SATURDAY MORNING Physics

Fermilab

Fermilab

Accelerators

Elvin Harms

Fermi National Accelerator Laboratory

Accelerator Division

Saturday Morning Physics **28 January 2012**

Saturday Morning Physics

Session II

January 7 – March 3, 2012

Class is <u>NEVER</u> cancelled!

✔	Jan. 7	Introduction to Science at Fermilab	R. Dixon	WH15 WH15 ACC	M. Cooke V. Chertluru X. Bu
✔	Jan. 14	Cosmology	C. Stoughton	ACC ACC WH15	J. Anderson M. Datta S. Desai
✔	Jan. 21	Detectors	R. Lipton	DØ CDF MIPP	Z. Ye J. Freeman D. Mason
→	Jan. 28	Accelerators	E. Harms	MIPP DØ CDF	A. Jung K. Kousouris S. Jindariani
	Feb. 4	Theory of Relativity	D. Hooper	CDF MIPP DØ	K. Mishra H. Yin M. Muether
	Feb. 11	Quantum Mechanics	P. Fox	GCC SiDet Tech. Div.	J. Osta B. Pahlka D. Perevalov
	Feb. 18	Energy and Climate	C. Brown	Tech. Div. GCC SiDet	M. Rominsky S. Sharma P. Tan
	Feb. 25	Theory of Everything	S. Jabeen	SiDet Tech. Div. GCC	Y. Xie F. Yang T. Yang
	Mar. 3	Physics & Society	E. Ramberg	***GRADUATION***	

Classes meet in One West

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

Web Address: http://smp.fnal.gov

Revised 01/11/2011

About the Speaker…

- Engineering Physicist, Accelerator Division
- Hometown: Edwardsville, IL
  - born in Oakland, CA
- 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 -- 30+ years
    - Operations (Main Control Room)
    - Antiproton source/Tevatron Collider
    - LHC/LARP
    - Superconducting RF & Photoinjector
    - **Outreach/Teaching**

email: *harms@fnal.gov*

Outline of Presentation

- What is a Particle Accelerator?
- 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?
- A historical tour of accelerators
- Fermilab Accelerators and their Operation
- The Future

*Special Thanks to **Mike Syphers, MSU**, for preparing much of this talk!*

What is a Particle Accelerator?

- *Webster* describes an accelerator (Physics) as:
  - ‘a mechanical device for increasing speed’
  - ‘A device, as an electrostatic generator, cyclotron, or linear accelerator, that accelerates charged subatomic particles or nuclei to energies useful for research’

- *Wikipedia* says:
  - ‘a particle accelerator (or atom smasher) is a device that uses electric fields to propel electrically-charged particles to high speeds and to contain them. There are two basic types: linear accelerators and circular accelerators

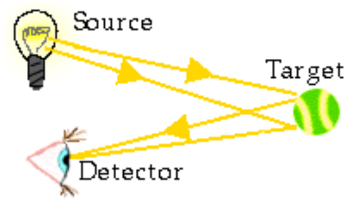
Why Do We Need Accelerators?

- ‘Needs’ in everyday life might include
  - Medical applications
    - X-ray machines, cancer diagnosis & treatment, etc. (new proton therapy facility in Warrenville)
  - Industrial applications
    - e^- beam welding, semiconductor processing, sterilization, etc.
- It is estimated that there are more 15,000 - 17,000* accelerators in use around the world
  - 97% for ‘commercial’ applications
  - http://www.symmetrymagazine.org/breaking/2009/05/02/the-stuff-you-can-do-with-accelerators/
  - very few, ~120, for physics research

*http://www.symmetrymagazine.org/breaking/2009/05/02/the-stuff-you-can-do-with-accelerators/
August 2009

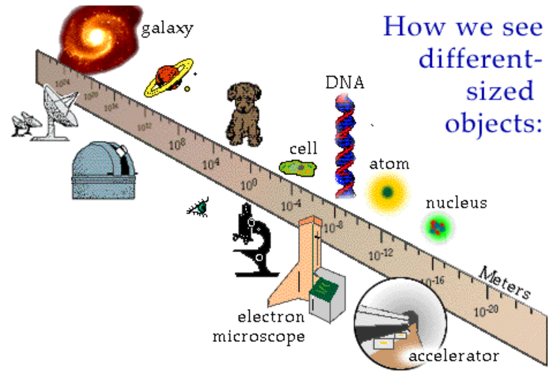
So, why Do *We* Need Accelerators?

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



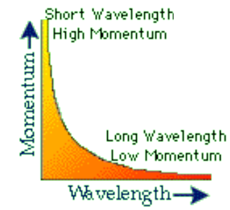
- We need to send source particles toward target particles and then detect the outcome. Last week, detectors were the topic; this week, we discuss how we generate our source (and, for the Tevatron Collider, the target as well!)
  - OK, so why do we need *High Energy*?

Wave-Particle Duality of Nature



DeBroglie showed that moving particles have an equivalent wavelength,

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



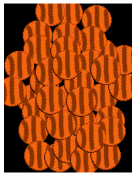
Plus, add a little bit of Einstein's work:

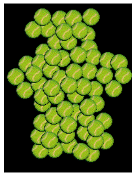
$$E^2 = (mc^2)^2 + (pc)^2$$

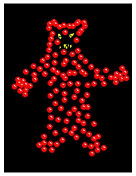
So, high energy gives us high momentum which gives us short wave lengths so we can make out small detail

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

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



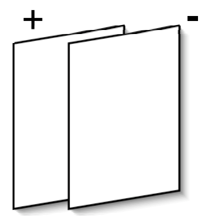




- Suppose you wanted to actually "see" an object. You can begin by firing a single photon (particle of light) at it, and see what you detect. The photon may "reflect" and give you a signal that something is there, or it could miss the object completely (since you don't know where or what it is). Firing 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!

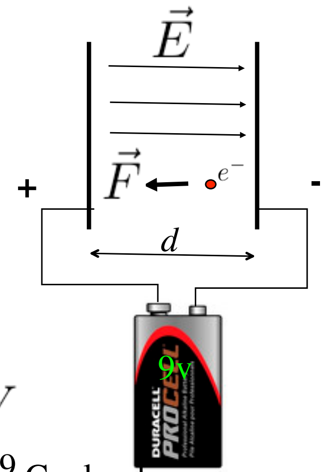
How to Accelerate Particles

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 $q = -e = -1.6 \times 10^{-19}$ Coulomb

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

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)

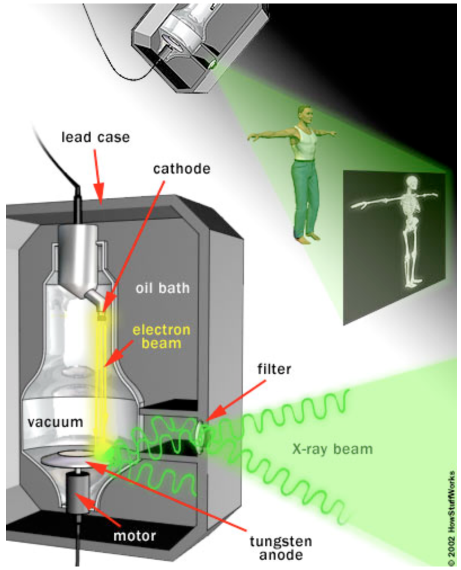
(c = 186,000 miles/sec = 300,000,000 m/sec)

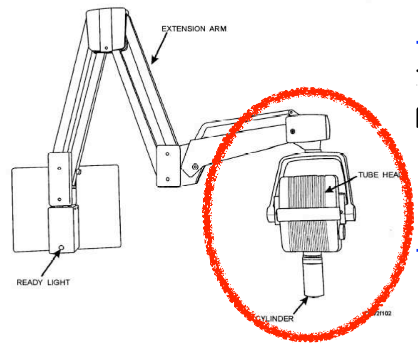
Note: if looked at a proton instead, its mass is 1836 times that of the electron. Thus, its speed would be *only* 0.00014c.
(= 90,000 mi/hr!)

Q: How much voltage can we deliver?

Let's look at a your dentist's X-ray machine:

Dental X-rays





So, how fast are we moving now?

- An electron in an X-ray machine, 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…
  - 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…
  - more on this topic next week

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

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

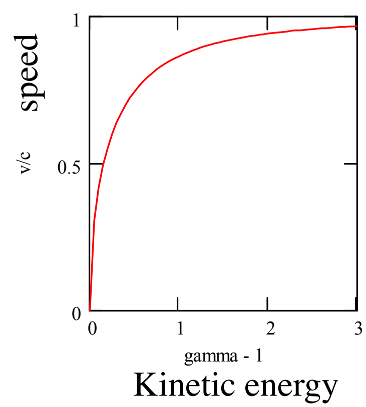
When $v \ll c$ this amounts to $E = mc^2 + \frac{1}{2}mv^2$. But, as the energy of the particle is increased, it's speed approaches (but never reaches!) the speed of light:

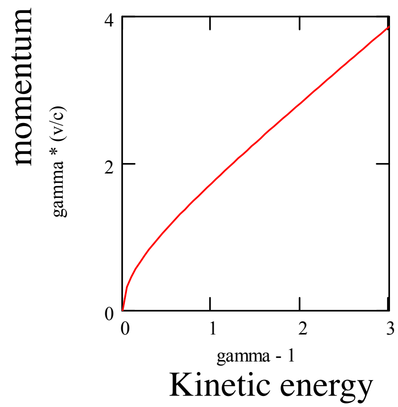
$$v = c \cdot \sqrt{1 - \left(\frac{mc^2}{E}\right)^2}$$

- 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

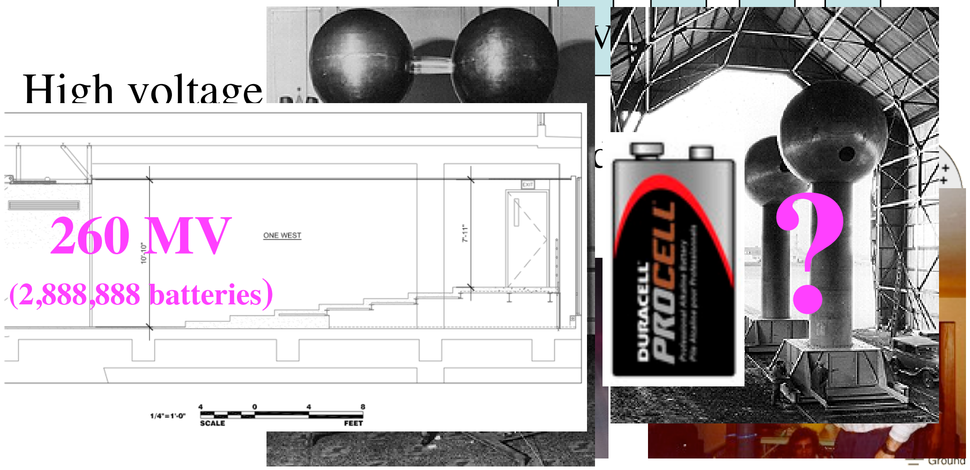
mc^2:

e-	0.5 MeV
p	938 MeV

So, Back to High Voltage!

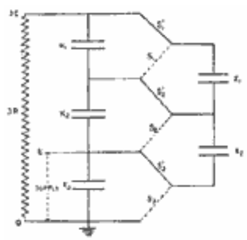
- How to get **high voltage**? How high can we go?
- String a bunch of batteries in series!
  - Not very practical…

- High voltage



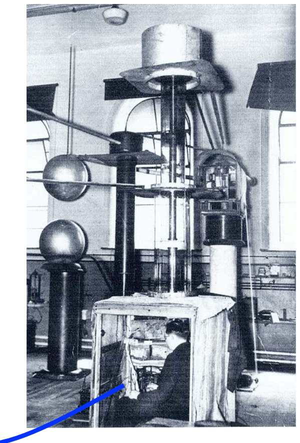
High Voltage

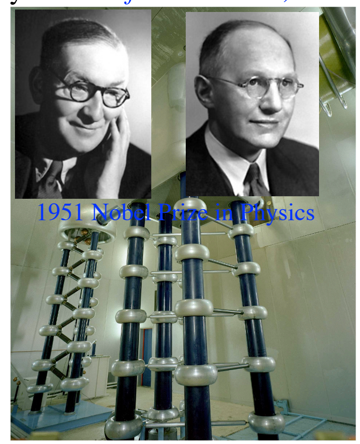
- van de Graaff's are used for particle accelerators (though, with a different configuration) and provide voltages up to ~25,500,000 V = 25 MV (10 MV is typical).
- Fermilab has a related device, called a Pelletron, which works on the same principle; produces electron beams with energies of about 4 MeV.
- 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??

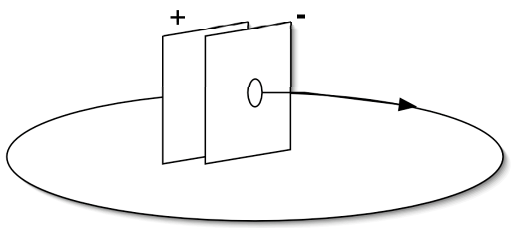




1951 Nobel Prize in Physics

Let's Re-use the E-field!

- The Cockcroft-Walton design can produce voltages up to a few MV, and the van de Graaff 10's of 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

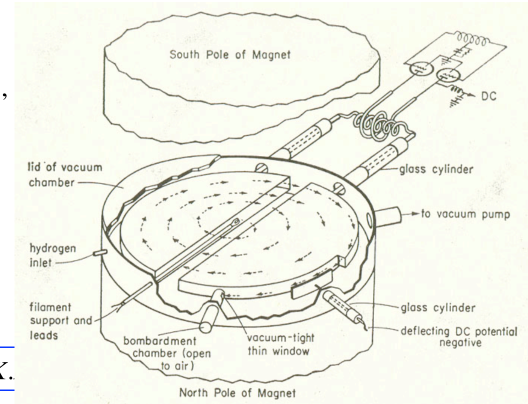
  $T = 2\pi r/v.$
- The force due to the magnetic field is

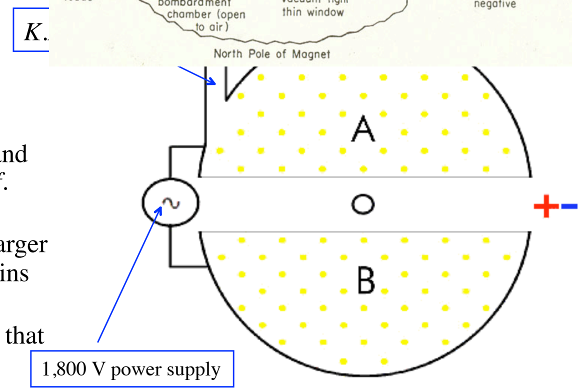
  $F = evB$
- The centripetal force is

  $F = mv^2/r$
- 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.





60-inch Cyclotron, Berkeley -- 1930's

Early Radiation Laboratory staff framed by the magnet for 60-inch cyclotron in 1939. *Front row, left to right:* John H. Lawrence, Robert Serber, Franz N. D. Kurie, Raymond T. Birge, Ernest O. Lawrence, Donald Cooksey, Arthur H. Snell, Luis W. Alvarez, Philip H. Abelson. *Second row:* John Backus, Wilfred B. Mann, Paul C. Aebersold, Edwin M. McMillan, Ernest Lyman, Martin D. Kamen, D. C. Kalbfell, W. W. Salisbury. *Last row:* Alex S. Langsdorf, Jr., Sam Simmons, Joseph G. Hamilton, David H. Sloan, J. Robert Oppenheimer, William Brobeck, Robert Cornog, Robert R. Wilson, Eugene Viez, J. J. Livingood. *(Lawrence Radiation Laboratory)*

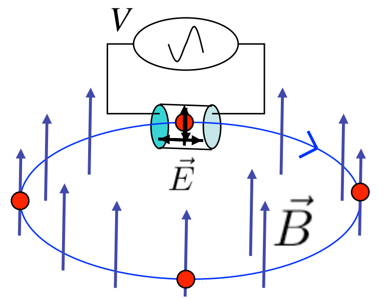
Circular Accelerators

- Since the entire cyclot
field, the magnets wou
- Also, as the particles c
speeds would begin to
would not keep in step
- “Synchrocyclotrons” w
these effects into acco
accelerators -- betatron

- But the one that won out, when it came to very high energy particle beams, was the ***synchrotron***.
- Invented by Edwin McMillan (1951 Nobel Prize - Chemistry) & Vladimir Veksler - late 1940’s.

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).



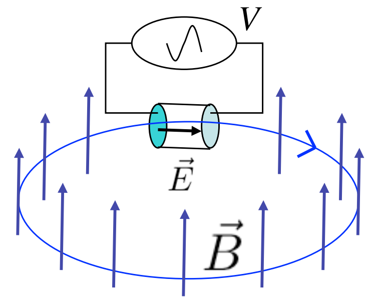
Voltage = $V \sin(2\pi f\, t + \delta)$

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

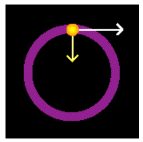
Each revolution,
energy changes by amount
$\Delta E\ =\ e\ \ V\ \sin(\delta)$

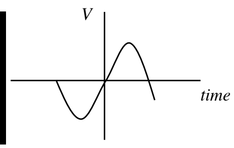
δ is called the *synchronous phase angle*

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:





$mv^2/R = evB$

$\Longrightarrow R = mv / eB$

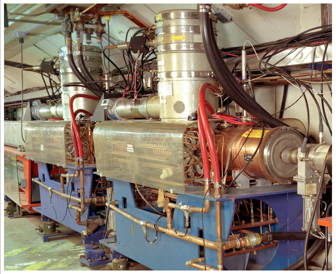
$= p / eB$

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!

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 *r*, has a natural frequency $f_{\text{nat}} = 2.4c / 2\pi r$.
  - For f_{nat} ~ 50 MHz, we see $r \sim 2$ 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

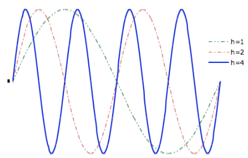


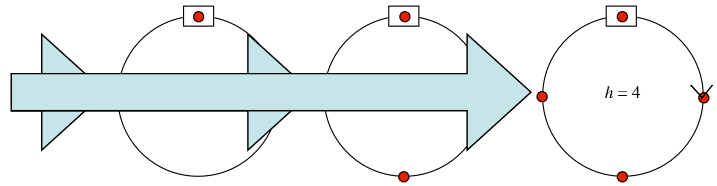
A 53 MHz cavity used in the Fermilab Booster synchrotron

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
$h = 84$

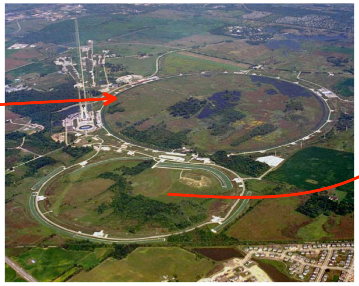
All use 53 MHz systems

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.

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

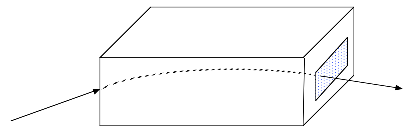
- What about Gravity?? Look at a proton…

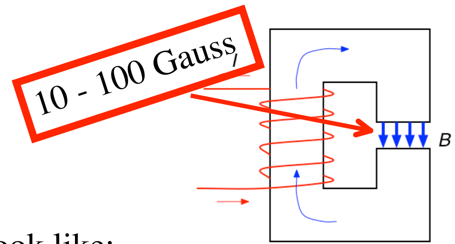
$$\frac{F_{gravity}}{F_{electric}} = \frac{mg}{eE} = \frac{(1.67 \times 10^{-27} \ kg)(9.8 \ m/s^2)}{(1.6 \times 10^{-19} \ C)(10 \times 10^6 \ V/m)} = 10^{-14} \quad !!$$

  – Not even a *player*!

Accelerator Magnets

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





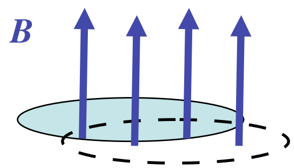
  – A simple electromagnet might look like:

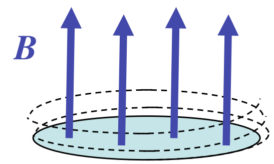
  – Accelerator magnet:
    - lots of current and lots of iron!
      - Iron-dominated magnets can obtain field strengths up to ~2 Tesla

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!

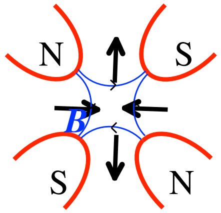




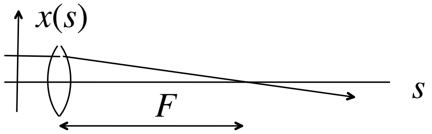
- Also, large number of particles in a real beam start out heading in every which direction!
  (sort of like a flashlight beam, spreading out away from the source)

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)

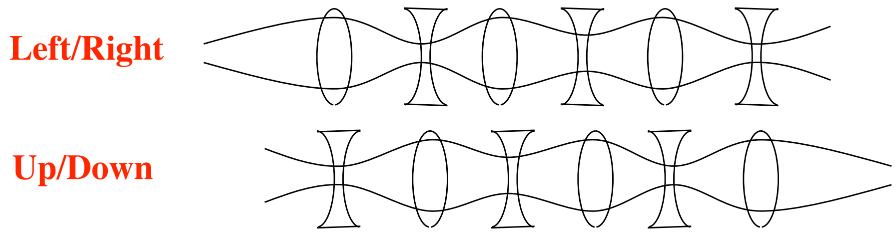


So, ***alternate*** lenses: + - + - + - …

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

Alternating Gradient Focusing

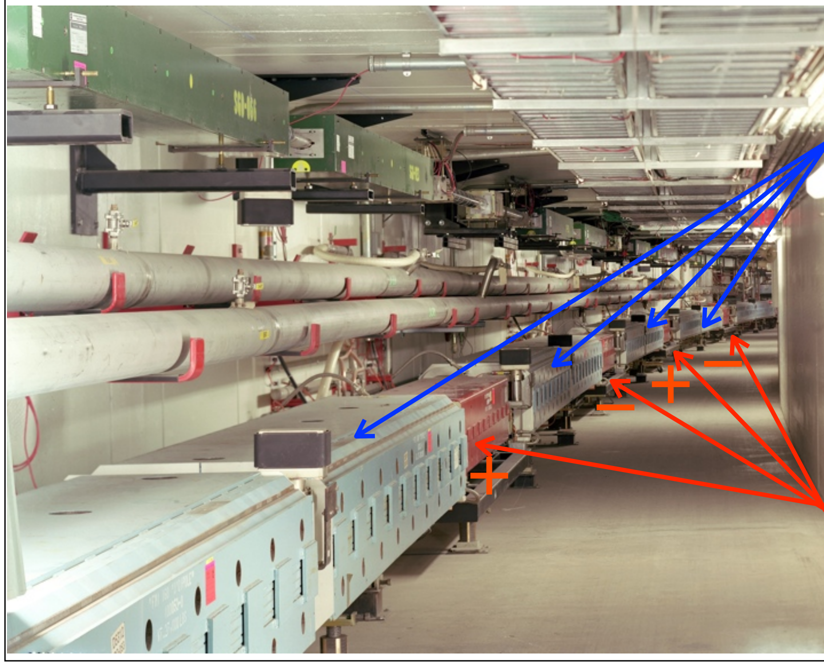
- By alternating the polarity of the Quadrupole magnets, they serve to alternately focus and defocus the beam, keeping it stable in all directions simultaneously



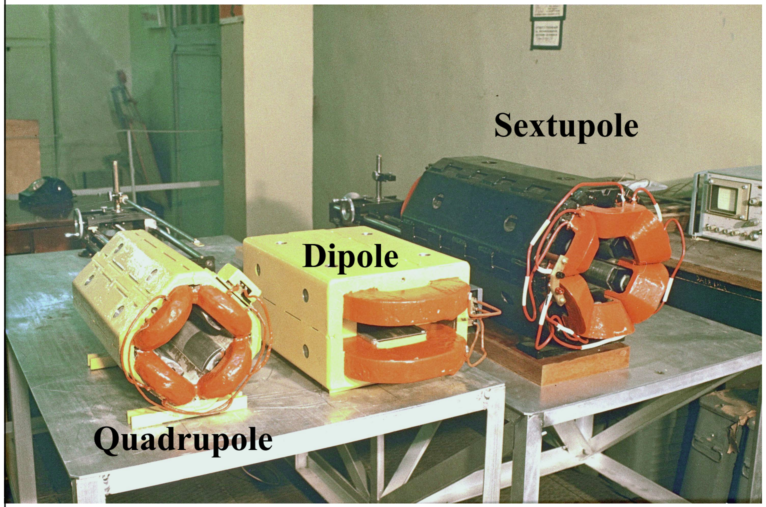
Smaller magnets are used to fine-tune the beam trajectory, and to perform special orbit manipulations

  – 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.

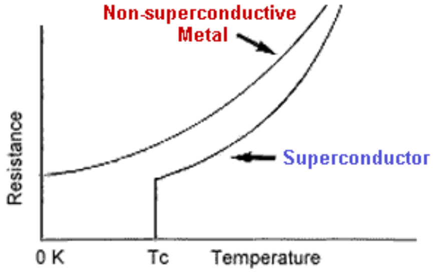
Iron: fields limited to about 2 Tesla (20,000 gauss)

Superconductivity

- Discovered in 1911 by Dutch physicist Heike Kamerlingh Onnes of Leiden University (Nobel prize - 1913)

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

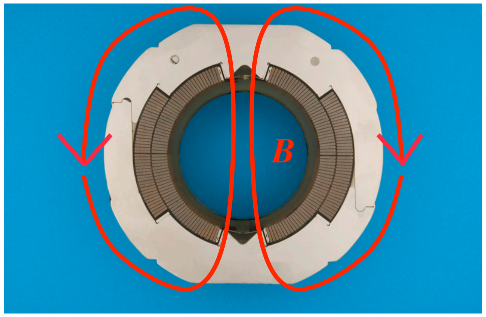
- Took many years to understand, and to perfect the production of superconducting materials suitable for commercial use

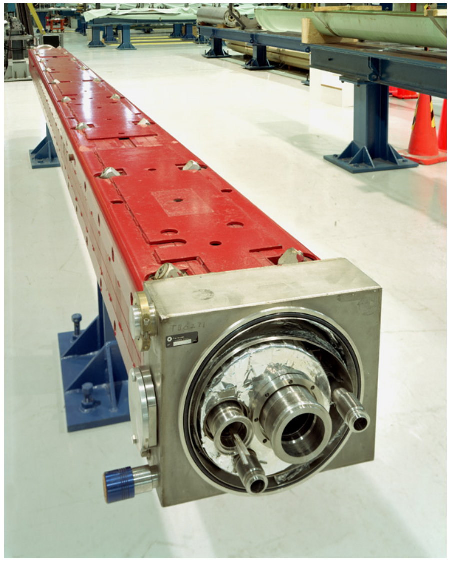


Superconducting Accelerator

- 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 Kelvin = -450 ^{o}F !
    - Liquid Helium Cryogenics Refrigeration System -- ***one of 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
- This technology is now being applied not just to magnets, but RF Cavities as well!

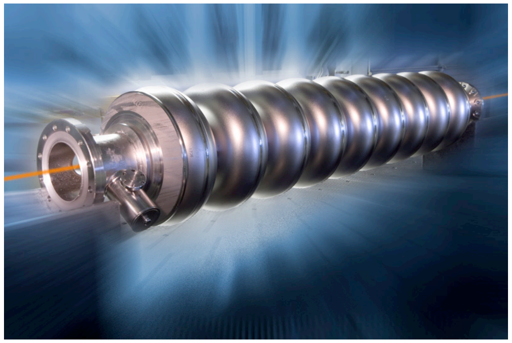
Superconducting Tevatron Magnet





- Outside is at room temperature; inside is ~4 Kelvin!
- 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)

Superconducting RF Cavity



- Typically made of high purity Niobium (Z = 41)
- Operate at ~2 Kelvin
- Generate accelerating gradients ~35 MV/m.
- complicated fabrication
- maturing technology

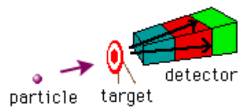
How Accelerators are Used at Fermilab

(after the break?)

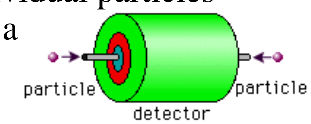
take a look at the show & tell items

Fixed Target Experiment
vs.
Colliding Beams Experiments

- Originally (and once again) Fermilab conducts its experiments exclusively by accelerating particles to high energy (up to 800 GeV), and then directing them toward a target (piece of metal, say) and observing the products. This is called a 'fixed target' experiment.

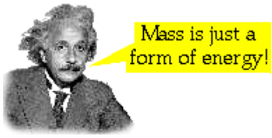


- With the Tevatron, it became feasible to store particles in the ring for long periods of time. By sending beams of particles going in both directions within the accelerator, and steering them to hit head-on at particular locations, we can pass groups of particles through each other over and over until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

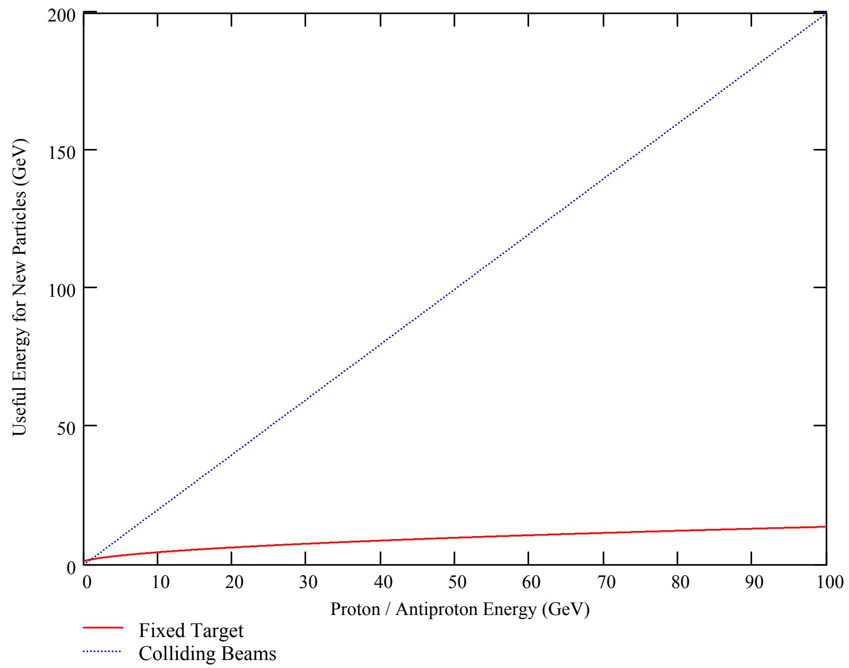


Colliding Beams

- 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*!

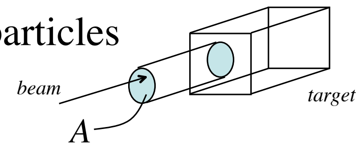


Available Energies



Luminosity

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



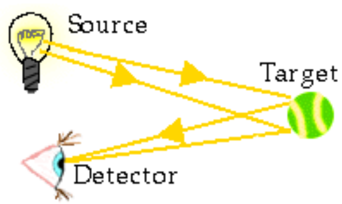
  - Rate of "interactions" --

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

  - 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:

$$R = \frac{\Sigma}{A} \times N_1 \times N_2 \times f$$

Frequency of bunches passing through each other

  - The 'luminosity' is:

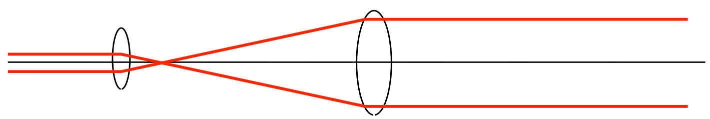
$$L = \frac{f N_1 N_2}{A}$$

$A = 4(\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*)^{1/2}$

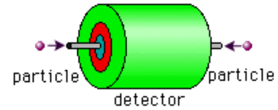
    - Depends upon the beam size, and number of particles in each beam
    - Note: has units of 1/(area x time)
    - Gives Experimenters feeling for performance of accelerator
- Thus, to be able to gather more data quickly, need lots of particles, and small beam sizes --
  - In Tevatron, 10^{12} - 10^{13}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

The "Final" Focus

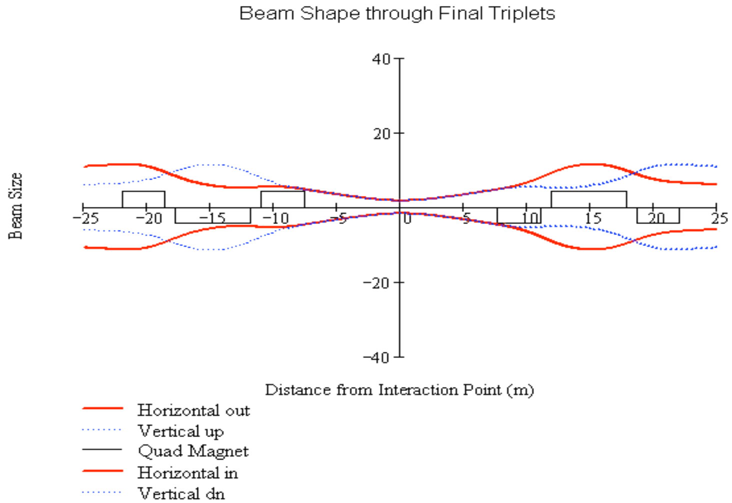
- In a collider, in order to increase the probability that particles in the two beams will actually hit each other, we squeeze the beam to very small sizes at the collision points.
- At an 'interaction point' the particle beams can be as narrow as 60 μm (~ the width of a human hair!)
- Performed using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

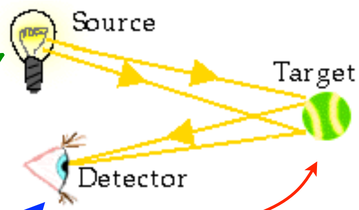


antiprotons

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

Some Numbers…

- For Tevatron operation,
  - $N_{protons}$ = 1x10^{13}, $N_{antiprotons}$ = 2.9x10^{12},
  - f = 36 x (3x10^{5} km/sec)/6 km,
  - $A = \pi$ (0.22 cm)^2
  - ---> **L = 3.2 x 10^{32} cm^{-2} sec^{-1}**



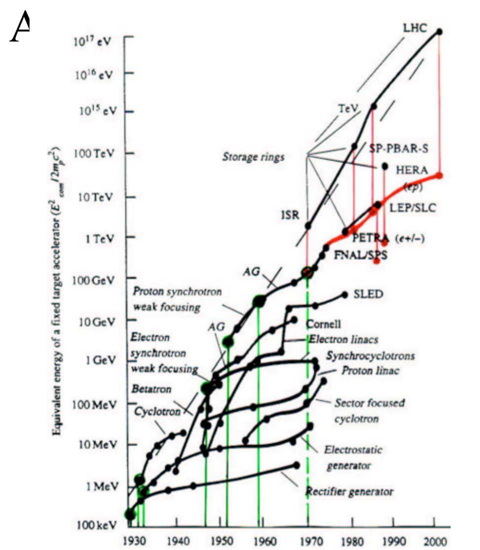
- Cross section of a proton/antiproton collision

  ~ 6 x 10^{-26} cm^2
- So, we got, could detect, about 200 x 10^6 collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store data at this rate (and they do!) ***(remember last week?)***
- Each proton/antiproton has energy of

  980 GeV = 980 x 10^9 x (1.6 x 10^{-19} J) = 1.6 x 10^{-7} J
- So, *power* delivered in the collision region is only

  2 x 1.6 x 10^{-7} J x 200 x 10^6 /sec ~ 64 watt!

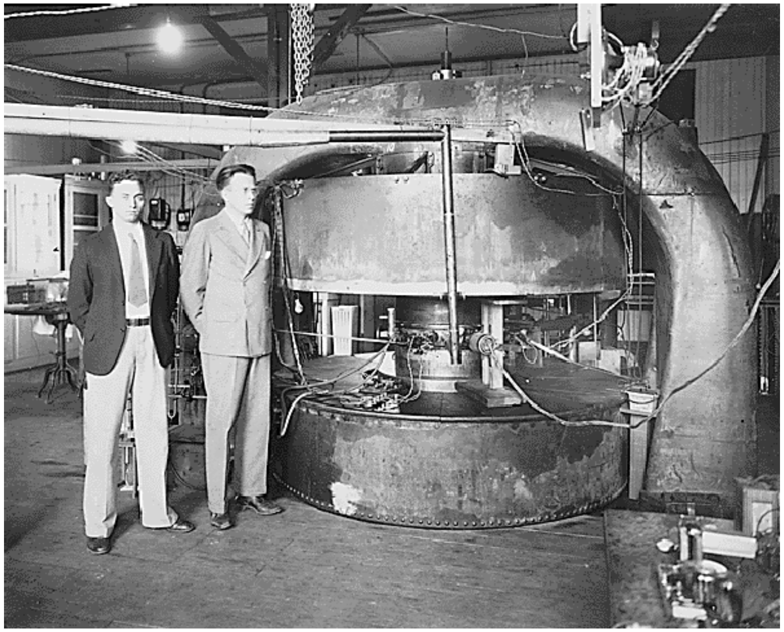
The World's High Energy Accelerators



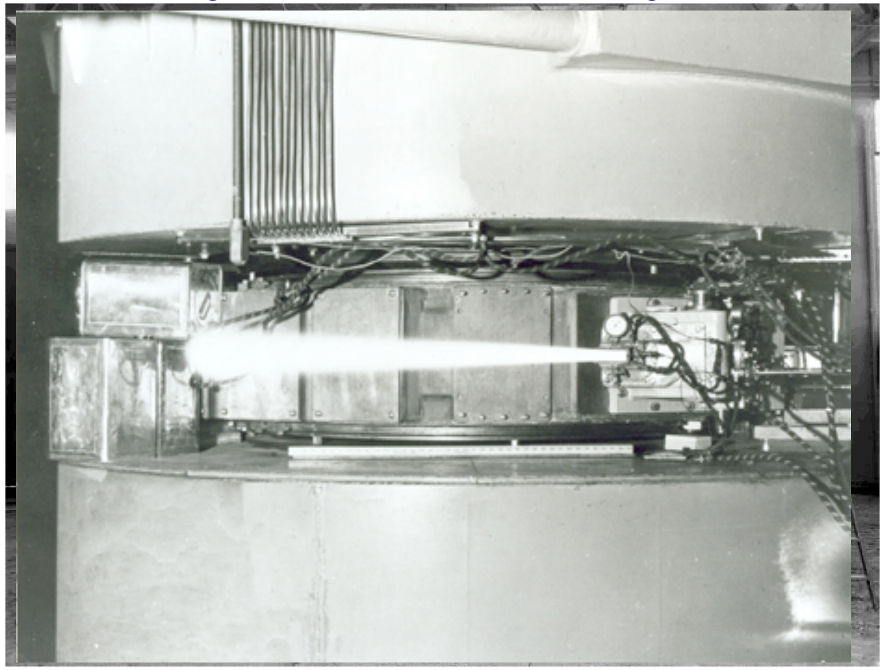
Berkeley Radiation Laboratory

The First Cyclotron, Berkeley -- 1930's

27-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

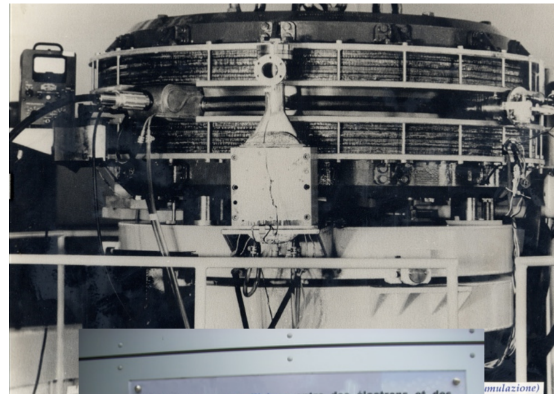
AGS, Brookhaven, New York

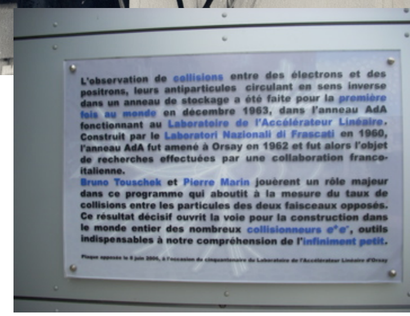
AGS, Brookhaven -- 1960's

PS, CERN -- 1960's

The first particle collider-- 1961

AdA (Anello di Accumulazione)
INFN Frascati and LAL, Orsay





U70, Serpukhov -- 1970's

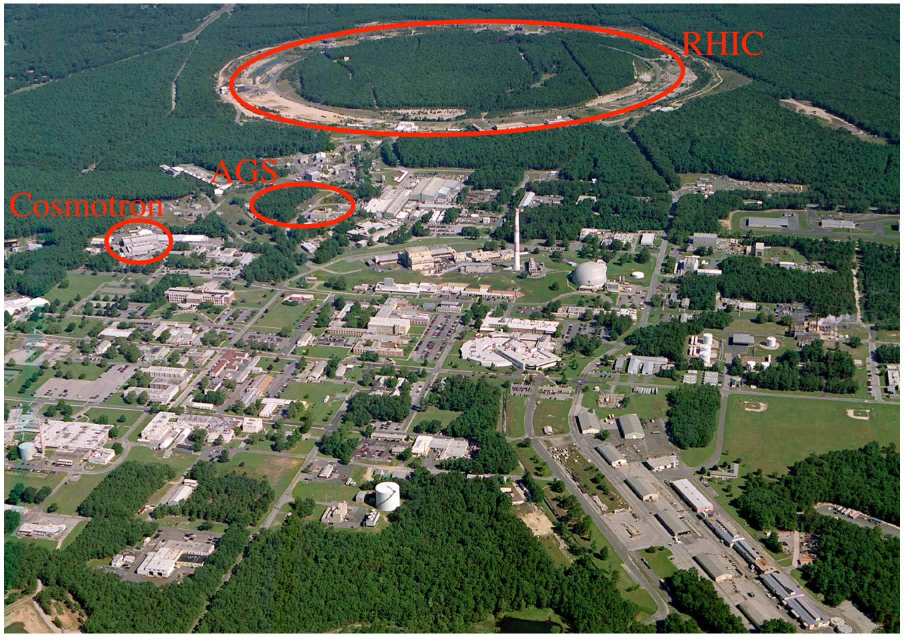
Main Ring (1970's) and
Tevatron (1980's), Batavia

HERA, Hamburg -- 1990's - 2000's

LEP, Geneva -- 1990's

Relativistic Heavy Ion Collider
Brookhaven -- 2000's - present

Brookhaven National Lab

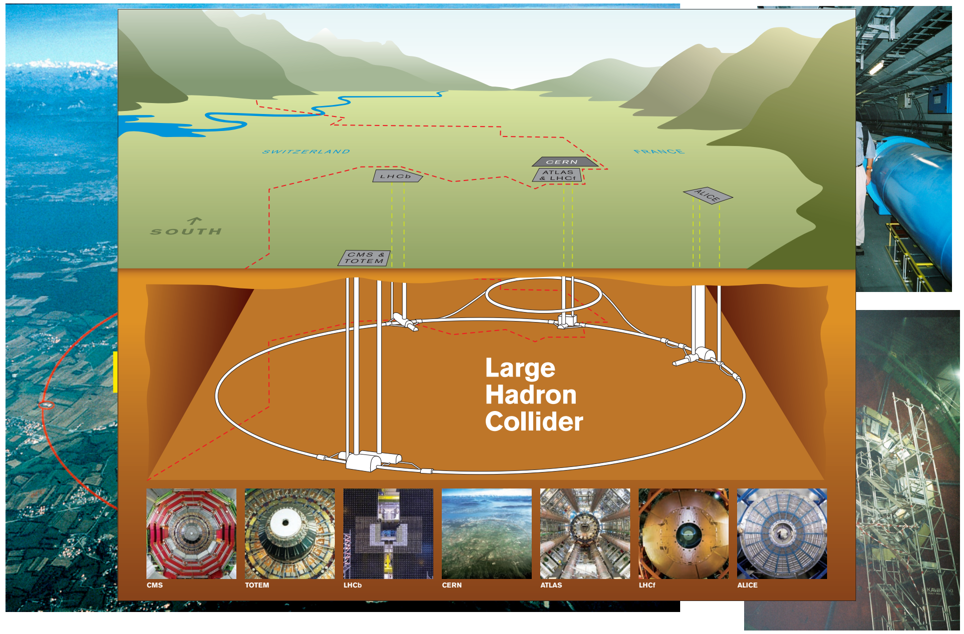


SLAC National Accelerator Lab

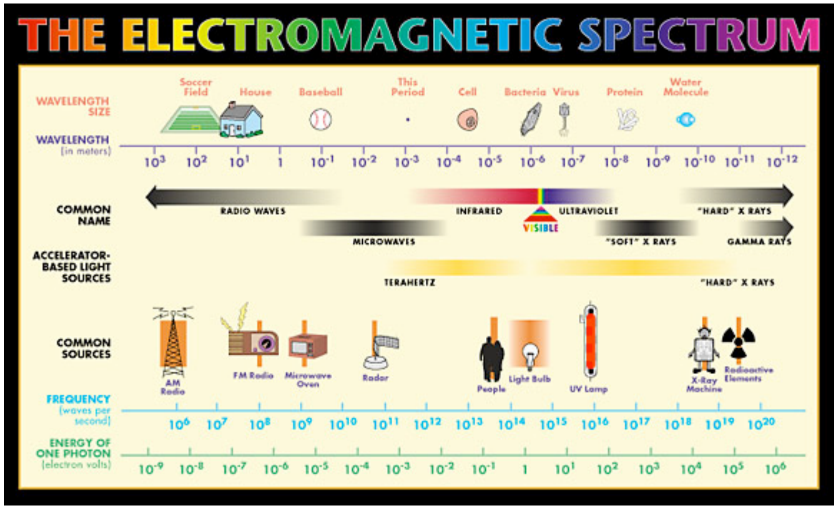
Fermilab

You are here!

European Organization for Nuclear Research (CERN)



Other Scientific Applications of Accelerators



Synchrotron Light source

- ~70 facilities worldwide
- APS just down the road at Argonne National Laboratory

Free Electron Laser

FLASH: Free-Electron LASer in Hamburg at DESY

Free Electron Lasers (FELs) represent an increasingly
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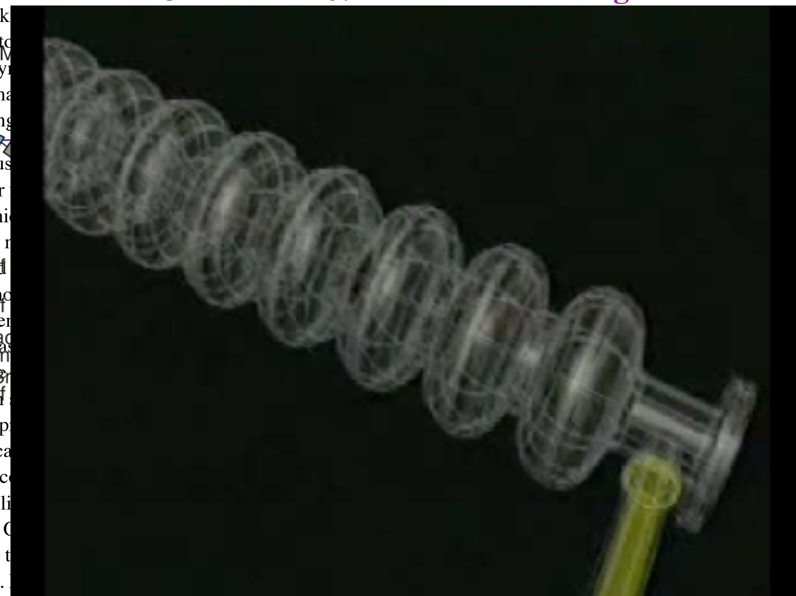

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What Can Be Done in a Light Source ?

Whether synchrotrons or FELs, light sources are advancing research and development in fields as diverse as:

- biosciences (protein crystallography, cell biology)
- medical research (microbiology, disease mechanisms, high-resolution imaging and cancer radiation therapy)
- chemical and environmental sciences (toxicology, atmospheric research, clean combustion and cleaner industrial production technologies)
- agriculture (plant genomics, soil studies, animal and plant imaging)
- minerals exploration (rapid analysis of drill core samples, comprehensive characterization of ores for ease of mineral processing)
- advanced materials (nanostructured materials, intelligent polymers, ceramics, light metals and alloys, electronic and magnetic materials)
- engineering (imaging of industrial processes in real time, high-resolution imaging of cracks and defects in structures, the operation of catalysts in large chemical engineering processes)
- forensics (identification of suspects from extremely small and dilute samples)
- materials modification and fabrication

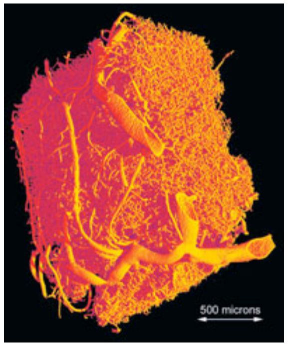


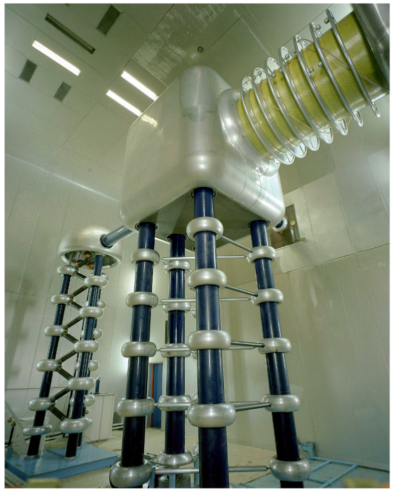
***Image:** 3D reconstruction of the brain of a transgenic mouse, study of Alzheimer's disease, Krucker et al. (SCRIPPS, UZh, ETHZ, PSI). (Courtesy: Swiss Light Source/ PSI)*

The Fermilab Accelerator Complex

Fermilab's Accelerator Complex

- The Fermilab Accelerator System is made up of a 'chain' of accelerators, each delivering particles to the downstream accelerator.
  - Cockcroft-Walton style "pre-accelerator" (Preacc)
    - 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*, operated at 0.98 TeV)
  - Plus, a couple others: Antiproton Accumulator, Recycler, etc.

Cockroft Walton Preaccelerator

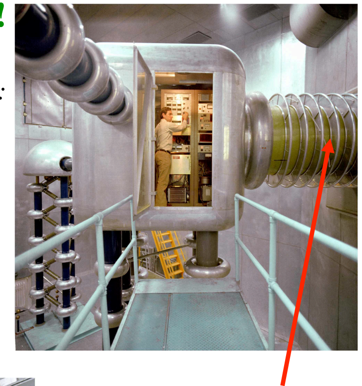


Final kinetic energy of the ions is 0.75 MeV, and their speed is ~ 0.04*c*

All starts here!

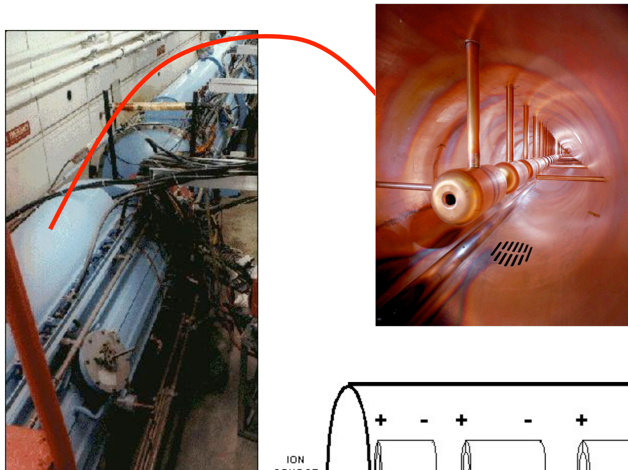
inside the dome:

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



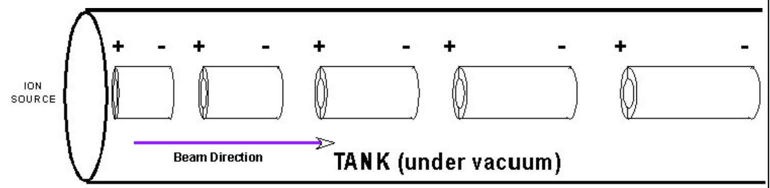
The H- ions are attracted toward the wall, through the column, and thus gain speed/energy

Linear Accelerator (Linac)

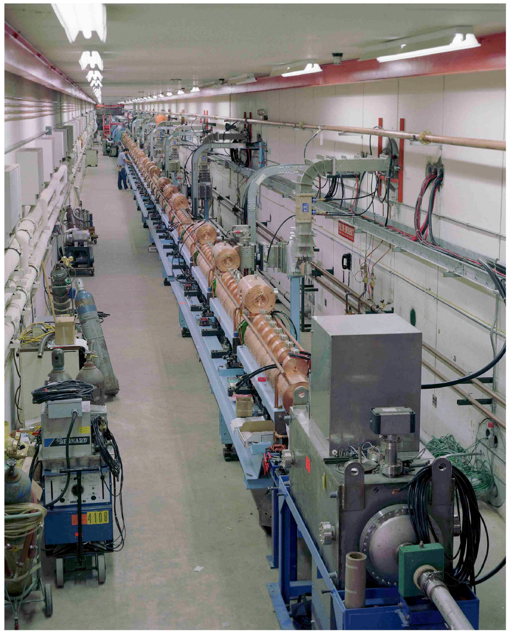


Upstream end of Linac:

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



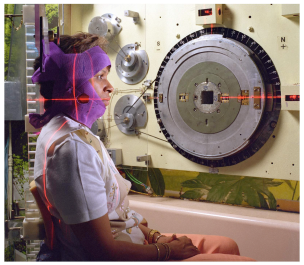
Linac (cont'd)



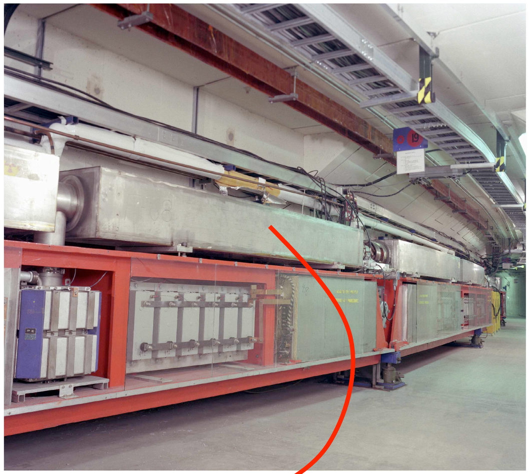
Downstream end of Linac:
- particle speed approaching 0.7*c*
- gap spacing not changing much; use different cavity structure

- 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!

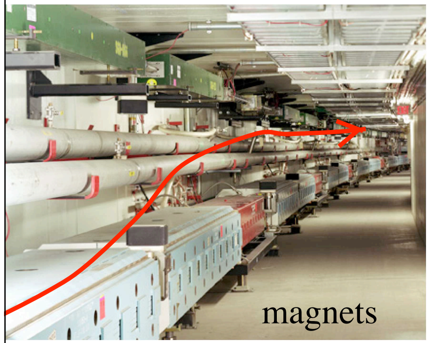
Protons circle the Booster 20,000 times, and gain 7600 MeV in K.E.
they exit traveling at 99% *c* !

Total process takes **0.033 seconds!**

Magnets

RF accelerating cavities

Main Injector

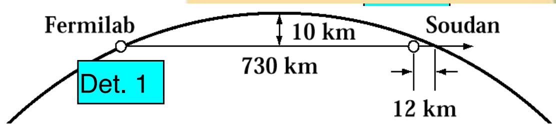


Particles enter with 8 GeV K.E.; accelerate up to 150 GeV (0.9999*c*)
Many uses…

- 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 experiments (NuMI/MINOS)

RF:

Neutrinos at the Main Injector

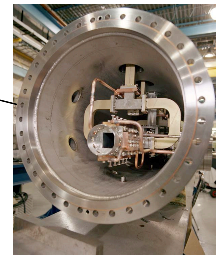


Search for neutrino oscillations (mass)
Sending neutrinos through the earth to Minnesota ***right now***!

Antiproton Source -- anti-matter!

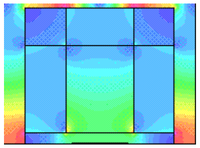
- 120 GeV proton beam from MI strikes target, produces LOTS of particles, every 2 seconds or so
- 8 GeV antiprotons are 'filtered' out and stored
- Stochastic Cooling system works on the beam, reducing its size and allowing room to grab/store more particles
- After about 10 hours or so, have ~1-2 Trillion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

Beam cooling systems

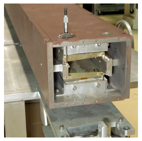


Recycler Synchrotron

- 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)
  - A key component to maximum Tevatron luminosity



Permanent Magnet field map



magnet

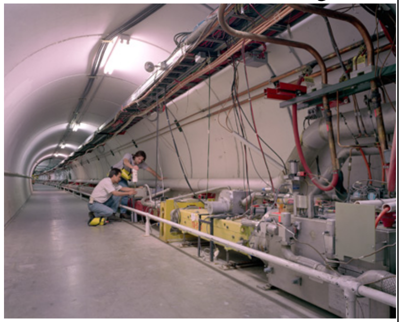
Pelletron

The Tevatron

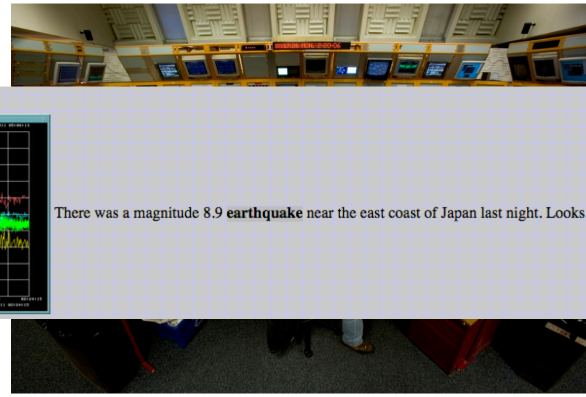
- From 1983 until December 2009 - the World's Highest Energy particle accelerator -- 0.98 TeV
- On September 30 - turned off forever....
  - Replaced 400 GeV "Main Ring" in the same tunnel (built ~1972)
  - 1st superconducting accelerator
  - Circumference = 2π km (+/- 5 cm!) = 4 miles
  - At 1 TeV, 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 10's of watts of power, as shown earlier, the stored energy of the proton beam is
  - $36 \times (300 \times 10^9) \times (1000 \times 10^9 \times 1.6 \times 10^{-19}$ J) = **1.7 MJ** !
    - 1.7 MJ = 3.6 X105 calories = kinetic energy of a modern submarine traveling 1 mph
    - 1.7 MJ ~ 1662 cups of plain M&M's
  - If lost in one revolution, instantaneous power: 1.5 MJ / 21 μsec = **71 GW**!
- CERN's LHC is now the world's most powerful accelerator ...
- Now destined to become a museum piece



Fermilab Main Control Room



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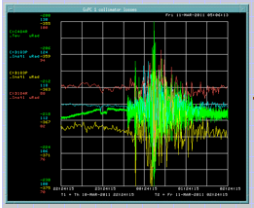


There was a magnitude 8.9 **earthquake** near the east coast of Japan last night. Looks like it shook up the TeV a bit!

From here, control and monitor properties of all accelerators

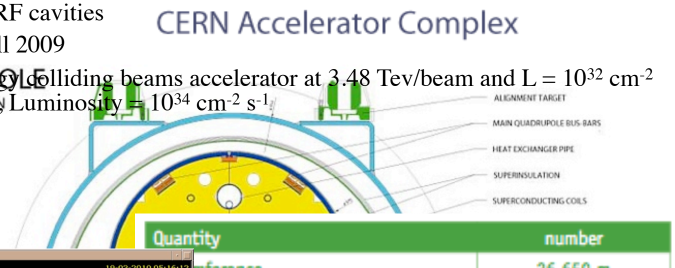
around the clock operation, 24/7 all year

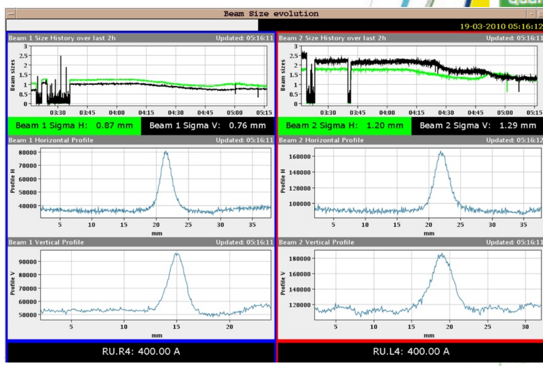
shut down periods occur, for maintenance

crews of 5-6 Accelerator Operators and Crew Chief

The LHC

- Large Hadron Collider
- Proton-proton collider in operation at CERN (Geneva, Switzerland)
- Superconducting magnets & RF cavities
- Achieved first collisions in fall 2009
- Now the world's highest energy colliding beams accelerator at 3.48 Tev/beam and L = 10^{32} cm^{-2} s^{-1}. Design is 7 TeV per beam, Luminosity = 10^{34} cm^{-2} s^{-1}.



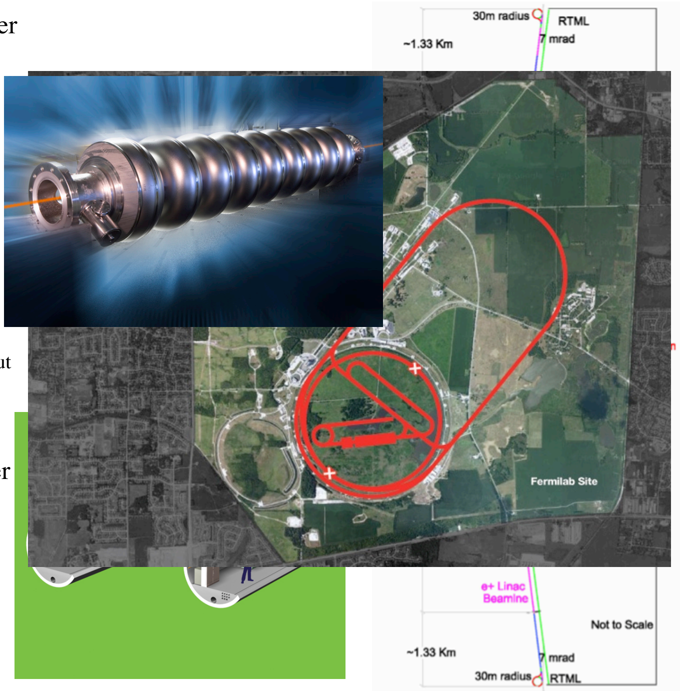


Now What?

- News of Fermilab's demise have been greatly exaggerated:
  - the lab is repositioning itself to be the premiere particle physics laboratory at the 'Intensity' and 'Cosmic' Frontiers and is formulating a plan for the future (2015 and beyond)
  - High-intensity particle beams
    - The best neutrino experiment in the world
    - Using muons to look beyond the Standard Model
  - The next-generation particle collider

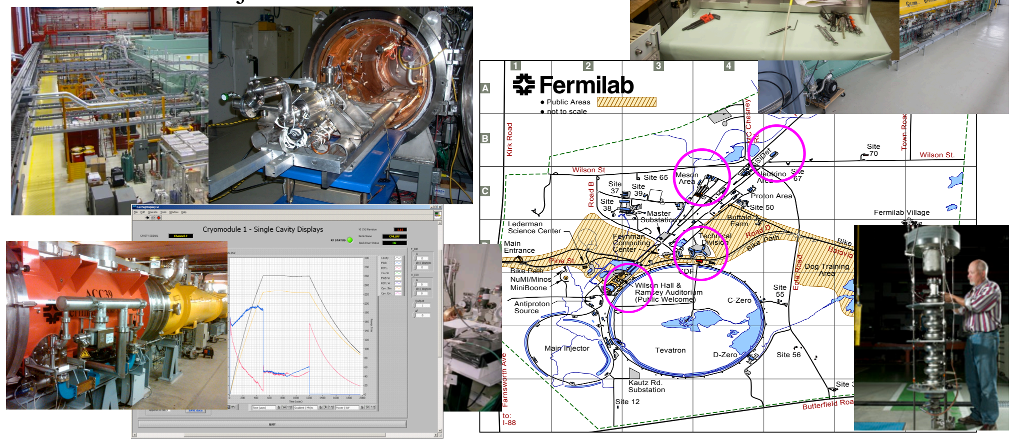
Current Accelerator R&D

- International Linear Collider (ILC)
  - Large international community looking into this project
  - Electron-positron collider, 250-500 GeV per particle
  - superconducting RF cavities - 1.3 GHz
  - 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???



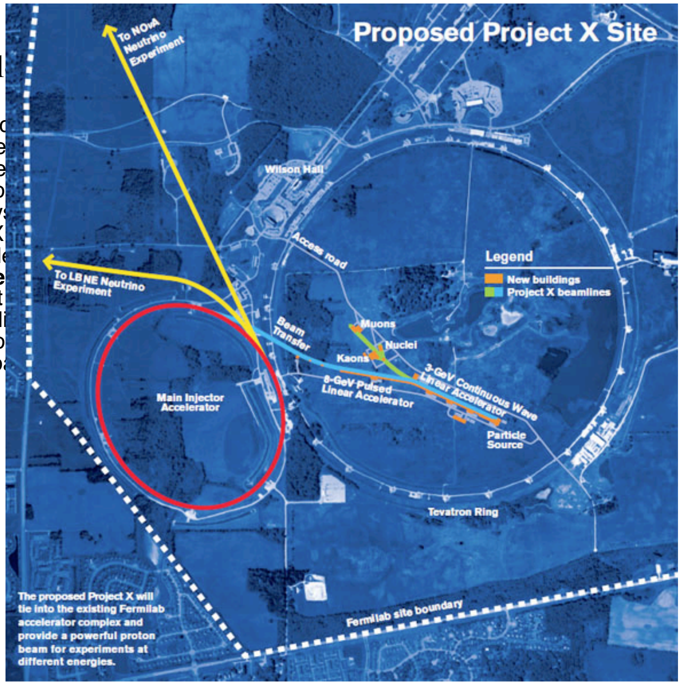
SRF at Fermilab

- Fermilab has been developing the infrastructure and expertise to be a key player in Superconducting RF technology applications
  - NML facility
  - Horizontal Test Stand & MP-9
  - Vertical Test Stand
  - A0 Photoinjector & Third Harmonic Effort

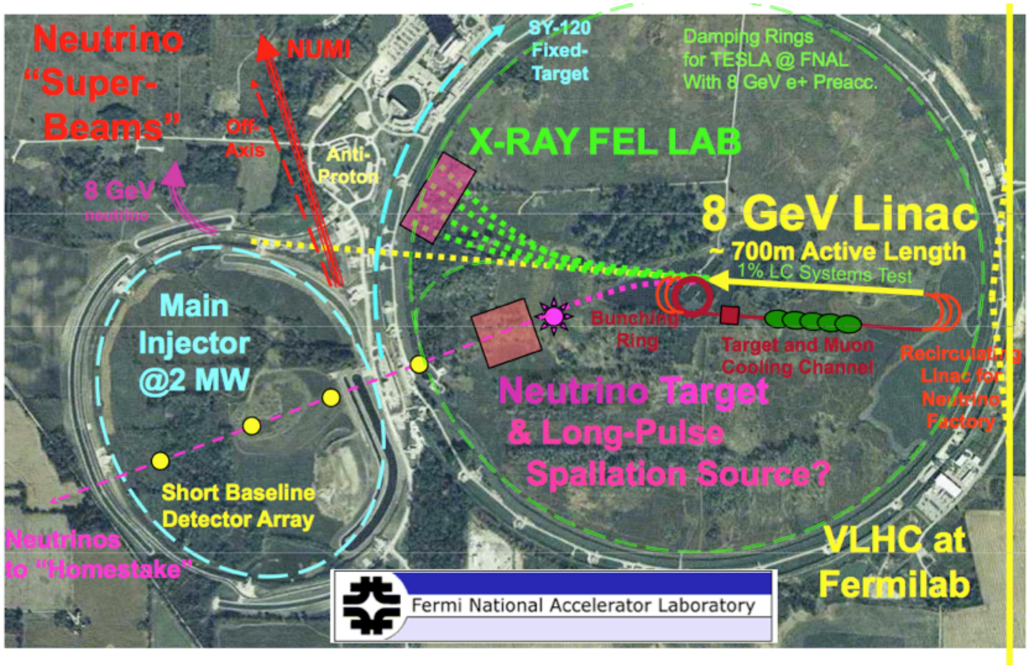


Project X

- Fermilab is preparing
  player in SRF technol
  - Project X is a multi-MW
    based on an H- linear ac
    the linchpin for future de
    opportunities at both the
    flexibility for intensity-fro
    program in neutrino phys
    technology for Project X
    applications, for example
    systems (ADS) for ene
    development for Project
    International Linear Colli
    contributor, to such a po
    could also provide the ba
  - Project X



beyond Project X?



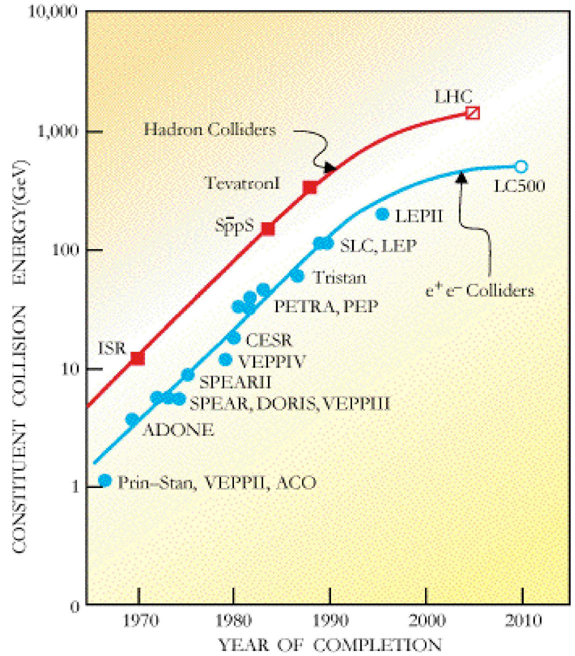
The Future…

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



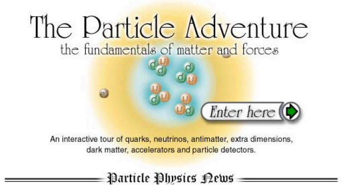
Summary

- Controlled experiments to study fundamental high energy particle physics rely on particle accelerators
- While they are complex devices accelerators are comprised mainly of 3 fundamental components
  - Radiofrequency cavities to impart energy to the particles
  - Magnets to steer and focus the particles
  - Evacuated beam pipe
- Fermilab's 30+ year reign as the capital of the highest energy particle accelerators has recently ended - eclipsed by CERN's LHC …
  - Still, center for neutrino physics experiments for some time!
  - 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...
- Accelerators for fundamental physics research are only the 'tip of the iceberg' in the use of Particle Accelerators.

These are interesting & challenging 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)
- A. Sessler & E. J. N. Wilson, *Engines of Discovery - A Century of Particle Accelerators*, World Scientific (2007)



- 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!* or *www.jacow.org*) --

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