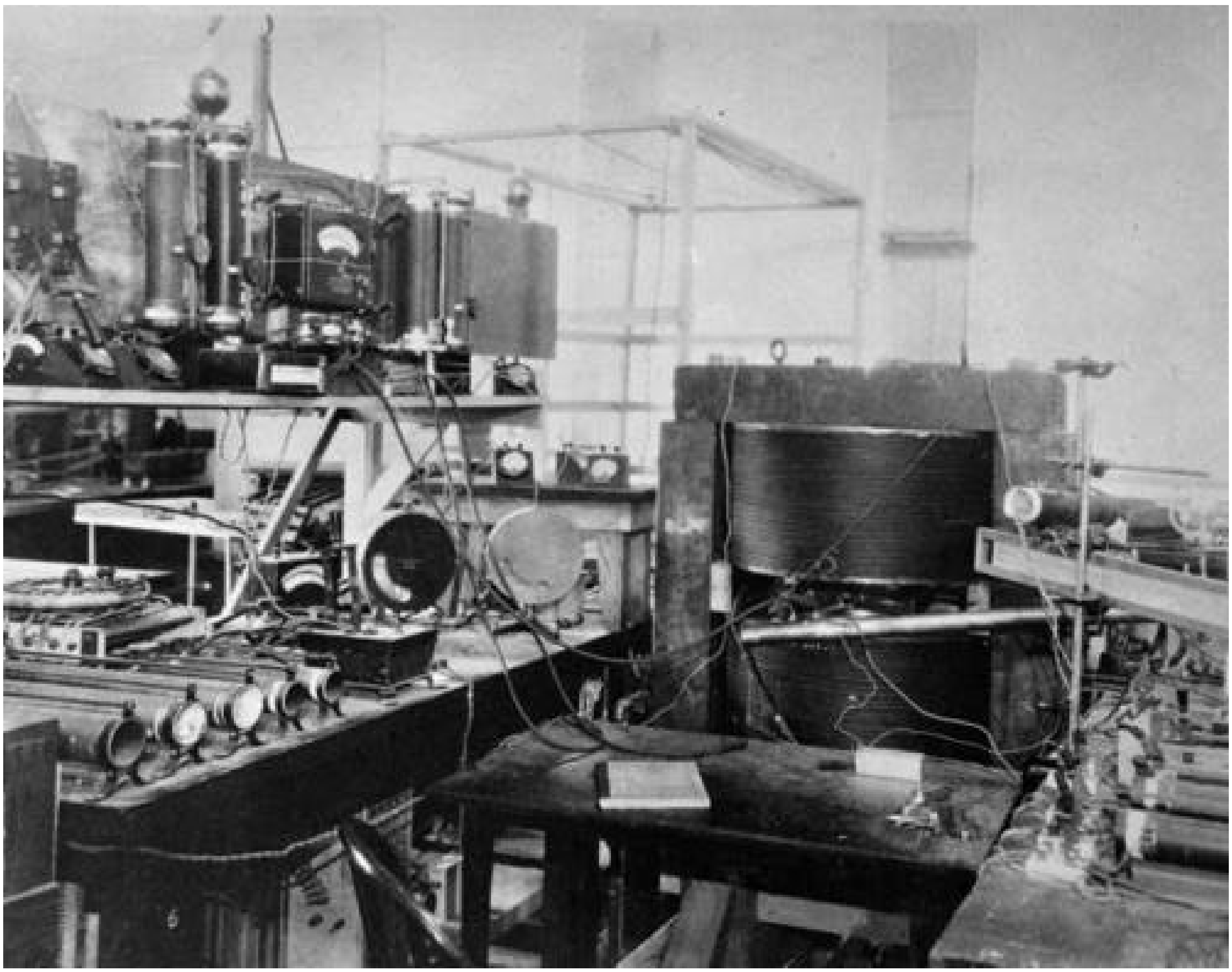
$$\boxed{E_{CM} = 2E_b}$$

Colliders have become the dominant tool of elementary particle physics over the last several decades because of their much more efficient translation of beam energy into center-of-mass energy.

III. Historical Development

The development of the particle accelerator dates back to **Ernest O. Lawrence**. In 1931 Lawrence, inspired by an article by a Norweigen engineer, Rolf Wideroe, describing a method for doubling the effective energy of an accelerating tube by using an alternating voltage, constructed the first functional cyclotron. The cyclotron established two concepts that still form the basis of most modern particle accelerators:

- Resonant acceleration (by way of time varying fields)
- The circular (or recirculating) accelerator

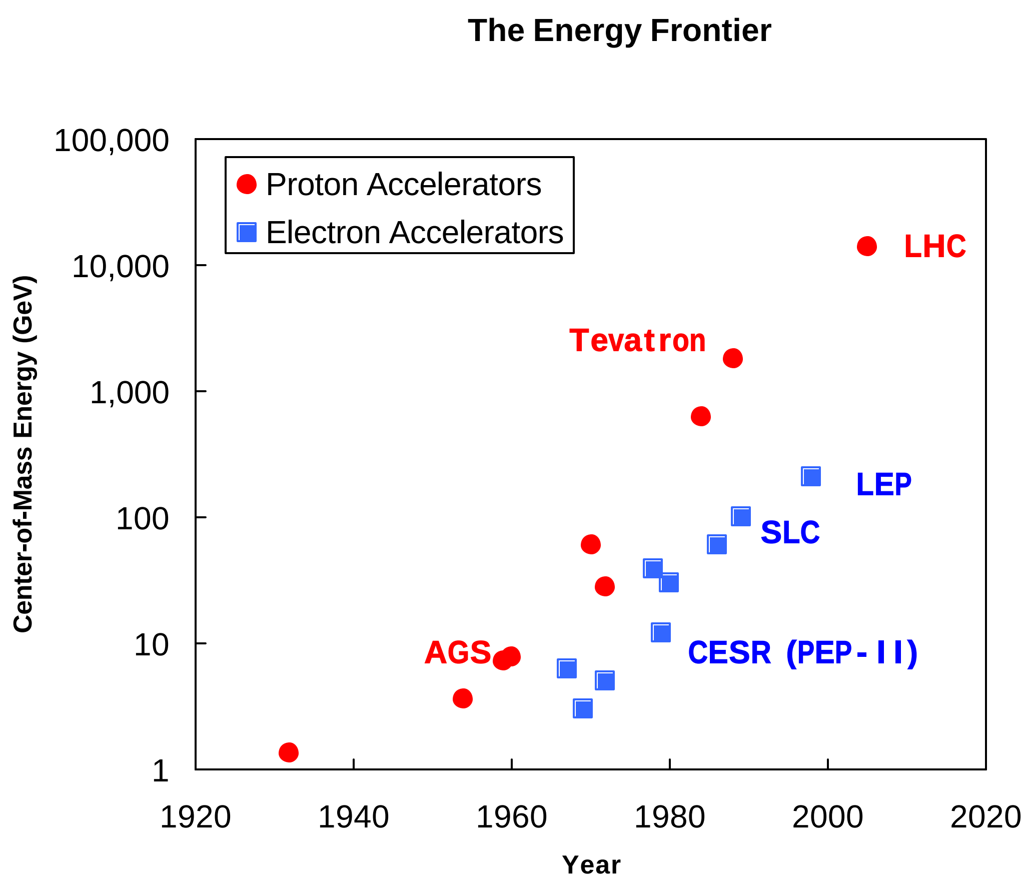


Ernest O. Lawrence's 11" cyclotron achieved 1,000,000 eV in 1931.

The cyclotron also established the roles of electric and magnetic field in a circular accelerator:

- Electric fields are used to accelerate charged particles
- Magnetic fields are used for confinement (focusing) and recirculation.

Starting with the cyclotron, a series of accelerators have been constructed over the last seventy years, with performance growing by a factor of **one million** (as measured by beam kinetic energy), or about one thousand if measured by center-of-mass energy.



(A word on electrons vs. protons: In general because of the fundamental nature of electrons, they are worth approximately a factor of ten more in E_{CM} than are protons.)

The key advances that have supported this rapid development have been both <u>conceptual</u> and <u>technological</u>:

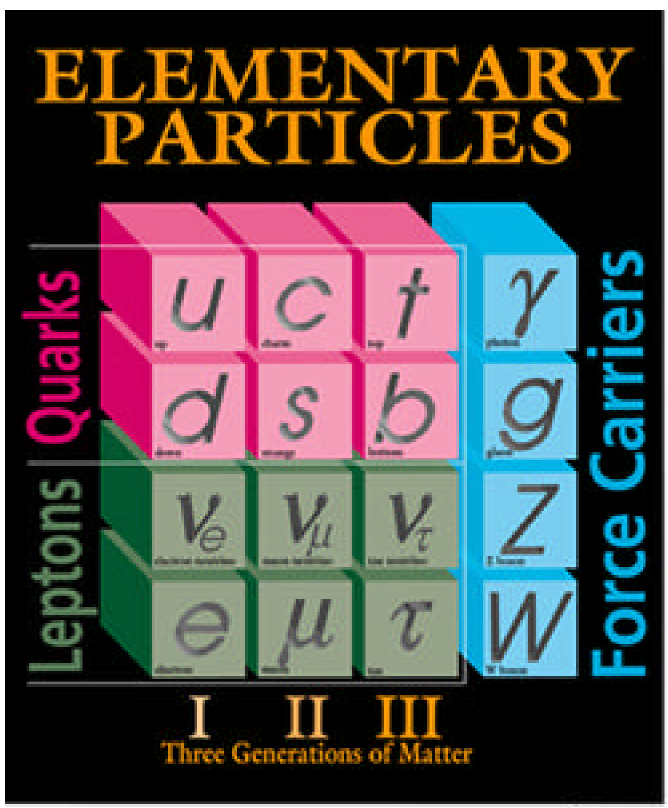
Conceptual

- Phase stability
- Strong (alternating gradient) focusing
- Landau damping and feedback

Technological

- RF power sources
- Superconducting magnets
- Resonant accelerating structures (both normal and superconducting)

These machines have led us to a physical understanding of the structure of matter that is described by the "**periodic table of quarks and leptons**"



However, despite the successful development of this deep understanding of matter, we remain confronted with many outstanding questions:

1. What is the orgin of mass? – Why the huge disparities in the masses of the fundamental constituents of matter? (M_T/M_e=350,000)
2. Is there a whole new set of "partner" particles in addition to antimatter? – known as supersymmetric particles?
3. Does space contain more than 3 dimensions? – Could explain why gravity is so weak compared to the other forces?
4. Can quantum mechanics be combined with gravity?
5. Is all matter composed of strings?—The answers to 1-4 are yes within a theoretical framework that has been developed over the last two decades called "string" theory. In this theory the elementary particles are different vibrational modes of extremely tiny strings embedded in a 11 dimensional space.
6. Why are there 3 generations of quarks and leptons?
7. Why is the universe made out of matter? – We believe that at the moment of the big bang equal amounts of matter and antimatter were present.
8. What is the dark matter that comprises the bulk of the universe? And what is the dark energy that is powering the expansion of the universe?
9. Why does time run forward?

Providing the answers to these, as well as the set of questions we are not yet smart enough to write down, represent the challenge of the 21st century.

IV. Accelerator Basics

A particle under the influence of an electromagnetic field is accelerated according to the law:

$$\boxed{\frac{d\vec{p}}{dt} = \vec{F} = q(\vec{E} + \vec{v} \times \vec{B})}$$

The change in the kinetic energy of the particle moving under the influence of an electromagnetic field is given by,

$$\boxed{\frac{dKE}{dt} = \vec{v} \cdot \vec{F} = q\vec{v} \cdot \vec{E}}$$

The only electromagnetic field component capable of changing the energy of a particle is an electric field component parallel to the velocity.

In general the acceleration comes from a radio frequency (rf) system. The rf system provides a time varying electric field ($\vec{E}$) over some physical length ($\vec{l}$) and we denote the energy gain as

$$\boxed{\Delta KE = q\vec{E} \cdot \vec{l} = qV_{rf}}$$

The linear accelerator

In a linear accelerator ("linac" for short) utilizes a set of rf accelerating structures arranged in series to accelerate a charged particle beam. The total energy of the beam is then the product of the electric field seen by the accelerating particle, the particle charge, and the length of the accelerator:

$$\boxed{KE = q \times E \times L}$$

The circular accelerator

In the circular accelerator particles are recirculated many times through an rf field with their kinetic energy incremented by eV_{rf} on each passage. So the ultimate energy becomes:

$$\boxed{KE = q \times V_{rf} \times N_{turns}}$$

As a practical matter the energy obtainable is not set by the rf voltage, but by the recirculation configuration

$$\boxed{p = q \times R \times B}$$

where p is the beam momentum, q is the particle charge, R is the radius of the orbit, and B is the magnetic bend field.

Focusing/Beam Emittance

Magnetic fields are also used to confine beams so that they remain within the confines of both linear and circular accelerators. In both instances particles are confined by quadrupole magnets:

$$\begin{cases} B_y = B'x \\ B_x = B'y \end{cases}$$

The function of **quadrupole magnets** in an accelerator is completely analogous to **lens** in an optical system. The force on a charge particle offset by an amount x in a quadrupole magnet is,

$$F_x = qv_z B_y = (qv_z B')x$$

There is a linear restoring (or anti-restoring, depending on the sign of B') force. It can be shown that if the polarity is chosen so that the force is restoring in the horizontal plane, then it is anti-restoring in the vertical plane, and visa-versa.

The motion of a single particle is governed by an equation that looks like a **harmonic oscillator** with a time varying spring constant:

$$\boxed{\frac{d^2x}{ds^2} + k(s)x = 0}$$

Not surprisingly, the solution to this equation looks like a harmonic oscillator with a **time varying amplitude and frequency**,

$$\boxed{x(s) = A\sqrt{b\,(s)}\cos(f(s) - f_o)}$$

A collection of particles have a variety of A's and ϕ_o's. The beam **emittance** is defined as,

$$\boxed{e = \frac{1}{2}\left\langle A_i^2 \right\rangle}$$

and the characteristic beam size is then given by,

$$\boxed{s\,(s) = \sqrt{eb}}$$

(Professor Kim will carry on from here in subsequent lectures)

V. Performance Limitations in Modern Accelerators

The performance of any collider is characterized by two parameters:

- Energy
- Luminosity

The "energy frontier" is defined by the maximum center-of-mass energy (of the interacting constituents) achievable with current technology.

→ Roughly speaking, lepton colliders have a factor of 5-10 comparative advantage over hadron colliders because all the energy is carried by a single constituent.

The **energy frontier currently resides at Fermilab**, 30 miles west of downtown Chicago, where the **Tevatron** collider provides collisions of protons and antiprotons at **2.0 TeV** in the center-of-mass.

- Upon completion of the **LHC**, a proton-proton collider operating at **14 TeV**, the energy frontier will move to CERN.

→Lepton collisions at 1-1.5 TeV would be roughly equivalent to LHC.←

Fundamental Performance Limitations

The fundamental limit on energy reach achievable in colliders depends on the particles accelerated.

Hadron colliders are limited by **real estate** and the **magnetic (bending) field** available:

$$\boxed{p = q \times R \times B}$$

Þ **The energy of a hadron collider is increased by increasing the product of radius times field. The maximum achievable bending fields today are based on superconducting magnet technology--approximately 8 T**

When electrons (or positrons) are forced to travel on a circle they radiate energy, known as synchrotron radiation. **Circular electron-positron colliders** are limited by **synchrotron radiated energy**:

$$\boxed{U(MeV) = \frac{8.85 \times 10^{-5} \times E^4(GeV)}{r(km)}}$$

(note: 8.85×10^{-5} is replaced by 7.8×10^{-18} for protons—pretty negligible at current energies.)

In a large electron-positron collider the radiated energy is very significant. For example LEP:

R=4.5 km
B=.075 Tesla
E_{beam}=100 GeV
Þ **U=2 GeV/turn**

Þ **The energy of a circular electron-positron collider is increased by increasing radius and decreasing the magnetic field.**

In practice, the optimum is usually achieved by increasing the radius as the square of the energy (and hence decreasing the magnetic field inversely with energy).

The limitations inherent in the above expression have led to the development of the **electron-positron linear collider** and consideration of the possibility of a **muon collider.**

Luminosity

The luminosity in any collider is given by

$$\boxed{L = \frac{fN_1N_2}{4\pi\sigma_x\sigma_y}F}$$

where f is the frequency of collisions between bunches, N_1 and N_2 are the number of particles in the colliding bunches, and σ_x and σ_y are the transverse beam dimensions, and F is a form factor related to the specifics of the collision geometry (forget about F for now).

Because of the inverse square relationship between reaction cross sections and center of mass energy the next generation of colliders must achieve luminosities in the range $10^{33\text{-}34}\text{cm}^{-2}\text{sec}^{-1}$.

Linear electron-positron linear colliders overcome the synchrotron radiation limitations by accelerating the electrons/positrons in a straight line. The energy is now just L×E (electric field). The downside to this configuration is that after acceleration particles have only one opportunity to interact before being disposed of. As a result the fundamental limitation in an electron-positron linear collider is governed by the **beam power** required to generate a useable luminosity.

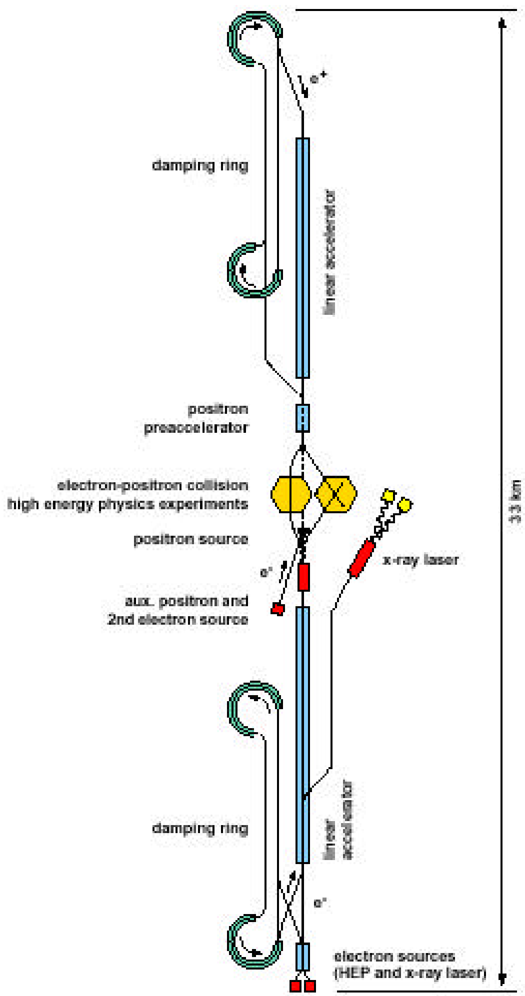
$$\boxed{L = \frac{f_{rep}n_bN^2}{4\pi\sigma_x\sigma_y}H_D = \frac{P_bNH_D}{4\pi E_{CM}\sigma_x\sigma_y}}$$

Where,

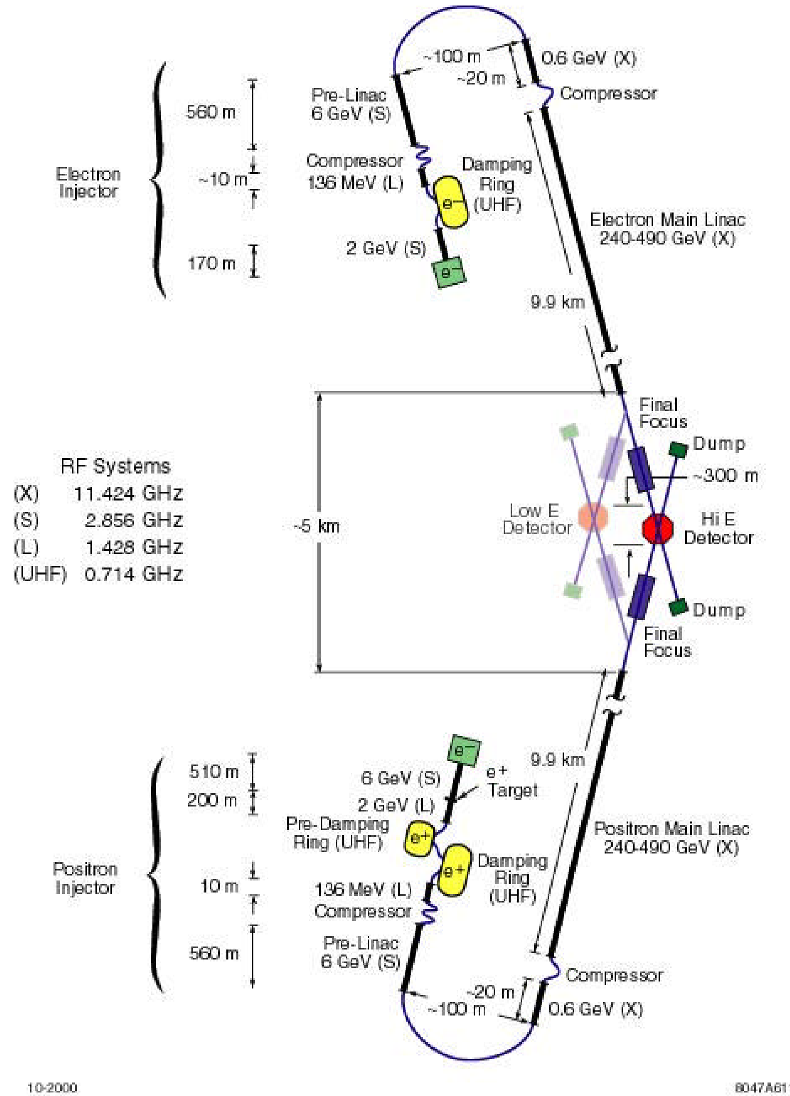
- f_{rep} is the pulse repetition rate.
- n_b is the number of bunches in a pulse.
- N is the number of particles in a bunch (assumed equal for the electron and positron beams).
- σ_x and σ_y are the rms transverse beam dimensions at the interaction point.
- P_b is the total beam power.
- H_D is a luminosity enhancement factor resulting from the self-focusing of the beams as they collide.

- **The energy of a linear electron-positron collider is maximized by increasing product of the length and the accelerating gradient. Current technologies provide about 50 MV/m in room temperature copper structures and 25 MV/m in superconducting structures. Producing a useable luminosity relies on high beam power and small beam size.**

This elucidation of these points represents the essence of this course.



e+
damping ring
linear accelerator
positron
preaccelerator
electron-positron collision
high energy physics experiments
positron source
e+
x-ray laser
aux. positron and
2nd electron source
damping ring
linear
accelerator
e-
electron sources
(HEP and x-ray laser)



~100 m
~20 m
0.6 GeV (X)
Compressor
Pre-Linac
6 GeV (S)
560 m
Electron
Injector
~10 m
Compressor
136 MeV (L)
Damping
Ring
(UHF)
e−
Electron Main Linac
240-490 GeV (X)
170 m
2 GeV (S)
e−
9.9 km
Final
Focus
Dump
~300 m
RF Systems
(X) 11.424 GHz
(S) 2.856 GHz
(L) 1.428 GHz
(UHF) 0.714 GHz
~5 km
Low E
Detector
Hi E
Detector
Dump
Final
Focus
9.9 km
e−
510 m
6 GeV (S)
e+
Target
200 m
2 GeV (L)
Pre-Damping
Ring (UHF)
e+
e+
Damping
Ring
(UHF)
Positron Main Linac
240-490 GeV (X)
Positron
Injector
10 m
136 MeV (L)
Compressor
560 m
Pre-Linac
6 GeV (S)
Compressor
~20 m
~100 m
0.6 GeV (X)
10-2000
8047A611