

Accelerators

Mike Syphers

Fermi National Accelerator Laboratory

Accelerator Division

Saturday Morning Physics

October 16, 2004

Fermilab Saturday Morning Physics
2004 - 2005
Session I
October 2 - December 4, 2004

Date	Subject	Lecturer	Tour Area	Group	Tour Guide
Oct. 2	Particle Physics Intro	R. Dixon	Central Lab	I	E. Ramberg
			Central Lab	II	A. Chou
			Accelerator	III	R. Dixon
Oct. 9	Cosmology	M. Jackson	Accelerator	I	M. Malek
			Accelerator	II	Y. Maravin
			Central Lab	III	R. Dixon
Oct. 16	Accelerators	M. Syphers	D0	I	P. Merkel
			CDF	II	H. Meyer
			KTeV	III	E. Ramberg
Oct. 23	Detectors	M. Demarteau	CDF	I	M. Mulders
			KTeV	II	E. Ramberg
			D0	III	B. Rebel
Oct. 30	Symmetry	C. Hill	KTeV	I	B. Reisert
			D0	II	N. Saoulidou
			CDF	III	J. Thom
Nov. 6	Relativity	R. Plunkett	FCC	I	M. Tomoto
			SiDet	II	M. Wang
			Magnet Facility	III	M. Weber
Nov. 13	Matter/Antimatter	R. Tschirhart	SiDet	I	M. Wobisch
			Magnet Facility	II	J. Yoo
			FCC	III	S. Burdin
Nov. 20	Quantum Mechanics	B. Dobrescu	Magnet Facility	I	C. Lin
			FCC	II	E. Ramberg
			SiDet	III	S. Fu
Nov. 27	No Class due to Thanksgiving				
Dec. 4	Physics & Society	E. Ramberg	GRADUATION		



Classes meet in 1 West

Lectures begin at 9:00 am

Tours begin at 11:00 am

Class is NEVER Cancelled

About the Speaker...

- Scientist, Accelerator Division
- Hometown: Indianapolis, IN (Ben Davis H.S.)
- College:
 - Indiana University, B.S
 - De Paul University, M.S.
 - University of Illinois - Chicago (UIC), Ph.D.
- Work Experience:
 - High School Teacher (Batavia H.S.!) -- 1 year
 - Fermilab -- 9 years + 6 years
 - In between:
 - SSC Laboratory (Supercollider), Texas -- 5 years
 - Brookhaven National Laboratory, New York -- 4 years

email: syphers@fnal.gov

web: <http://www-ap.fnal.gov/~syphers/>

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 **E. Harms, FNAL/AD**, for help in preparation of this talk.*

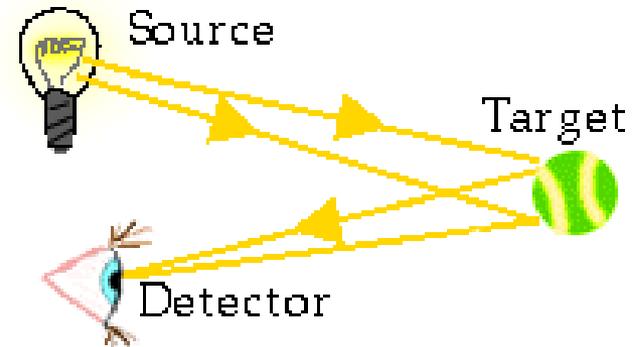
Why Do We Need Accelerators?

- Your parents might say otherwise, but you probably say 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.

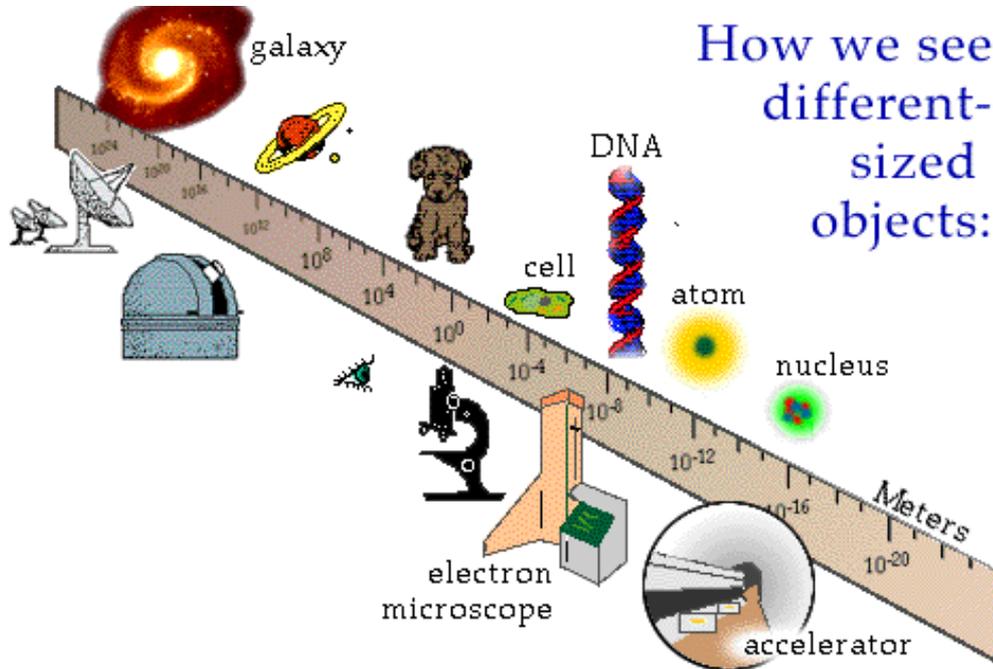
So, why Do *We* Need Accelerators?

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



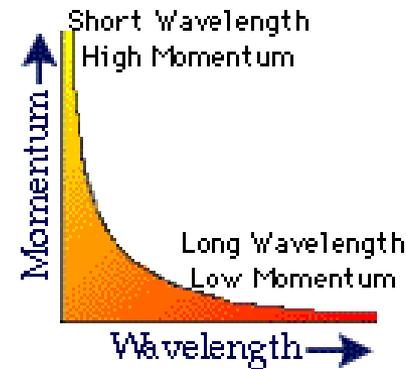
- We need to send source particles toward target particles and then detect the outcome. Next week, will discuss detectors; this week, we discuss how we generate our source (and, for the Tevatron Collider, the target as well!)
 - But, why do we need High Energy?

Wave-Particle Duality of Nature



DeBroglie said moving particles have an equivalent wavelength,

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



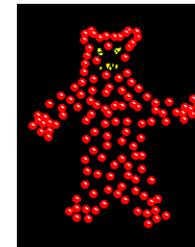
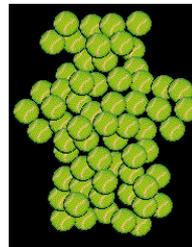
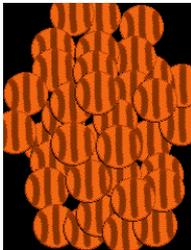
Plus, add a little bit of Einstein's work:

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

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

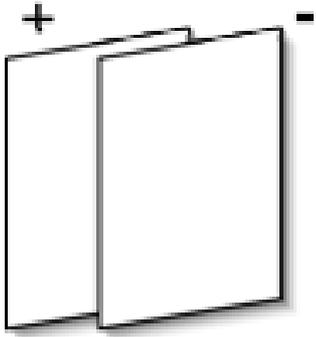
So, why Do *We* Need Accelerators? (cont'd)

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



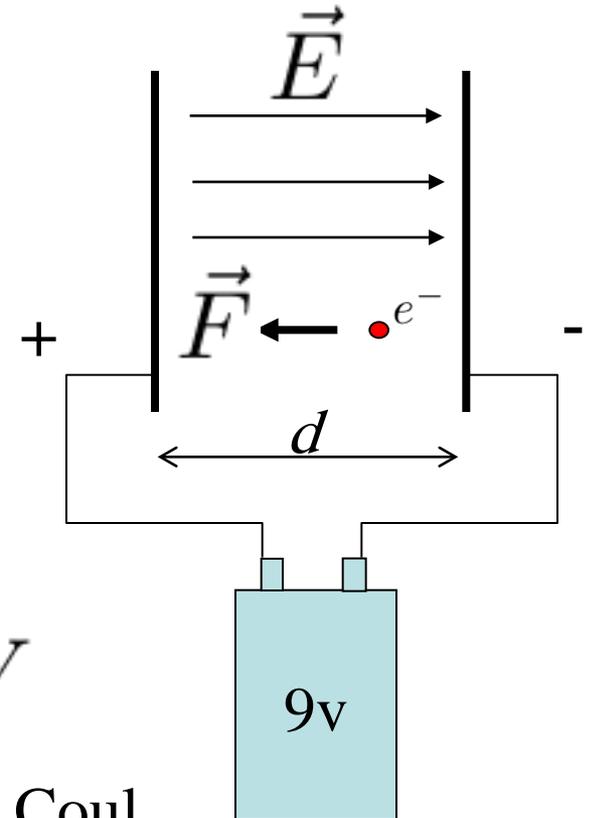
- Also, through $E=mc^2$, ability to create new particles (mass) from energy!
- But, we also require large numbers of particles plus the ability to control the particles (steer, focus, increase/decrease intensity, for instance) in order to conduct experiments efficiently and in a controlled fashion.

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 $\Delta E = 1$ eV (1 **electron volt**) ($= 1.6 \times 10^{-19}$ 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 $v = \sqrt{2\Delta E/m}$

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

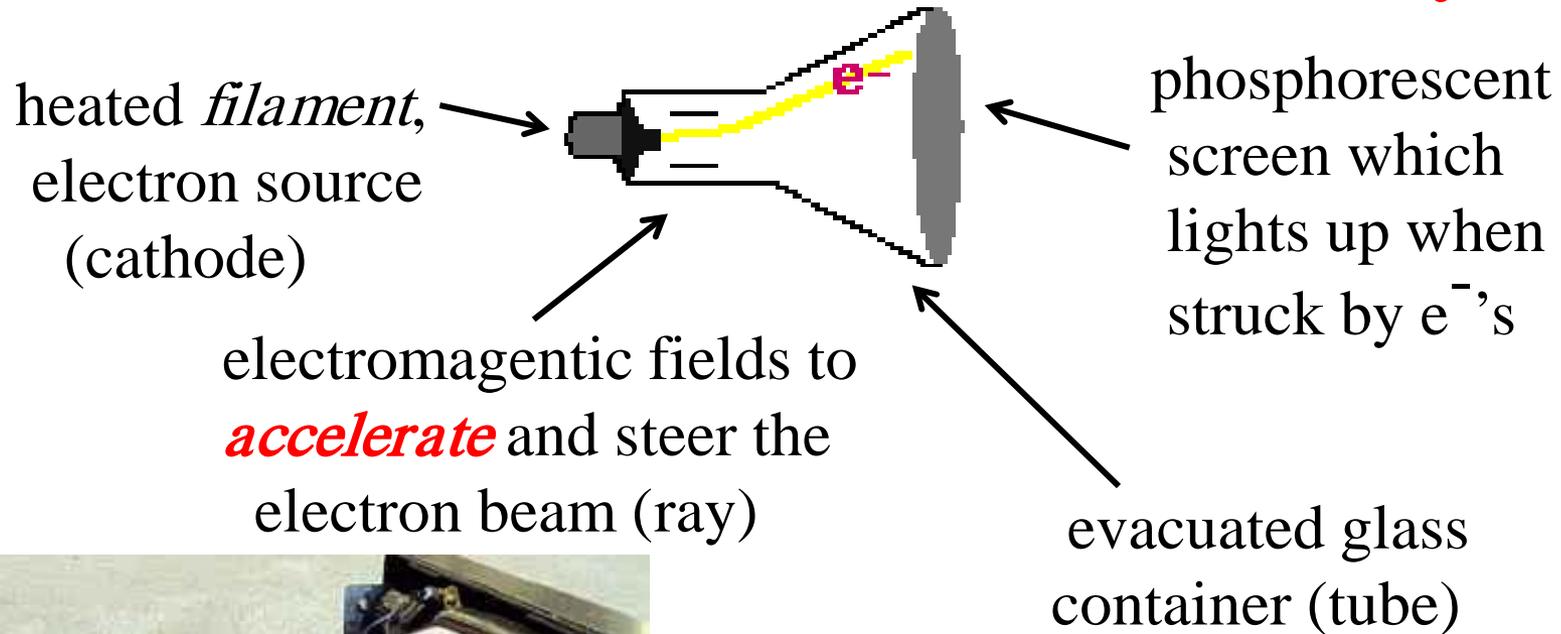
This is **4 million** miles/hr ! = 0.6% the speed of light ($0.006c$)

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

Q: How much voltage can we deliver?

Your TV Set

- The “classic” television is a **Cathode Ray 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**, say!

So, how fast are we moving now?

- The electron in a 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 $0.2c$.
- Does this mean a 50 keV electron would be moving at the speed of light? 100 keV, $2 \times c$???
 - No! Relativistic effects kick in...
 - Will see much more of this in a subsequent class (scheduled for Saturday, November 6!)
 - For now, a few 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, its speed approaches (but never reaches!) the speed of light:

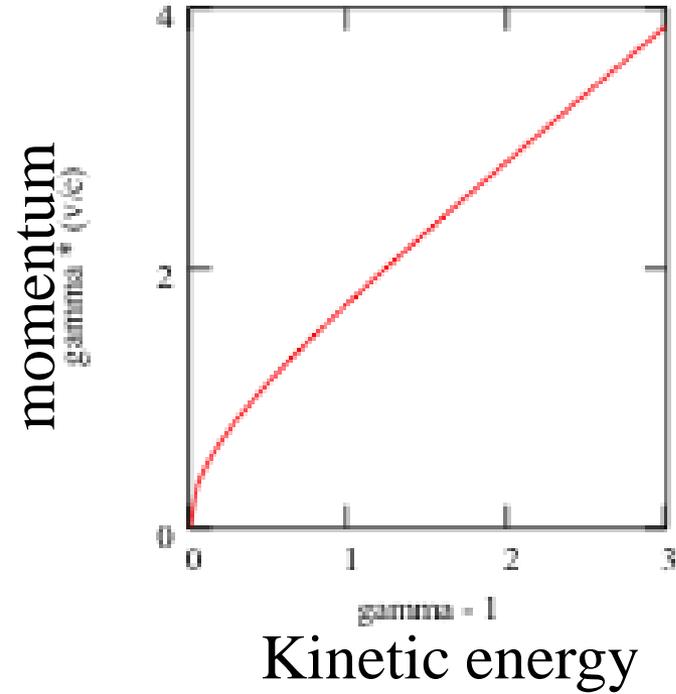
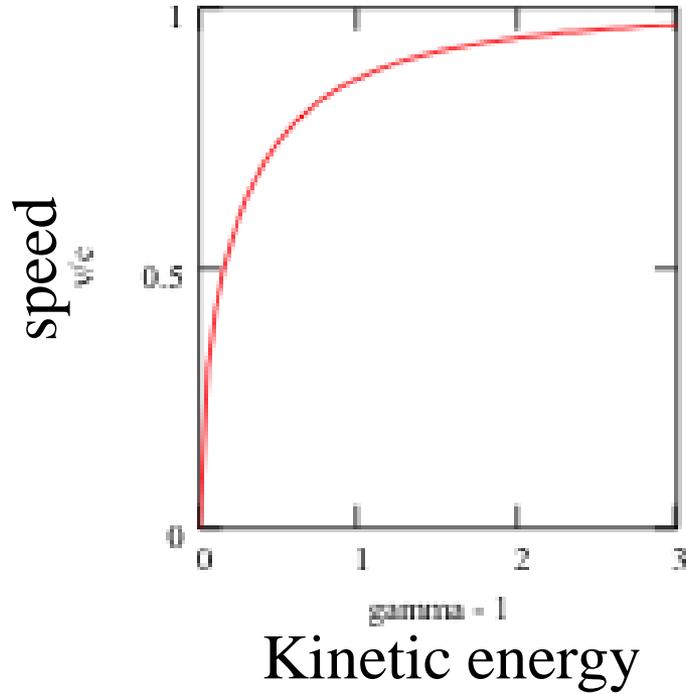
$$v = c \cdot \sqrt{1 - \left(\frac{mc^2}{E}\right)^2}$$

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

$$E = \gamma mc^2 \text{ is the total energy.}$$

- Similarly, the total momentum is defined as $p = \gamma mv$.

Speed, Momentum vs. Energy



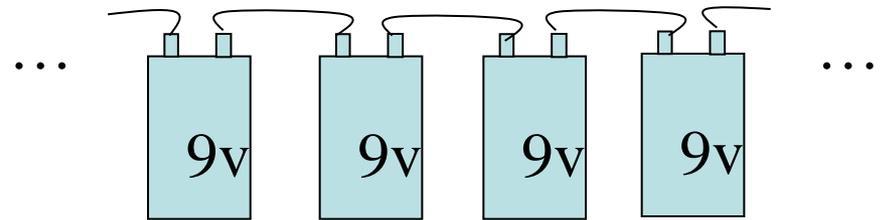
	0	0.5	1.0	1.5	MeV
Electron:	0	0.5	1.0	1.5	MeV
Proton:	0	1000	2000	3000	MeV

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!)



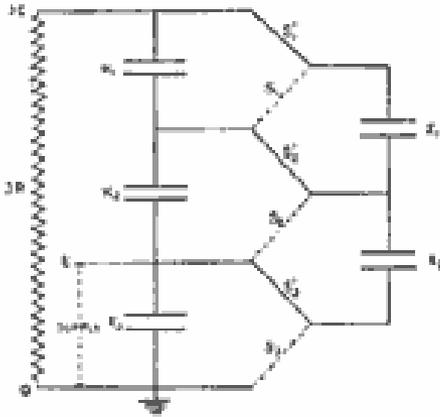
Sharply pointed metal comb at top allows charge to spread out



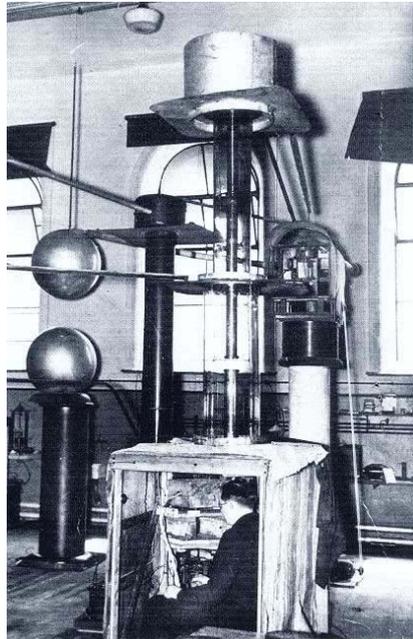
motor-driven pulley and insulating belt
ground

High Voltage

- van de Graaf's are used for particle accelerators (though, with a different configuration) and provide voltages up to $\sim 10,000,000 \text{ V} = 10 \text{ MV}$.
- 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 developed in early 1930's by *Cockcroft and Walton* is named after them:

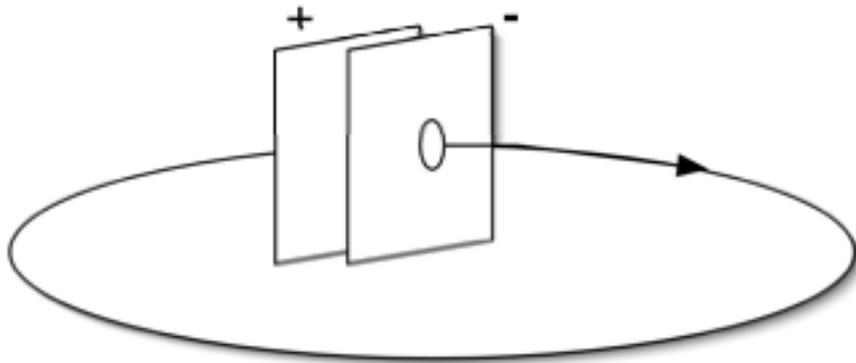


Converts AC voltage V to
DC voltage $n \times V$



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”
- 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!

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

$$T = 2\pi r/v.$$

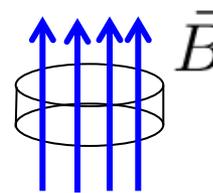
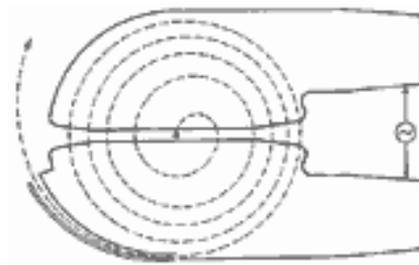
- The force due to the magnetic field is

$$F = evB$$

- The centripetal force is

$$F = mv^2/r$$

- Equating these, we find $r/v = m/eB$
- And so, $T = 2\pi m / eB$
- Oscillate the 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.

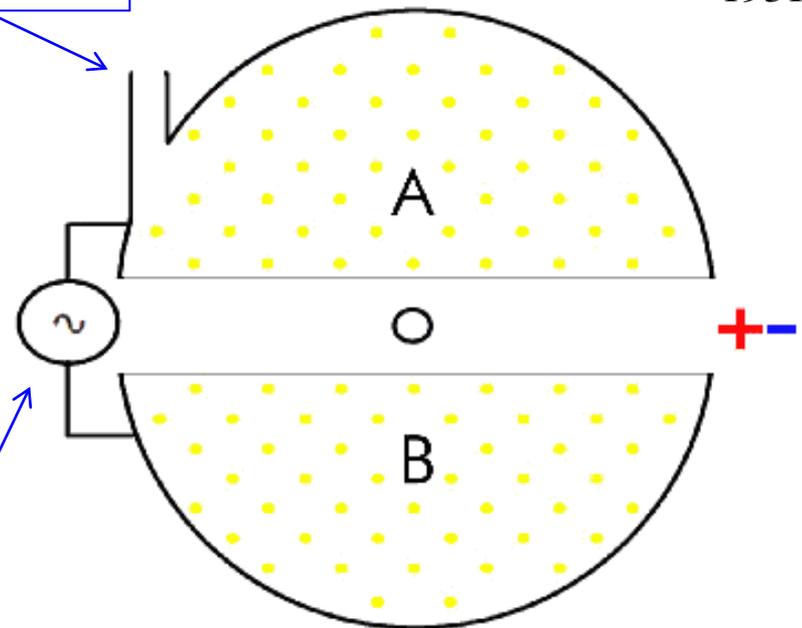


4.5 in.
↔



*E.O. Lawrence,
1931*

K.E. = 80,000 eV!



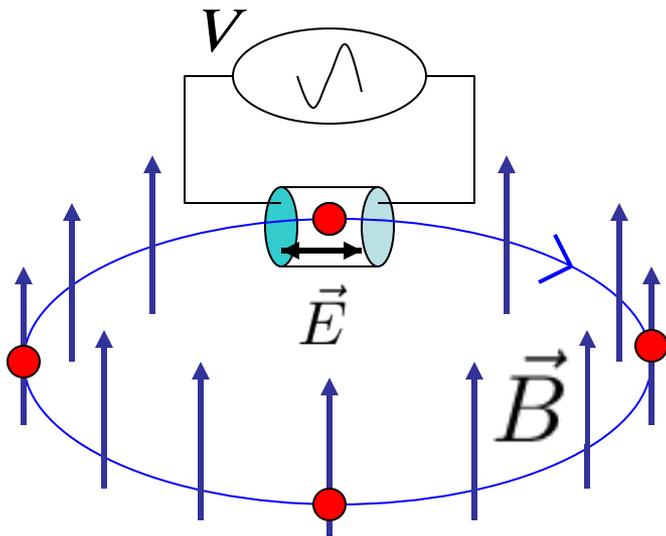
1,800 V power supply

The Synchrotron

- 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*.

Synchrotron (cont'd)

- 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).



$$\text{Voltage} = V \sin(2\pi f t + \delta)$$

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

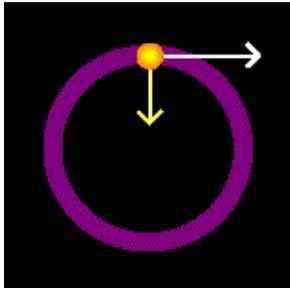
Each revolution,
energy changes by amount
 $\Delta E = e V \sin(\delta)$

δ is called the *synchronous phase angle*

Synchrotron (cont'd)

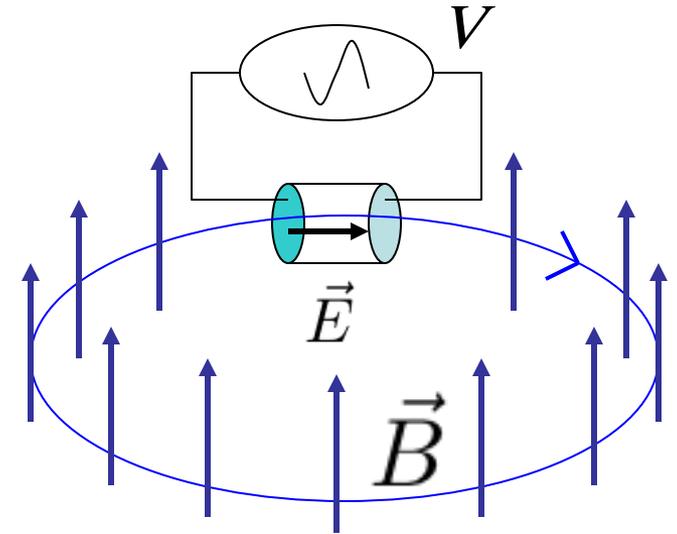
- As the electromagnet fields are slowly increased, the particle will be accelerated by the cavity enough to keep its momentum in step with the magnetic field and keep the orbit radius constant:

$$mv^2/R = evB \implies R = mv / eB = p / eB$$



that is, we synchronize the magnetic field with the changing momentum (due to acceleration) to keep the particles on a constant orbit.

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



What frequencies do we need?

Let's say $v \sim c$,
 and say $R = 1 \text{ m}$
 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 much technology which could be used in the particle accelerator business.
- 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

$h = 1113$

plus a few more!



Main Injector

Will see more details
later in this talk...

The Need for Focusing

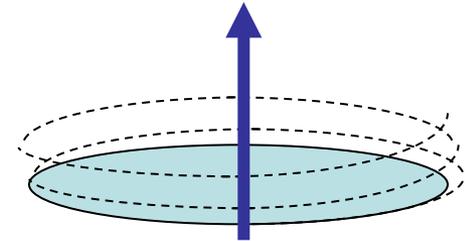
- Particles move in circular orbits in a uniform magnetic field
- What happens if we deflect a particle as it is going around?
- Deflections in a Uniform magnetic field:

– Horizontal -- stable

Vertical -- **NOT**

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

B



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

Deflection of Particle Trajectories

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

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

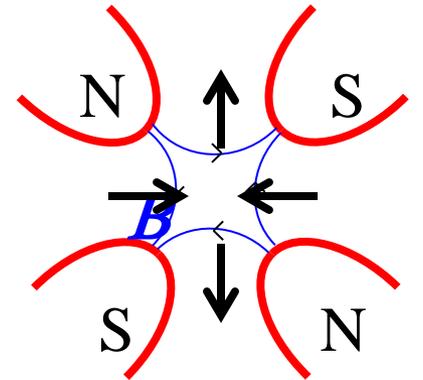
- What about Gravity?? Look at a proton...

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

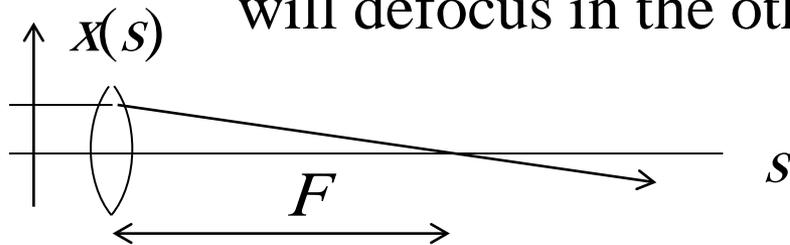
– Not even a *player*!

Focusing

- So, as particles move around the accelerator, we 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)

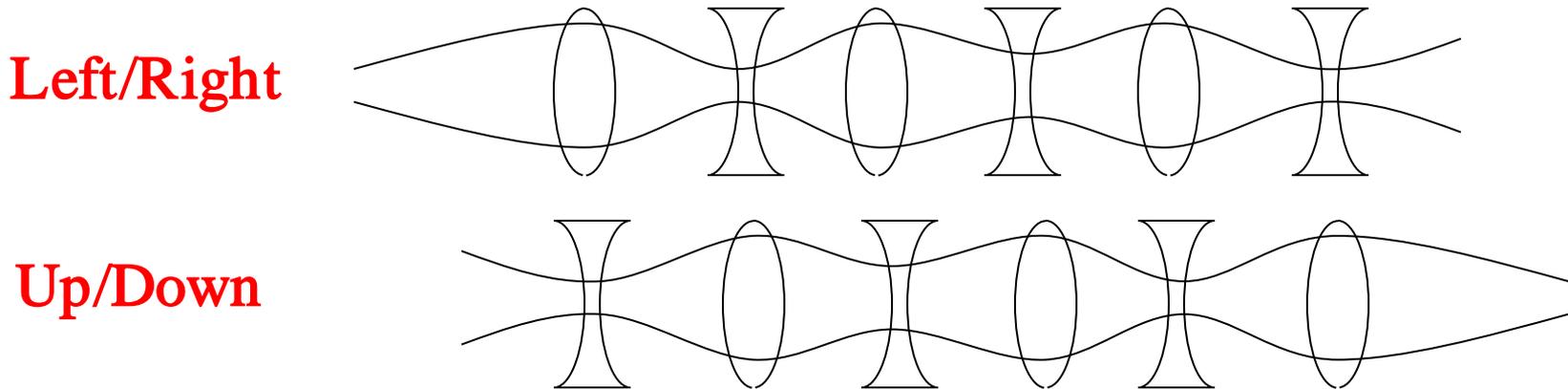


So, **alternate** lenses: + - + - + - ...

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



- 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!

Some Basic Accelerator Hardware

- Acceleration Cavities
 - “pillbox - like” cavity, with radius a , has natural frequency $f_{\text{nat}} = 2.4c / 2\pi a$.
 - For $f_{\text{nat}} \sim 50$ MHz, we see $a \sim 2$ m. (rather big)
 - So, we design other cavity “structures” which are more compact, but which have similar natural freq’s

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

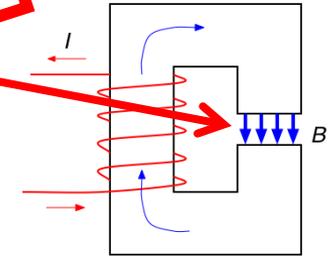


Basic Hardware (cont'd)

- Bending Magnets

- A simple electromagnet might look like:

10 - 100 Gauss



- Accelerator magnet: lots of current and lots of iron!

- Iron-dominated magnets can obtain field strengths up to ~2 Tesla

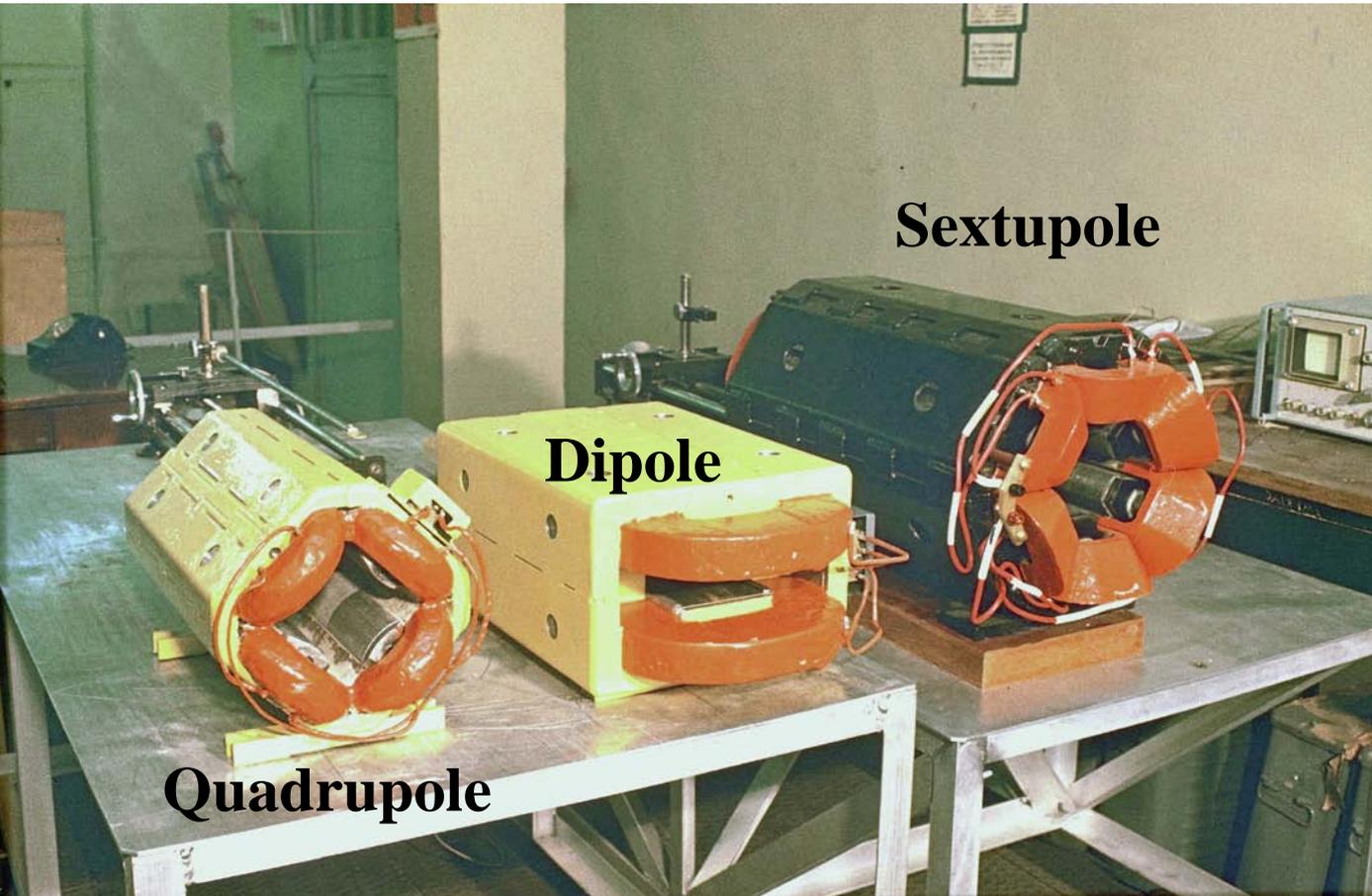
20,000 Gauss!!



- Superconducting coils can generate much higher fields

- Tevatron: 1st superconducting accelerator: $B \sim 4.4$ T
 - Nowadays, technology limit for accel. mag. is about 10-15 T

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.

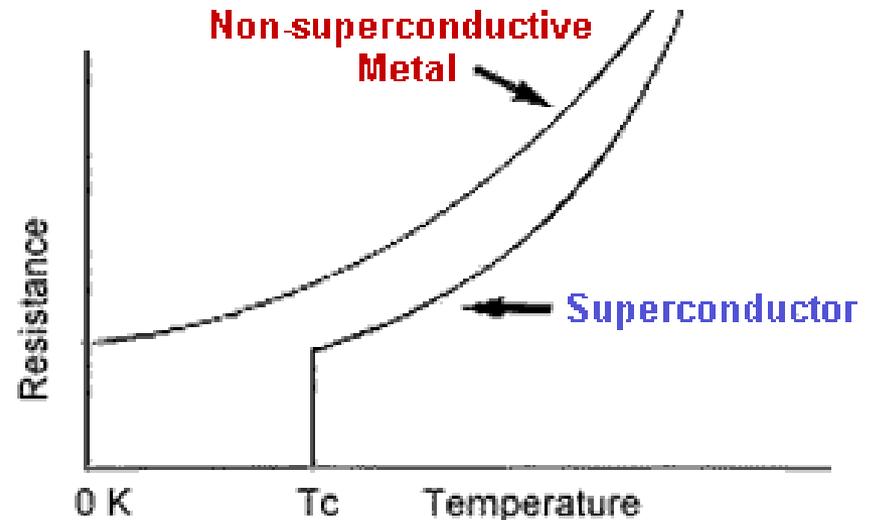
Iron: fields limited to about 2 Tesla (20,000 gauss)

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*



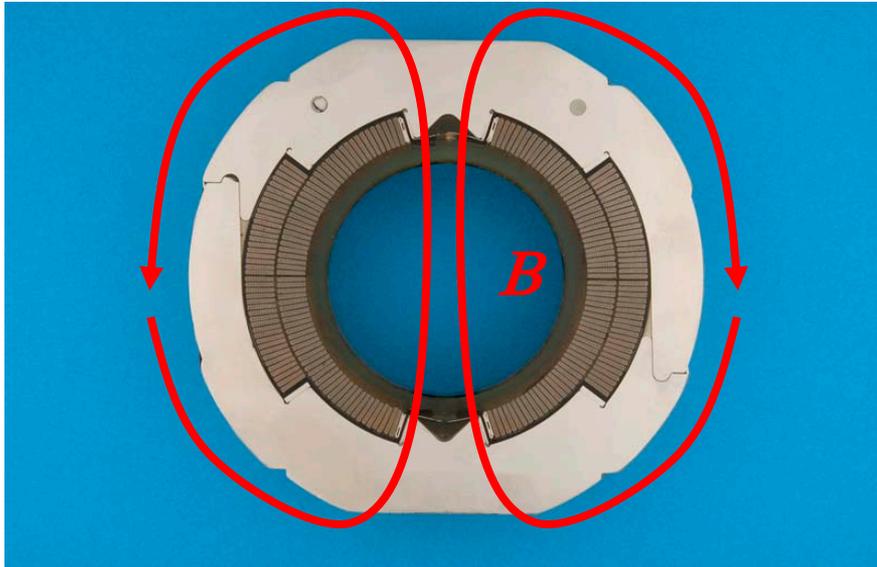
- Took many years to understand, and to perfect the production of superconducting materials suitable for commercial use



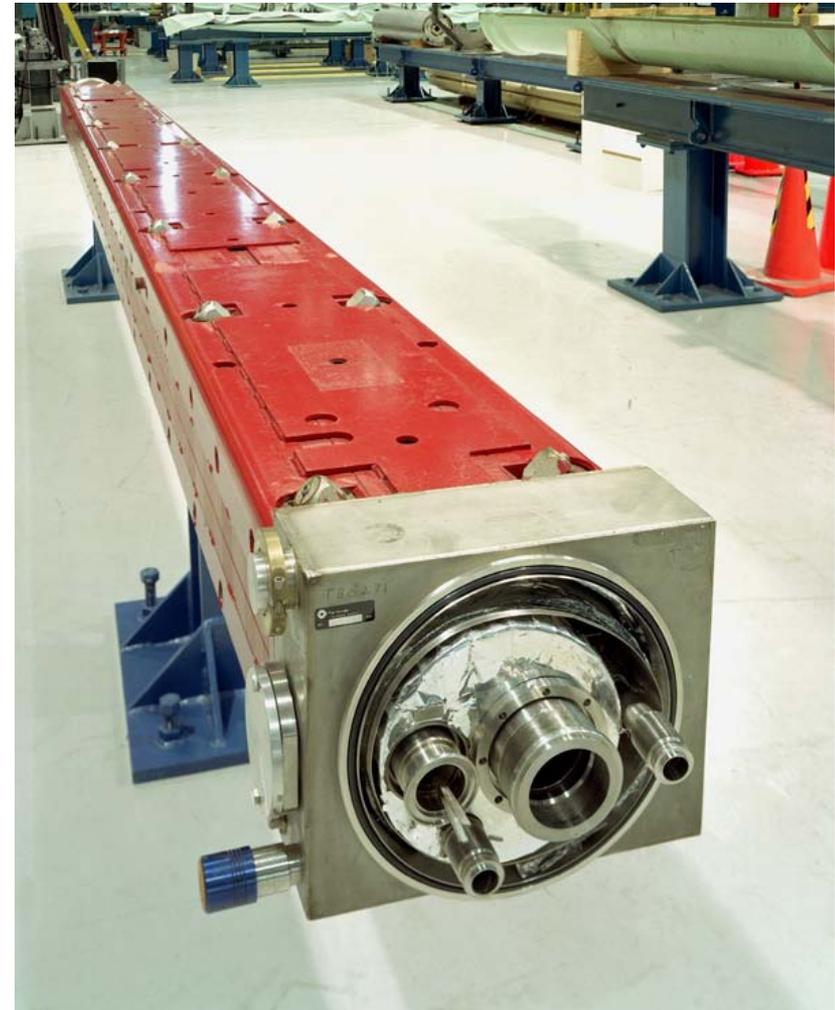
Superconducting Accelerator

- 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 $4\text{ }^{\circ}\text{K} = -450\text{ }^{\circ}\text{F}$!
 - 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°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)

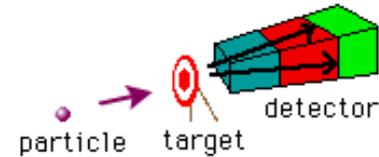


Fixed Target Experiment

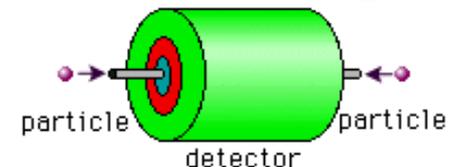
vs.

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.

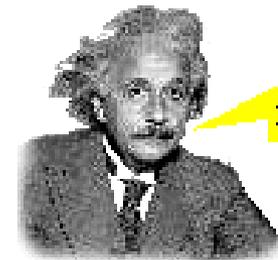


- With the Tevatron, it became feasible to store particles in the ring for long periods of time. By sending beams of particles going in both directions within the accelerator, and steering them to hit head-on at particular locations, we can pass groups of particles through each other over and over until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



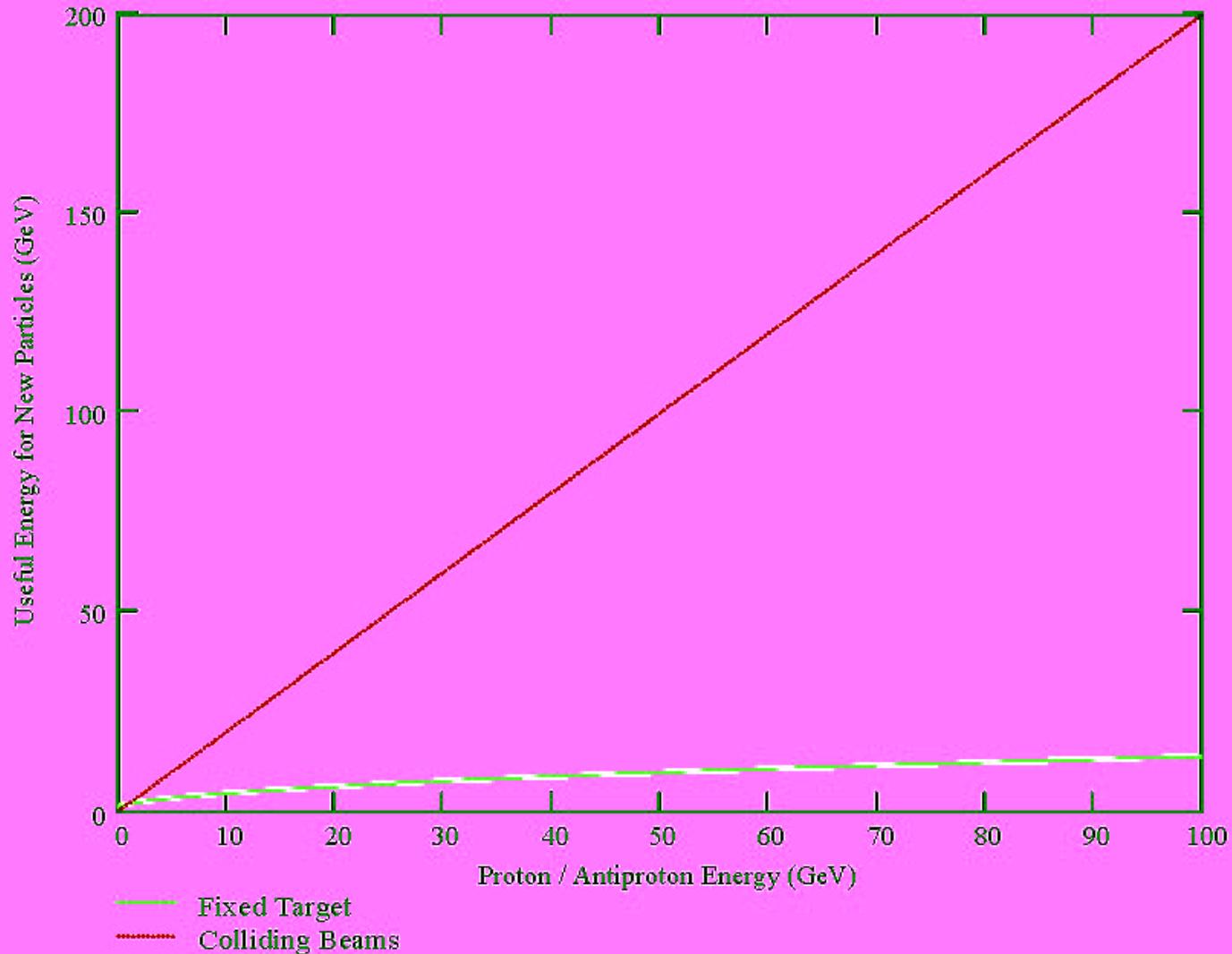
Colliding Beams

- 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*!



Mass is just a form of energy!

Available Energies



Luminosity

- Fixed Target Experiments:

- *Illuminate* a target with beam particles

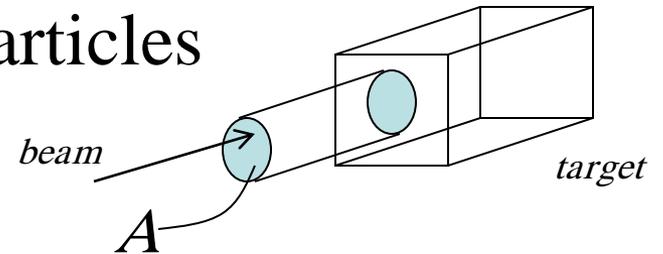
- cross sectional area Σ

- Rate of “interactions” --

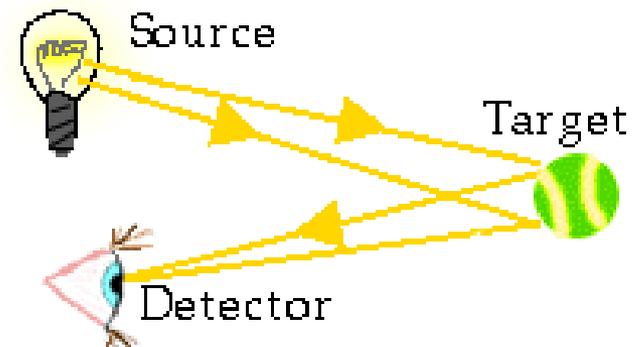
$$R \sim \frac{\Sigma}{A} \times (density \times A \times \ell) / (gm/target) \times (\#particles/sec)$$

- 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:

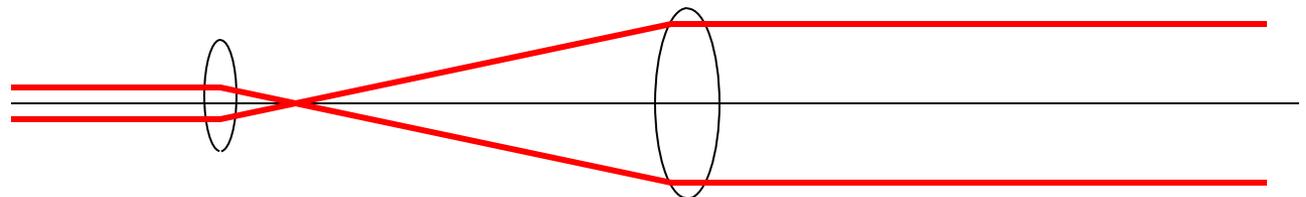
$$L = \frac{f N_1 N_2}{A}$$

Frequency of bunches passing through each other

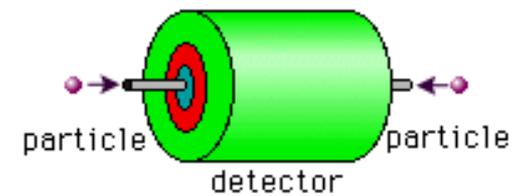
- Depends upon the beam size, and number of particles in each beam
 - Note: has units of $1/(\text{area} \times \text{time})$
 - Gives Experimenters feeling for performance of accelerator
- Thus, to be able to gather more data quickly, need lots of particles, and small beam sizes --
 - In Tevatron, 10^{12} - 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 $60\ \mu\text{m}$ wide (\sim 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...



protons
→

←
antiprotons

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

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

Some Numbers...

- For Tevatron operation,

- $N_{\text{protons}} = 2 \times 10^{11}$, $N_{\text{antiprotons}} = 4 \times 10^{10}$,

- $f = 36 \times (3 \times 10^5 \text{ km/sec}) / 6 \text{ km}$,

- $A = \pi (60 \mu\text{m})^2 = \pi (0.0060 \text{ cm})^2$

- $\text{---> } L = 1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$

- 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!

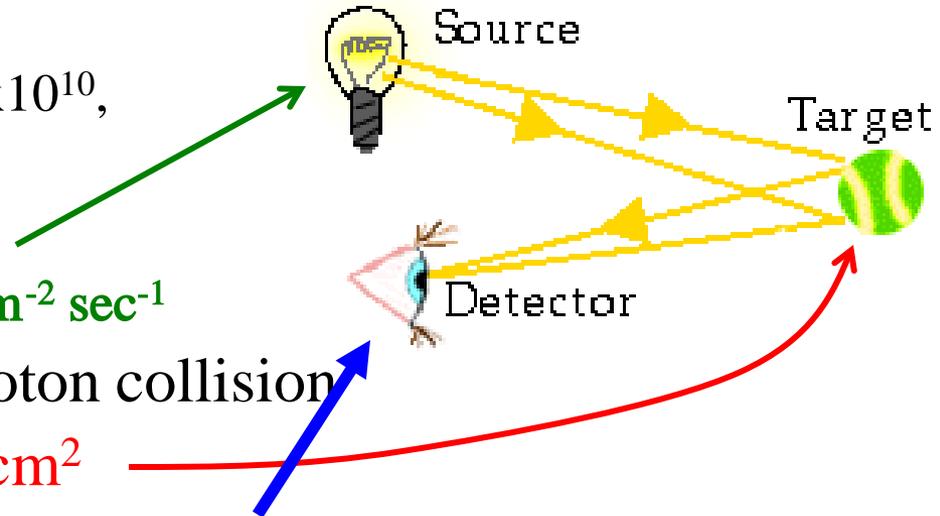
- The Collider detectors must be able to gather, examine, sort, store data at this rate (and they do!)

- 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...

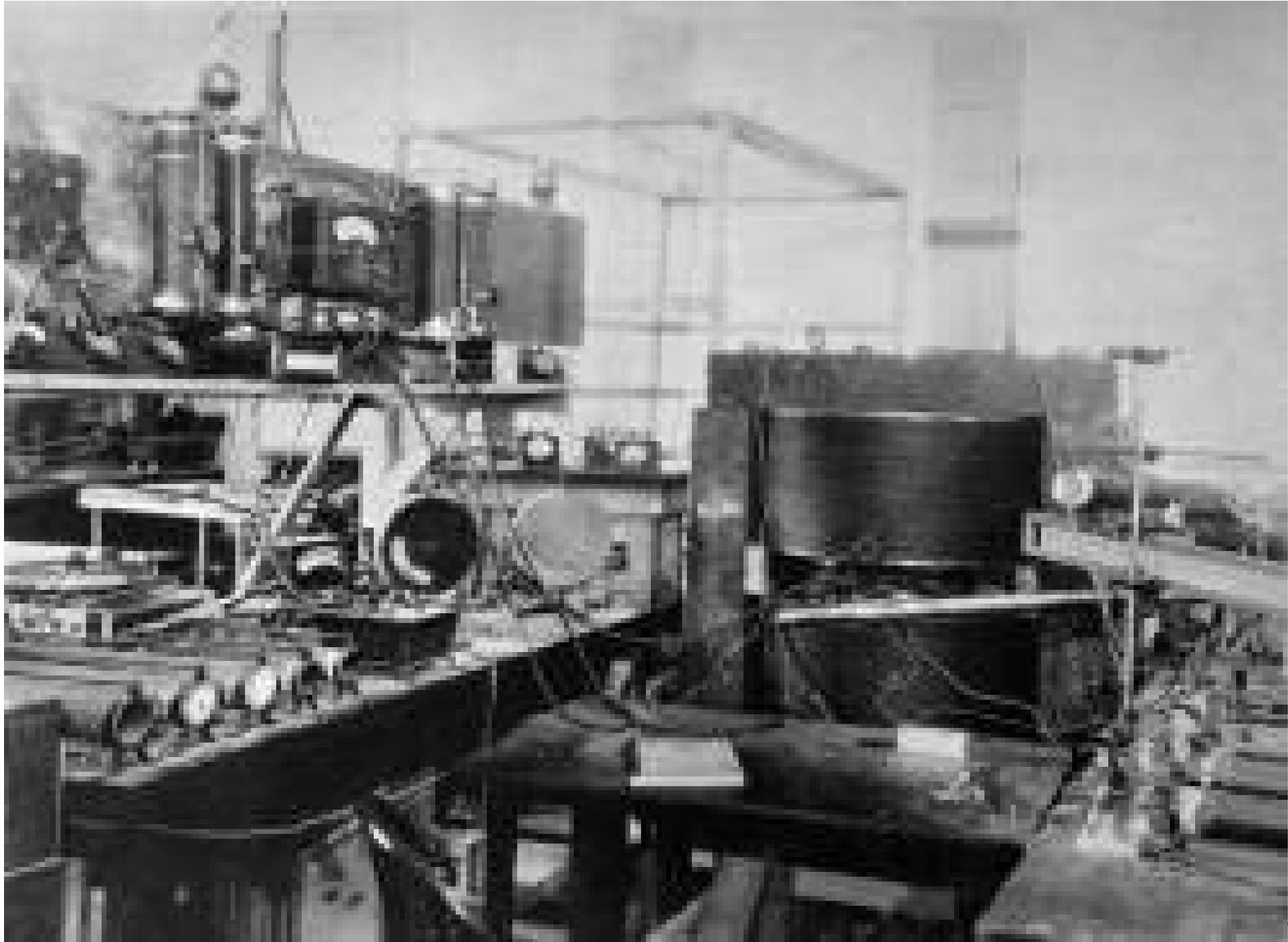
Berkeley Radiation Laboratory



The First Cyclotron, Berkeley -- 1930's



11-inch Cyclotron, Berkeley -- 1930's



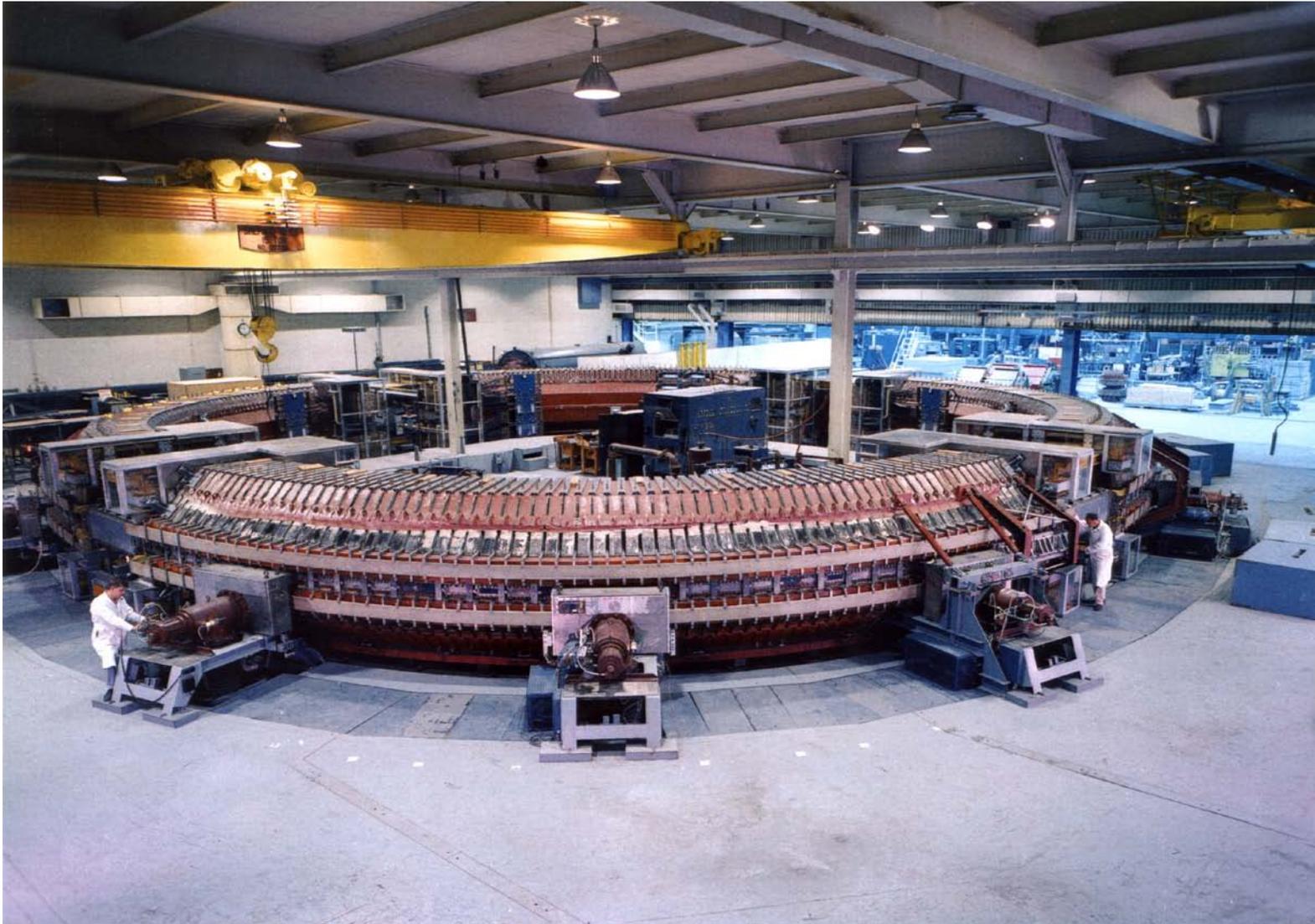
60-inch Cyclotron, Berkeley -- 1930's



184-inch Cyclotron, Berkeley -- 1940's



Cosmotron, Brookhaven -- 1950's



Synchrophasotron, Dubna -- 1950's



AGS, Brookhaven -- 1960's



AGS, Brookhaven, New York



U70, Serpukhov -- 1970's



U70, Serpukhov, Russia



Tevatron, Batavia -- 1980's



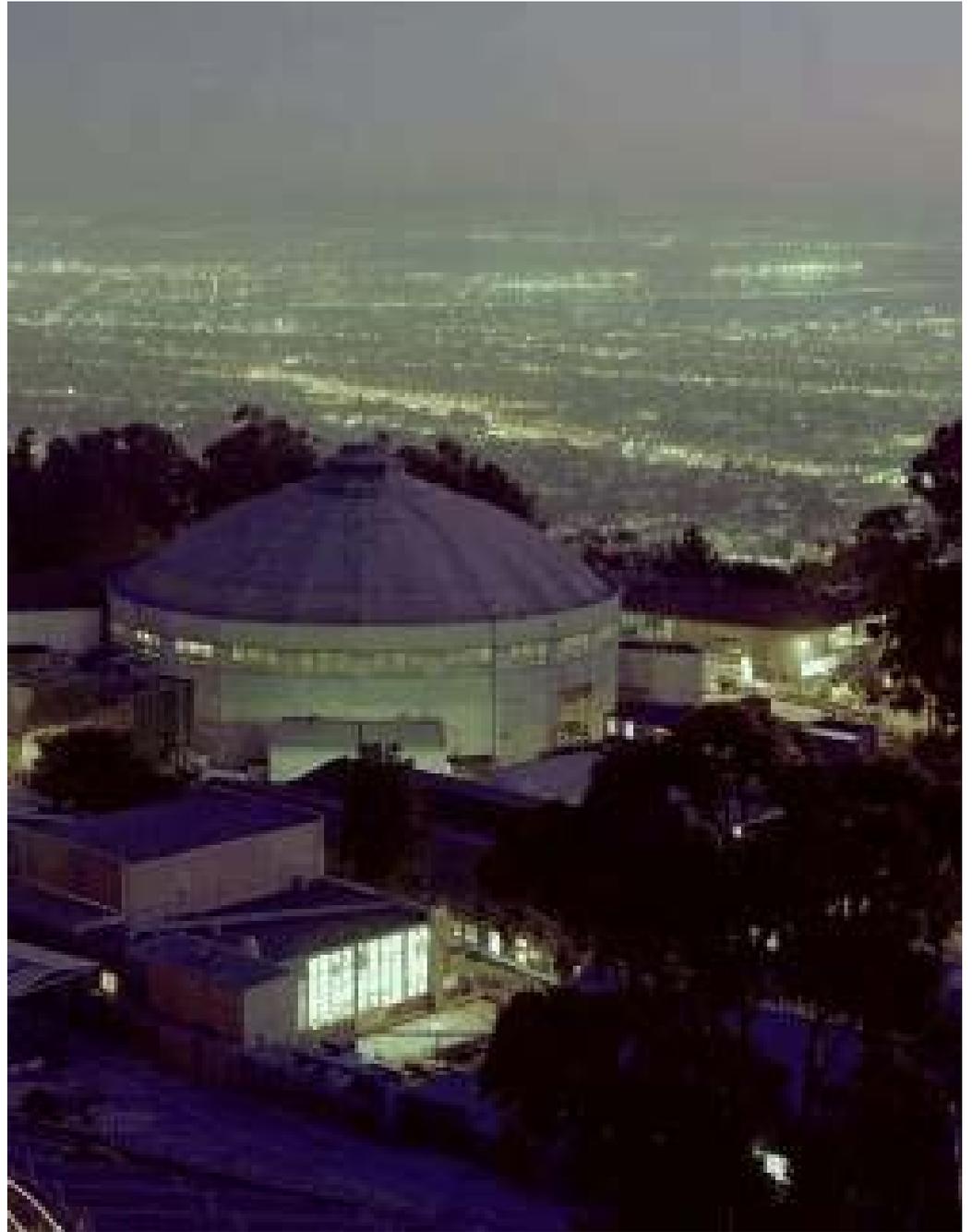
LEP, Geneva -- 1990's



Relativistic Heavy Ion Collider Brookhaven -- 2000's



Lawrence Berkeley National Laboratory



Cornell University -- CESR



Stanford Linear Accelerator Center



Brookhaven National Lab



Fermilab



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.



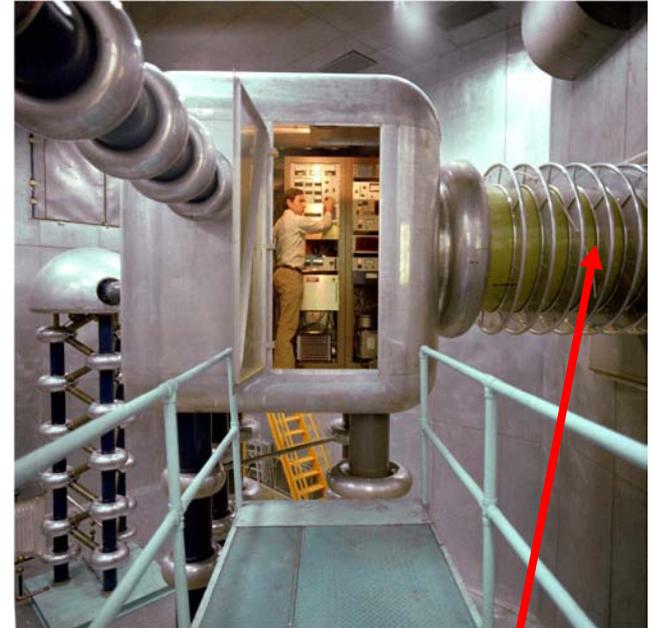
Cockroft Walton Preaccelerator



All starts here!

inside the dome:

Begins with a bottle of hydrogen gas, H_2 , which is combined with Cesium to produce H^- ions
($1 p^+ + 2e^-$)

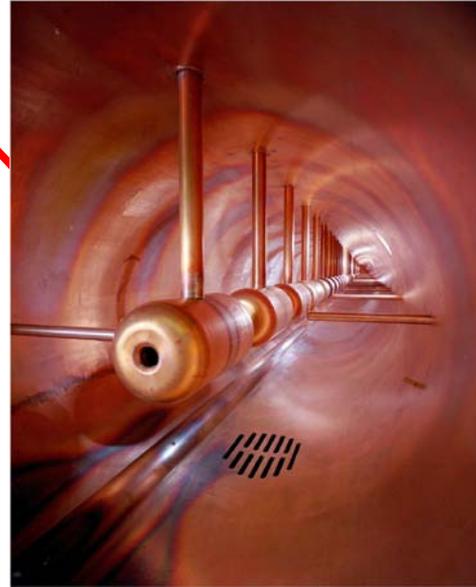


Final kinetic energy of the ions is 0.75 MeV, and their speed is $\sim 0.04c$

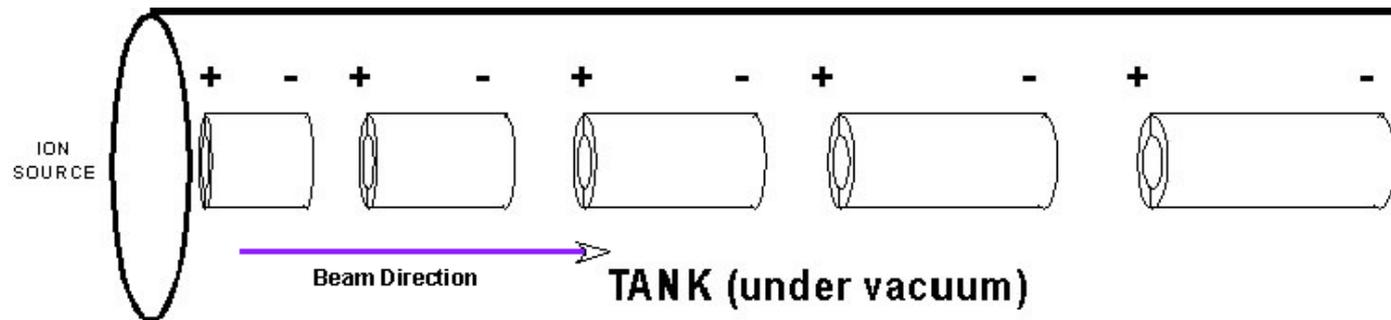


The H^- ions are attracted toward the wall, through the column, and thus gain speed/energy

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 $0.7c$
- gap spacing not changing much; use different cavity structure
- here, field oscillates at 800 MHz
- Total Linac length:
- Final kinetic energy: 400 MeV

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

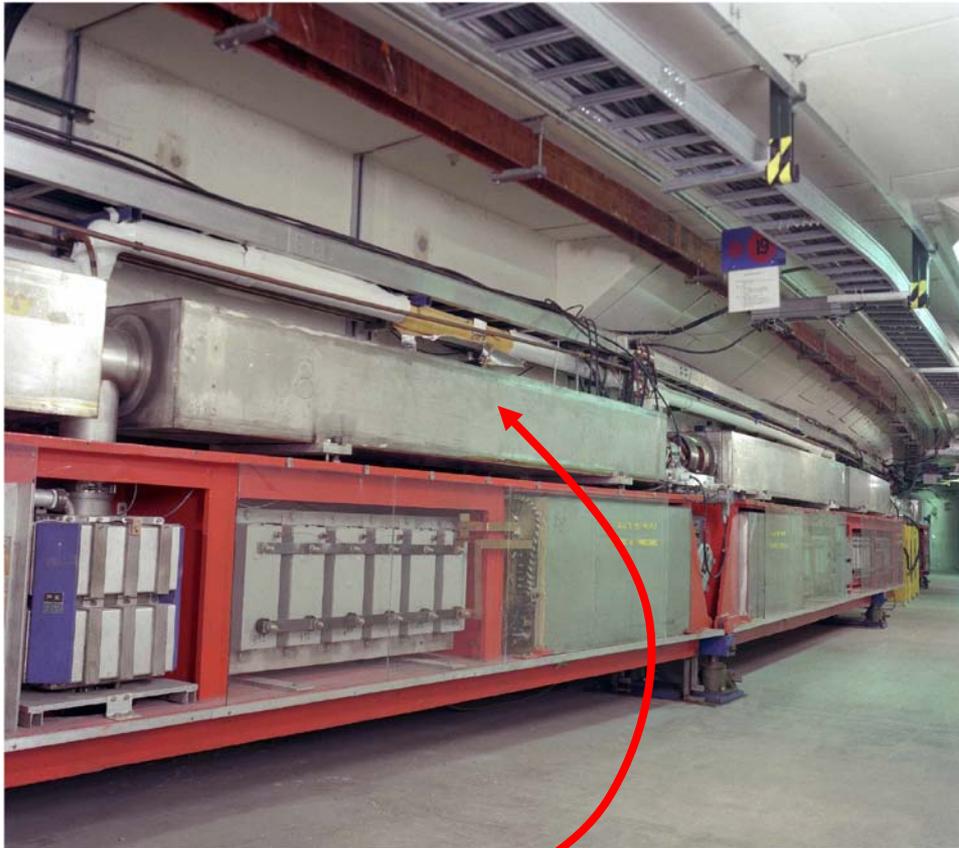


Booster Synchrotron

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.; leave traveling at 99% c !

Total process takes **0.033 seconds!**



Magnets

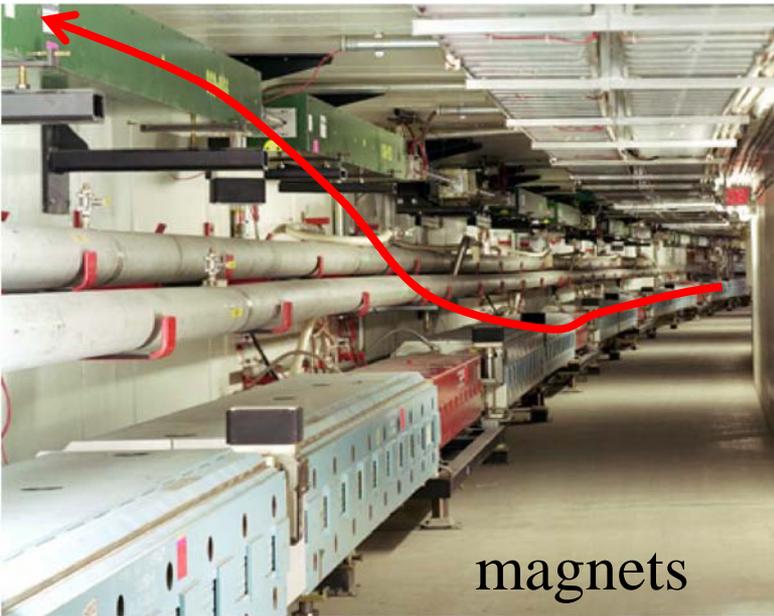
RF accelerating cavities



Main Injector

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

- Protons to Antiproton Source
- 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)



magnets



RF:

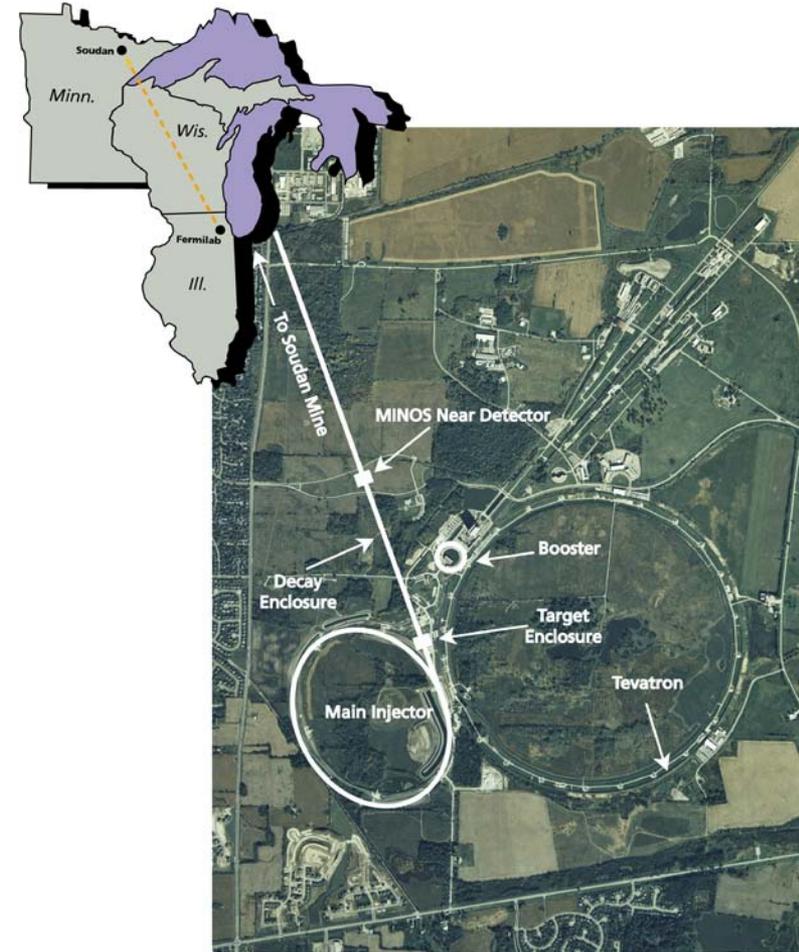
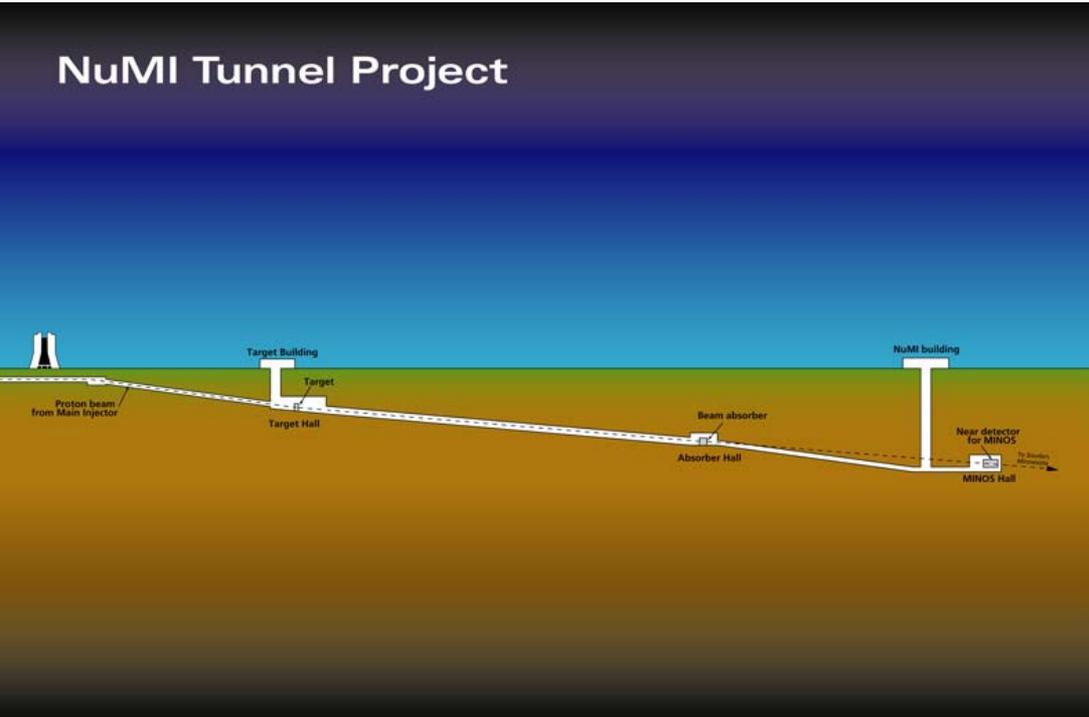


To Minnesota!

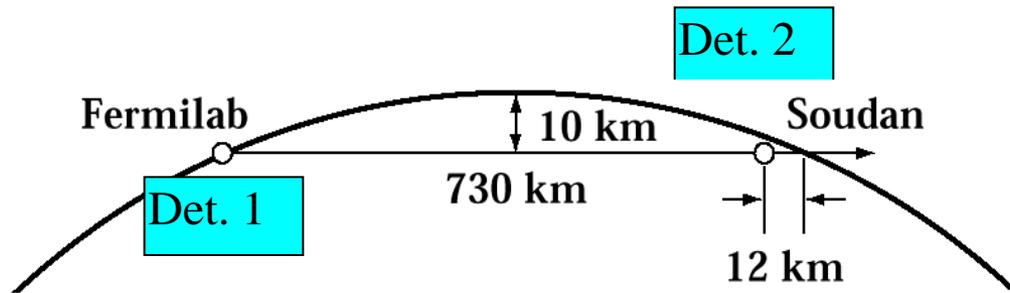


Neutrinos at the Main Injector

NuMI Tunnel Project



FERMILAB #98-1321D



Search for neutrino oscillations (mass)
Under construction; will be starting up
next year ...

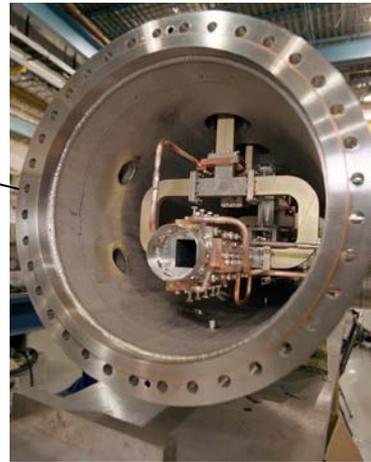
Antiproton Source

- 120 GeV proton beam from MI strikes target, produces LOTS of particles, every 2 seconds or so
- 8 GeV antiprotons are 'filtered' out and stored
- Stochastic Cooling system works on the beam, reducing its size and allowing room to grab/store more particles
- After about 10 hours or so, have ~1 Trillion antiprotons! Send to the Collider!



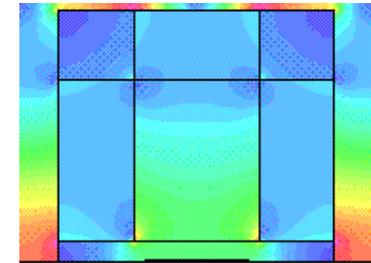
Beam cooling systems

Tunnel
Movie



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
 - Still! Commissioned in 1983
 - 1st superconducting accelerator
 - Circumference = 2π km (+/- 5 cm!) = 4 miles
 - At 1 TeV, protons, antiprotons are traveling at speed of $0.9999996 c$!
 - One round trip for a proton takes 21 μ sec (48,000 revolutions/second)
- Acceleration takes place with 8 RF cavities, total ~20 m. Rest of circumference is magnets, bringing particles back to the cavities!
- Two beams circulate about the ring in opposite directions, only few mm apart, and brought into collision at two detector regions
- While collisions only generate 1-2 watts of power, as shown earlier, the stored energy of the beam is
 - $36 \times (3 \times 10^{11}) \times (1000 \times 10^9 \times 1.6 \times 10^{-19} \text{ J}) = 1.7 \text{ MJ}$!
 - 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: $1.7 \text{ MJ} / 21 \mu\text{sec} = 80 \text{ GW}$!



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

-- *now, for instance!*

crews of 5-6 Accelerator Operators and Crew Chief

The Future...

Compare hadrons and leptons

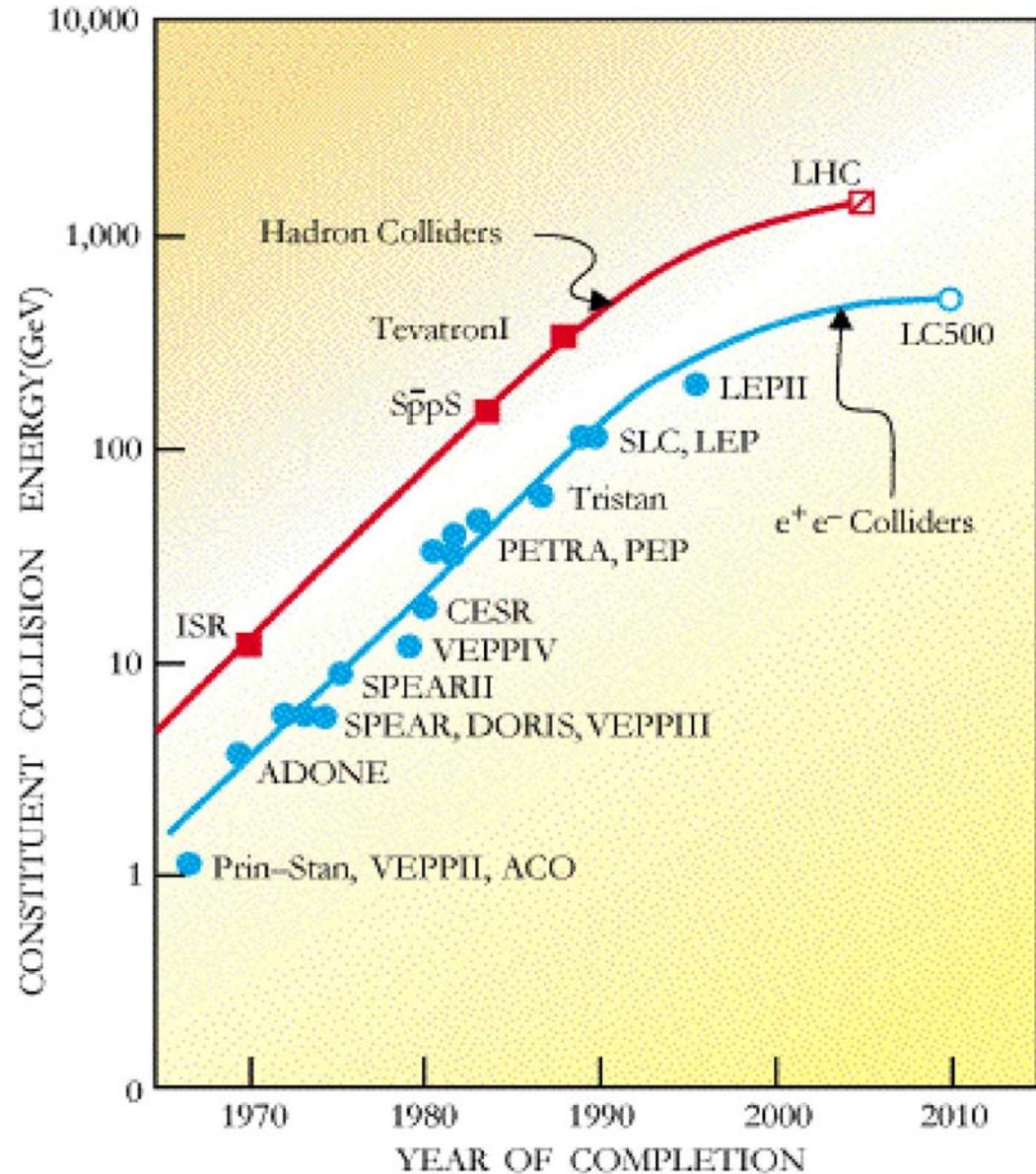
- constituent hadron collision energy is about 1/10 of total hadron beam energies (protons made up of quarks!)
- constituent lepton collision energy is all of total lepton beam energies

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

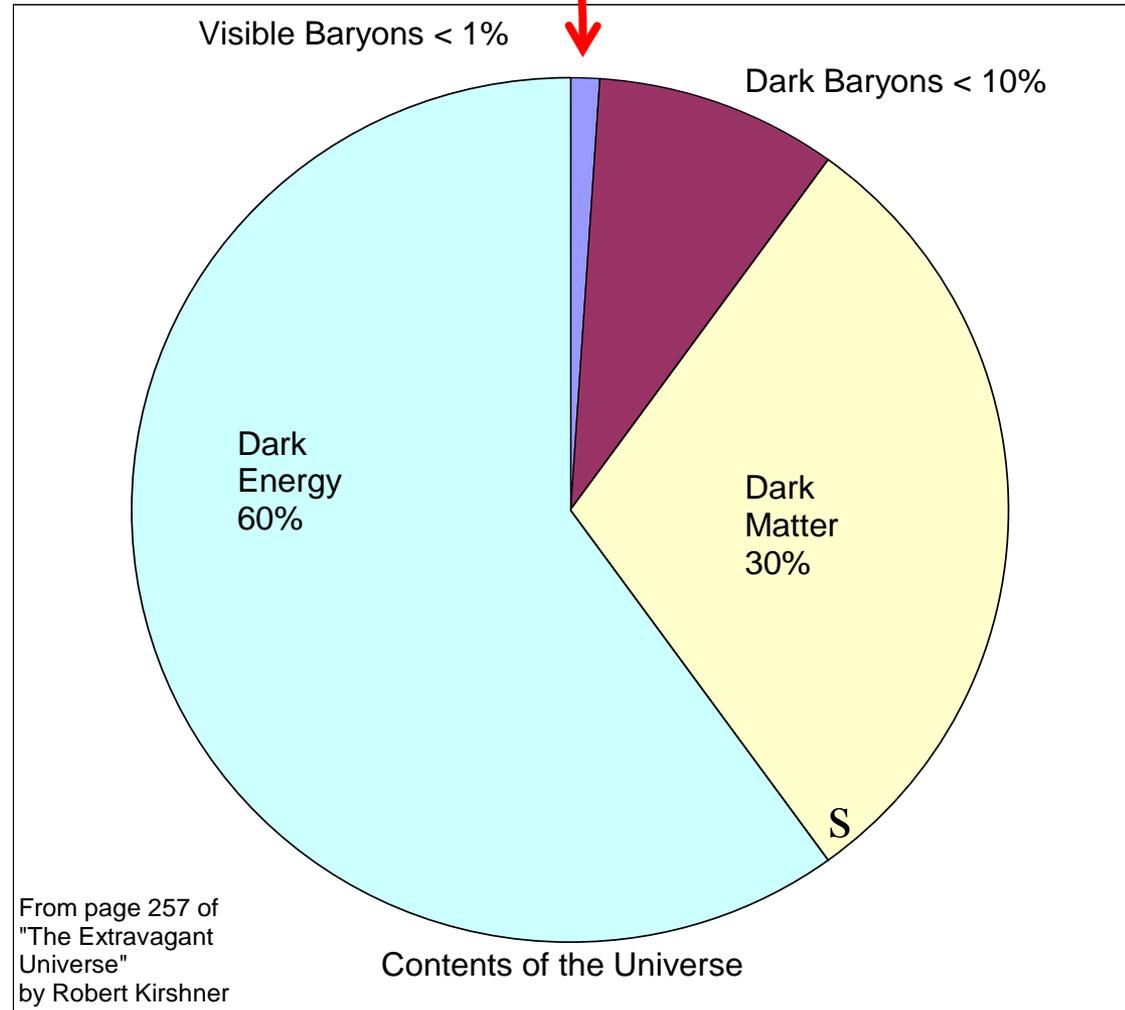
- Large Hadron Collider
 - Proton-proton collider, being constructed at CERN
 - 7000 GeV per particle; but protons contain quarks and gluons
 - Ready in ~3-4 years
- International Linear Collider
 - Large international community looking into this project
 - Electron-positron collider, 250-500 GeV per 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???

Is it almost all figured out??

Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top
	<i>d</i> down	<i>s</i> strange	<i>b</i> bottom
	ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino
Leptons	<i>e</i> electron	μ muon	τ tau
	I	II	III
	The Generations of Matter		

The Universal Pie.

Although we can be proud that we have filled up the diagram above, the biggest slice of energy-density in the universe is dark energy, which we don't understand, and the next biggest is dark matter, which we don't understand. There is *plenty* more work to be done.



Summary

- Controlled experiments to study fundamental high energy particle physics rely on accelerators
- Highest energy accelerator(s) in the world at Fermilab -- soon to be eclipsed by CERN's LHC ...
- 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 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 (2003, 2001, ...)
 - European Particle Accelerator Conference (2004, 2002, ...)