CORNELL UNIVERSITY LEPP

LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

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

$$E_c = \frac{3}{4\pi}\frac{hc}{\rho}\left(\frac{E_b}{mc^2}\right)^3$$

- 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

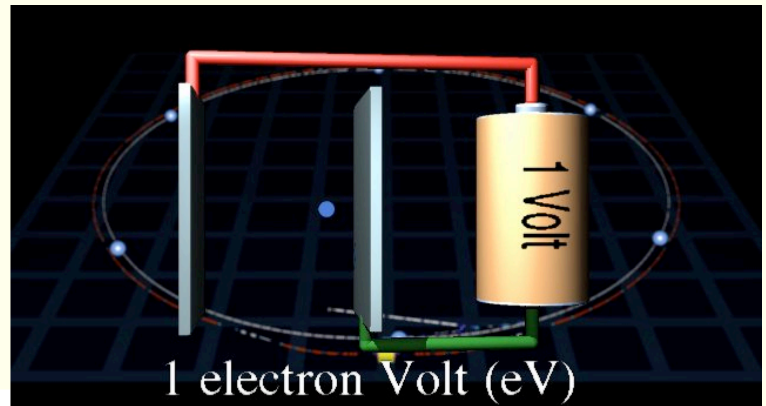
Important Reminders

- Make Use of the Lorentz Force $\vec{F} = q\,[\,\vec{E} + \vec{v} \times \vec{B}\,]$

  ==> Acceleration Requires Charged Particles

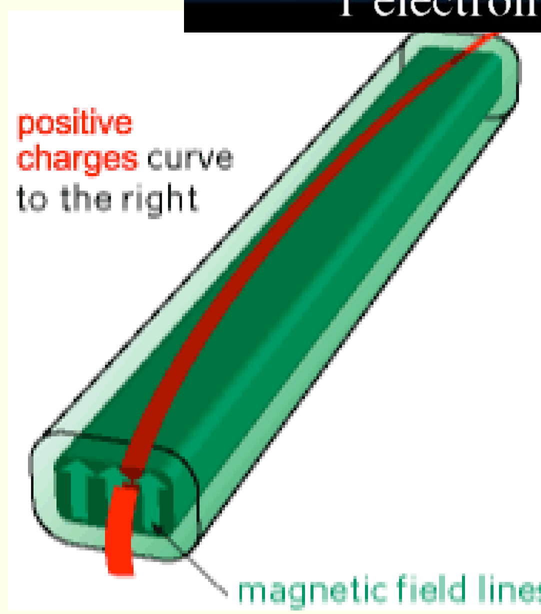
- Energy of Particles Measured in eV

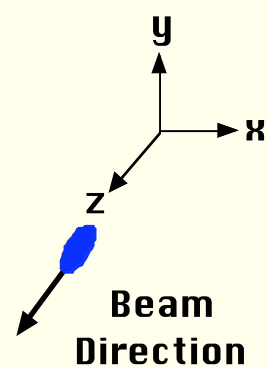
  Energy gain of 1 eV
  = Energy of 1 electron Passing through
  1V of Potential Difference



- Deflection of Particle Beams

  Uses Magnetic Fields

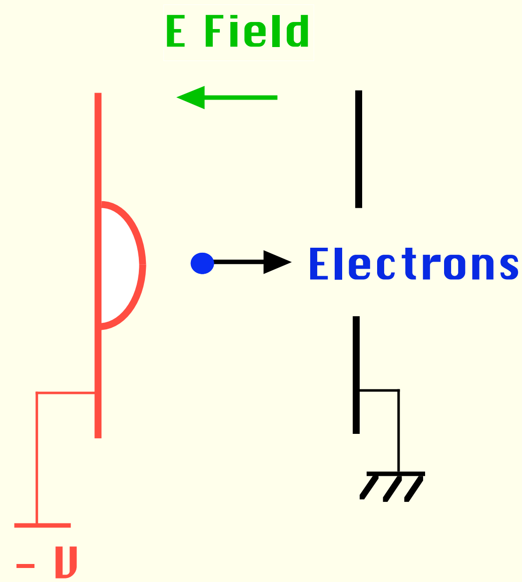




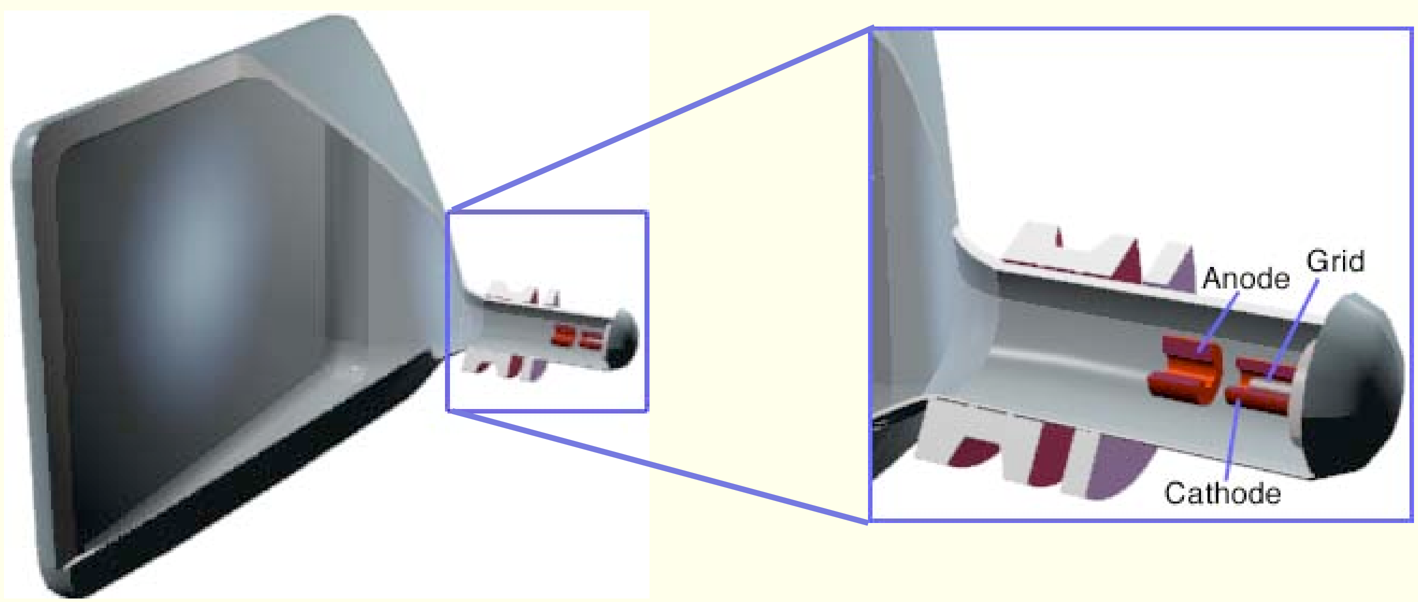
Tools of the Trade: Particle Sources

- Electron Source

Boil Electrons Off of a Hot Cathode



Television Tube as an Accelerator

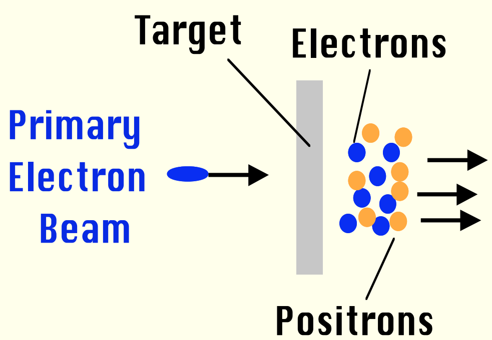


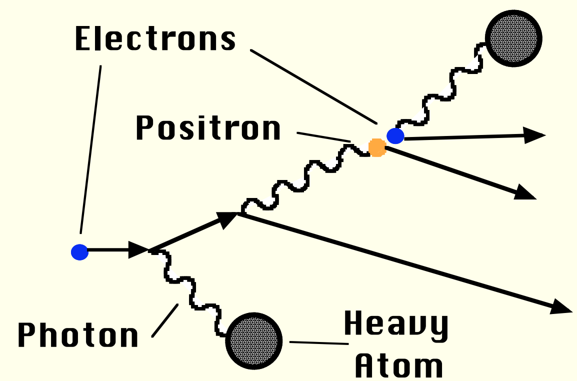
Tools of the Trade: Particle Sources

- Positron Source

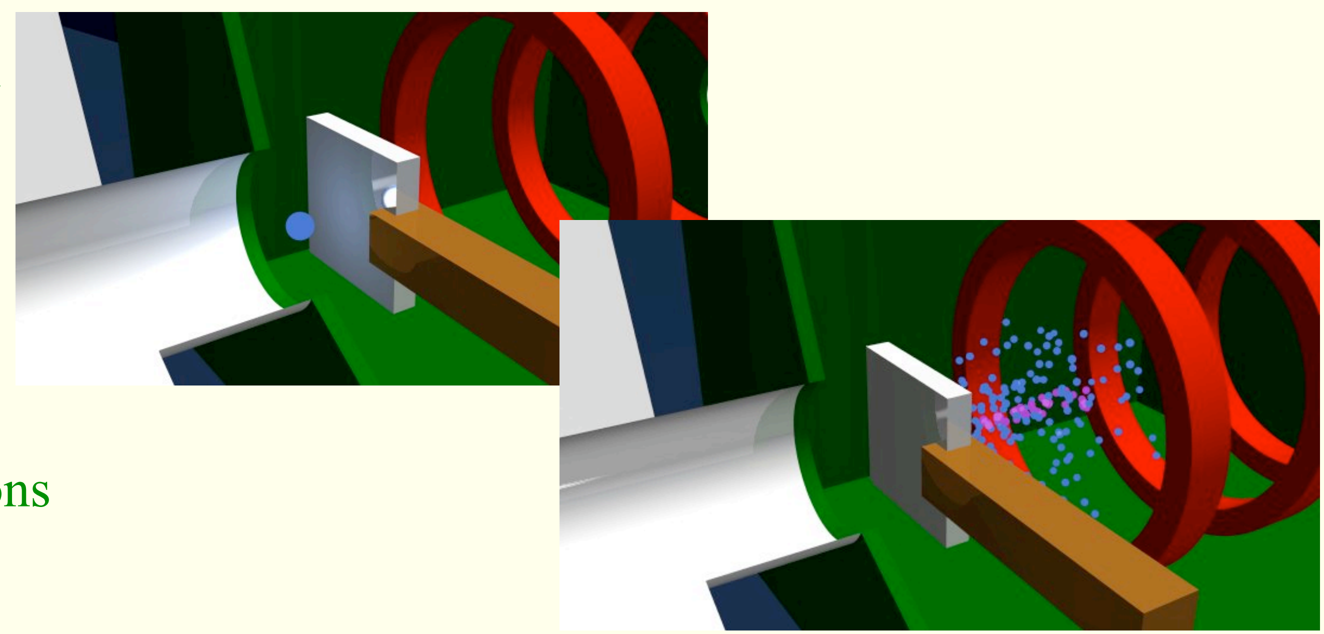
Electron Beam Incident on a Target Can Generate
Positrons via Bremsstrahlung and Pair Production

Requires a Fairly High Energy Electron Beam:





Electrons Incident



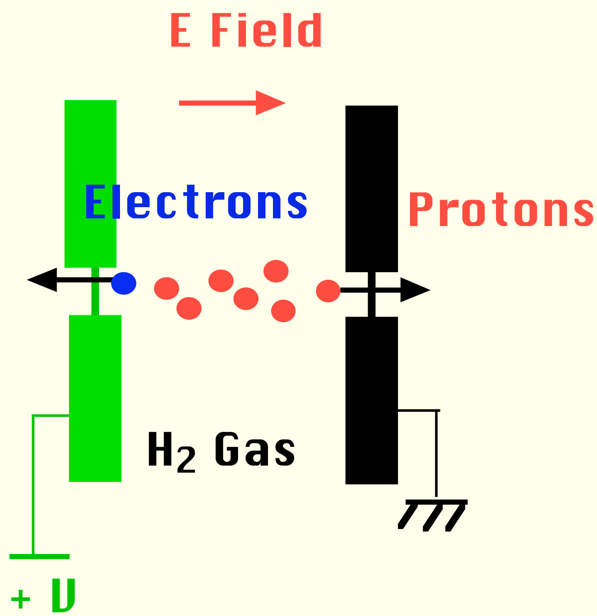
Then Capture and Accelerate Positrons

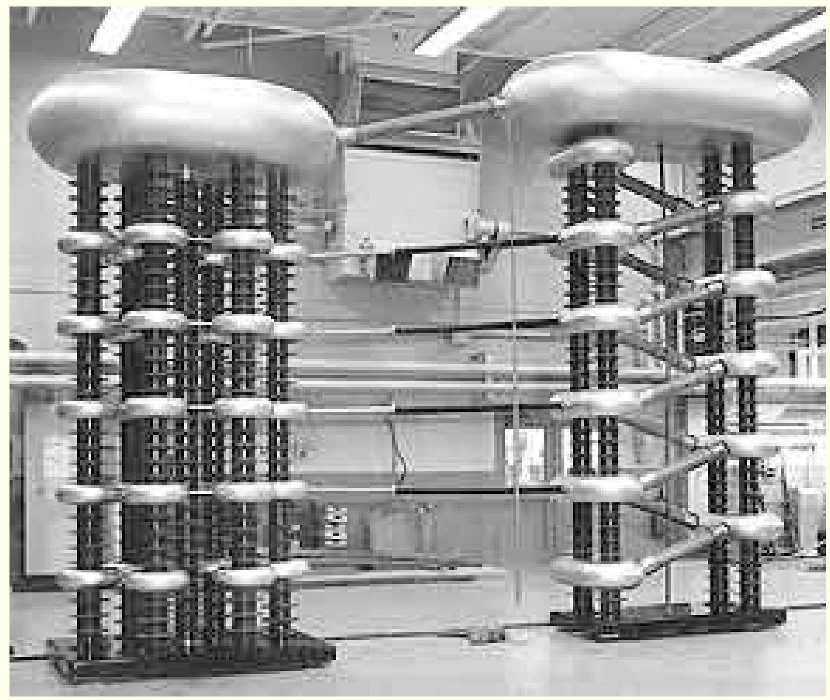
Tools of the Trade: Particle Sources

- Proton Source

Use Electrons to Ionize a Hydrogen Gas Target

Pulse HV after the Electron Beam Passes



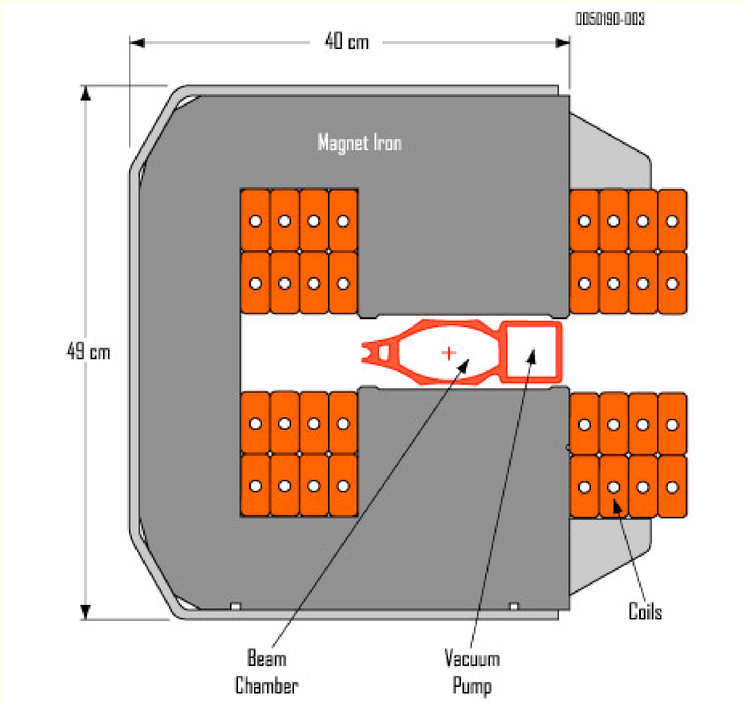


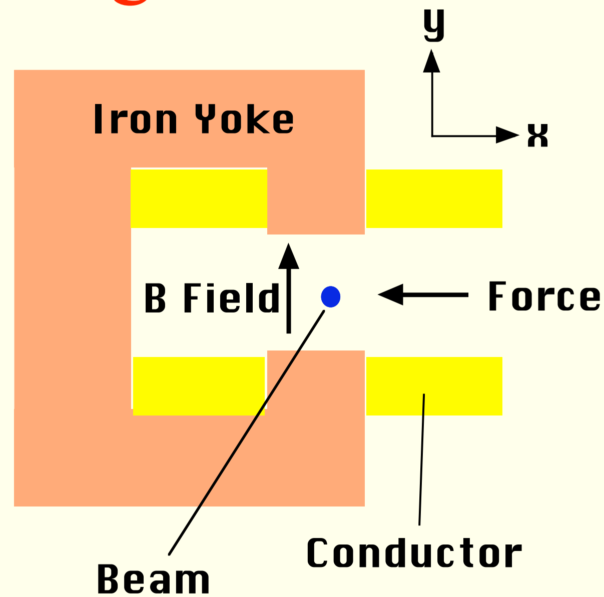
Tools of the Trade: Magnets

- Dipole

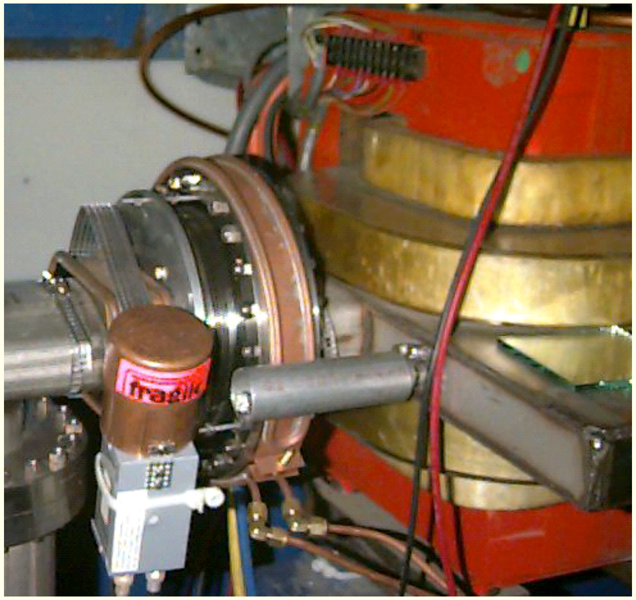
$$\vec{B} = B_0 \hat{y}$$

$$\vec{F} = -qcB_0\hat{x}$$





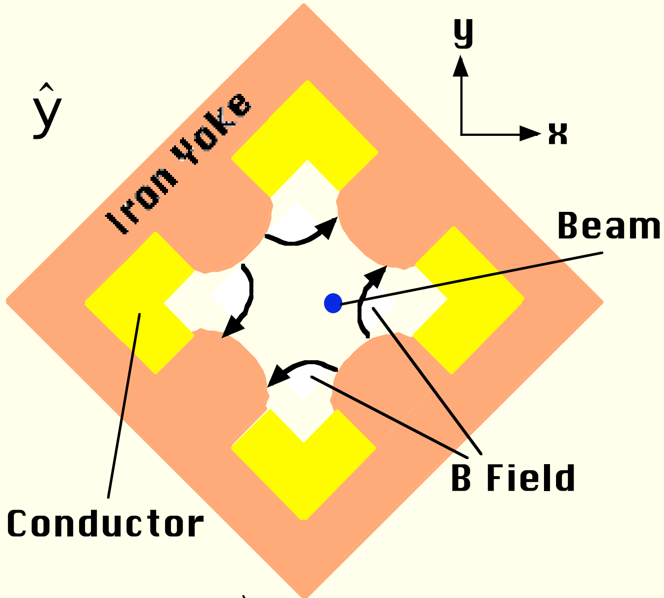
Purpose: Bends Beam on "Circular" Path



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

$$\vec{F} = q\ c\ k\left(-\ x\ \hat{x}\ +\ y\ \hat{y}\right)$$

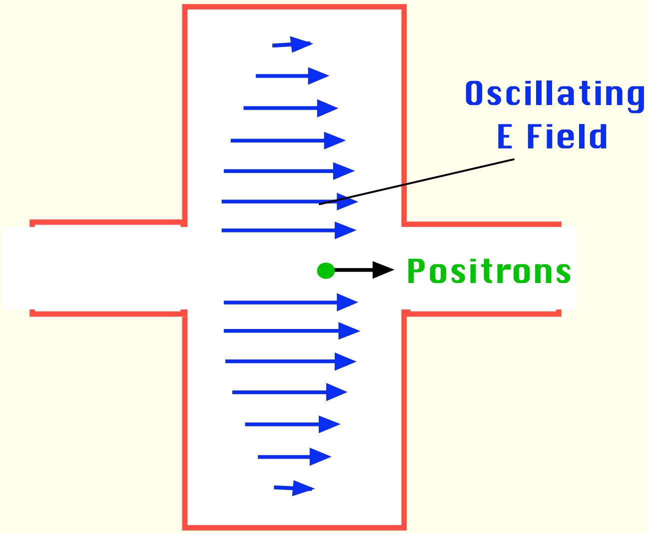
- Purpose – Focus/Defocus Beam (**Lens**)

- Net Effect of Alternating Focus/Defocus Lenses is to Focus the Beam – “Principle of Strong Focusing”

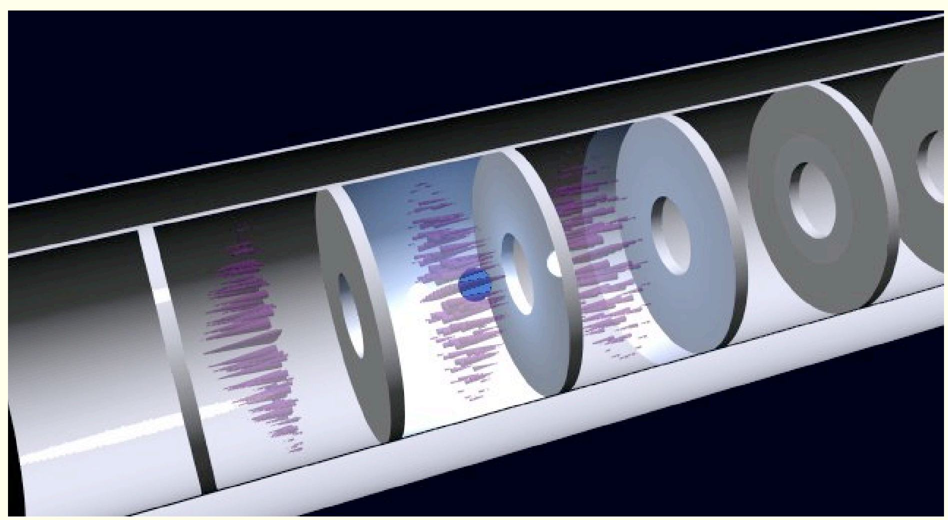
Tools of the Trade: Accelerator Structures

- "RF" Accelerator Structures

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



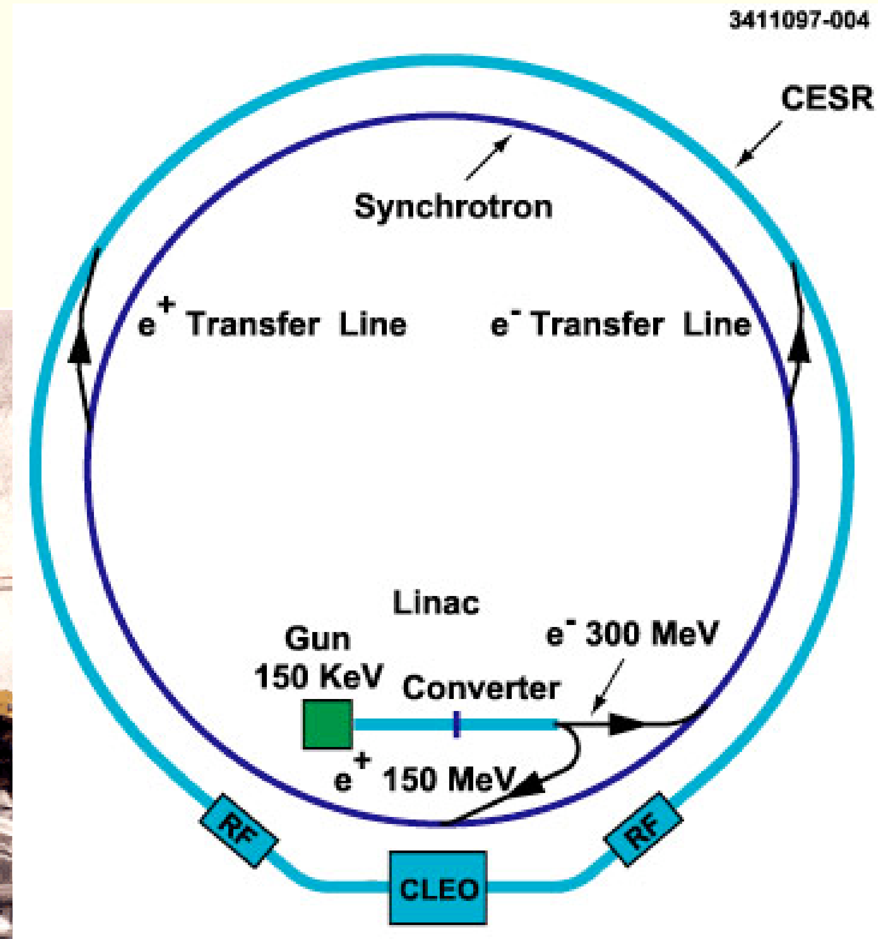
$$V(t) = V_0 \cos \omega t$$



- Can Generate 10's MV/m Accelerating Electric Fields

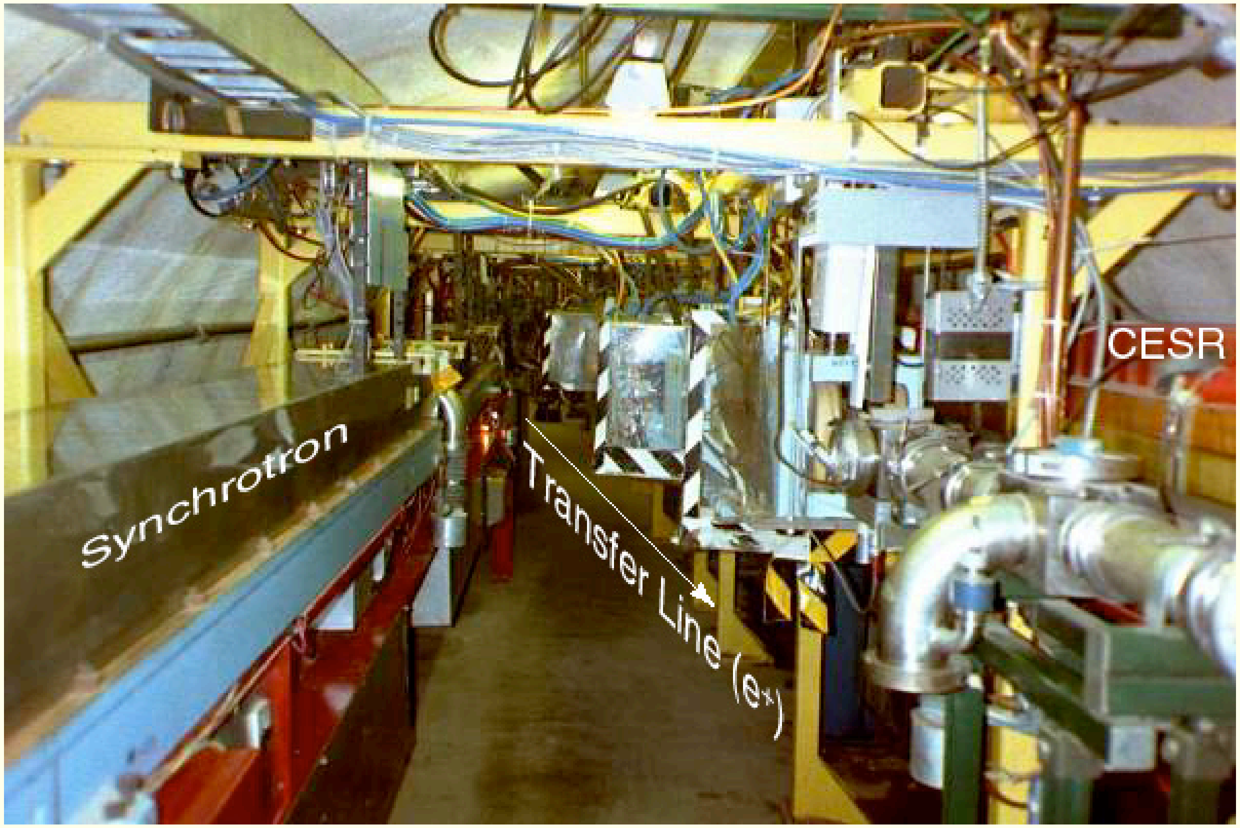
Introduction to CESR-C

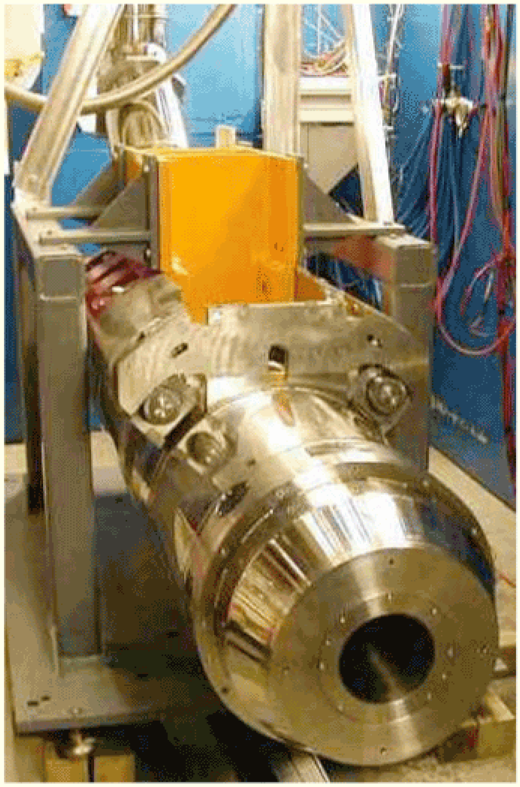
- Create electrons/positrons
  Accelerate to 99.9999995% of
  the speed of light
  Store large numbers of particles
  Collide beams in CLEO
  (Interaction Point)



CESR-C Continued

- Transfer Line – takes beam from Synchrotron to CESR





•Final Focusing Quad

Focuses beams
going into CLEO

Fast History of Accelerators

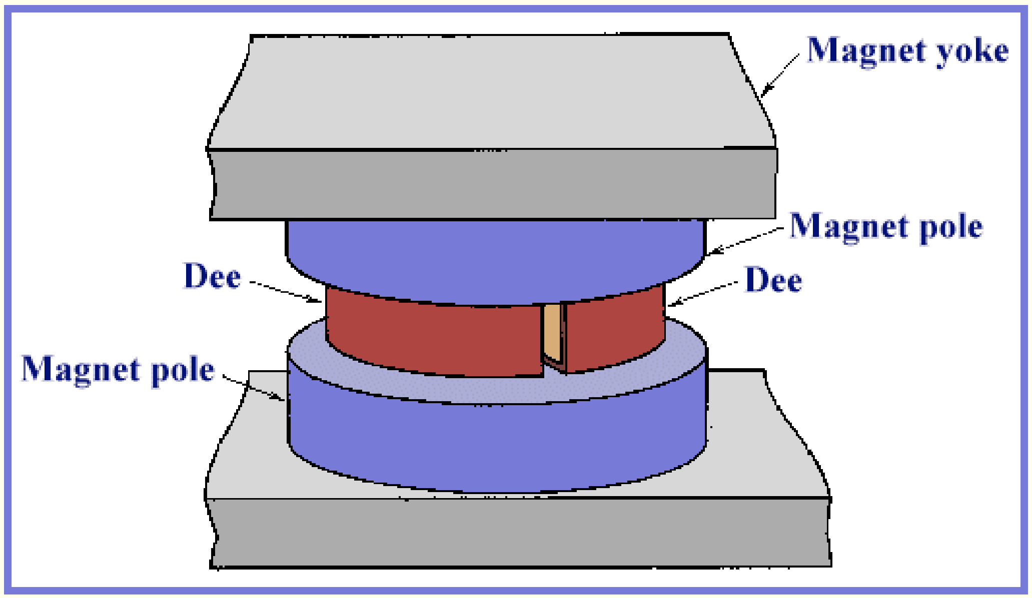
1895: Roentgen discovers x-rays with cathode ray

1919: Rutherford produces first nuclear reactions with natural alpha particles, ^{4}He $\quad$ $^{14}N + {}^{4}He \mapsto {}^{17}O + p$

Cyclotron

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

Low Energy Accelerator Develops RF Voltage Between the Two DEEs

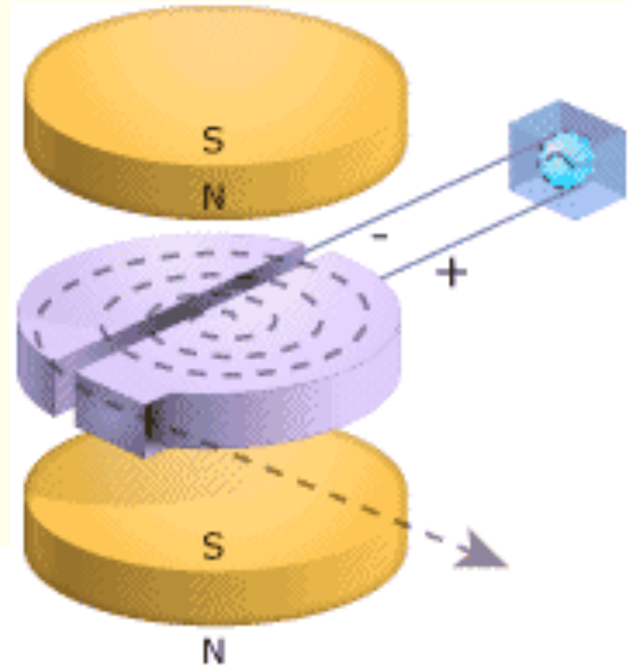


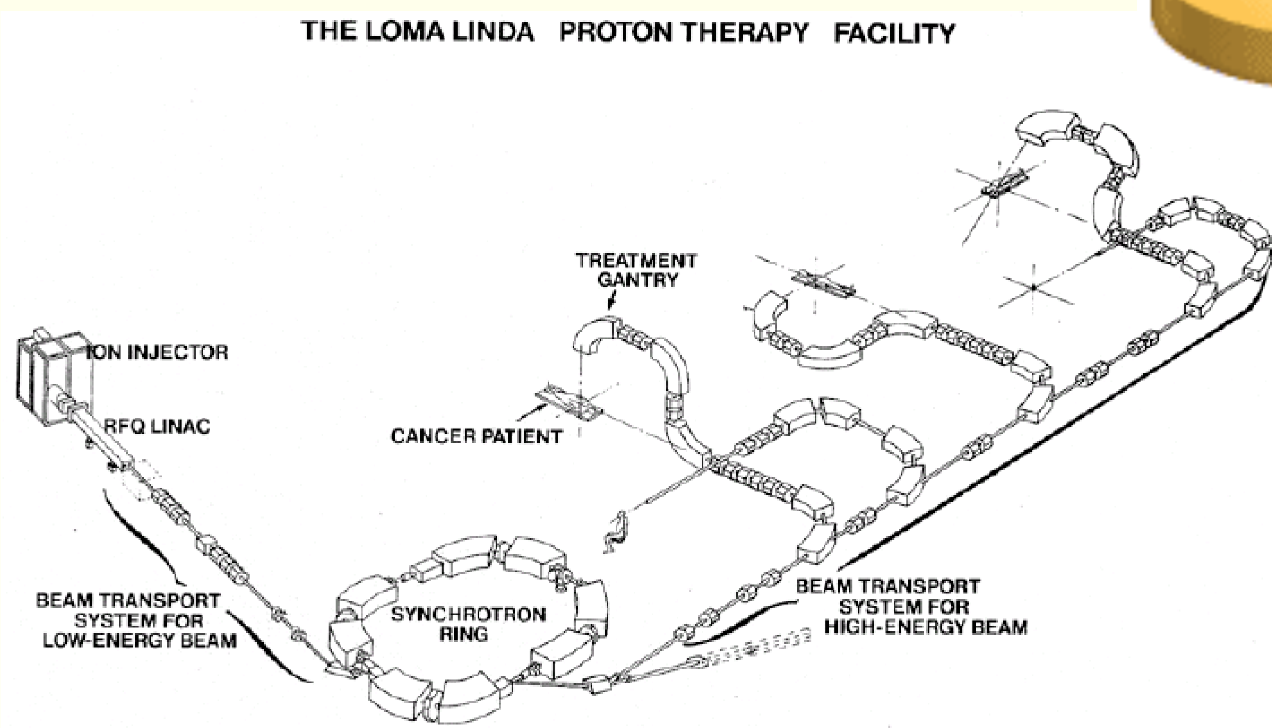
$$\omega = \frac{e B_0}{m}$$

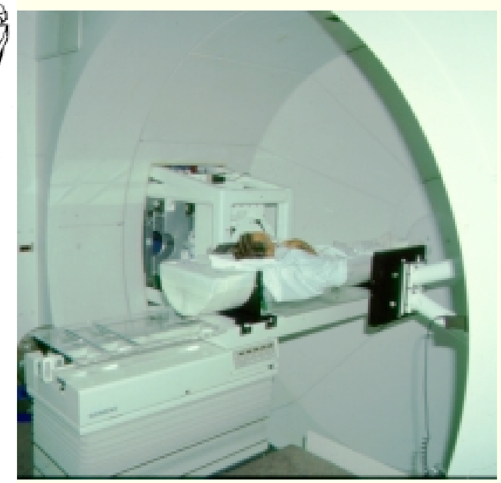
$$\text{Radius} = \frac{m v}{e B_0}$$

1939: Lawrence uses 60” cyclotron for
9 MeV protons,
19 MeV deuterons,
and 35MeV ^{4}He.

First tests of tumor therapy with neutrons

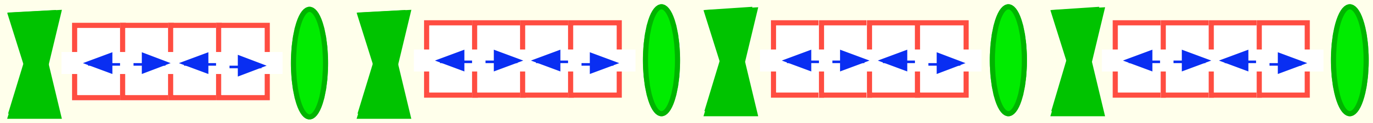






- LINear ACcelerator

  Single Pass Accelerator

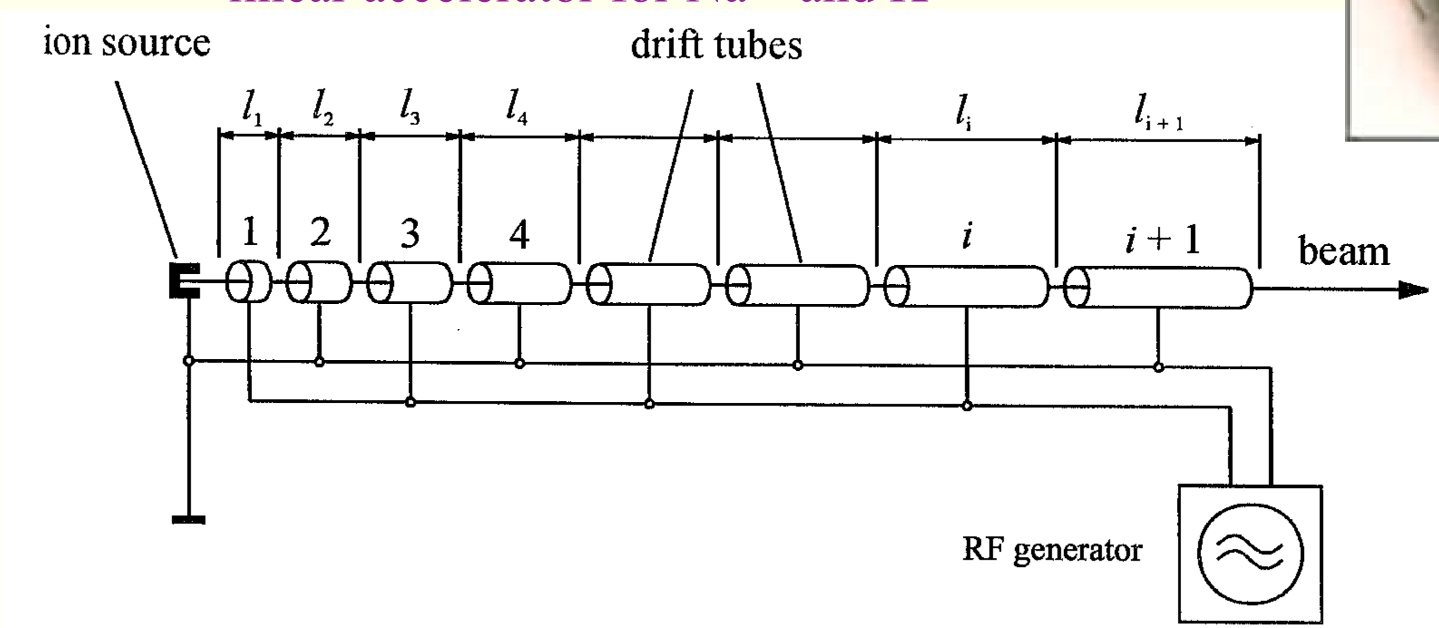


Highest Energy (Electron) LINAC is SLAC LINAC

=> 50+ GeV Beam Energy

1928: Wideroe builds the first drift tube

linear accelerator for Na^+ and K^+

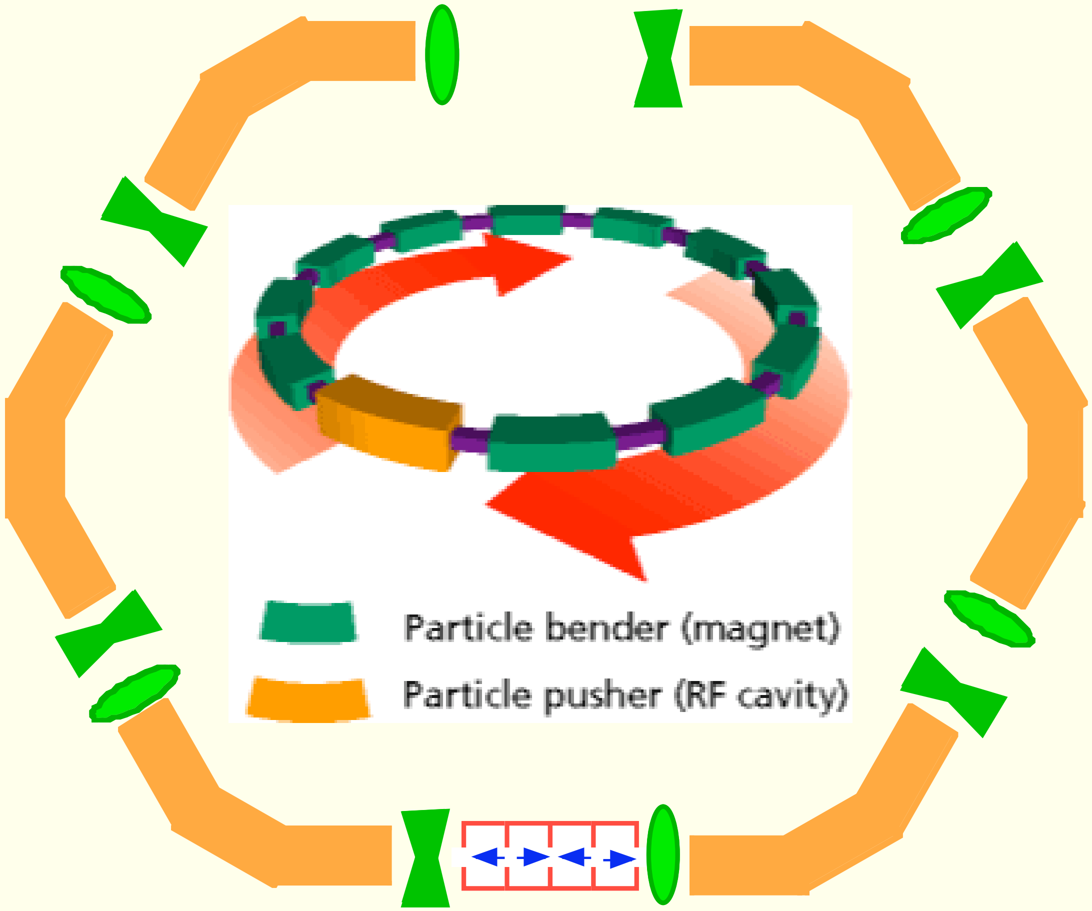


Examples of Simple Accelerators

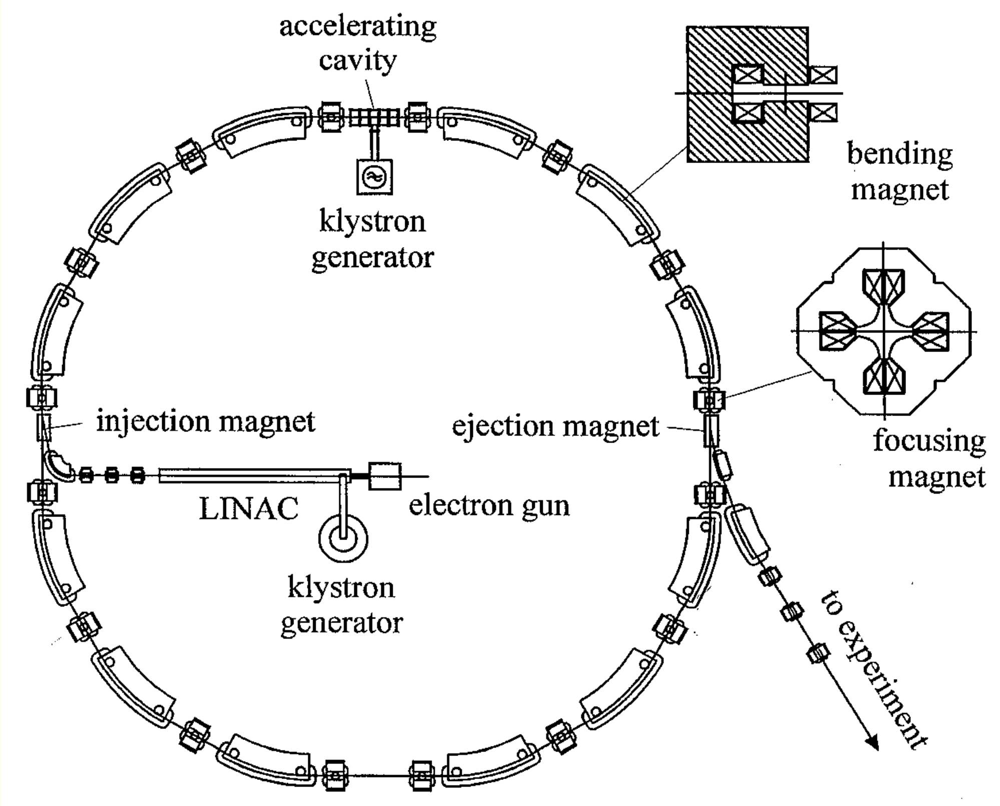
- Circular Accelerator, e.g. Synchrotron

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



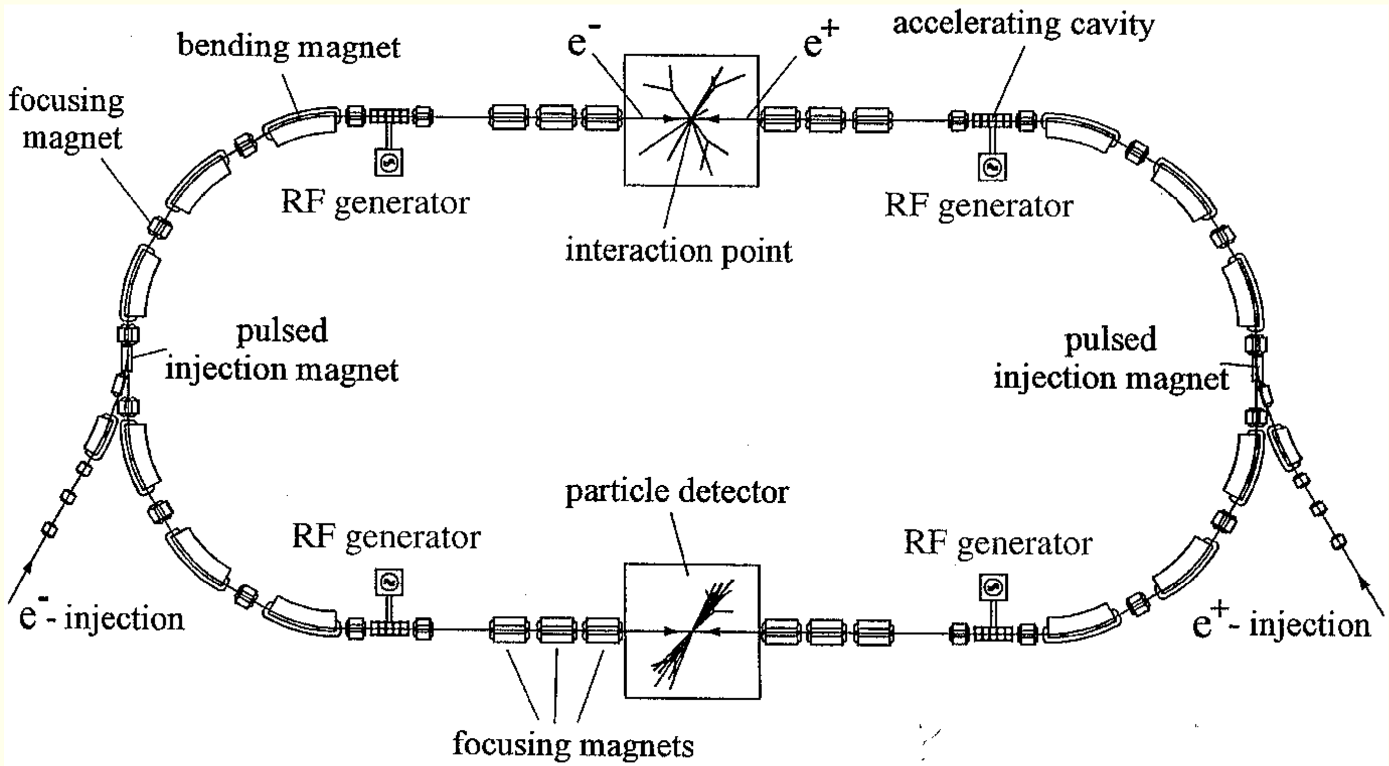
Highest Energy Accelerator is
Tevatron $E_b = 1$ TeV

Storage Ring

Footprint Same as Synchrotron, BUT

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

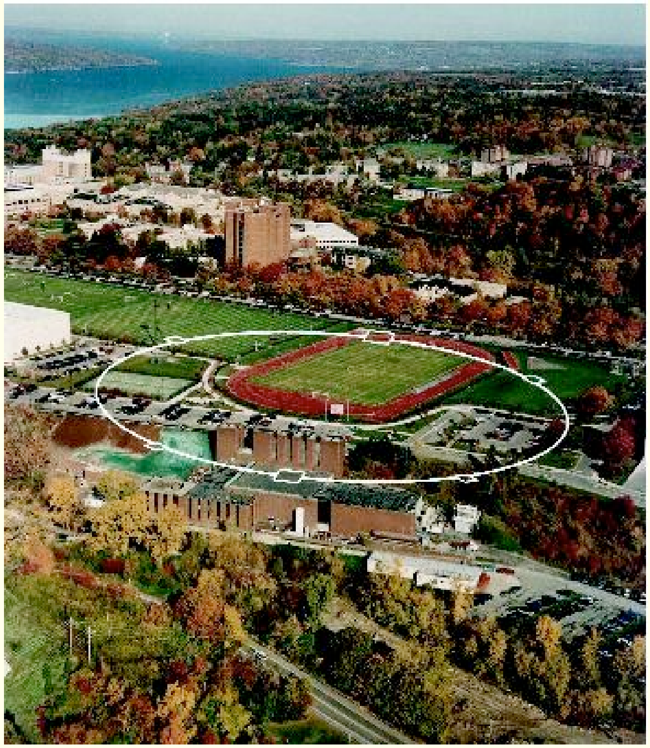
Can be used for
“Head-On”
Collisions:

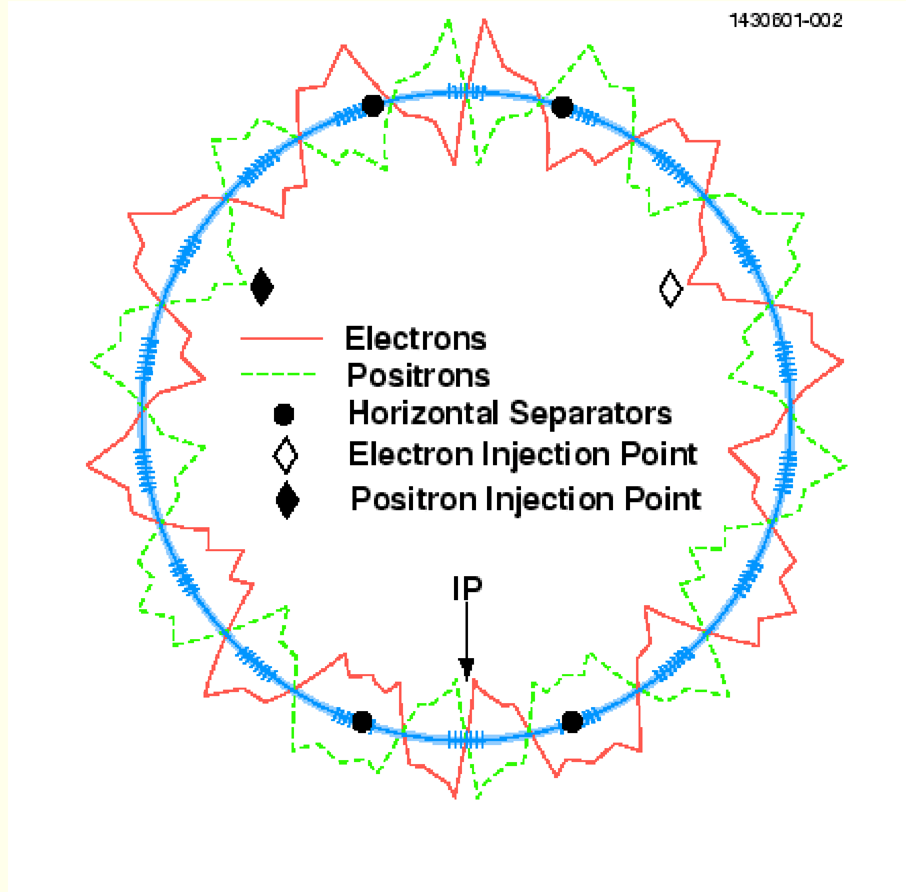


1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV

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)



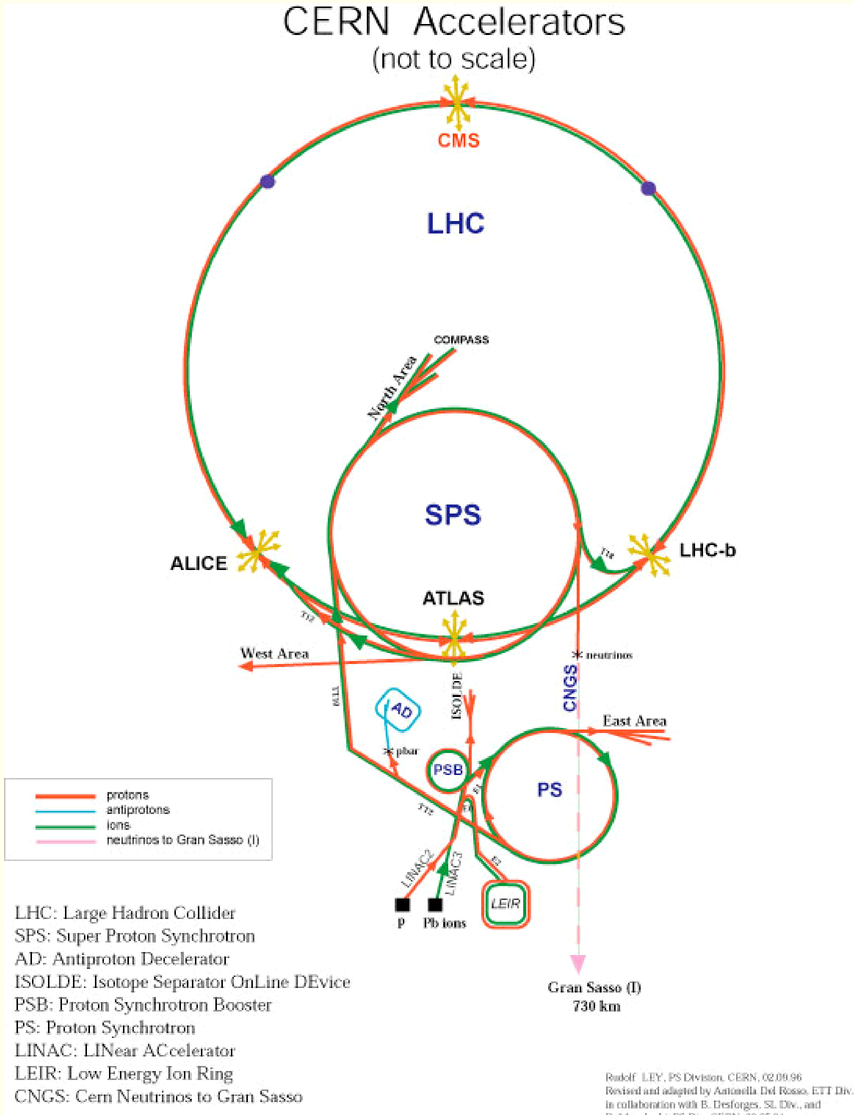


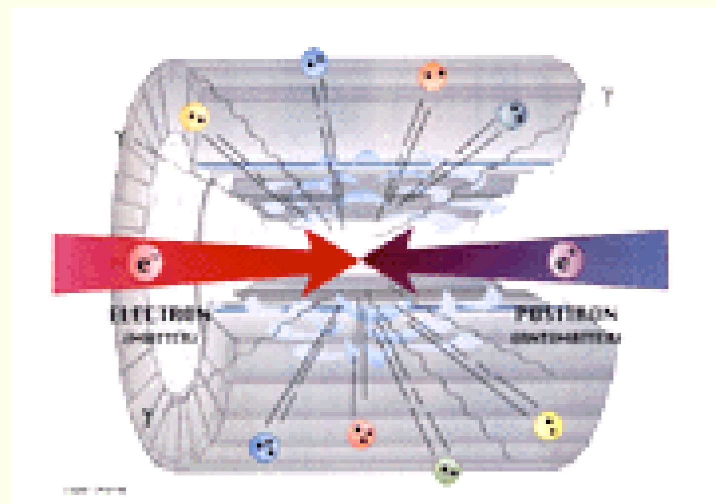
1987: Start of the super-conducting TEVATRON at FNAL

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

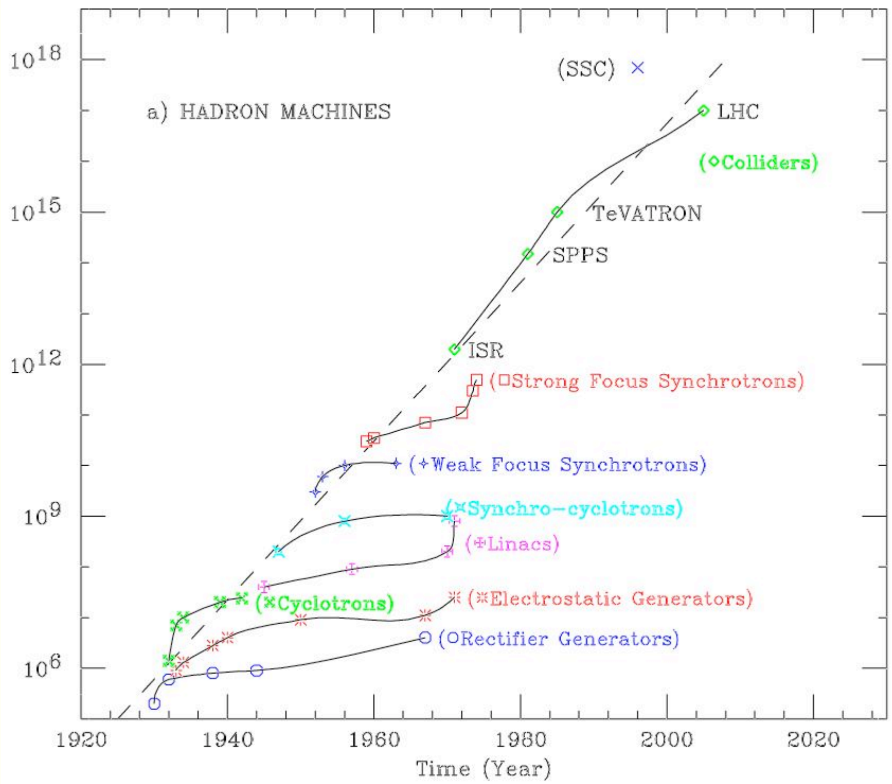
1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II

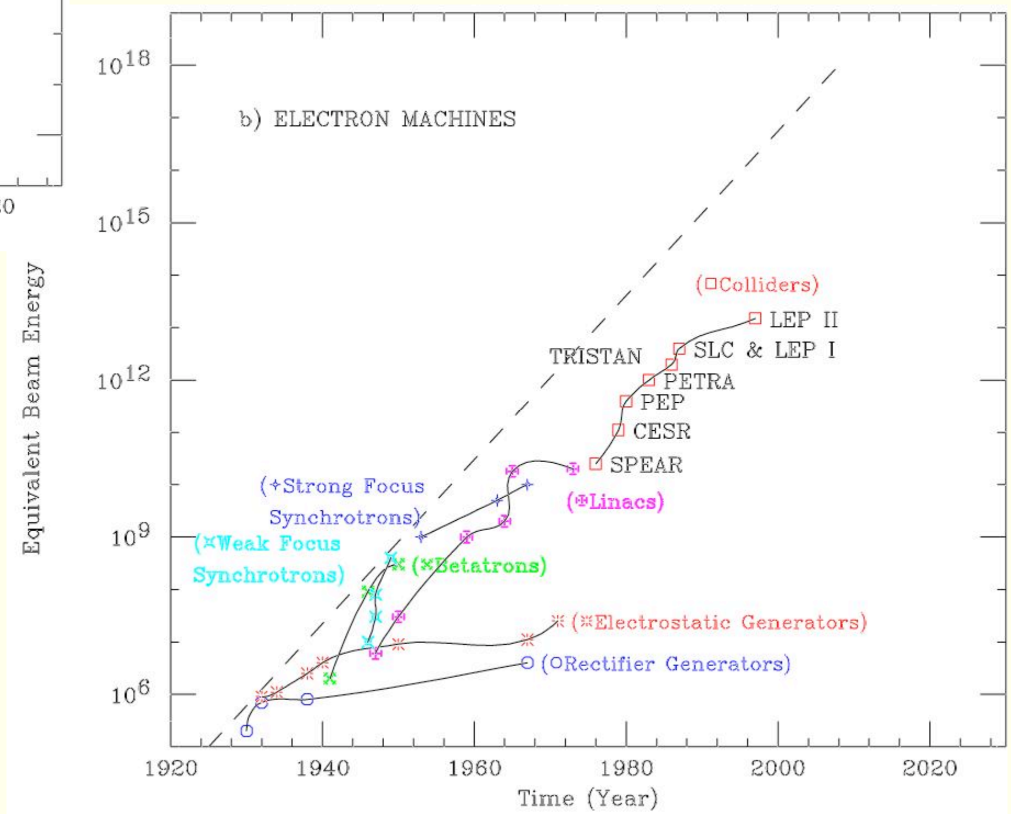




Today: 27km, 7 TeV proton collider LHC being build at CERN

Energy Available for Collisions vs Time for Hadron and Electron Accelerators





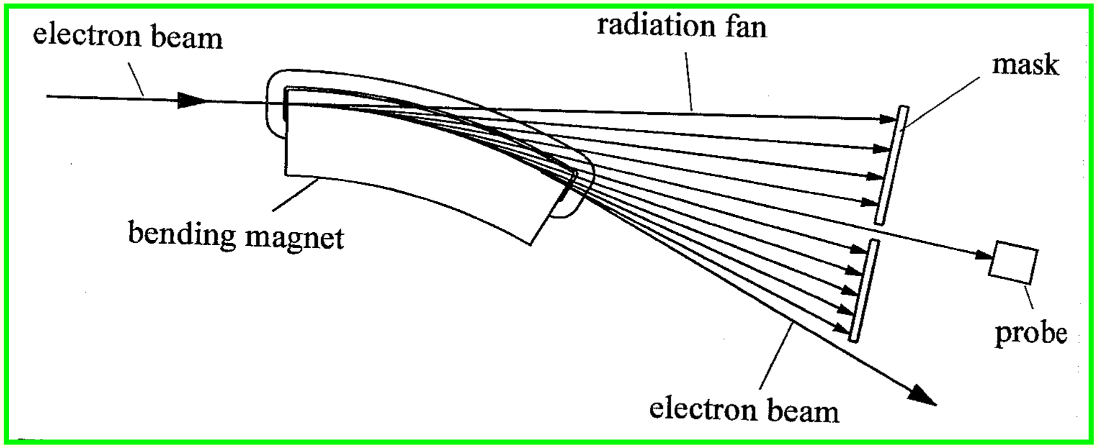
Synchrotron Light Sources

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)

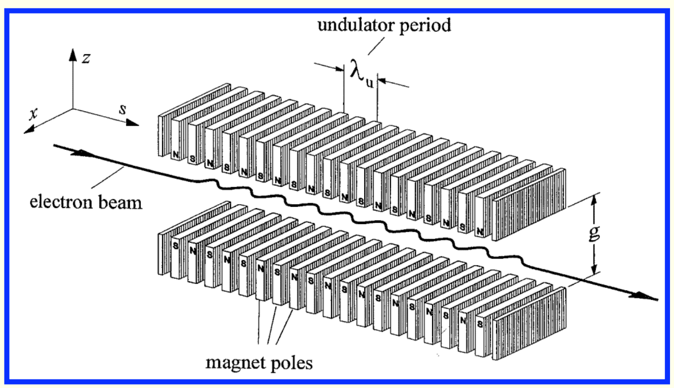


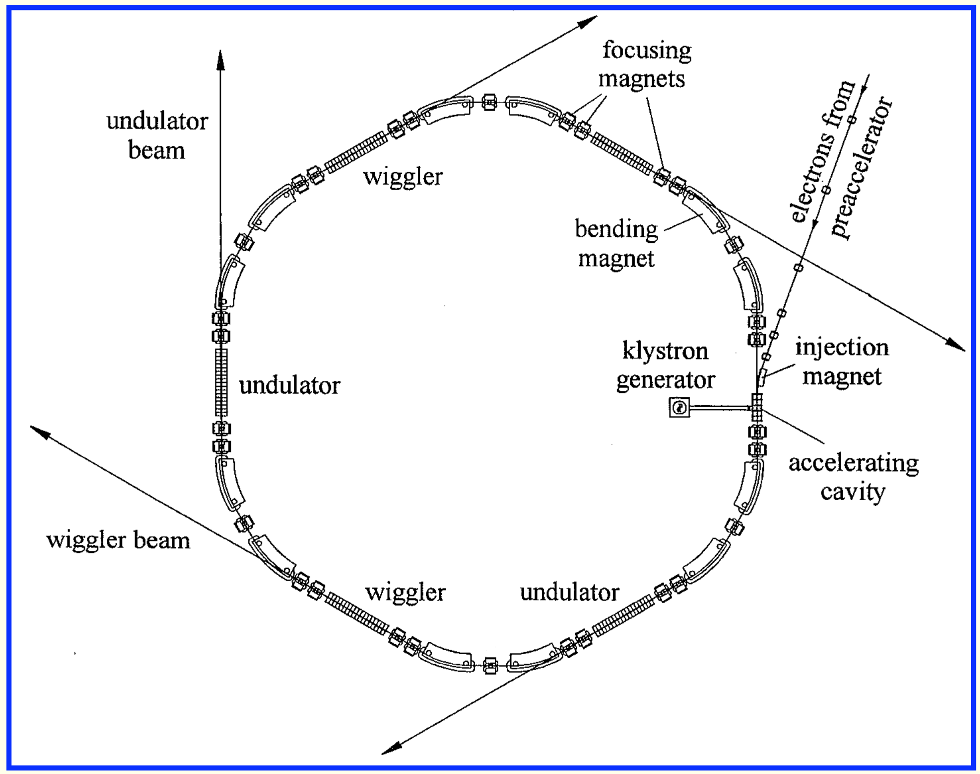
3rd Generation (1990s):

Several rings with dedicated radiation devices (wigglers and undulators)

Today (4th Generation):

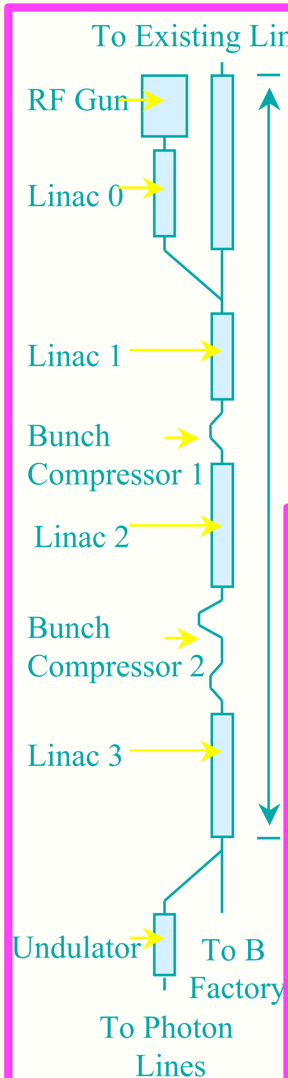
Construction of Free Electron Lasers (FELs) driven by LINACs

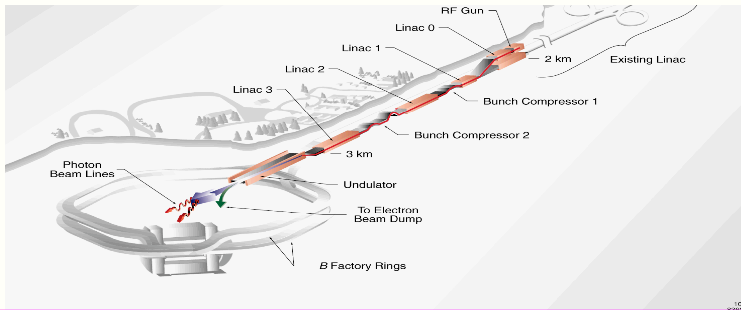




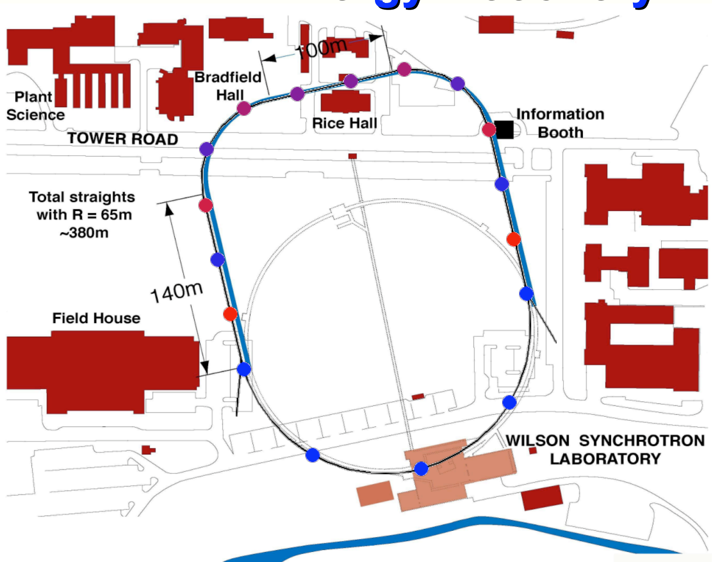
Future Accelerators

SASE Free Electron Lasers

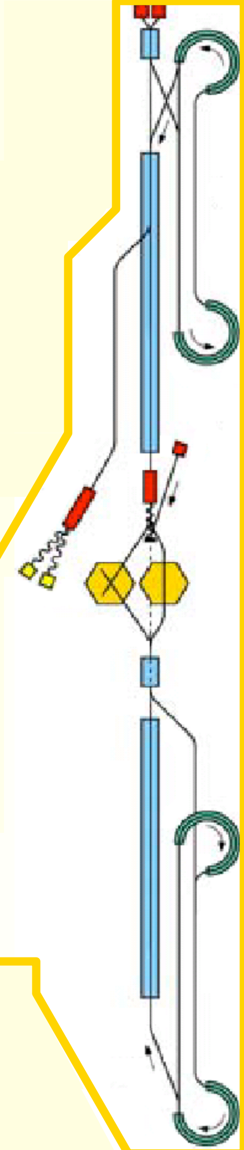




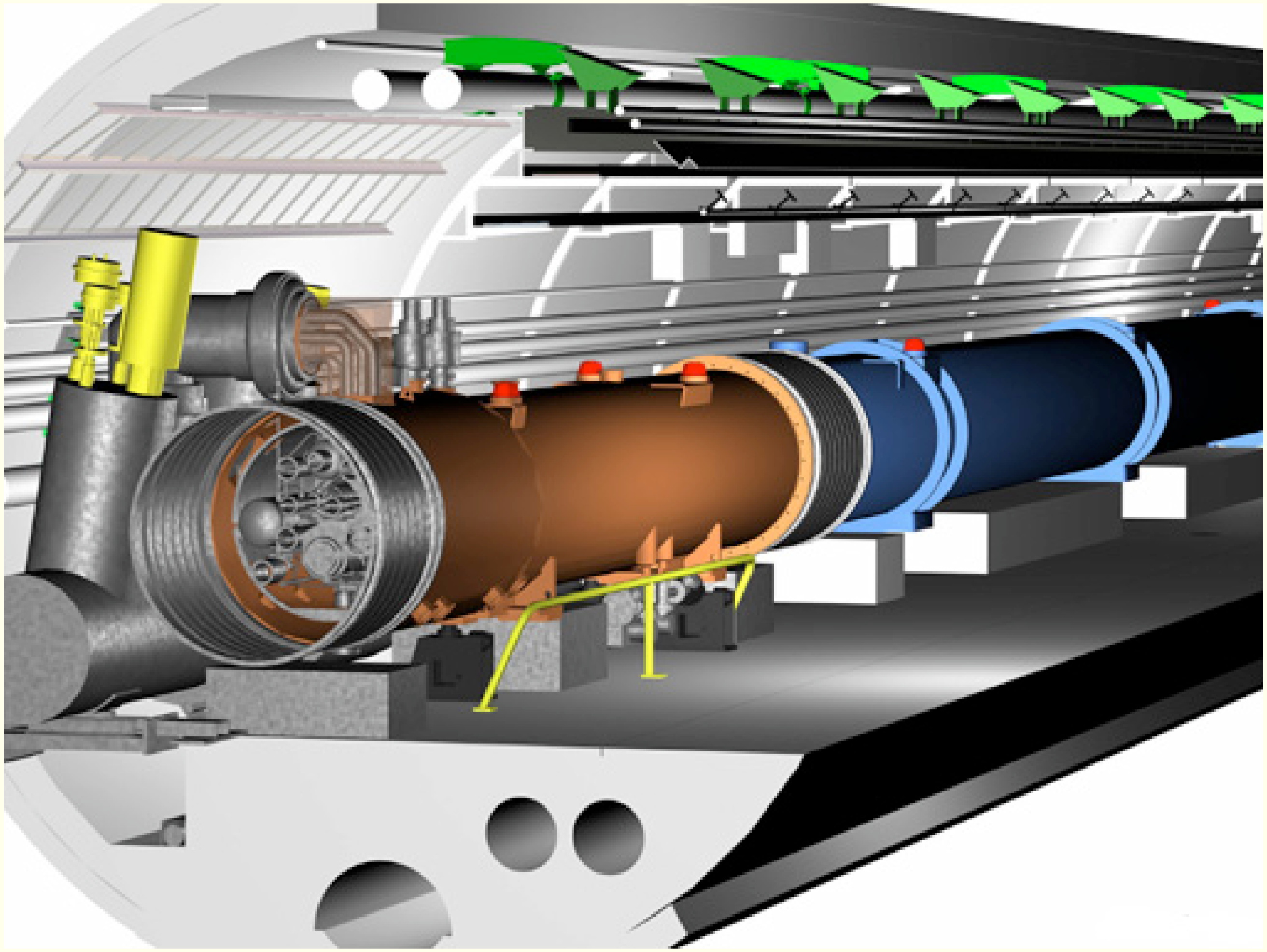
Energy Recovery Linacs



Linear Collider



Large Hadron Collider – CERN

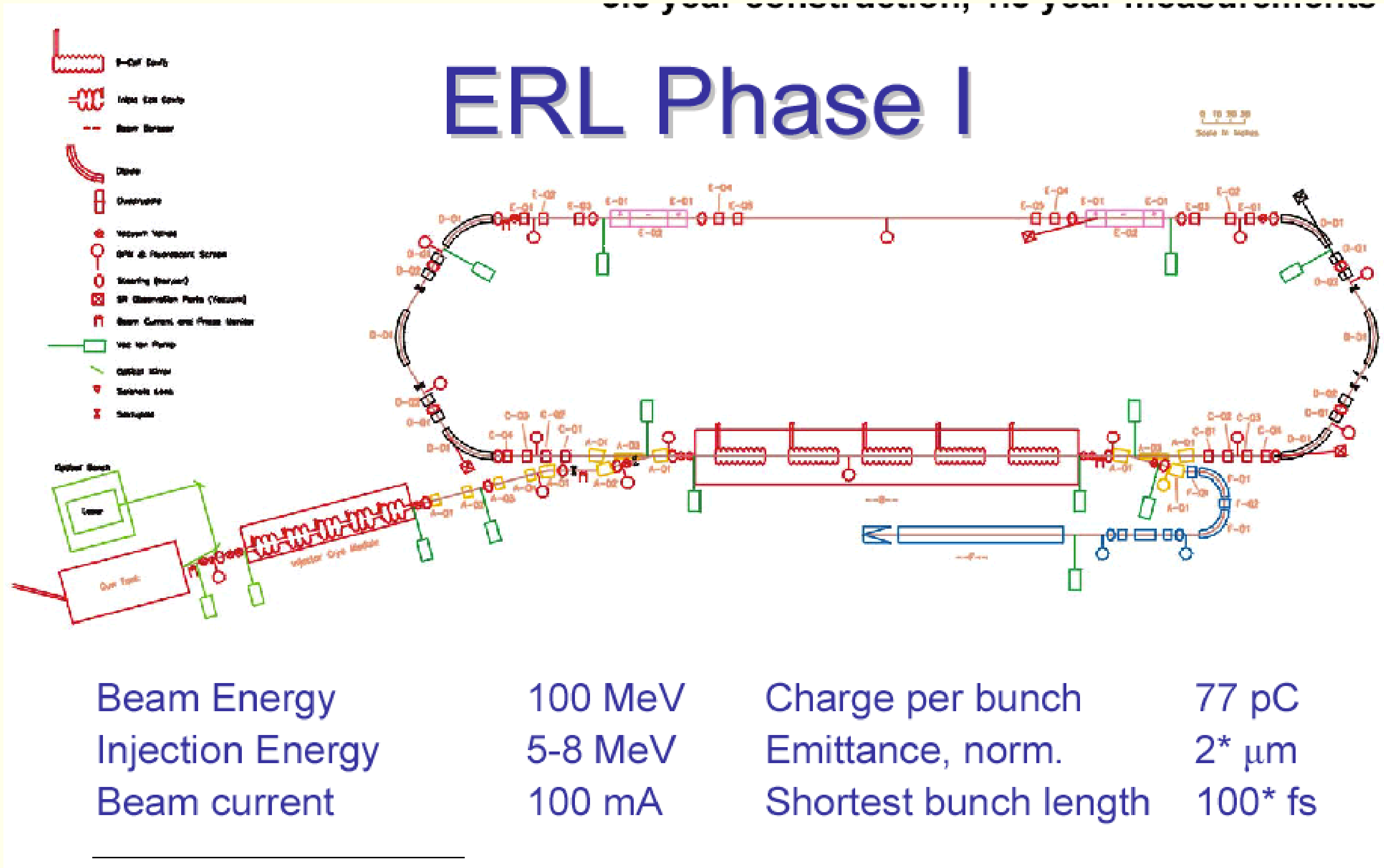


7 TeV Protons on
  7 TeV Protons

26 km Ring of
  Superconducting
  Magnets

Soon to begin
  operation in Switzerland and France

Energy Recovery Linac



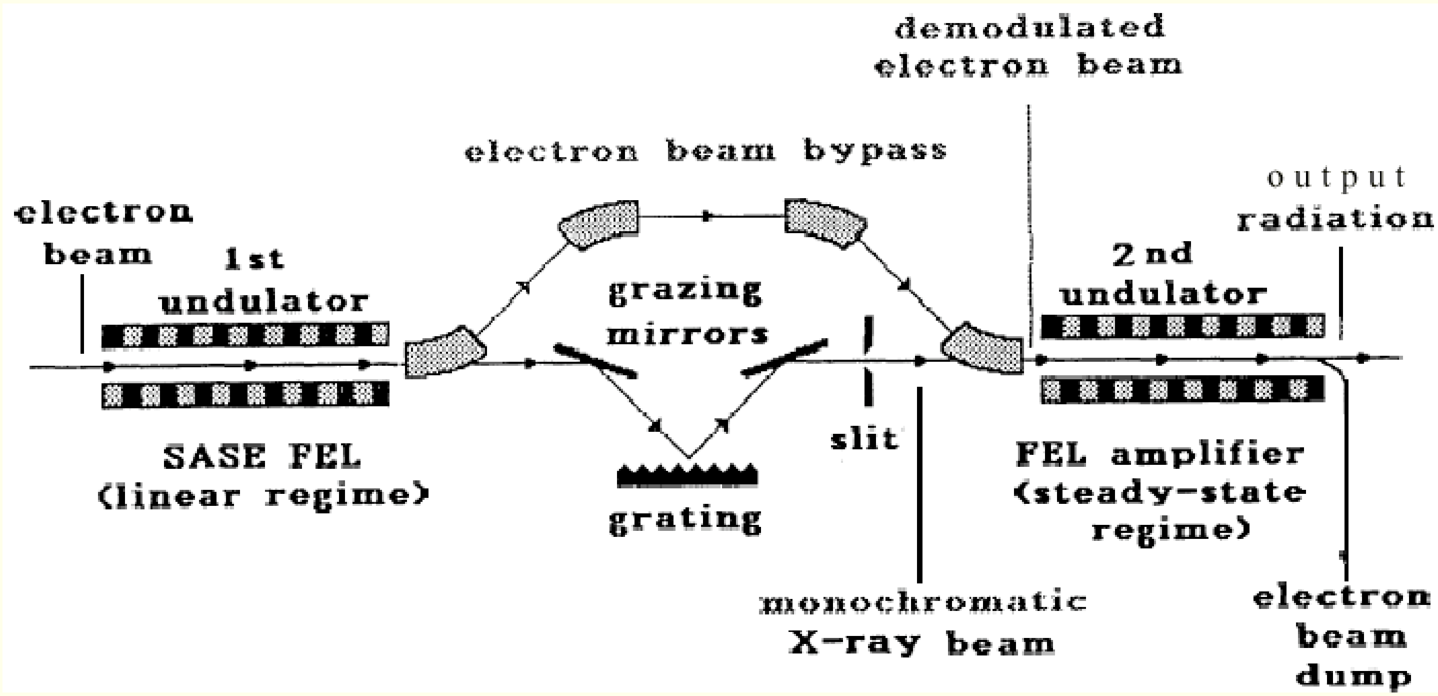
Compact Beam From Linac Accelerated in Superconducting RF cavities

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 wiggler 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

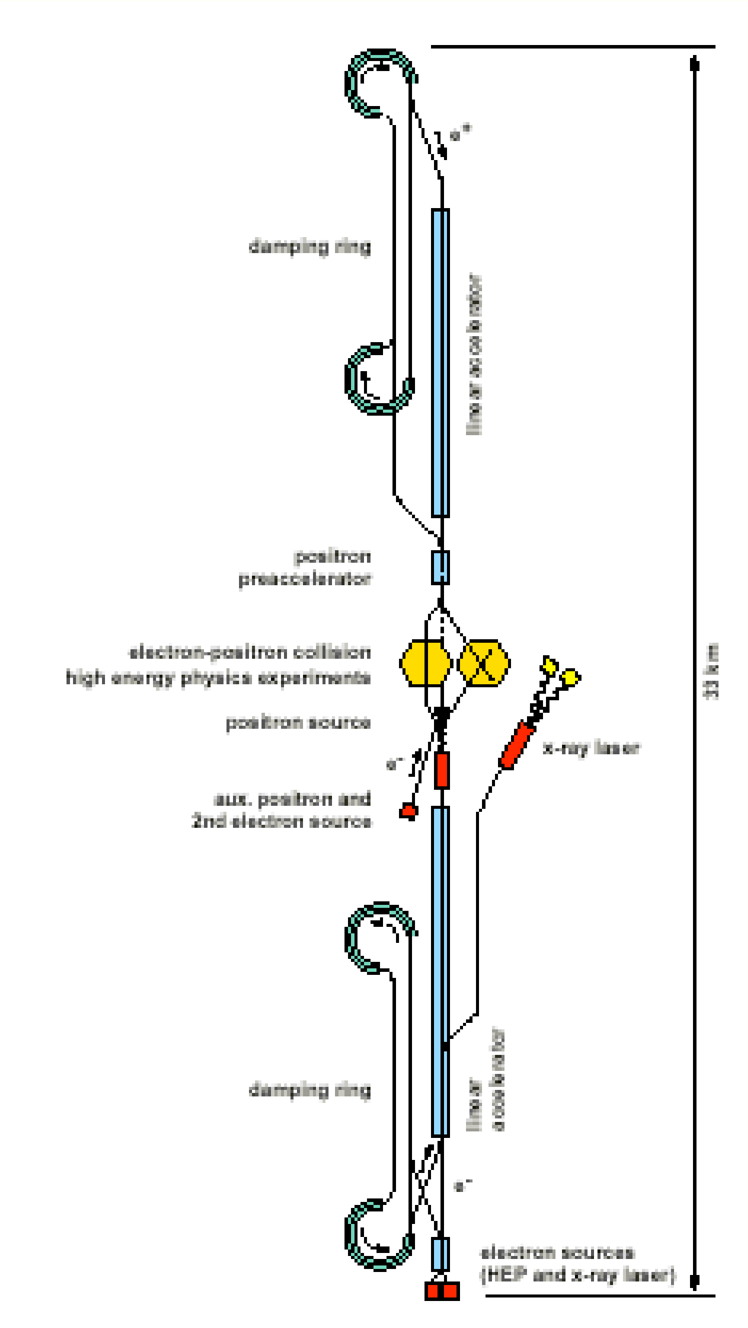
350 GeV Electron-Positron Collider

One Possibility is TESLA:

Two Linacs Pointed at each other

Two Damping rings to compress the transverse beam sizes

Uses Superconducting RF Accelerator Structures



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

"Accelerators and Beam Physics Group", CERN, http://slap.web.cern.ch/slap/

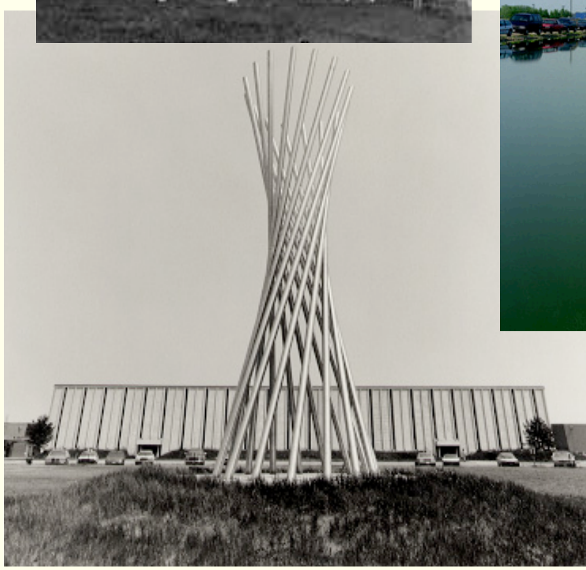
Special Thanks to

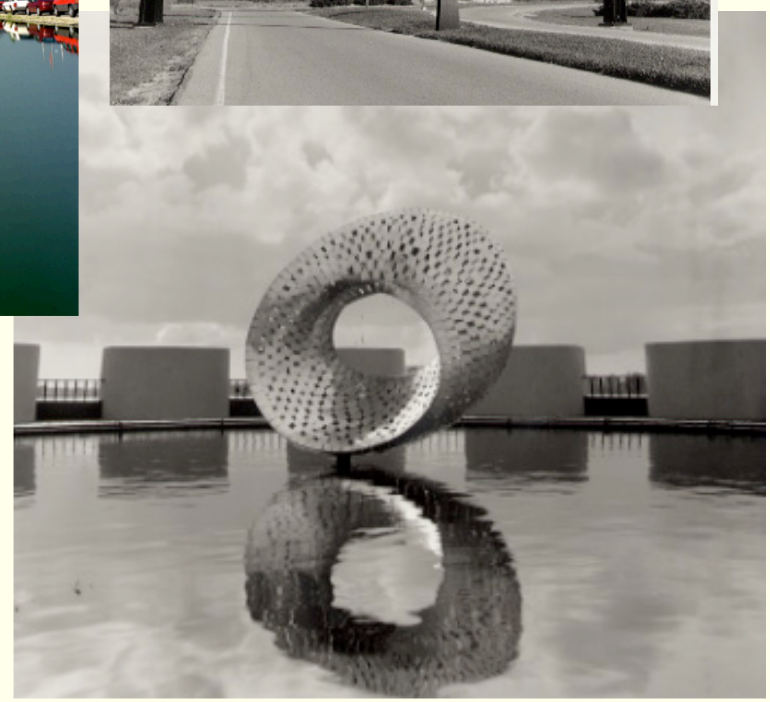
Georg Hoeffsteatter, Many excerpts from the first lecture in the undergraduate level course, Physics 456, "Introduction to Accelerator Physics and Technology"

Lora Hine, LEPP Education Outreach Coordinator

Reflection: Not All Accelerator Physics is Physics Alone

Some is Art





FNAL

Artist:

Robert R Wilson, Cornell & FNAL