Accelerators

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Accelerator Division

Saturday Morning Physics **October 14, 2006**

Saturday Morning Physics

2006 - 2007

October 7 – December 3, 2006

✔	Oct. 7	Particle Physics	R. Dixon	WH15 WH15 ACC	S. Desai S. Fu M. Wang
	Oct. 14	Accelerators	E. Harms	ACC ACC WH15	M. Weber M. Wobisch M. Datta
	Oct. 21	Detectors	M. Demarteau	DØ CDF KTeV	A. Golossanov S. Pranko M. Wobisch
	Oct. 28	Cosmology	M. Jackson	CDF KTeV DØ	K. Sato E. Ramberg A. Chou
	Nov. 4	Symmetry	C. Hill	KTeV DØ CDF	S.-S. Yu I. Bloch D. Mason
	Nov. 11	Relativity	R. Plunkett	FCC SiDet Mag Fac	C. Noeding P. Tan L. Uplegger
	Nov. 18	Quantum Mechanics	B. Dobrescu	SiDet Mag Fac FCC	F. Yumiceva J.H. Yoo B. Rebel
	Nov. 25	**NO Class - Thanksgiving Break**			
	Dec. 2	Anti-matter	B. Tschirhart	Mag Fac FCC SiDet	H. Meyer M. Ellis R. Eusebi
	Dec. 9	Physics & Society	E. Ramberg	GRADUATION	

Classes meet in One West

Lectures begin at 9:00 a.m. **Tours begin at 11:00 a.m.**

Class is **NEVER** cancelled!

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About the Speaker…

- Engineering Physicist, Accelerator Division
- Hometown: Edwardsville, IL (go Cardinals!)
  - born in Oakland, CA (go A's?)
- College:
  - Valparaiso University
  - such a great undergraduate education didn't immediately pursue graduate school
  - Fermilab - a great school for Accelerator Physics
    - people
    - facilities
- Work Experience:
  - Fermilab -- 27+ years
    - Operations (MCR)
    - Antiproton source
    - Superconducting RF & Photoinjector
    - LHC
    - **Outreach/Teaching**

email: *harms@fnal.gov*

Outline of Presentation

- Why do we need particle accelerators?
- How do we accelerate particles?
- How do we keep billions of particles all going around together?
- How do we use accelerators to do High Energy Physics experiments?
- Fermilab Accelerators and their Operation
- The Future

*Special Thanks to **Mike Syphers, FNAL/AD**, for preparing much of this talk!*

Why Do We Need Accelerators?

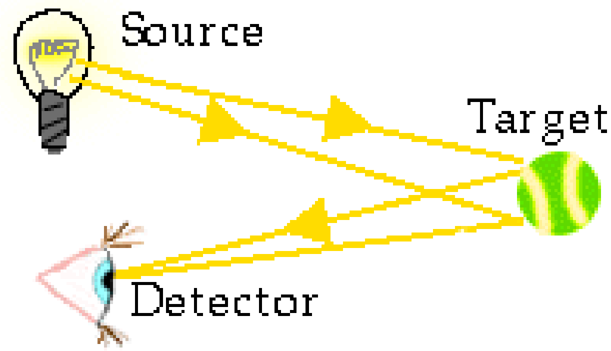
- Your parents might say otherwise, but you probably tell them you need these:

  TV's! (not LCD display or plasma TV, though…)
- Other 'needs' in everyday life might include
  - Medical applications: X-ray machines, etc.
  - Industrial applications
    - e^- beam welding, semiconductor modification, etc.
- In fact, a study in 1994* showed there were about 10,000 accelerators world-wide at that time:
  - only about **112** were used for 'High Energy' Physics!
  - ~5000 biomedical, ~4900 industrial
  - (does not include TV's! ;-)

*Scharf & Chomicki, *Physica Medica* XII(4), 1996.

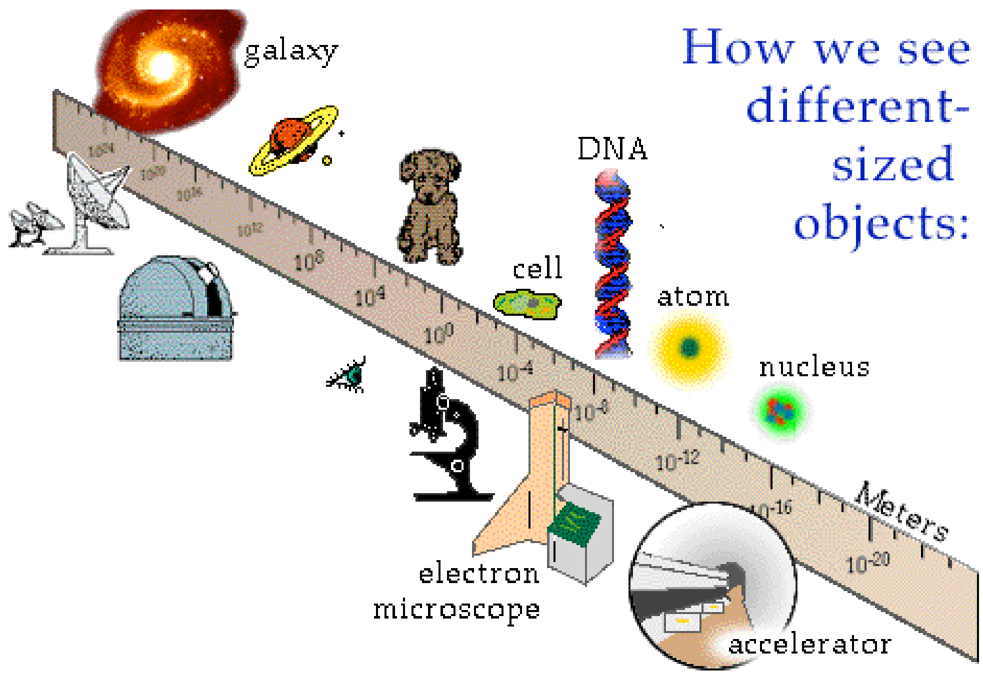
So, why Do *We* Need Accelerators?

- That is, why high energy particle accelerators, like at Fermilab?
- How do we "see" things?



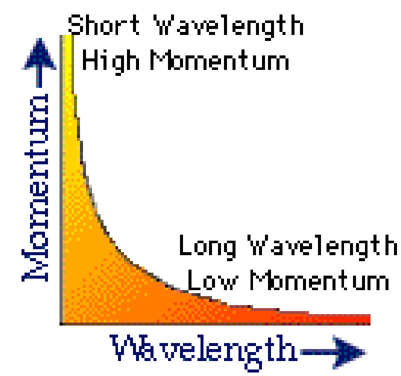
- We need to send source particles toward target particles and then detect the outcome. In two weeks, will discuss detectors; this week, we discuss how we generate our source (and, for the Tevatron Collider, the target as well!)
  - OK, so why do we need *High Energy*?

Wave-Particle Duality of Nature



DeBroglie showed that moving particles have an equivalent wavelength,

$$\lambda \propto \frac{1}{p}$$



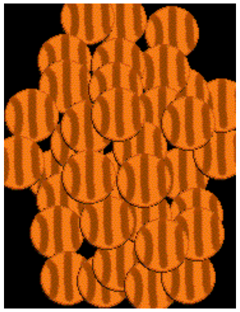
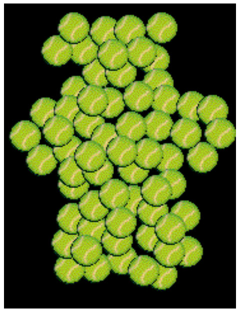
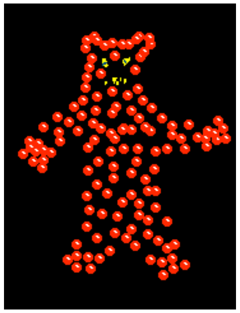
Plus, add a little bit of Einstein's work:

$$E^2 = (mc^2)^2 + (pc)^2$$

So, high energy gives us high momentum which gives us short wave lengths so we can make out small detail

So, why Do *We* Need Accelerators? (cont'd)

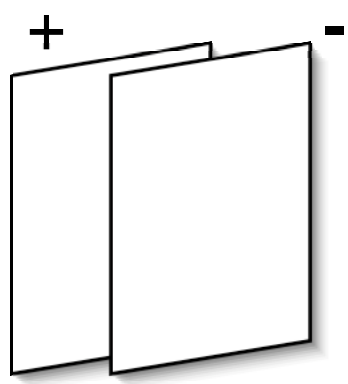
- High energy gives us small wavelength probes, thus *finer* detailed information

- Suppose you wanted to actually "see" an object. You can begin by firing a single photon (particle of light) at it, and see what you detect. The photon may "reflect" and give you a signal that something is there, or it could miss the object completely (since you don't know where or what it is). Firing one photon at a time, it would take a very long time to detect the person next to you (and to realize it was a person!).
- So, we obviously want to fire many particles at a time toward our *target* in order to *illuminate* it and to detect sufficient detail within a reasonable amount of time.
- In addition to a large number of particles, we also want the ability to control the particles (steer, focus, increase/decrease intensity, for instance) in order to conduct experiments efficiently and in a controlled fashion.
- And finally, through $E=mc^2$, ability to create new particles (mass) from energy!

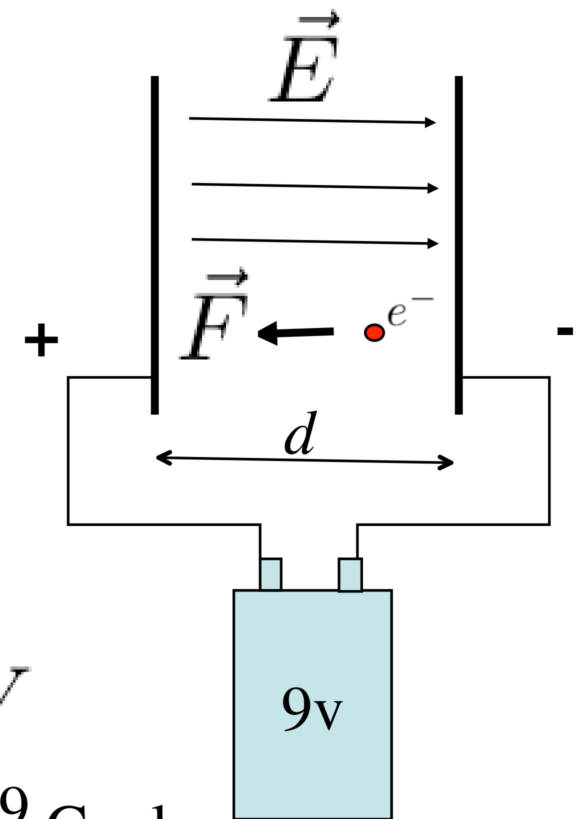
How to Accelerate Particles

How to Accelerate Charged Particles



$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$



As the electron accelerates from the right hand plate to the left, the change in energy is the work done,

different E!

$$\Delta E = F \times d = qV$$

The charge on an electron is $q = -e = -1.6 \times 10^{-19}$ Coul

(on a proton, $+1.6 \times 10^{-19}$ Coul $= +e$)

So, we say that an electron/proton accelerated through 1 volt gains an amount of energy ΔE = 1 eV (1 **electron volt**) (= 1.6×10^{-19} J)

In example above, the electron would gain energy of amount 9 eV.

How fast is this electron moving?

If started from rest, $\Delta E = \frac{1}{2}mv^2$, and so $v = \sqrt{2\Delta E/m}$

$$= \sqrt{2 \times 9(1.6 \times 10^{-19} J)/(9 \times 10^{-31} kg)} = 1.8 \times 10^6 \text{ m/s!}$$

This is 4 million miles/hr ! = 0.6% the speed of light (0.006*c*)

(*c* = 186,000 miles/sec = 300,000,000 m/sec)

Note: if looked at a proton instead, its mass is 1836 times that of the electron. Thus, its speed would be *only* 0.00014*c*.
(= 90,000 mi/hr!)

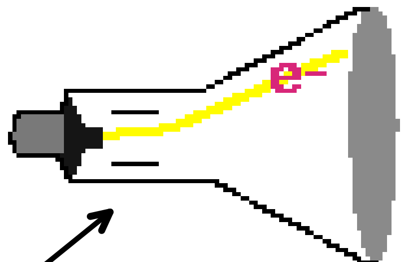
Q: How much voltage can we deliver?

Let's look at a TV set...

Your TV Set

- The "classic" television is a **Cathode Ray Tube**

heated *filament*, electron source (*cathode*)



phosphorescent screen which lights up when struck by electrons

electromagentic fields to ***accelerate*** and steer the electron beam (*ray*)

evacuated glass container (*tube*)

OK, so it's a *little* more than that…
but not much! *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10 keV**!

So, how fast are we moving now?

- An electron in a typical TV set, with **10 keV** kinetic energy, say, would thus be moving about

  $(10{,}000\ \text{eV} / 9\ \text{eV})^{1/2}$ = 30 times faster, or about **0.2*c***.
- Does this mean a 50 keV electron would be moving at the speed of light? 100 keV, *2* x *c* ???
  - No! "Relativistic effects" kick in…
    - Will see much more of this in a subsequent class (scheduled for Saturday, November 11!)
  - Relativity (*near the speed of light*) plays a big role in high energy particle acceleration -- for now, look at some relativity *basics* useful for particle accelerators…

Relativity in Action

Einstein said $E = mc^2$, but this strictly is the "rest energy" for a particle sitting still, with rest mass m. When in motion, its total energy is

$$E = \frac{mc^2}{\sqrt{1-(v/c)^2}}.$$

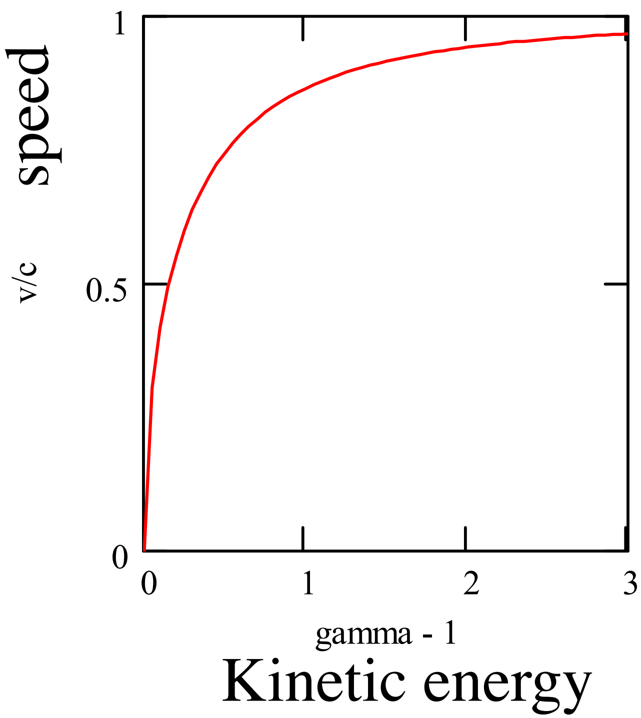
When $v \ll c$ this amounts to $E = mc^2 + \frac{1}{2}mv^2$. But, as the energy of the particle is increased, it's speed approaches (but never reaches!) the speed of light:

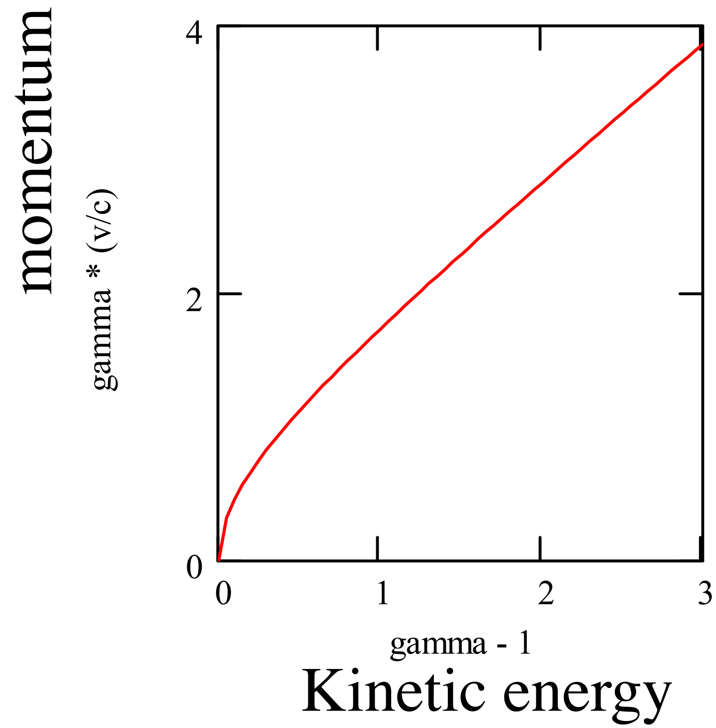
$$v = c \cdot \sqrt{1-\left(\frac{mc^2}{E}\right)^2}$$

- In High Energy Physics, the ratio E/mc^2 is often denoted by the symbol γ (gamma), and so

  $E = \gamma\, mc^2$ is the total energy.
- Similarly, the total momentum is defined as $p = \gamma\, mv$.

Speed, Momentum vs. Energy





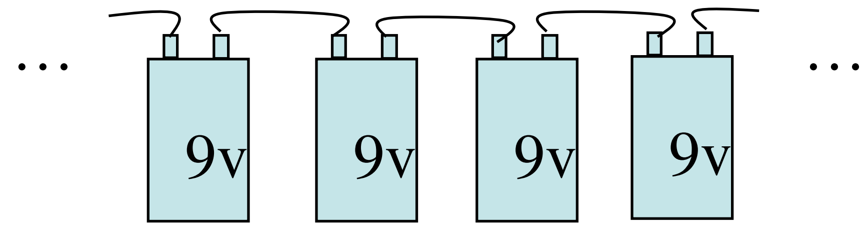
Electron:	0	0.5	1.0	1.5	MeV
Proton:	0	1000	2000	3000	MeV

mc^2:

e-	0.5 MeV
p	938 MeV

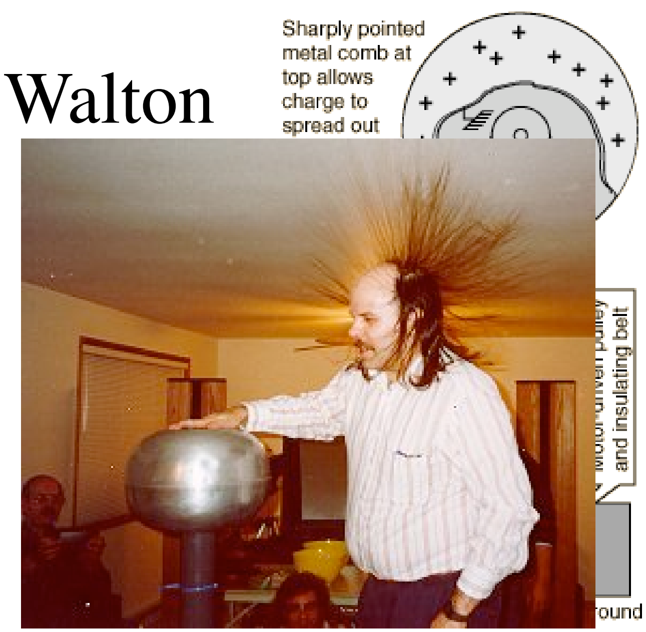
So, Back to High Voltage!

- How to get **high voltage**? How high can we go?
- String a bunch of batteries in series!
  - Not very practical…



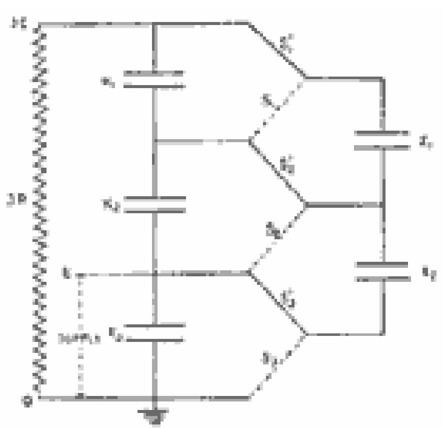
- High voltage Generators
  - Ex: van de Graaf, Cockcroft and Walton
- The ***van de Graaf*** Generator:
  - probably familiar …
  - static electricity

  (as shown -- 75,000 V!)

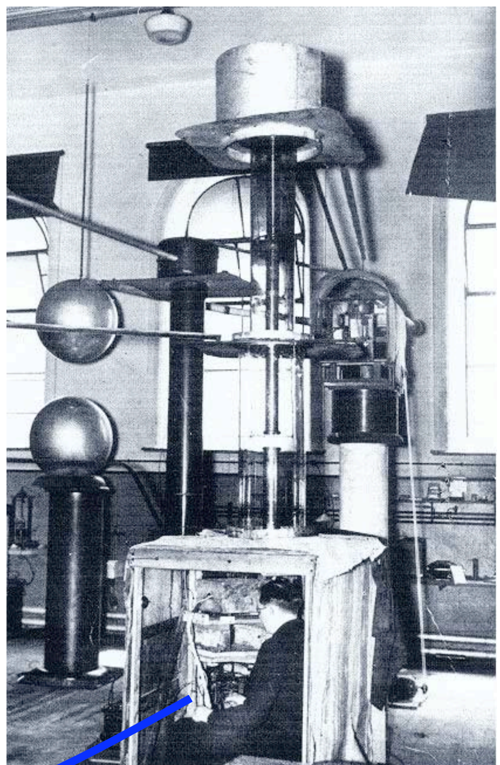


High Voltage

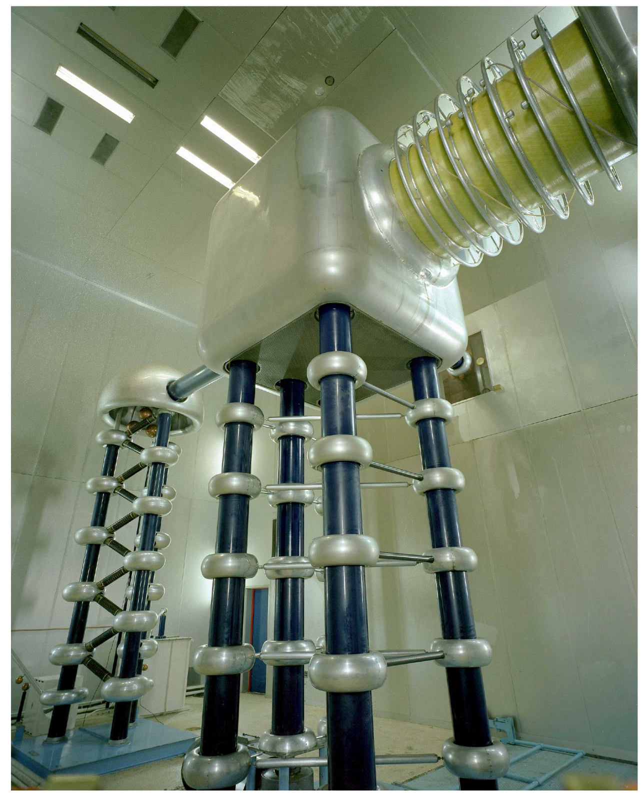
- van de Graaf's are used for particle accelerators (though, with a different configuration) and provide voltages up to ~10,000,000 V = 10 MV.
- Fermilab has a related device, called a Pelletron, which works on the same principle; produces electron beams with energies of about 4 MeV.
- Another device was developed in early 1930's by *Cockcroft and Walton,* and is named after them:



Converts AC voltage V to DC voltage n x V

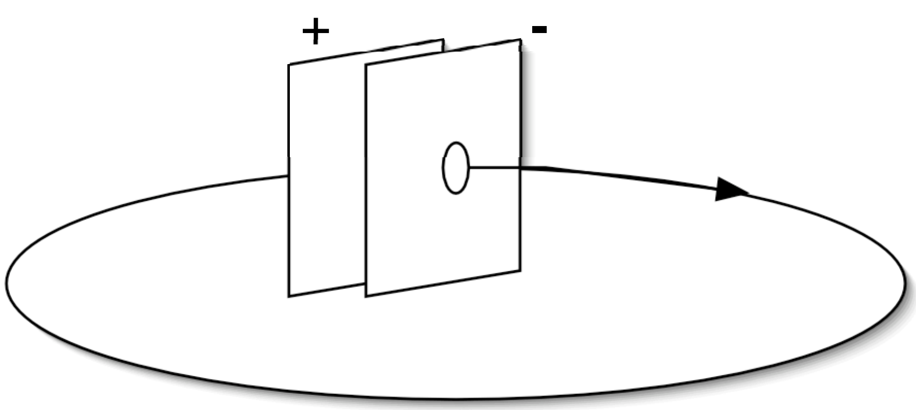


Is that Cockcroft, or Walton??



Let's Re-use the E-field!

- The Cockcroft-Walton design can produce voltages up to a few MV, and the van de Graaf up to about 10 MV; at these voltages, materials begin to experience "high voltage break-down"
  - Takes only a few MV to generate lightning
- So, to continue to higher particle energies, would like to re-use the electric fields we generate:



BUT! If the voltage is DC, then though particle is accelerated when in between the plates, it will be *decelerated* while outside the plates!
-- *net acceleration* = 0 !
SO, need a field which can be switched on and off -- an AC system!

The Cyclotron

- A charged particle in a magnetic field, B, moves in a circular path of radius r at a speed v. The time to orbit once is

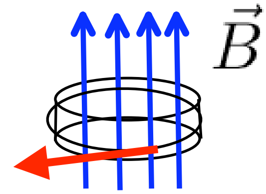
  $T = 2\pi r/v.$
- The force due to the magnetic field is

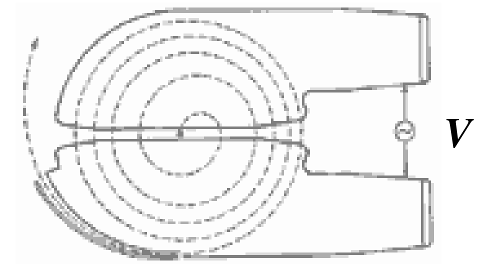
  $F = evB$
- The centripetal force is

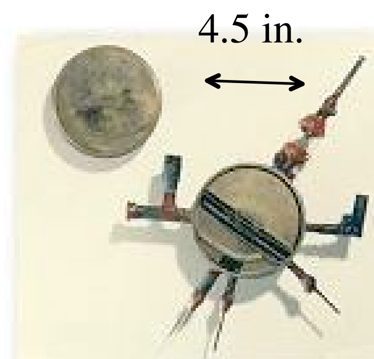
  $F = mv^2/r$
- Equating these, we find $r/v = m/eB$
- And so, $T = 2\pi m \,/\, eB$

Now, put a metallic chamber into the magnetic field, and split it in two...

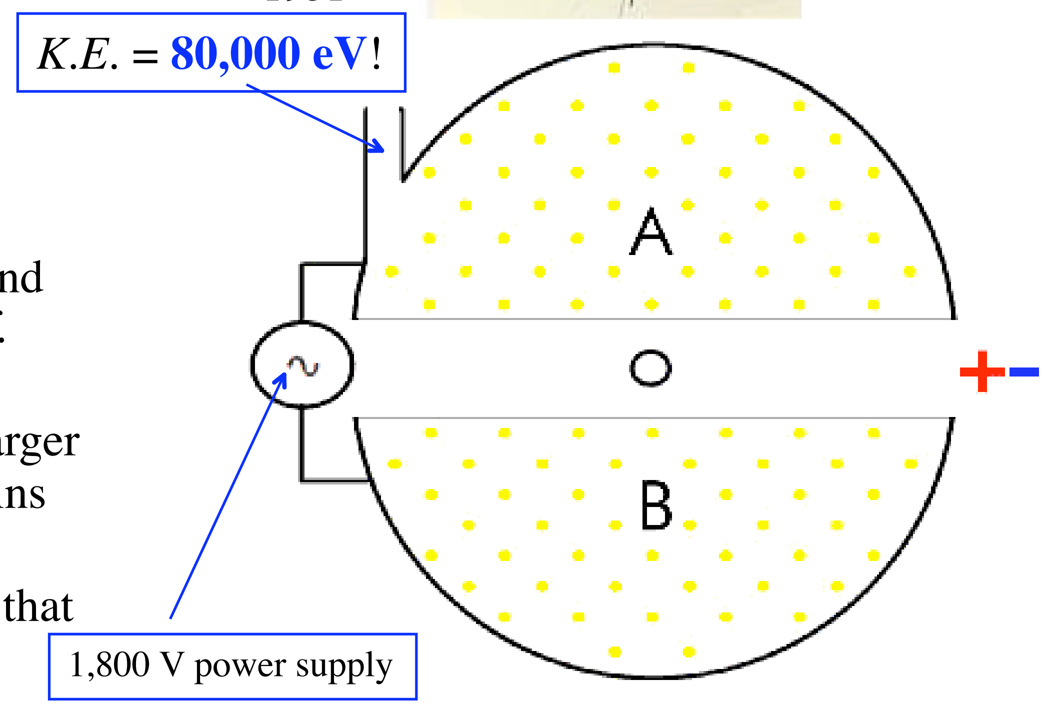
- Apply a voltage with a frequency f and adjust the magnetic field until $T = 1/f$.
- As the particle passes the gap, it gets accelerated, circulates on a slightly larger orbit, but the time to go around remains fixed.
- Eventually, the orbit gets big enough that the particle leaves the device.







E.O. Lawrence, 1931



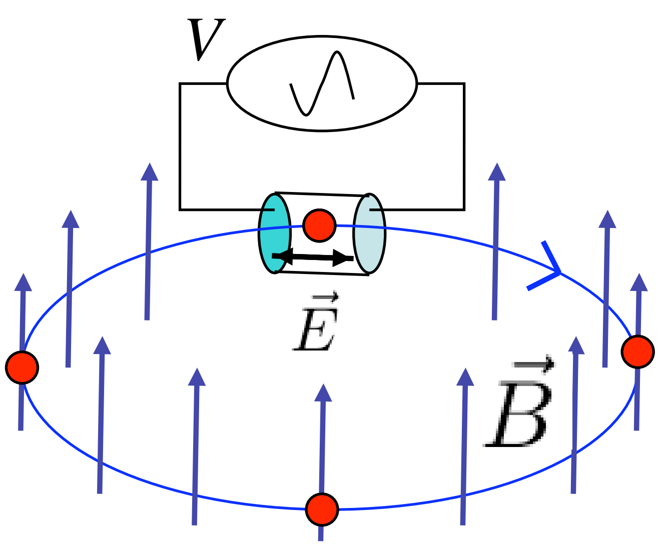
60-inch Cyclotron, Berkeley -- 1930's

Circular Accelerators

- Since the entire cyclotron had to be in a magnetic field, the magnets would become very large.
- Also, as the particles continued to accelerate, their speeds would begin to approach c, and thus they would not keep in step with the changing voltage.
- "Synchrocyclotrons" were invented to try to take these effects into account, as well as other types of accelerators -- betatron, microtron, …
- But the one that won out, when it came to very high energy particle beams, was the ***synchrotron***.

The Synchrotron

- Use a single device which develops an electric field along the direction of motion, and which oscillates at a tunable frequency.
  - A simple 'metal can' may do this, for instance, if powered correctly
- Use a series of tunable electromagnets whose strength is adjusted to keep the particle(s) on a circular orbit back to the accelerating device (cavity).



Voltage = $V \sin(2\pi f\, t + \delta)$

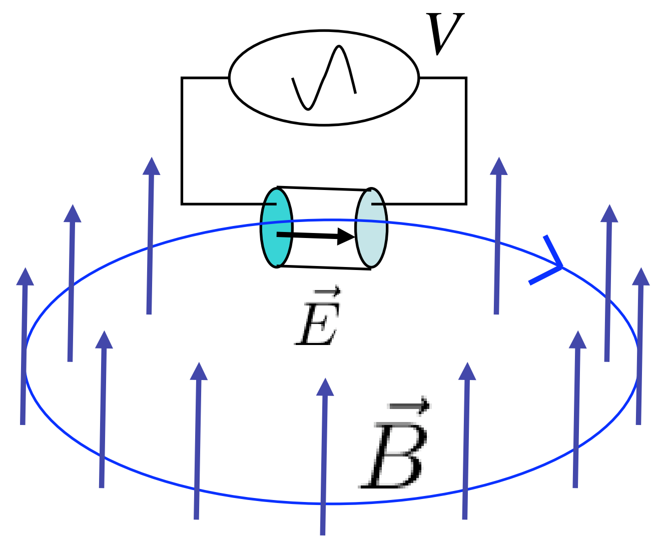
$f = 1/T = v\, /\, 2\pi R$

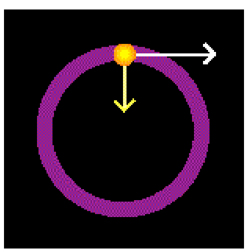
Each revolution,
energy changes by amount
$\Delta E = e\ V\ \sin(\delta)$

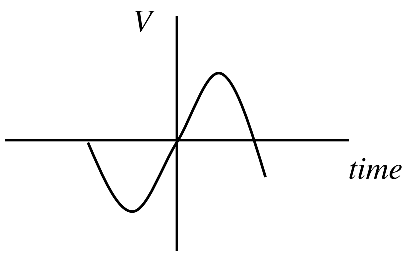
δ is called the *synchronous phase angle*

Synchrotron (cont'd)

- If the magnetic field is slowly increased, the particle will not have enough momentum to keep on the same orbit; thus it will arrive at the cavity later than desired.
- However, this results in giving the particle more voltage! It will be accelerated by the cavity enough to keep its average momentum in step with the magnetic field and keep the average orbit radius constant:







$$mv^2/R = evB$$

$$\Longrightarrow R = mv / eB$$

$$= p / eB$$

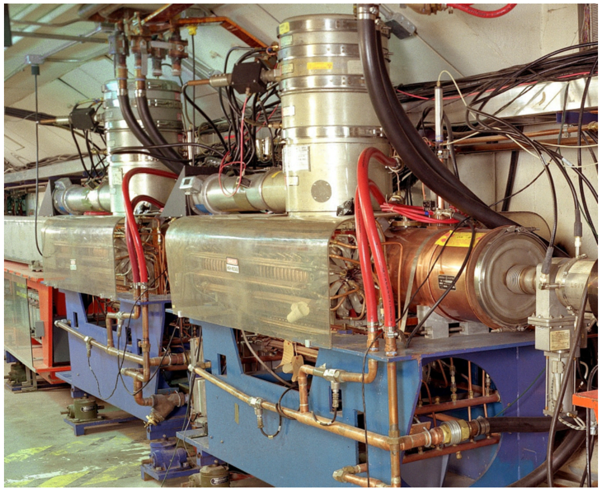
And as the particle speeds up, the frequency of the cavity must change in step ("in sync")

thus, we use RF cavities and power sources...
FM Radio Stations: 88 - 108 MHz!

What frequencies do we need?
Let's say v ~ c,
and say R = 1 m
then,
$f = v / 2\pi R$
$= (3 \times 10^8 \text{ m/s}) / (2\pi \text{ 1m})$
$= 5 \times 10^7 / \text{s} = 50 \text{ MHz}$

Radio Frequency Cavities

- The Radio and RADAR industries, in 1940-50's, developed a lot of technology which could be used in the particle accelerator business.
  - A simple "pillbox-like" cylindrical cavity, with radius a, has a natural frequency $f_{nat} = 2.4c / 2\pi a$.
  - For $f_{nat} \sim 50$ MHz, we see $a \sim 2$ m. Could make this, but is rather big... So, we design other cavity "structures" which are more compact, but which have similar natural freq's

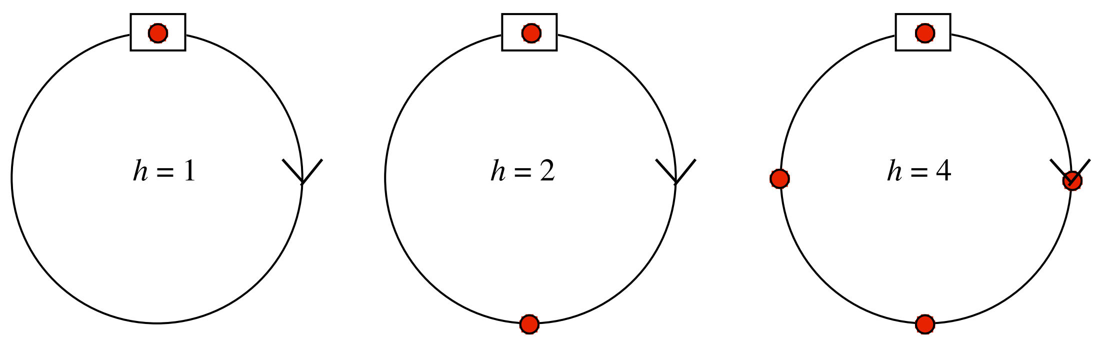


A 53 MHz cavity used in the Fermilab Booster synchrotron.

A 106 MHz cavity used in the Fermilab Main Injector synchrotron.

Radio Frequency Cavities

- Radio frequencies are used, even for very large circumference accelerators, by developing "bunches" of particles
  - If the RF cavity frequency is twice the revolution frequency, then there can be two bunches sustained in the synchrotron. If $f_{rf} = h \times f_0$, then there can be h bunches.



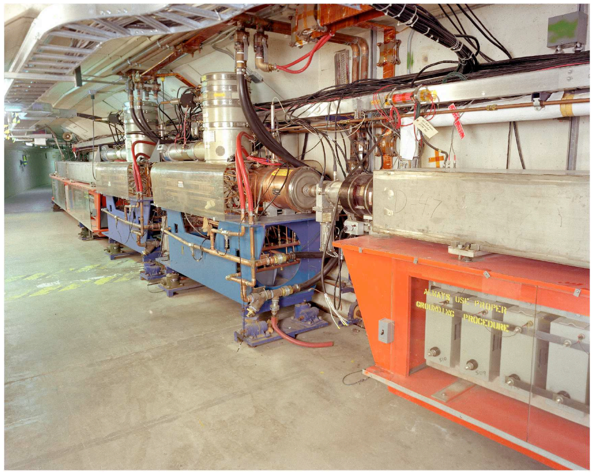
  - Most common frequency at Fermilab (though others are used) is 53 MHz.

Synchrotrons at Fermilab

Booster

$R = 75$ m

$h = 84$



All use 53 MHz systems

h = # possible ‘bunches’ in the accelerator

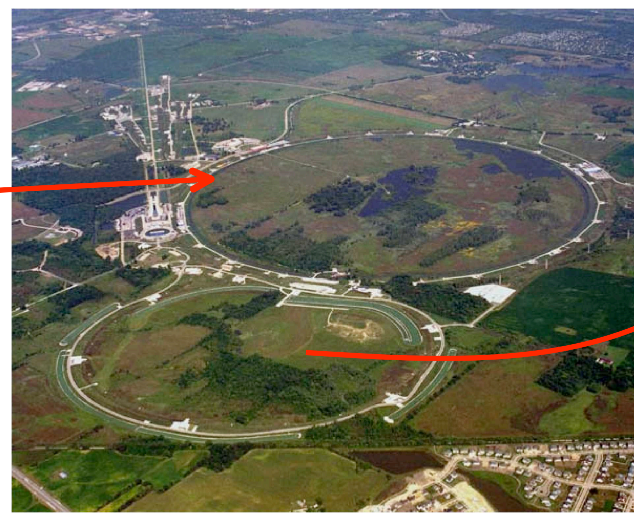
$R = 500$ m

$h = 588$

Tevatron

$R = 1000$ m

$h = 1113$



Main Injector

Will see more details later in this talk…

How to Deflect Particle Trajectories

In addition to accelerating the particles, we wish to steer their trajectories...

- Electric Forces too weak at high energies; need to use magnetic fields to alter trajectories.

$$\frac{F_{magnetic}}{F_{electric}} = \frac{evB}{eE} = \frac{vB}{E} = \frac{(3 \times 10^8 \ m/sec)(2 \ Tesla)}{10 \times 10^6 \ V/m} = 60$$

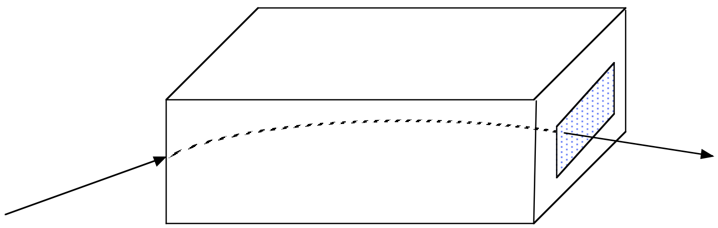
- What about Gravity?? Look at a proton…

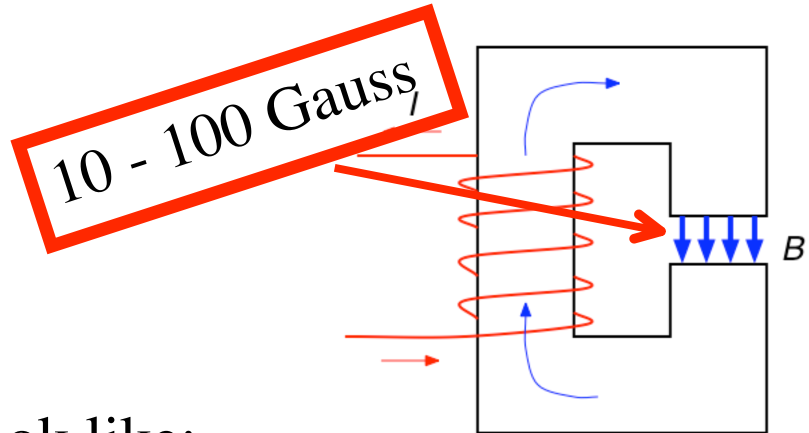
$$\frac{F_{gravity}}{F_{electric}} = \frac{mg}{eE} = \frac{(1.67 \times 10^{-27} \ kg)(9.8 \ m/s^2)}{(1.6 \times 10^{-19} \ C)(10 \times 10^6 \ V/m)} = 10^{-14} \quad !!$$

  – Not even a *player*!

Accelerator Magnets

- To steer the particles, we need to use strong magnetic fields -- electro-magnets:



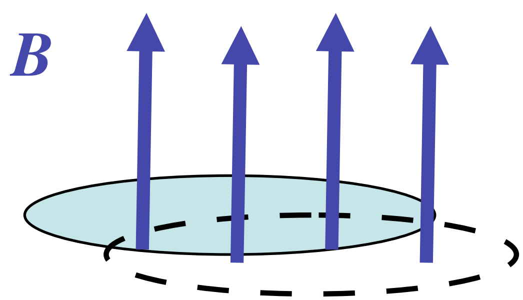


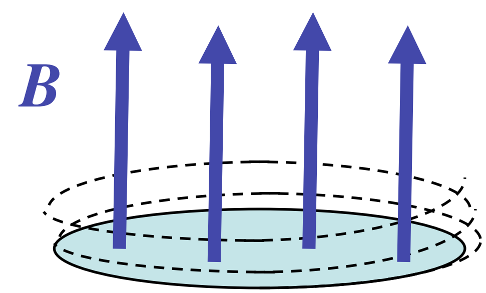
  - A simple electromagnet might look like:
  - Accelerator magnet:
    - lots of current and lots of iron!
      - Iron-dominated magnets can obtain field strengths up to ~2 Tesla

The Need for Focusing

- Particles move in circular orbits when in a uniform magnetic field
- What happens if we deflect a particle as it is going around?
- Deflections in a Uniform magnetic field:

Horizontal -- stable   Vertical -- NOT -- spirals away!

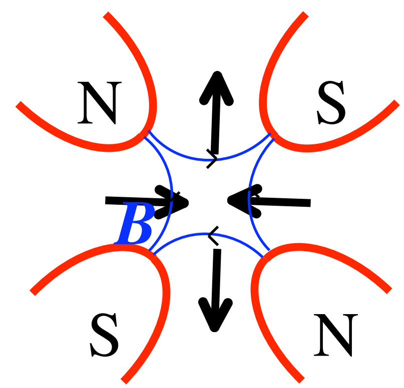




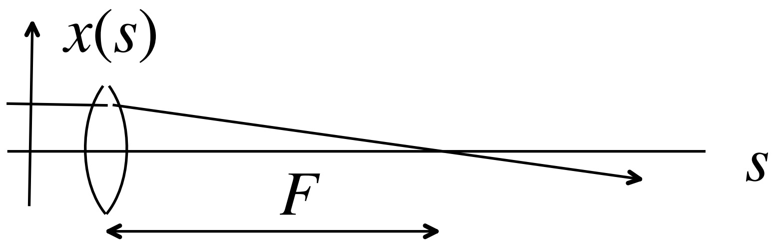
- Also, large number of particles in a real beam start out heading in every which direction!   (sort of like a flashlight beam, spreading out away from the source)

Focusing

- So, as particles move around the accelerator, we need to use other electromagnets to steer and focus them
- Arrangement of focusing magnets, much like lenses, keeps the particle beam contained…
  - Focusing lens: a "quadrupole" magnet:
  - Since $\underline{F} = e\underline{v} \times \underline{B}$, then this magnet will focus in one direction (L/R), but will defocus in the other (up/down)



(particles coming out of the page, say)



So, ***alternate*** lenses: + - + - + - …

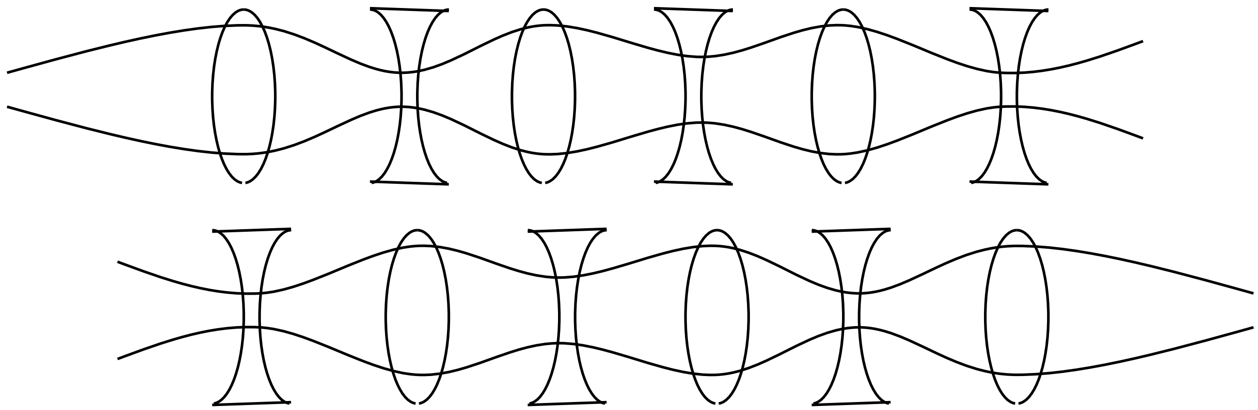
End up with net focusing both L/R and U/D

Alternating Gradient Focusing

- By alternating the polarity of the Quadrupole magnets, they serve to alternately focus and defocus the beam, keeping it stable in all directions simultaneously

Left/Right

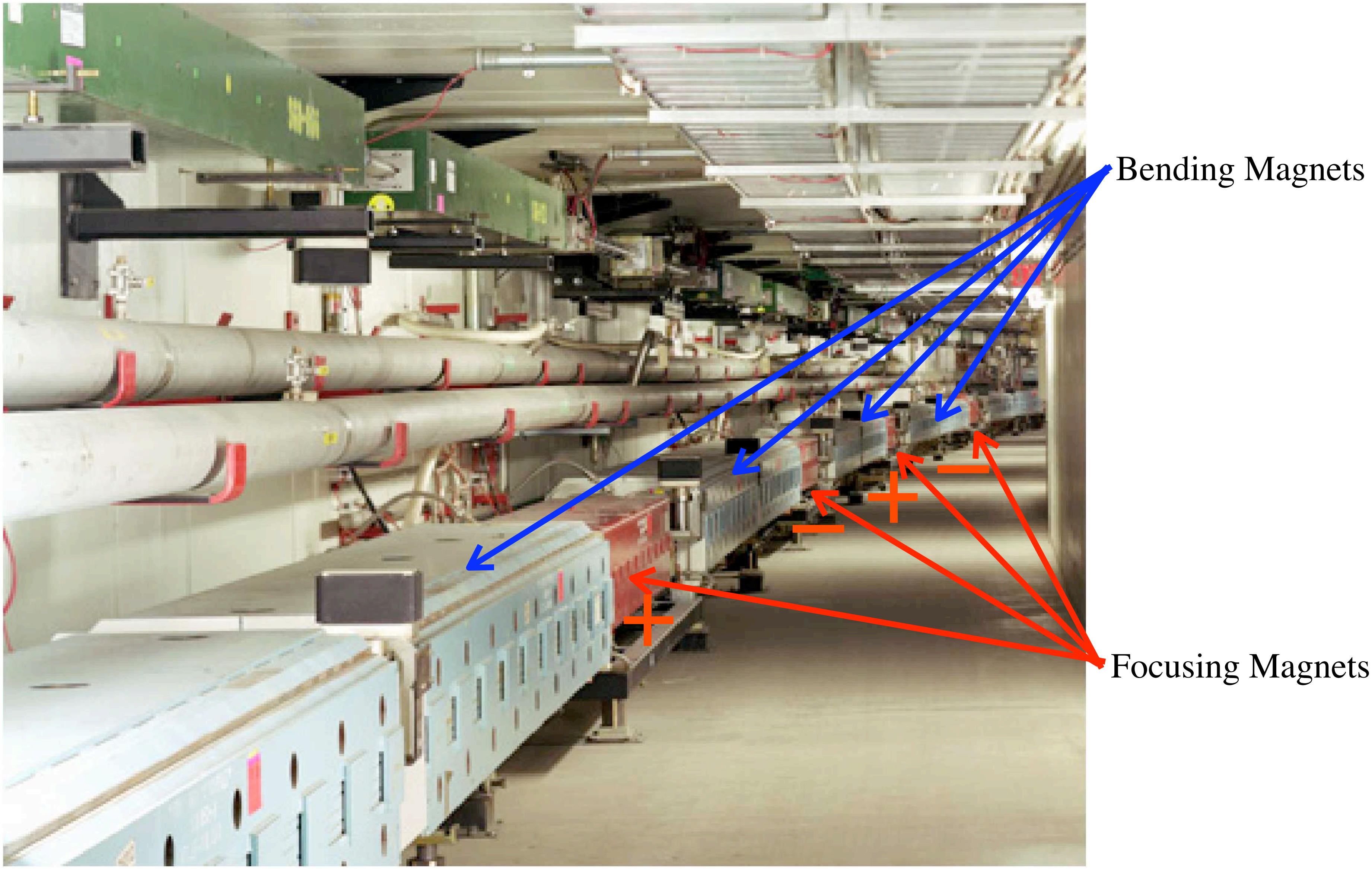
Up/Down



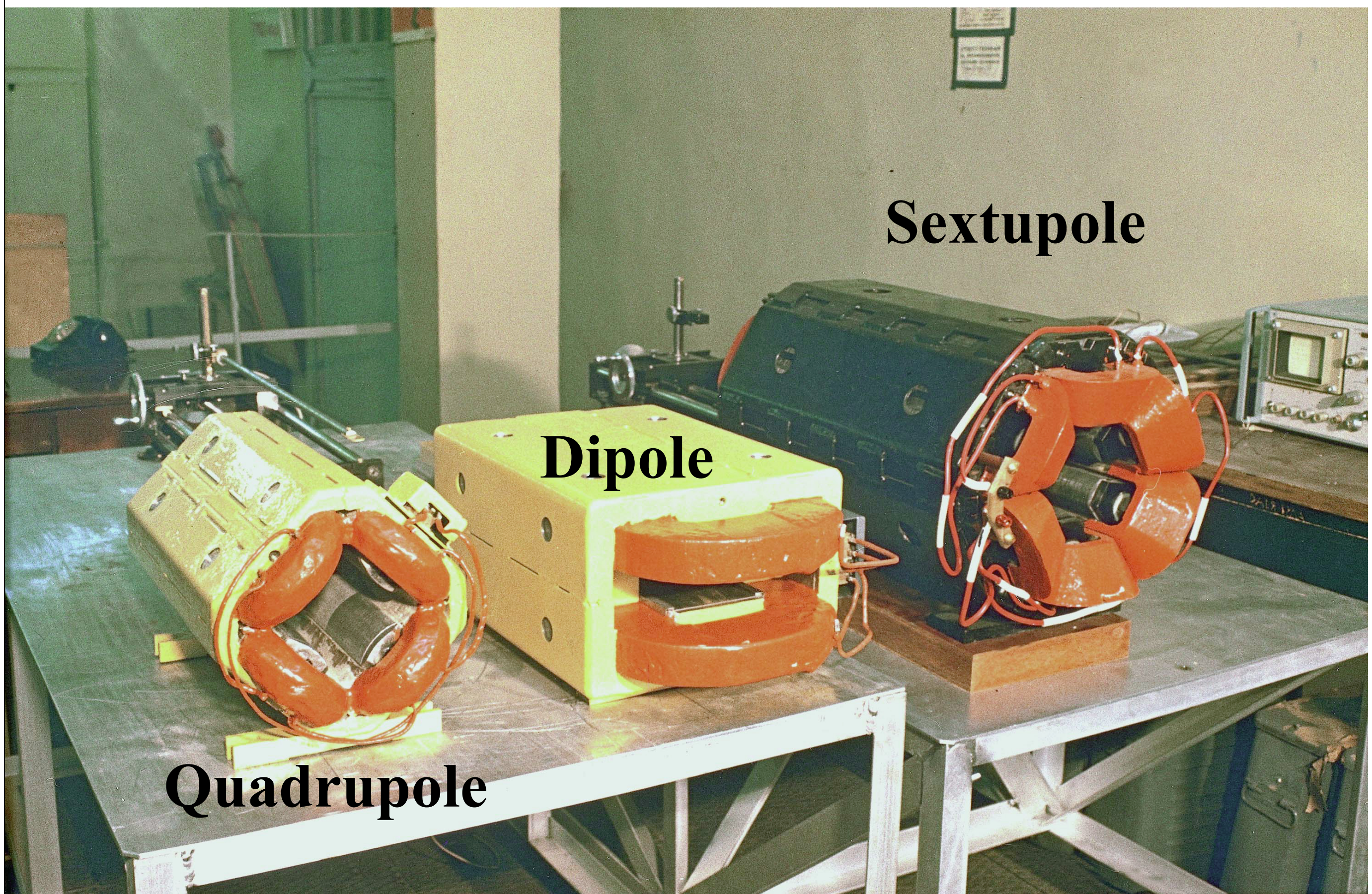
Smaller magnets are used to fine-tune the beam trajectory, and to perform special orbit manipulations

- – Note: The beam in the Tevatron, for example, is only ~1 mm wide! Its orbit is controlled to a fraction of a mm! Yet, the orbit itself is 6.28 km (4 mi) around!

Example: Fermilab Main Injector



Iron-Dominated Magnets



Dipole used for steering particles to keep them on a central orbit.

Quadrupole focuses particles towards the central orbit in one plane … but defocuses in the other plane.

Sextupole is used to keep off-energy particles close to the desired orbit.

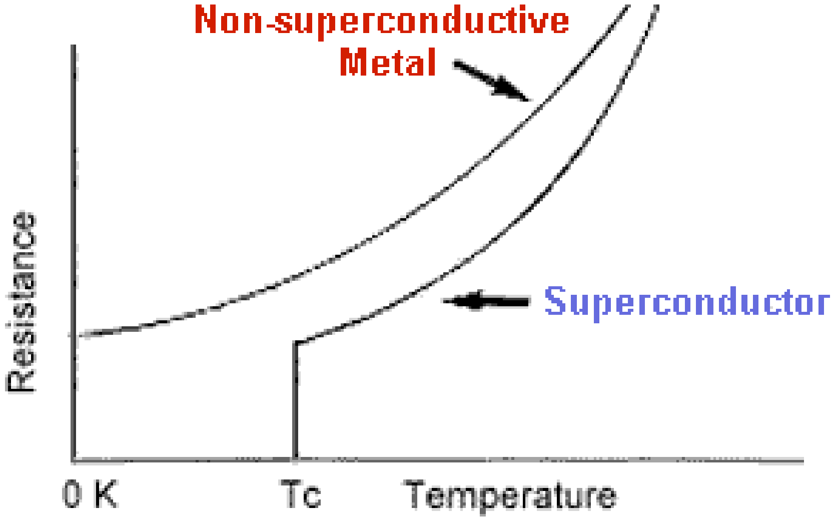
Iron: fields limited to about 2 Tesla (20,000 gauss)

Superconductivity

- Discovered in 1911 by Dutch physicist Heike Kamerlingh Onnes of Leiden University

- Certain metals and alloys, when cooled to low temperatures, offer no resistance to the flow of electrical current -- ***superconductors***

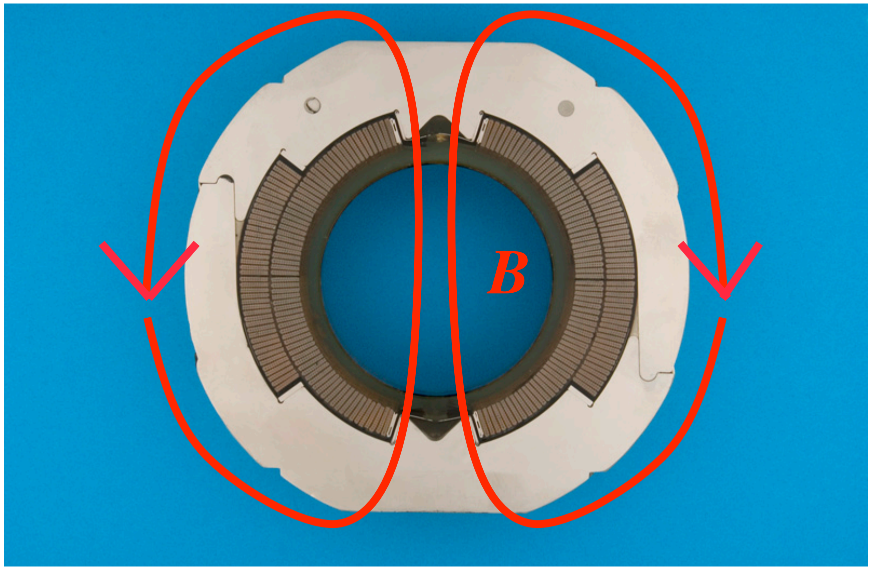
- Took many years to understand, and to perfect the production of superconducting materials suitable for commercial use

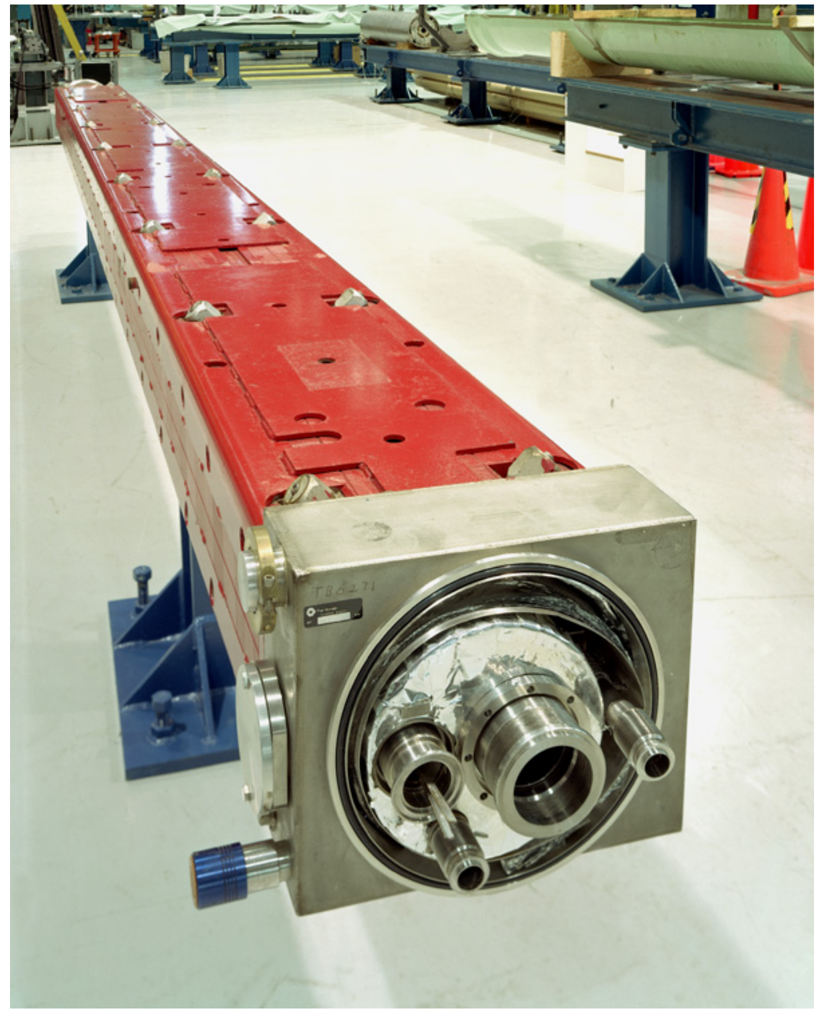


Superconducting Accelerator

- The Tevatron at Fermilab was the first synchrotron making use of superconducting materials in its magnets
  - Generate the field by placement of conductor, not by saturating iron; thus, can go to higher fields, higher particle energies
  - Can keep the fields turned on with practically no additional electricity costs
    - Thus, can make a very cost effective "storage ring" -- ***colliding beams***!
  - The "critical temperature" for the Tevatron's superconductor is about 4 ^{O}K = -450 ^{O}F !
    - Liquid Helium Cryogenics Refrigeration System -- ***the world's largest!***
    - So, while no resistance in the superconductor, still have to pay for keeping the magnets cold! But overall operating cost is still lower.
- Future large-scale (and, some smaller scale!) accelerators are now using this technology

Superconducting Tevatron Magnet





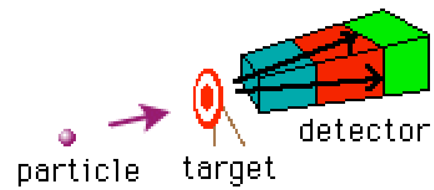
- Outside is at room temperature;
  inside is at 4^{O}K!
- Field is **4.4** Tesla @ ~4,000 A
- Each magnet is ~20 ft long,
  and weighs about 4 tons
- ~1000 magnets in the Tevatron
  (~800 dipoles, ~200 quadrupoles)

How Accelerators are Used at Fermilab

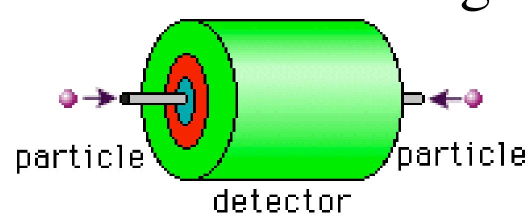
(after the break?)

Fixed Target Experiment
vs.
Colliding Beams Experiments

- Originally, Fermilab conducted its experiments by accelerating particles to high energy, and then directing them toward a target (piece of metal, say) and observing the products. This is called a 'fixed target' experiment.

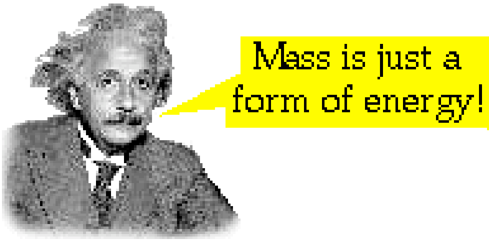


- With the Tevatron, it became feasible to store particles in the ring for long periods of time. By sending beams of particles going in both directions within the accelerator, and steering them to hit head-on at particular locations, we can pass groups of particles through each other over and over until individual particles eventually collide with each other. This is called a 'colliding beams' experiment.

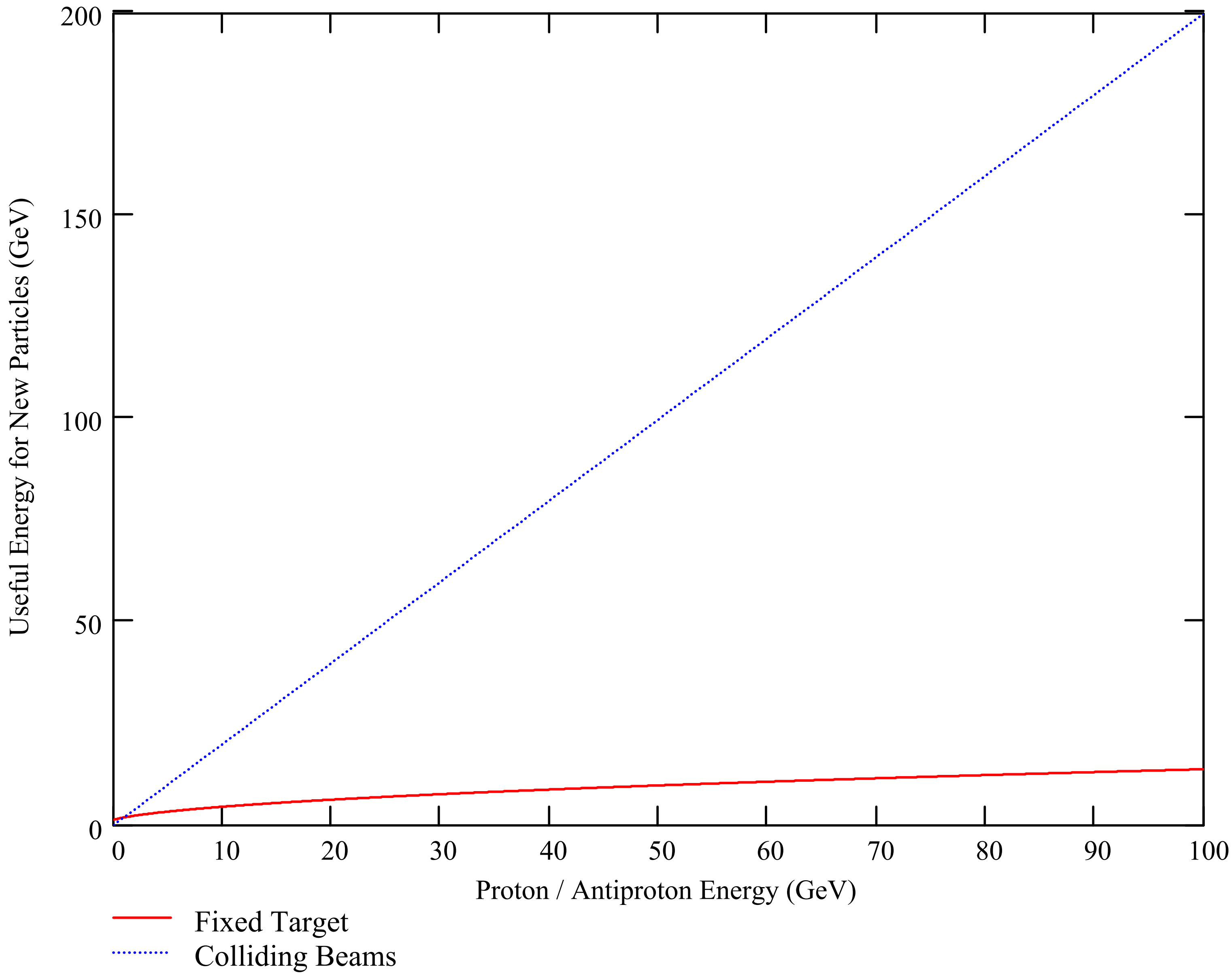


Colliding Beams

- Imagine a truck running into a stationary truck, versus two trucks running into each other head-on!
- OK, well, look at particles then…
  - The energy of the collision can be used to produce new particles (mass = energy!)
  - Energy and Momentum must be conserved
  - Einstein: $E^2 = (mc^2)^2 + (pc)^2$
  - Fixed target scenario -- still must have momentum after the collision, therefore less energy available for new stuff!
  - **Collider**: zero momentum before AND after. Thus, ***ALL*** energy can be converted into *new stuff*!

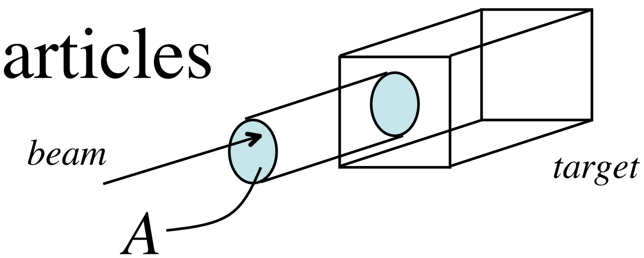


Available Energies



Luminosity

- Fixed Target Experiments:
  - *Illuminate* a target with beam particles
    - cross sectional area Σ



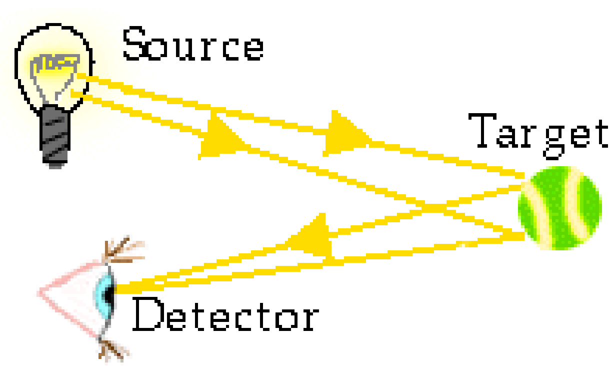
  - Rate of "interactions" --

$$R \sim \frac{\Sigma}{A} \times (density \times A \times \ell)/(gm/target) \times (\#particles/sec)$$

  - So, the "luminosity" is just:

$$L = (density \times \ell)/(gm/target\ particle) \times (\#particles/sec)$$

i.e., the type of material used for the target, as well as the *rate* at which particles generated by the accelerator determine the luminosity of the experiment



Collider Luminosity

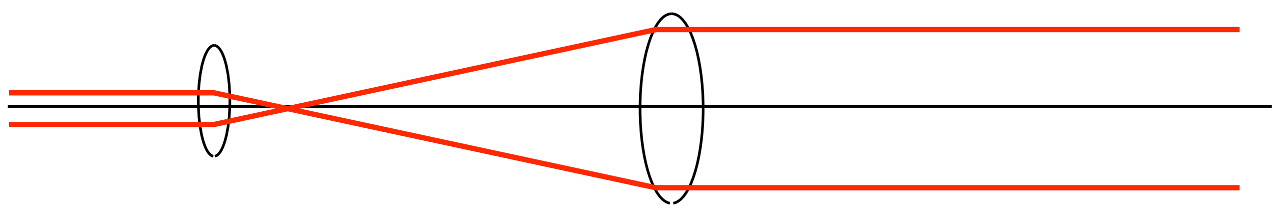
- Similar to previous, but here the "targets" are just the on-coming particles from the other beam!
- So,
  - Interaction Rate: $$R = \frac{\Sigma}{A} \times N_1 \times N_2 \times f$$
  - The 'luminosity' is: $$L = \frac{f N_1 N_2}{A}$$

Frequency of bunches passing through each other

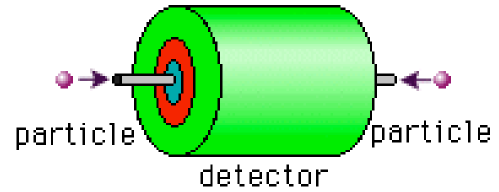
    - Depends upon the beam size, and number of particles in each beam
    - Note: has units of 1/(area x time)
    - Gives Experimenters feeling for performance of accelerator
- Thus, to be able to gather more data quickly, need lots of particles, and small beam sizes --
  - In Tevatron, 10^{12} - 10^{13} per beam, spot sizes of **60 μm** = 6% of one mm!!

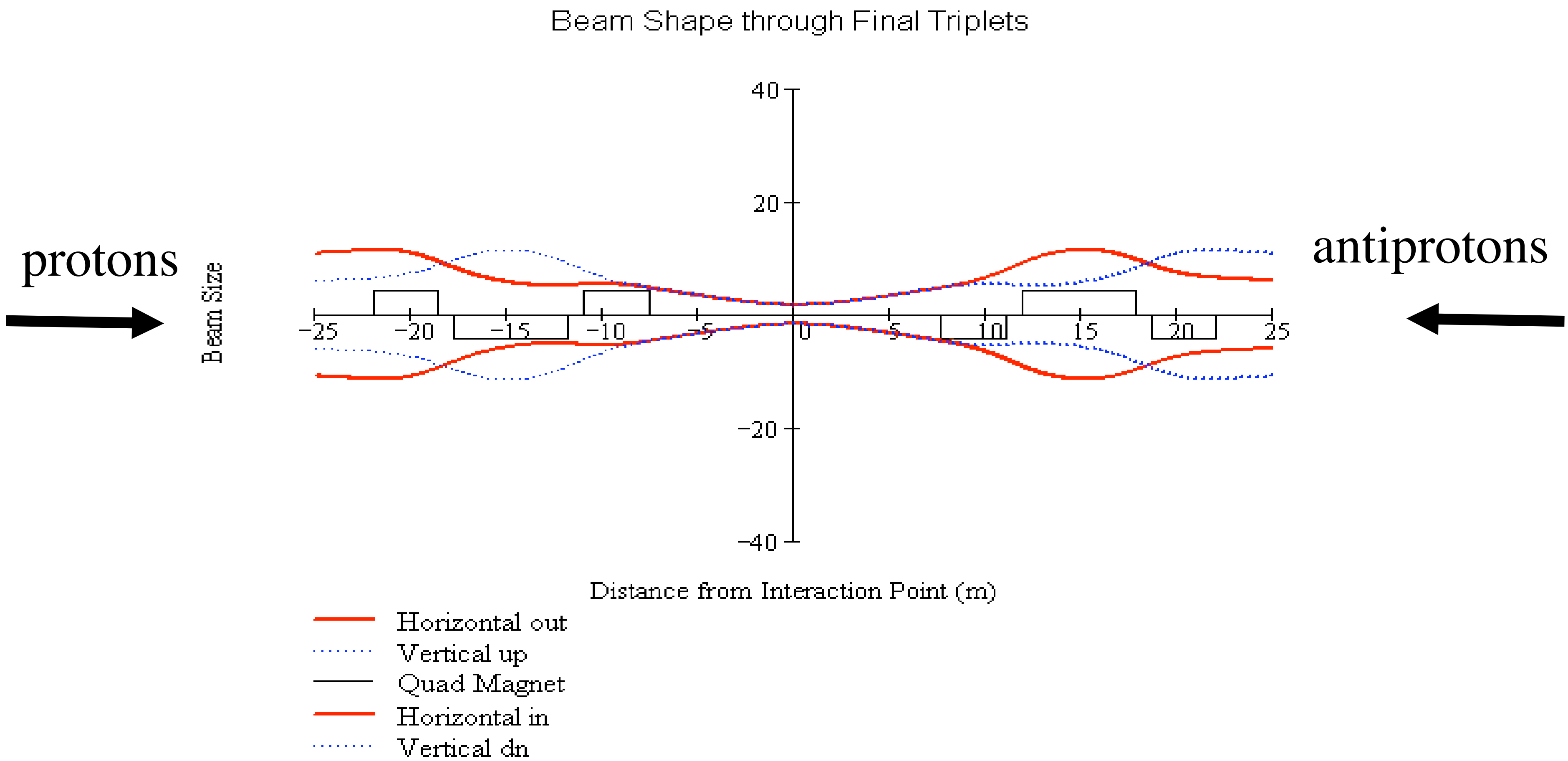
The “Final” Focus

- In a collider, in order to increase the probability that particles in the two beams will actually hit each other, we squeeze the beam to very small sizes at the collision points.
- At an ‘interaction point’ the particle beams are only about 60 µm wide (~ the width of a human hair!)
- Performed using sets of strong focusing quadrupole magnets, and adjusting their strengths
  - Sort of like a telescope -- strong magnets near the collision point act like the Objective Lens; weaker magnets away from the collision point act like the Eyepiece:



Squeeze Play…

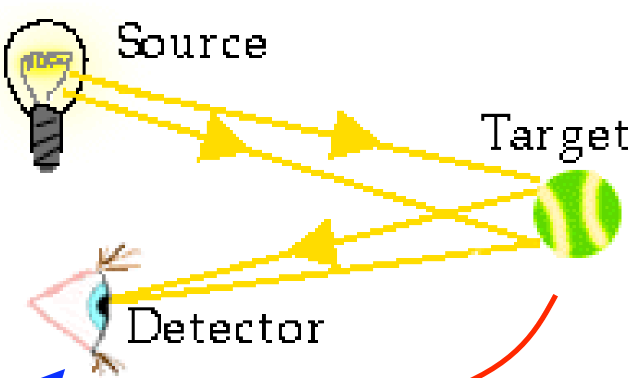




We change the strengths of quadrupole magnets to focus the beam stronger, thus increasing chance for collisions

Some Numbers…

- For Tevatron operation,
  - $N_{protons} = 2 \times 10^{11}$, $N_{antiprotons} = 4 \times 10^{10}$,
  - $f = 36 \times (3 \times 10^5 \text{ km/sec})/6 \text{ km}$,
  - $A = \pi\,(60\ \mu\text{m})^2 = \pi\,(0.0060\ \text{cm})^2$
  - ---> $L = 1 \times 10^{32}\ \text{cm}^{-2}\ \text{sec}^{-1}$



- Cross section of a proton/antiproton collision

  $\sim 6 \times 10^{-26}\ \text{cm}^2$

- So, we get, and wish to detect, about 6×10^6 collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store data at this rate (and they do!) ***(see the Sat. Morning Physics talk October 21!)***
- Each proton/antiproton has energy of

  $980\ \text{GeV} = 980 \times 10^9 \times (1.6 \times 10^{-19}\ \text{J}) = 1.6 \times 10^{-7}\ \text{J}$

- So, *power* delivered in the collision region is only about

  $2 \times 1.6 \times 10^{-7}\ \text{J} \times 6 \times 10^6\ /\text{sec} \sim 2\ \text{watt!}$

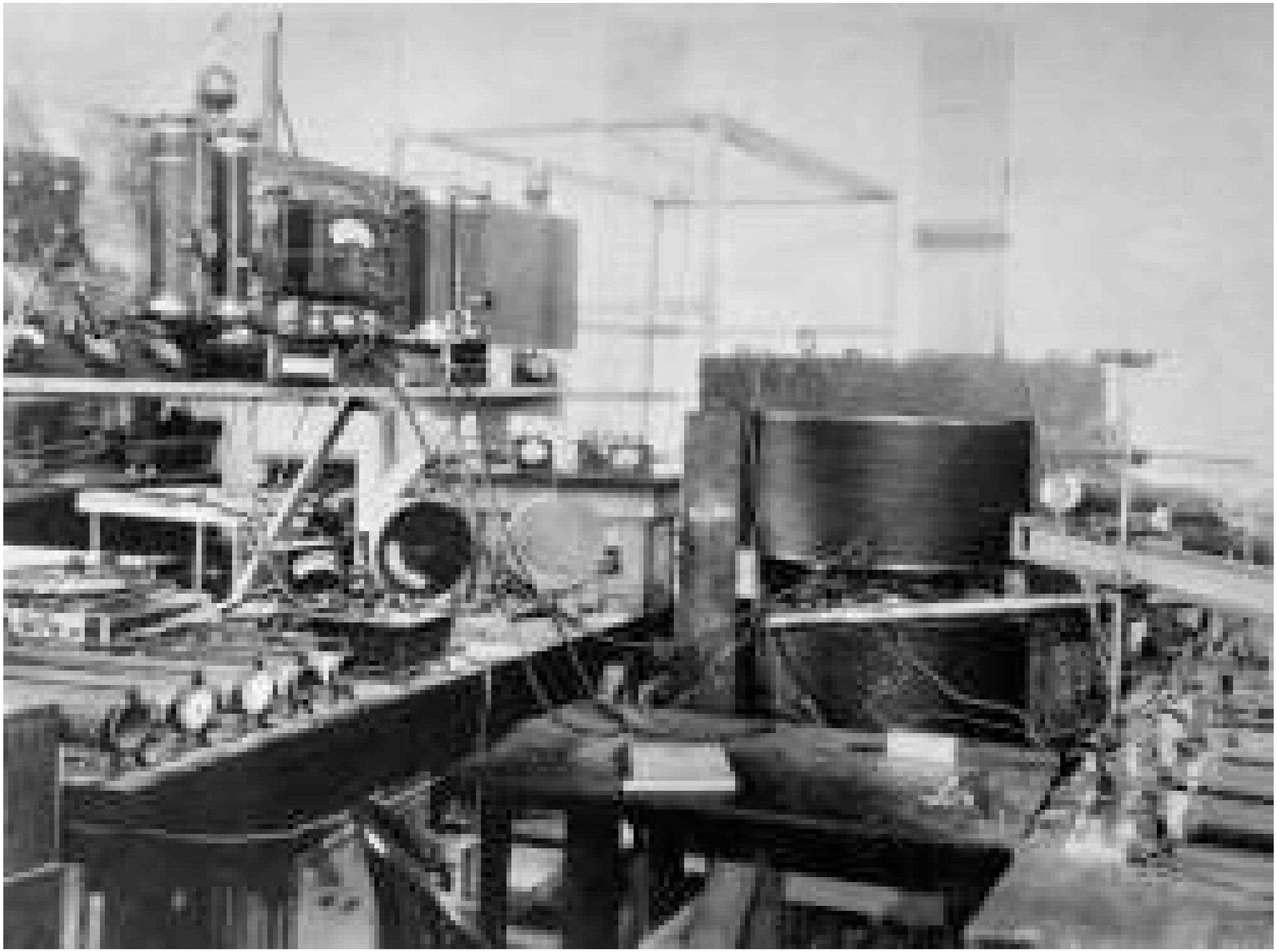
The World's High Energy Accelerators

A brief tour and history…

Berkeley Radiation Laboratory

The First Cyclotron, Berkeley -- 1930's

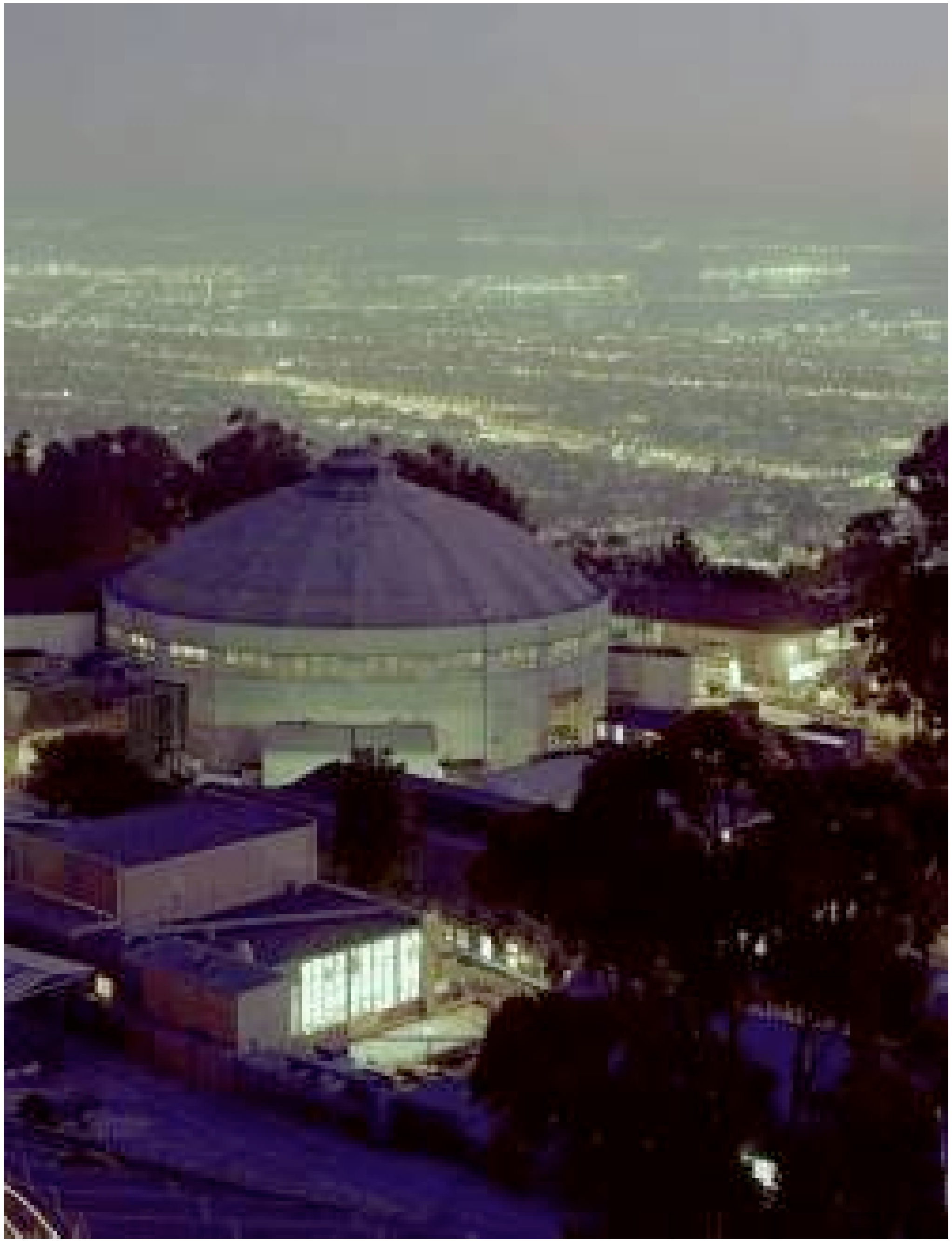
11-inch Cyclotron, Berkeley -- 1930's



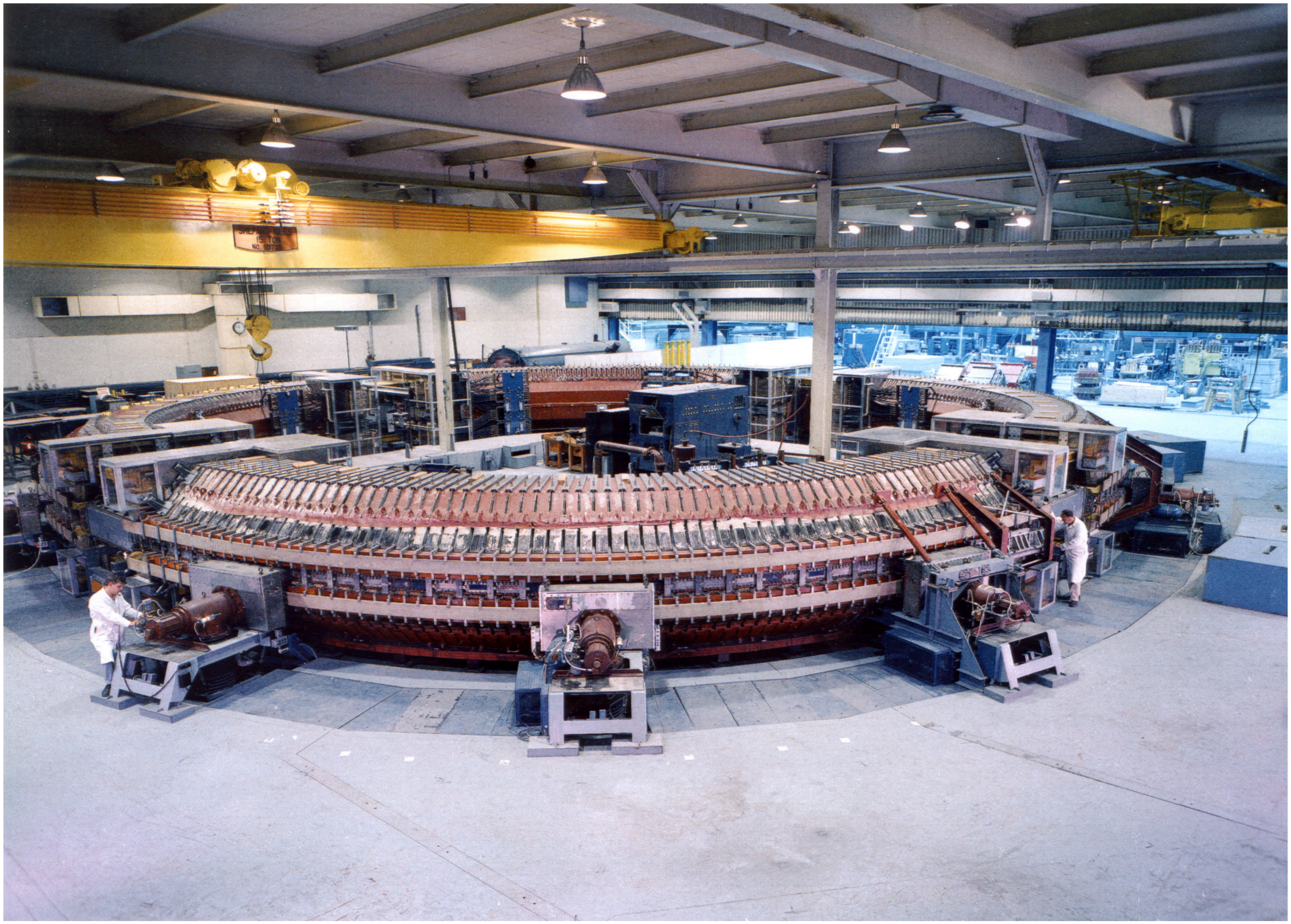
60-inch Cyclotron, Berkeley -- 1930's

184-inch Cyclotron, Berkeley -- 1940's

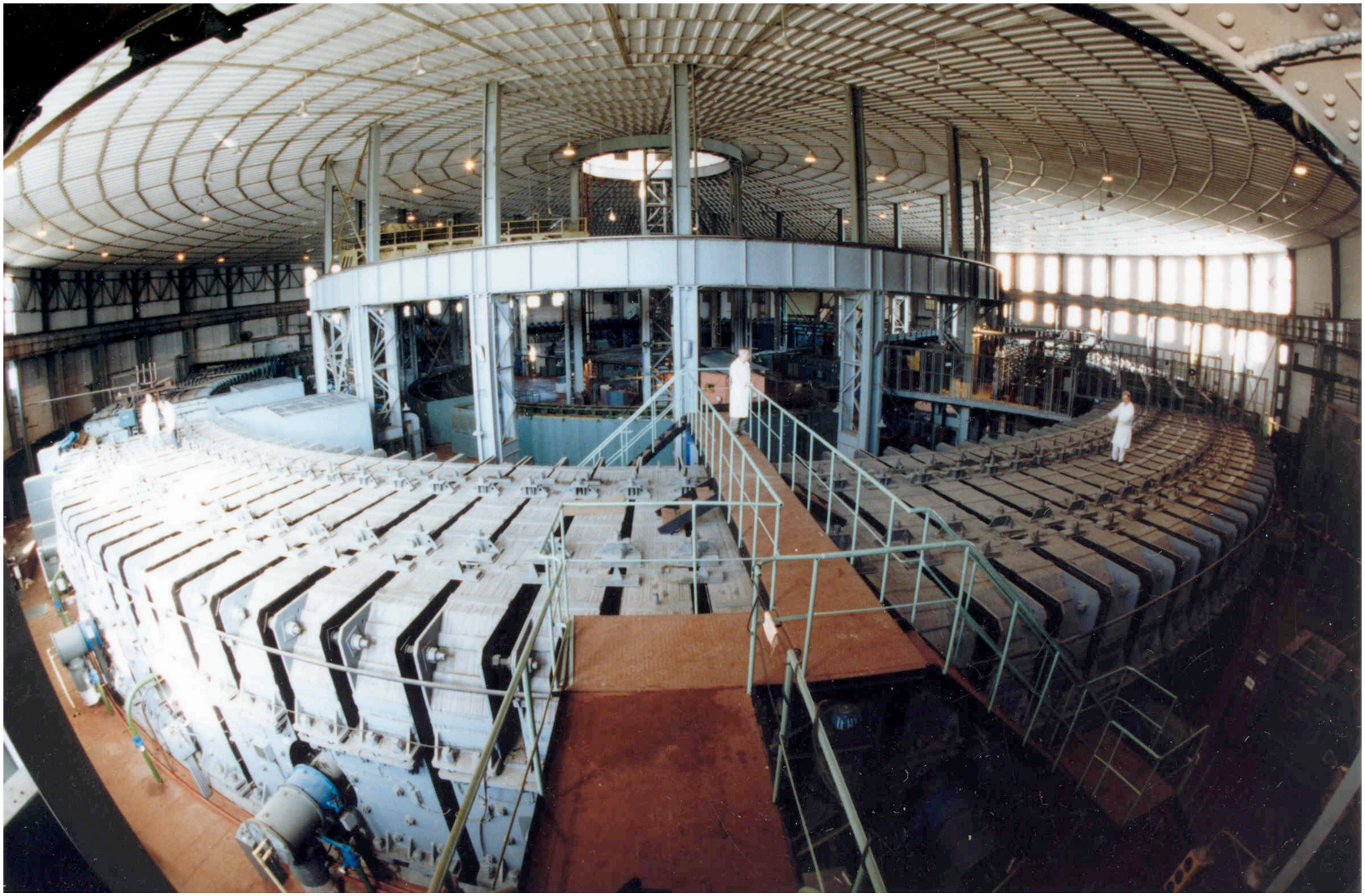
Lawrence Berkeley National Laboratory



Cosmotron, Brookhaven -- 1950's

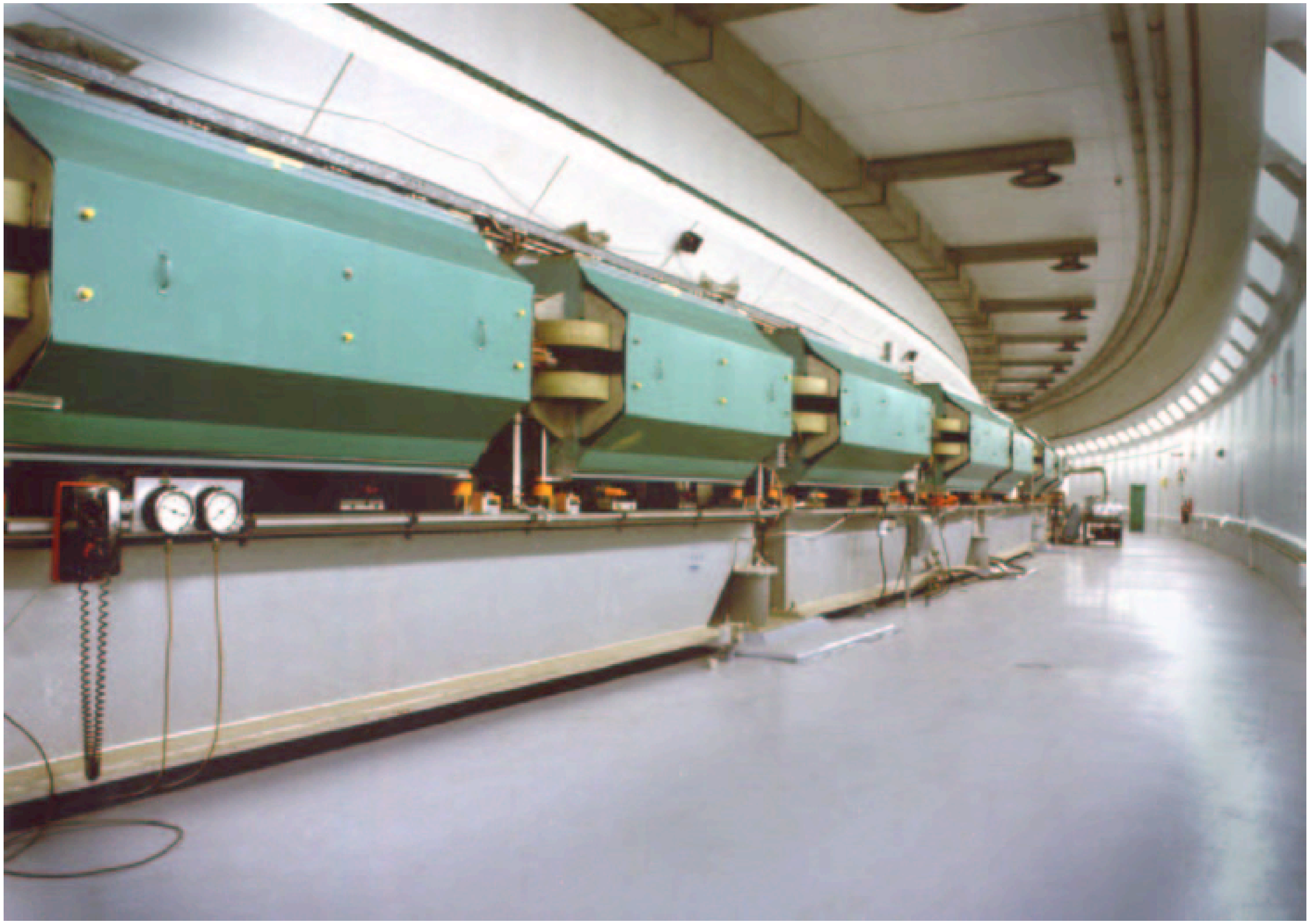


Synchrophasotron, Dubna -- 1950's



AGS, Brookhaven, New York

AGS, Brookhaven -- 1960's



U70, Serpukhov -- 1970's

Main Ring (1970's) and Tevatron (1980's) , Batavia

HERA, Hamburg -- 1990's

LEP, Geneva -- 1990's

Relativistic Heavy Ion Collider
Brookhaven -- 2000's

Brookhaven National Lab

Cornell University -- CESR

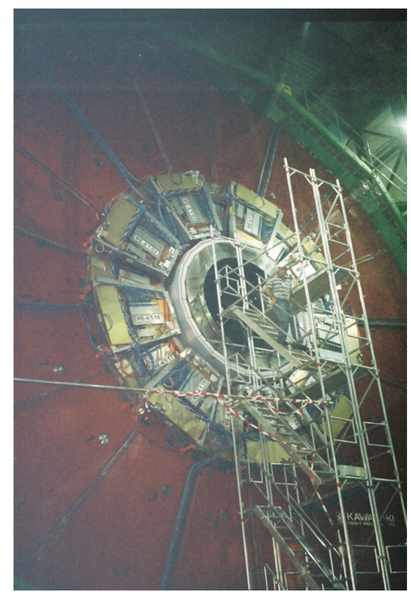
Stanford Linear Accelerator Center

U70, Serpukhov, Russia

Fermilab

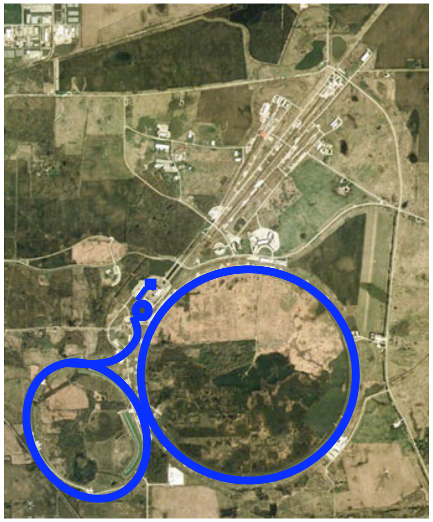
You are here!

European Organization for Nuclear Research (CERN)

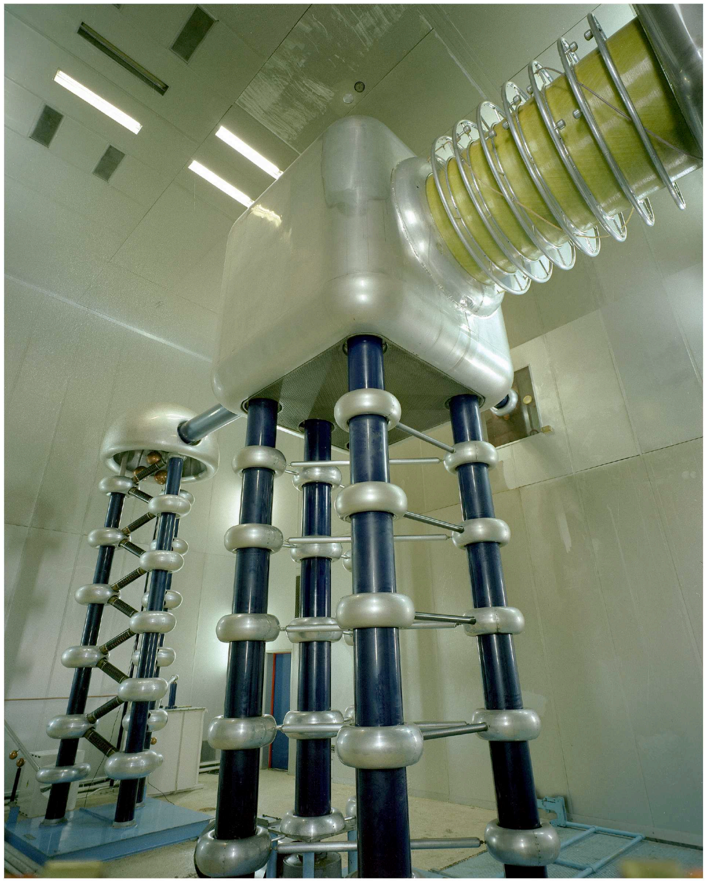


Fermilab's Accelerators

- The Fermilab Accelerator System is made up of a 'chain' of accelerators, each delivering particles to the downstream accelerator.
  - Cockcroft-Walton style "pre-accelerator" (Preac)
    - 0 - 750,000 eV (= 750 keV = 0.75 MeV)
  - Linear Accelerator (Linac)
    - 0.75 MeV - 400 MeV
  - Booster Synchrotron
    - 400 MeV - 8000 MeV (= 8 GeV)
  - Main Injector Synchrotron
    - 8 GeV - 150 GeV
  - Tevatron Synchrotron
    - 150 GeV - 1000 GeV (= 1 TeV) (*actually*, operates at 0.98 TeV)
  - Plus, a couple others: Antiproton accumulator, Recycler, etc.

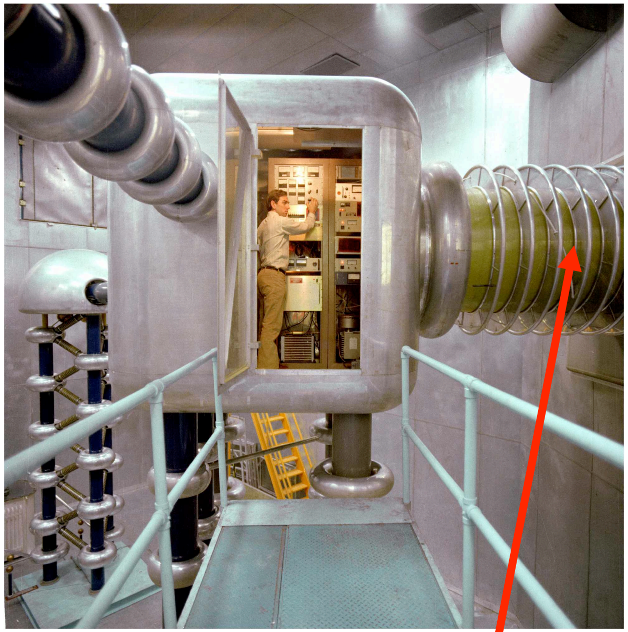


Cockroft Walton Preaccelerator



All starts here!

inside the dome:



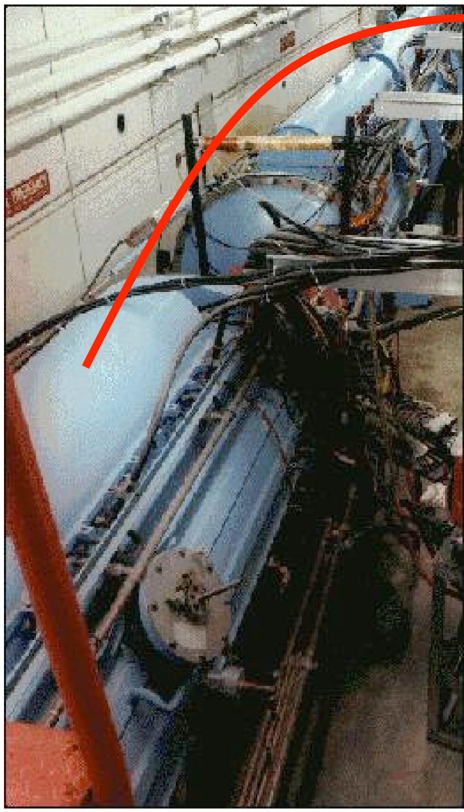
Begins with a bottle of hydrogen gas, H_2, which is combined with Cesium to produce H- ions

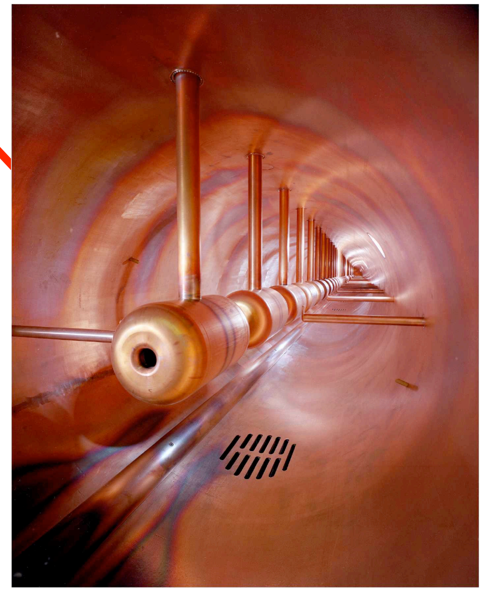
$(1\ p^+ + 2e^-)$

The H- ions are attracted toward the wall, through the column, and thus gain speed/energy

Final kinetic energy of the ions is 0.75 MeV, and their speed is ~ 0.04*c*

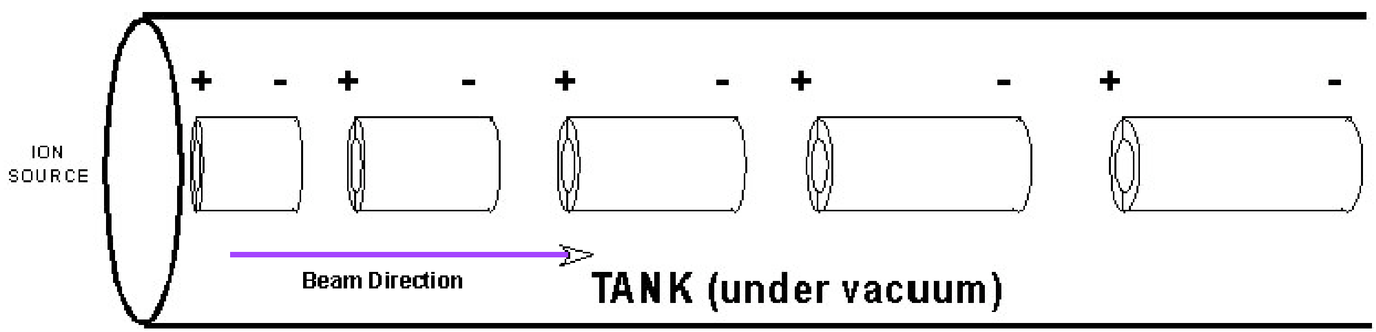
Linear Accelerator (Linac)



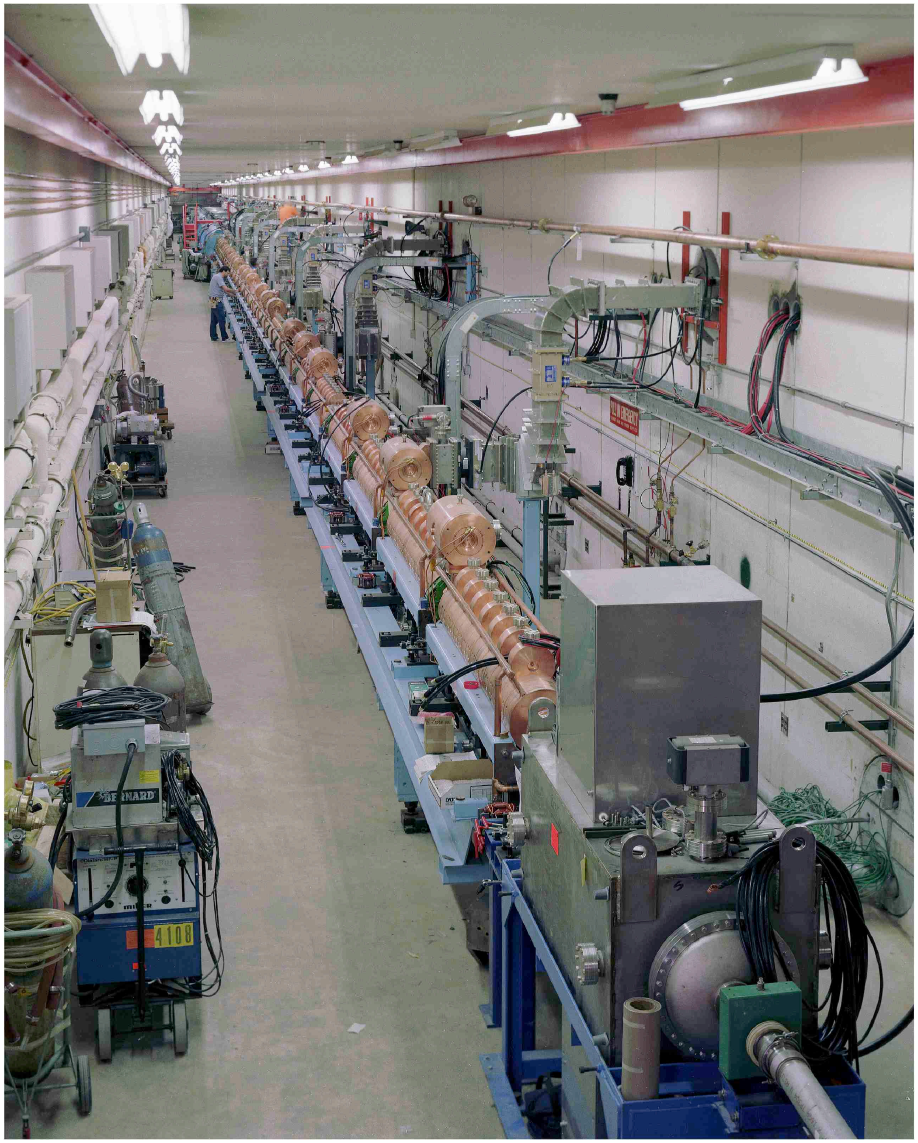


Upstream end of Linac:

- Field inside oscillates at 200 MHz
- Particles are accelerated in the 'gaps'
- Gaps get spaced further apart as particle speed increases



Linac (cont'd)

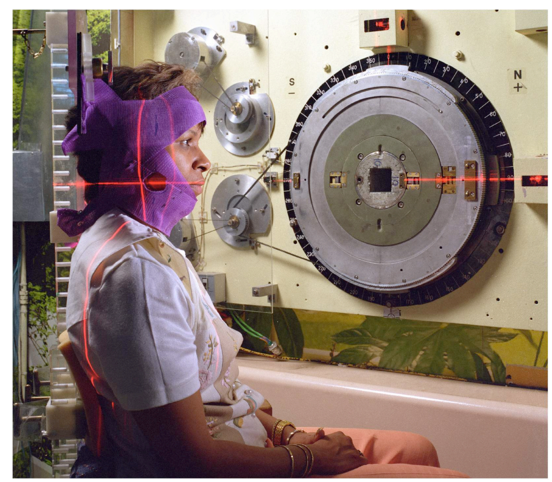


Downstream end of Linac:

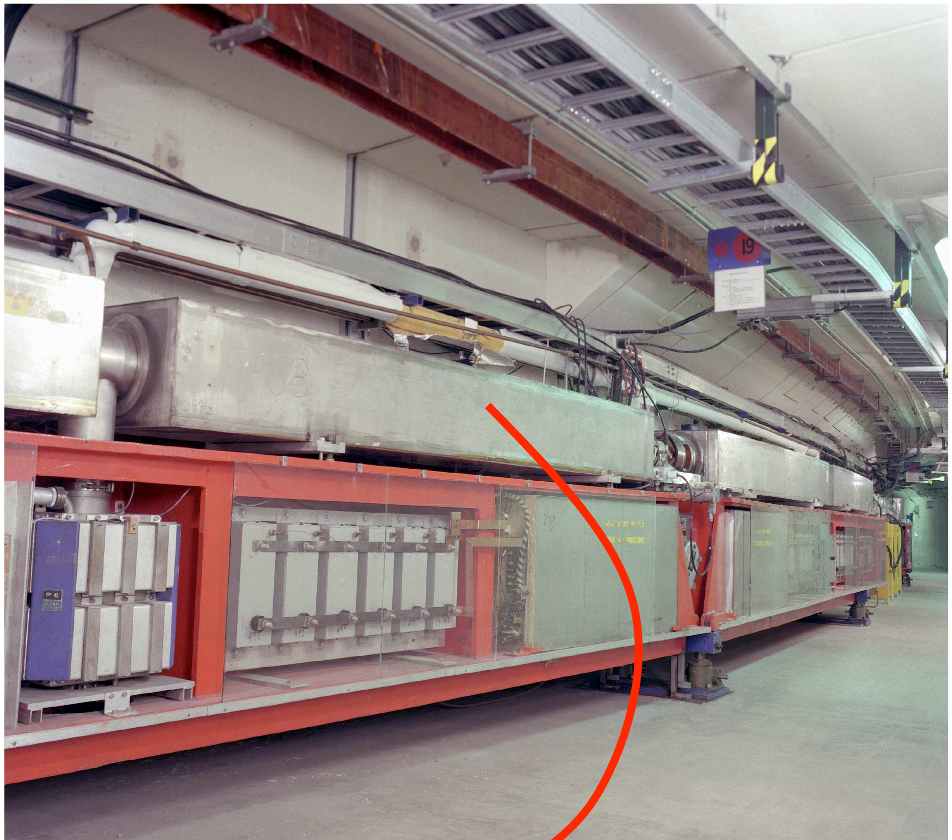
- particle speed approaching 0.7*c*
- gap spacing not changing much; use different cavity structure

- here, field oscillates at 800 MHz
- Total Linac length: 145 m (475 ft)
- Final kinetic energy: 400 MeV

Mid-way, can take particles out and direct toward target; forms neutrons; used for cancer therapy!



Booster Synchrotron



At entrance, beam passes through a foil, and the electrons are stripped away from the H^- ions -- leaving protons!

Protons circle the Booster 20,000 times, and gain 7600 MeV in K.E.
they exit traveling at 99% *c* !

Total process takes **0.033 seconds!**

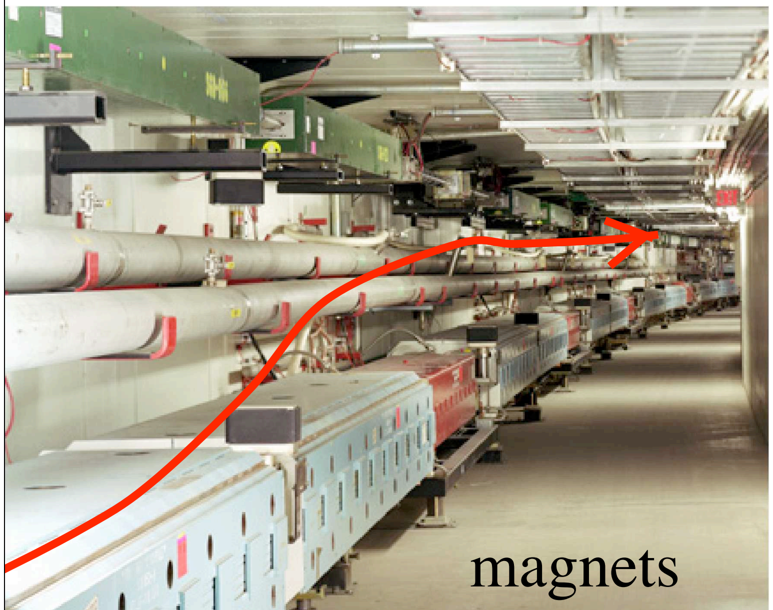
Magnets

RF accelerating cavities

Main Injector

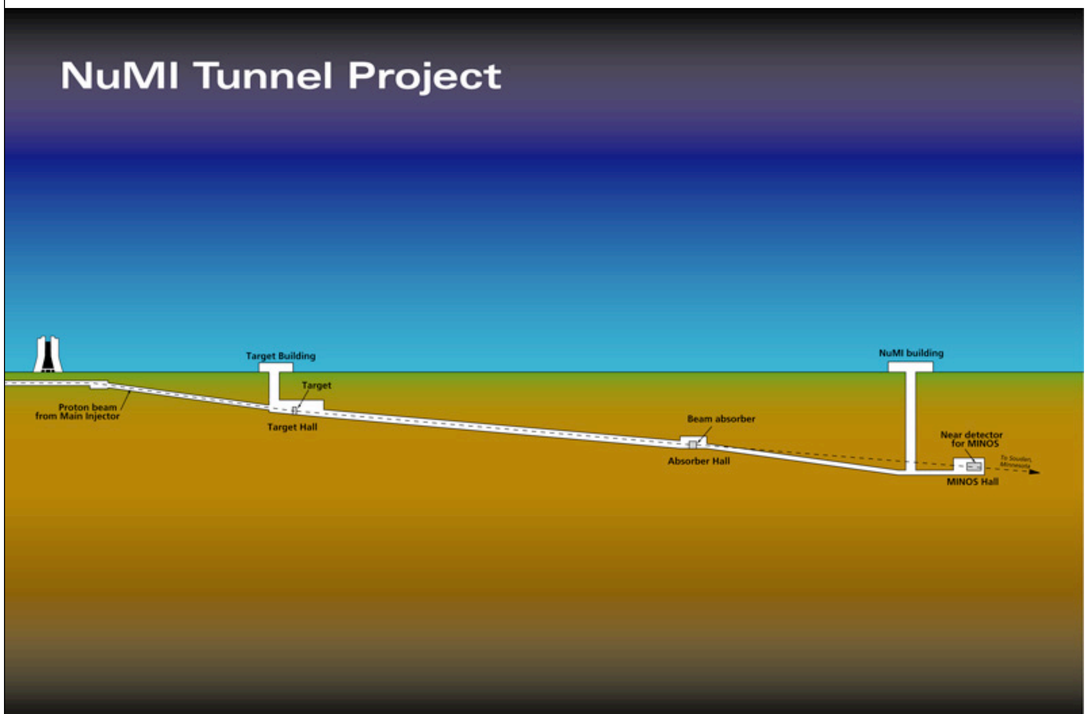
Particles enter with 8 GeV K.E.; accelerate up to 150 GeV (0.9999*c*)
Many uses…

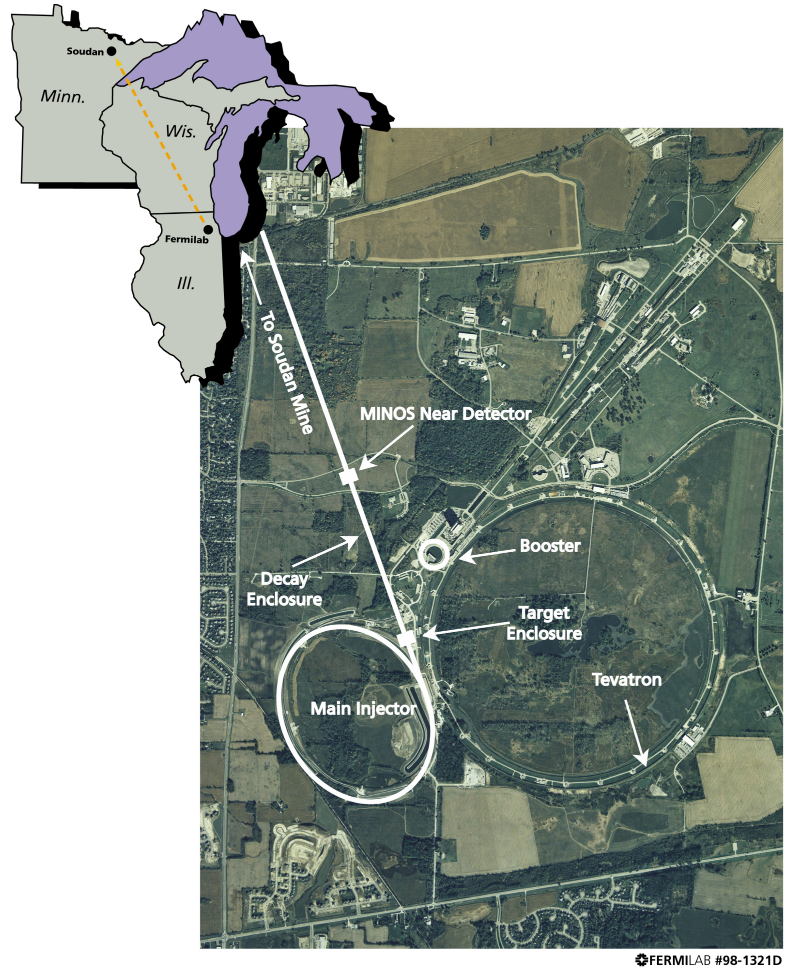
- Protons to Antiproton Source, to make antimatter
- Antiprotons into the Recycler synchrotron for storage
- Protons and Antiprotons to the Tevatron for collisions
- Proton beam to the Test Beam experimental area
- Proton beam for neutrino oscillation experiment (NuMI/MINOS)

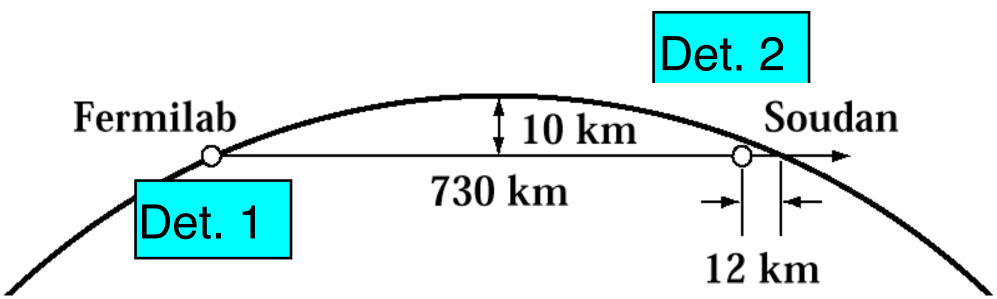


RF:

Neutrinos at the Main Injector



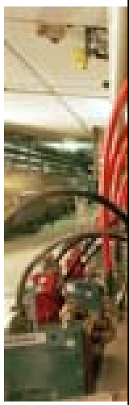


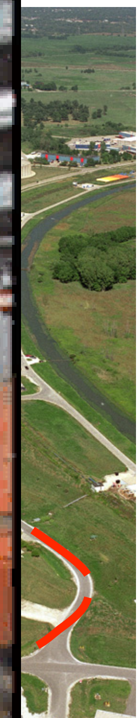


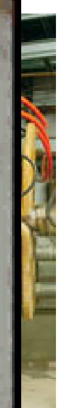
Search for neutrino oscillations (mass)
Sending neutrinos through the earth to Minnesota ***right now***!

Antiproton Source -- anti-matter!

- 120
  proc
- 8 Ge
- Stoc
  redu
  mor
- Afte
  anti

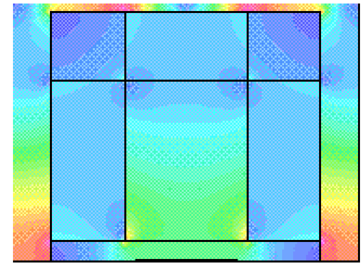




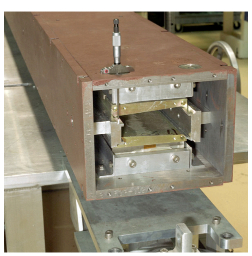


Recycler Synchrotron

- Originally built to recover left-over antiprotons at the end of a Tevatron colliding beams store
- Resides in Main Injector tunnel, near ceiling
- Later, realized more efficient to store antiprotons previously conditioned in the Antiproton Source, and *then* send to the Tevatron -- actually provides higher luminosity overall when used this way
  - Will store up to ~6 Trillion antiprotons
  - Permanent magnets are used -- not electromagnets (since beam is stored at one energy -- 8 GeV)
  - Has been used successfully to set luminosity records in the Tevatron
  - Continuing to improve



Permanent Magnet field map



magnet

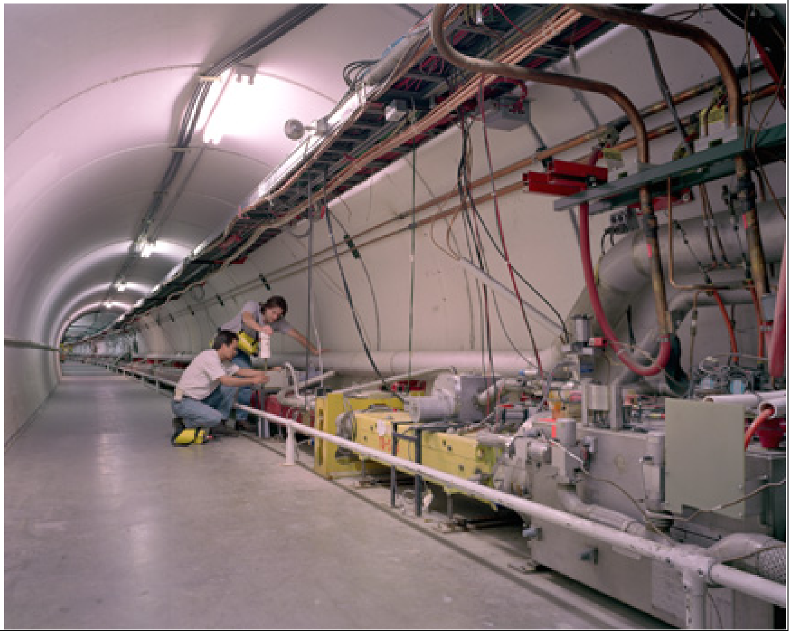
Pelletron

The Tevatron

- World's Highest Energy particle accelerator -- 0.98 TeV
  - **Still**! Commissioned in 1983
  - Replaced 400 GeV "Main Ring" in the same tunnel (built ~1972)
  - 1st superconducting accelerator
  - Circumference = 2π km (+/- 5 cm!) = 4 miles
  - At 1 TeV, protons, antiprotons speed is 0.9999996 *c* !
  - One round trip for a proton takes 21 μsec (48,000 revolutions/sec)
- Acceleration takes place with 8 RF cavities, total ~20 m. Rest of circumference is magnets, bringing particles back to the cavities!

The Tevatron (cont'd)

- Two beams (matter & antimatter!) circulate in opposite directions, only few mm apart, brought into collision at two detector regions
- While collisions only generate 1-2 watts of power, as shown earlier, the stored energy of the proton beam is
  - $36 \times (3 \times 10^{11}) \times (1000 \times 10^{9} \times 1.6 \times 10^{-19}$ J) = **1.7 MJ** !
    - 1.7 MJ = kinetic energy of a 6 ton truck moving at 60 mph
    - 1.7 MJ ~ 2 jelly doughnuts
  - If lost in one revolution, instantaneous power: 1.7 MJ / 21 μsec = **80 GW**!
- Soon, CERN's LHC will take over as world's most powerful accelerator ...



Fermilab Main Control Room

From here, control and monitor properties of all accelerators

around the clock operation, 24/7 all year

shut down periods occur, for maintenance

crews of 5-6 Accelerator Operators and Crew Chief

The Future…

Compare hadrons and leptons

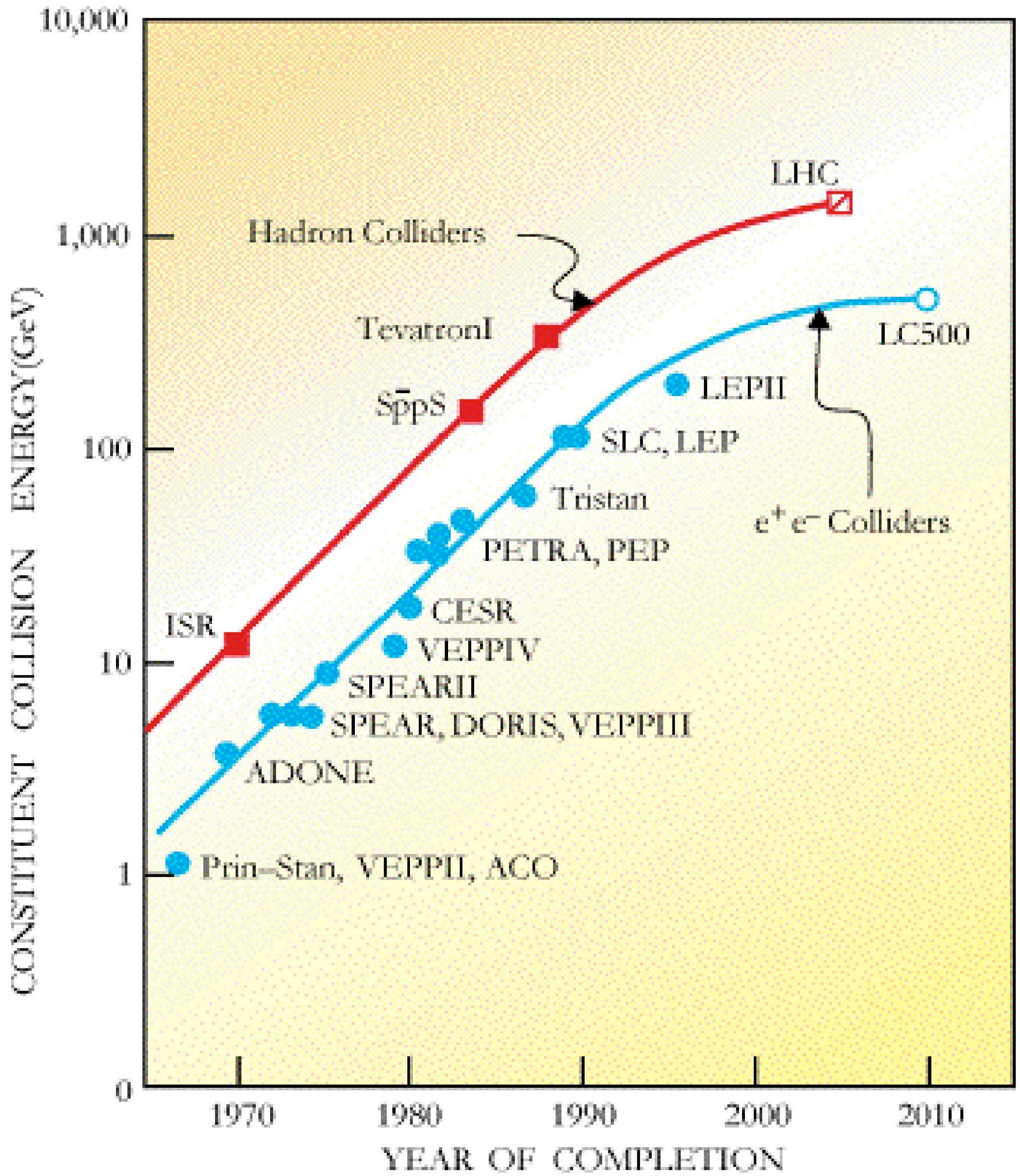
- constituent hadron collision energy is about 1/10 of total hadron beam energies (protons made up of quarks!)
- constituent lepton collision energy is all of total lepton beam energies

Great growth in accelerator- based science during past half-century.

Slower in recent years…

- projects have become large
- necessarily international
- using same old technology

However, present projects require many people and offer many opportunities



Current Accelerator R&D

- Large Hadron Collider (LHC)
  - Proton-proton collider, being constructed at CERN (Geneva, Switzerland)
  - 7000 GeV per particle; but protons contain quarks and gluons
  - Ready in ~2 years
- International Linear Collider (ILC)
  - Large international community looking into this project
  - Electron-positron collider, 250-500 GeV per particle
  - Lower energy than LHC, but fundamental particle probes!
- Muon Collider / Neutrino Factory
  - Use muons, which are point-like, but heavier than electrons
  - Muons decay, generating neutrinos; good for neutrino studies?
- Very Large Hadron Collider
  - More of the same (like LHC), only *VERY* big…
- Plasma acceleration, Wake Field accelerators, …
- Other???

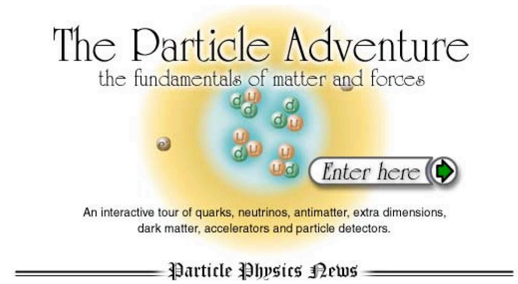
Summary

- Controlled experiments to study fundamental high energy particle physics rely on accelerators
- Highest energy accelerator in the world at Fermilab -- soon to be eclipsed by CERN's LHC …
  - Still, center for neutrino physics experiments for some time!
- But, the laboratory continues to look into future projects which can be funded at a reasonable cost and which can best benefit the High Energy Physics community (and, society!)
- Fermilab will continue to be at the frontier of fundamental physics research and accelerator development for many years to come...

These are exciting times!

References

- D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, John Wiley & Sons (1993)
- S. Y. Lee, *Accelerator Physics*, World Scientific (1999)
- E. J. N. Wilson, *An Introduction to Particle Accelerators*, Oxford University Press (2001)



- Web sites:
  - Particle Adventure
    - http://particleadventure.org
    - http://www.lbl.gov/Education/ (many other links here)

- Particle Accelerator Schools --
  - USPAS: http://uspas.fnal.gov
  - CERN CAS: http://cas.web.cern.ch

- Conference Proceedings (use *Google!*) --
  - Particle Accelerator Conference (2005, 2003, 2001, …)
  - European Particle Accelerator Conference (2004, 2002, …)

email: *syphers@fnal.gov* web: *http://www-ap.fnal.gov/~syphers/*

Saturday Morning Physics

2006 - 2007

October 7 – December 3, 2006

√ Oct. 7	Particle Physics	R. Dixon	WH15 WH15 ACC	S. Desai S. Fu M. Wang
√ Oct. 14	Accelerators	E. Harms	ACC ACC WH15	M. Weber M. Wobisch M. Datta
Oct. 21	Detectors	M. Demarteau	DØ CDF KTeV	A. Golossanov S. Pranko M. Wobisch
Oct. 28	Cosmology	M. Jackson	CDF KTeV DØ	K. Sato E. Ramberg A. Chou
Nov. 4	Symmetry	C. Hill	KTeV DØ CDF	S.-S. Yu I. Bloch D. Mason
Nov. 11	Relativity	R. Plunkett	FCC SiDet Mag Fac	C. Noeding P. Tan L. Uplegger
Nov. 18	Quantum Mechanics	B. Dobrescu	SiDet Mag Fac FCC	F. Yumiceva J.H. Yoo B. Rebel
Nov. 25	**NO Class - Thanksgiving Break**			
Dec. 2	Anti-matter	B. Tschirhart	Mag Fac FCC SiDet	H. Meyer M. Ellis R. Eusebi
Dec. 9	Physics & Society	E. Ramberg	GRADUATION	

Classes meet in One West

Lectures begin at 9:00 a.m. **Tours begin at 11:00 a.m.**

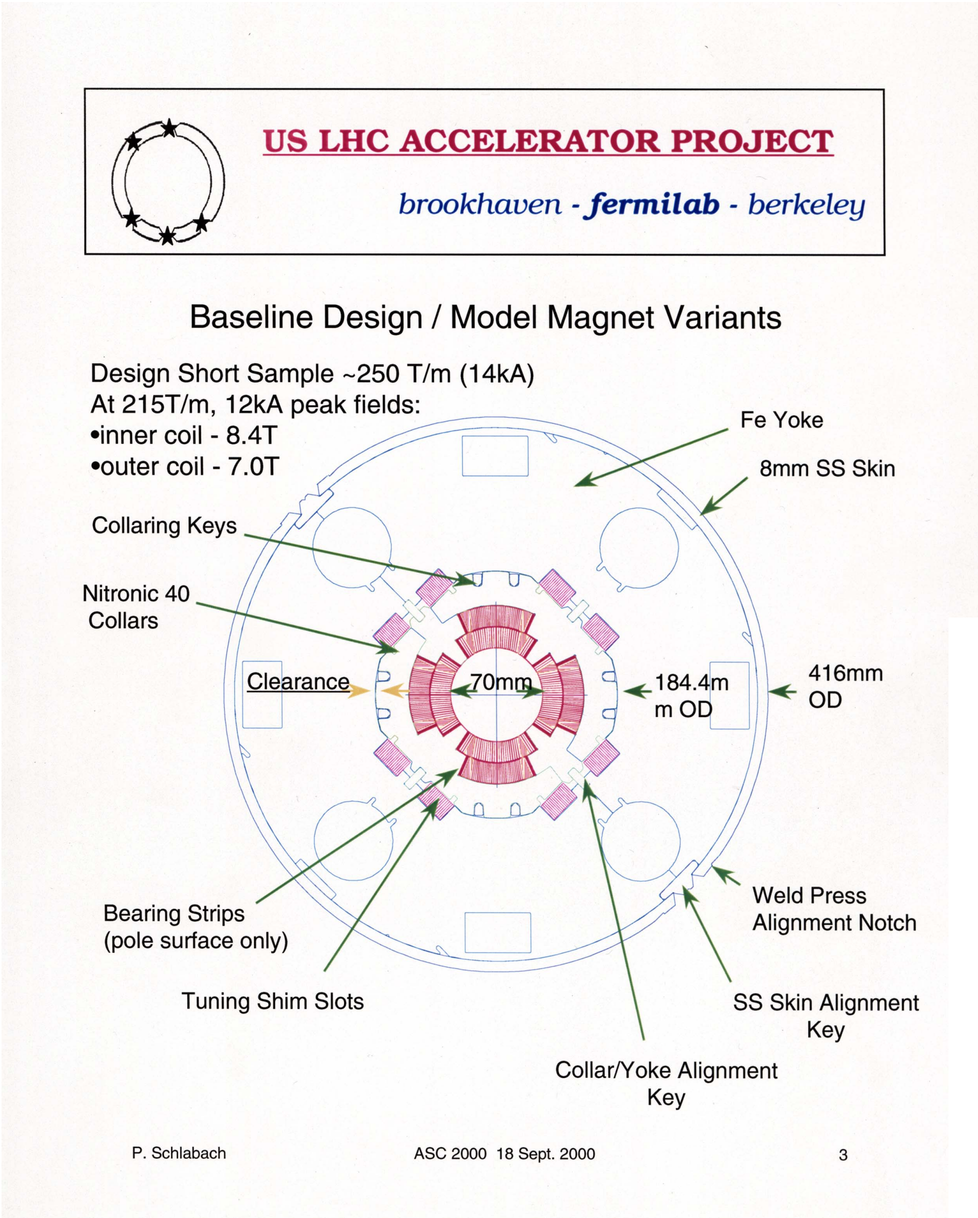
Class is **NEVER** cancelled!

9/28/2006 4:00:36 PM

LHC -- the next big accelerator

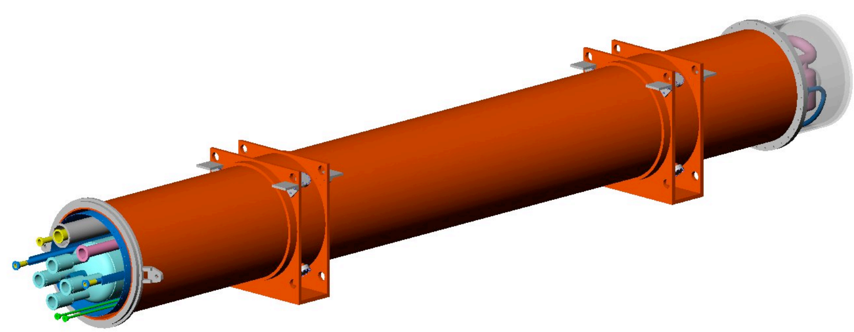
- CERN, on the border of Switzerland and France, near Geneva, is converting their Large Electron - Positron (LEP) synchrotron tunnel into a (**l**arge) **h**adron **c**ollider facility -- LHC.
- The U.S. is contributing to the project, both in equipment and manpower. Fermilab plays a vital role.
- Fermilab has built superconducting quadrupole magnets to be used to focus the beams at the LHC interaction regions.
- Fermilab scientists will be involved in the start-up of the LHC accelerator, as well as the massive LHC detectors.

LHC Quadrupole Magnet (Cold Mass Only) for use in Interaction Regions

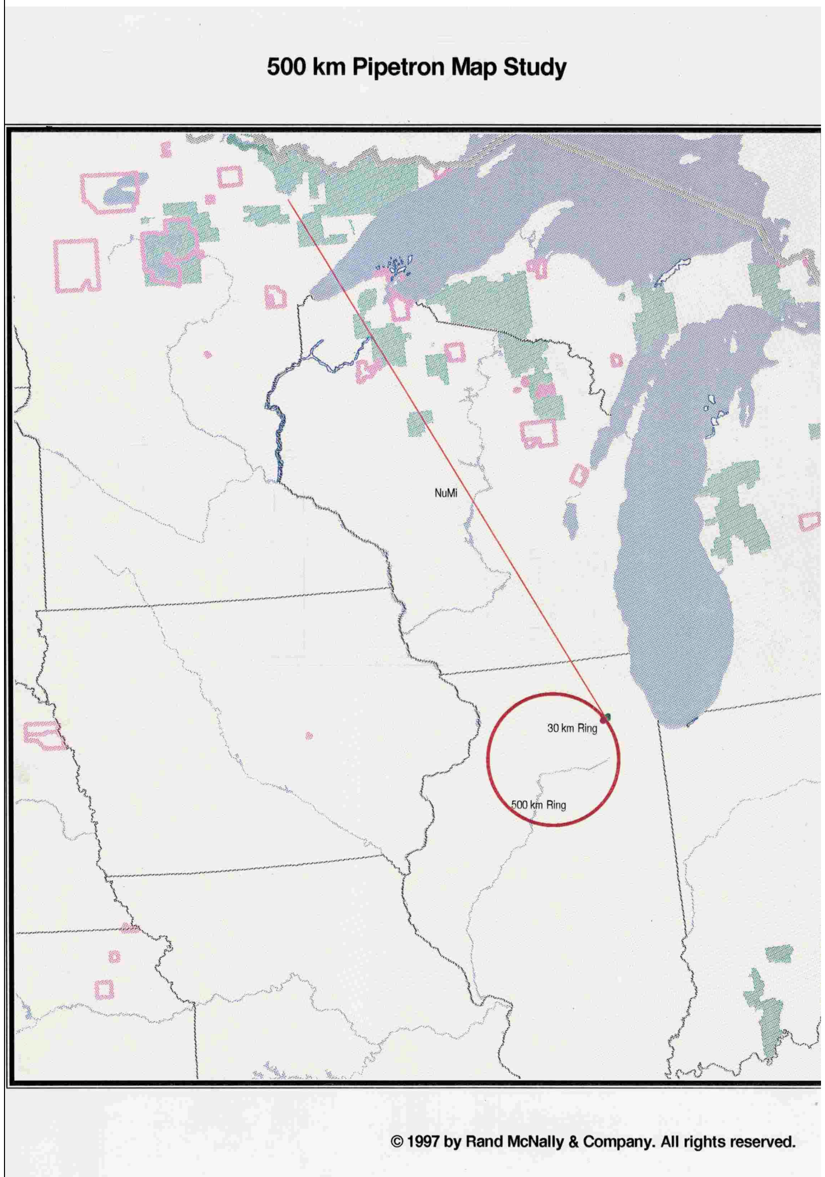


Courtesy Phil Schlabach

This quadrupole magnet is 36 inches in diameter and about 7 meters long



A *Very* Large Hadron Collider?



It would not really be "at Fermilab".

Rather it would be under "Northern Illinois"

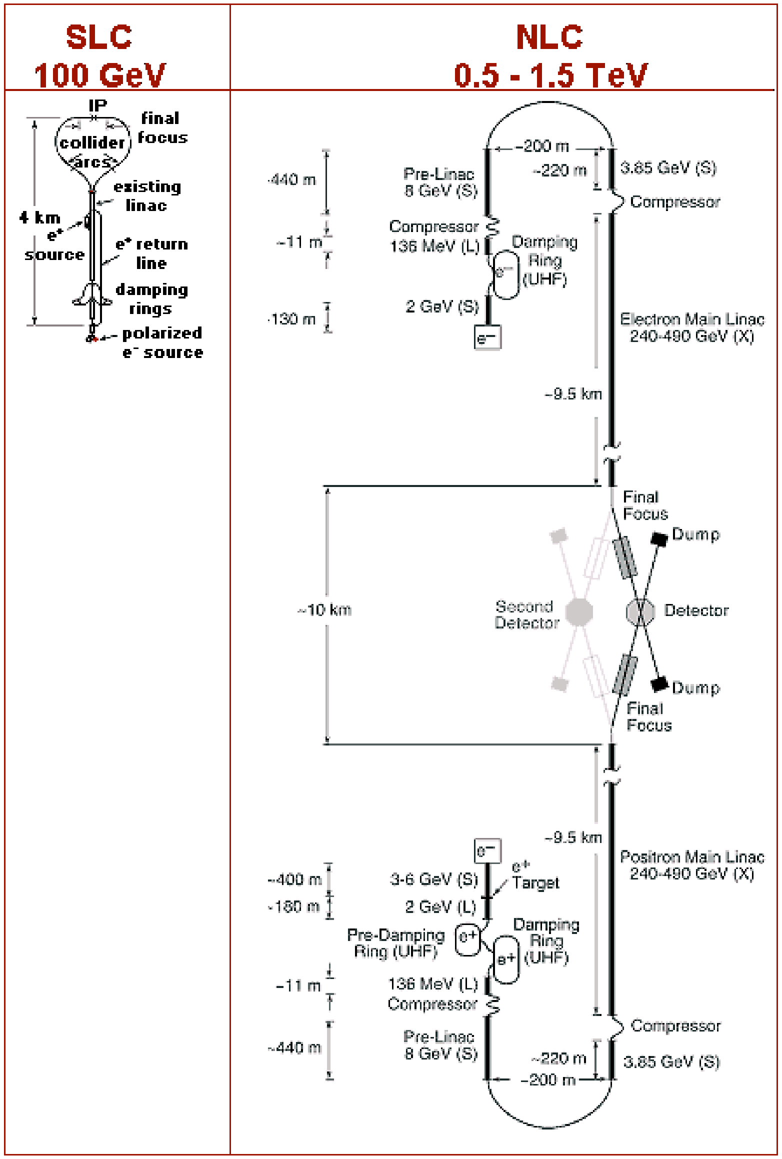
To go to energies like 20 - 100 TeV, would require a circumference of about 150 miles!

Maybe a far-future project…

Today, however, physicists are looking at a smaller (yet, still large!) project, involving electron beams rather than proton beams…

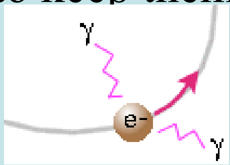
International Linear Collider

An early design concept:



(SLC = *SLAC Linear Collider*, 1990's)

- A 1 TeV proton is actually a collection of quarks and gluons; thus, their collisions are "messy"
- Electrons are point-like, and thus their collisions are more "clean" and somewhat easier to analyze
- However, electrons radiate energy when their paths are bent; so, best to keep them moving in a straight line!



- The ILC is an e+e- Option. It would be complementary to the LHC, for example
- Two straight accelerators about 10 km long each providing 250 GeV beams.
- Several smaller (and rather complicated) accelerators and devices to feed them …
- "Final Focus" regions, and a detector

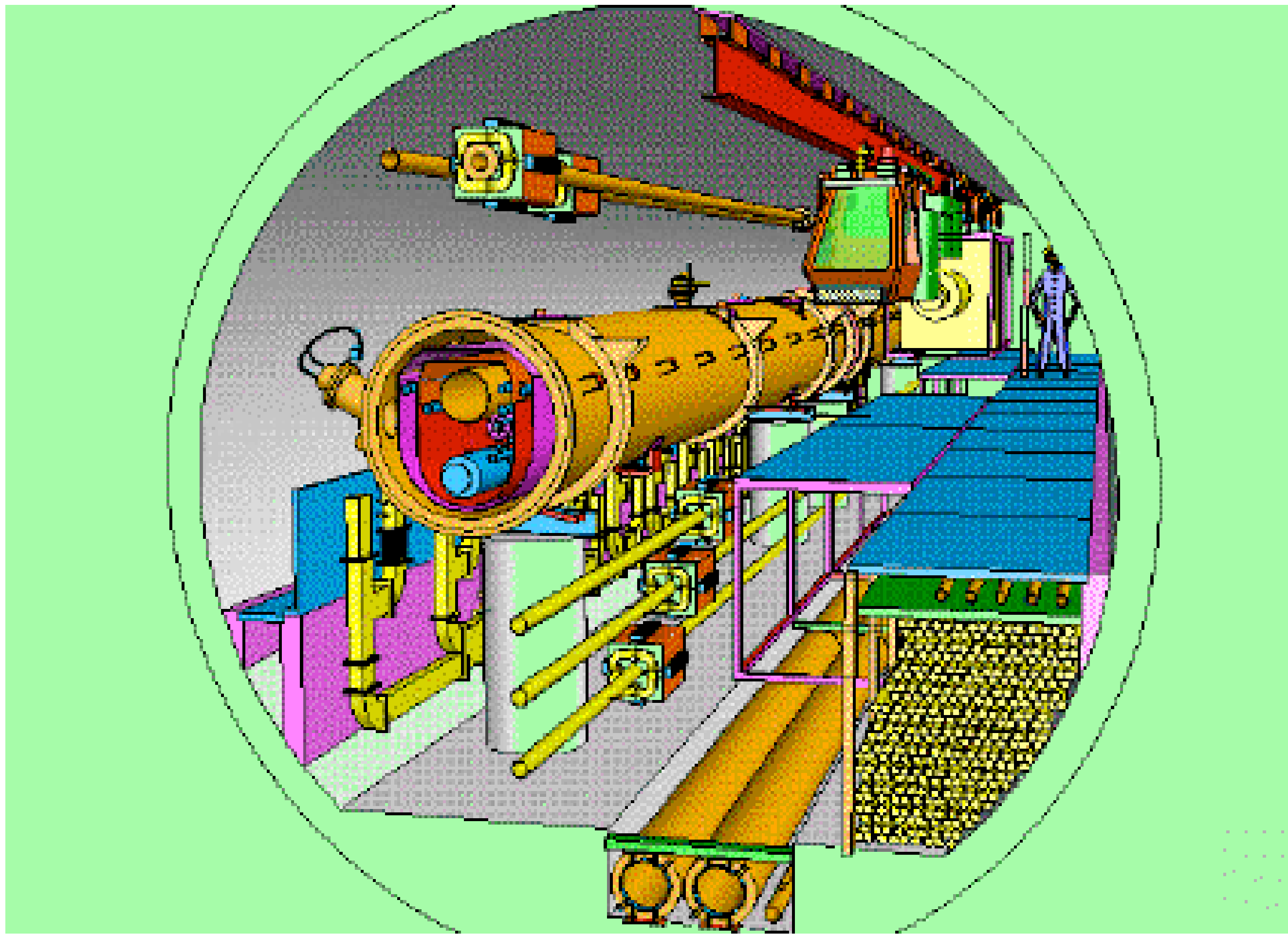
Total Length = about **30 km**.

A Superconducting Linear Collider

A technology direction for an e+e- collider has been established.

Accelerator will be made of superconducting RF cavities.

Lower operating costs, easier alignment, …

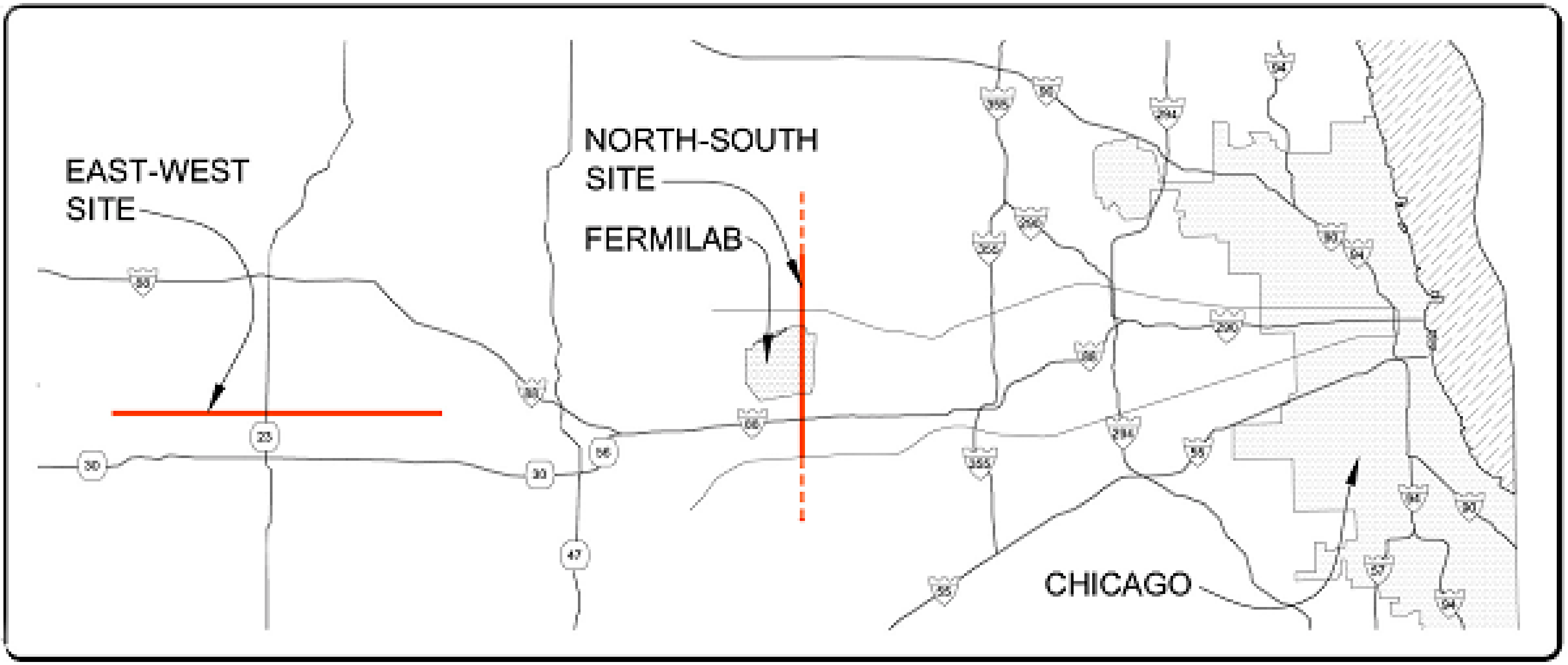


The Size of a Linear Collider

In California, for example …

The Size of a Linear Collider

In Illinois, as ***another*** example …

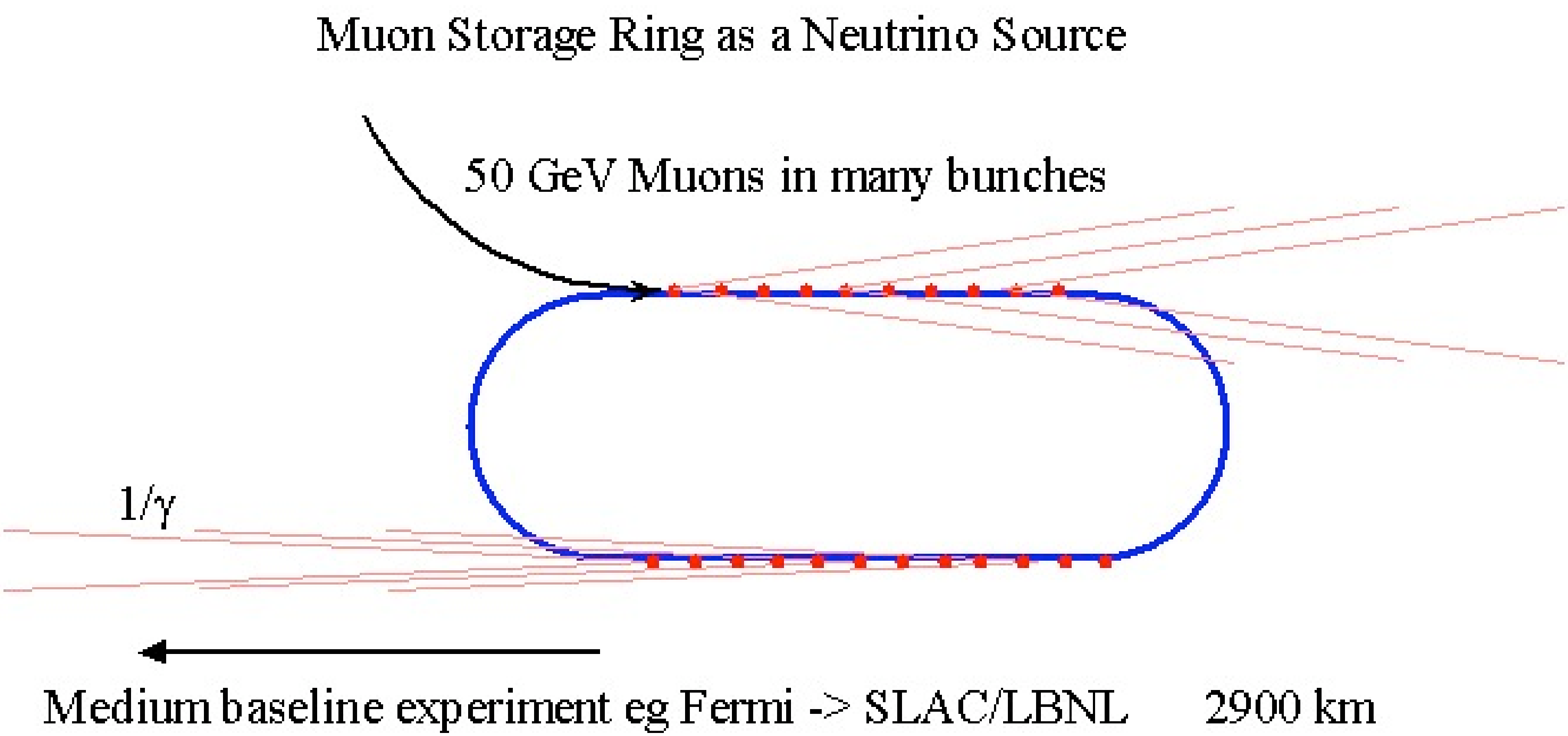


Muons on Muons

- Muons are fundamental particles, like electrons, but are heavier, and thus do not radiate as easily as electrons. So, could consider a mu-mu collider.
- However,
  - They only stay around for 0.000 002 seconds (or so)
  - They decay into electrons … which then radiate a lot!
  - … and into neutrinos … hmmm …
  - Is this short lifetime so bad?
  - Can it be used to our advantage?   >>> See next slides

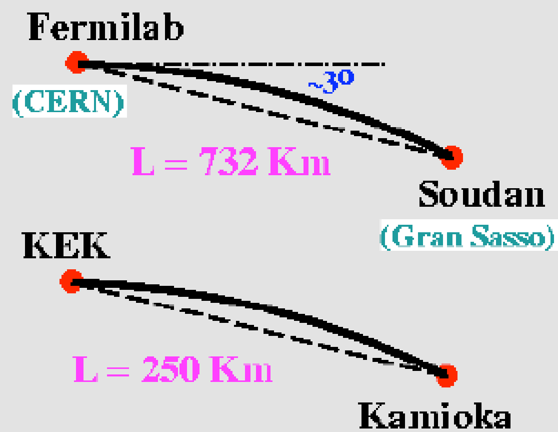
Neutrino Factory

Concept (from Steve Geer / Fermilab)

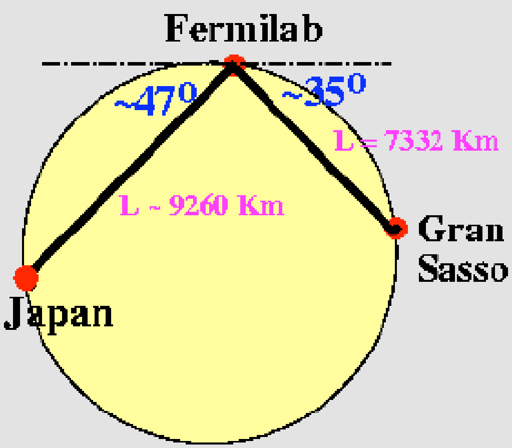


Neutrino Factory

	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL –> Soudan	732	3	336
FNAL –> Gran Sasso	7332	35	50
FNAL –> Kamioka	9263	47	325



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3
50	14.6	5.0



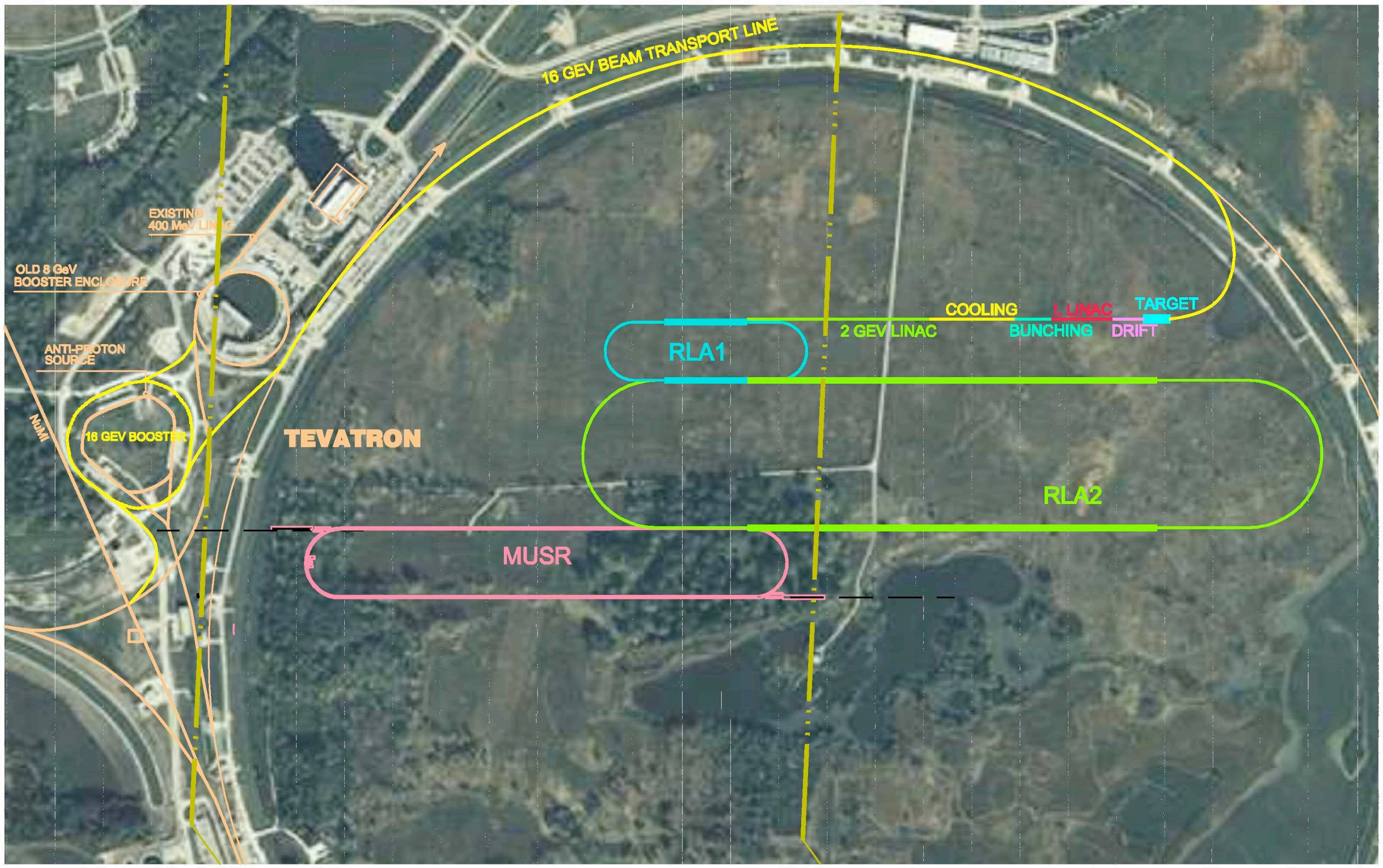
E_ν (GeV)	L/E (Km/GeV) Gran S.	Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

Physics Guidance:

- The Distance *L* between the Neutrino Source and Neutrino Detector is important.
- And so is the ratio of *L* to the Energy *E* of the neutrino beam.

Courtesy S. Geer

A Neutrino Factory at Fermilab

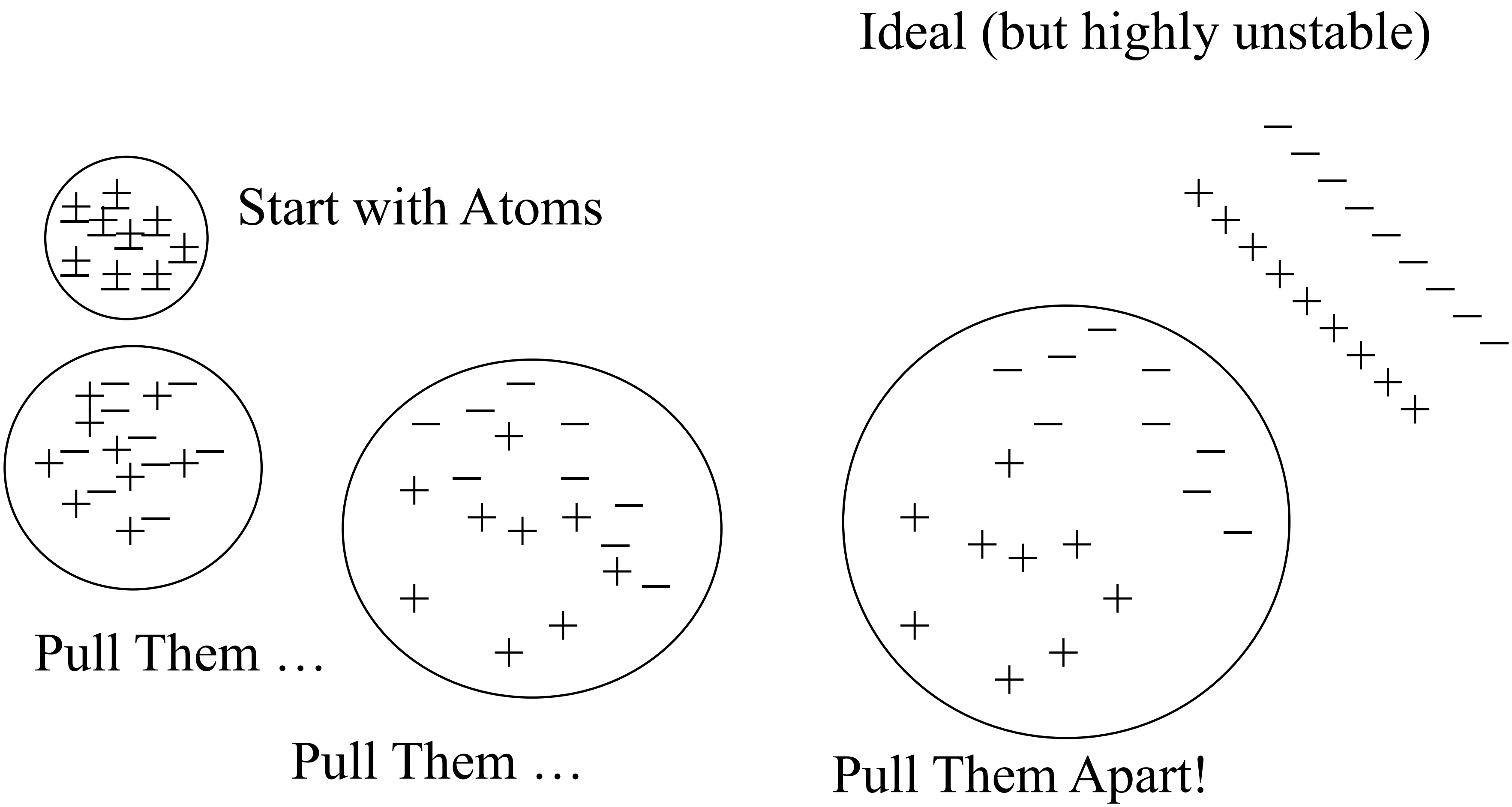


And Into the Beyond ...

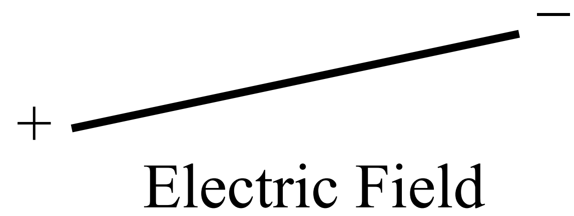
- Problem with far-future sources of acceleration:
  - Hasn't been done before …
  - And, usually, for good reasons -- it's hard!
- One example is Plasma acceleration concept:
  - 100 TeV center of mass … and ...
  - All the equipment fits on the Fermilab site
  - But is costs too much to operate …
  - At least … using today's ideas and technology

Plasma

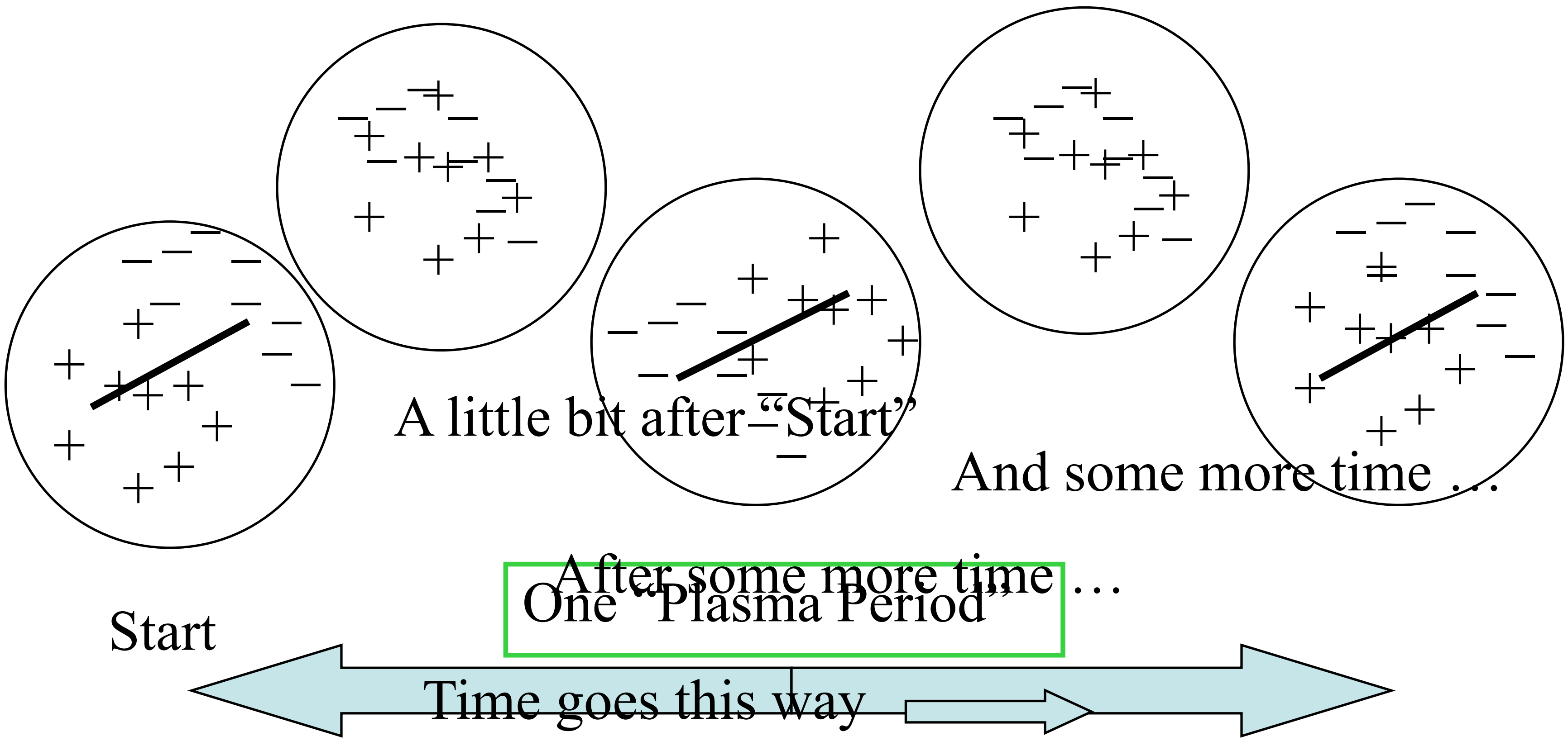
- How is it made?



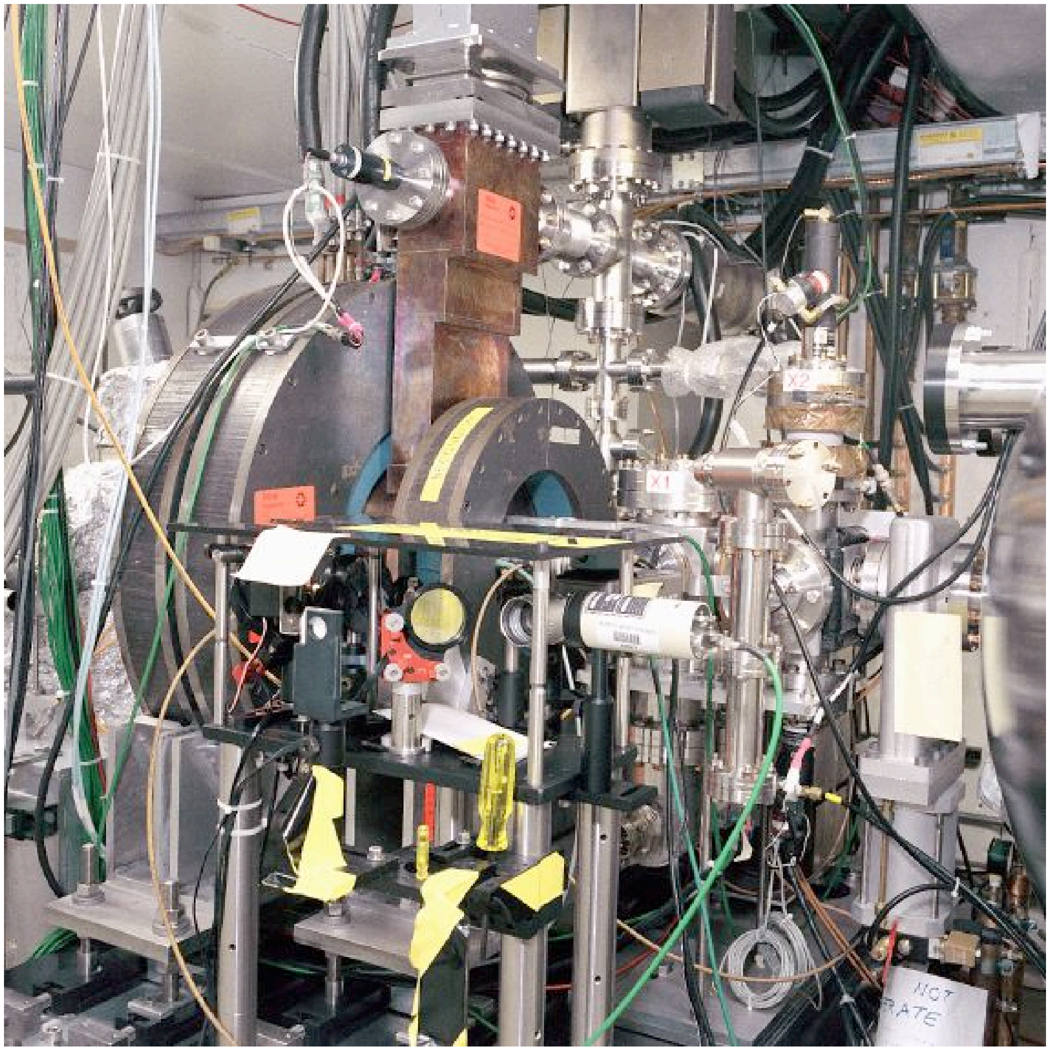
Plasma



- How does it act?



Fermilab NICADD Photoinjector Laboratory



RF Gun and focusing solenoids

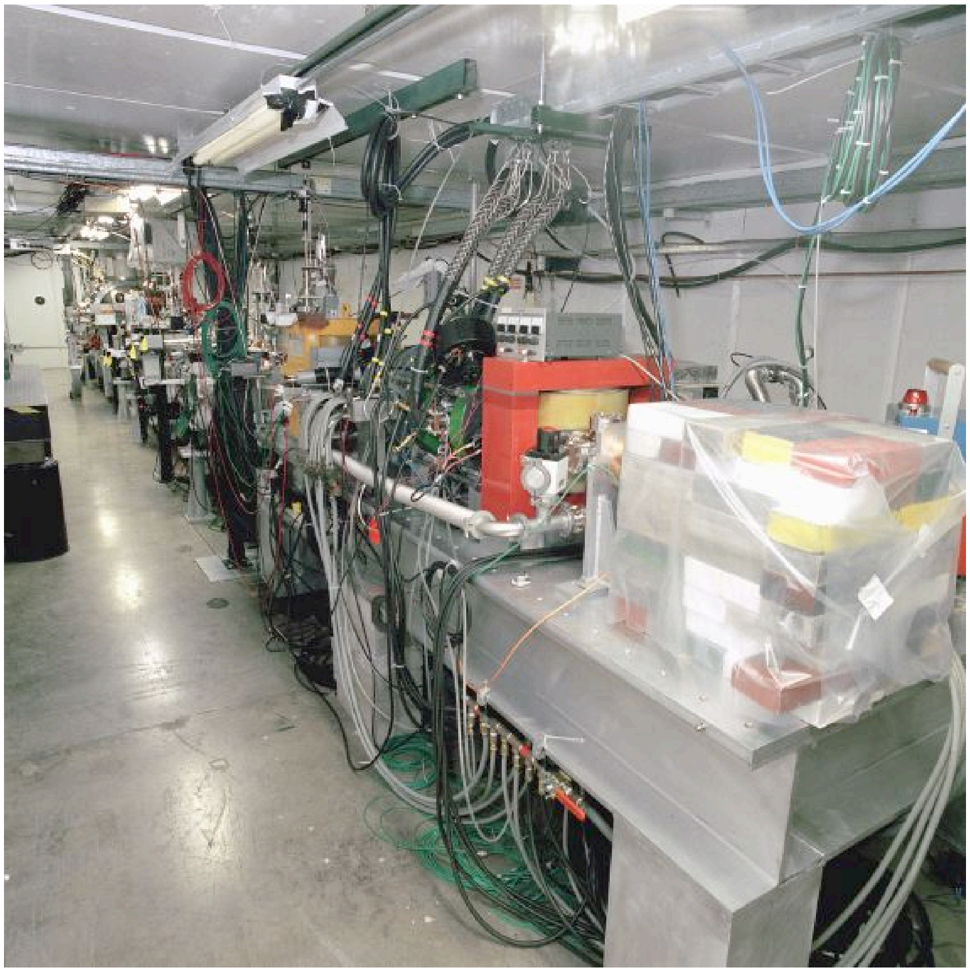
NICADD =

Northern Illinois Center for Accelerator and Detector Development

NIU (Northern Illinios University)

http://www-ap.fnal.gov/A0PI/a0pics.html

FNPL at Fermilab



Spectrometer magnets, plasma chamber, and beam dump

Facility is used for tests of many new and novel ideas in accelerator physics

http://www-ap.fnal.gov/A0PI/a0pics.html