



Particle Accelerators

Eric Prebys, FNAL
Saturday Morning Physics
October 8, 2016

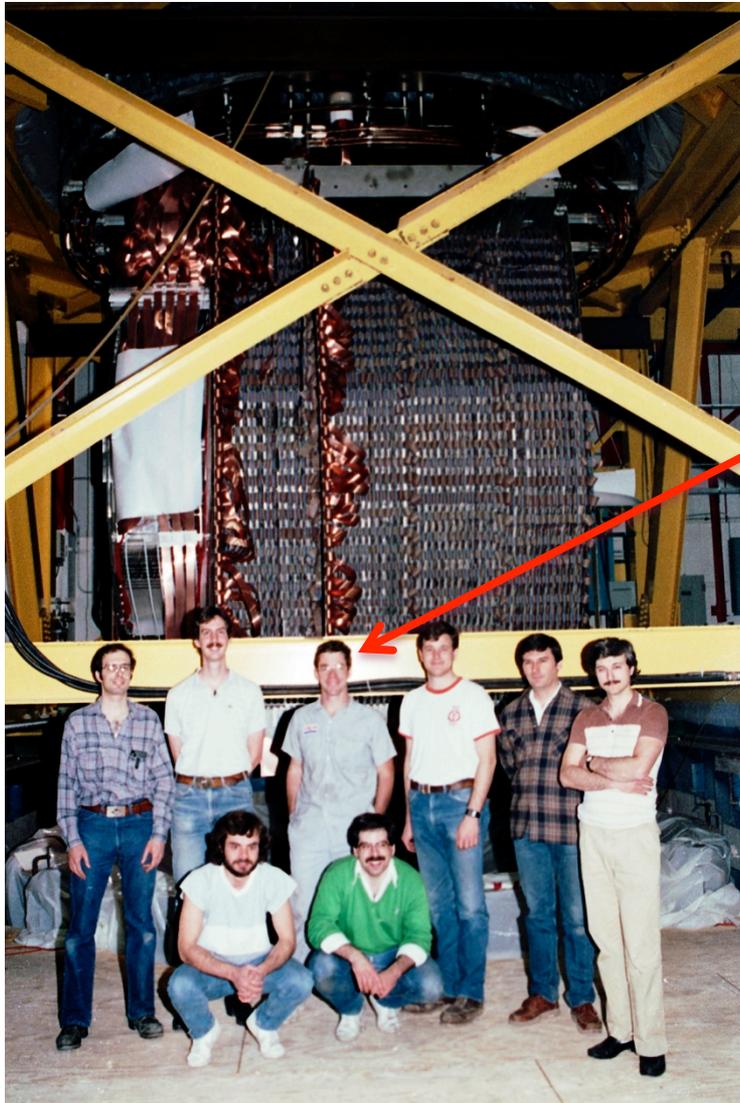


My Background

- ◉ Home town: Phoenix, Arizona
- ◉ 1984: BS in Engineering Physics, University of Arizona
 - Got a job in an HEP group (after being fired from a gas station).
- ◉ 1984-1990: Grad Student, University of Rochester
 - PhD topic: Photon Production in Hadronic Interactions (FNAL)
- ◉ 1990-1992: CERN Fellow, CERN (Geneva, Switzerland)
 - Worked on OPAL Experiment at LEP e^+e^- collider
- ◉ 1992-2001: RA and Assistant Professor, Princeton Univ.
 - Worked on Superconducting Super Collider (Texas) 😞
 - Belle e^+e^- Experiment at KEK, Japan
 - Laser-electron scattering experiment at SLAC (Stanford)
- ◉ 2001-Present: Scientist, Fermilab
 - Past:
 - ◉ MiniBooNE short baseline neutrino oscillation experiment
 - ◉ Proton Source (Linac+Booster) Department Head
 - ◉ Director of LHC Accelerator Research Program (LARP)
 - ◉ Director of Joint University-Laboratory PhD Program
 - Present:
 - ◉ Mu2e rare muon conversion experiment
 - ◉ Integrable Optics Test Accelerator (IOTA) proton injection
 - ◉ Program director for Lee Teng Undergraduate Internship
 - ◉ Occasional Instructor at US Particle Accelerator School

Experimental
HEP

Accelerator
Physics (mostly)



Fermilab E-706 Rochester Group
~1987



Me

“Buck’s River Road Exxon”



Rough Outline

- Understanding energy scales
- Motivation for particle accelerators
- Acceleration
- Getting to higher energy
 - Cyclotrons
 - RF Cavities
 - Synchrotrons
 - Strong magnetic focusing
 - Colliding beams
- Superconducting magnets
- Other uses for accelerators
- State of the art
- The future



Acknowledgments

- Former lecturers, for giving me material
 - Fernanda Garcia
 - Elvin Harms
 - Mike Syphers
- USPAS for providing some “show and tell” stuff
 - Susan Winchester and Elvin Harms
- The army that helped to get the fine beam/Helmholtz demo working
 - Tube: Marge Bardeen, Mark Adams, and Hans Jostlein, Ed. Helmholtz coil: Chris Olsen and Todd Johnson, Operations
 - Power supplies:
 - Joy in PREP
 - Kermit Carlson, AD
 - Jamie Santucci, AD
 - Great camera setup
 - Reidar Hahn in VMS
- SMP for logistics and inviting me
 - Roger Dixon
 - Erik Ramberg
 - Susan Webber



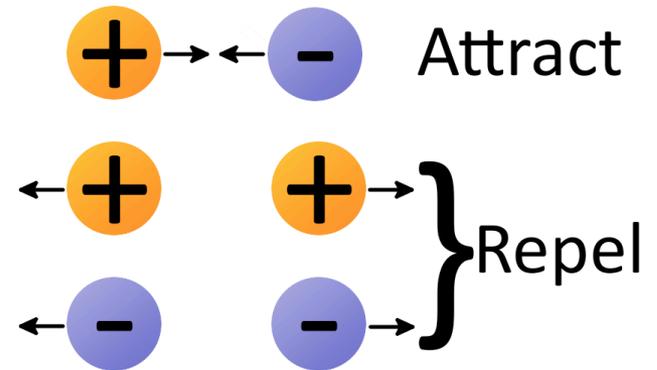
Disclaimer

- ⦿ We will talk mostly about the quest to reach the highest energy in accelerators, because that has driven the technology.
- ⦿ In fact, high energy accelerators make up only a tiny fraction of the accelerators in the world.
- ⦿ We'll summarize some of the many other applications of accelerators near the end.

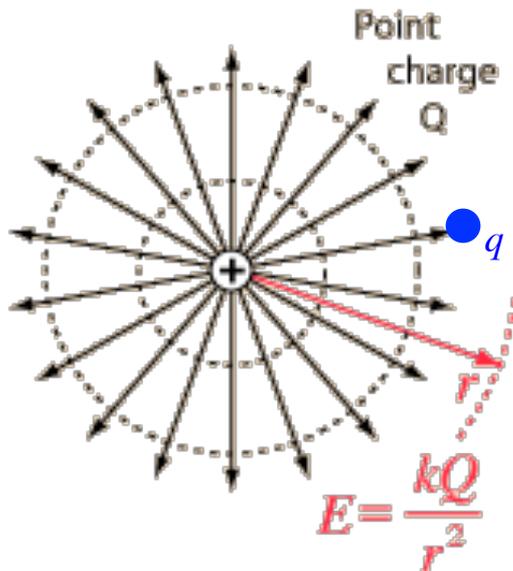


Background: Electric Charges and Electric Fields*

- You've all learned (I hope) that like charges repel and opposite charges attract



- This can be interpreted as one charge creating an “electric field” which *accelerates* the other charge.



$$\vec{F} = q\vec{E} = m\vec{a}$$

Charge [Coulombs] → q
 “Electric Field” [Newtons/Coulomb] or [Volts/Meter] → \vec{E}
 Acceleration [m/s²] → \vec{a}
 Mass [kg] → m
 Force [Newtons] → \vec{F}

*we'll get to magnetic fields shortly

Work Done by Electric Fields → Voltage

- “Work” is force over a distance.

$$W[\text{Joules}] = F[\text{Newtons}] \cdot \Delta x[\text{meters}]$$

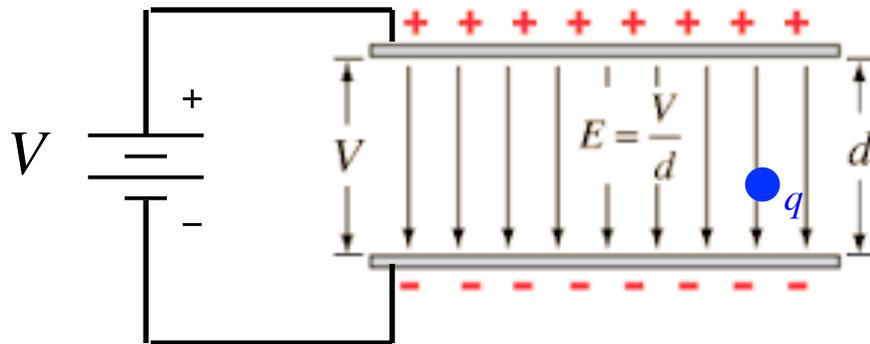
- For an electric field, this becomes

$$W = F \cdot \Delta x = qE \cdot \Delta x = q(E \cdot \Delta x) \equiv q(\Delta V[\text{Joules/Coulomb} = \text{Volts}])$$



Electric field over distance = “voltage change”

- In practice, our sources of electric fields generally involve chemical or mechanical work, so we usually turn this relationship around. For example, consider a plate capacitor:



The voltage of the source produces charge distributions on the two plates, resulting in a uniform field

$$E = \frac{V}{d}$$

The force felt by a charged particle between the plates will be

$$F = qE = q \frac{V}{d}$$

And the total energy gained by a particle crossing the gap will be

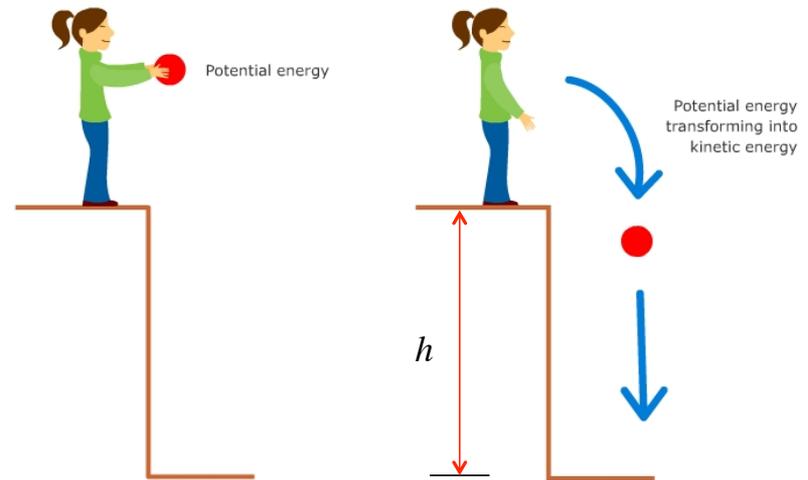
$$W = Fd = qEd = q \frac{V}{d} d = \boxed{qV}$$

Which leads us to...

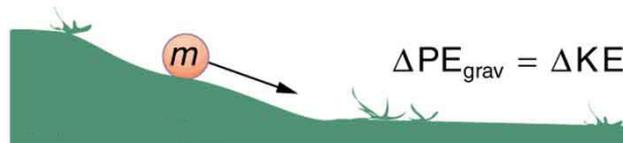
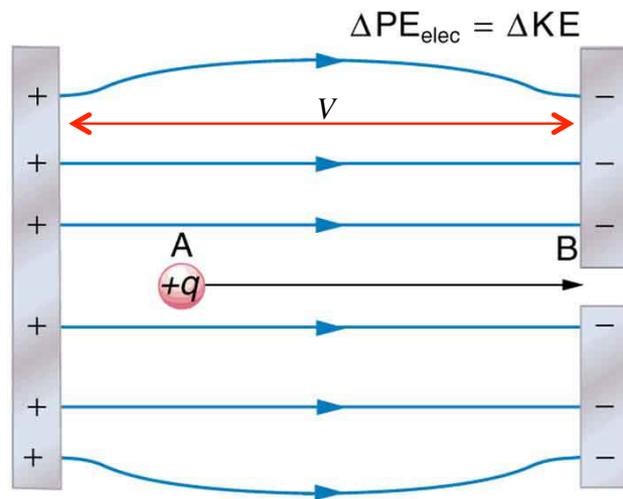


Units of Energy

- Energy is (force) \times (distance)
- For example, when you drop something, gravity “work” through the change in height to convert “potential energy” to “kinetic energy”.



$$(\text{kinetic energy}) = (\text{mass}) \times (\text{gravity}) \times (\text{height})$$



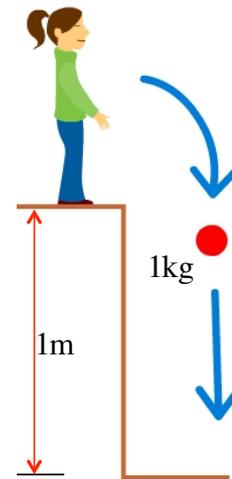
$$(\text{kinetic energy}) = (\text{charge}) \times (\text{voltage})$$

- In the same way, when we accelerate something in an electric field, electrical potential (“voltage”) is converted to kinetic energy.
- For this reason, a convenient unit of energy is the “electron-volt (eV)” which is the energy you get when you accelerate a charge of one electron (or proton) over a 1 Volt potential.



Understanding electron-volts

- The eV is a *really small* unit of energy.
 - 1.6×10^{-19} (= .000000000000000000016) Joules - our usual unit of energy.
 - A 1 kg weight dropped 1m would have 6×10^{18} (6000000000000000000) eV of energy!



- On the other hand, it's a very useful unit when talking about individual particles
 - If we accelerate a proton using an electrical potential, we know exactly what the energy is.

- It's also useful when thinking about mass/energy equivalence

$$(\text{proton mass}) \times c^2 = 938,000,000 \text{ eV} \approx 1 \text{ billion eV} = 1 \text{ GeV}$$

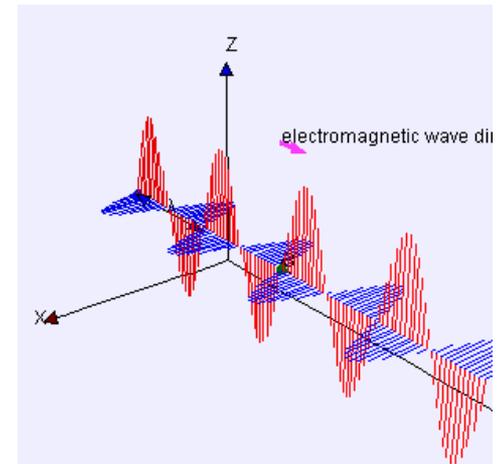
$$(\text{electron mass}) \times c^2 = 511,000 \text{ eV} \approx \frac{1}{2} \text{ MeV}$$

Remember these!



The Theory of Relativity: Motivation

- In 1861, James Clerk Maxwell attempted to write a set of mathematical equations summarizing everything that was known about electric and magnetic fields
 - Magnetic fields are caused by electric currents
 - Electric fields are caused by charges OR changing magnetic fields
- He added an extra equation *just to make the math work (!)*
 - Magnetic fields can be caused by changing electric fields
- The implication of this extra equation was that electricity and magnetism could propagate as waves
- The *calculated* velocity matched the *measured* speed of light
 - → Light is an electromagnetic wave!!
- Problem: the math seemed to say that these waves could propagate in a vacuum (i.e. no frame of reference) and that the velocity would be independent of the velocity of the source
 - Confirmed experimentally (Michelson and Morley, 1887)
- How the heck could this be?
- It was of the biggest mysteries in science for almost 20 years, until...





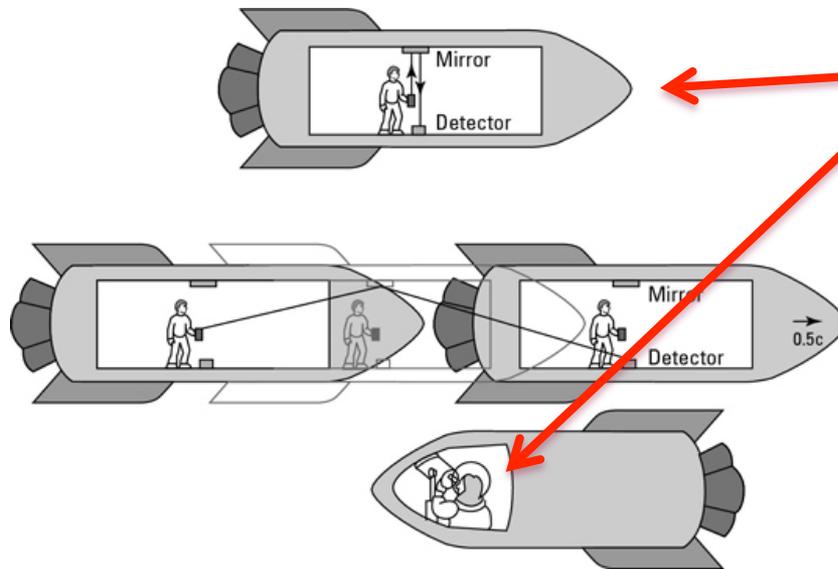
Einstein to the Rescue

- In 1905, Albert Einstein postulated that perhaps the equations meant exactly what they appeared to mean:
 - The speed of light was the same *in any frame* in which it was measured.
- He showed that this could “work”, but only if you gave up the notion of fixed time.
 - → “Special Theory of Relativity”
- Profound implications...



Example: Time Dilation

- Einstein said, “The speed of light must be the same in any reference frame”. For example, the time it takes light to bounce off a mirror in a spaceship must be the same whether it’s measured by someone in the spaceship, or someone outside of the spaceship.



- These two people have to measure *the same* speed for light, even though light is traveling a different distance for the two of them.
- The only solution? More time passes for the stationary observer than the guy in the spaceship!
 - “Twin Paradox”

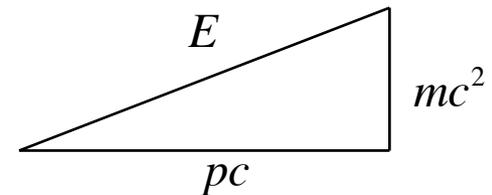
- This seems weird, but it applies to everything we do at the lab
 - Example: the faster pions and muons move, the longer they live.
- It also affects how we think about kinematics...

Momentum and Energy in Special Relativity

○ Classically: momentum: $\vec{p} = m\vec{v}$

$$\text{kinetic energy: } K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

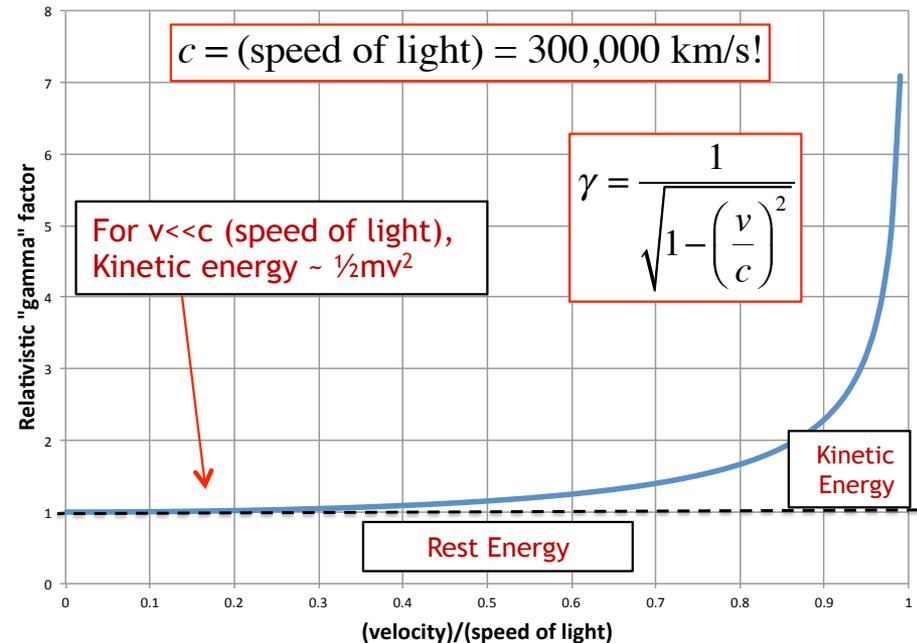
○ Relativistically:



$$\text{momentum: } \vec{p} = \frac{m\vec{v}}{\sqrt{1 - (v/c)^2}}$$

$$\text{total energy: } E^2 = (mc^2)^2 + (pc)^2$$

$$\text{kinetic energy: } K = E - mc^2$$





Mass and Energy

- High Energy Physics is based on Einstein's equivalence of Mass and Energy

$$E = mc^2$$

- All reactions involve some mass changing either to or from energy

Chemical Explosion



.00000005% of mass converted to energy.

Hydrogen Bomb



~.1% (of just the Hydrogen!) converted.

- If we could convert a kilogram of mass entirely to energy, it would supply all the electricity in the United States for *almost a day*.

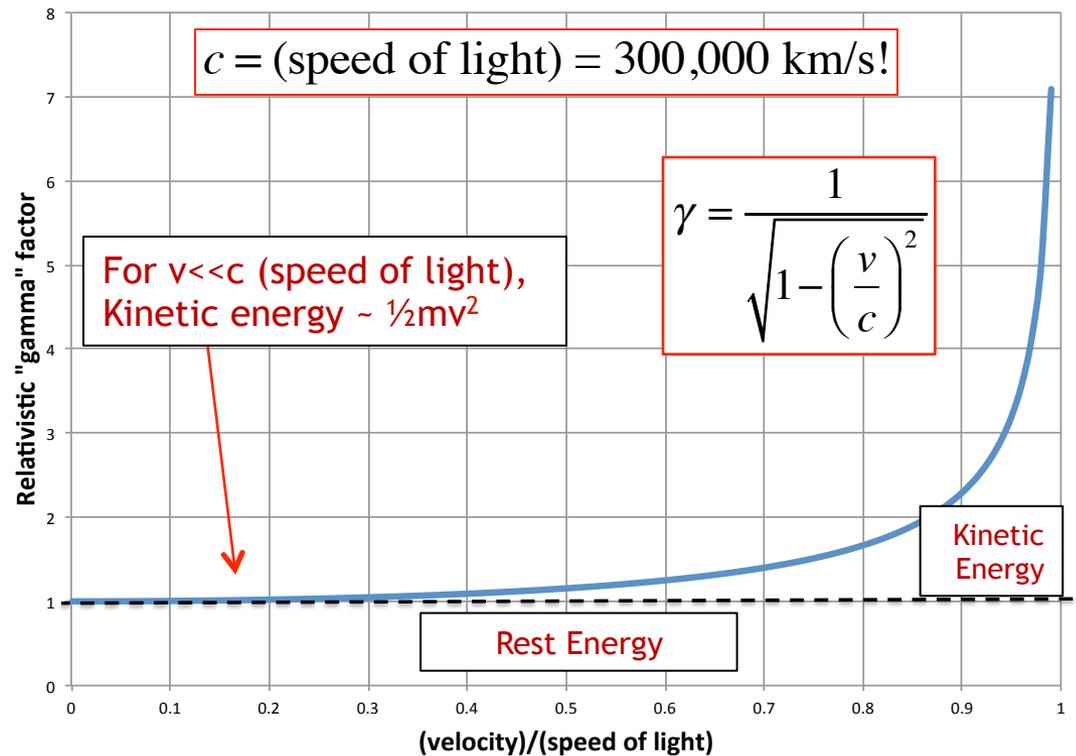


Kinetic Energy

- A body in motion will have a total energy given by

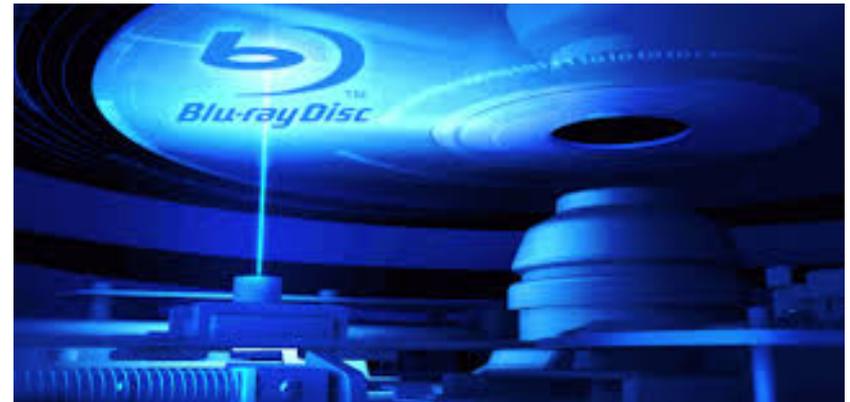
$$E = \frac{mc^2}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \equiv \gamma mc^2$$

- The difference between this and mc^2 is called the “kinetic energy”
- Here are some examples of kinetic energy

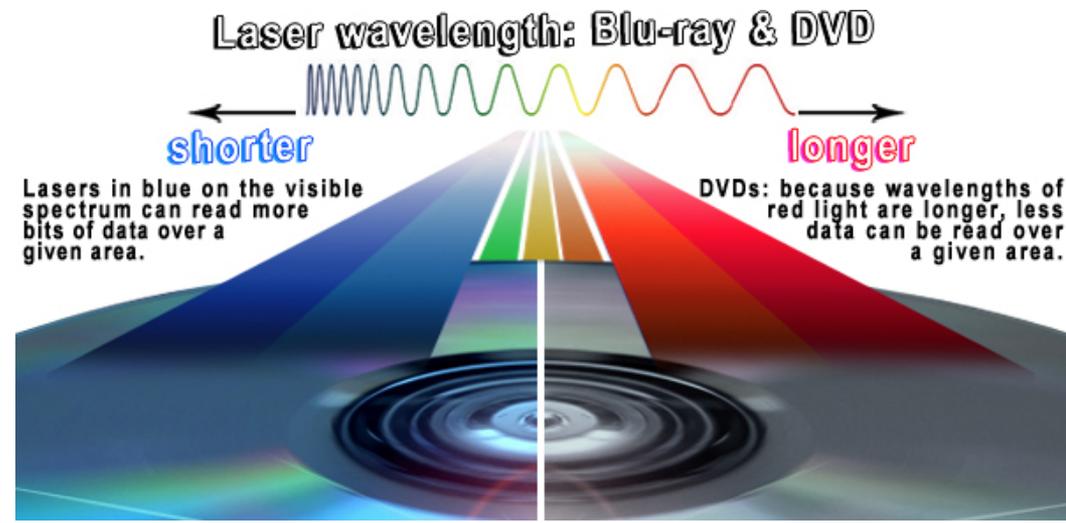


Another way to look at energy...

- Question: Why are “blue ray” players blue?



- Answer: because blue light is more energetic and has a shorter wavelength, so the “bits” can be smaller



“Planck Constant”

$$\lambda = \frac{hc}{E}$$

wavelength →

Energy ←

Wavelengths of other particles

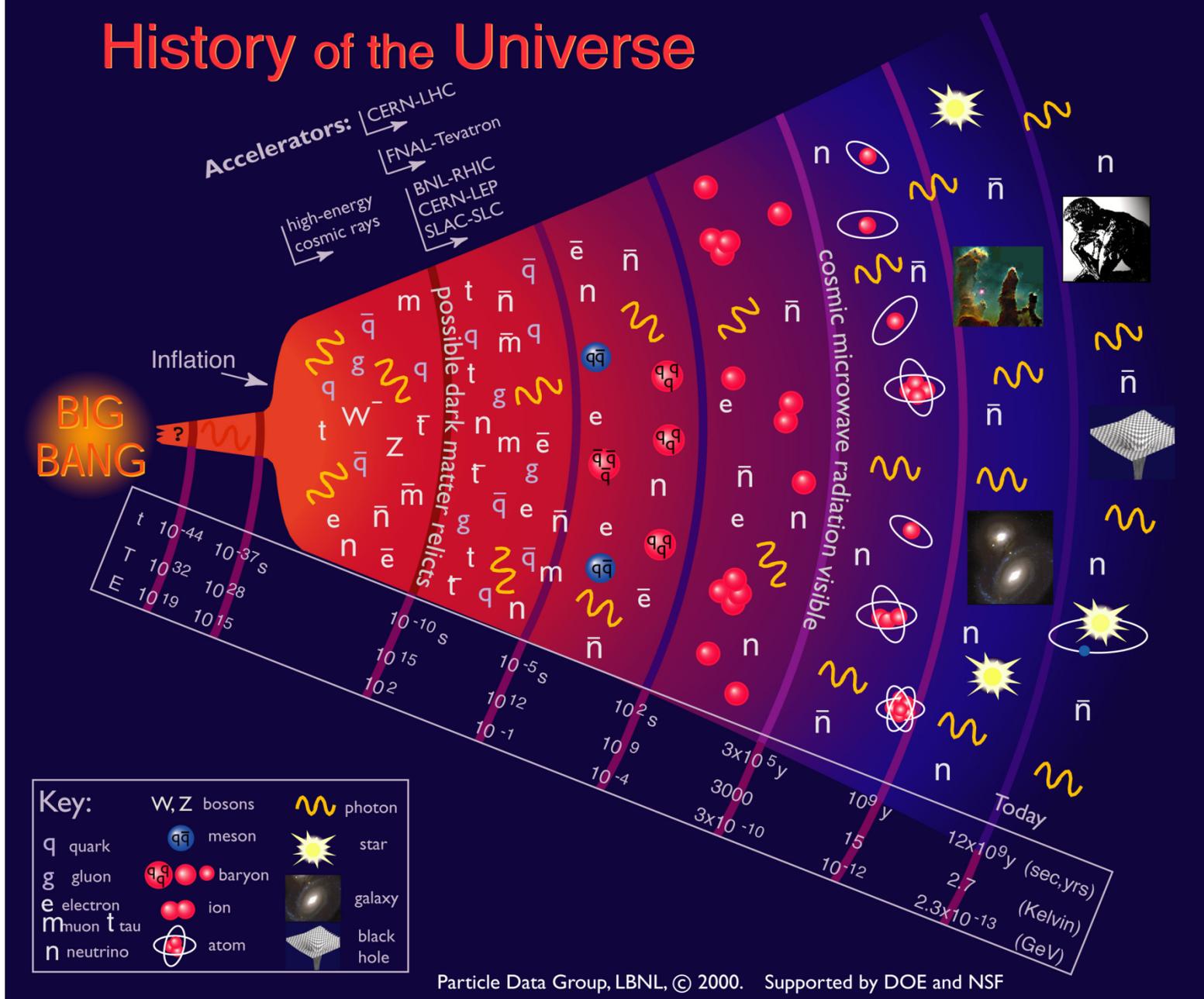
- It turns out that all particles have a wavelength

$$\lambda = \frac{\overset{\text{“Planck Constant”}}{h}}{\underset{\text{momentum}}{p}} \approx \frac{\text{(size of a proton)}}{\text{Energy (in GeV)}}$$

- So going to higher energy allows us to probe smaller and smaller scales
- If we put the high equivalent mass and the small scales together, we have...



History of the Universe

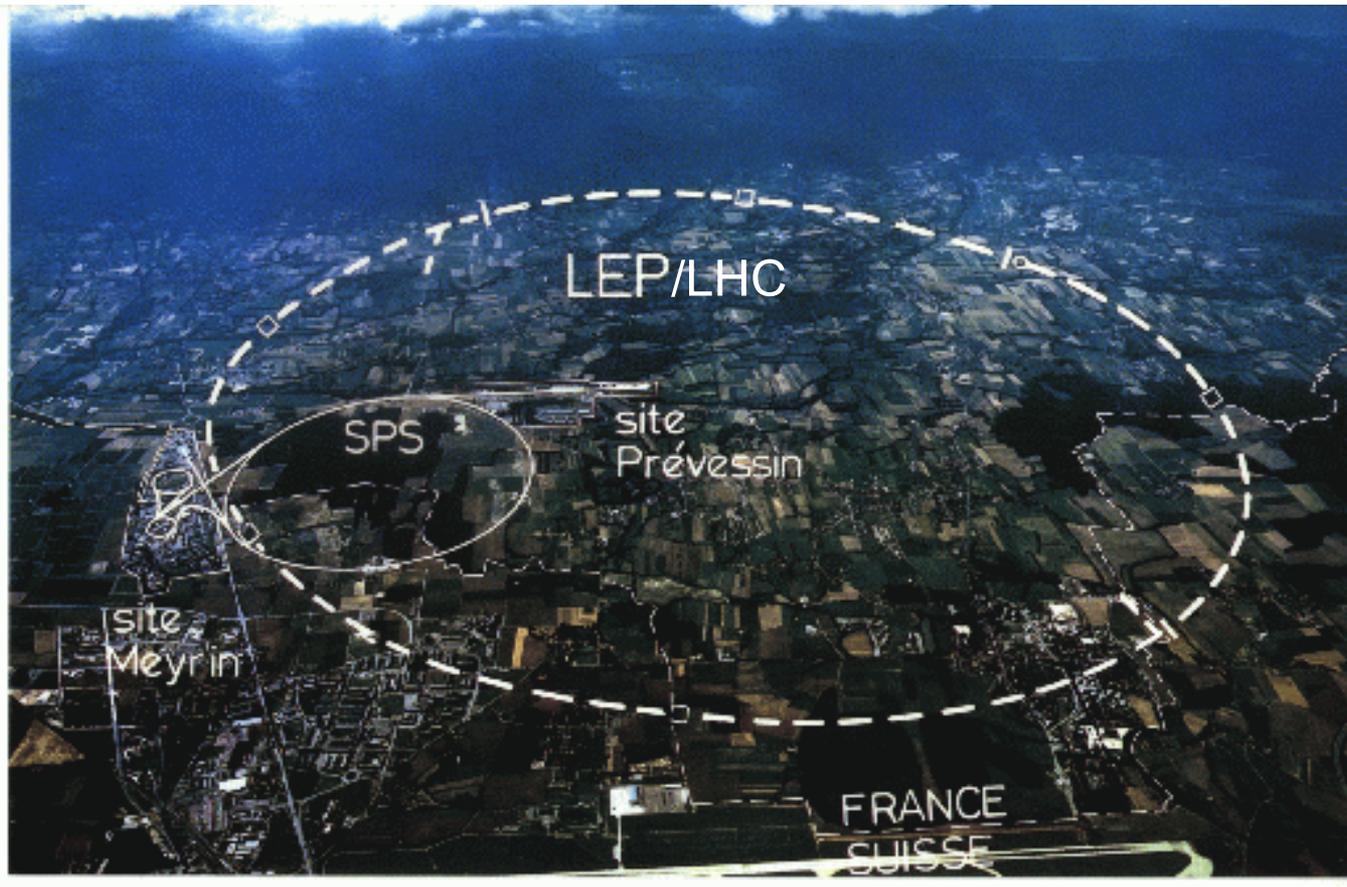


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Going to higher energies = going back in time



State of the art: Large Hadron Collider (LHC)



- Built at CERN, straddling the French/Swiss border
- 27 km in circumference
- Currently colliding proton beams at 6500 GeV (6.5×10^{12} eV) each
- That's where we are. Now let's see how we got here...

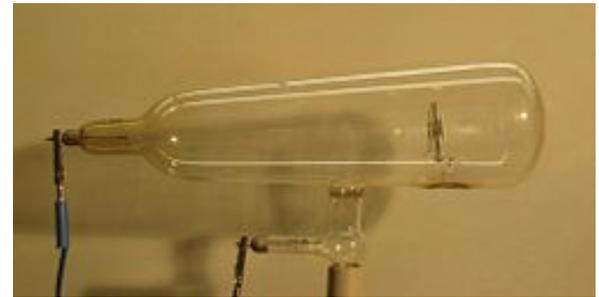


The Main Parts of an Accelerator

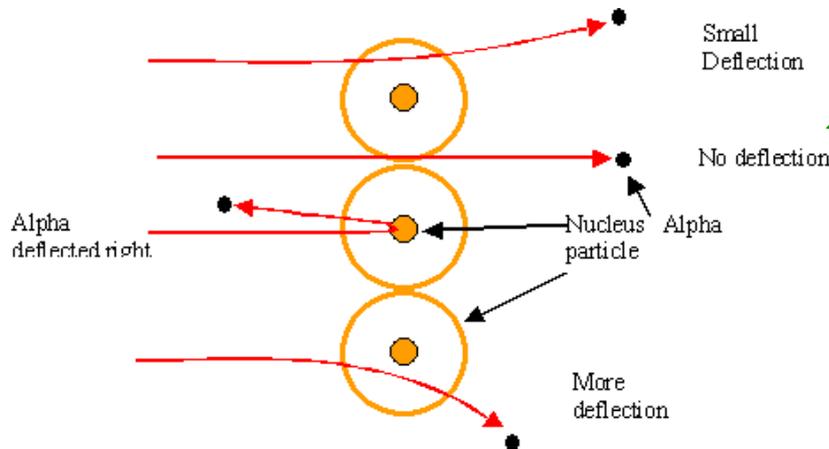
- A source of particles
 - Electrons
 - Filament
 - Laser->surface
 - Radiofrequency (RF) “gun”
 - Protons/ions
 - Plasma (gas heated until electrons and nuclei separate)
- A method of acceleration
 - Electric fields
 - Static
 - RF
 - Lasers
- A way to store and focus beams
 - Magnetic fields
 - Cyclotrons
 - Synchrotrons
 - Magnetic focusing



Rewind: Some pre-history

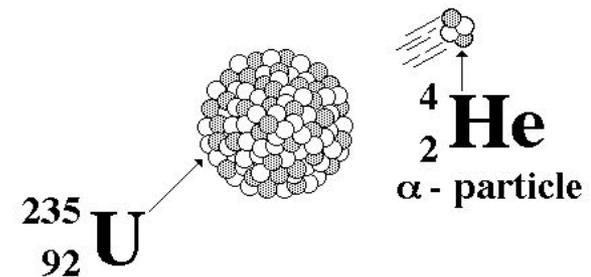


- The first artificial acceleration of particles was done using “Crookes tubes”, in the latter half of the 19th century
 - These were used to produce the first X-rays (1875)
 - At the time no one understood what was going on
- The first “particle physics experiment” told Ernest Rutherford the structure of the atom (1911)



Study the way radioactive particles “scatter” off of atoms

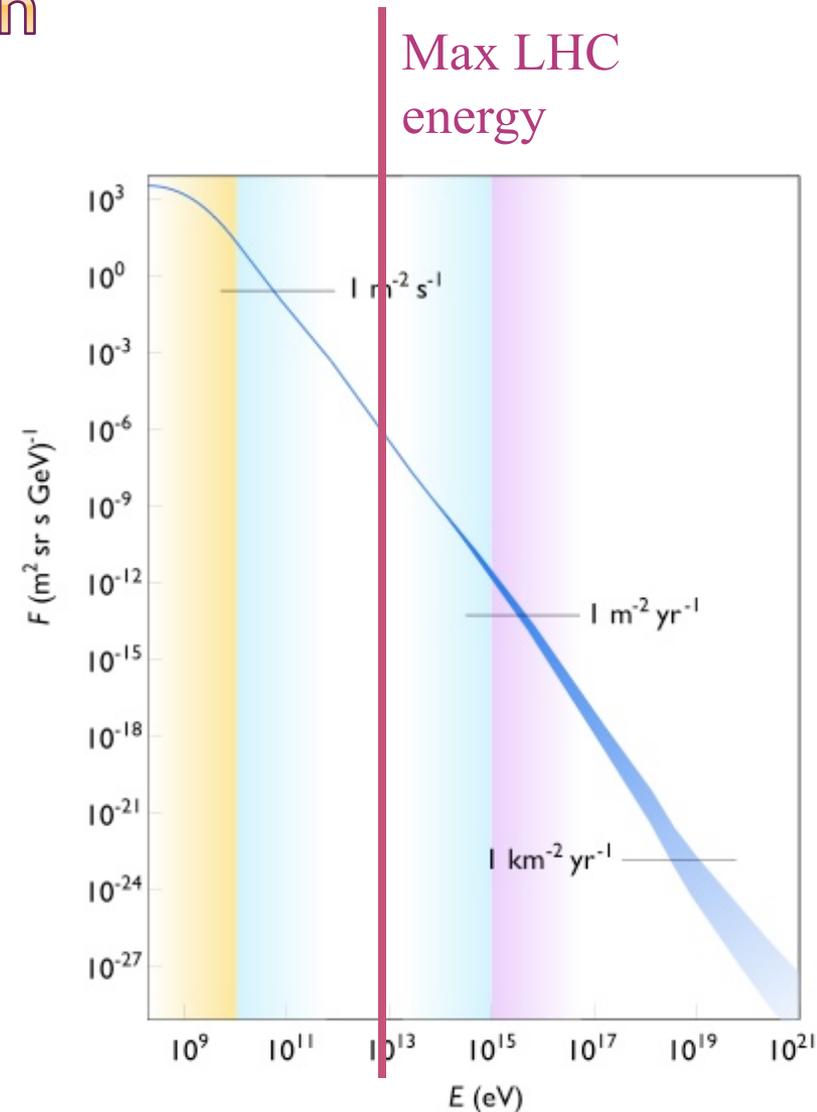
- In this case, the “accelerator” was a naturally decaying ^{235}U nucleus





Natural particle acceleration

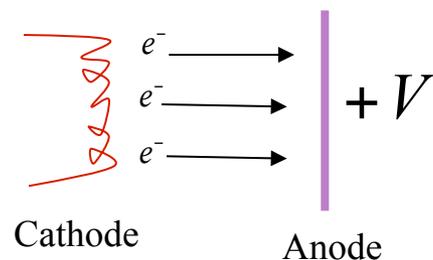
- Radioactive sources produce maximum energies of a few million electron volts (MeV)
- Cosmic rays reach energies of $\sim 1,000,000,000 \times$ LHC but the rates are too low to be useful as a study tool
 - Remember what I said about “luminosity”.



Man-made particle acceleration



The simplest accelerators accelerate charged particles through a *static* electric field. Example: vacuum tubes (or CRT TV's)



$$K = eEd = eV$$

Limited by magnitude of electric field:

- TV Picture tube ~keV
- X-ray tube ~10's of keV
- Van de Graaf ~MeV's

Solutions:

- Alternate fields to keep particles in accelerating fields -> **Radio Frequency (RF) acceleration**
- Use magnetic fields to bend particles so they see the same accelerating field over and over -> **cyclotrons, synchrotrons**

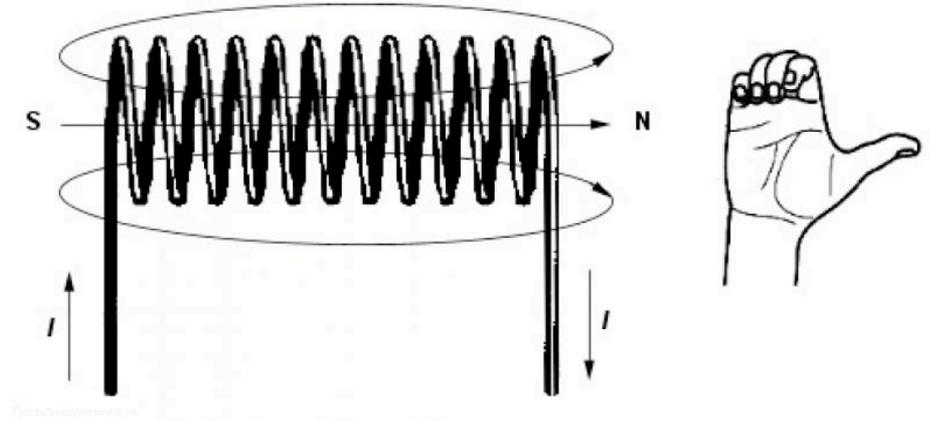
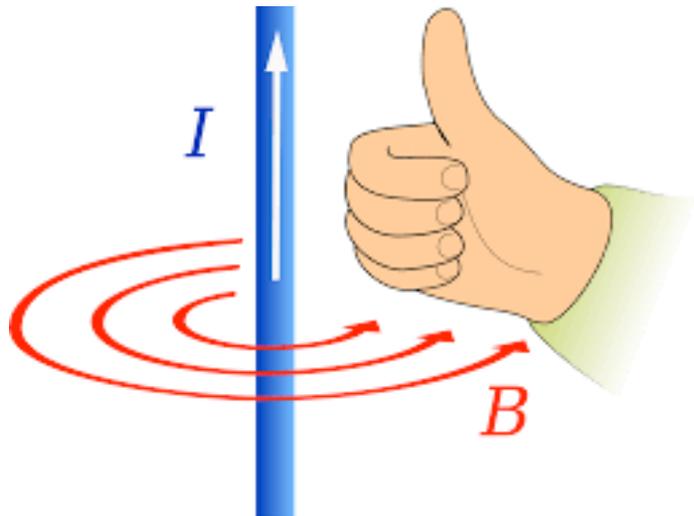


FNAL Cockcroft-Walton
= 750 kV



Magnetic Fields

- Magnetic are produced by electric currents, according to the “right hand rule”



Wire:

- put thumb along direction of current
- Field circles wire in direction of fingers

Coil (“solenoid”):

- Wrap fingers in direction of current.
- Field points in direction of thumb.



Forces in a Magnetic Field

- Moving charged particles in a magnetic field experience a force which is *perpendicular* to both the field and the direction of motion, with a direction given by the “right hand rule” multiplied by the charge

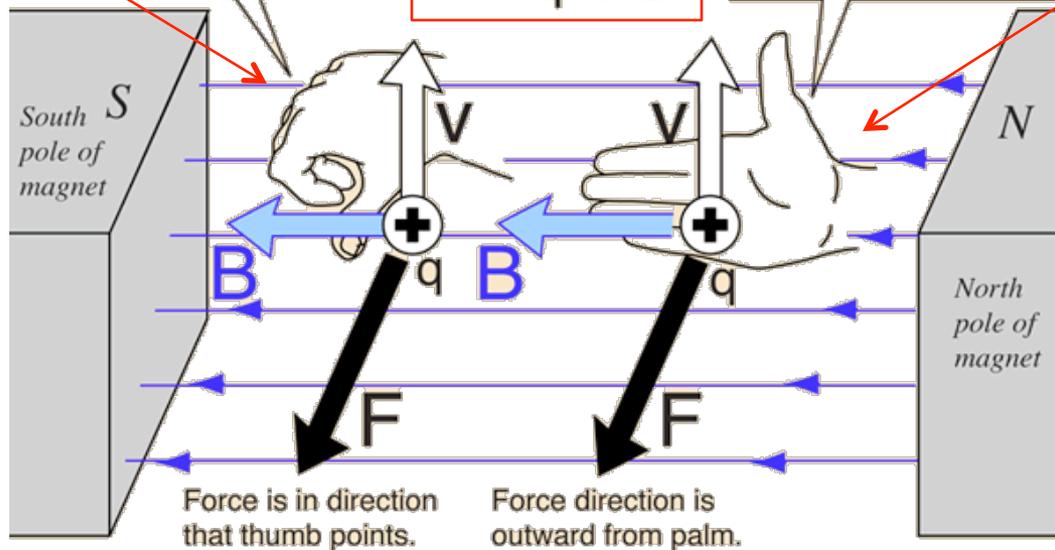
I do it this way

Curl fingers as if rotating vector \vec{v} into vector \vec{B} . Thumb is in the direction of force.

$$\vec{F} = q\vec{v} \times \vec{B}$$

Point thumb in direction of velocity, fingers in magnetic field direction. Then palm direction is direction of force on charge.

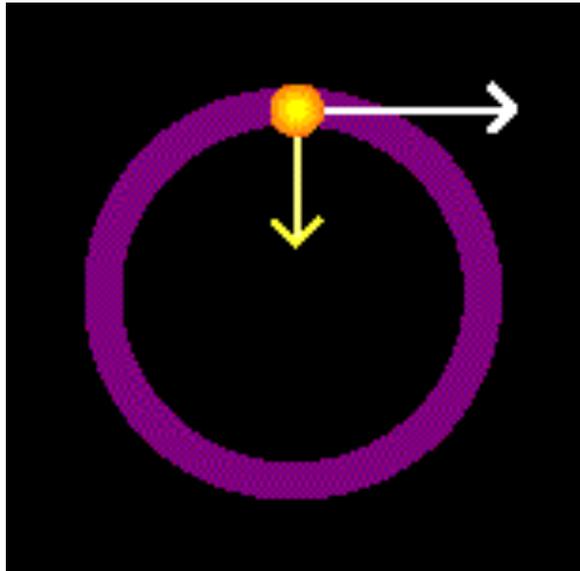
A lot of books teach it this way



Note: force reverses for negative charge!

Motion in a Magnetic Field

- Because the force is always *perpendicular* to the direction of motion, magnetic fields can only change the direction of a particle. The velocity (and therefore the kinetic energy) remain constant!
- When the direction of motion changes, the direction of the force changes to remain perpendicular
 - circular motion



$$\vec{F} = q\vec{v} \times \vec{B} = m\vec{a}$$

$$\rightarrow qvB = m \frac{v^2}{\rho}$$

$$\rightarrow \rho = \frac{mv}{qB}$$

$$= \frac{p}{qB}$$

Relativistically
correct

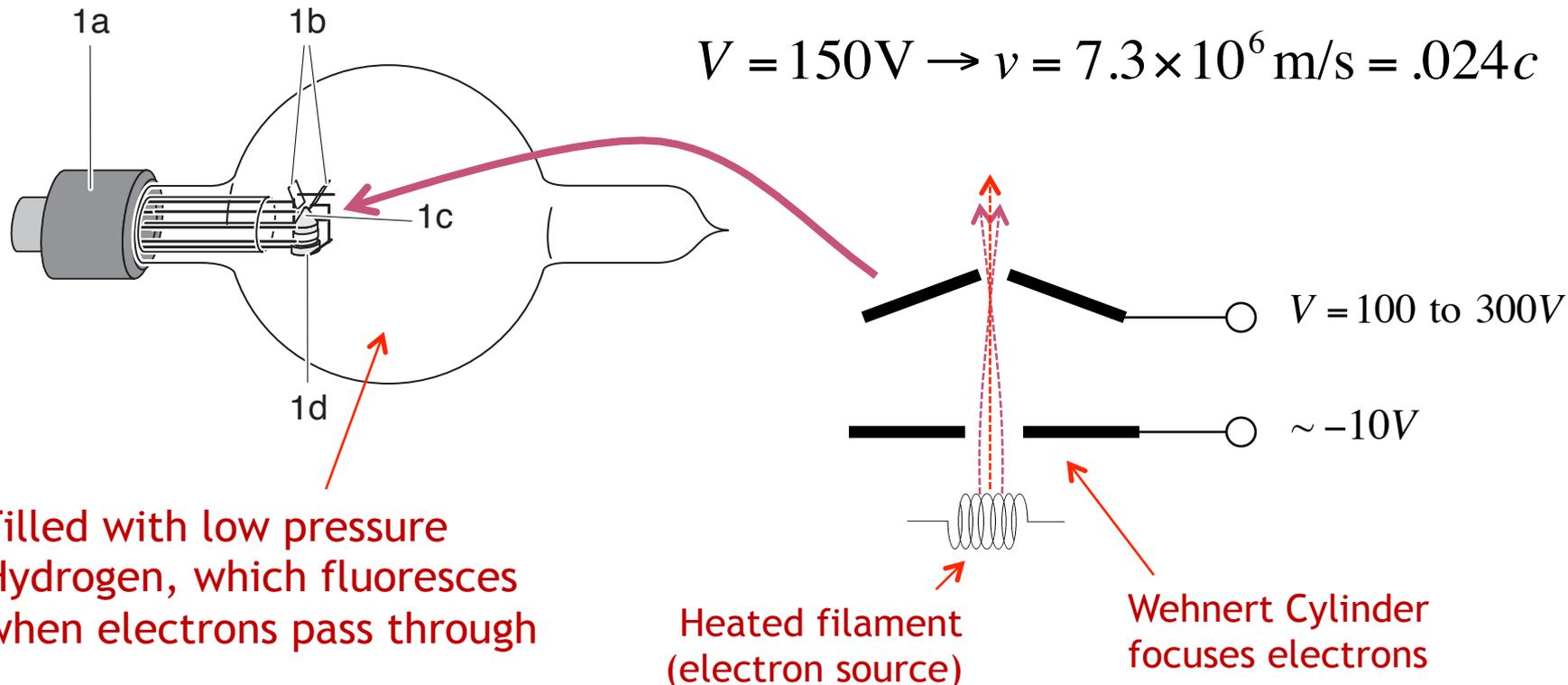


Fine Beam Tube/Helmholtz Coil Demonstration

- The tube generates an electron beam using a hot filament/cathode, “Wehnelt Cylinder”, and accelerating anode.

$$eV = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2eV}{m}}$$

$$V = 150V \rightarrow v = 7.3 \times 10^6 \text{ m/s} = .024c$$



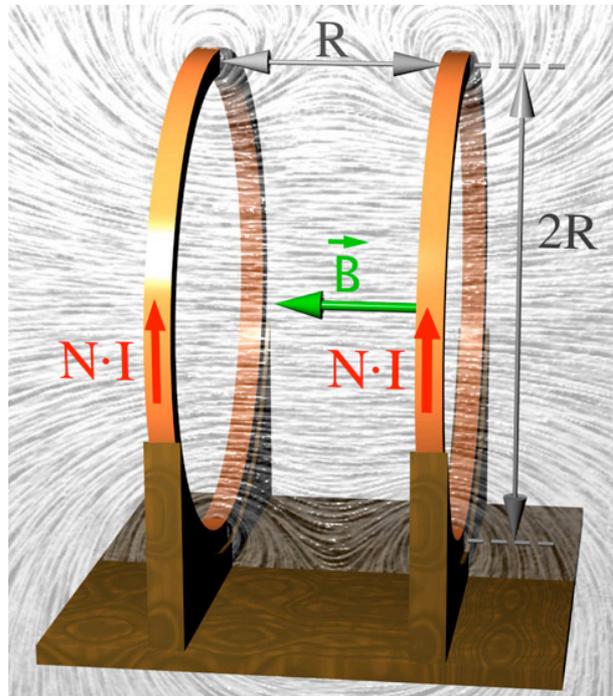
Filled with low pressure Hydrogen, which fluoresces when electrons pass through

Heated filament (electron source)

Wehnert Cylinder focuses electrons

Demo (cont'd)

- The Helmholtz Coils produce a ~uniform magnetic field



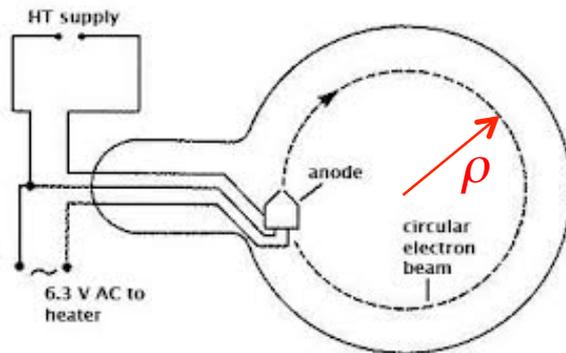
$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{R} \propto I$$

$$\rho = \frac{mv}{eB}$$

$$= \frac{m}{eB} \sqrt{\frac{2eV}{m}}$$

$$= \frac{1}{B} \sqrt{\frac{2mV}{e}}$$

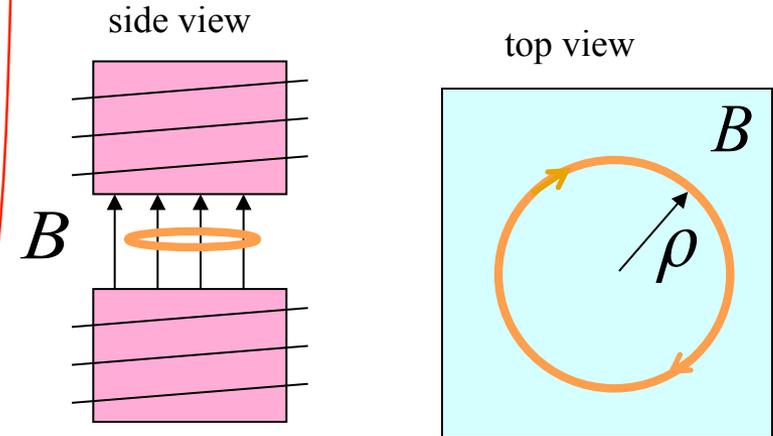
$$\propto \frac{\sqrt{V}}{I}$$



The Cyclotron (1930's)

- A charged particle in a uniform magnetic field will follow a circular path of radius

would not work for electrons!



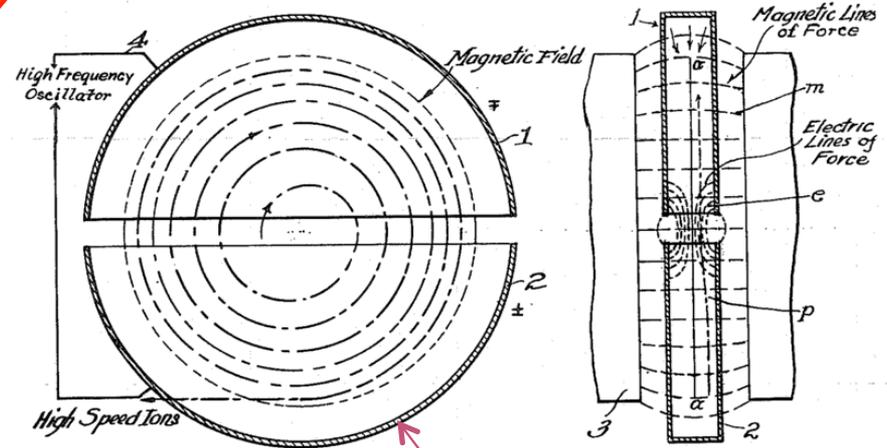
$$\rho = \frac{p}{qB} \approx \frac{mv}{qB} \quad (v \ll c)$$

$$f = \frac{v}{2\pi\rho}$$

$$= \frac{qB}{2\pi m} \quad (\text{constant!!})$$

$$\Omega_s = 2\pi f = \frac{qB}{m}$$

“Cyclotron Frequency”



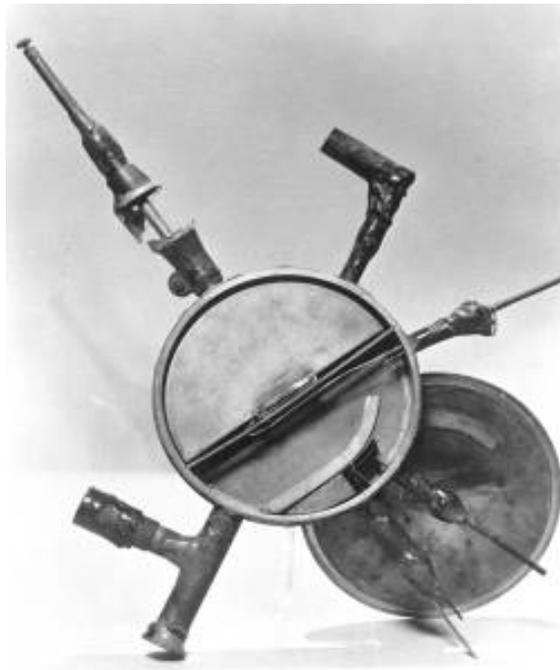
Accelerating “DEES”: by applying a voltage which oscillates at f_c , we can accelerator the particle a little bit each time around, allowing us to get to high energies with a relatively small voltage.

For a proton:

$$f_c = 15.2 \times B[T] \text{ MHz}$$

i.e. “RF” range

Round we go: the first cyclotrons



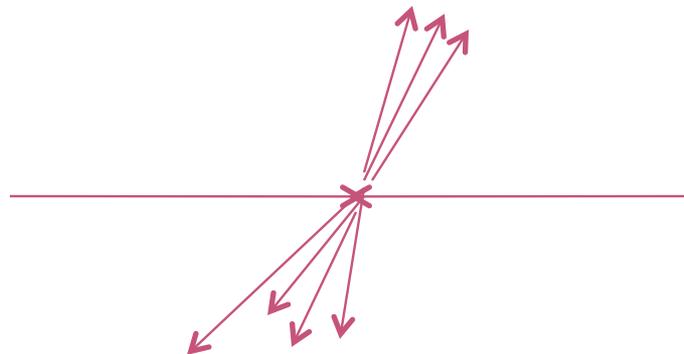
- ~1930 (Berkeley)
 - Lawrence and Livingston
 - $K=80\text{keV}$

- 1935 - 60" Cyclotron
 - Lawrence, et al. (LBL)
 - ~19 MeV (D_2)
 - Prototype for many





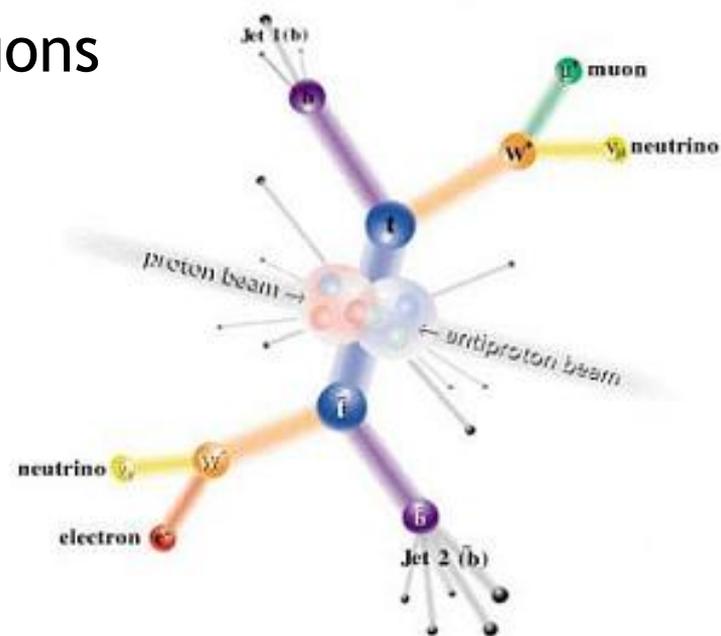
Interlude: Electrons vs. Protons



- Electrons are point-like
 - Well-defined initial state
 - Full energy available to interaction

- Protons are made of quarks and gluons

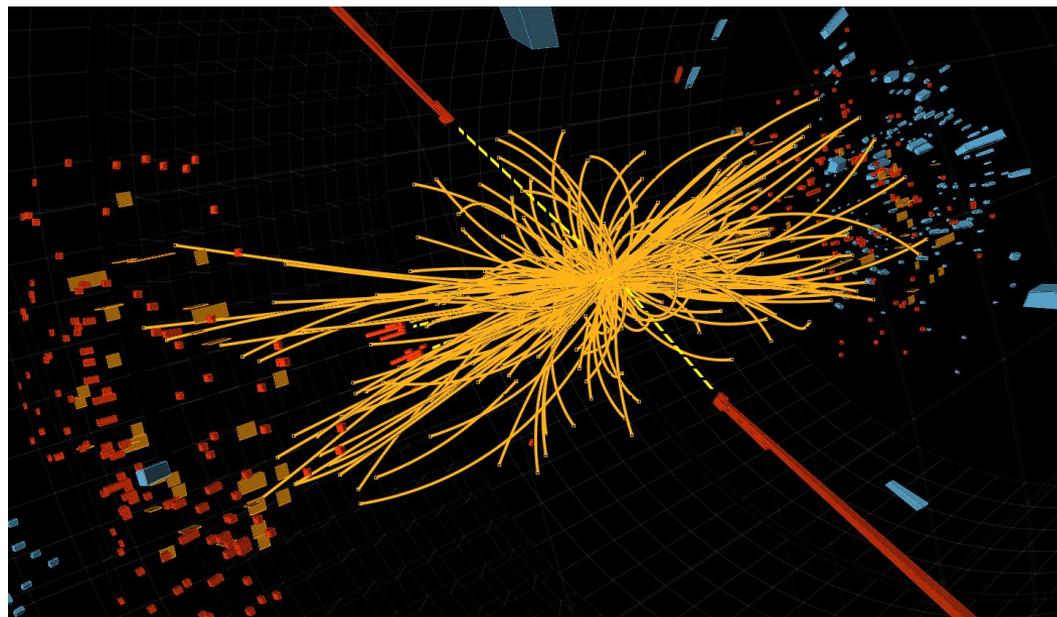
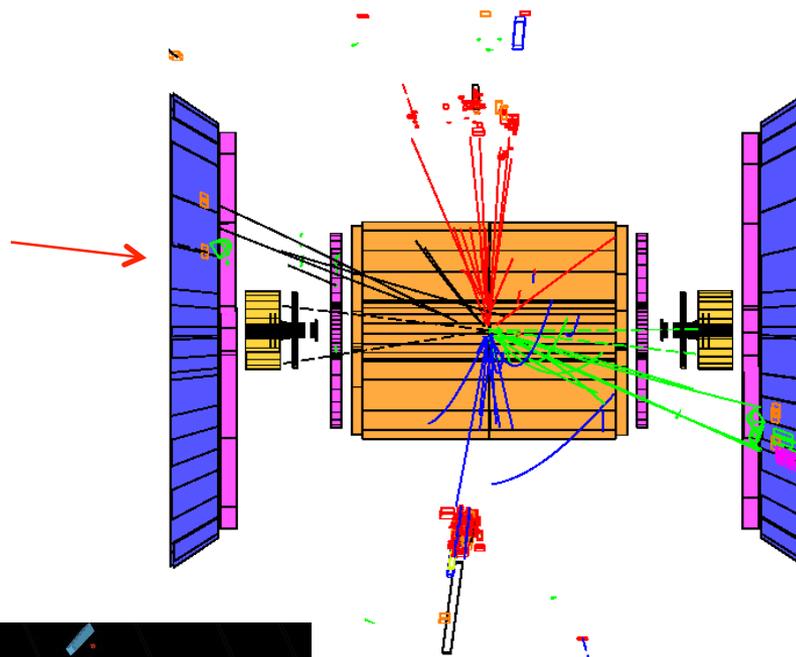
- Interaction take place between these constituents.
- Only a small fraction of energy available, not well-defined.
- Rest of particle fragments -> big mess!





Examples

e^+e^- collision at the LEP collider

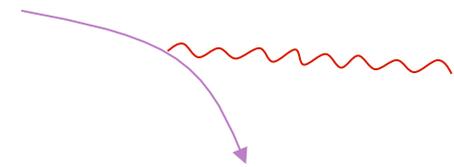


proton-proton collision at the LHC collider

So why don't we stick to electrons??

Synchrotron Radiation

As the trajectory of a charged particle is deflected, it emits “synchrotron radiation”



Radiated Power $\propto \frac{1}{\rho^2} \left(\frac{E}{m} \right)^4$

Radius of curvature

An electron will radiate about 10^{13} times more power than a proton of the same energy!!!!

- **Protons:** Synchrotron radiation does not affect kinematics very much
 - Energy limited by strength of magnetic fields and size of ring
- **Electrons:** Synchrotron radiation dominates kinematics
 - To go higher energy, we have to *lower* the magnetic field and go to *huge* rings
 - Eventually, we lose the benefit of a circular accelerator, because we lose all the energy each time around.

Since the beginning, the energy frontier has belonged to proton (and/or antiproton) machines



Onward and Upward!

- Two major advances allowed accelerators to go beyond the energies possible at cyclotrons
 - “Synchrotron” - in which the magnetic field is increased as the energy increases, such that particles continue to follow the same path.
 - Edward McMillan, 1945
 - “Strong focusing” - a technique in which magnetic gradients (non-uniform fields) are used to focus particles and keep them in a smaller beam pipe than was possible with cyclotrons.
 - Courant, Livingston and Snyder, 1952*
 - Courant and Snyder wrote a follow-up paper in 1958 that is still the basis for every particle accelerator in the world, *including the LHC*.

*actually invented in 1949 by a Greek-American electrical engineer name Nicholas Christofilos, but it was completely ignored at the time!



Understanding Beam Motion: Beam “rigidity”

- The relativistically correct form of Newton’s Laws for a particle in an electromagnetic field is:

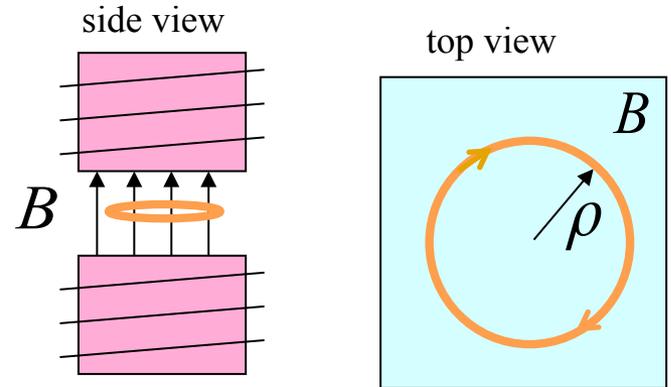
$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}); \quad \vec{p} = \gamma m \vec{v}$$

- A particle of unit charge in a uniform magnetic field will move in a circle of radius

$$\rho = \frac{p}{eB}$$

$$\longrightarrow (B\rho) = \frac{p}{e} \quad \leftarrow \text{constant for fixed energy!}$$

$$\text{T}\cdot\text{m}^2/\text{s}=\text{V} \quad \longrightarrow (B\rho)c = \frac{pc}{e} \quad \leftarrow \text{units of eV in our usual convention}$$



Beam “rigidity” = constant at a given momentum (even when $B=0$!)

$$(B\rho)[\text{T}\cdot\text{m}] = \frac{p[\text{eV}/c]}{c[\text{m}/\text{s}]} \approx \frac{p[\text{MeV}/c]}{300}$$

Remember forever!

If all magnetic fields are scaled with the momentum as particles accelerate, the trajectories remain the same
 → “synchrotron” [E. McMillan, 1945]



Example Beam Parameters

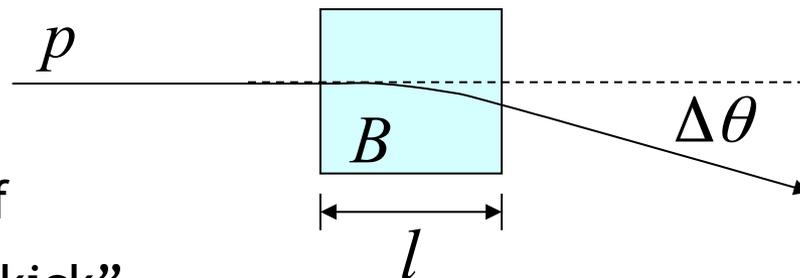
- Compare Fermilab LINAC (K=400 MeV) to LHC (K=7000 GeV)

Parameter	Symbol	Equation	Injection	Extraction
proton mass	m [GeV/c ²]		0.938	
kinetic energy	K [GeV]		.4	7000
total energy	E [GeV]	$K + mc^2$	1.3382	7000.938
momentum	p [GeV/c]	$\sqrt{E^2 - (mc^2)^2}$	0.95426	7000.938
rel. beta	β	$(pc) / E$	0.713	0.999999991
rel. gamma	γ	$E / (mc^2)$	1.426	7461.5
beta-gamma	$\beta\gamma$	$(pc) / (mc^2)$	1.017	7461.5
rigidity	(Bρ) [T-m]	$p[\text{GeV}] / (.2997)$	3.18	23353.

This would be the radius of curvature in a 1 T magnetic field or the field in Tesla needed to give a 1 m radius of curvature.

Thin lens approximation and magnetic “kick”

- If the path length through a transverse magnetic field is short compared to the bend radius of the particle, then we can think of the particle receiving a transverse “kick”

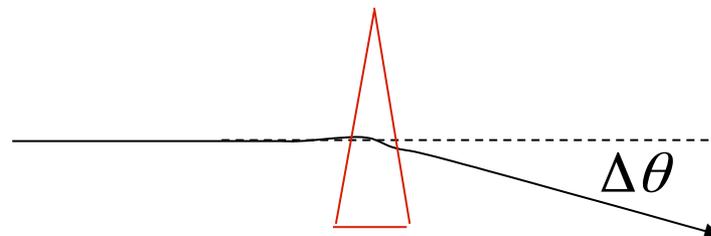


$$p_{\perp} \approx qvBt = qvB(l/v) = qBl$$

and it will be bent through small angle

$$\Delta\theta \approx \frac{p_{\perp}}{p} = \frac{Bl}{(B\rho)}$$

- In this “thin lens approximation”, a dipole is the equivalent of a prism in classical optics.



Weak Focusing

- Cyclotrons relied on the fact that magnetic fields between two pole faces are never perfectly uniform.
- This prevents the particles from spiraling out of the pole gap.
- In early synchrotrons, radial field profiles were optimized to take advantage of this effect, but in any weak focused beams, *the beam size grows with energy*.
- The highest energy weak focusing accelerator was the Berkeley Bevatron, which had a kinetic energy of 6.2 GeV
 - High enough to make antiprotons (and win a Nobel Prize)
 - It had an aperture 12"x48"!

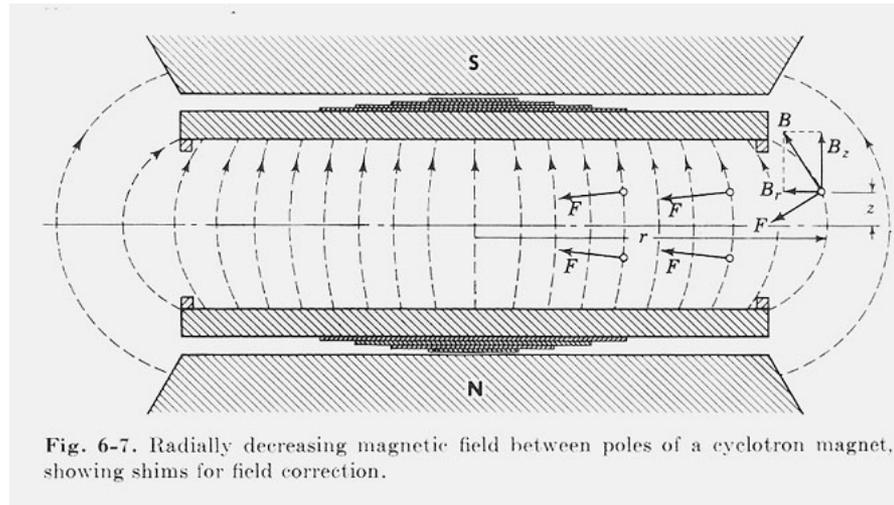
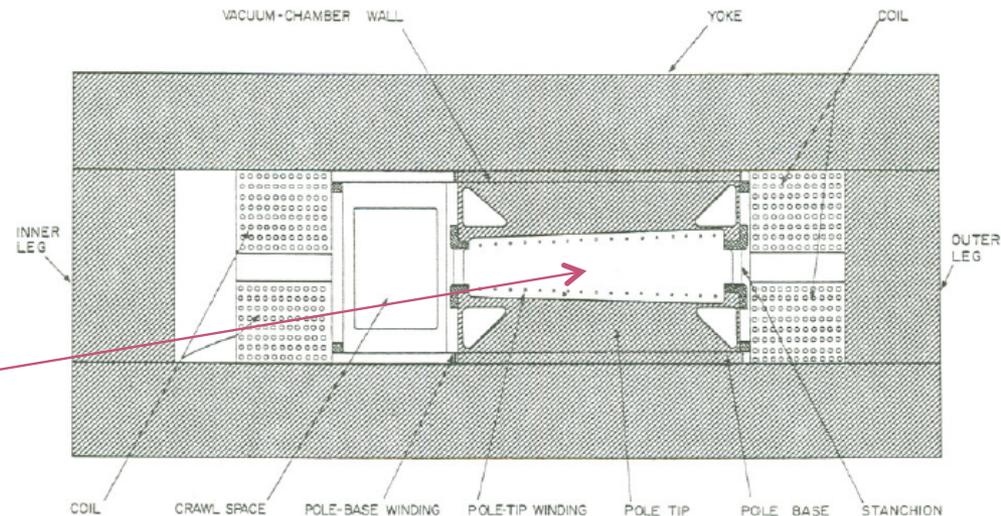
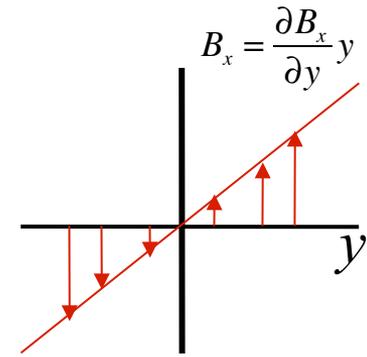
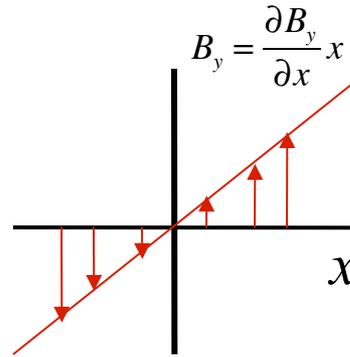
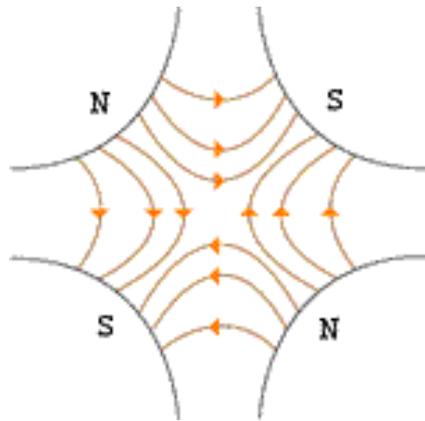


Fig. 6-7. Radially decreasing magnetic field between poles of a cyclotron magnet, showing shims for field correction.





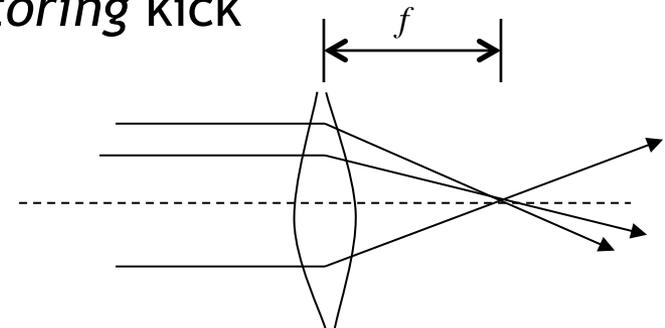
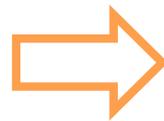
Strong Focusing: Quadrupole Magnets* as Lenses



Note: $\vec{\nabla} \times \vec{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} \equiv B'$

- A positive particle coming out of the page off center in the horizontal plane will experience a *restoring* kick *proportional to the displacement*

$$\Delta\theta \approx -\frac{B_y l}{(B\rho)} = -\frac{B' l x}{(B\rho)}$$



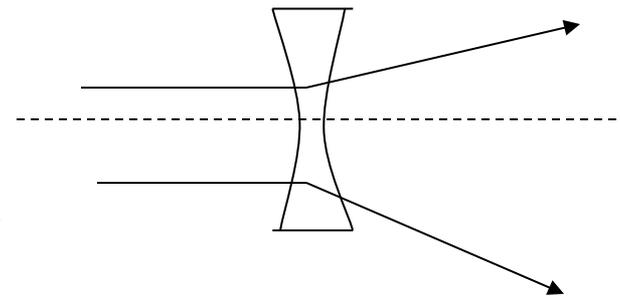
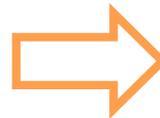
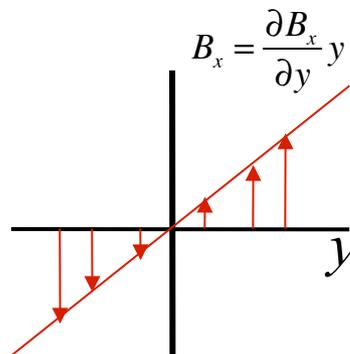
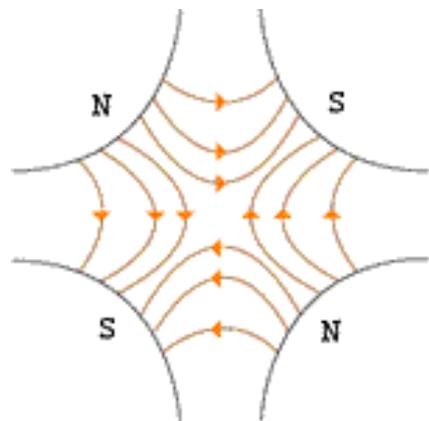
just like a “thin lens” with focal length

$$f = \frac{x}{\Delta\theta} = \frac{(B\rho)}{B'l}$$

*or quadrupole term in a gradient magnet



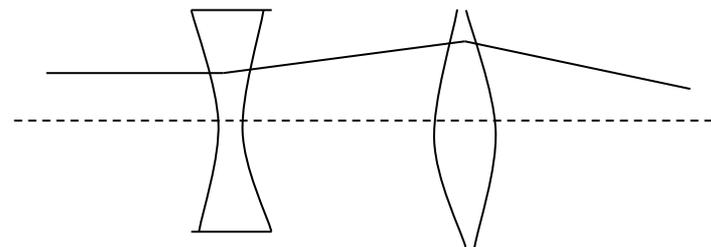
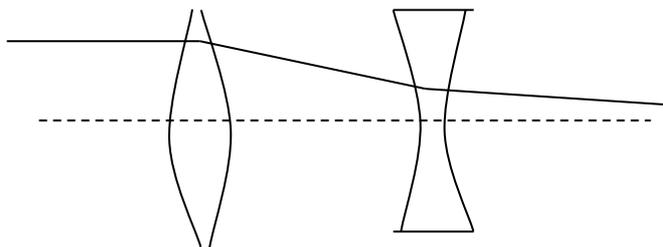
What About the Other Plane?



$$f = -\frac{(B\rho)}{B'l}$$

Defocusing!

Luckily, if we place equal and opposite pairs of lenses, there will be a net focusing *regardless of the order*.

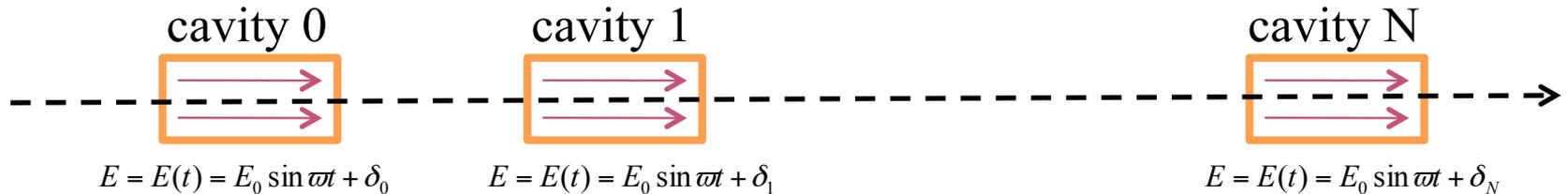


→ pairs give net focusing in *both* planes -> “FODO cell”



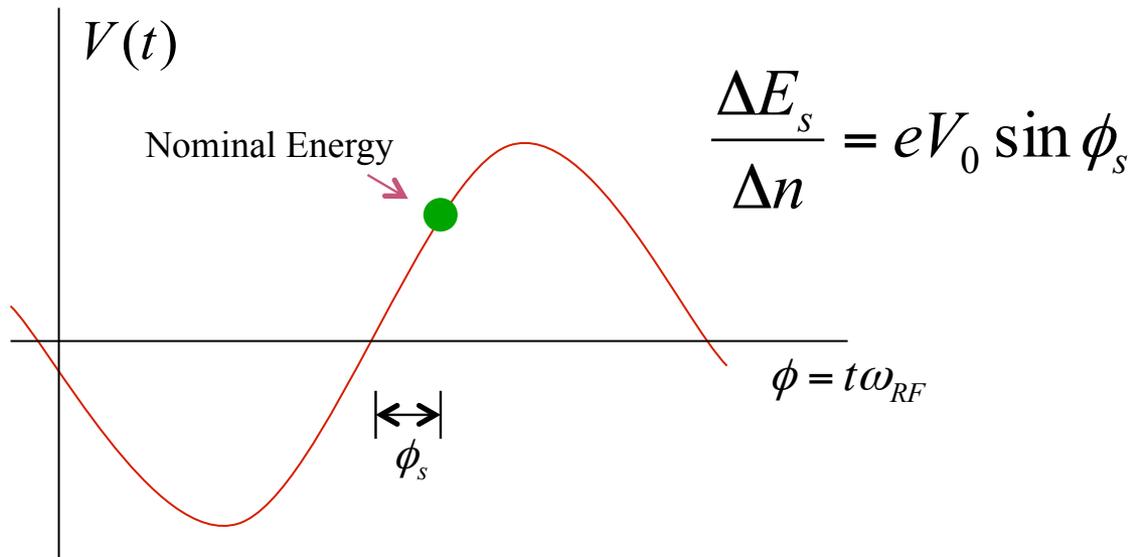
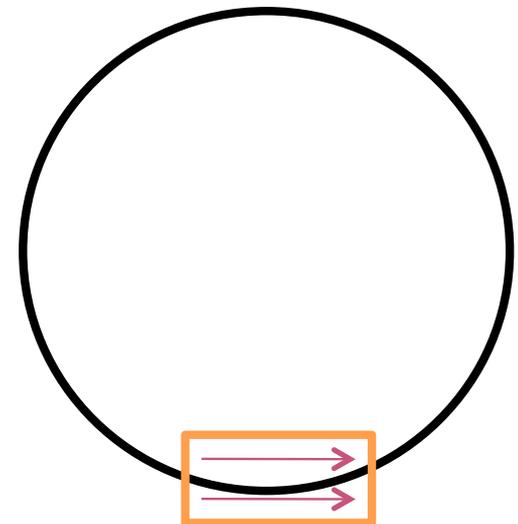
Longitudinal Motion

- We will generally accelerate particles using structures that generate time-varying electric fields (RF cavities), either in a linear arrangement



or located within a circulating ring

- In both cases, we want to phase the RF so a nominal arriving particle will see the same accelerating voltage and therefore get the same boost in energy





Examples of Accelerating RF Structures



Fermilab Drift Tube Linac (200MHz): oscillating field uniform along length

37->53MHz Fermilab Booster cavity

Biased ferrite frequency tuner



ILC prototype elliptical cell “ π -cavity” (1.3 GHz): field alternates with each cell



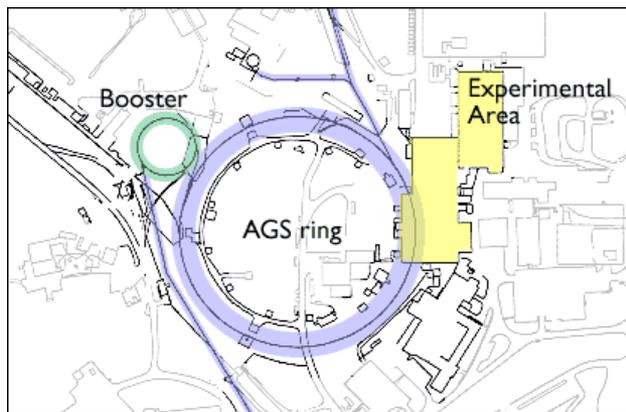
Some important early synchrotrons



- Berkeley Bevatron,
- 1954 (weak focusing)
 - 6.2 GeV protons
 - Discovered antiproton

CERN Proton Synchrotron (PS)

- 1959
- 628 m circumference
- 28 GeV protons
- Still used in LHC injector chain!



The Alternating Gradient Synchrotron complex

CERN Proton Synchrotron (PS)

- 1960
- 808 m circumference
- 33 GeV protons
- Discovered charm quark, CP violation, muon neutrino



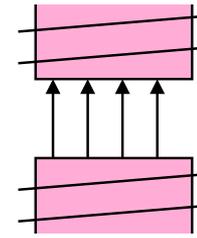
Combined Function vs. Separated Function

Strong focusing was originally implemented by building magnets with non-parallel pole faces to introduce a linear magnetic gradient



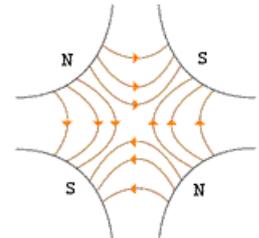
CERN PS (1959, 29 GeV)

$$B_y(x) = B_0 + \frac{\partial B_y}{\partial x} x$$



dipole

+



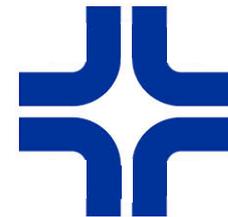
quadrupole

Later synchrotrons were built with physically separate dipole and quadrupole magnets. The first “separated function” synchrotron was the Fermilab Main Ring (1972, 400 GeV)



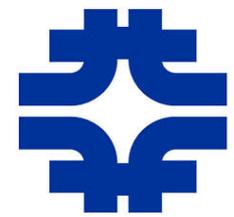
dipole

+



quadrupole

=



Fermilab

Strong focusing is also much easier to *teach* using separated functions, so we will...



Colliding Beams

- Two cars hitting each other at 60 mph...
- ...is about the same as one car going 120 mph hitting a parked car.
- But things get very different as we approach the speed of light...



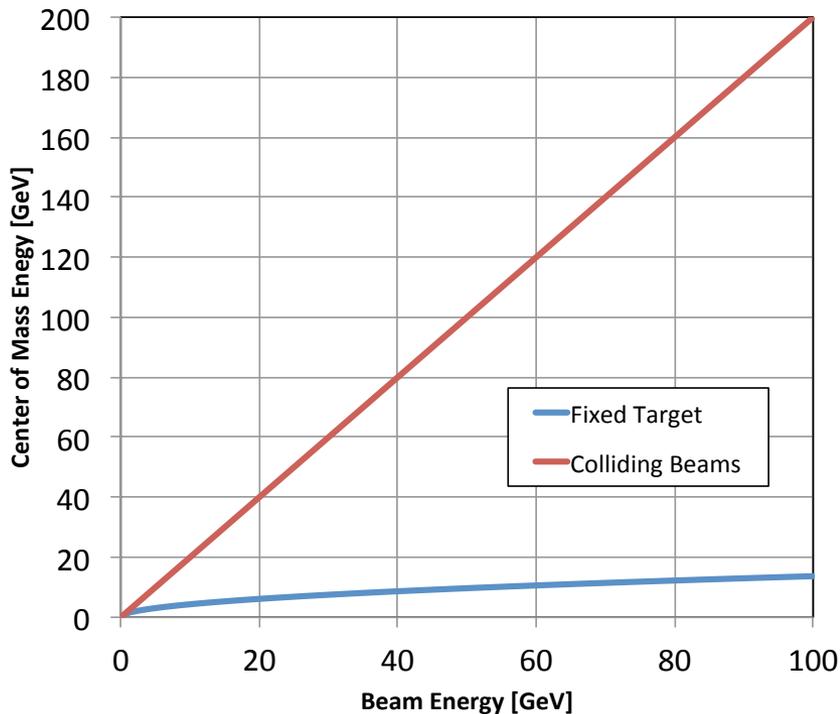
The Case for Colliding Beams

- Beam hitting a stationary proton, the “center of mass” energy is


$$E_{\text{CM}} = \sqrt{2E_{\text{beam}} m_{\text{target}} c^2}$$

- On the other hand, for colliding beams (of equal mass and energy) it's


$$E_{\text{CM}} = 2E_{\text{beam}}$$



- To get the 14 TeV CM design energy of the LHC with a single beam on a fixed target would require that beam to have an energy of 100,000 TeV!

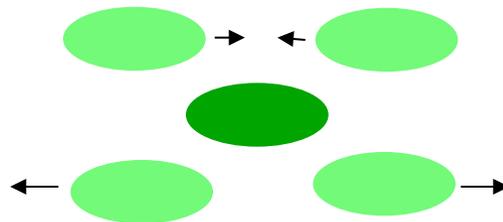
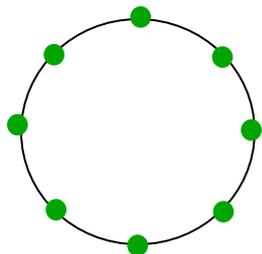
Would require a ring 10 times the diameter of the Earth!!



Colliding Beam Luminosity

Circulating beams typically “bunched”

(number of interactions)



$$= \left(\frac{N_1}{A} \right) N_2 \sigma$$

↑
Cross-sectional
area of beam

Total Luminosity:

$$L = \left(\frac{N_1 N_2}{A} \right) r_b = \left(\frac{N_1 N_2}{A} \right) n \frac{c}{C}$$

↑
crossing rate

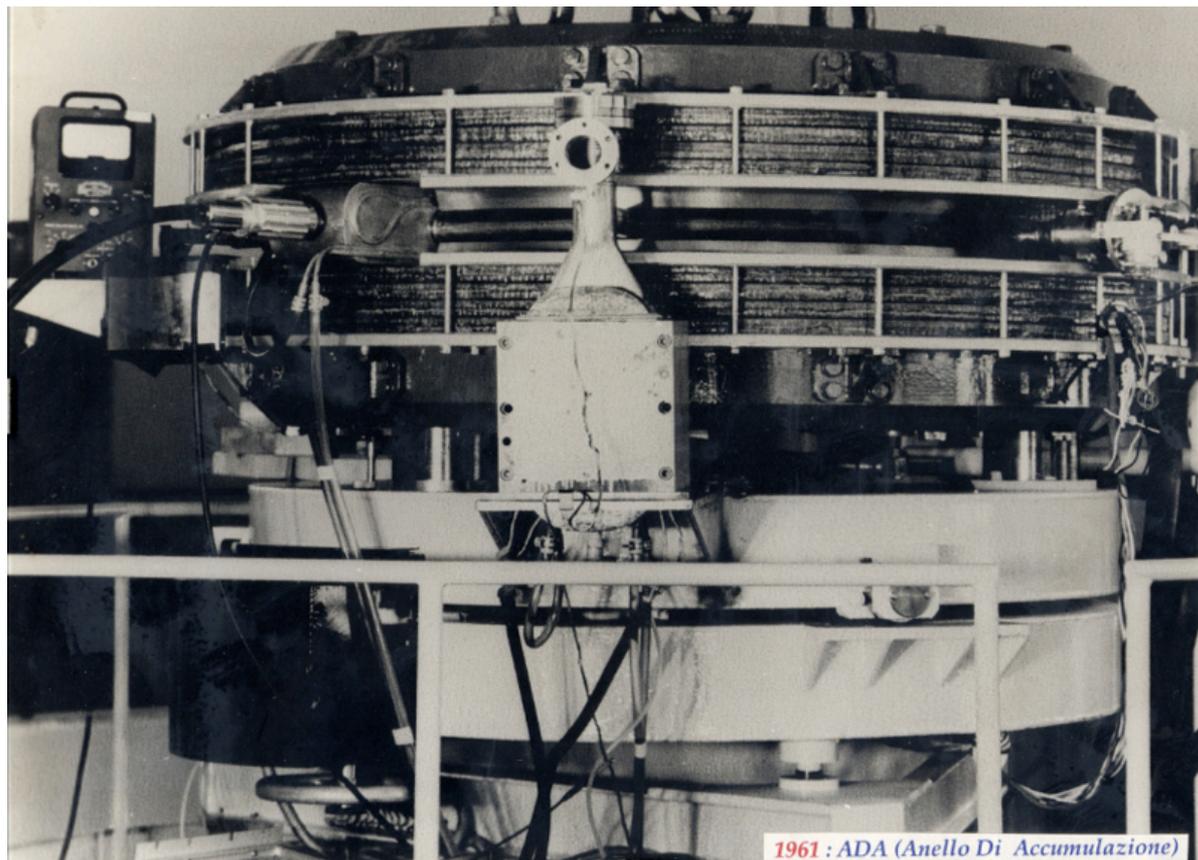
←
Circumference
of machine

↑
Number of
bunches



First e^+e^- Collider

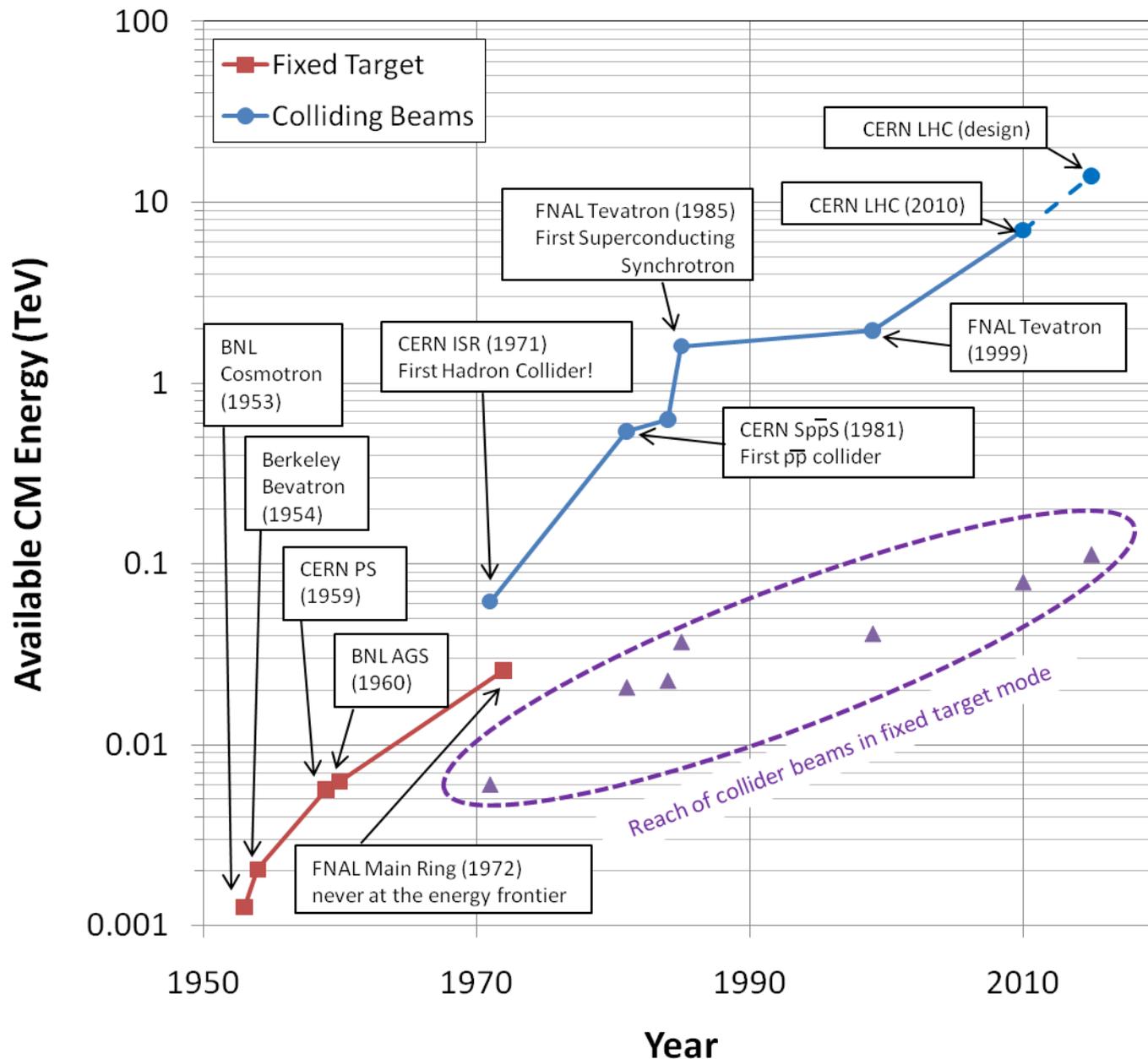
- ⊙ ADA (Anello Di Accumulazione) at INFN, Frascati, Italy (1961)
 - 250 MeV e^+ x 250 MeV e^-



- ⊙ It's easier to collide e^+e^- , because synchrotron radiation naturally “cools” the beam to smaller size.



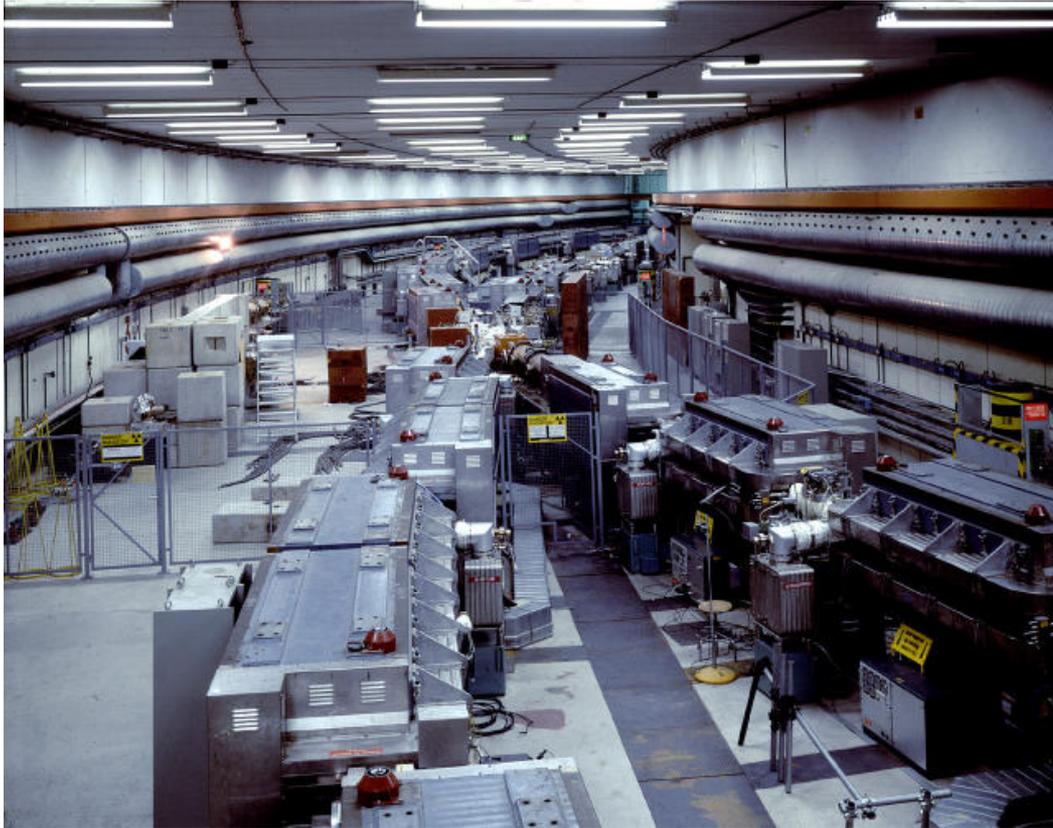
Evolution of the Energy Frontier



~a factor
of 10
every 15
years

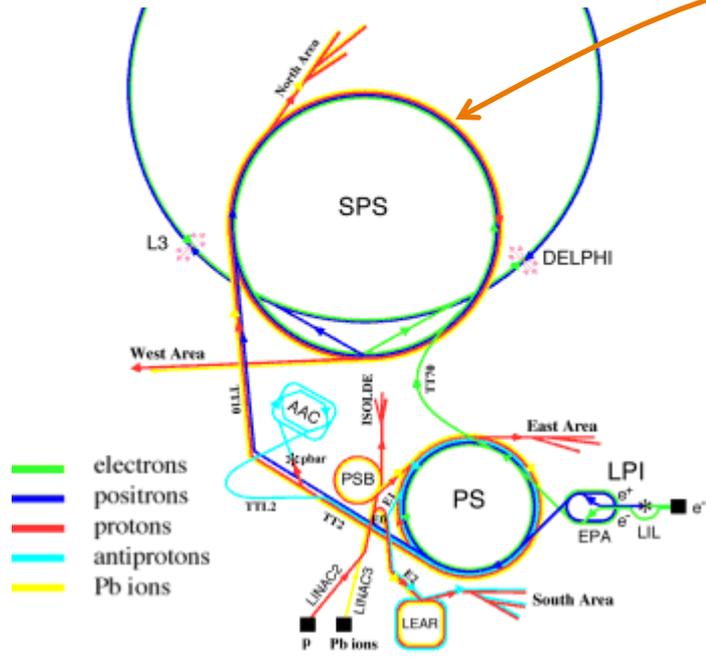


First Proton Collider: CERN Intersecting Storage Rings (ISR)



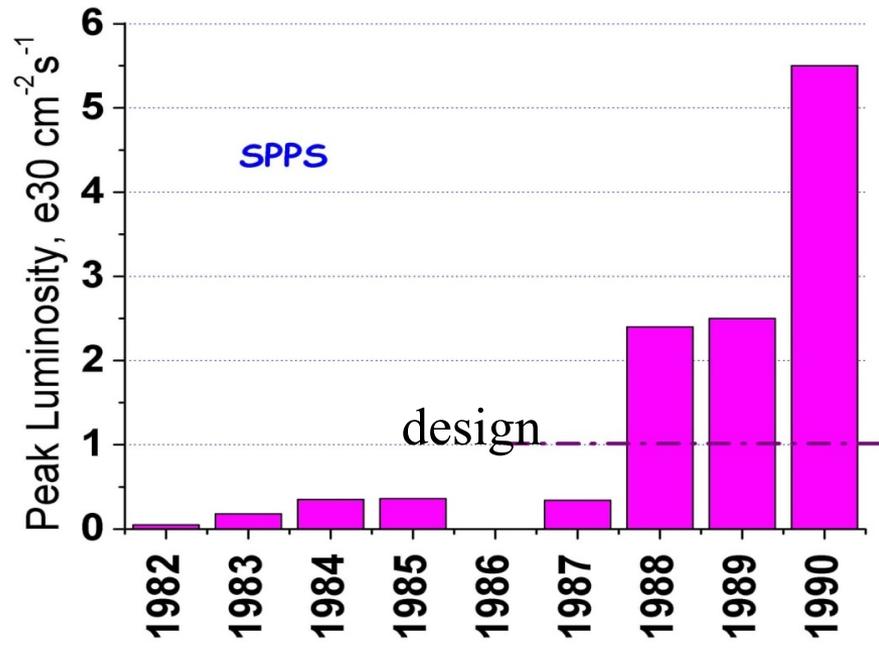
- 1971
- 31 GeV + 31 GeV colliding proton beams.
 - Highest CM Energy for 10 years
- Set a luminosity record that was not broken for 28 years!

SppS: First proton-antiproton Collider



- Protons from the SPS were used to produce antiprotons, which were collected
- These were injected in the opposite direction (same beam pipe) and accelerated
- First collisions in 1981
- Discovery of W and Z in 1983
 - Nobel Prize for Rubbia and Van der Meer

- Energy initially 270+270 GeV
- Raised to 315+315 GeV
- Limited by power loss in magnets!

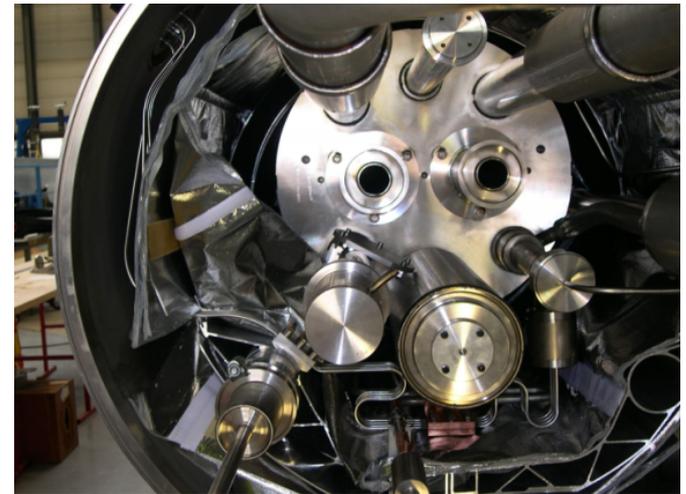
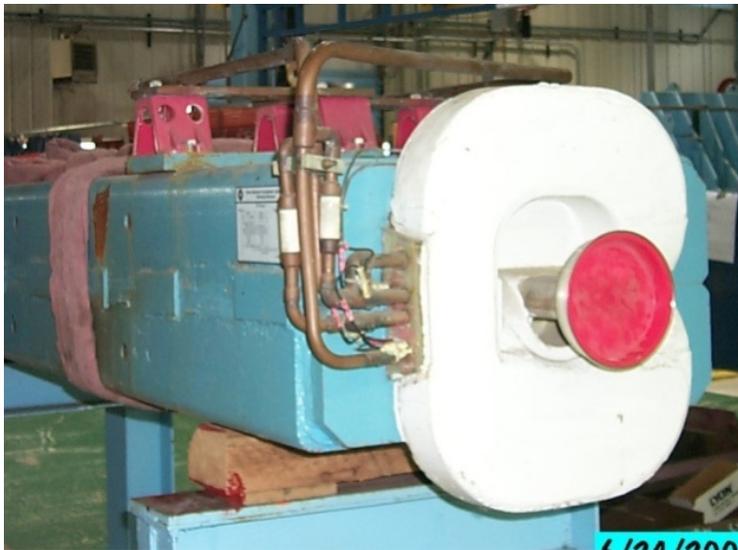




Superconductivity: Enabling Technology

- The maximum Sp̄p̄S energy was limited by the maximum power loss that the conventional magnets could support.
 - LHC made out of such magnets would be roughly the size of Rhode Island!
- Highest energy colliders only possible using superconducting magnets
- Must take the bad with the good
 - Conventional magnets are simple and naturally dissipate energy as they operate

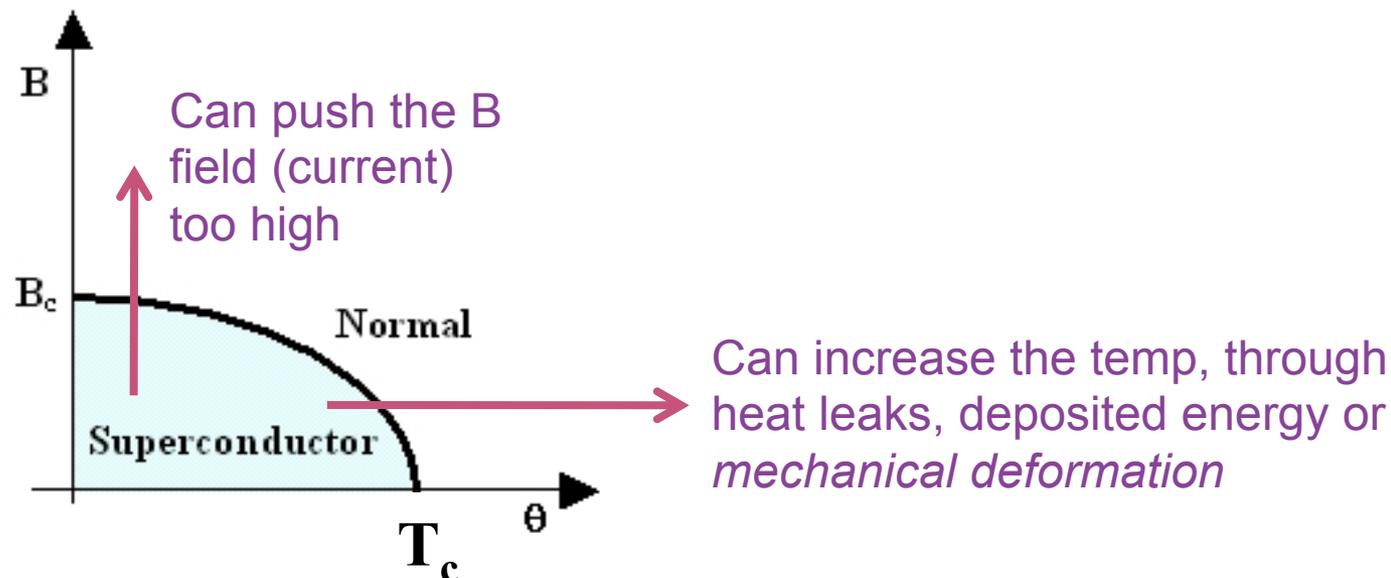
Superconducting magnets are complex and represent a great deal of stored energy which must be handled if something goes wrong



$$E \propto B^2$$

When is a superconductor not a superconductor?

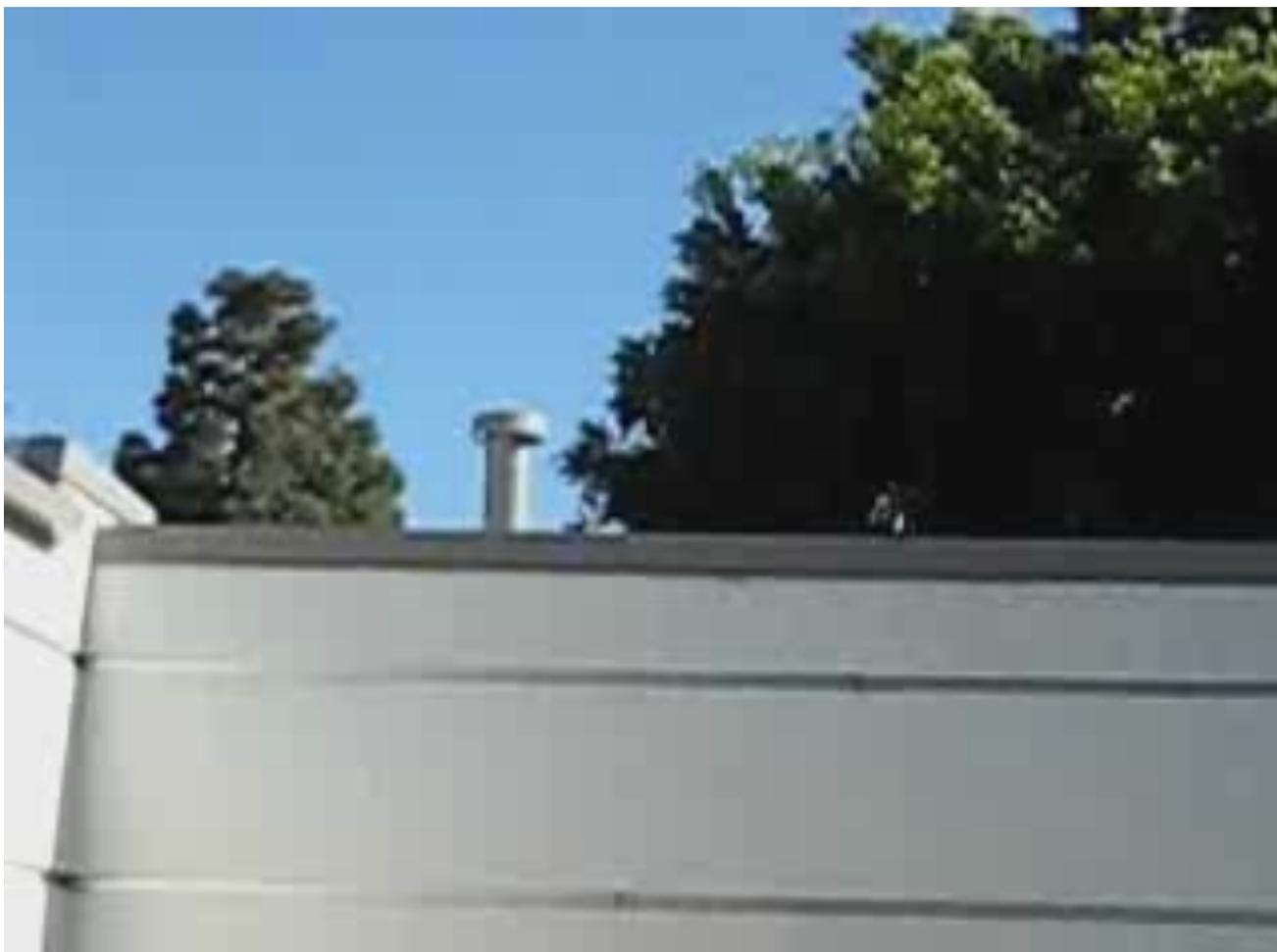
- Superconductor can change phase back to normal conductor by crossing the “critical surface”



- When this happens, the conductor heats quickly, causing the surrounding conductor to go normal and dumping lots of heat into the liquid Helium → “quench”
 - all of the energy stored in the magnet must be dissipated in some way
- Dealing with quenches is the single biggest issue for any superconducting synchrotron!



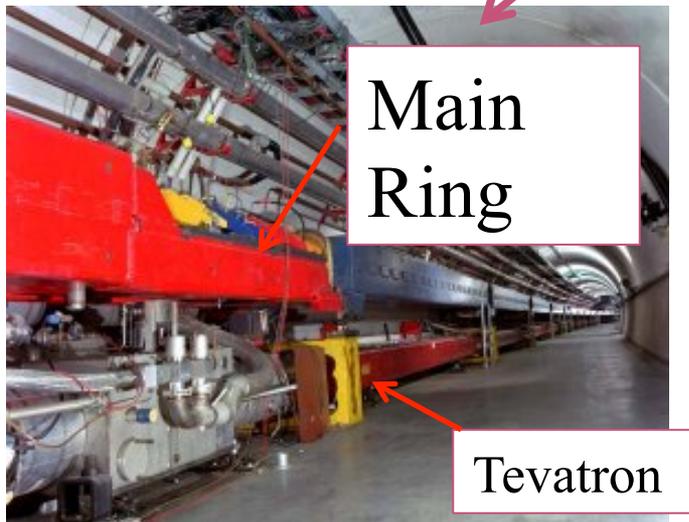
Quench Example: MRI Magnet*



*pulled off the web. We recover our Helium.



Tevatron: First Superconducting Synchrotron



- 1968 - Fermilab Construction Begins
- 1972 - Beam in Main Ring
 - (normal magnets)
- Plans soon began for a superconducting collider to share the ring.
 - Dubbed “Saver Doubler”
(later “Tevatron”)
- 1985 - First proton-antiproton collisions in Tevatron
 - Most powerful accelerator in the world *for the next quarter century*
- 1995 - Top quark discovery
- 2011 - Tevatron shut down after successful LHC startup



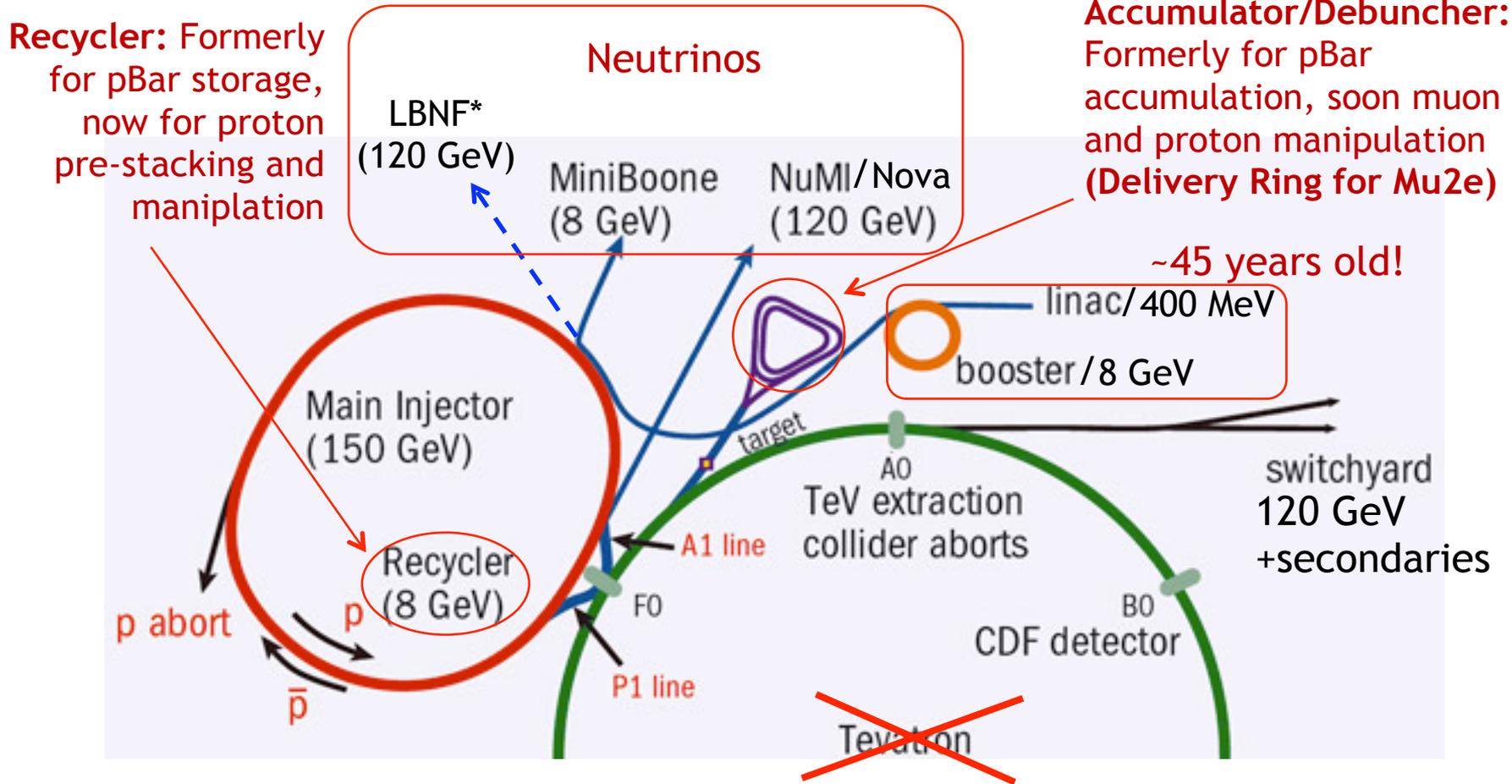
Multi-stage Acceleration

- Early synchrotrons had low energy injection and provided all the acceleration in a single stage.
- The energy range of a single synchrotron is limited by
 - Beams get smaller as they accelerate, so an aperture large enough for the injected beam is unreasonably large at high field.
 - Hysteresis effects result in excessive nonlinear terms at low energy (very important for colliders)
- Typical range 10-20 for colliders, larger for fixed target
 - Fermilab Main Ring: 8-400 GeV (50x)
 - Fermilab Tevatron: 150-980 GeV (6.5x)
 - LHC: 400-7000 GeV (17x)
- The highest energy beams require multiple stages of acceleration, with high reliability at each stage
- How is this done?



Example: Fermilab Accelerator Complex Today

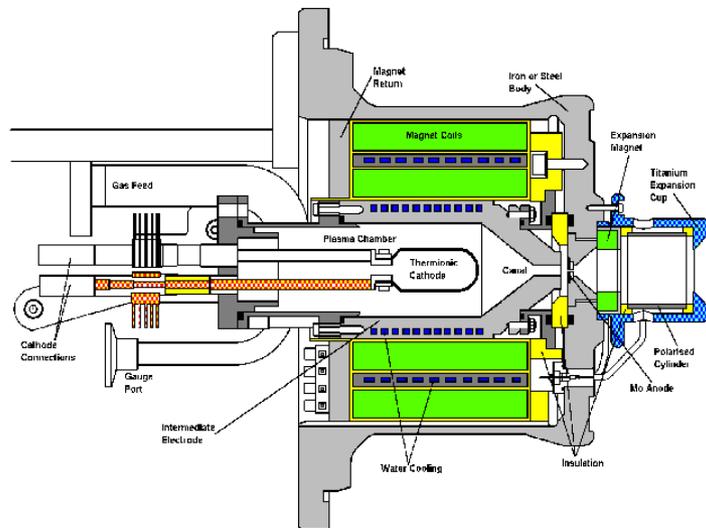
- As LHC takes over the Energy Frontier, Fermilab focuses on intensity-based physics



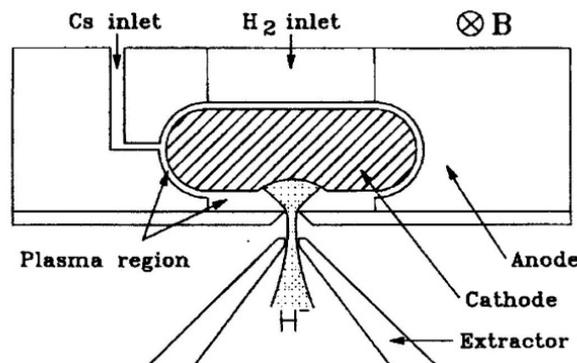
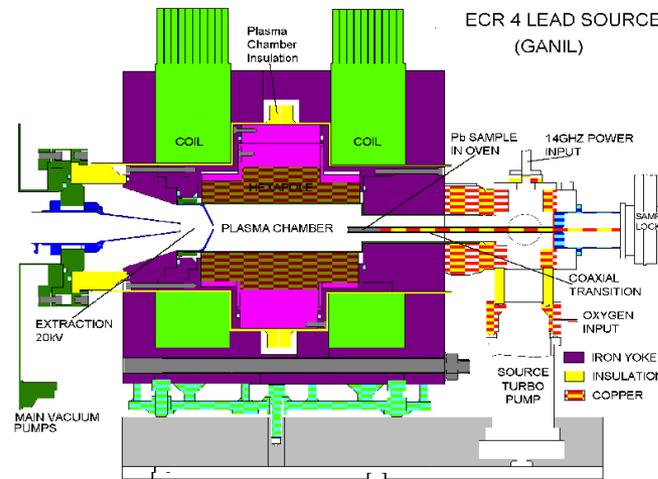
*proposed

Getting Started: Ion Sources

CERN proton source



CERN Lead source



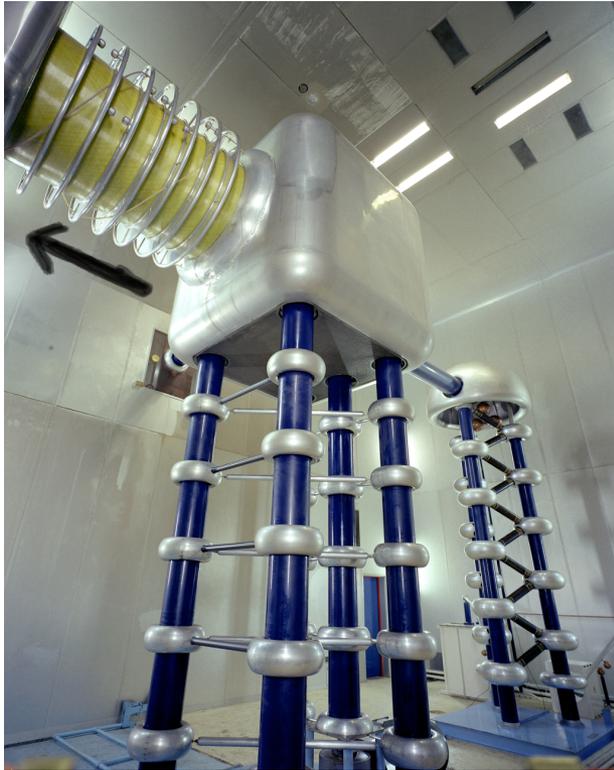
FNAL H- source.
Mix Cesium with Hydrogen to add electron. (why? we'll get to that)

Typically 10s of keV and mAs to 10s of mA of current. Want to accelerate as fast as possible before space charge blows up the beam!



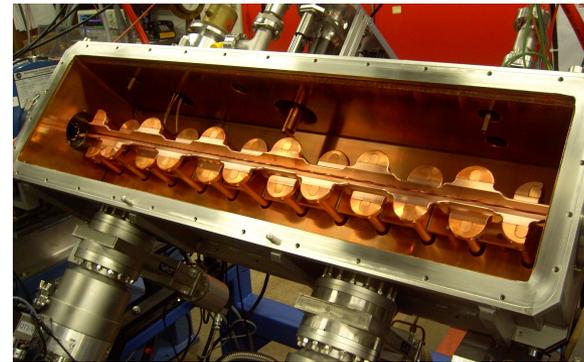
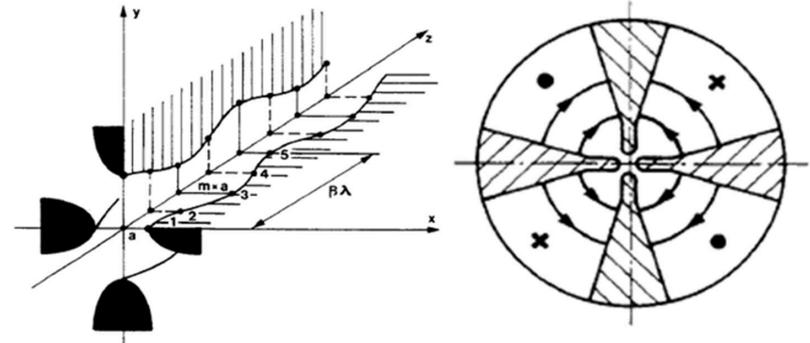
Initial Acceleration

Old: Static



Static acceleration from
Cockcroft-Walton.
FNAL = 750 keV
max ~1 MeV

New: RF Quadrupole (RFQ)

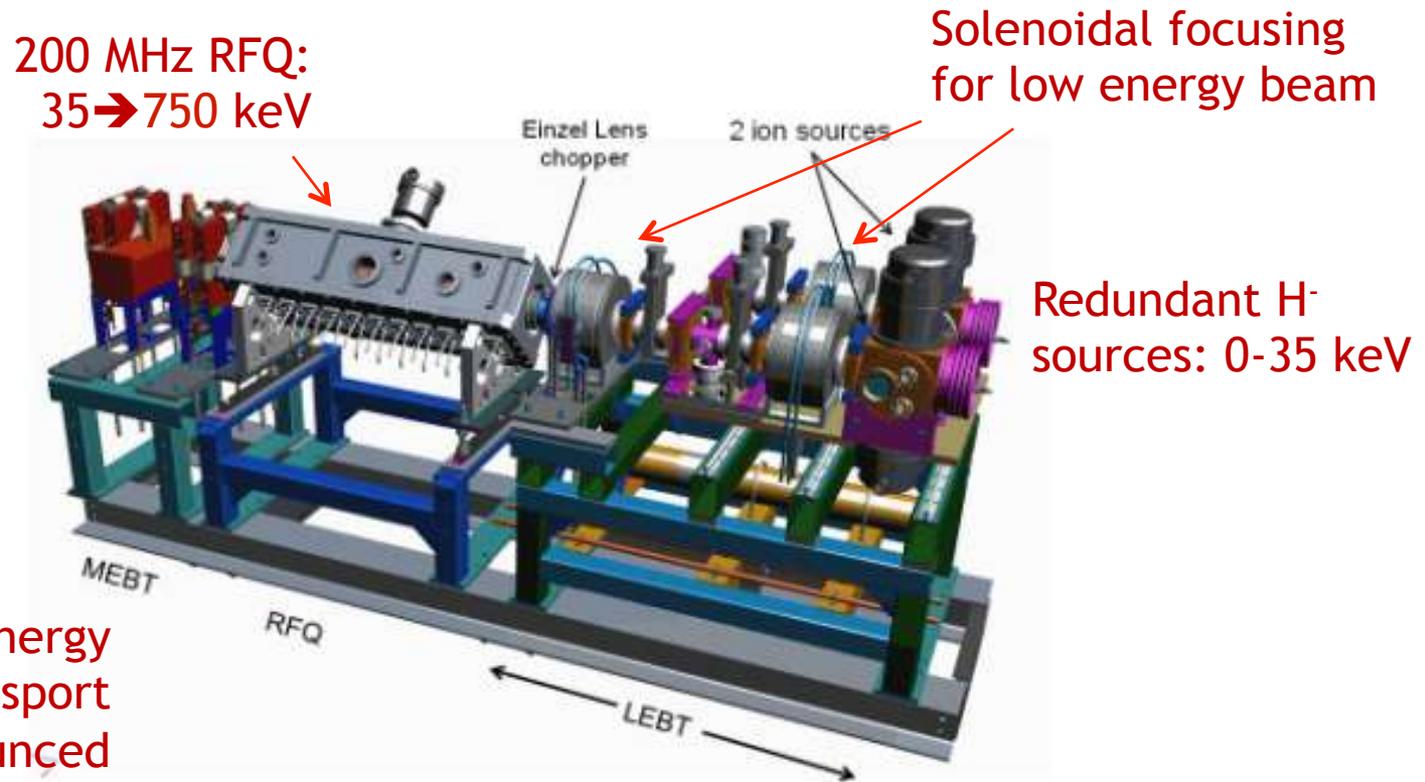


RF structure combines an electric
focusing quadrupole with a
longitudinal accelerating gradient.



Early Stages

- The front end of any modern hadron accelerator looks something like this (Fermilab front end)



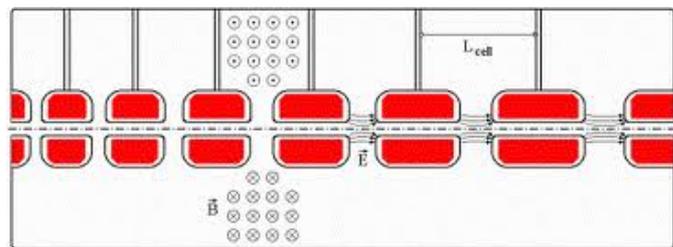
Medium Energy
Beam Transport
(MEBT, pronounced
“mebbit”): 750 keV

Low Energy Beam Transport (LEBT,
pronounced “lebbbit”): 35 keV



Drift Tube (Alvarez) Cavity

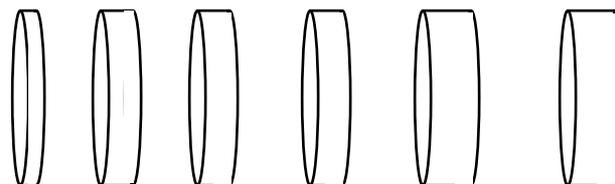
- Because the velocity is changing quickly, the first linac is generally a Drift Tube Linac (DTL), which can be beta-matched to the accelerating beam.
- Put conducting tubes in a larger pillbox, such that inside the tubes $E=0$



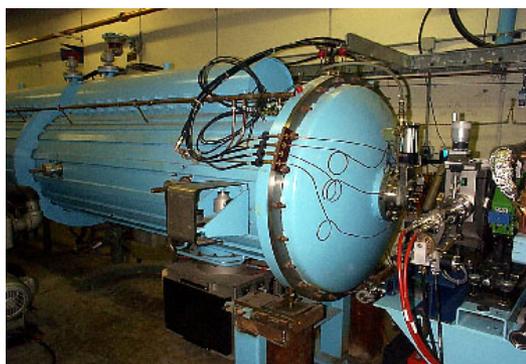
$$d = \frac{v}{f}$$

Gap spacing changes as velocity increases

Bunch of pillboxes



Drift tubes contain quadrupoles to keep beam focused



Fermilab low energy linac



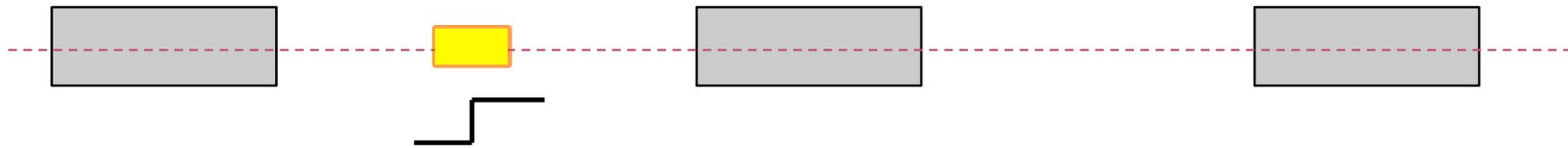
Inside

- As energy gets higher, switch to “pi-cavities”, which are more efficient

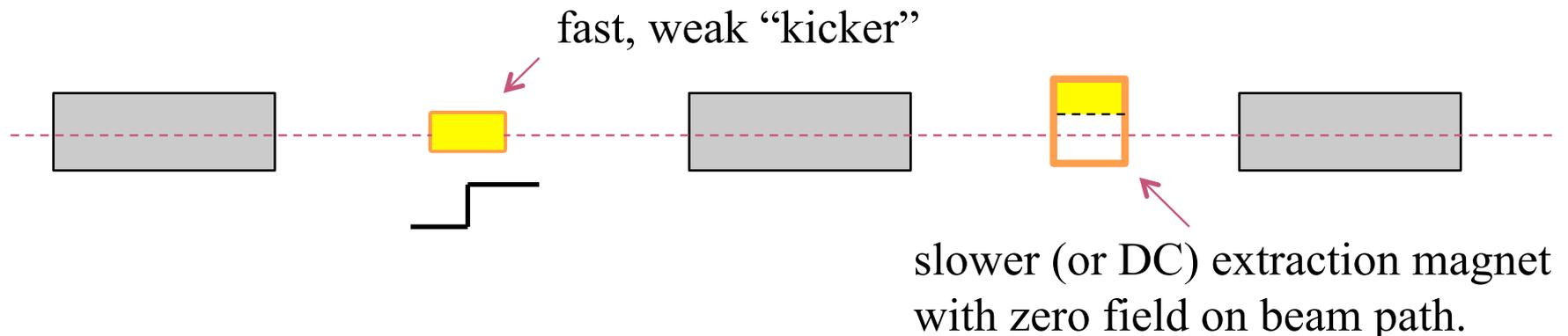


Injection and Extraction

- ◉ We typically would like to extract (or inject) beam by switching a magnetic field on between two bunches (order ~ 10 - 100 ns)



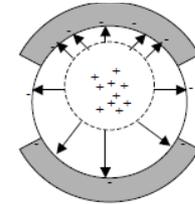
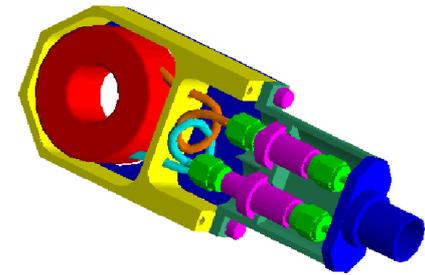
- ◉ Unfortunately, getting the required field in such a short time would result in prohibitively high inductive voltages, so we usually do it in two steps:





Standard Beam Instrumentation

- Bunch/beam intensity are measured using inductive toroids
- Beam position is typically measured with beam position monitors (BPM's), which measure the induced signal on a opposing pickups
- Longitudinal profiles can be measured by introducing a resistor to measure the induced image current on the beam pipe -> Resistive Wall Monitor (RWM)

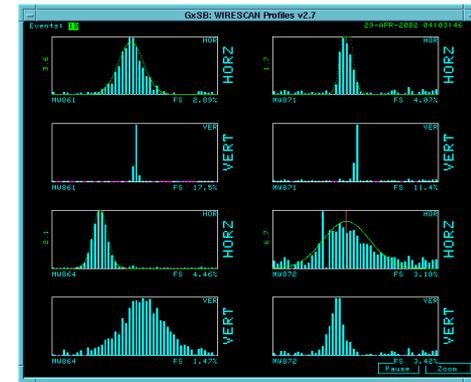


$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

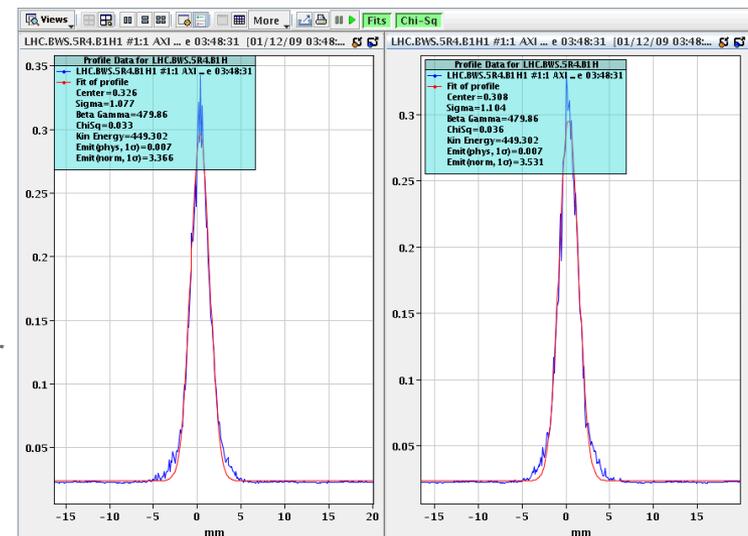


Beam Instrumentation (cont'd)

- Beam profiles in beam lines can be measured using secondary emission multiwires (MW's)
- Can measure beam profiles in a circulating beam with a “flying wire scanner”, which quickly passes a wire through and measures signal vs time to get profile
- Non-destructive measurements include
 - Ionization profile monitor (IPM): drift electrons or ions generated by beam passing through residual gas
 - Synchrotron light
 - Standard in electron machines
 - Also works in LHC



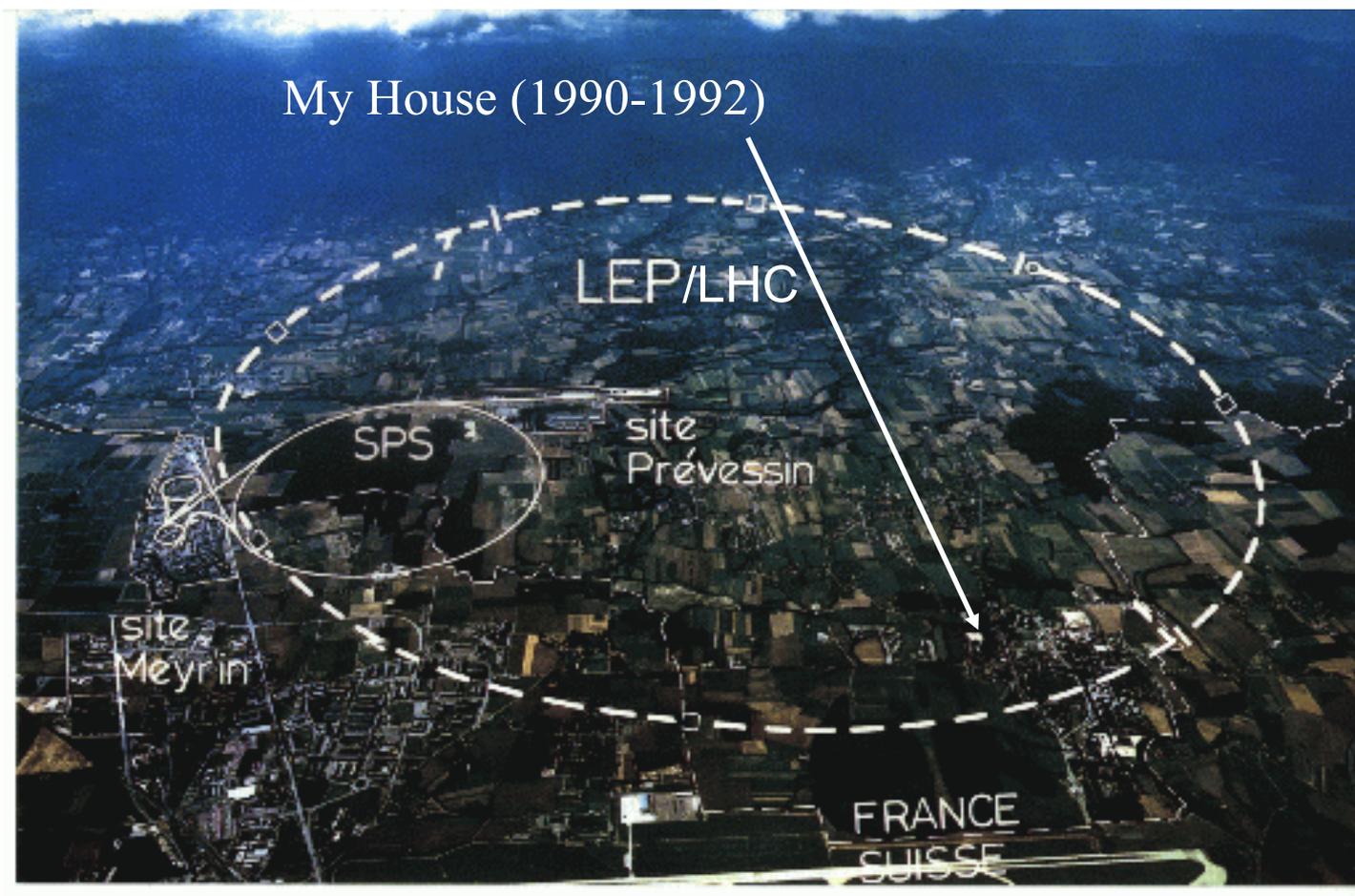
Beam profiles in MiniBooNE beam line



Flying wire signal in LHC



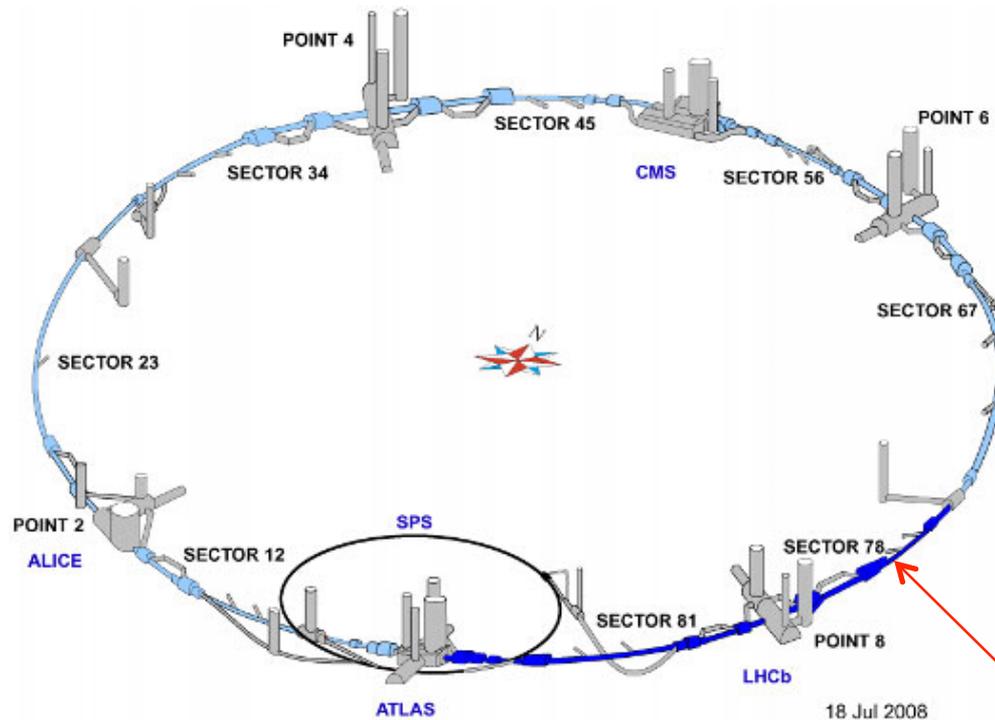
State of the art: Large Hadron Collider (LHC)



- Tunnel originally dug for LEP
 - Built in 1980's as an electron positron collider
 - Max 100 GeV/beam, but 27 km in circumference!!



LHC Layout and Numbers



Design:

- 7 TeV+7 TeV proton beams
 - Can't make enough antiprotons for the LHC
 - Magnets have two beam pipes, one going in each direction.
- Stored beam energy 150 times more than Tevatron
 - Each beam has only 5×10^{-10} grams of protons, but has the energy of a train going 100 mph!!
- These beams are focused to a size *smaller than a human hair* to collide with each other!

- 27 km in circumference
- 2 major collision regions: CMS and ATLAS
- 2 “smaller” regions: ALICE and LHCb





Explaining the LHC*...



*Kate McAlpine (<http://www.youtube.com/user/alpinekat>)



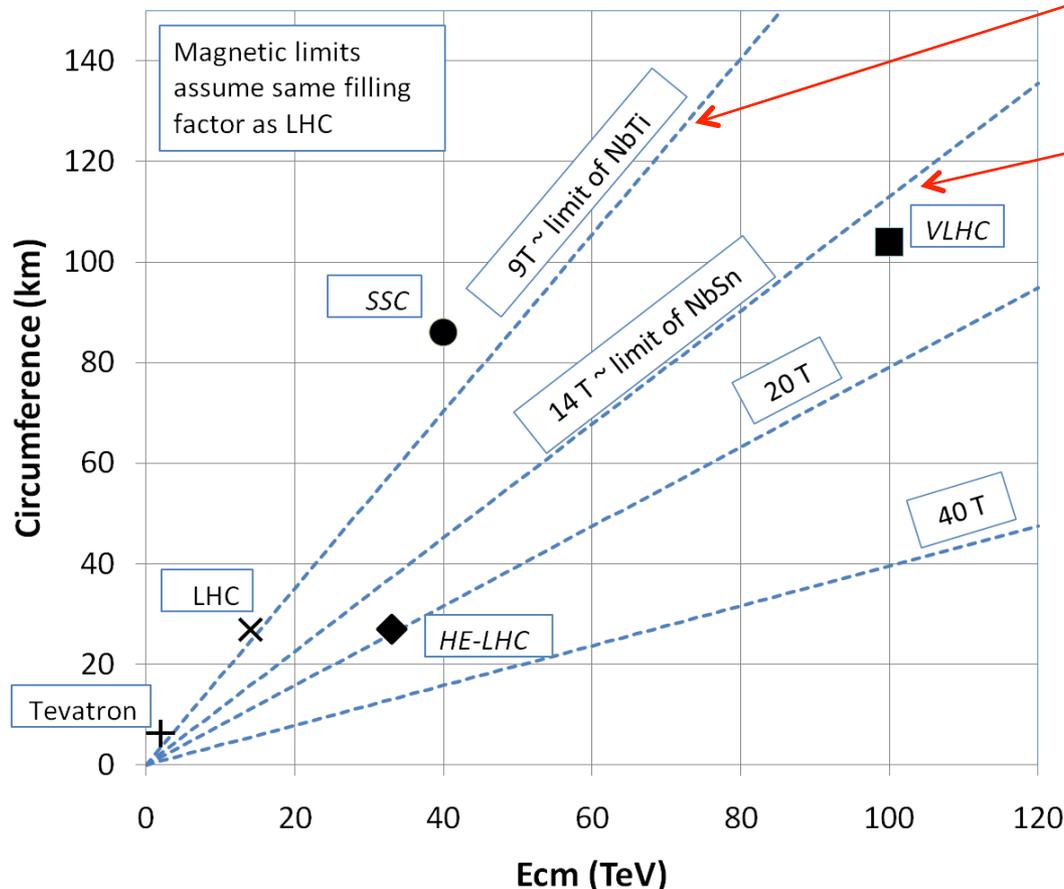
What next?

○ The energy of Hadron colliders is limited by feasible size and magnet technology. Options:

- Get very large (~100 km circumference)
- More powerful magnets (requires new technology)

All accelerator magnets based on this

Future magnets could be based on this





Future Circular Collider (FCC)

- Currently being discussed for ~2030s
- 80-100 km in circumference
- Niobium-3-Tin (Nb_3Sn) magnets.
- ~100 TeV center of mass energy

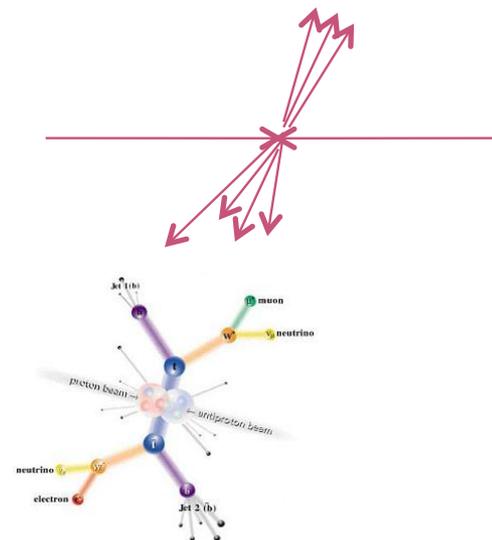




Other Paths to the Energy Frontier

Leptons vs. Hadrons revisited

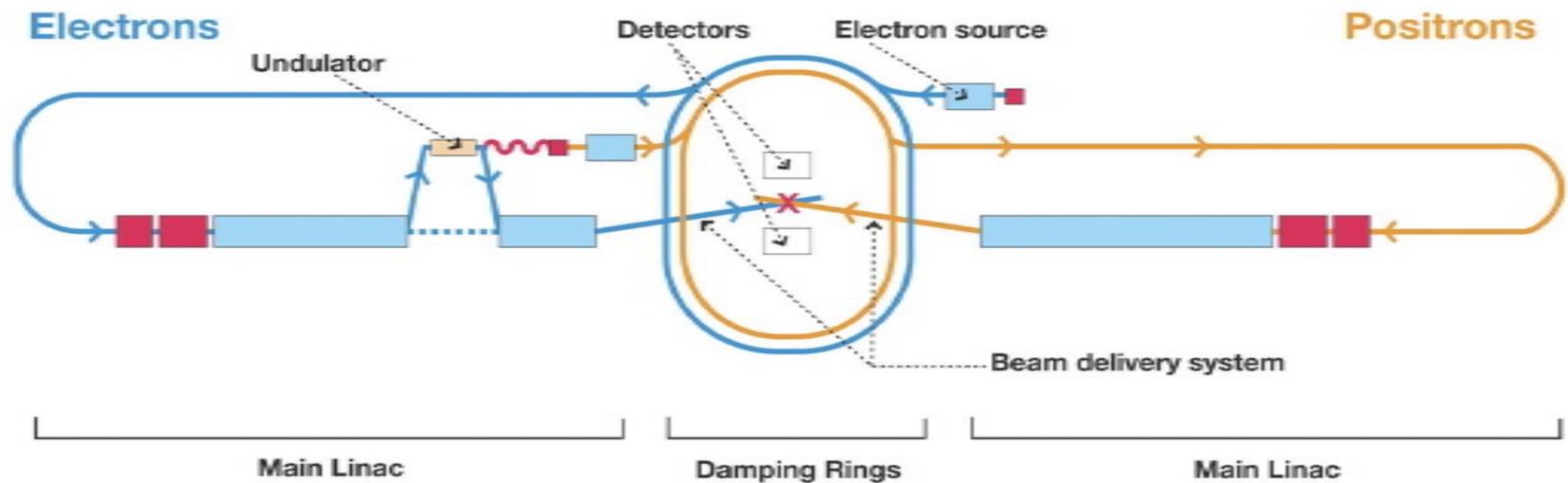
- Because 100% of the beam energy is available to the reaction, a lepton collider is competitive with a hadron collider of ~ 5 - 10 times the beam energy (depending on the physics).
 - A lepton collider of >1 TeV/beam could compete with the discovery potential of the LHC
 - A lower energy lepton collider could be very useful for precision tests, but I'm talking about direct *energy frontier* discoveries.
 - Unfortunately, building such a collider is VERY, VERY hard
 - Eventually, circular e^+e^- colliders will radiate away all of their energy each turn
 - LEP reached 100 GeV/beam with a 27 km circumference synchrotron!
- Next e^+e^- collider will be linear





International Linear Collider (ILC)

- LEP was the limit of circular e^+e^- colliders
 - Next step must be linear collider
 - Proposed ILC 30 km long, 250 x 250 GeV e^+e^- (NOT energy frontier)

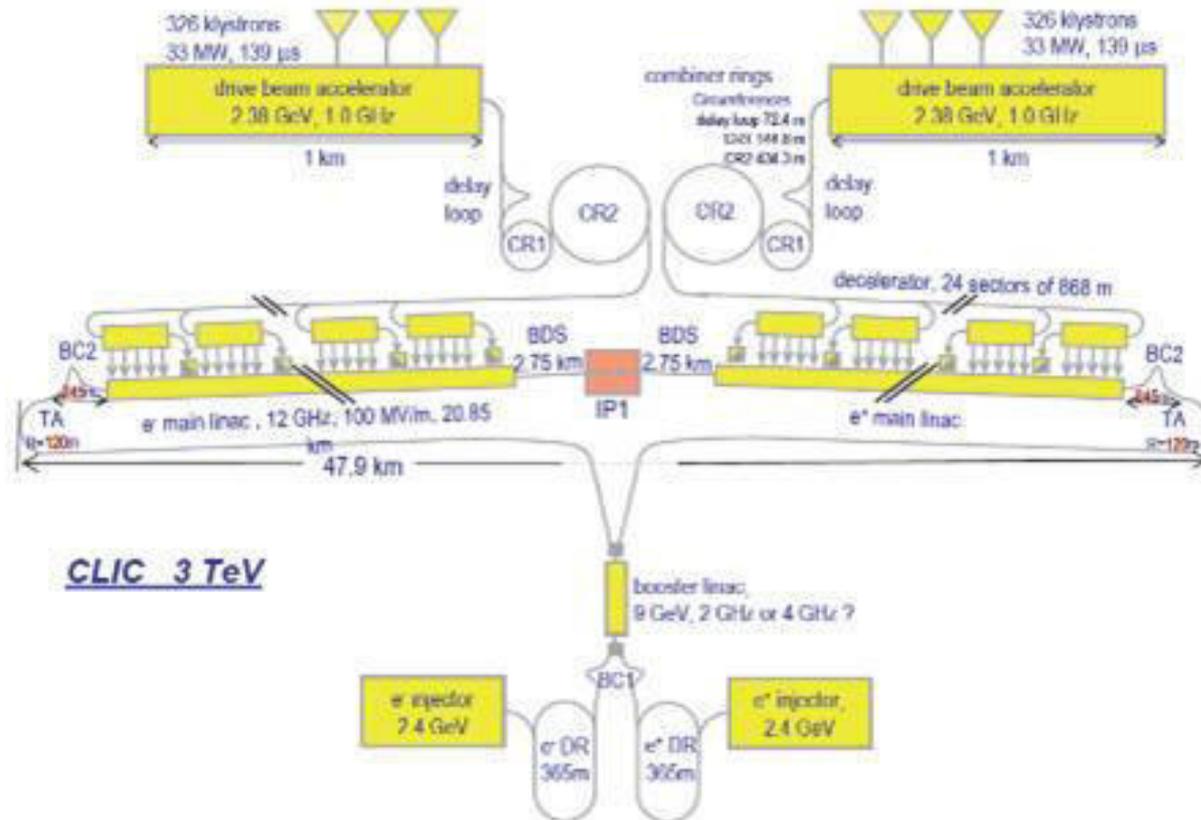


- We don't yet know whether that's high enough energy to be interesting
 - Need to wait for LHC results
 - What if we need more?



“Compact” (ha ha) Linear Collider (CLIC)?

- Use low energy, high current electron beams to drive high energy accelerating structures

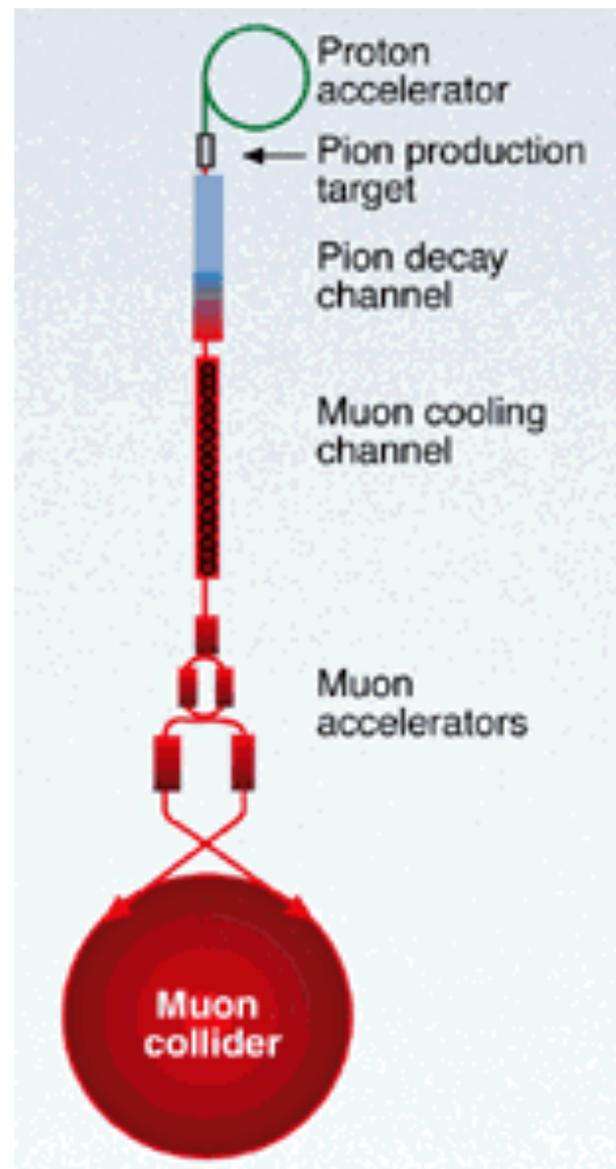


- Up to 1.5 x 1.5 TeV, but VERY, VERY hard



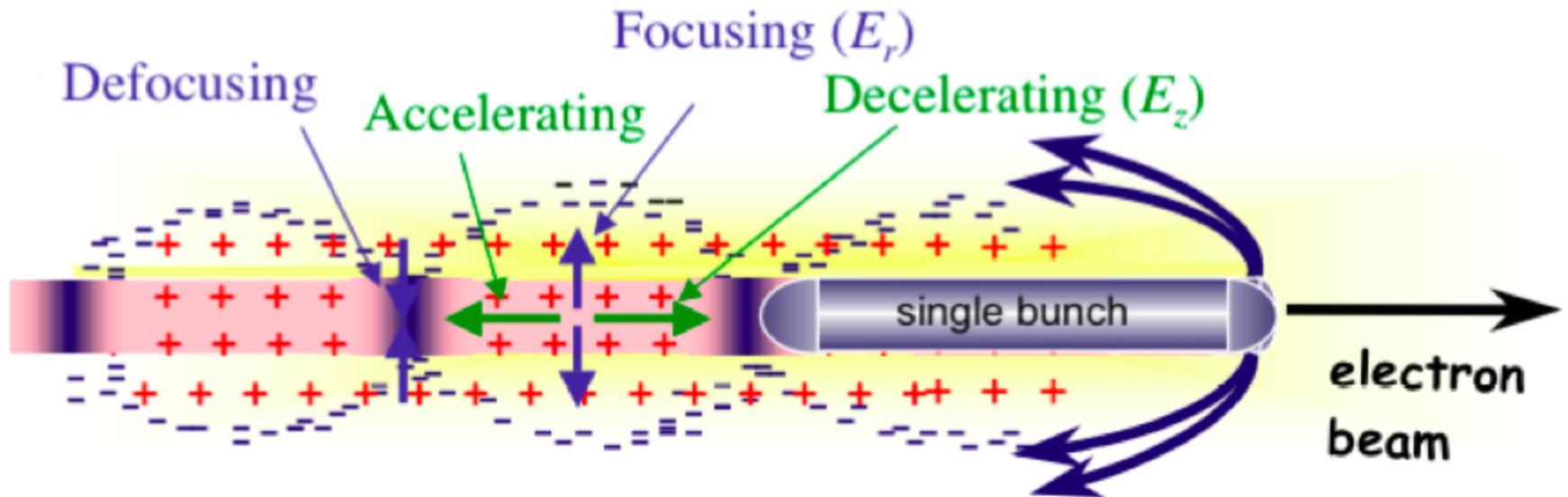
Muon colliders?

- Muons are pointlike, like electrons, but because they're heavier, synchrotron radiation is much less of a problem.
- Unfortunately, muons are unstable, so you have to produce them, cool them, and collide them, before they decay.



Wakefield accelerators?

- Many advances have been made in exploiting the huge fields that are produced in plasma oscillations.



- Potential for accelerating gradients many orders of magnitude beyond RF cavities.
- Still a long way to go for a practical accelerator.

Some other important accelerators (past):

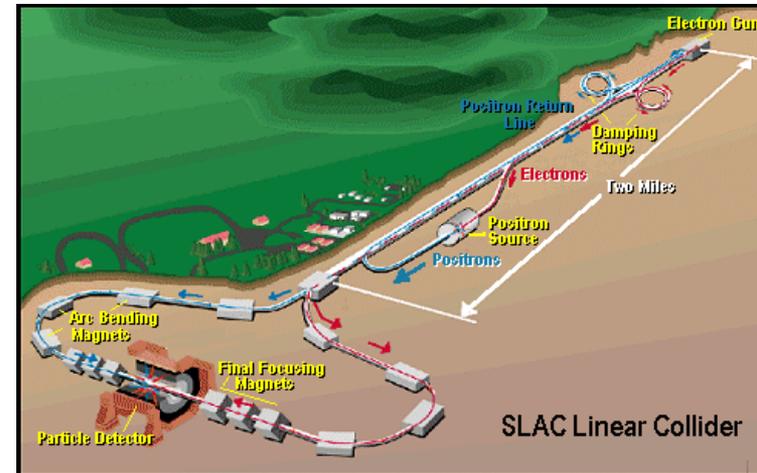


LEP (at CERN):

- 27 km in circumference
- e^+e^-
- Primarily at $2E=M_Z$ (90 GeV)
- Pushed to $E_{CM}=200\text{GeV}$
- $L = 2E31$
- **Highest energy *circular* e^+e^- collider that will ever be built.**
- Tunnel now houses LHC

SLC (at SLAC):

- 2 km long LINAC accelerated electrons AND positrons on opposite phases.
- $2E=M_Z$ (90 GeV)
- polarized
- $L = 3E30$
- **Proof of principle for linear collider**



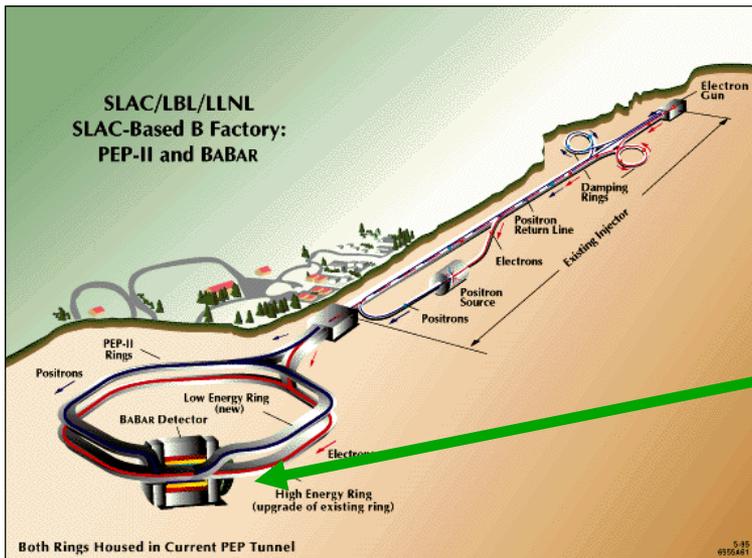


B-Factories

- B-Factories collide e^+e^- at $E_{CM} = M(\Upsilon(4S))$.
- Asymmetric beam energy (moving center of mass) allows for time-dependent measurement of B-decays to study CP violation.

KEKB (Belle Experiment):

- Located at KEK (Japan)
- 8 GeV e^- x 3.5 GeV e^+
- Peak luminosity $> 1e34$

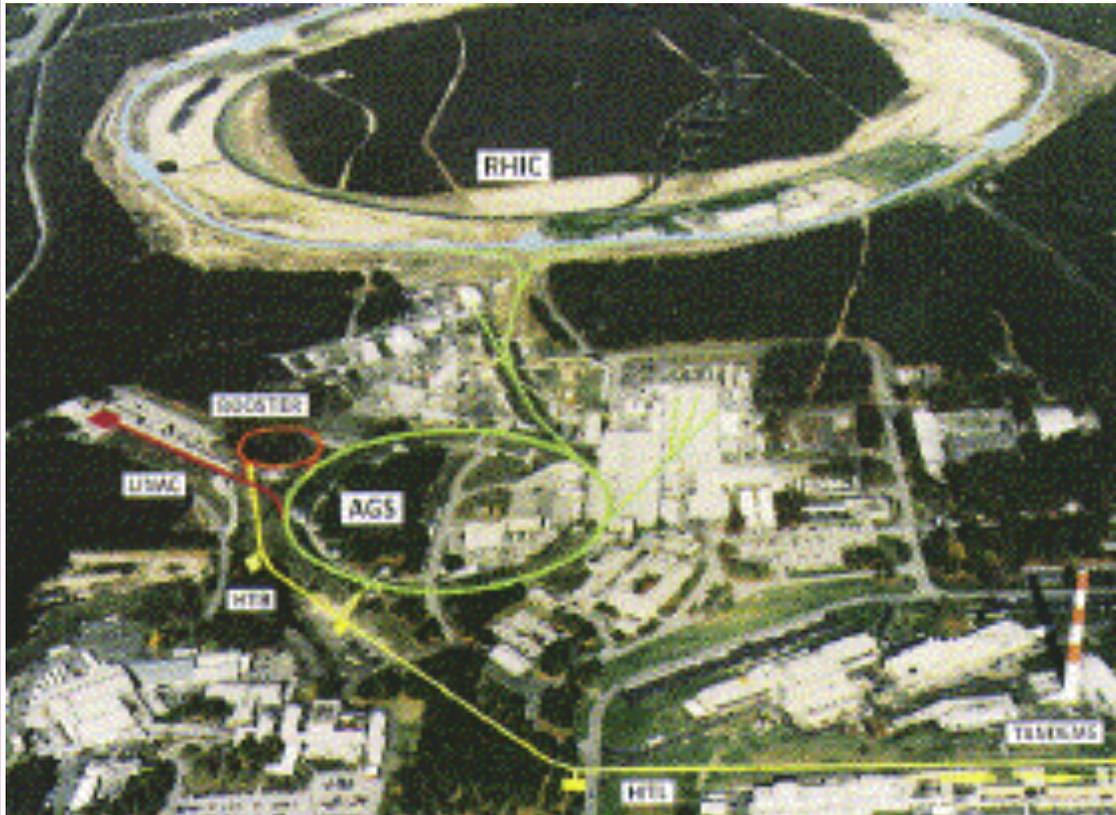


PEP-II (BaBar Experiment)

- Located at SLAC (USA)
- 9 GeV e^- x 3.1 GeV e^+
- Peak luminosity $> 1e34$



Relativistic Heavy Ion Collider (RHIC)



- Located at Brookhaven:
- Can collide protons (at 28.1 GeV) and many types of ions up to Gold (at 11 GeV/amu).
- Luminosity: $2E26$ for Gold
- **Goal: heavy ion physics, quark-gluon plasma, ??**

Continuous Electron Beam Accelerator Facility (CEBAF)

Jlab, the aerial view



Kees de Jager

Bernhard Mecking

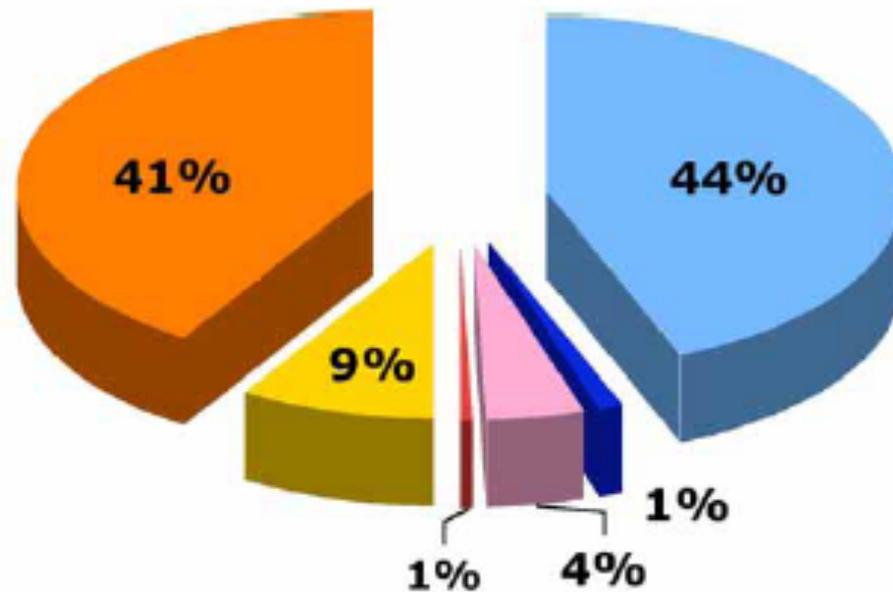
Rolf Ent

- Locate at Jefferson Laboratory, Newport News, VA
- 6GeV e⁻ at 200 μ A continuous current
- Nuclear physics, precision spectroscopy, etc



Research Machines: Just the Tip of the Iceberg

**Number of accelerators worldwide
~ 26,000**



Radiotherapy (>100,000 treatments/yr)*

Medical Radioisotopes

Research (incl. biomedical)

>1 GeV for research

Industrial Processing and Research

Ion Implanters & Surface Modification

Annual growth is several percent

Sales >3.5 B\$/yr

Value of treated good > 50 B\$/yr **



Example: Spallation Neutron Source (Oak Ridge, TN)

A 1 GeV Linac loads 1.5×10^{14} protons into a non-accelerating synchrotron ring.

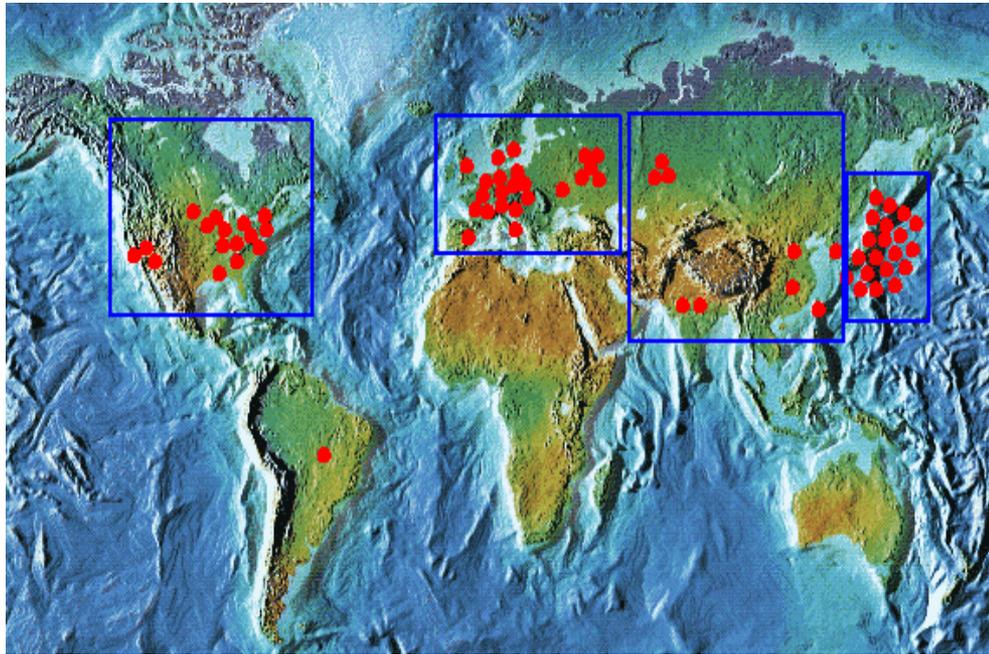


These are fast extracted onto a Mercury target

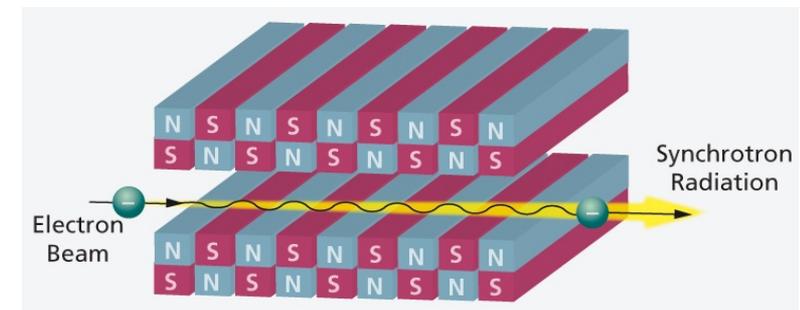
This happens at 60 Hz -> 1.4 MW

Neutrons are used for biophysics, materials science, industry, etc...

Light sources: too many to count



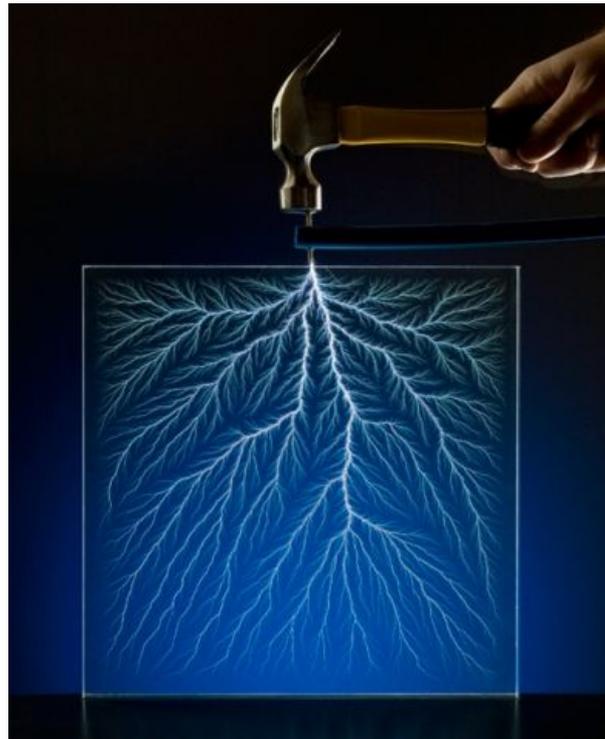
- ◎ Put circulating electron beam through an “undulator” to create synchrotron radiation (typically X-ray)
- ◎ Many applications in biophysics, materials science, industry.
- ◎ New proposed machines will use very short bunches to create coherent light.





Other uses of accelerators

- ◉ Radioisotope production
- ◉ Medical treatment
- ◉ Electron welding
- ◉ Food sterilization
- ◉ Catalyzed polymerization
- ◉ Even art...



In a “Lichtenberg figure”, a low energy electron linac is used to implant a layer of charge in a sheet of lucite. This charge can remain for weeks until it is discharged by a mechanical disruption.