# Particle Accelerators

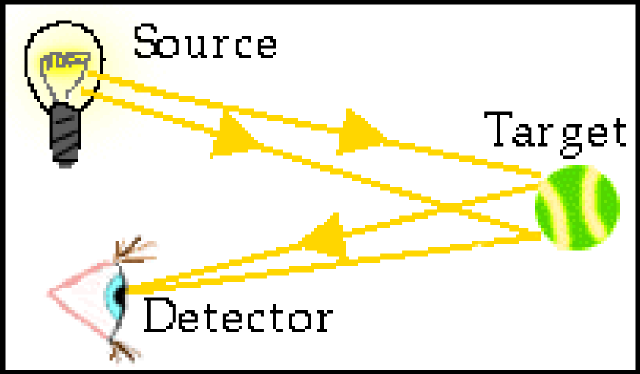
Arden Warner
Fermi National Accelerator Laboratory
*Accelerator Division*

**Summer Lectures 09** **June 16th, 2009**

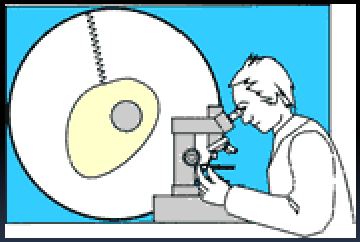
# Out-line of Presentation

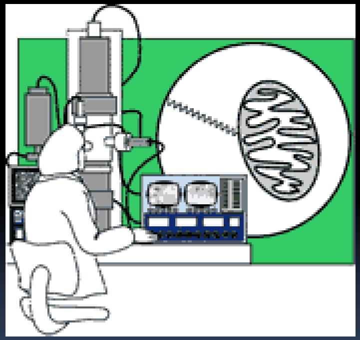
- What is an accelerator and why do we need them?
- Some History of Accelerators
- How do we accelerate particles?
- Keeping particles together.
- How do we use accelerators to do High Energy Physics experiments?
- Fermilab Accelerators and there operation.
- Accelerator  techniques, diagnostics and instrumentation.
- Summary.

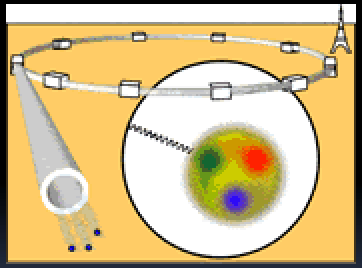
# How we see small objects




We aim source particles at target particles and detect the result







To view living cells we use optical microscopes
Resolution~ $10^{-6}$ m

Down to the size of atomic dimensions we use electron microscopes, where electron of a few hundred KV are typical.
Resolution ~ $10^{-10}$ m

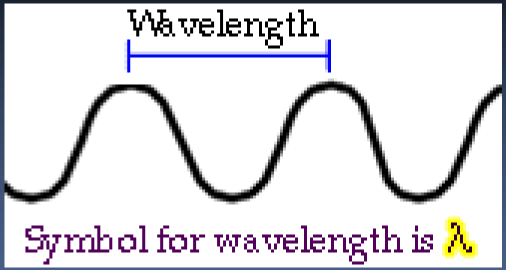
To view the inner workings of nucleons (protons and neutrons) we need particle accelerators .
Resolution < $10^{-15}$ m

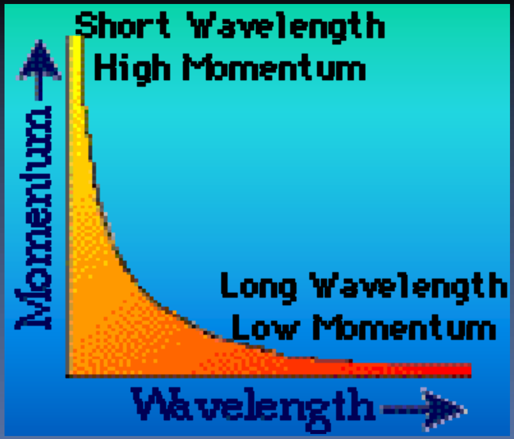
Nucleons inside atomic nuclei have a size ~ $10^{-15}$ m and are separated by distances of the same order. The electrons orbiting atomic nuclei as well as the quarks in side nucleons have a size, if any < $10^{-18}$ m

The resolving power of these devices is determined by the de Broglie wavelength of the source particles.

$$\text{Higher momentum} \Rightarrow \text{Shorter wavelengths}$$

$$\lambda = h/p$$



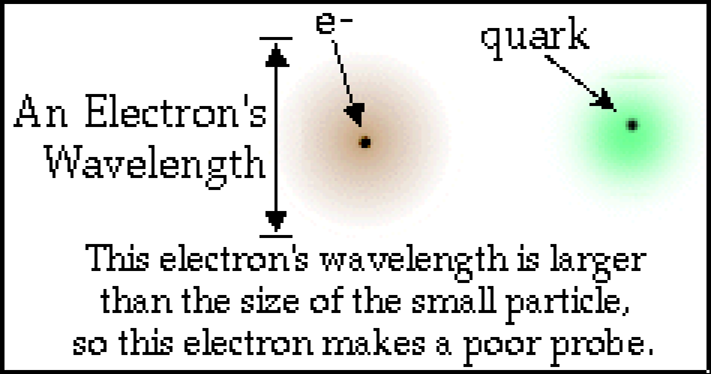




Example: if an electron is required to have a de Broglie wavelength comparable to the size of the nucleon, it must have a kinetic energy of 1200 MeV. Several thousand higher than an electron microscope.

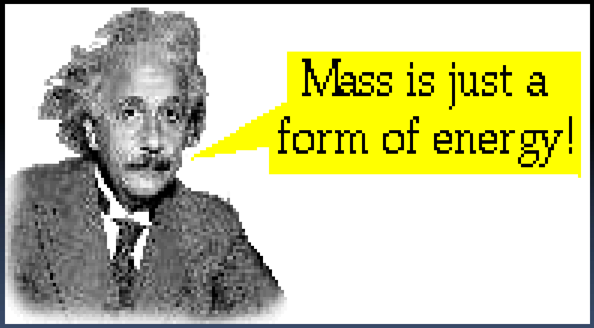
For an electron energy above 10 MeV, kinetic energy is proportional momentum.

# Some Advantages of Particle Accelerators

- Since all particles behave like waves, physicists use accelerators to increase a particle's momentum, thus decreasing its wavelength enough that they can use them to poke inside atoms.




- "High energy" particles can have their energy converted into mass ($E = mc^2$), and so new particle states can be created and observed.




- Accelerators provide the ability to control the particles (steer, focus, increase/decrease intensity, for instance) in order to conduct experiments efficiently and in a controlled fashion.

# Accelerating Charged Particles

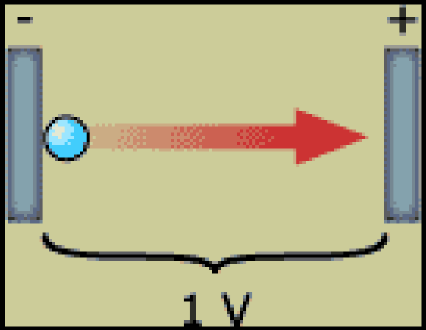
# A Little History

In the first accelerators, particles were accelerated by a high voltage applied over the gap between a cathode and an anode – cathode ray tubes (1890s).

- Using cathode ray tubes x-rays were discovered in 1895 by Wilhelm Röntgen – First Nobel Prize in physics (1901).

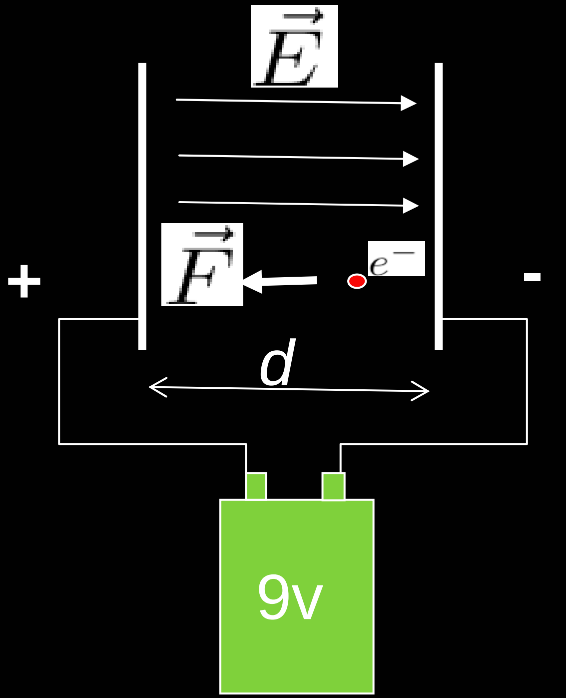
- 1896 Joseph Thomson studied the cathode rays and found that they had a precise charge to mass ratio and discovered the first elementary particle (the electron) – Nobel prize (1906)

- Cathode ray tubes are still the most common type of accelerator today (TV)




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

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




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

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

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 (0.006*c*)

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

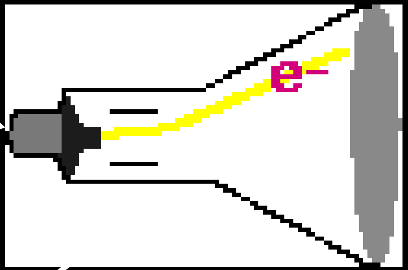
***Note***: if looked at a proton instead, its mass is 1836 times that of the electron. Thus, its speed would be *only* 0.00014*c*.
(= 90,000 mi/hr!)

Q: How much voltage can we deliver?

Let's look at a TV set...

# Your TV Set

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*)

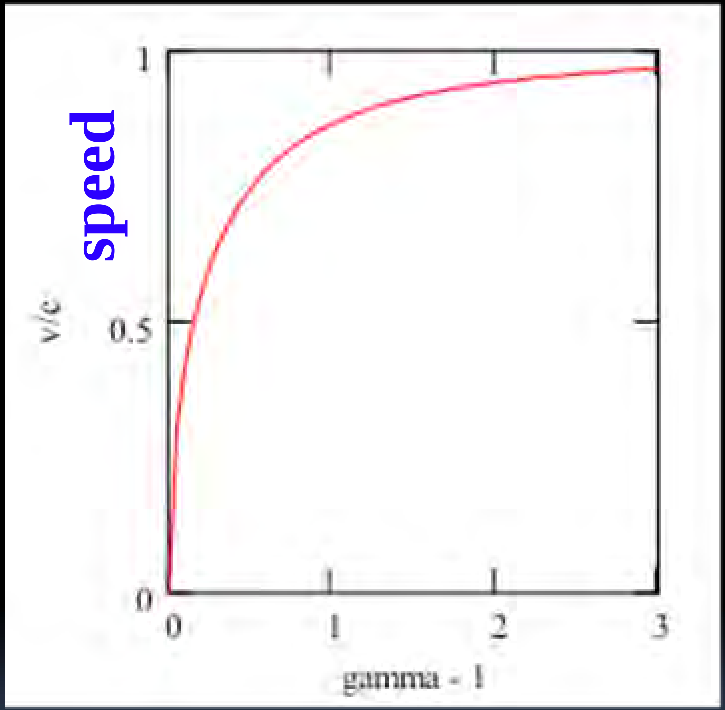
OK, so it's a *little* more than that… but not much! *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10,000 eV**!

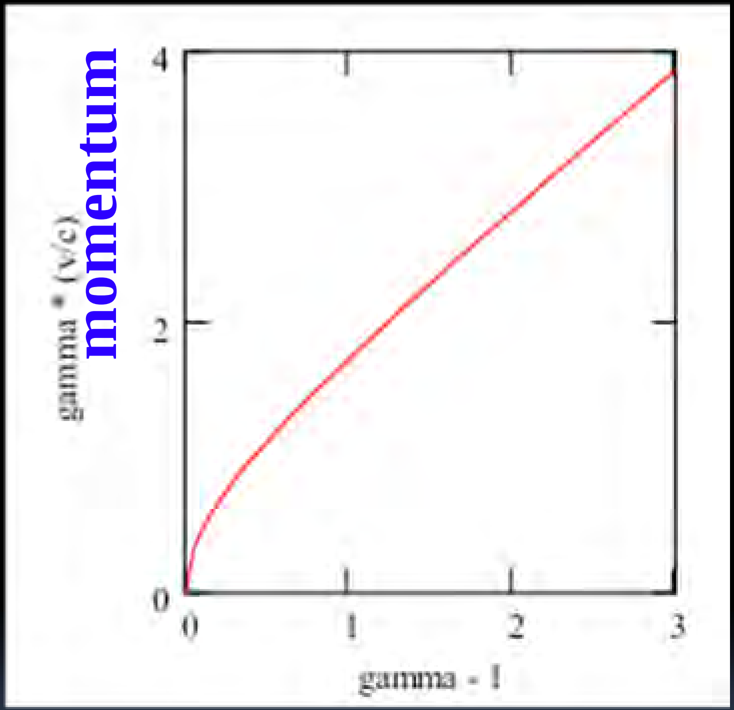
# So, how fast are we moving now?

- 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…
  - Special Relativity (*near the speed of light*) plays a big role in high energy particle acceleration

# Speed, Momentum vs. Energy




Kinetic energy




Kinetic energy

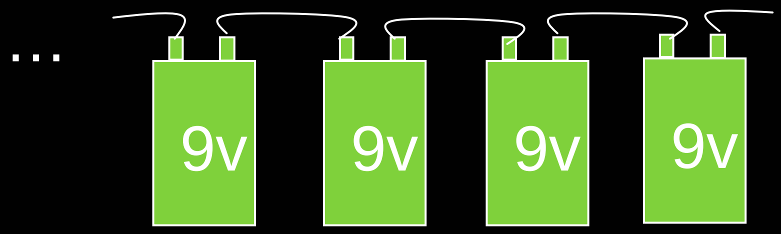
| | | | | | |
|---|---|---|---|---|---|
| Electron: | 0 | 0.5 | 1.0 | 1.5 | MeV |
| Proton: | 0 | 1000 | 2000 | 3000 | MeV |

rest energy, $mc^2$:

| | |
|---|---|
| e- | 0.5 MeV |
| p | 938 MeV |

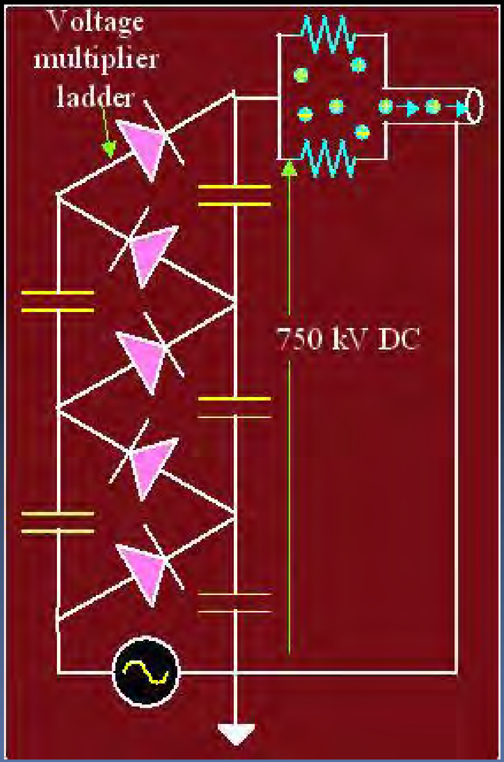
# So, Back to High Voltage!

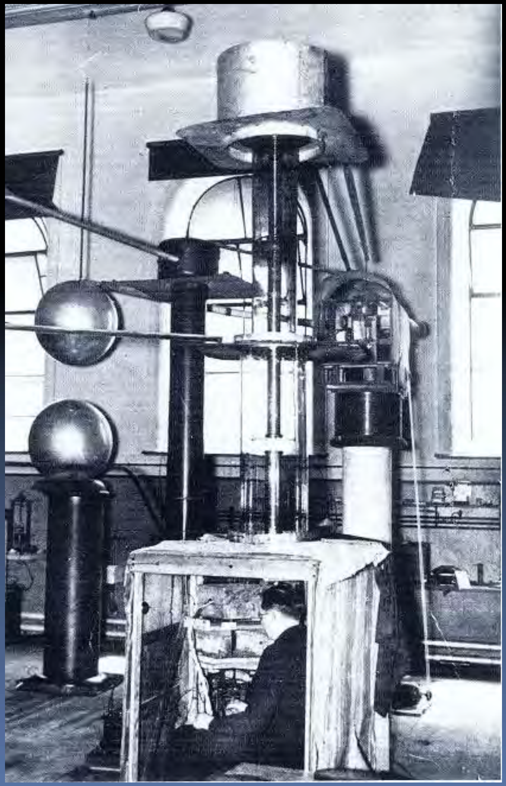
- How to get **high voltage**? How high can we go?
- String a bunch of batteries in series!
  - Not very practical…

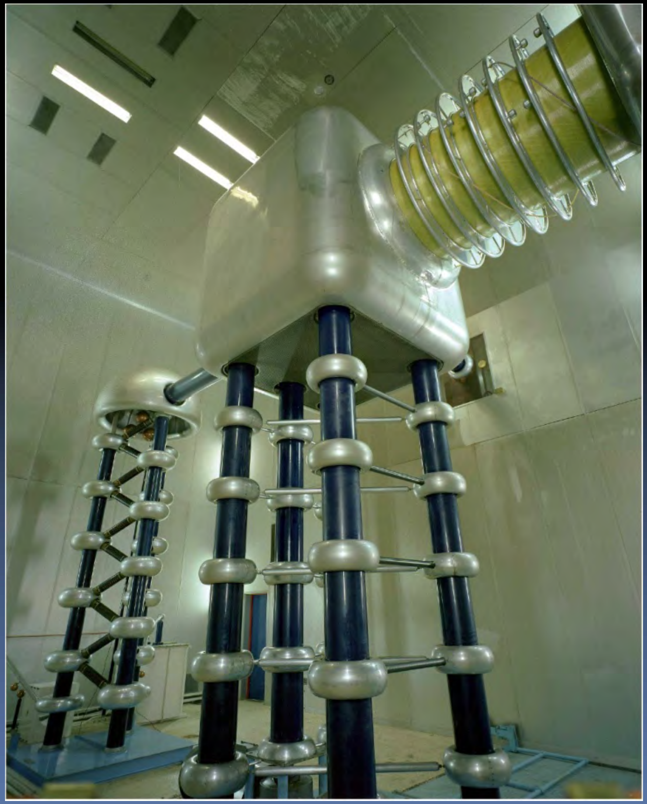


# High Voltage

The first high voltage particle accelerator had a potential drop of ~100 KV and was developed in early 1930's by *Cockcroft and Walton,* and is named after them: In 1951 they obtained the Nobel prize in physics for their work on the transmutation of atomic nuclei by artificially accelerated atomic particles.

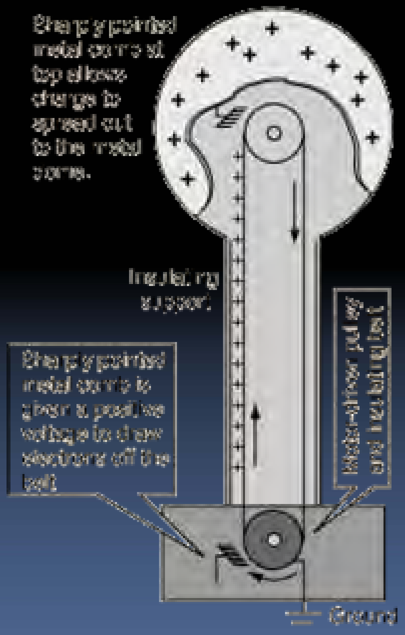


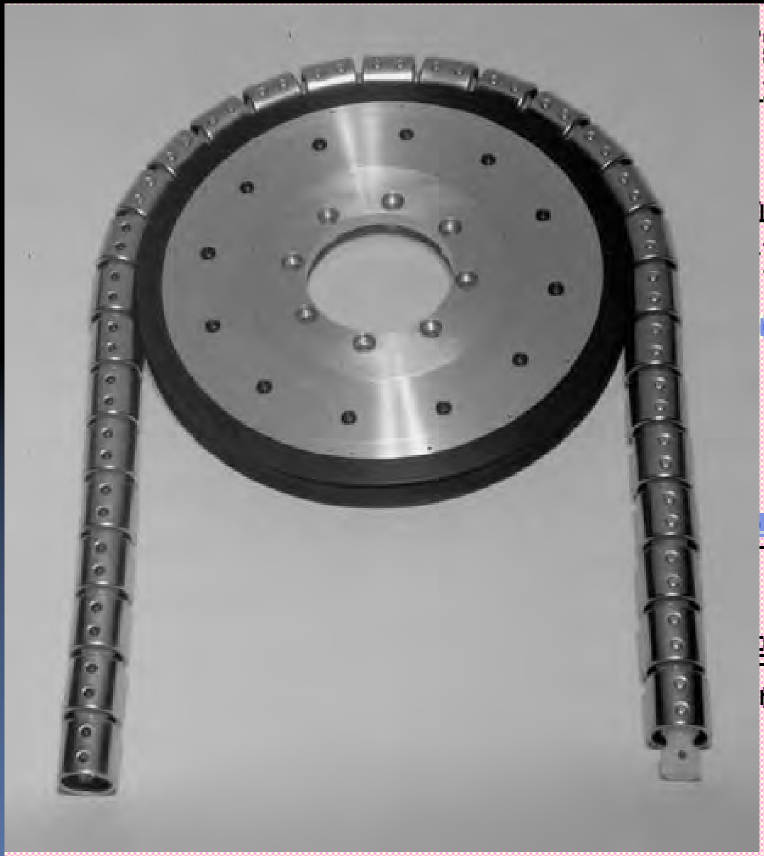


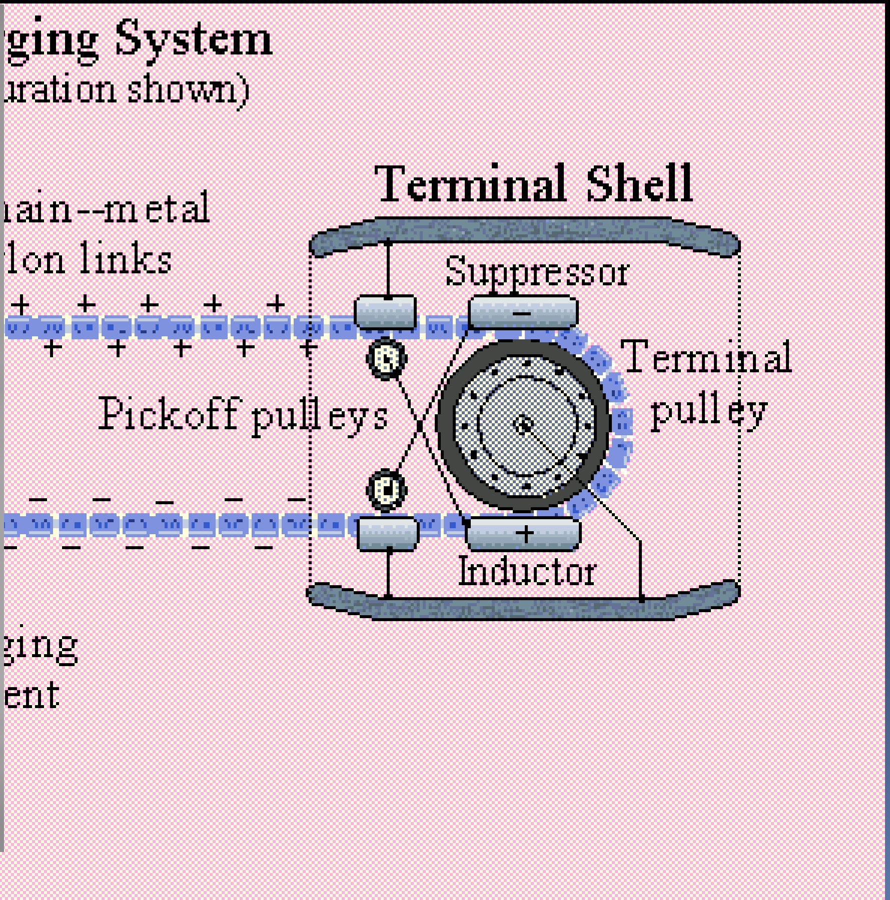
# High Voltage continued!

The most common potential-drop accelerator in use today is the Van de Graaff. Several configurations exist and have achieved voltages > 25 MV.



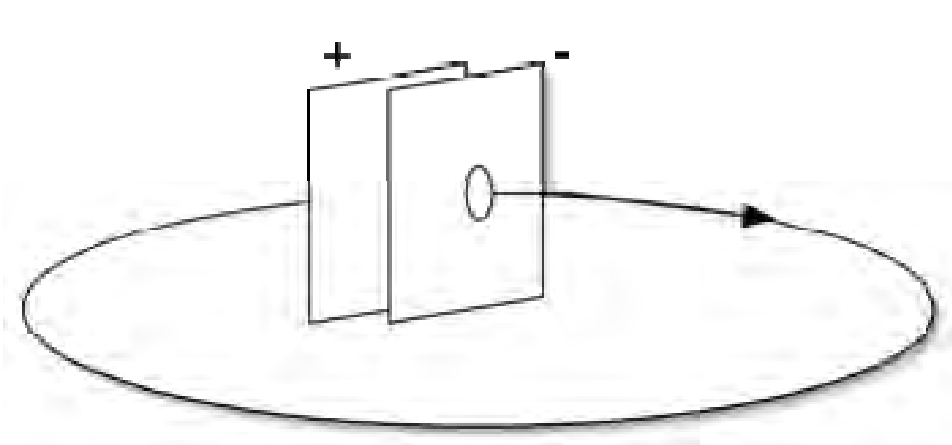
The Fermilab pelletron provides 4.3 MeV electrons. These electrons are used to manipulate the phase space of anti-protons in the recycler in a process called electron cooling. More on this later.





# 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:



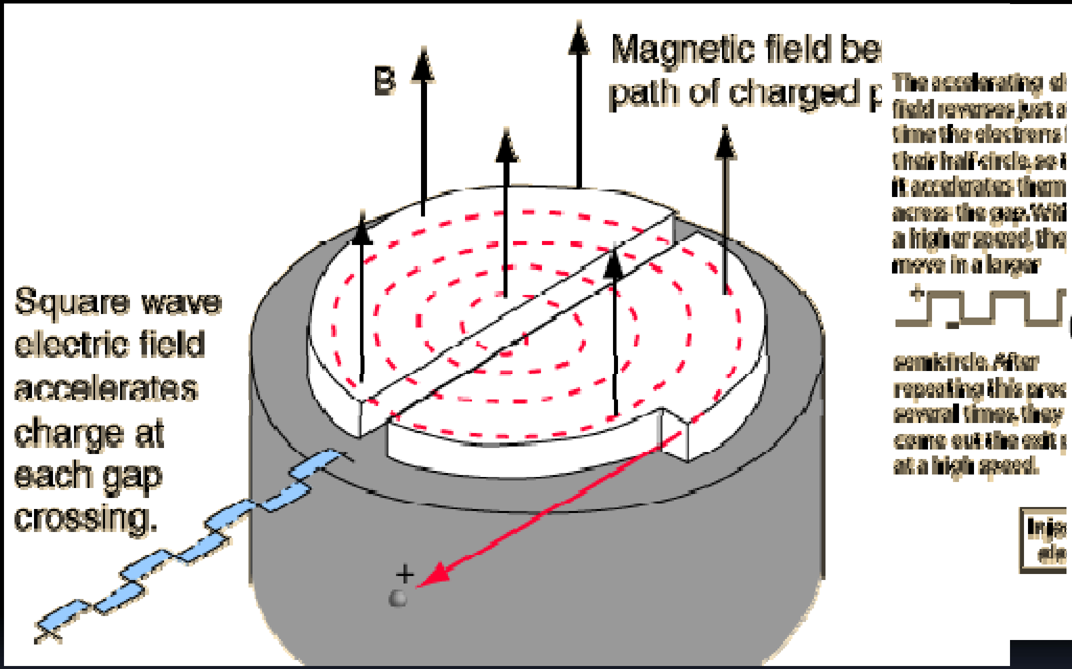

**BUT**! If the voltage is DC, then though particle is accelerated when in between the plates, it will be *decelerated* while outside the plates!

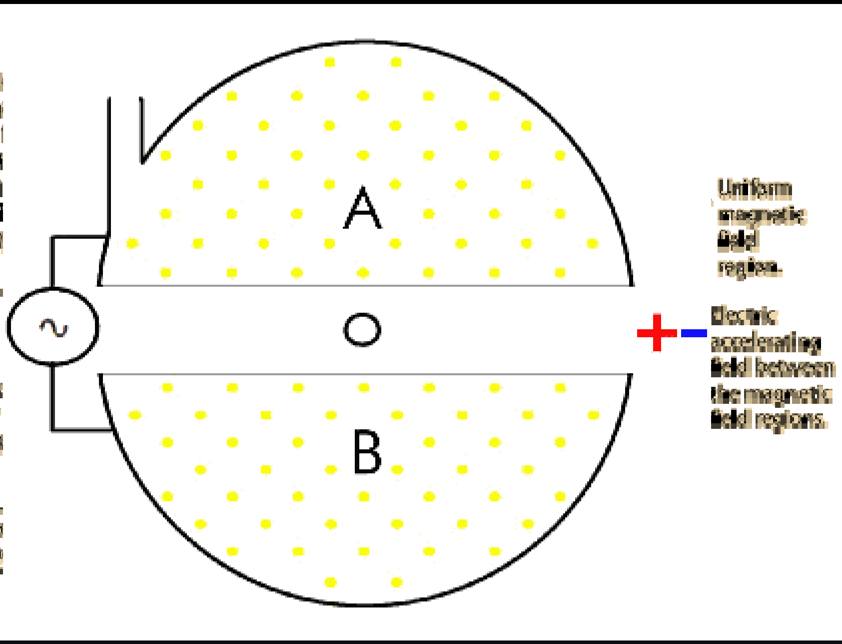
-- *net acceleration* = 0 !

SO, need a field which can be switched on and off -- an AC system!

# Circular Accelerators

➢The first circular accelerator was the cyclotron.




$$mv^2/r = evB$$

$$\Longrightarrow r = mv / eB$$

$$T = \frac{2\pi r}{v} = \frac{2\pi mv}{qBv} = \frac{2\pi m}{qB}$$

$$\omega_{cyclotron} = \frac{qB}{m}$$

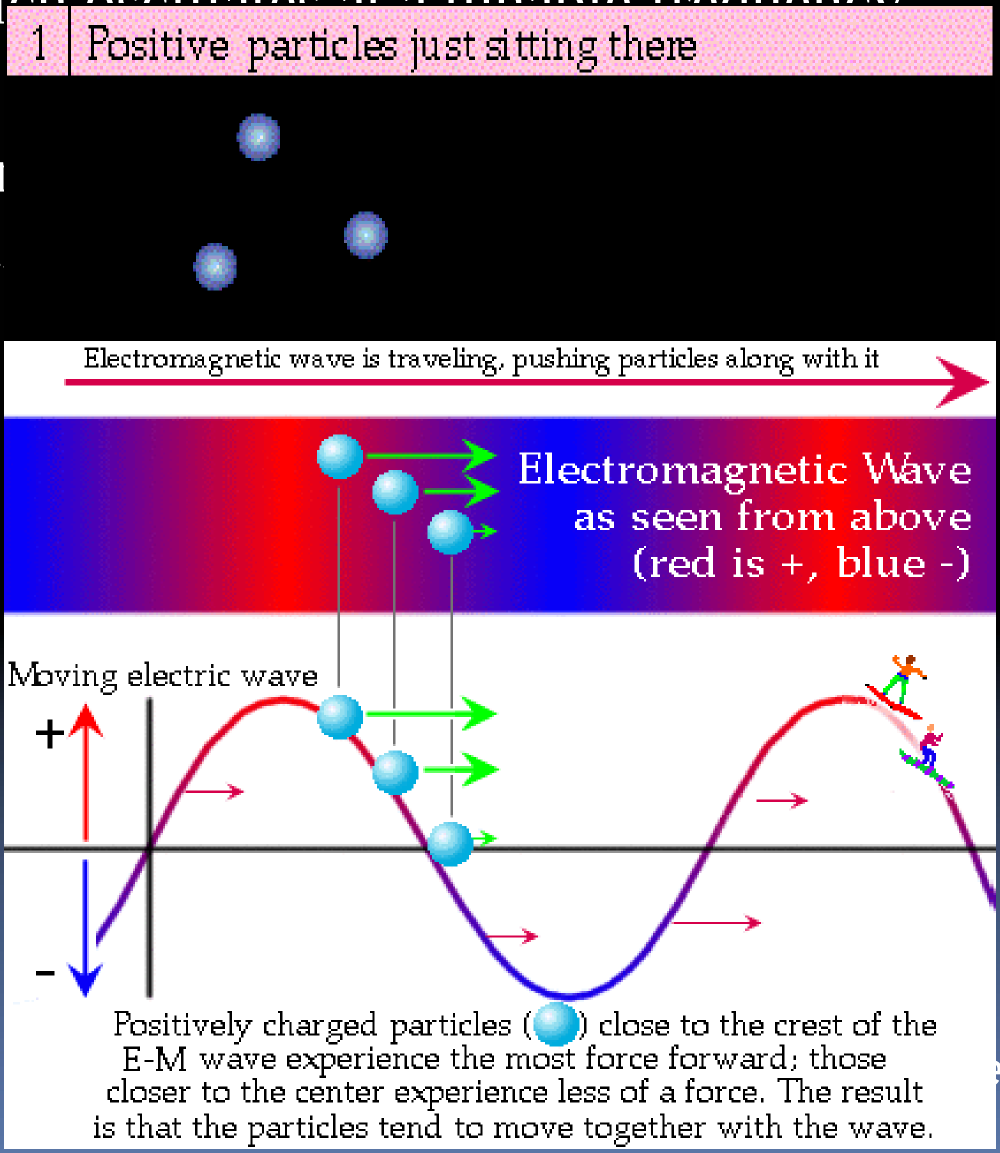
# Circular Accelerators

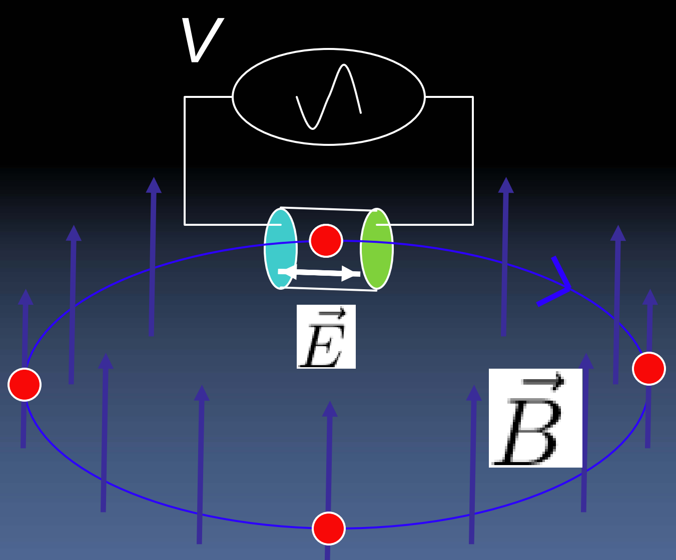
- Since the entire cyclotron had to be in a magnetic field, the magnets would become very large.
- Also, as the particles continued to accelerate, their speeds would begin to approach *c*, and thus they would not keep in step with the changing voltage.

- “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

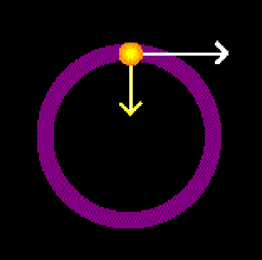
- Use a single device which develops an electric field along the direction of motion, and which oscillates at a tunable frequency
- Use a series of tunable electr
  to keep the particle(s) on a c
  device (cavity).



# Synchrotron (cont'd)

- *Slowly* increase the magnetic field, and particles will accelerate to "keep up," and the particles will remain on the same radius circle

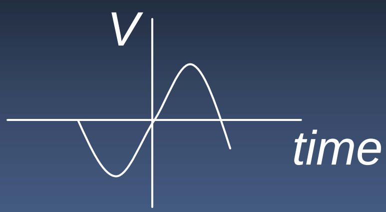


$$mv^2/R = evB$$

$$\Longrightarrow R = mv / eB$$

$$= p / eB$$

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,

$f = v / 2\pi R$

$= (3 \times 10^8$ m/s$) / (2\pi$ 1m$)$

$= 5 \times 10^7$ / s $= 50$ MHz

# Synchrotrons at Fermilab

**Booster**

*R* = 75 m
*h* = 84

*R* = 500 m
*h* = 588

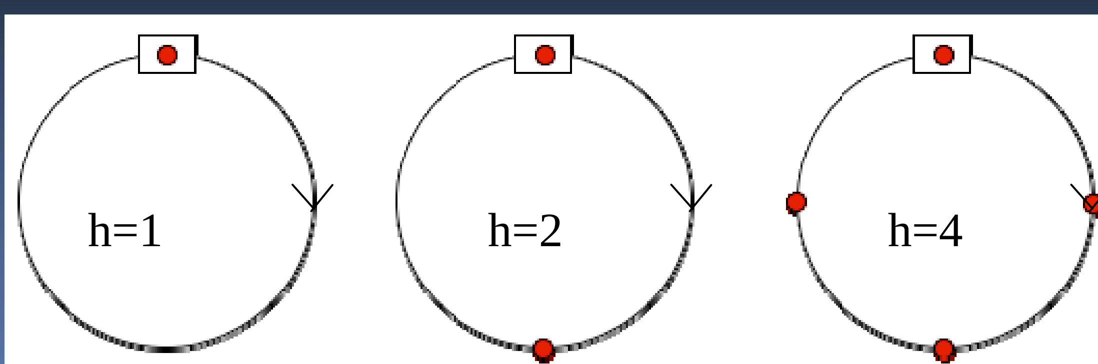
**Main Injector**

***All use 53 MHz systems***

*h = # possible 'bunches' in the accelerator*

**Tevatron**

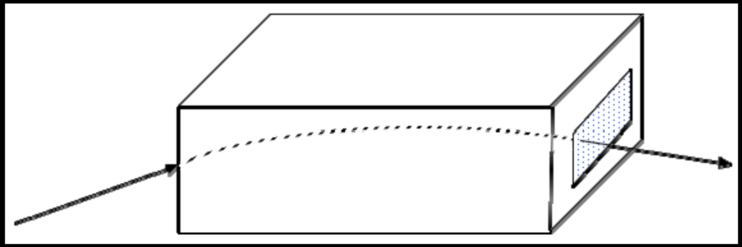
*R* = 1000 m
*h* = 1113

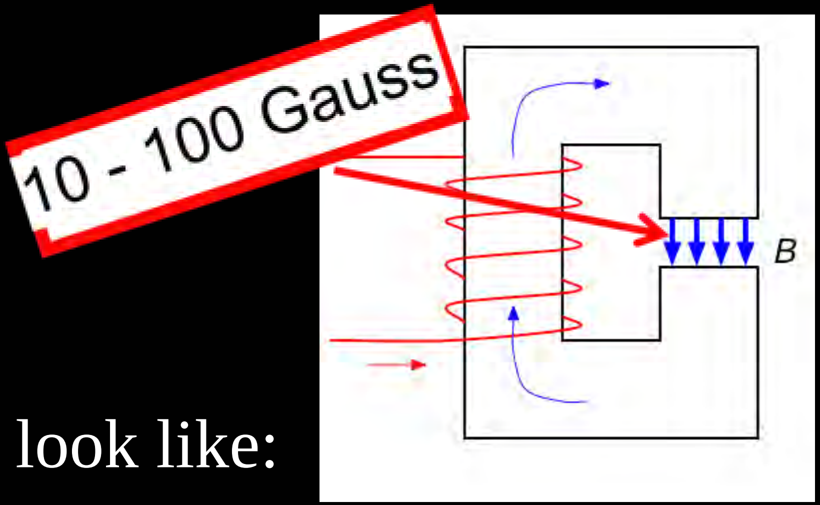


So much for acceleration, ...
what else do we need?

# Accelerator Magnets

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



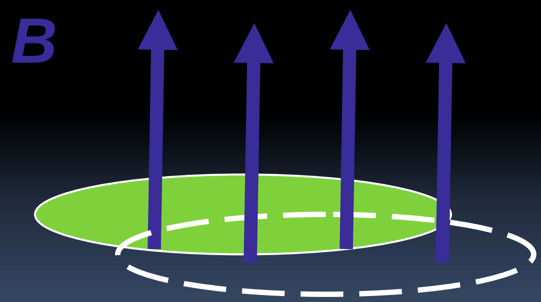


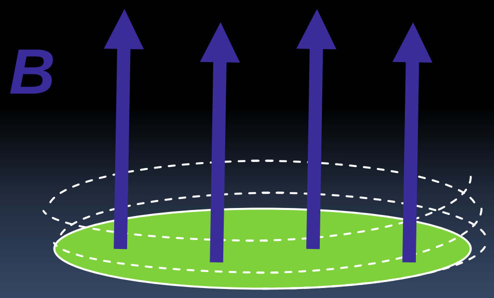

  - A simple electromagnet might look like:

  - Accelerator magnet:
    - lots of current and lots of iron!
      - Iron-dominated magnets can obtain
  - field strengths up to ~2 Tesla

# Also, 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!

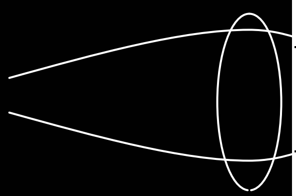


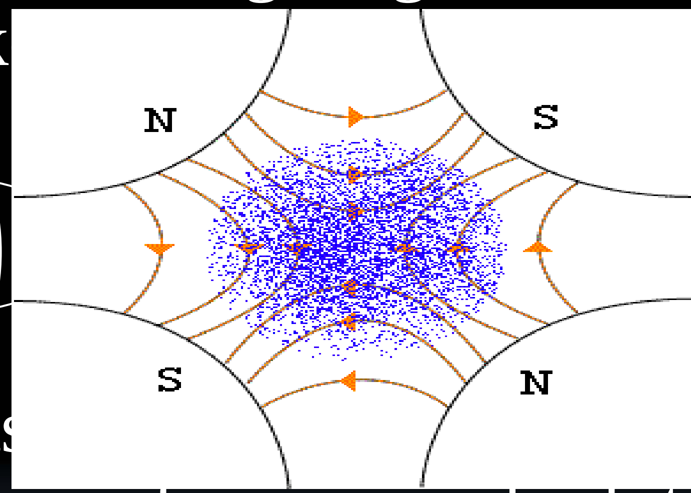



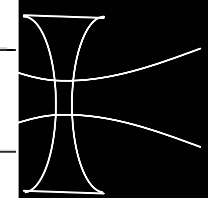

- Also, large number of particles in a real beam start out heading in every which direction! (sort of like a flashlight beam, spreading out away from the source)

# Focusing

- So, as particles move around the accelerator, we need to use other electromagnets to steer and focus them
- Arrangement of focusing magnets, acting much like optical lenses, k contained…

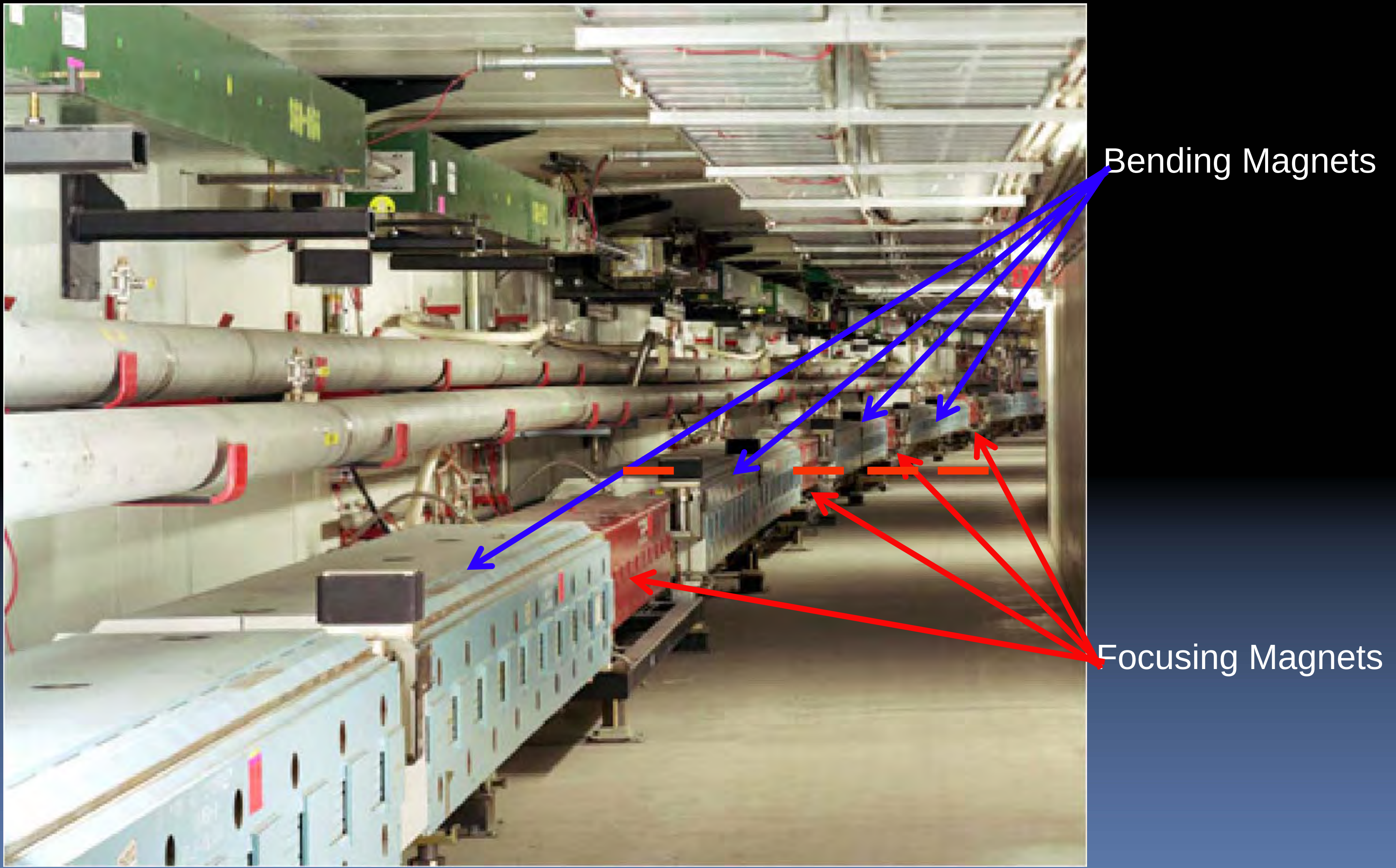




- Smaller magnets he beam trajectory, and to perform special orbit manipulations
  - Note: The beam in the Tevatron, for example, is only about 1 mm wide! Its orbit is controlled to a fraction of a mm! Yet, the orbit itself is 6.28 km (4 mi) around!

# Example: Fermilab Main Injector

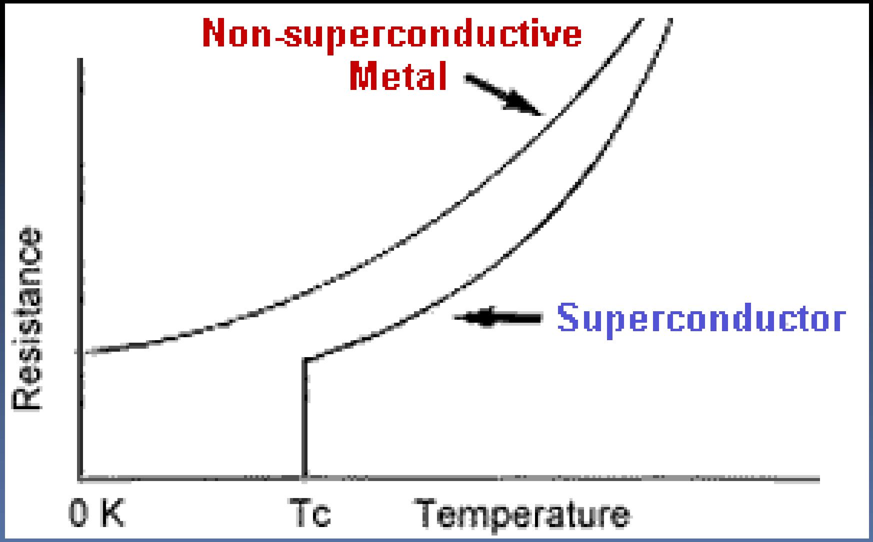


# Superconductivity

- 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***

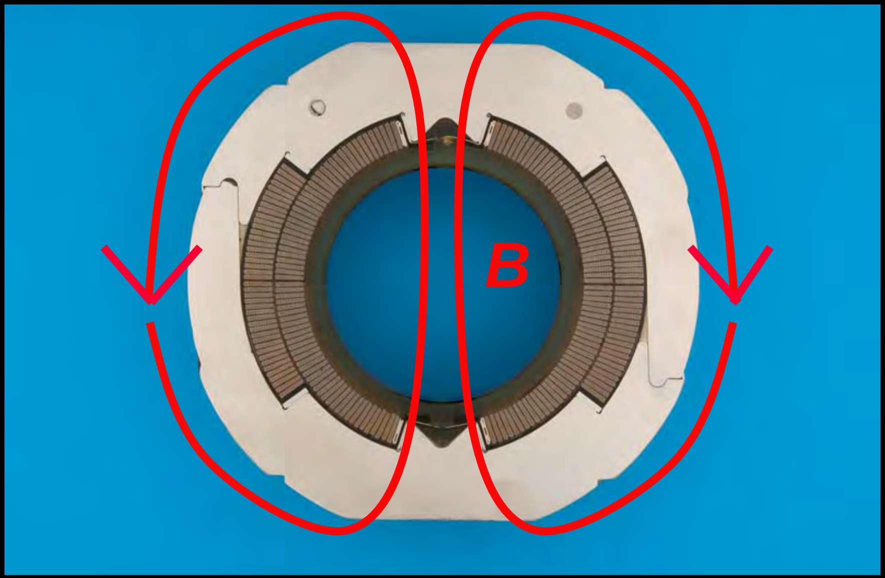
- Took many years to understand, and to perfect the production of superconducting materials suitable for commercial use

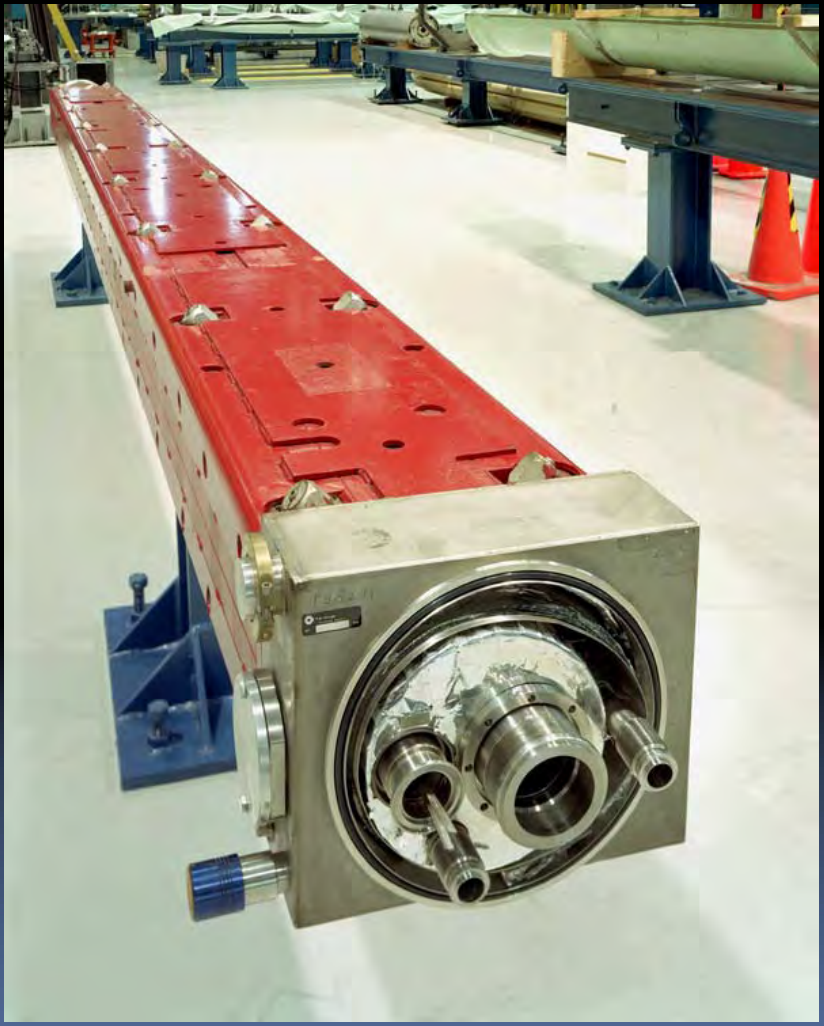


# Superconducting Accelerator

- The Tevatron at Fermilab was the first synchrotron making use of superconducting materials in its magnets
  - Allowed Fermilab to go to higher fields, higher particle energies -- *Energy Doubler*
  - 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 – was ***the world's largest!***
    - Though 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 using this technology

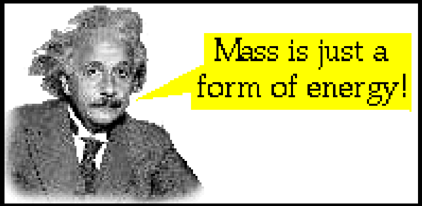
# Superconducting Tevatron Magnet



- Outside is at room temperature; inside is at 4ºK!
- Field is **4.4** Tesla @ ~4,000 A
- Each magnet is ~20 ft long, and weighs about 4 tons
- ~1000 magnets in the Tevatron

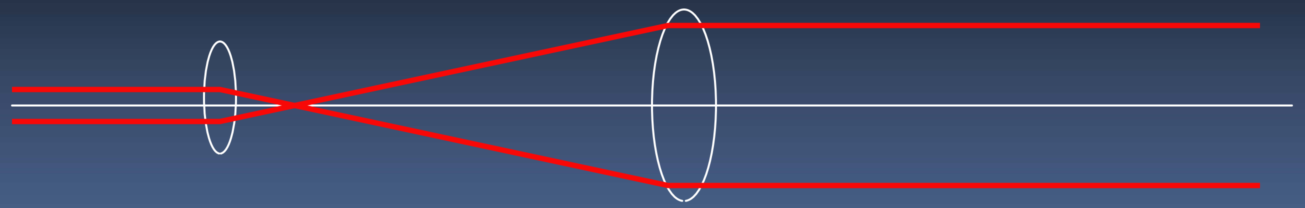
# How accelerators are used at Fermilab

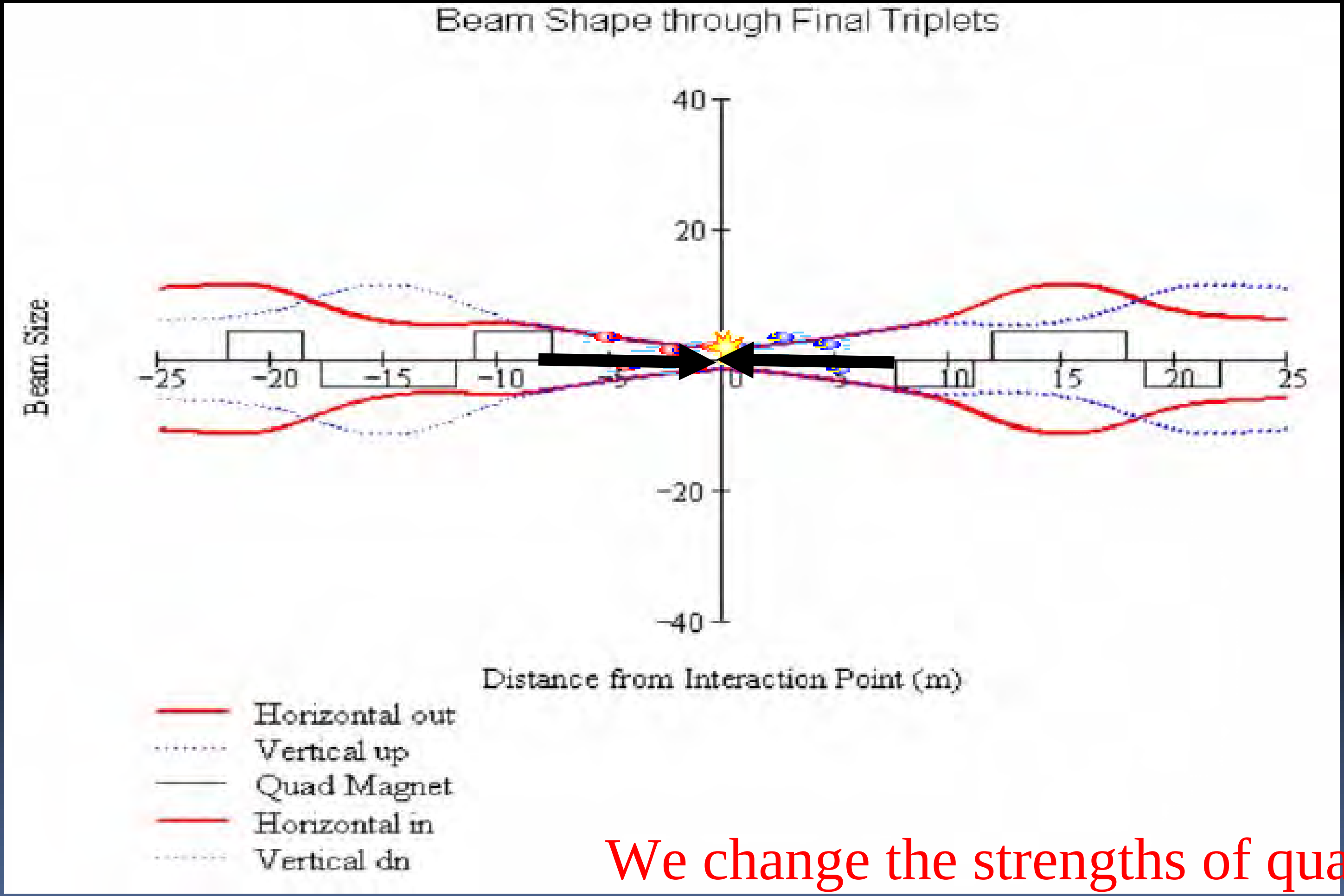



- Collide beam of particles into a stationary target
  - Neutrino experiments, for example
- Collide beams of particles moving in opposite directions:
  - The energy of the collision can be used to produce new particles (mass = energy!)
  - Energy and Momentum must be conserved
  - Einstein: $E^2 = (mc^2)^2 + (pc)^2$
  - **Collider**: zero momentum before AND after. Thus, ***ALL*** energy can be converted into *new stuff* !

# The "Final" Focus

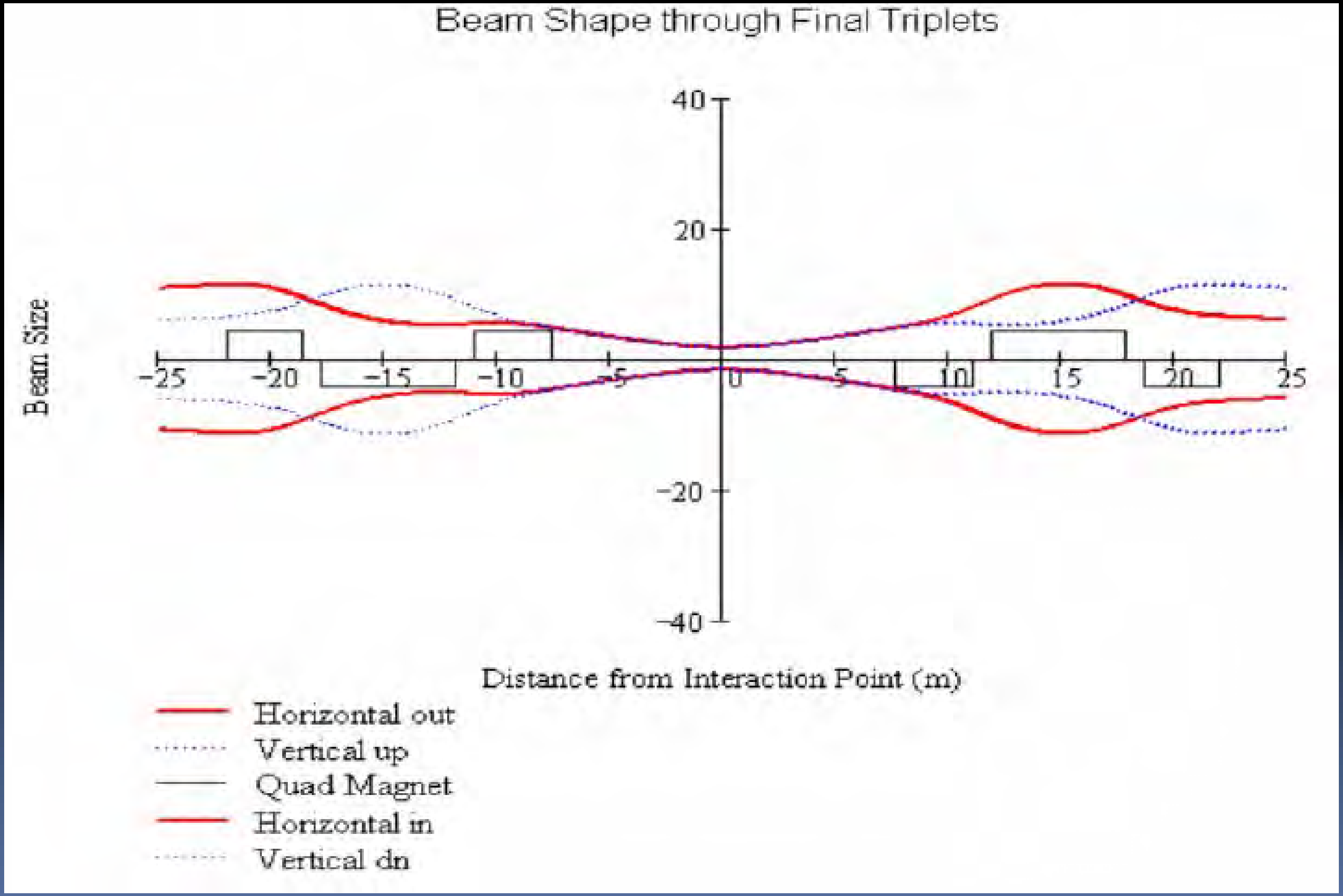
- In a collider, in order to increase the probability that particles in the two beams will actually hit each other, we squeeze the beam to very small sizes at the collision points.
- At an 'interaction point' the particle beams are only about 60 μm wide (~ the width of a human hair!)
- Performed using 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:





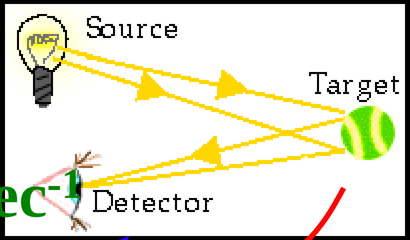

We change the strengths of quadrupole magnets to focus the beam stronger, thus increasing chance for collisions

# Beta-Squeeze



# Some Numbers…

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




- Cross section of a proton/antiproton collision
- ~ $6 \text{ x } 10^{-26}\ \text{cm}^2$
- So, we get, and wish to detect, about $6 \text{ x } 10^{6}$ collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store relevant data at this rate (and they do!)
- Each proton/antiproton has energy of
- 980 GeV = $980 \text{ x } 10^{9} \text{ x } (1.6 \text{ x } 10^{-19}\ \text{J}) = 1.6 \text{ x } 10^{-7}$ J
- So, *power* delivered in the collision region is only about
- $2 \text{ x } 1.6 \text{ x } 10^{-7}$ J x $6 \text{ x } 10^{6}$ /sec ~ 2 watt!

# Fermilab's Accelerators

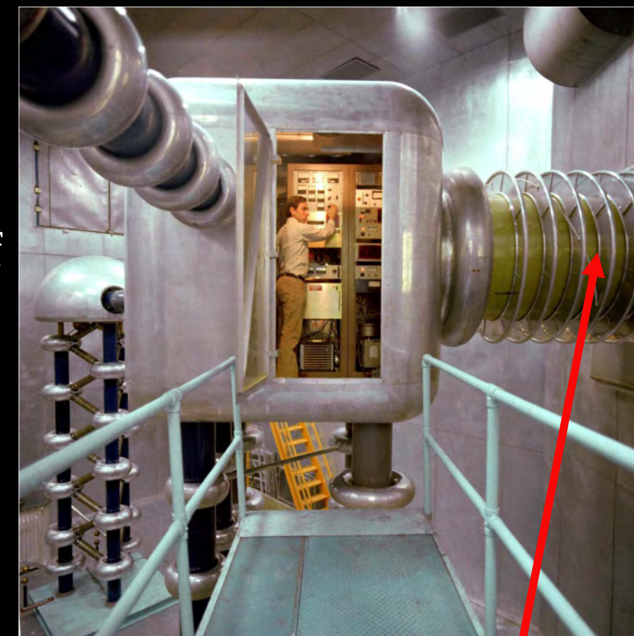
- The Fermilab Accelerator System is made up of a 'chain' of accelerators, each delivering particles to the downstream accelerator.
  - Cockcroft-Walton style "pre-accelerator" (Preac)
    - 0 - 750,000 eV (= 750 keV = 0.75 MeV)
  - Linear Accelerator (Linac)
    - 0.75 MeV - 400 MeV
  - Booster Synchrotron
    - 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.

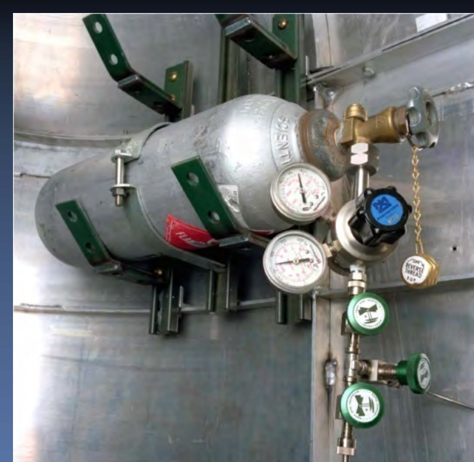
## All starts here!

*inside the dome:*

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

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





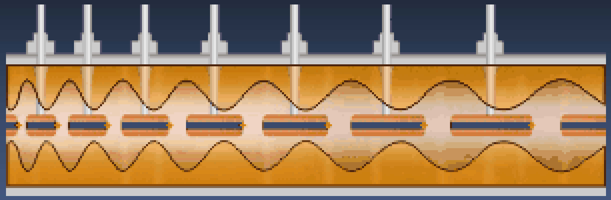
Final kinetic energy of the ions is 0.75 MeV, and their speed is ~ 0.04*c*

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)

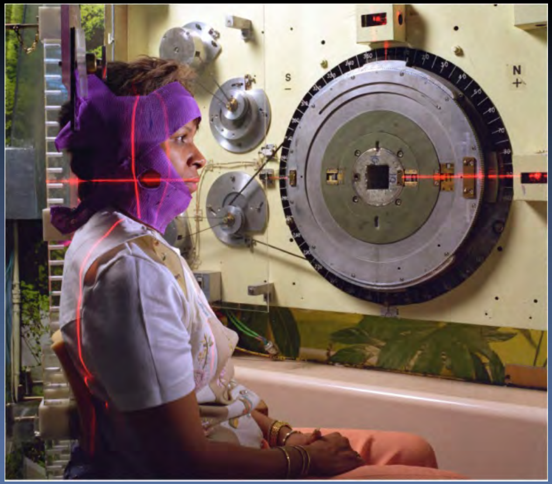
Downstream end of Linac:

- particle speed approaching 0.7*c*
- gap spacing not changing much;

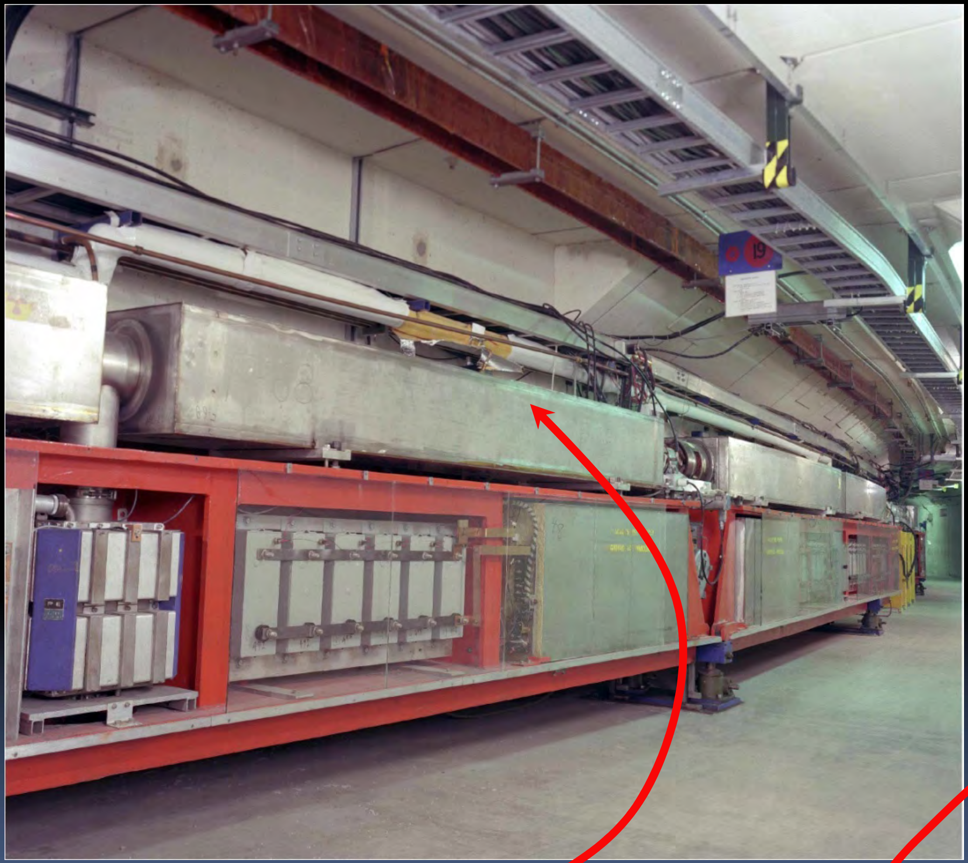
use different cavity structure

- 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, 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…

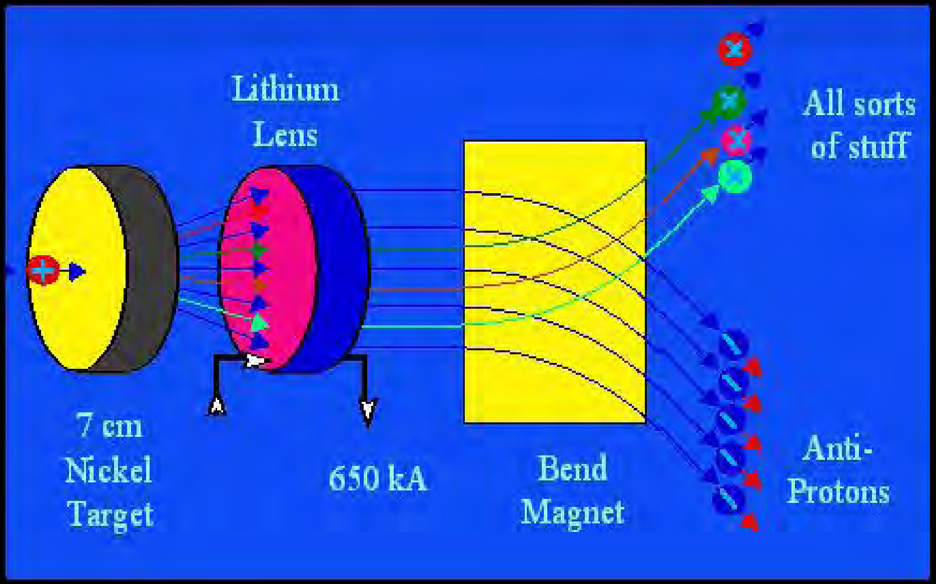
- Protons to Antiproton Source, to make antimatter
- Antiprotons into the Recycler synchrotron for storage
- Protons and Antiprotons to the Tevatron for collisions
- Proton beam to the Test Beam experimental area
- Proton beam for neutrino oscillation experiment (NuMI/MINOS)


RF:

# Antiproton Source -- anti-matter!

- 120 GeV proton beam from MI strikes target, produces LOTS of particles, every 2 seconds or so
- 8 GeV antiprotons ‘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 ~1-2 Trillion antiprotons!     Send to the Collider!

# The Anti-proton Source

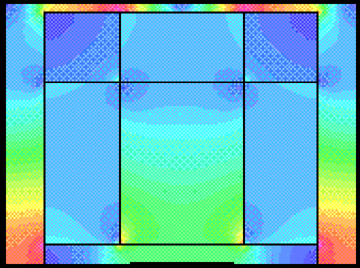




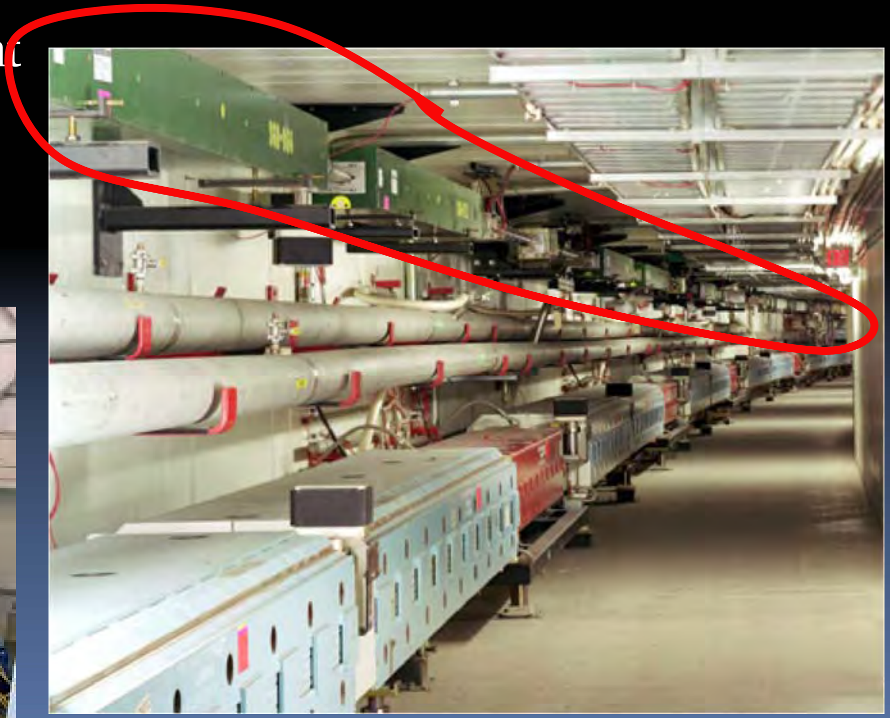
**A beam of 120 GeV protons from the Main Injector is smashed on to a inconel (nickel alloy) Target every 1.5 sec. In the collisions many particles are created. (remember E=mc2). For every 1 million protons that hit the target, only about twenty 8 GeV pbars survive to make it into the Accumulator.**

# Recycler Synchrotron

- Resides in Main Injector tunnel, near ceiling
- More efficient to store antiprotons previously conditioned in the Antiproton Source, and *then* send to the Tevatron -- 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*

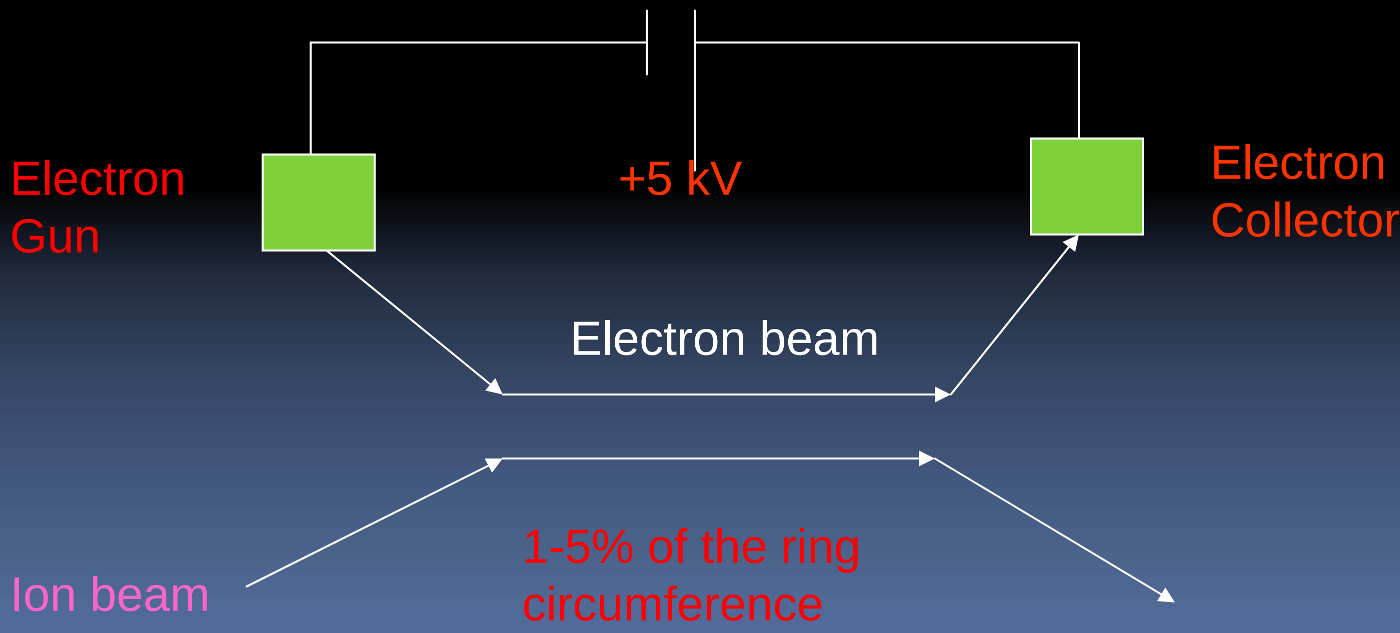
# Electron Cooling of Anti-Matter

- Every container has a practical limit to how much stuff it can hold before it over-flows.
  - The storage rings also have a limit to how much anti-matter it can hold before space charge forces (intra-beam scattering) start to dominate and create instabilities in the beam.
  - Transferring the beam to a bigger vessel and/or using a more aggressive cooling system is a way to combat the problem.

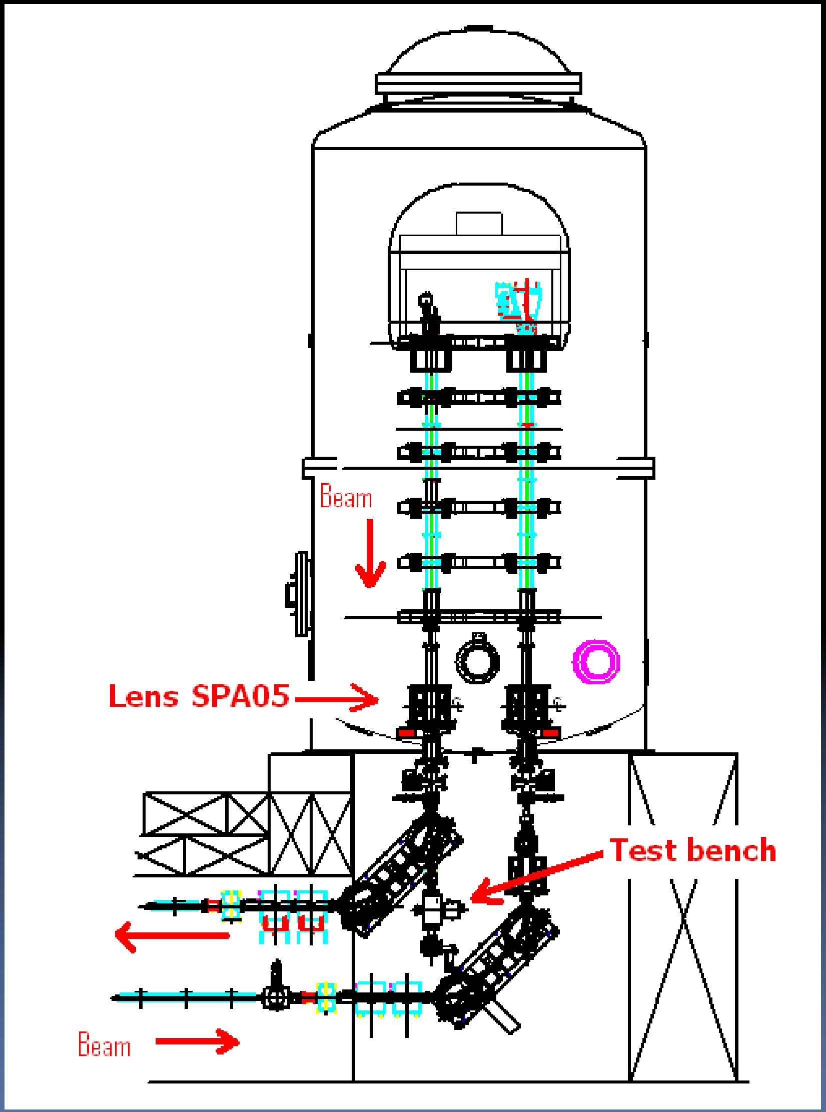
# How does electron cooling work?

A stored ion beam is overlapped with a nearly monochromatic and parallel electron beam in one of the straight sections of a storage ring.
The velocity of the electrons is made equal to the average velocity of the ions.

The ions undergo Coulomb scattering in the electron "gas" and lose (or gain) energy until some thermal equilibrium is attained.

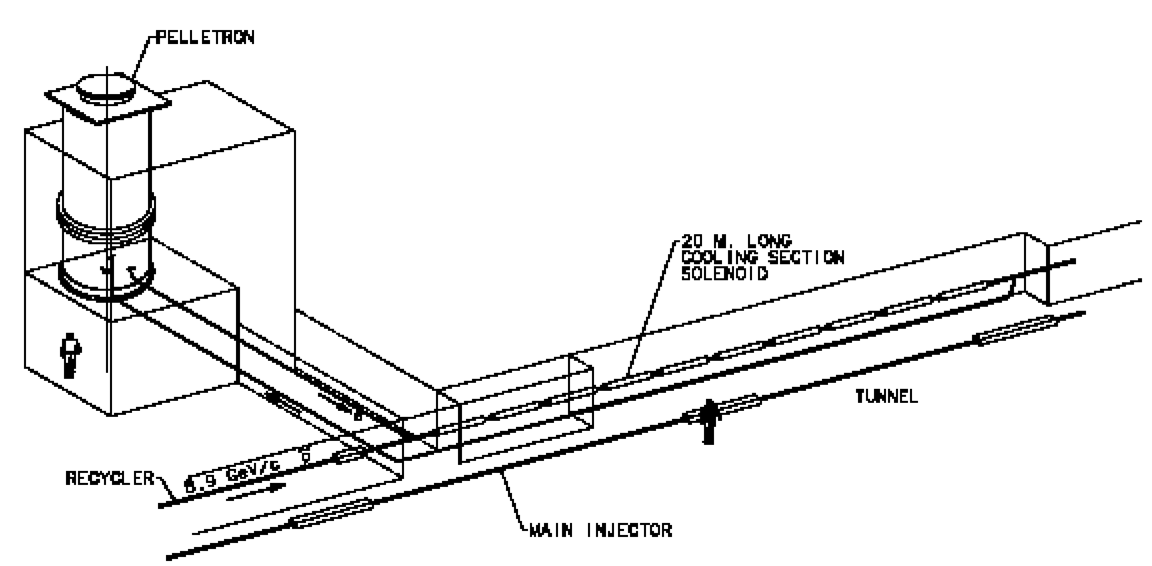


# Pelletron Accelerator.



# Electron Cooling System Parameters

| Parameter | Value | Units |
|---|---|---|
| **Electrostatic Accelerator** | | |
| Terminal Voltage | 4.3 | MV |
| Electron Beam Current | 0.5 | A |
| Terminal Voltage Ripple | 500 | V (FWHM) |
| Cathode Radius | 2.5 | mm |
| Gun Solenoid Field | 600 | G |
| **Cooling Section** | | |
| Length | 20 | m |
| Solenoid Field | 150 | G |
| Vacuum Pressure | 0.1 | nTorr |
| Electron Beam Radius | 6 | mm |
| Beam angular spread | ≤ 80 | μrad |

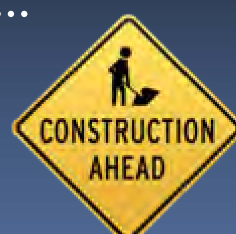


# The Tevatron

- World's Highest Energy particle accelerator -- 0.98 TeV
  - **Still**! Commissioned in 1983
  - Replaced 400 GeV "Main Ring" in the same tunnel (built ~1972)
  - $1^{st}$ superconducting accelerator
  - Circumference =
  - $2\pi$ 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)

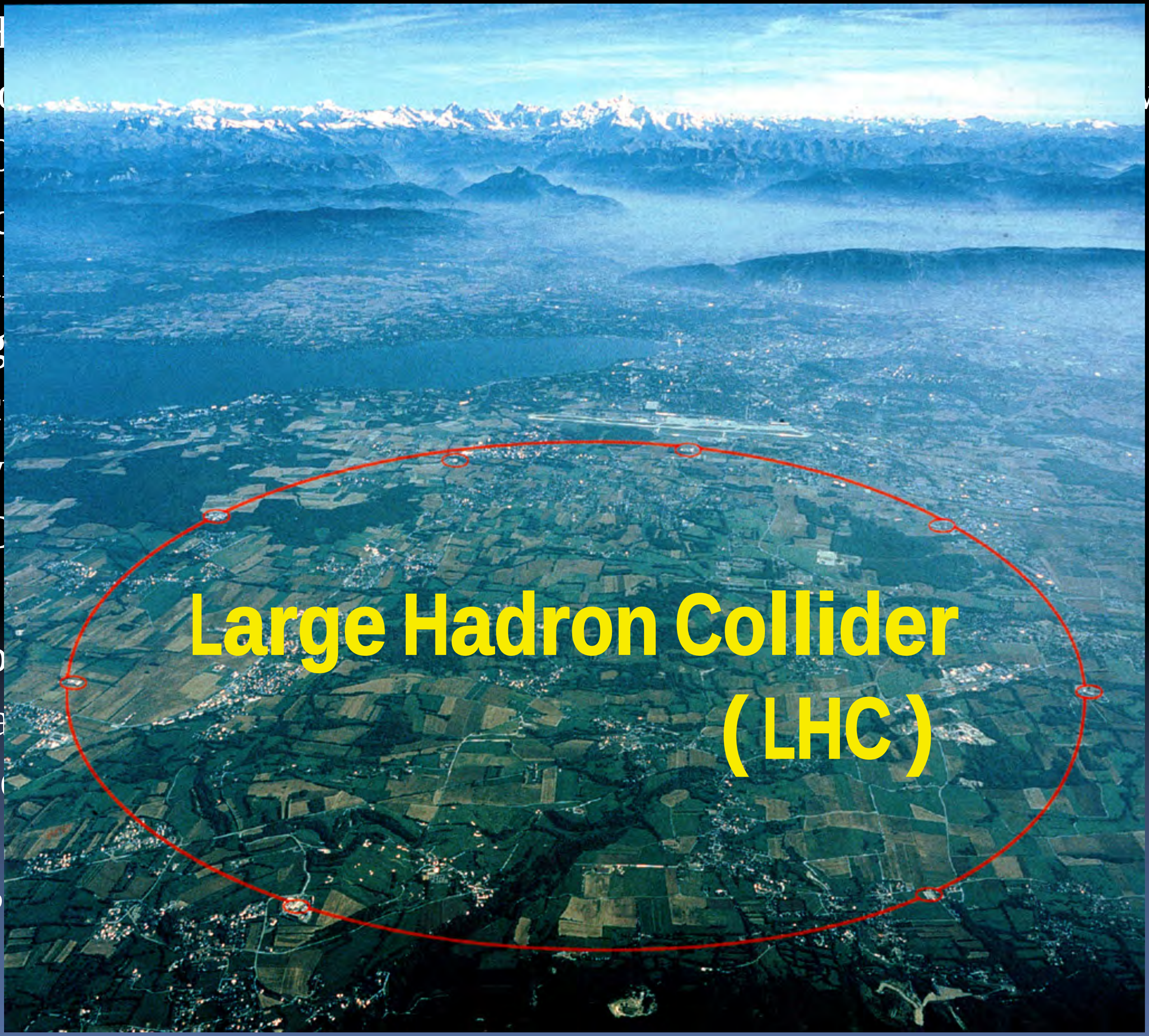

- Two beams (matter & antimatter!) circulate in opposite directions, only few mm apart, brought into collision at two detector regions
- While collisions only generate 1-2 watts of power, as shown earlier, the stored energy of the proton beam is
  - 36 x ($3 \times 10^{11}$) x ($1000 \times 10^{9}$ x $1.6 \times 10^{-19}$ J) = **1.7 MJ** !
    - 1.7 MJ = kinetic energy of a 6 ton truck moving at 60 mph
  - 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 ...




# Current Accelerator R&D

- Large H
  - Prot
  - 7000
  - Reac
- Internat
  - Larg
  - Elec
  - Low
- Muon C
  - Use
  - Muo
- Very La
  - More
- Plasma
- Other??

vitzerland)



# Fermilab Main Control Room

From here, control and monitor properties of all accelerators

around the clock operation, 24/7 all year

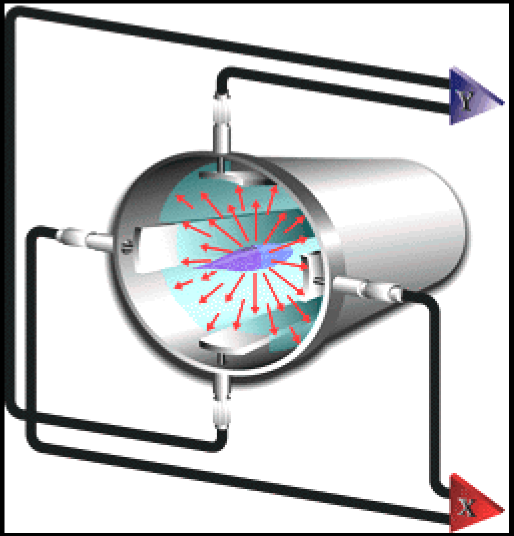
shut down periods occur, for maintenance

crews of 5-6 Accelerator Operators and Crew Chief

# Accelerator Diagnostics

- So, where is the beam in the machine?
- How big or how small is the beam ?
- How many particles are in the beam?
- How is it shaped?……etc
- Why is the beam not here or there?

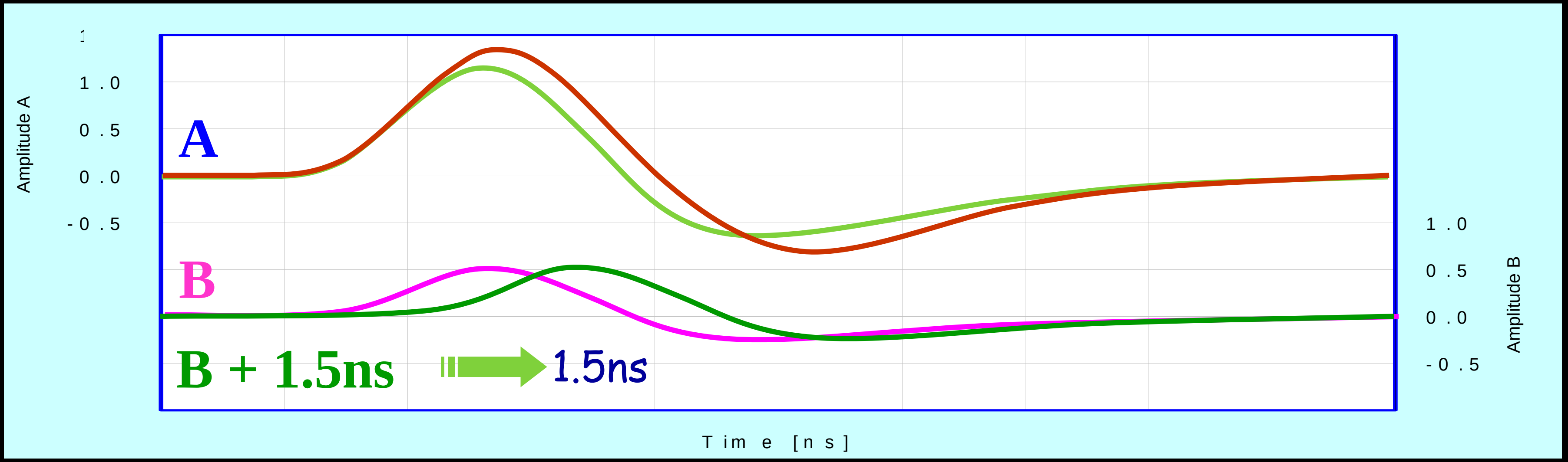
# Beam Position Monitors

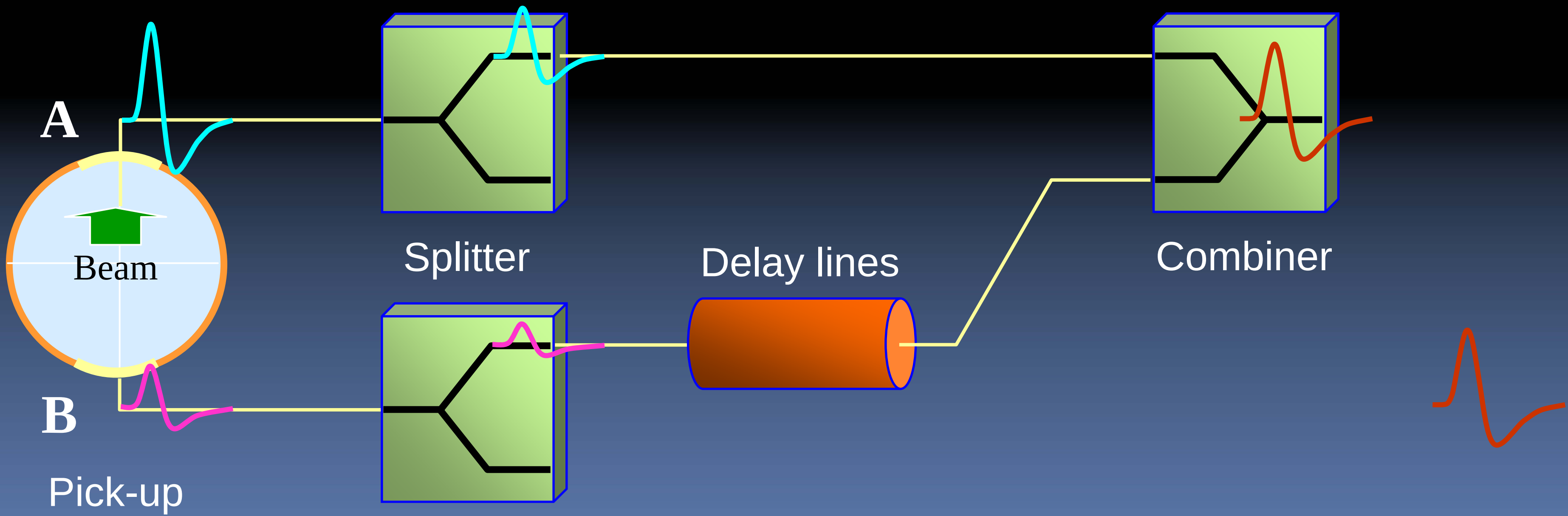



The BPM consists of four metal strips on the inside of the accelerator structure, connected to wires that extend outside the structure and are grounded. The entire apparatus is electrically isolated from the accelerator structure itself.

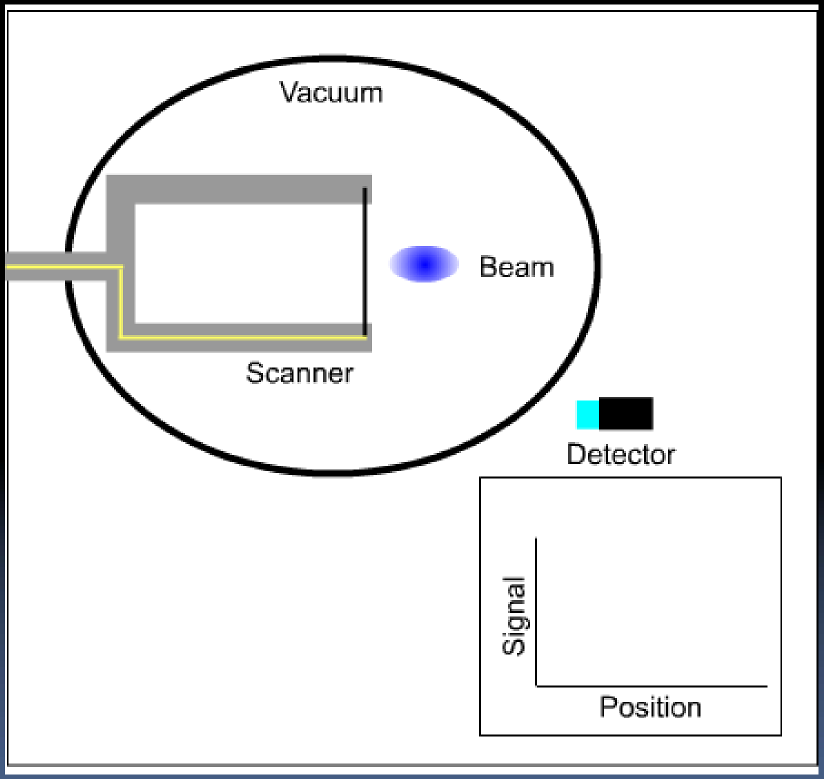
Beam positions can be determined down to the micron levels on some systems depending on the electronics. Intensity information is also determined.

# Example Measurement



# Wire scanners



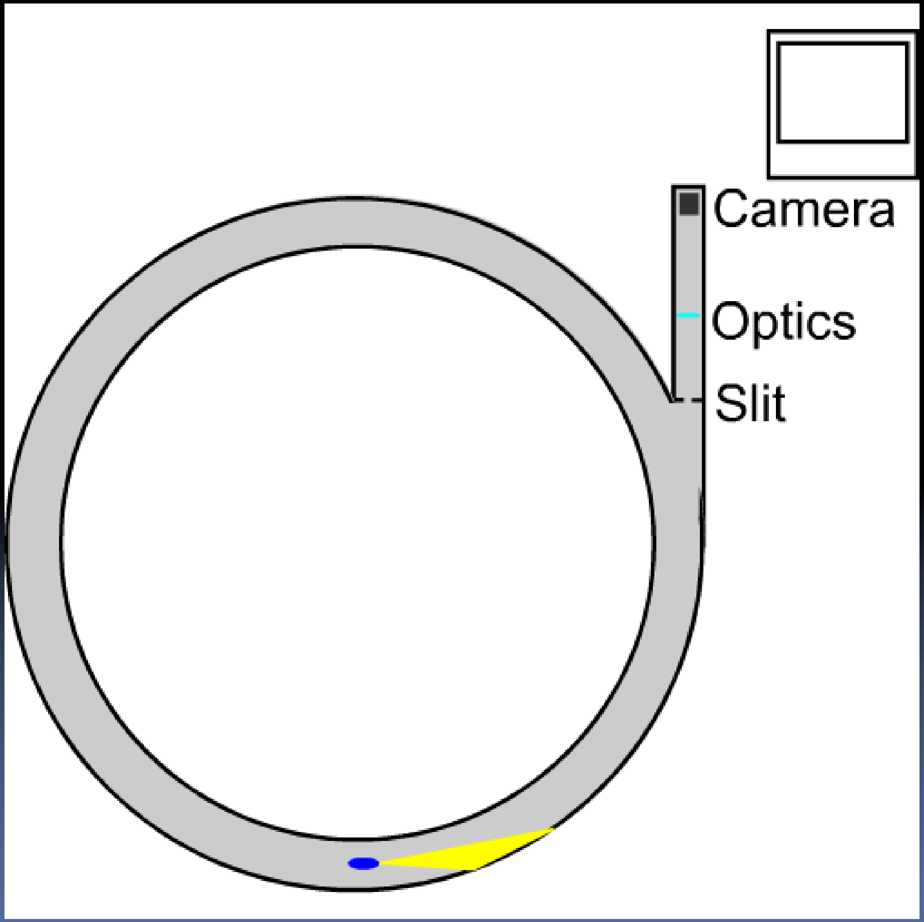

## Principle

Scan a thin wire trough the beam

Detect secondary particles created in the interactions between the beam and the wire

- SEM (low energy electrons evaporated from the wire) by measuring the electric current on the wire
- High energy secondary from nuclear interactions between the atoms of the wire and the beam using a scintillator + PMT downstream of the wire

# Synchrotron light



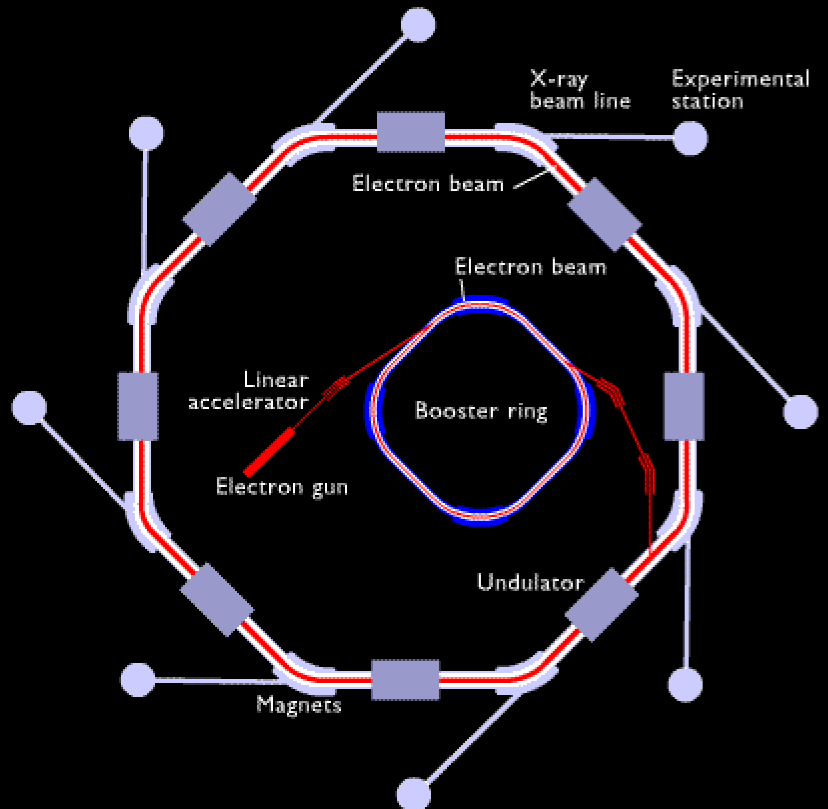

Principle

Charged particles emit synchrotron radiation (visible light or X Rays) when accelerated (curved) by the magnets

Use an optical system to acquire images of the beam

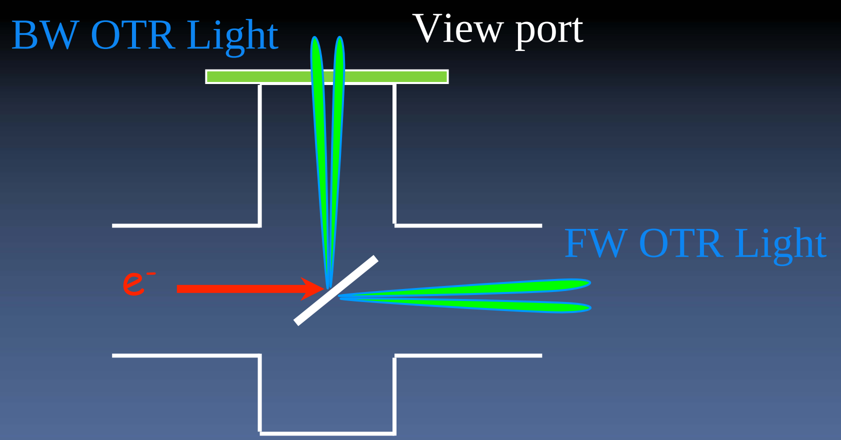
As the source is not well defined in case of bending magnets, angular filtering is needed (slits)

Synchrotron  Radiation is put to use at light sources for material, biological and industrial applications. Extremely stable beams are required.



# Optical transition radiation

- OTR is emitted when charged particles cross the surface of a metal foil
- The backward emission can easily be observed by an optical system
- The image of the beam can be acquired



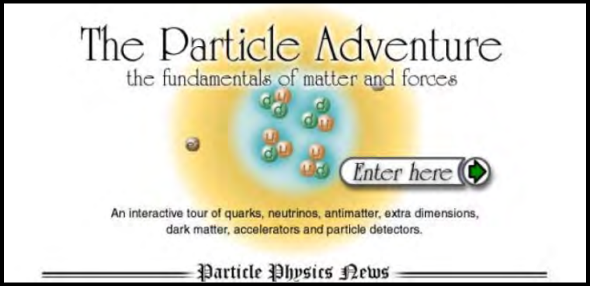
# Summary

- 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, Fermilab continues to work on future projects which can be funded at reasonable cost to best benefit the High  Energy Physics community (and, society!)

*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, …)