Accelerators and High Energy Physics

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Student Visit

Understanding 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

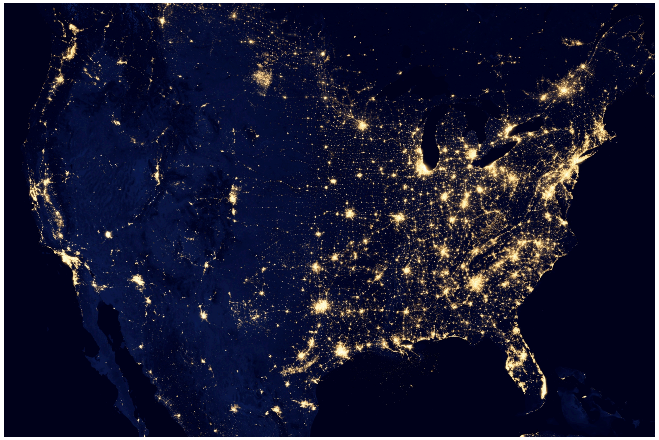
Chemical Explosion

.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.*

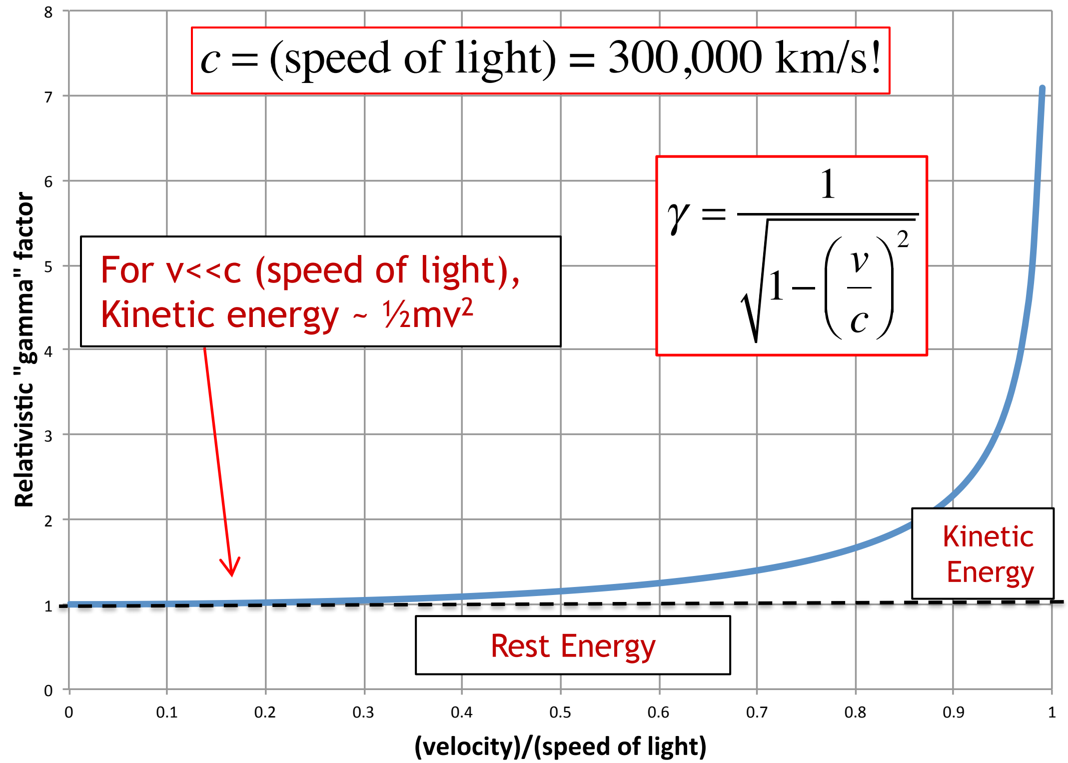


Kinetic Energy

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

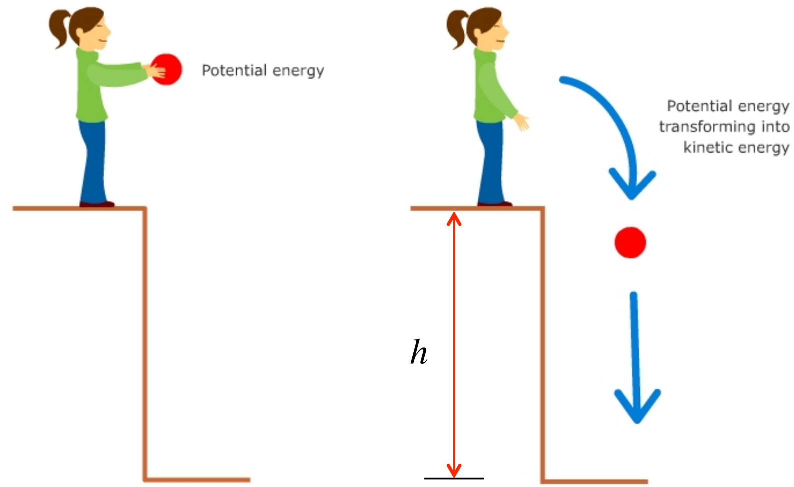
$$E = \frac{mc^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \equiv \gamma mc^2$$

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

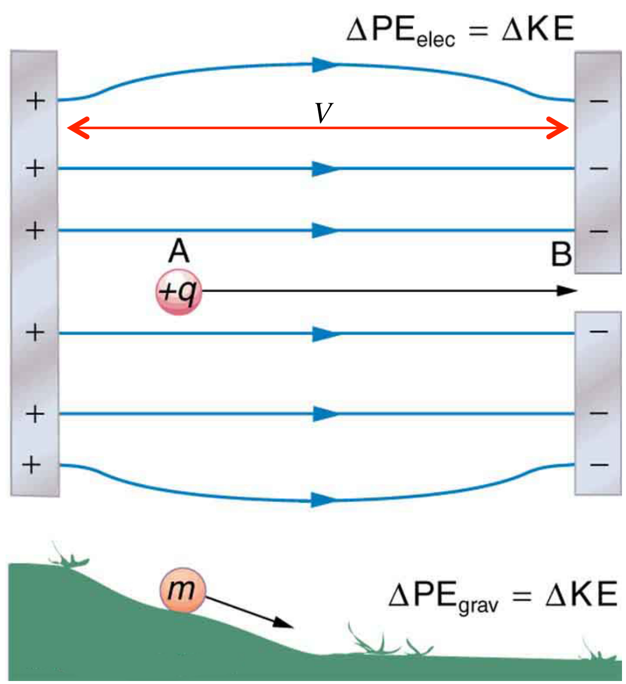


Units of Energy

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



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



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

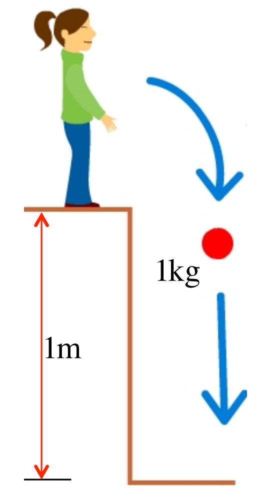
- In the same way, when we accelerate something in an electric field, electrical potential ("voltage") is converted to kinetic energy.
- For this reason, a convenient unit of energy is the

  "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} (=.00000000000000000016) Joules - our usual unit of energy.
  - A 1 kg weight dropped 1m would have 6×10^{18} eV of energy!



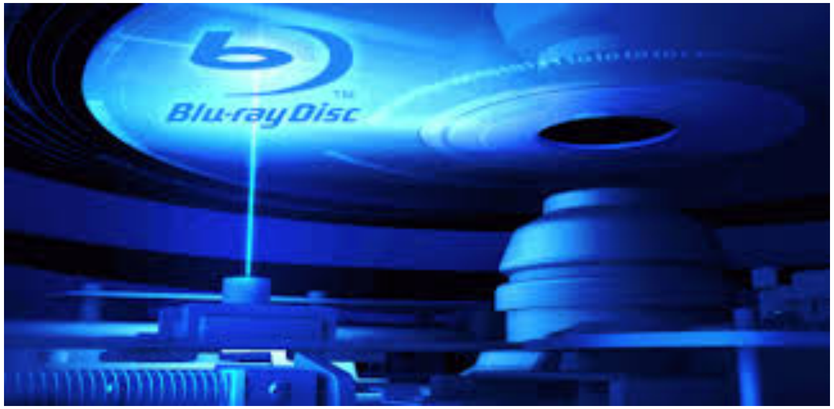
- On the other hand, it's a very useful unit when talking about individual particles
  - If we accelerate a proton using an electrical potential, we know exactly what the energy is.
  - It's also useful when thinking about mass/energy equivalence

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

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

Another way to look at energy…

- Question: Why are "blue ray" players blue?



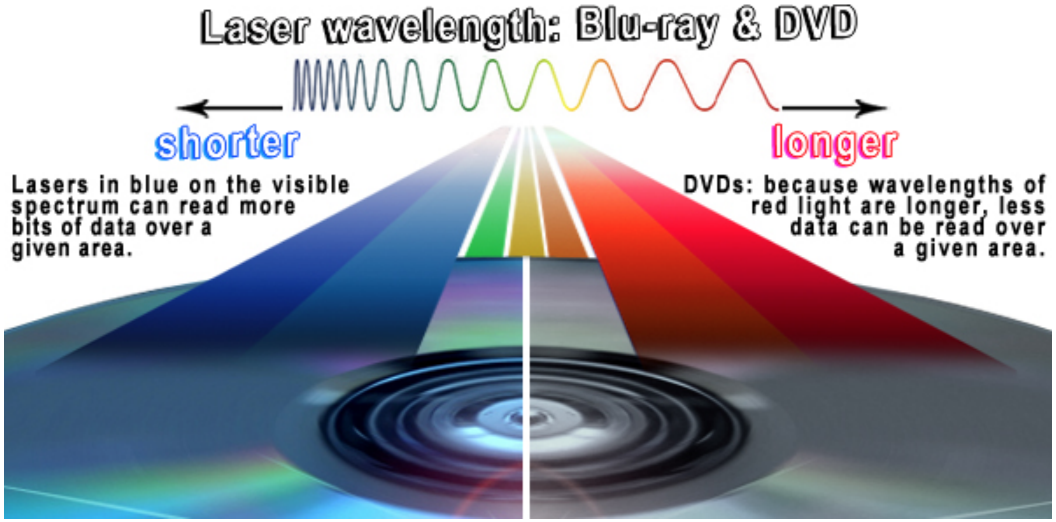
- Answer: because blue light is more energetic and has a shorter wavelengths, so the "bits" can be smaller

"Planck Constant" → h

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

wavelength → λ

Energy → E



Wavelengths of other particles

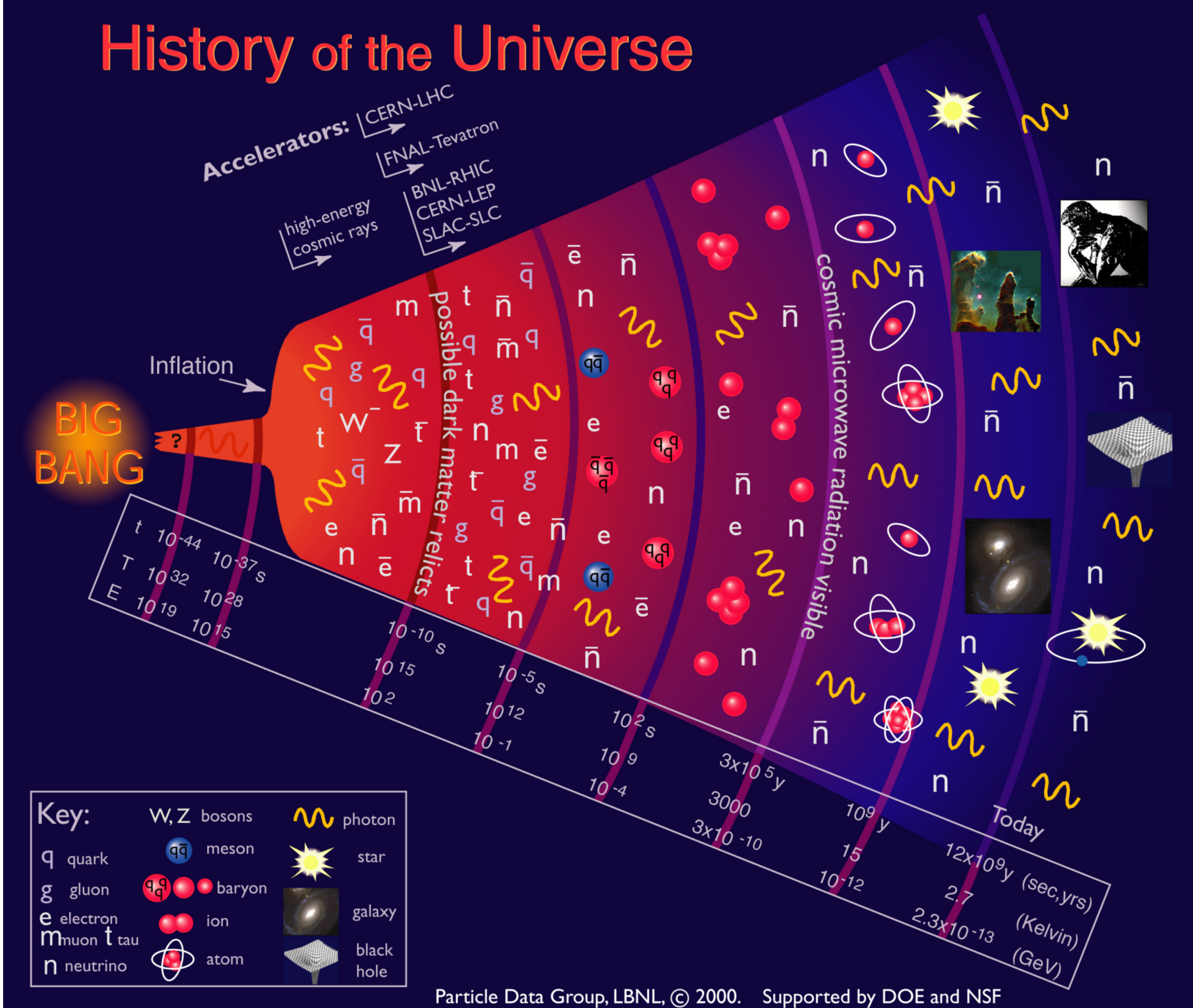
- It turns out that all particles have a wavelength

"Planck Constant" → h

$$\lambda = \frac{h}{p} \approx \frac{(\text{size of a proton})}{\text{Energy (in GeV)}}$$

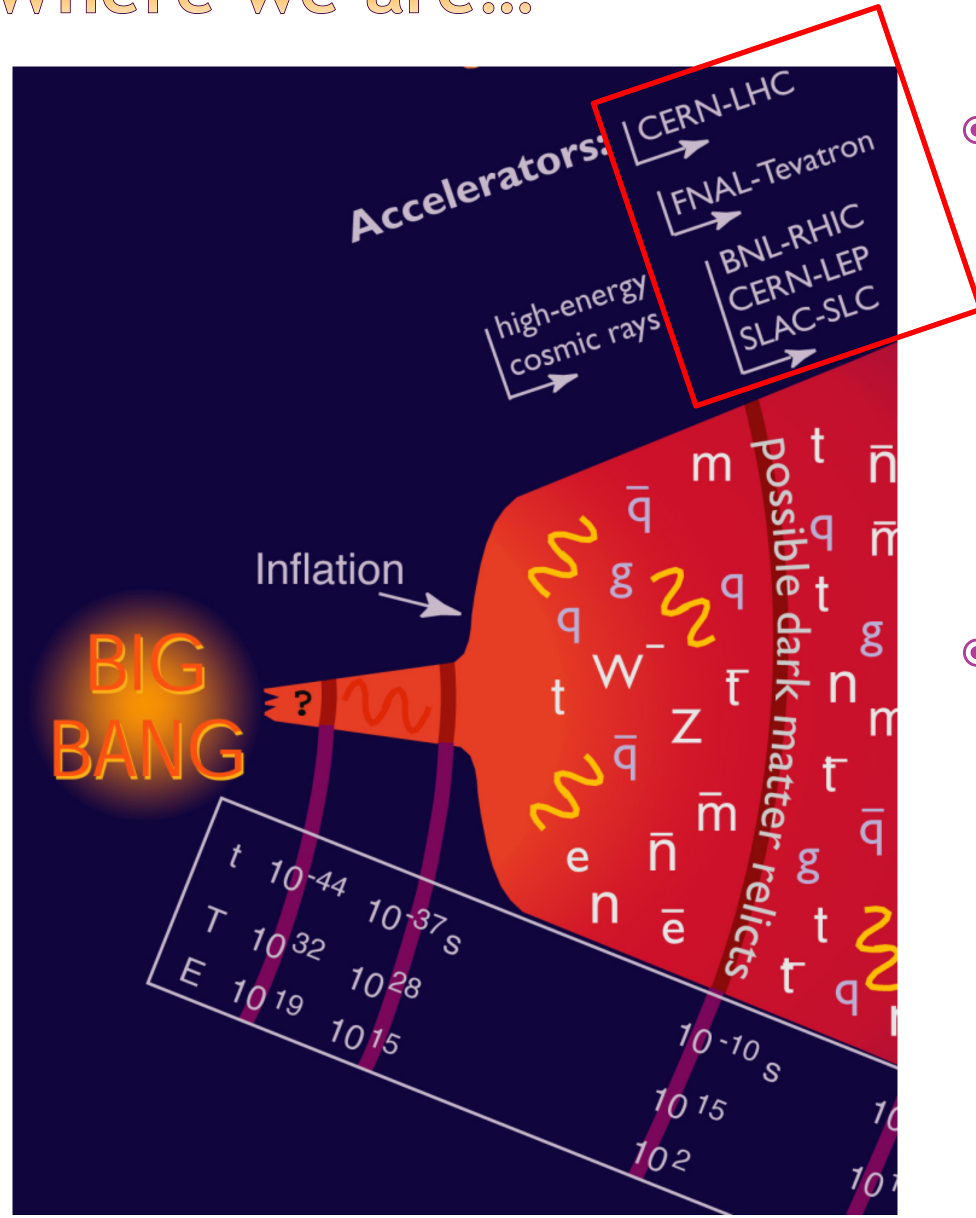
momentum → p

- 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…



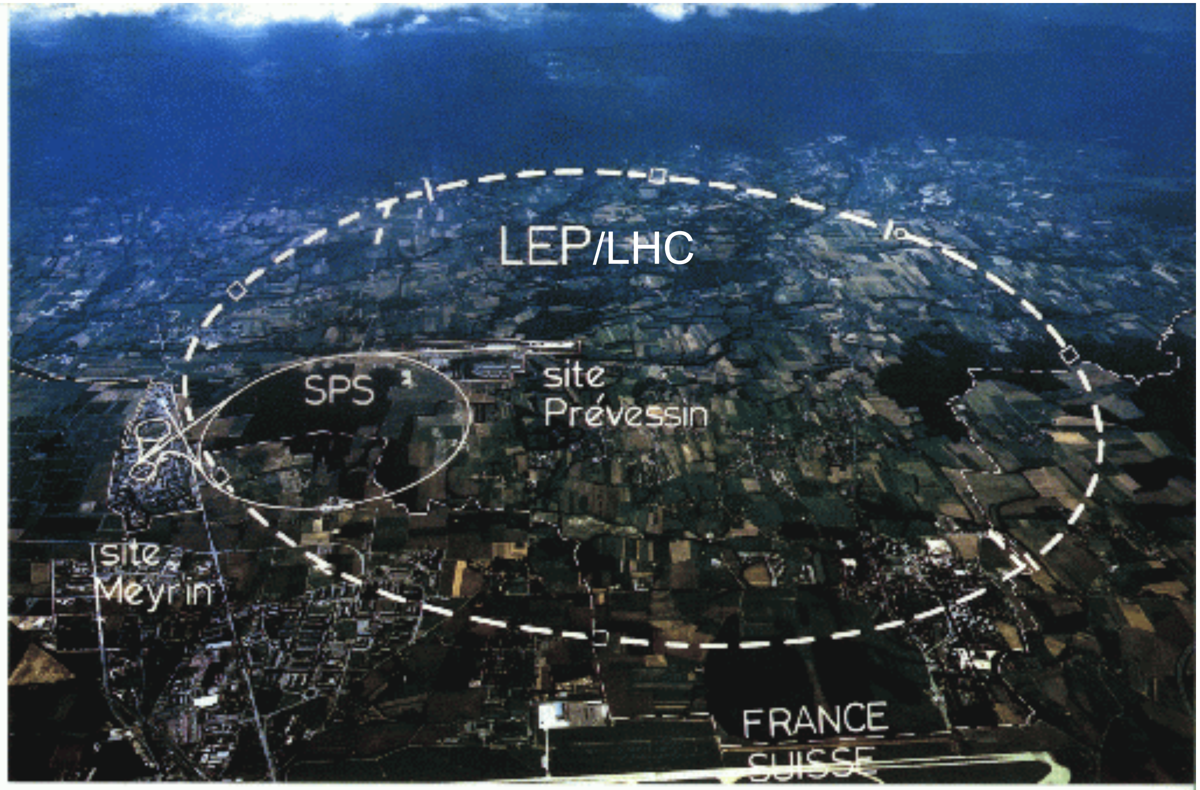
Going to higher energies = going back in time

Where we are…



- Accelerators allow us to go back 13.8 *billion years* and recreate conditions that existed a *few trillionths of a second* after the Big Bang
  - the place where our current understanding of physics breaks down.
- In addition to high energy, we need high "luminosity" that is, lots of particles interacting, to see rare processes.

State of the art: Large Hadron Collider (LHC)

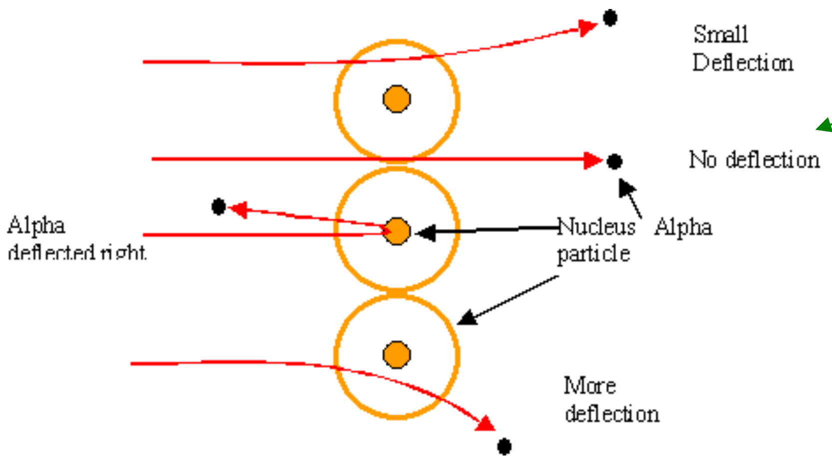


- Built at CERN, straddling the French/Swiss border
- 27 km in circumference
- Has collided two proton beams at 4000 GeV each
- In 2015, will reach design energy of 7000 GeV/beam.
- That’s where we are. Now let’s see how we got here…

Rewind: Some pre-history

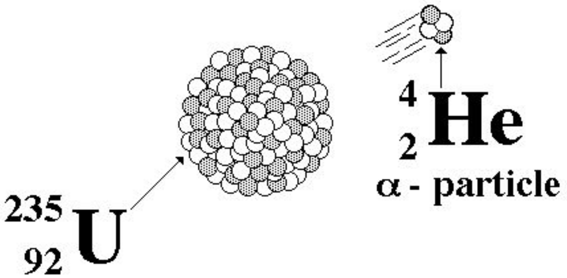
- The first artificial acceleration of particles was done using "Crookes tubes", in the latter half of the 19th century
  - These were used to produce the first X-rays (1875)
  - At the time no one understood what was going on

- The first "particle physics experiment" told Ernest Rutherford the structure of the atom (1911)



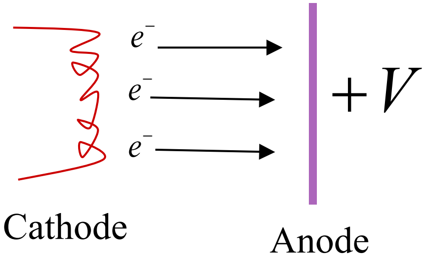
Study the way radioactive particles "scatter" off of atoms

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



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

FNAL Cockroft-Walton = 750 kV

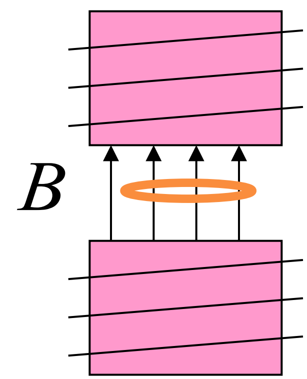
Solutions:

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

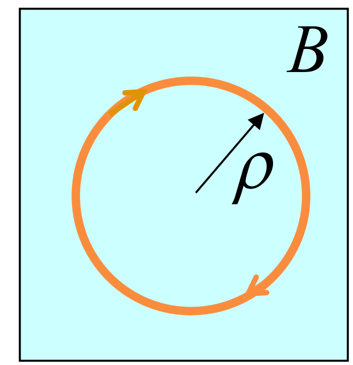
The Cyclotron (1930s)

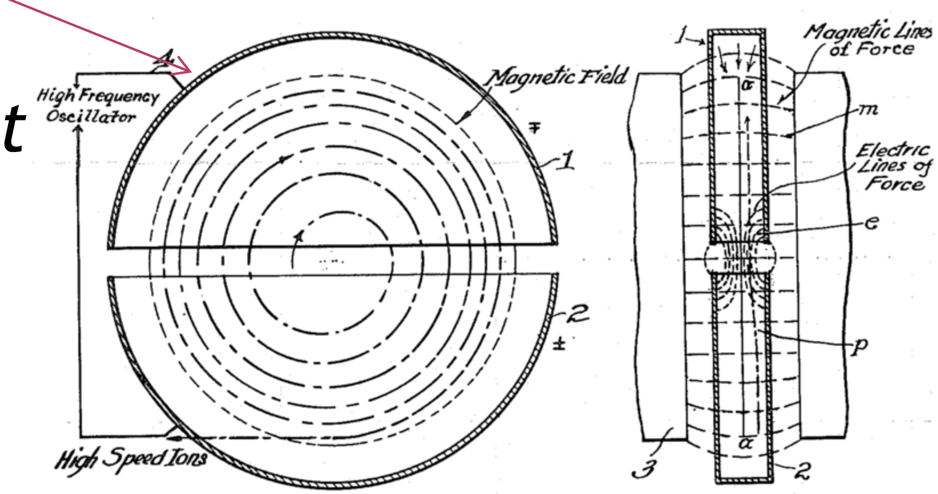
- A charged particle in a magnetic field will follow a circular path
- Can accelerate particles by alternating the voltage on two accelerating "DEES"
- Can get to high energies by adding just *a little bit* of energy each time around.

side view



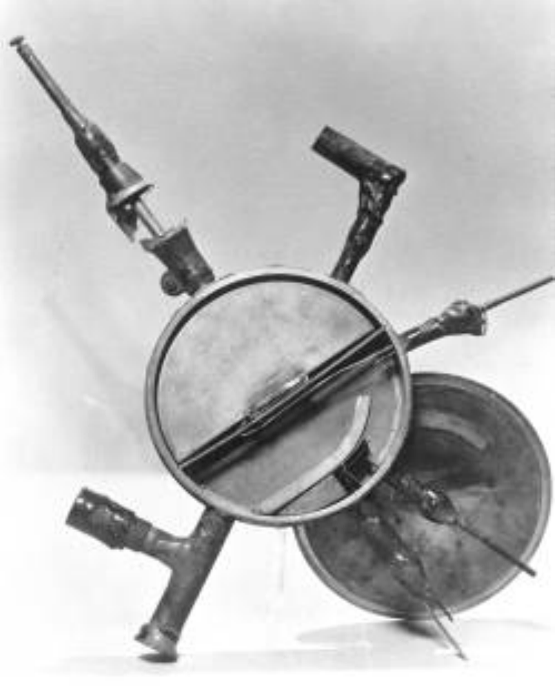
top view





Accelerating "DEES"

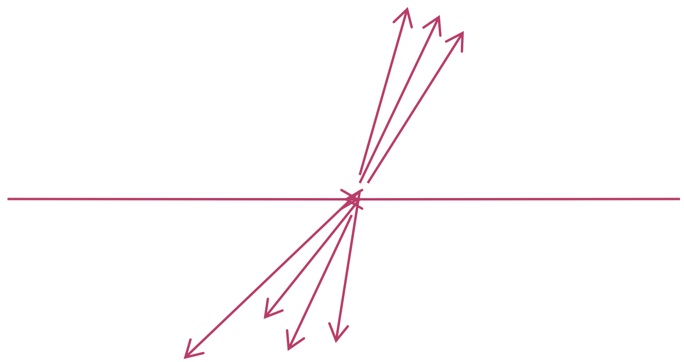
Round we go: the first cyclotrons



- ~1930 (Berkeley)
  - Lawrence and Livingston
  - K=80keV

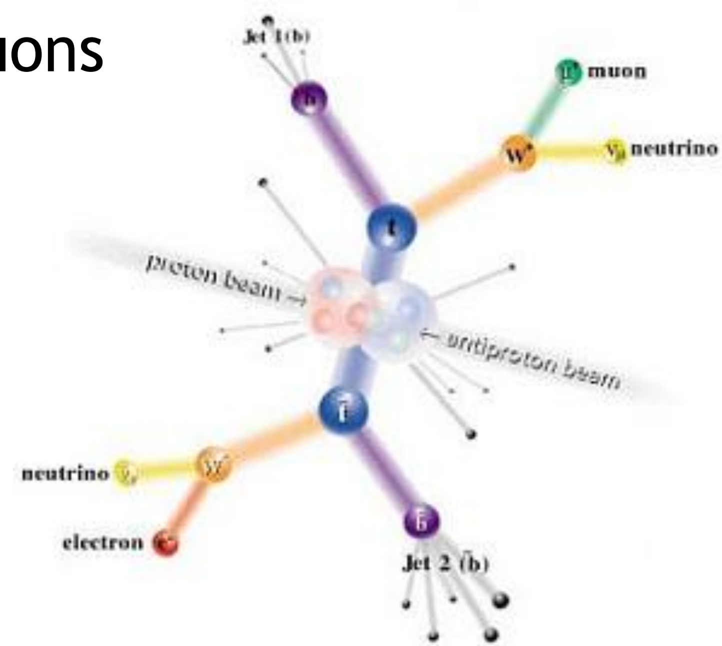
- 1935 - 60” Cyclotron
  - Lawrence, et al. (LBL)
  - ~19 MeV (D_2)
  - Prototype for many

Interlude: Electrons vs. Protons



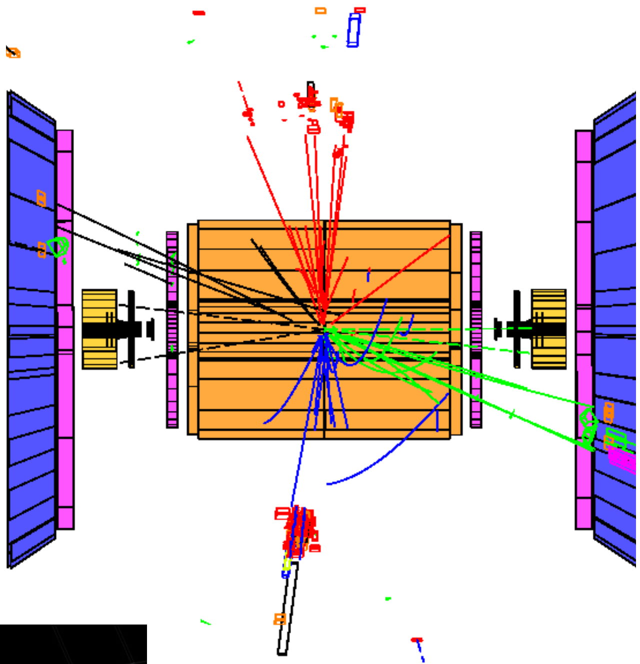
- Electrons are point-like
  - Well-defined initial state
  - Full energy available to interaction

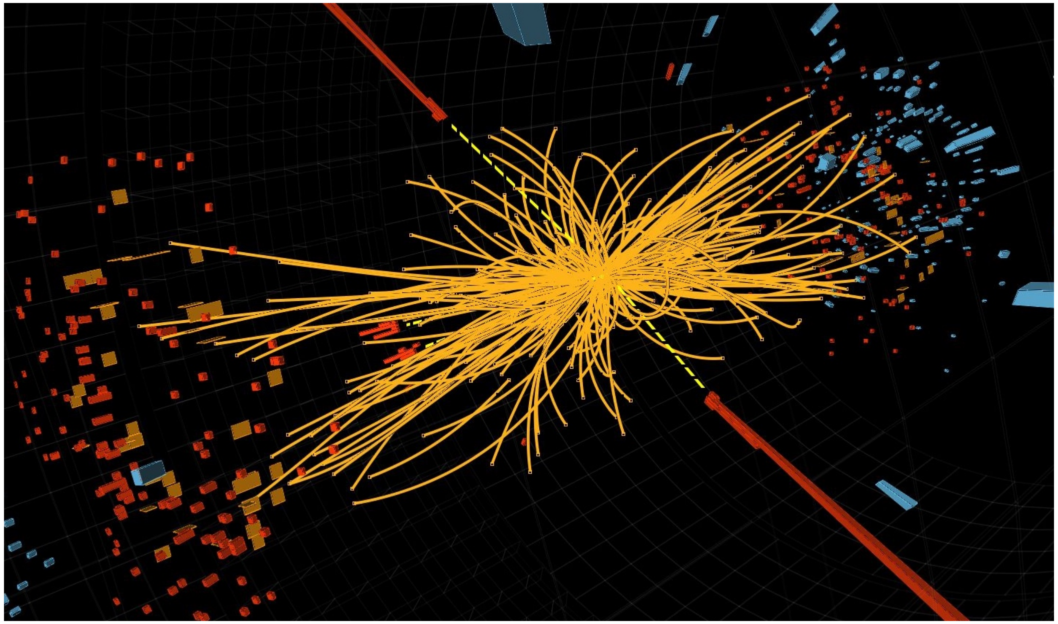
- Protons are made of quarks and gluons
  - Interaction take place between these consituents.
  - Only a small fraction of energy available, not well-defined.
  - Rest of particle fragments -> big mess!



Examples

e^+e^- collision at the LEP collider



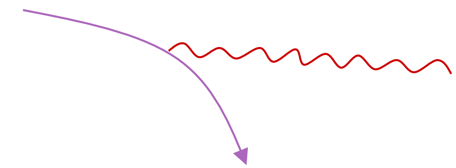


proton-proton collision at the LHC collider

So why don't we stick to electrons??

Synchrotron Radiation

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



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

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 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.

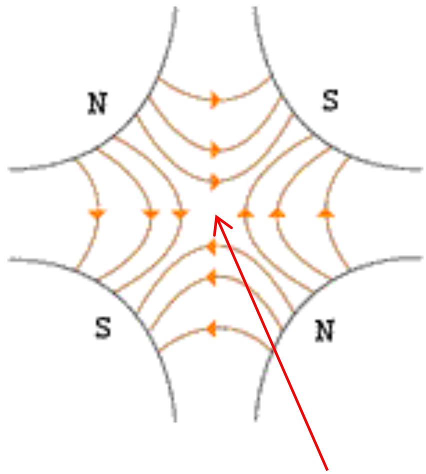
Since the beginning, the energy frontier has belonged to proton (and/or antiproton) machines

Onward and Upward!

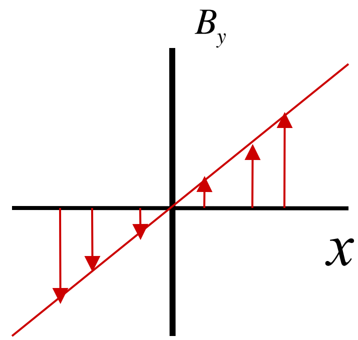
- Two major advances allowed accelerators to go beyond the energies possible at cyclotrons
  - "Synchrotron" – in which the magnetic field is increased as the energy increases, such that particles continue to follow the same path.
    - Edward McMillan, 1945
  - "Strong focusing" – a technique in which 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*

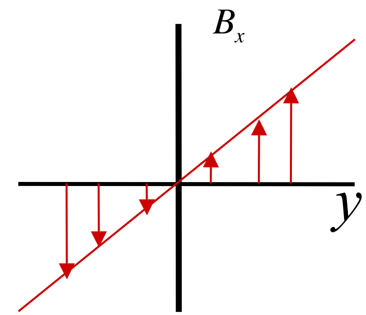
*actually invented in 1949 by a Greek-American electrical engineer name Nicholas Christofilos, but it was completely ignored at the time!

Strong focusing: quadrupole magnets as lenses



All fields cancel at the center



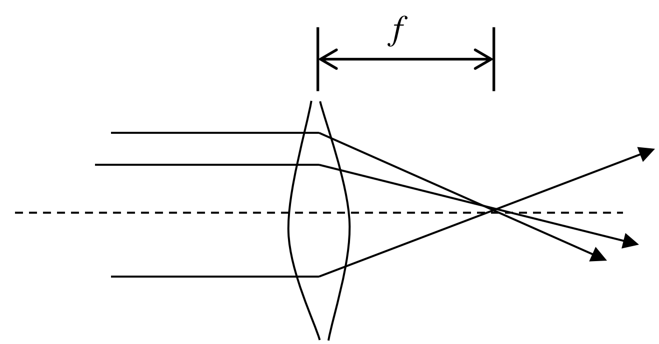


$$B_y = B'x \qquad B_x = B'y$$

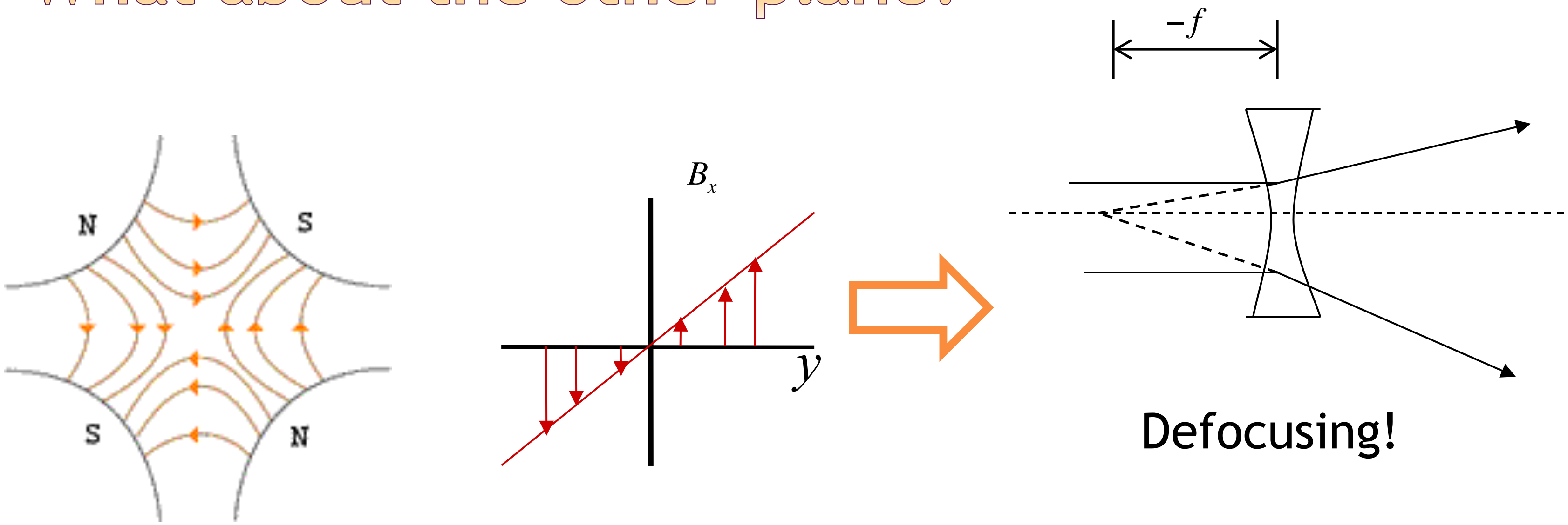
$$B' \equiv \text{"gradient"}$$

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

Just like a "thin lens" in classical optics

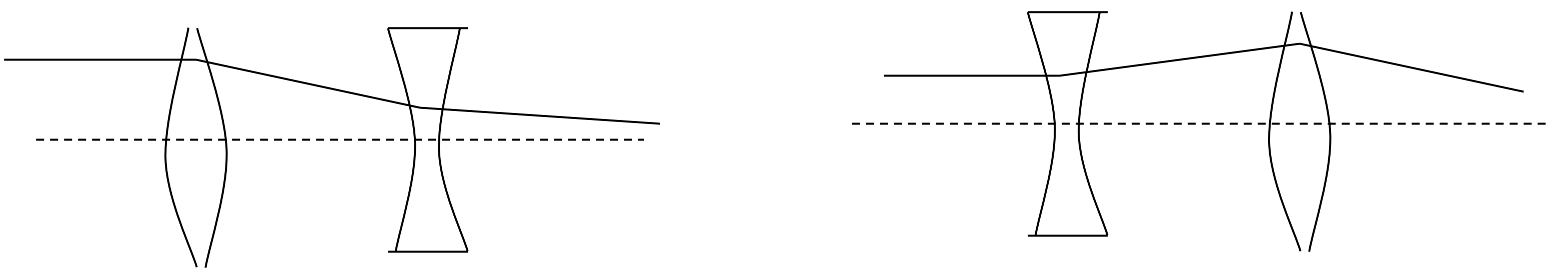


What about the other plane?



Defocusing!

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

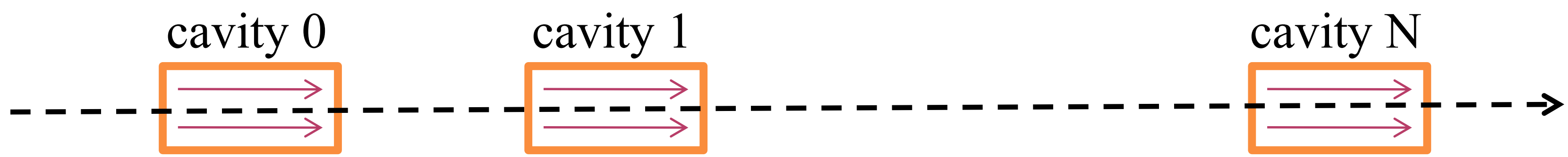


➔pairs give net focusing in *both* planes -> “FODO cell”

The fundamental building block of synchrotrons and beam lines!

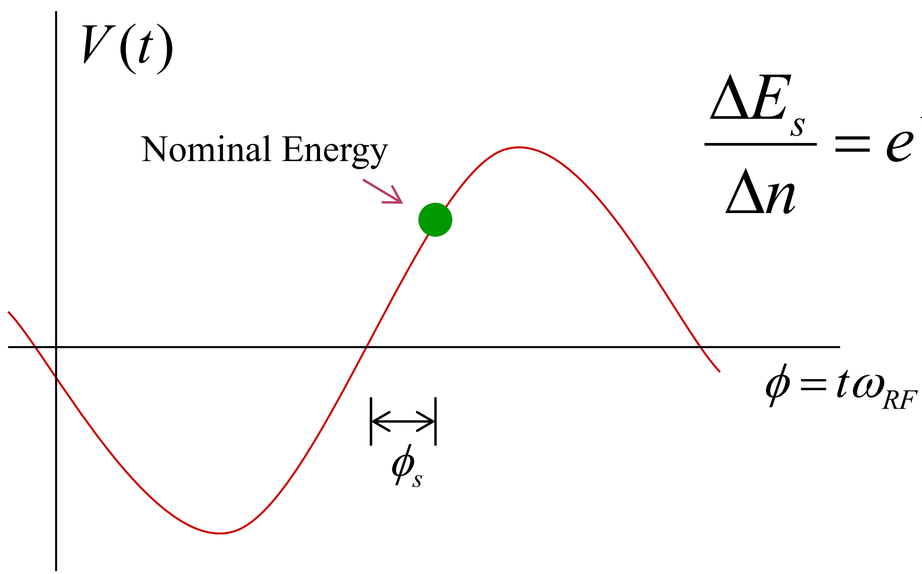
Longitudinal motion (acceleration)

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

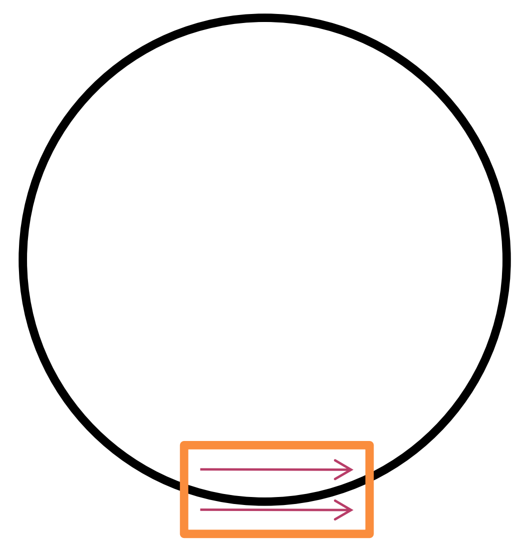


or located within a circulating ring

- 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



$$\frac{\Delta E_s}{\Delta n} = eV_0 \sin\phi_s$$



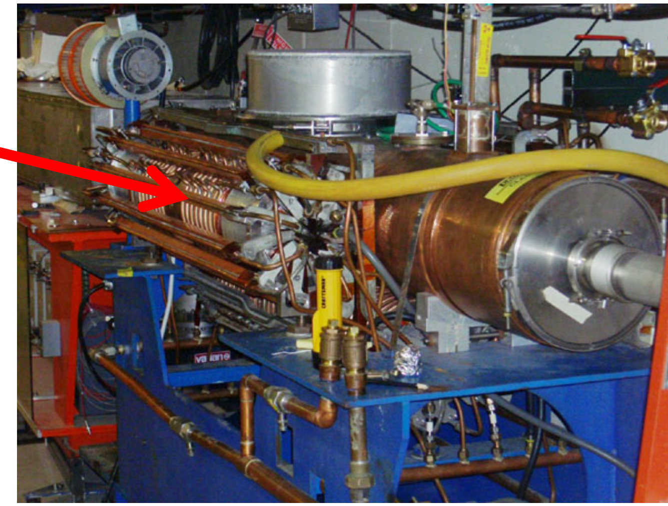
Examples of accelerating RF structures

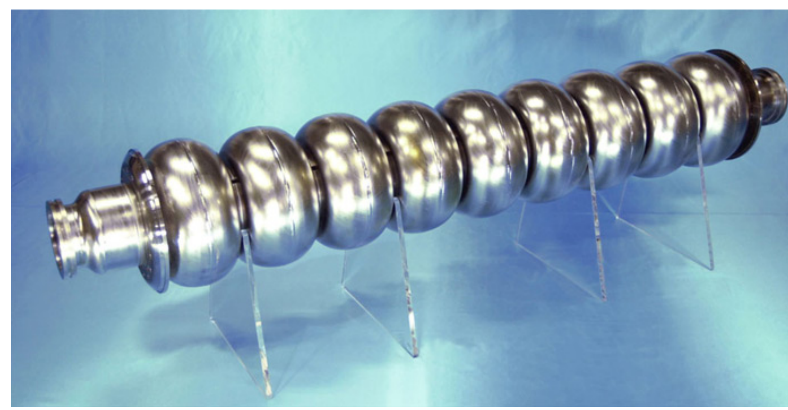
Use resonant structures to make efficient use of power

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

37->53MHz Fermilab Booster cavity

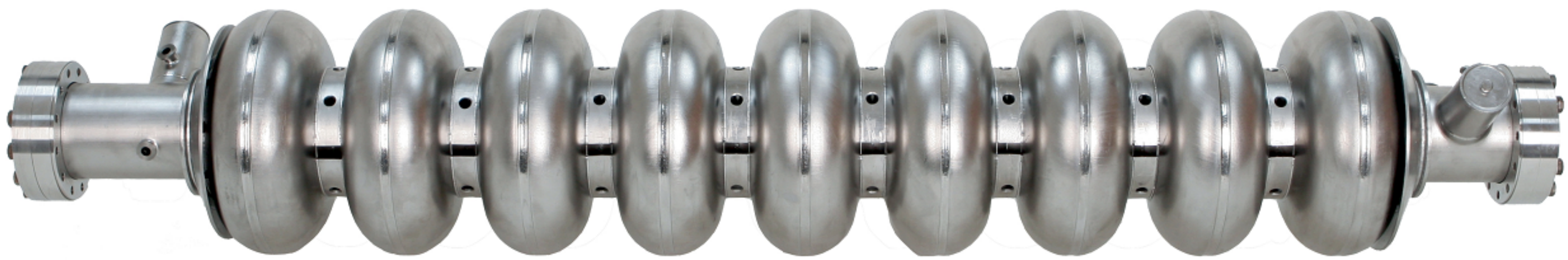
Biased ferrite frequency tuner





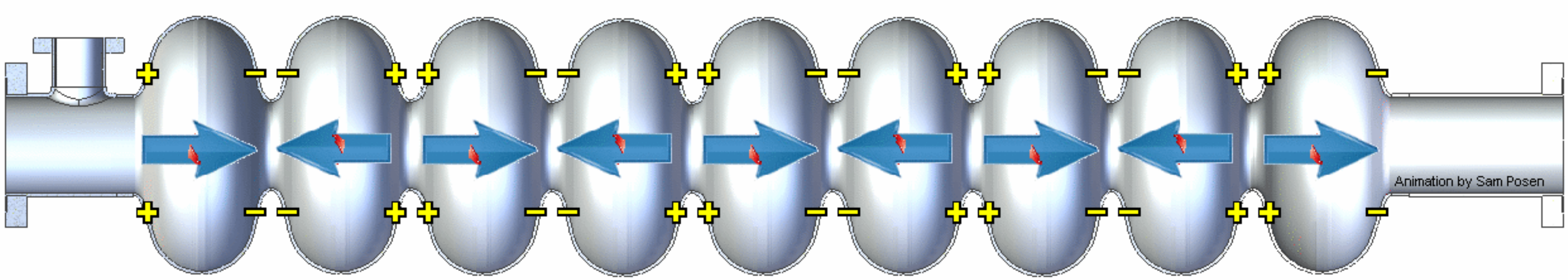
ILC prototype elipical cell "π-cavity" (1.3 GHz): field alternates with each cell

How RF Cavities Accelerate*



Input RF power at 1.3 GHz

Slowed down by factor of approximately 4x10^9



~1 m

*Animation from Sam Posen

Colliding Beams

- Two cars hitting each other at 60 mph…

- …is about the same as one car going 120 mph hitting a parked car.

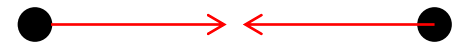
- But things get very different as we approach the speed of light…

The Case for Colliding Beams

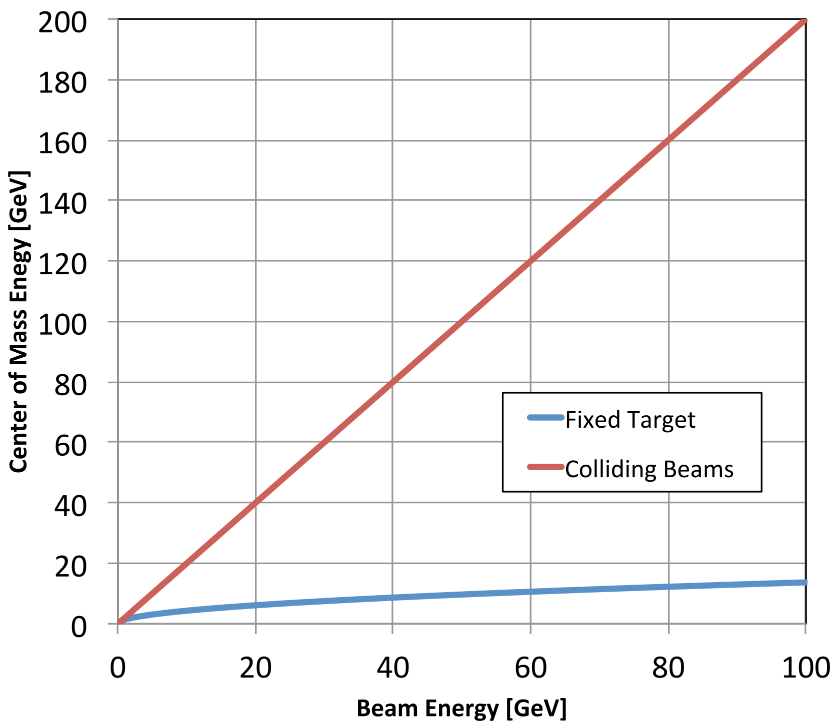
- Beam hitting a stationary proton, the "center of mass" energy is

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

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

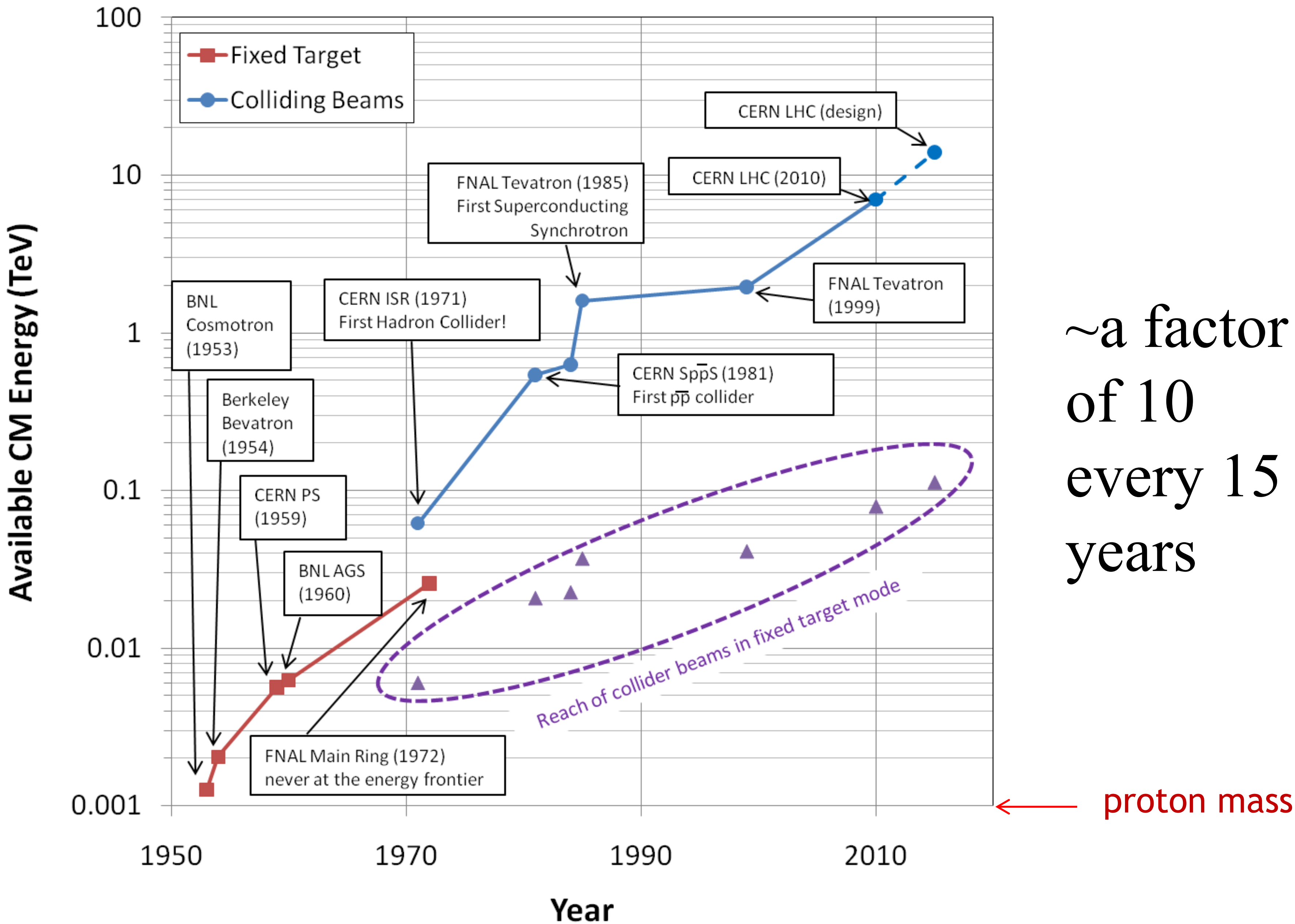


$$E_{CM} = 2E_{beam}$$



- 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!!*

Evolution of the Energy Frontier

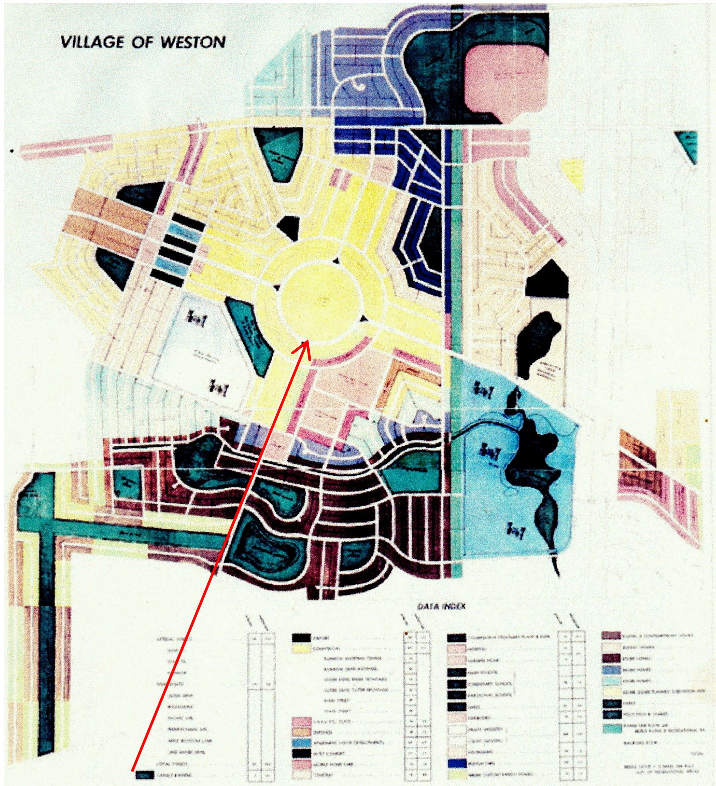


~a factor of 10 every 15 years

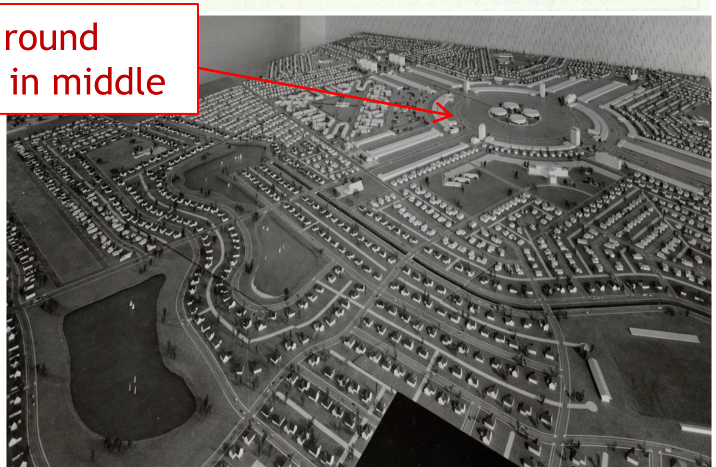
Fermilab: Early History

- 1963 – Committee chaired by Norman Ramsey recommends the construction of a 200 BeV synchrontron
  - to be located at Berkeley (of course)
- 1965 - Joint Committee on Atomic Energy (JCAE) and the National Academy of Sciences (NAS) endorse the Ramsey Report
  - but as a "National Accelerator Lab", with a nation-wide site selection.
- 1966 – Weston, IL chosen as the site
- 1967 – Cornell physicist Robert Wilson named first director
- 1968 – Construction of NAL begins
- 1972 – First 200 GeV beam in the Main Ring (400 GeV later that year)
  - Extracted to three fixed target, experimental beam lines: Meson, Neutrino, and Proton
- 1974 – Iconic "High Rise" completed. Lab dedicated to Enrico Fermi, and renamed "Fermi National Accelerator Laboratory"
  - Fermi's widow, Laura, attended the ceremony

What Was Weston?



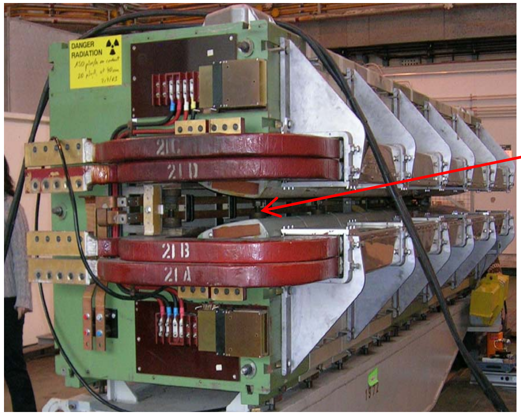
Note round thing in middle



- In 1964, developer William Riley began construction of Weston, IL, a planned community with houses, apartments, parks, churches, and shopping centers.
- The development went bankrupt less than a year later, after the completion of only a small portion.
- Local politicians convinced the state to propose the site for to the AEC for the new National Accelerator Lab
  - Residents did not realize they would have to move!
- In 1996, Weston site was chosen out of 126 proposals with over 200 sites.
- The small completed part became the Fermilab Village.
- Since it was the 60s, the mob had of course been involved. Faced with bankruptcy and threats, Riley testified against them and subsequently disappeared into witness protection.

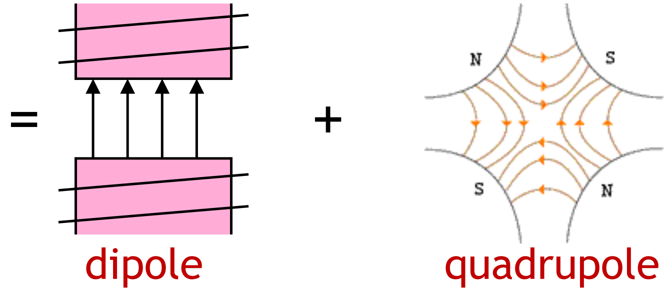
Main Ring: First Separated Function Synchrotron

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

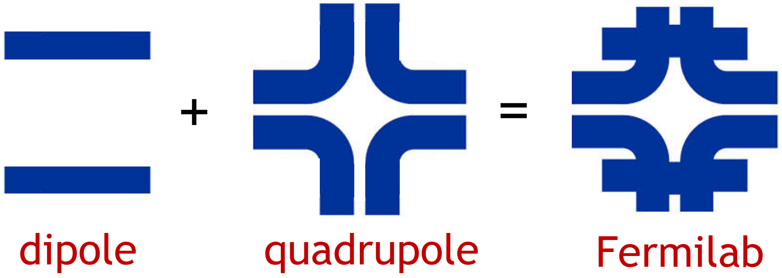


CERN PS (1959, 29 GeV)

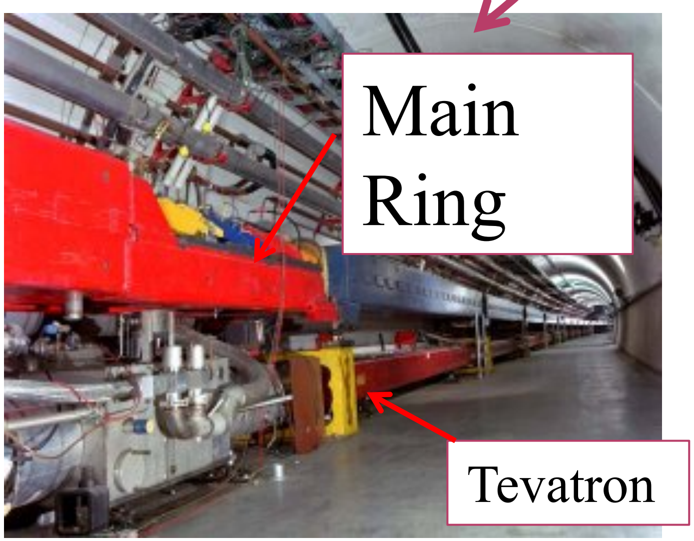
$$B_y(x) = B_0 + B_1 x$$



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

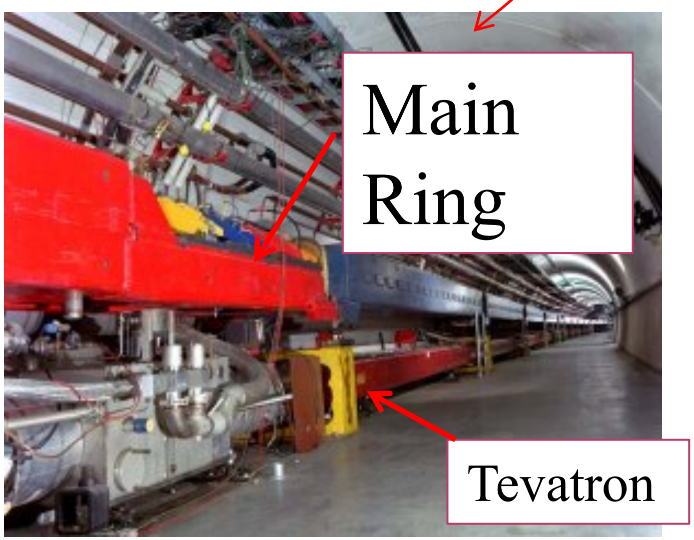


Tevatron: First Superconducting Synchrotron



- 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

Tevatron: First Superconducting Synchrotron

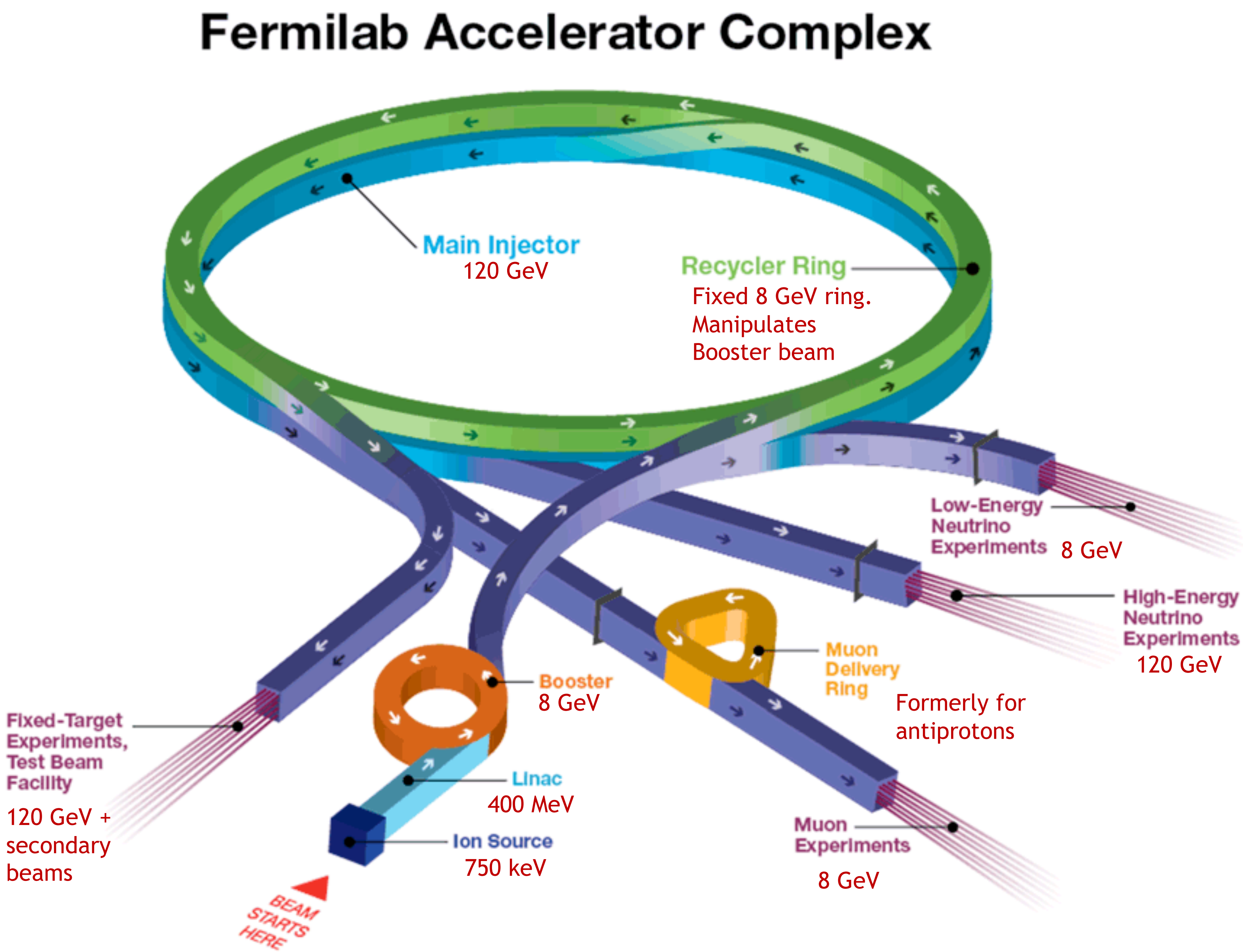


- From the beginning, Wilson was making plans for a superconducting ring to share the tunnel with the Main Ring
  - Dubbed "Saver Doubler" (later "Tevatron")
- 1982 – Magnet installation complete
- 1985 – First proton-antiproton collisions observed at CDF (1.6 TeV CoM). Most powerful accelerator in the world for the next quarter century
  - Alternated collider and fixed target program.
- 1995 – Top quark discovery
- Late 1990's – major upgrades to increase luminosity, including separate ring (Main Injector) to replace Main Ring
  - Also removed extraction hardware to eliminate Tevatron fixed target program.
- 1999 – Tevatron Energy reaches 1.96TeV CoM energy
- 2011 – Tevatron shut down after successful LHC startup

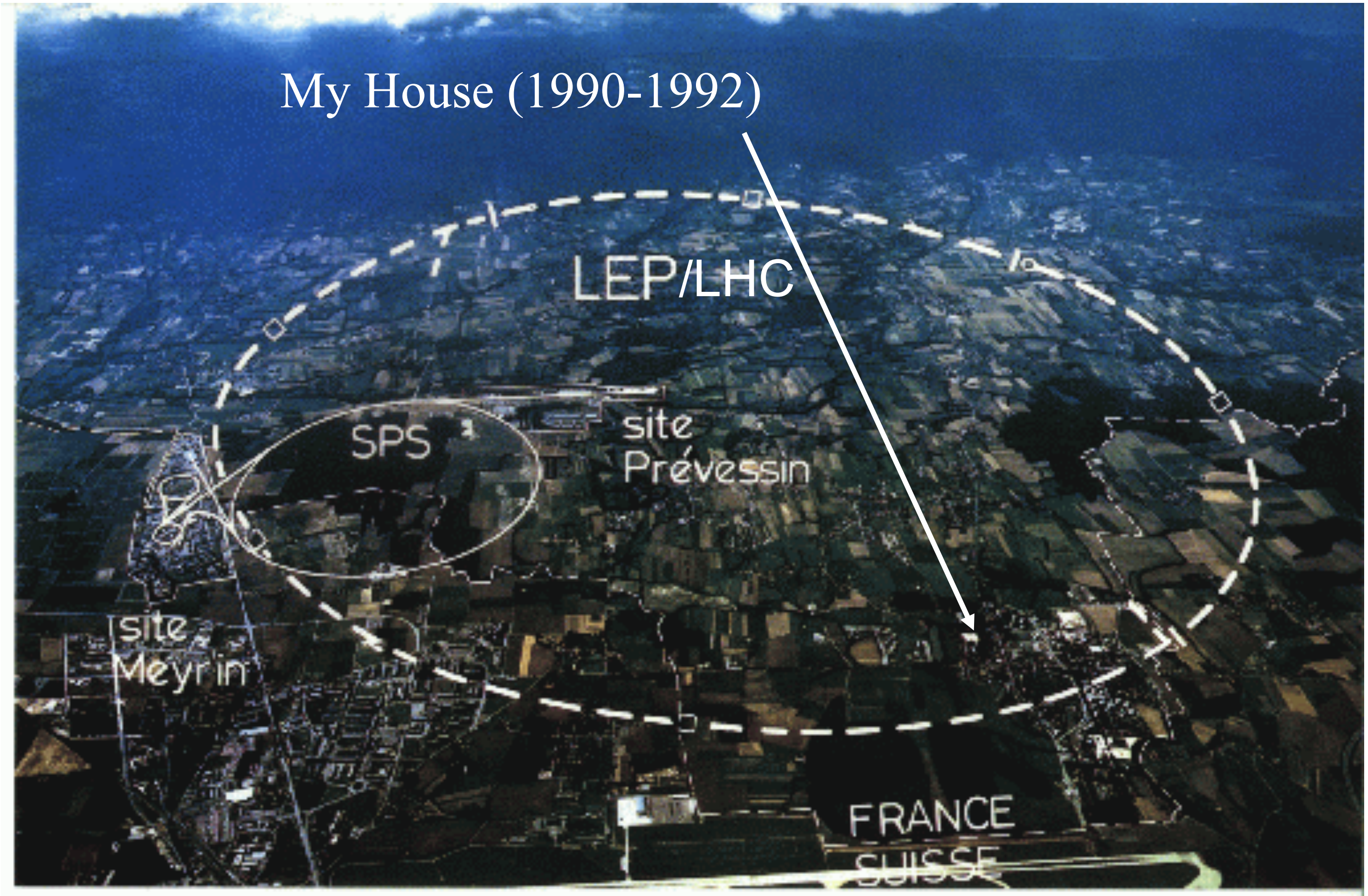
Fermilab Firsts and Records

- Firsts:
  - First separated function synchrotron:
    - Main Ring, 1972
  - First superconducting synchrotron/collider
    - Tevatron, 1983 (first collisions in 1986)
  - First permanent magnet storage ring
    - Recycler, 2000
- Records:
  - Highest energy proton beam
    - Main Ring, 1972 (breaks AGS record)➔1983 (broken by Tevatron)
    - Tevatron, 1983-2008 (broken by LHC)
  - Highest energy hadron collider
    - Tevatron, 1986 (breaks SppS record)➔2009 (broken by LHC)
  - Highest hadronic luminosity
    - Tevatron, 2005 (broke ISR *p-p* record!) ➔ 2011 (broken by LHC)
  - Highest energy p-pbar collider
    - Tevatron, 1986 (breaks SppS record)➔ present
  - Highest p-pbar luminosity
    - Tevatron, 1992 (broke SppS record)➔ present

Example: Fermilab complex today

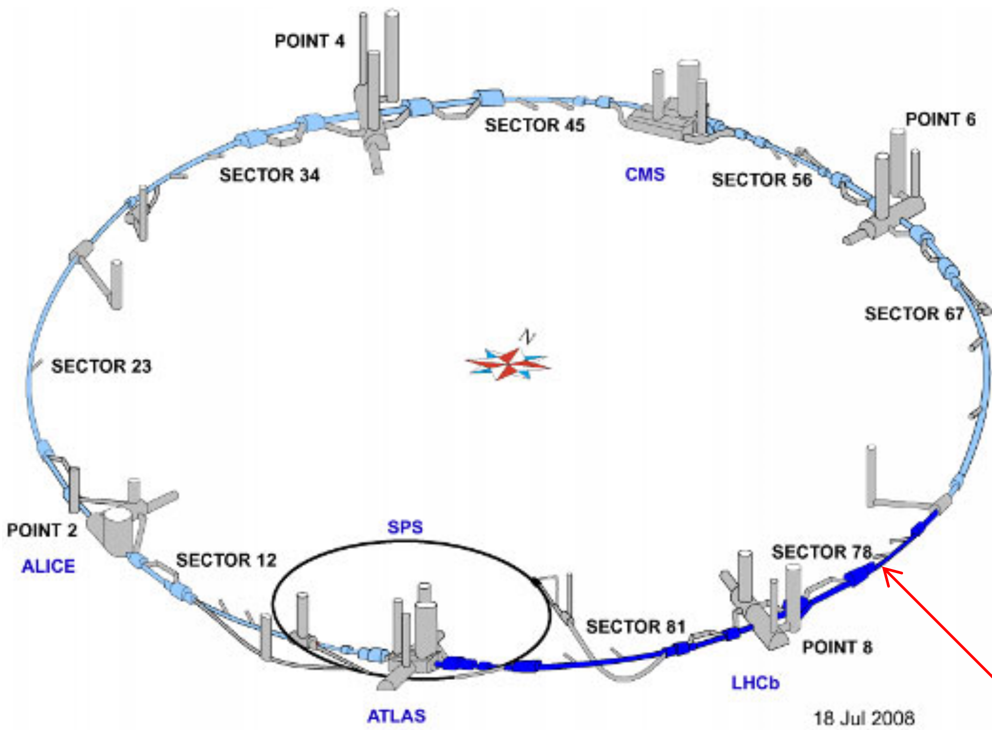


LHC: Location, Location, Location…



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

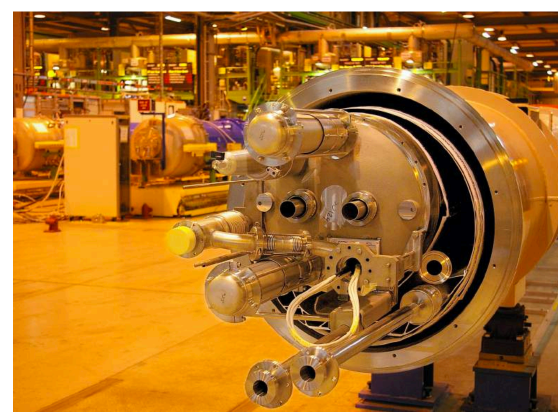
LHC Layout and Numbers



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

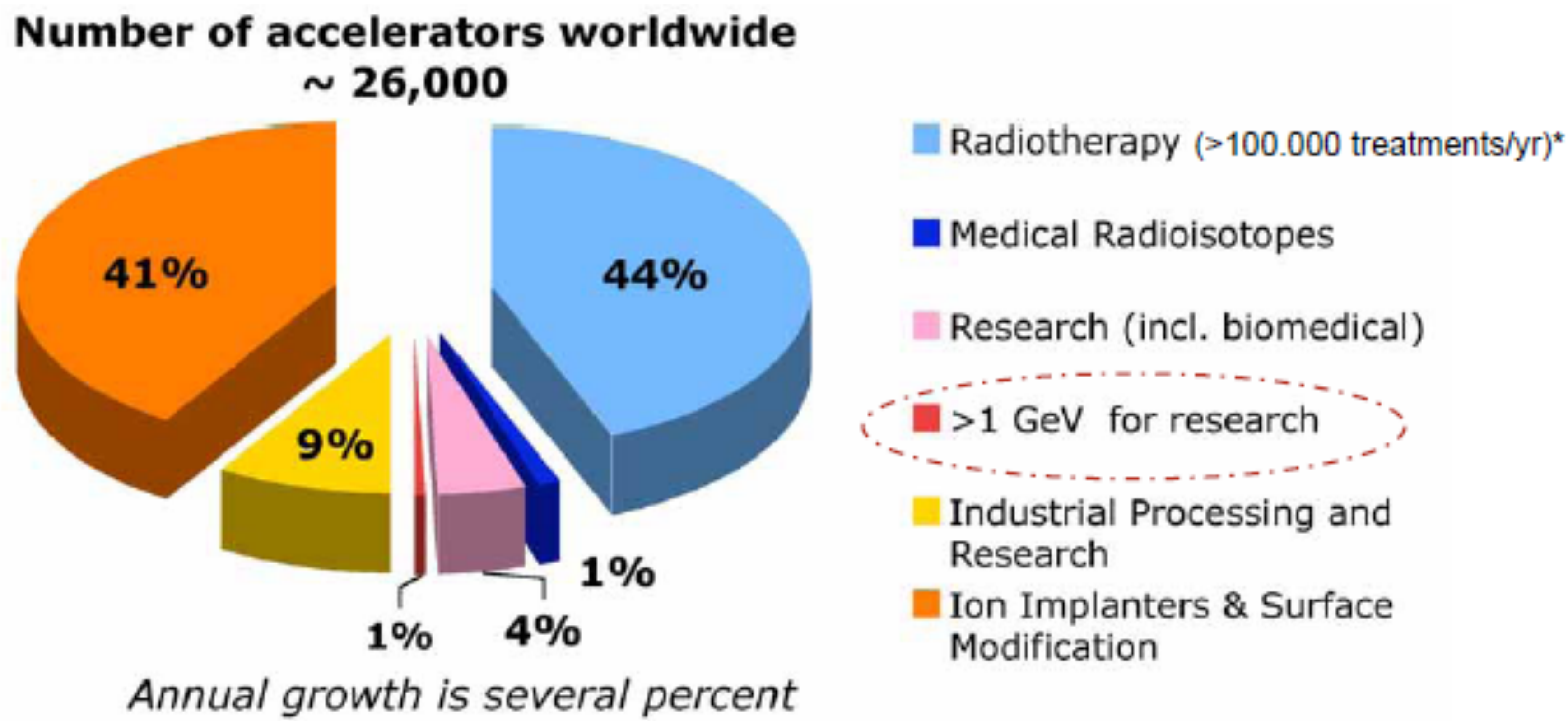
Design:

- 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!



Just the Tip of the Iceberg

Energy frontier machines have always driven the technology, which has then been applied to many other things…



Sales >3.5 B$/yr

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

Example: Spallation Neutron Source (Oak Ridge, TN)

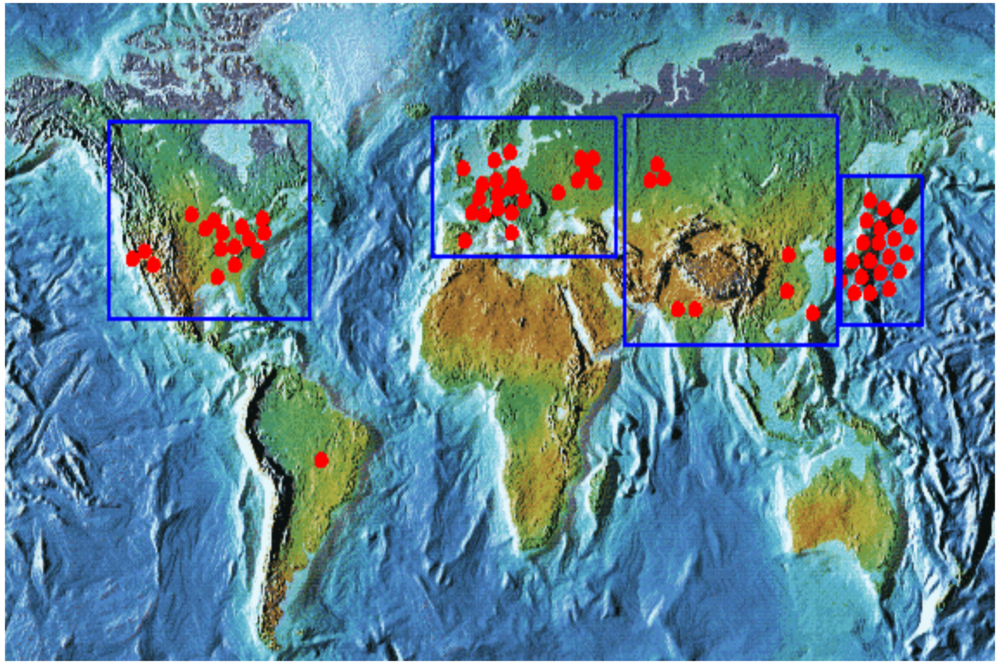
A 1 GeV Linac loads 1.5E14 protons into a non-accelerating synchrotron ring.

These are fast extracted onto a Mercury target

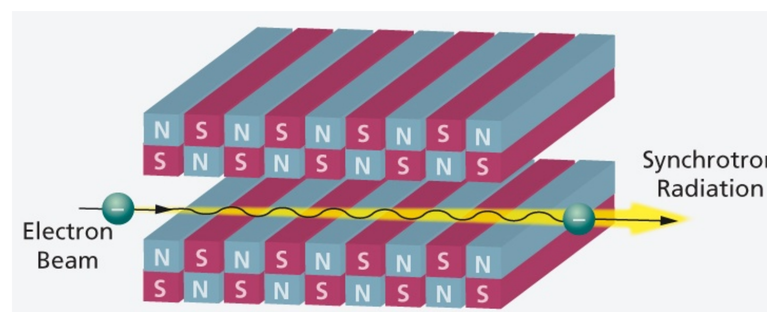
This happens at 60 Hz -> 1.4 MW

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

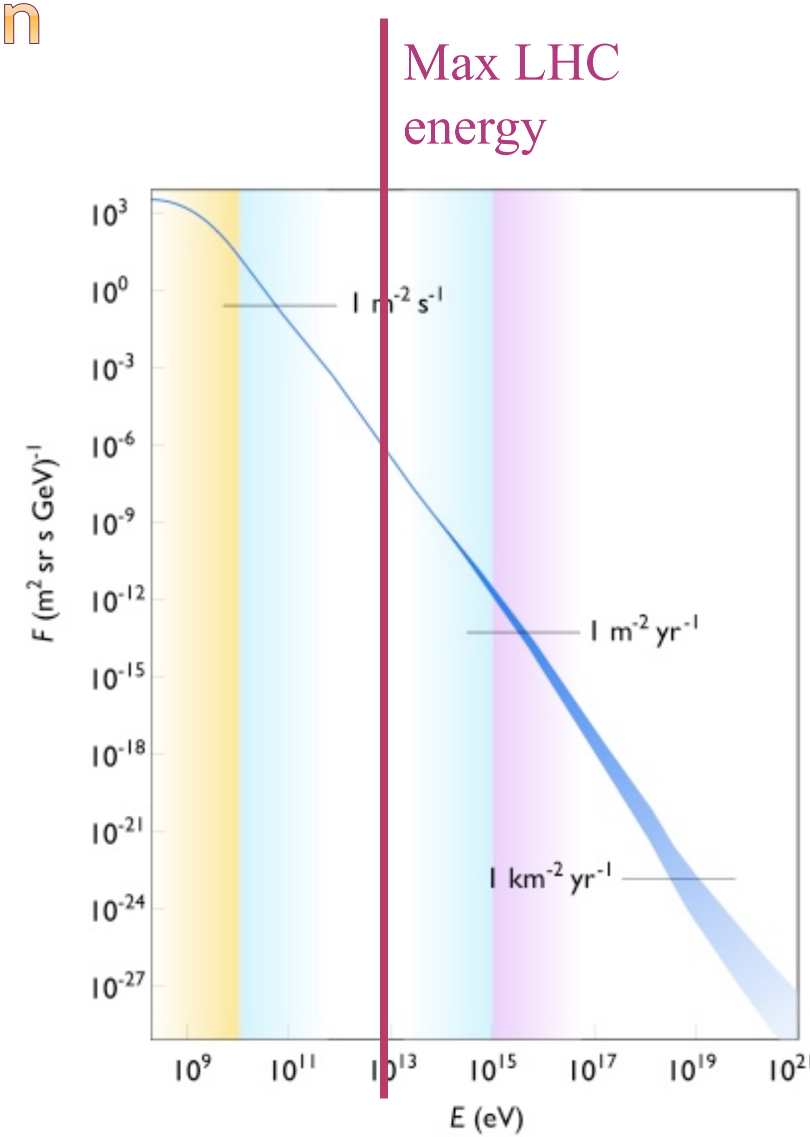
- Radioisotope production
- Medical treatment
- Electron welding
- Food sterilization
- Catalyzed polymerization
- Even art…

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.

BACKUPS

Natural particle acceleration

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



Weak focusing

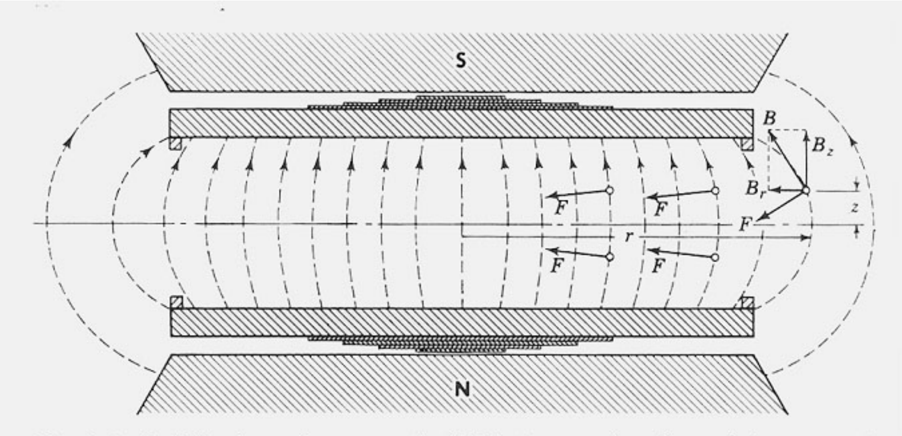
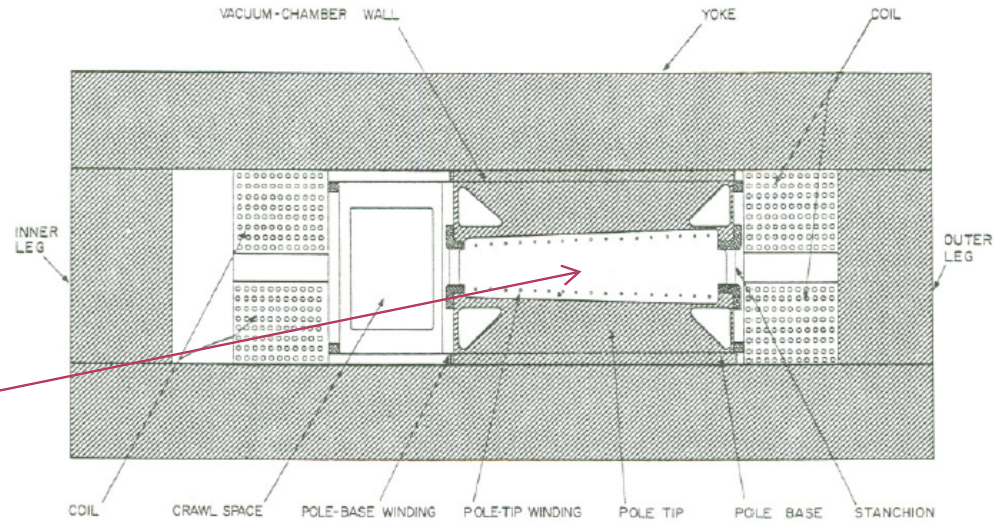
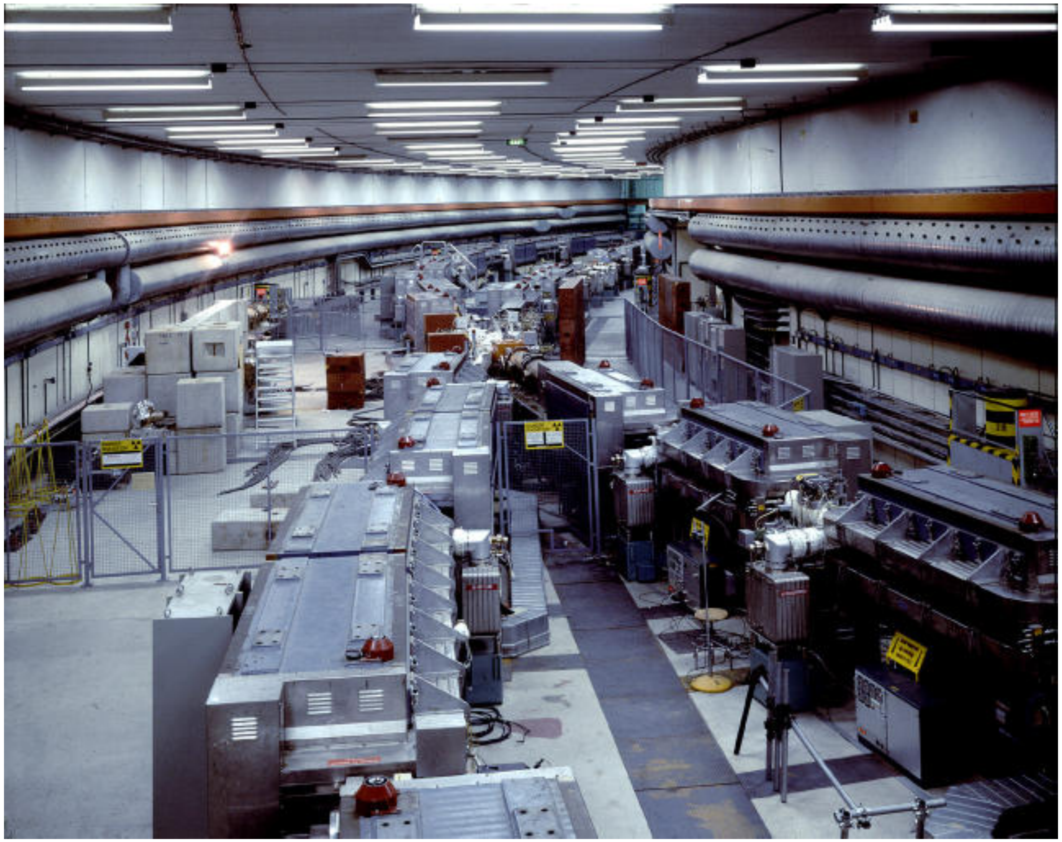


Fig. 6-7. Radially decreasing magnetic field between poles of a cyclotron magnet, showing shims for field correction.

- 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 most famous weak focusing accelerator was the Berkeley Bevatron, which had a kinetic energy of 6.2 GeV
  - High enough to make antiproton (and win a Nobel Prize)
  - It had an aperture 12"x48"!

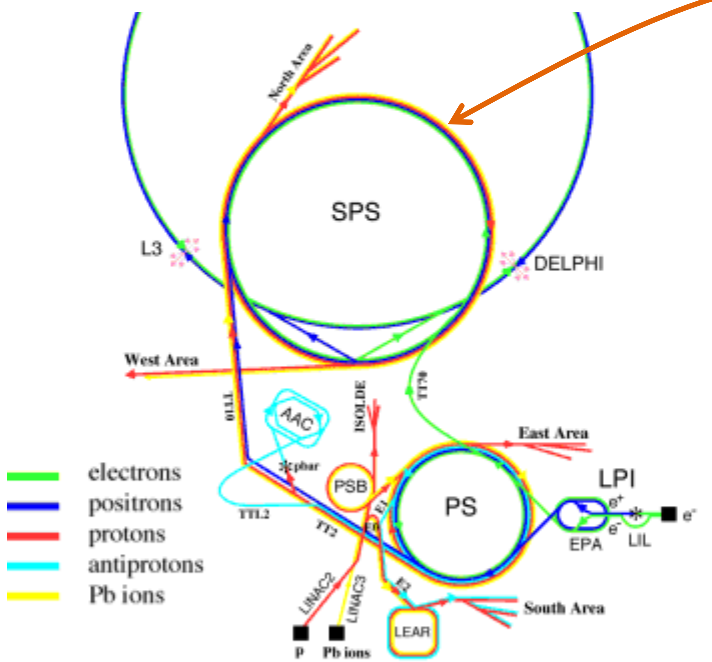


First Proton Collider: CERN Intersecting Storage Rings (ISR)



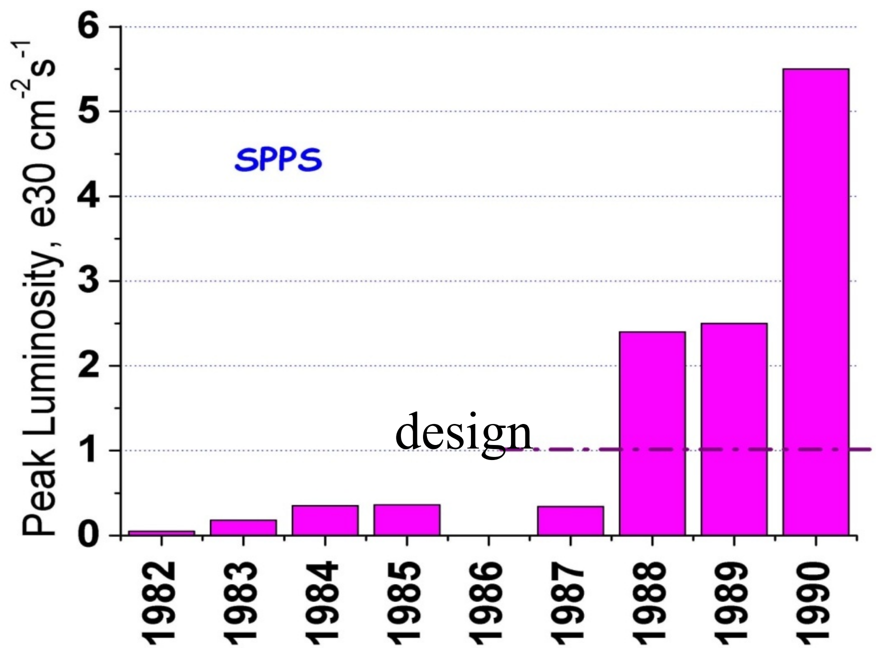
- 1971
- 31 GeV + 31 GeV colliding proton beams.
  - Highest CM Energy for 10 years
- Set a luminosity record that was not broken for 28 years!

$Sp\bar{p}S$: First proton-antiproton Collider



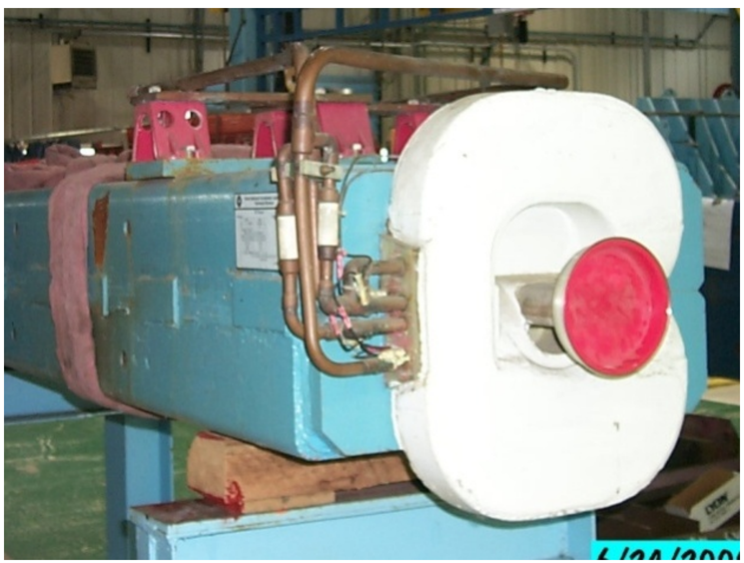
- Protons from the SPS were used to produce antiprotons, which were collected
- These were injected in the opposite direction (same beam pipe) and accelerated
- First collisions in 1981
- Discovery of W and Z in 1983
  - Nobel Prize for Rubbia and Van der Meer

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

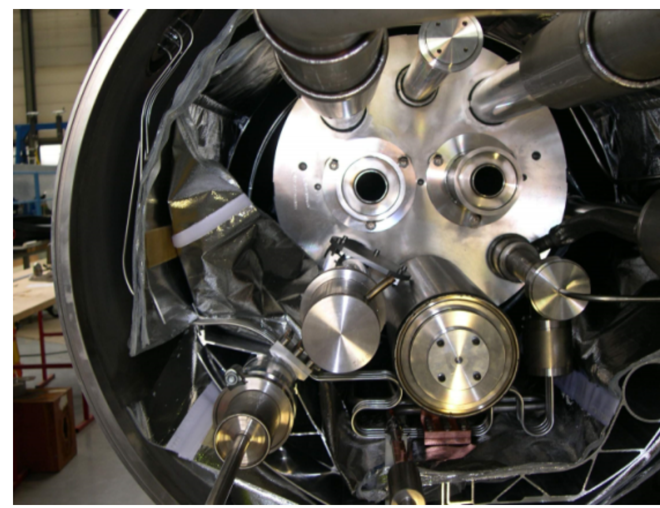


Superconductivity: Enabling Technology

- The maximum $Sp\bar{p}S$ 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



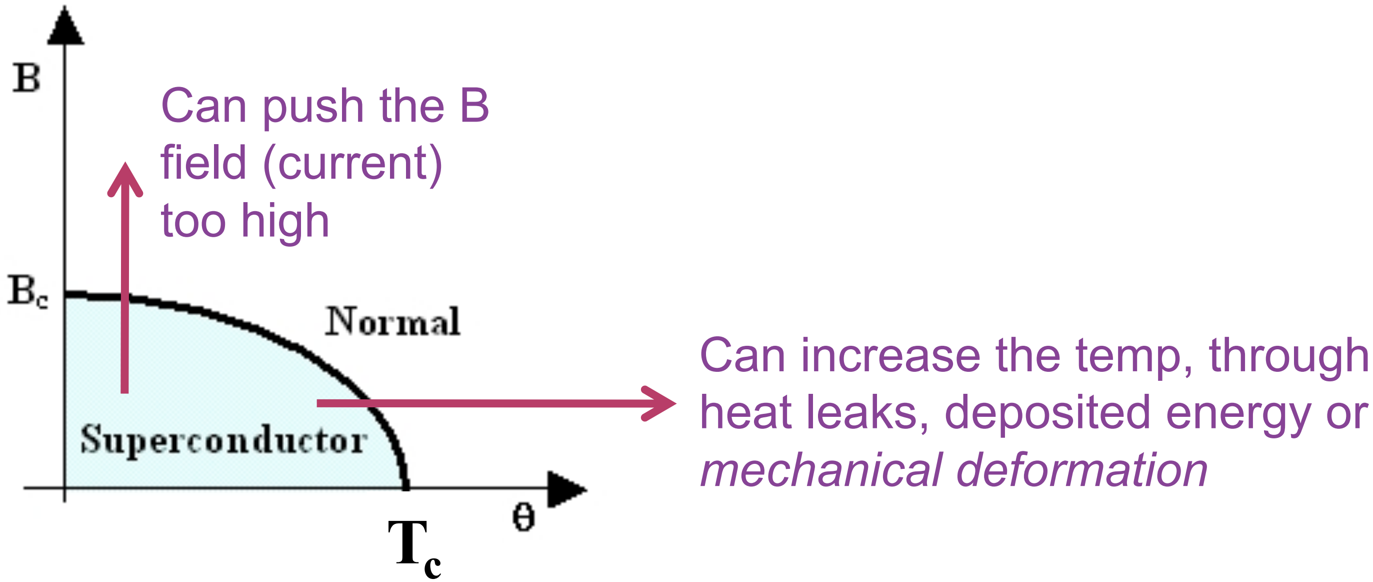
Superconducting magnets are complex and represent a great deal of stored energy which must be handled if something goes wrong



$$E \propto B^2$$

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.

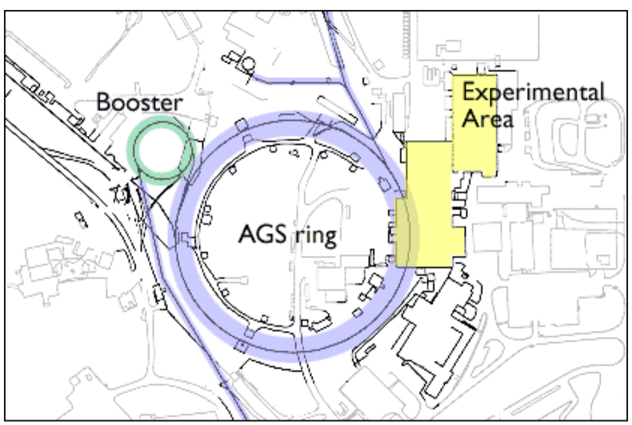
A Dead-end on the Road to Higher Energy

- 1980's - US begins planning in earnest for a 20 TeV+20 TeV "Superconducting Super Collider" or (SSC).
  - 87 km in circumference!
  - Considered superior to the "Large Hadron Collider" (LHC) then being proposed by CERN.
- 1987 – site chosen near Dallas, TX
- 1989 – construction begins
- 1993 – amidst cost overruns and the end of the Cold War, the SSC is cancelled after 17 shafts and 22.5 km of tunnel had been dug.

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

Explaining the LHC*…

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

Partial LHC Timeline

- 1994:
  - The CERN Council formally approves the LHC
- 2000:
  - LEP completes its final run
  - First dipole magnet delivered
- 2007
  - Last magnet delivered
  - First sector cold
  - All interconnections completed
- 2008
  - Accelerator complete
  - Last public access
  - Ring cold and under vacuum
  - September 10th: First circulating beam
  - September 19th: BAD accident brings beam down for almost 2 years

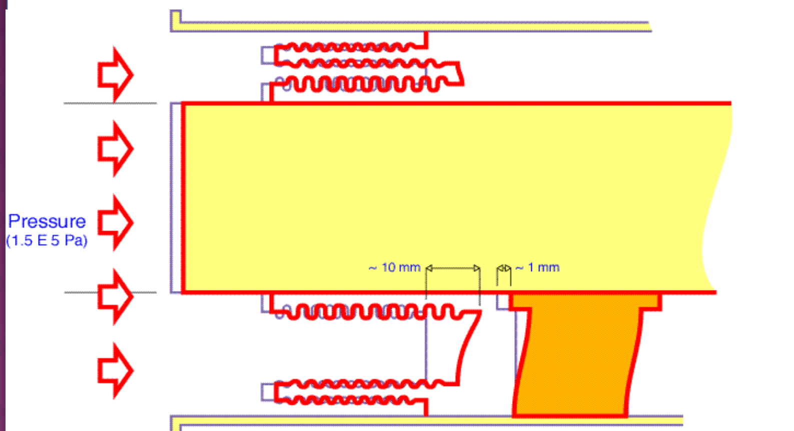
It begins…

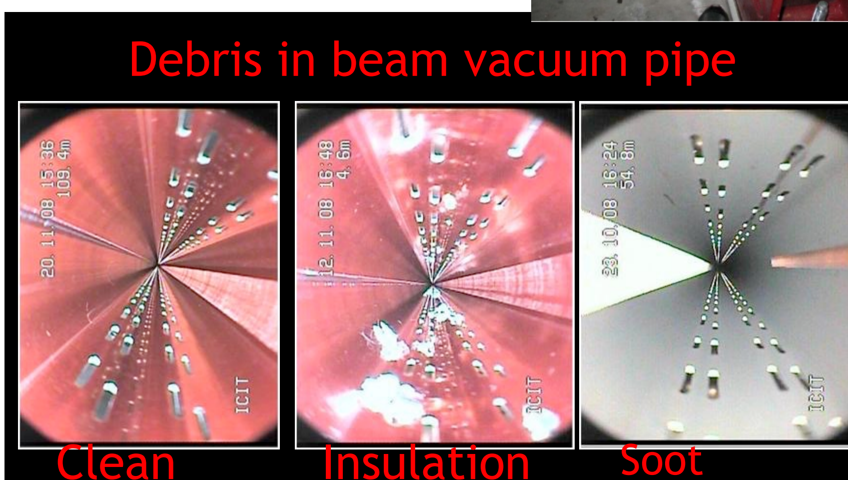
- 9:35 – First beam injected
- 9:58 – beam past CMS to point 6 dump
- 10:15 – beam to point 1 (ATLAS)
- 10:26 – First turn!
- …and there was much rejoicing

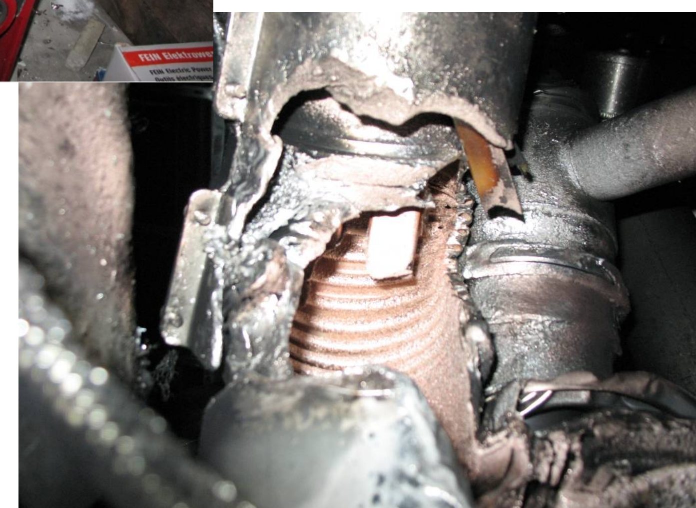
Commissioning proceeded smoothly and rapidly until September 19th, when *something* very bad happened

It Ends: “The Incident”

- A quench developed into an arc
- This caused Helium to boil
- The resulting pressure did a great deal of damage, and kept the machine off for more than



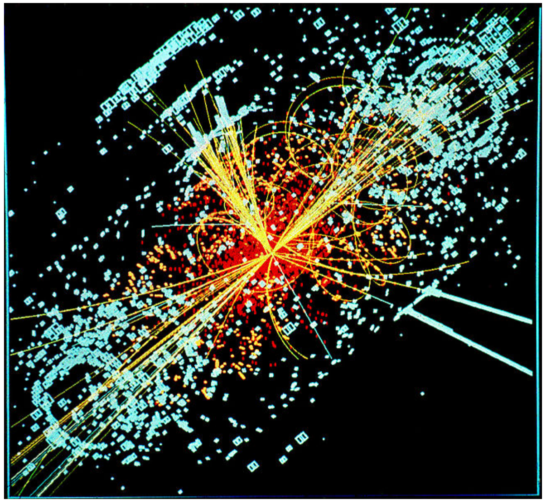




Secondary arcs

After the Incident

- The LHC was off for almost two years to repair the damage and partially address the cause.
- 2010: Came up at a reduced energy: 3.5 TeV + 3.5 TeV
- 2012: Increased energy to 4 TeV + 4 TeV
- Announced the discovery of Higgs particle July 4, 2012
  - Responsible to giving particles mass
  - Last piece of the "Standard Model"



- 2013 Nobel prize to Higgs and Englert

Plans for LHC

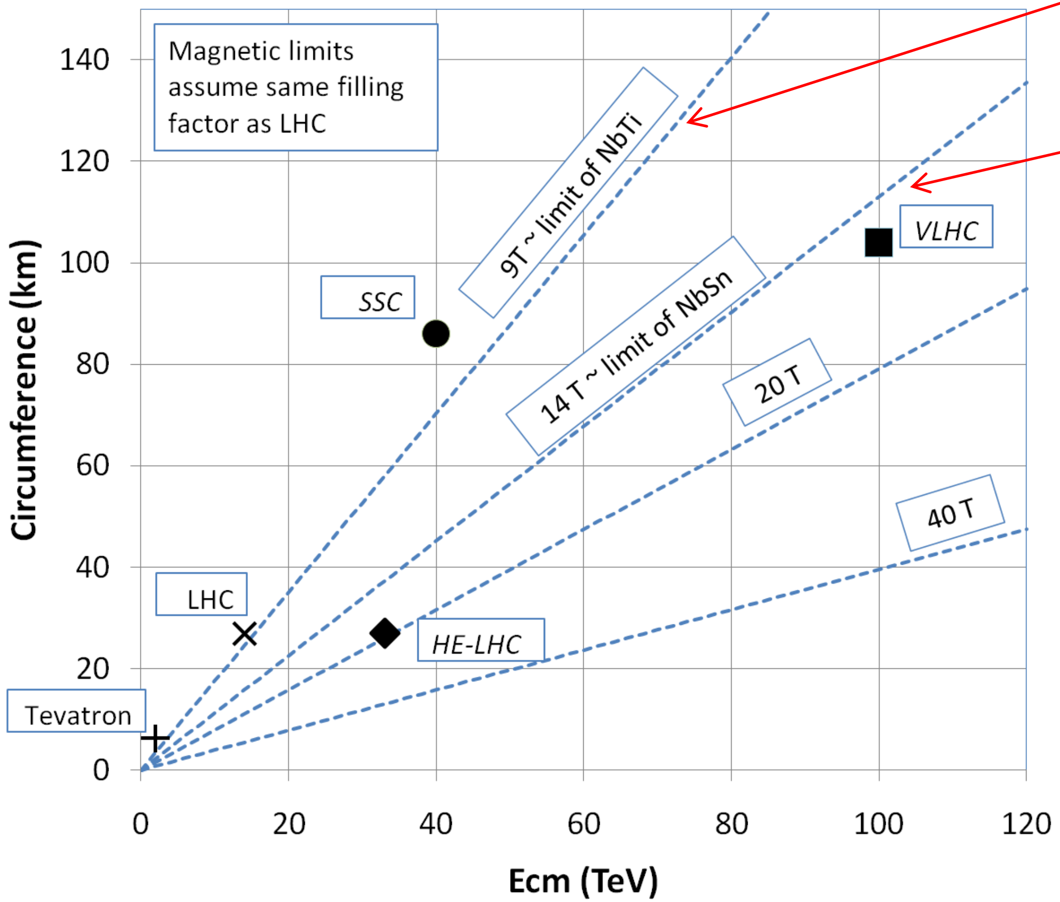
- The LHC will be the centerpiece of the world's energy frontier physics program for at least the next 15-20fd years.
- The machine is currently of to fix the issue which cause "the incident"
- Accelerator will come back up in 2015 at something close to the design energy
  - At least 6.5 TeV/beam
- Planning major upgrades to increase luminosity in ~2023

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

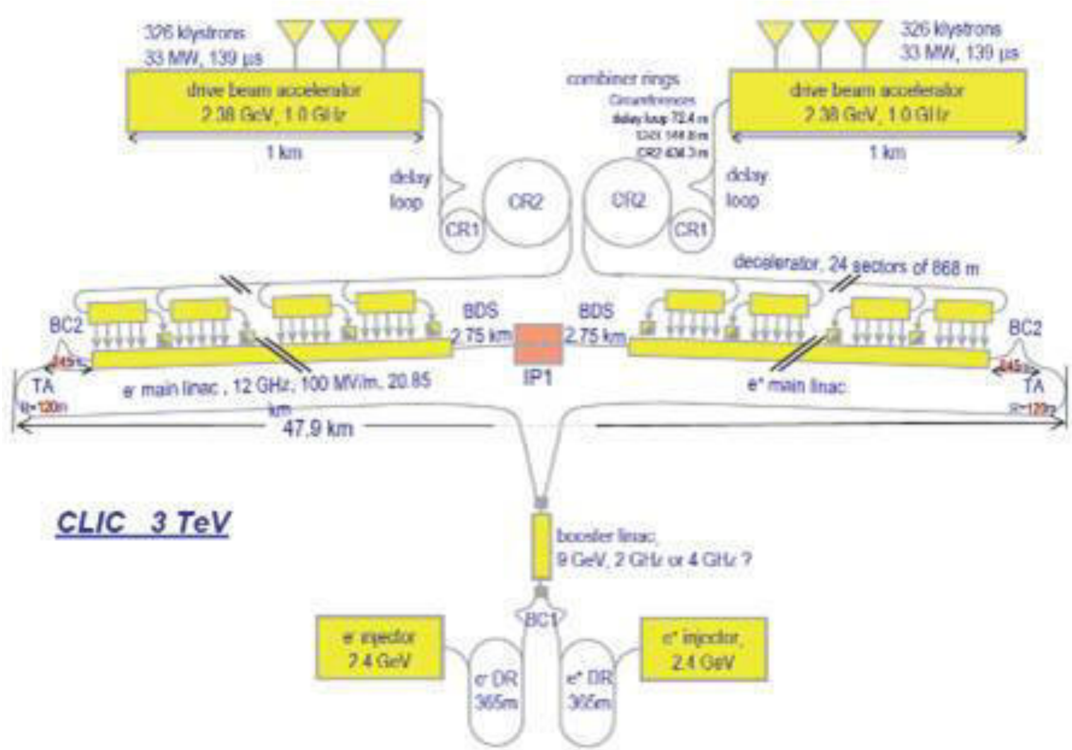


Future Circular Collider (FCC)

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

Rethinking Electrons

- Next e+e- collider would have to be linear
- Possibly use low energy, high current electron beams to drive high energy accelerating structures

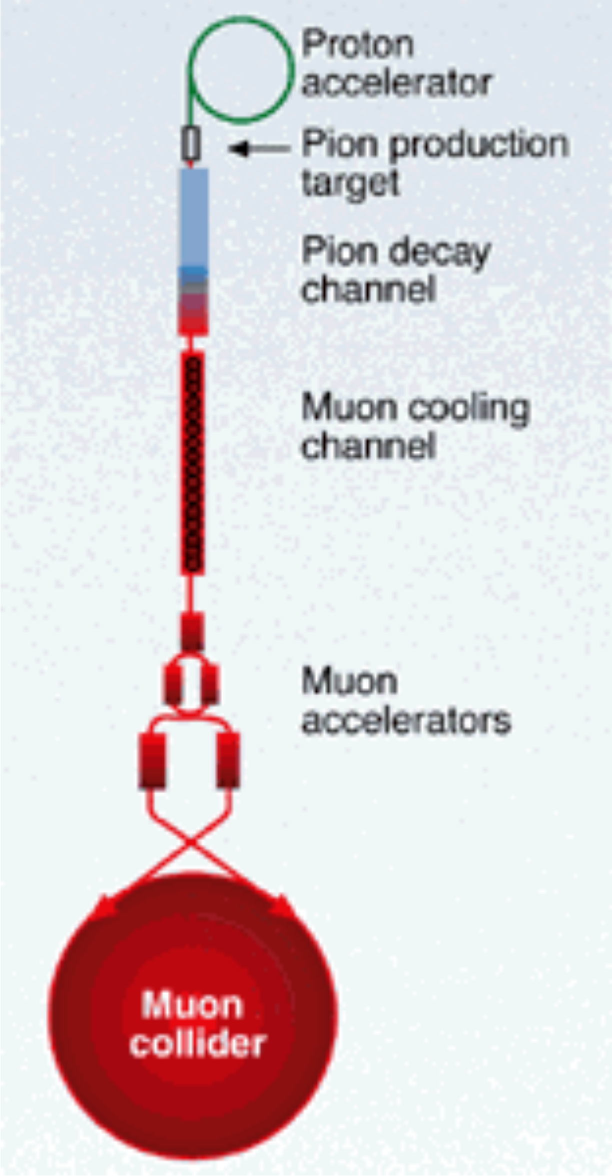


"Compact" (ha ha) Linear Collider (CLIC) proposed by CERN.

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

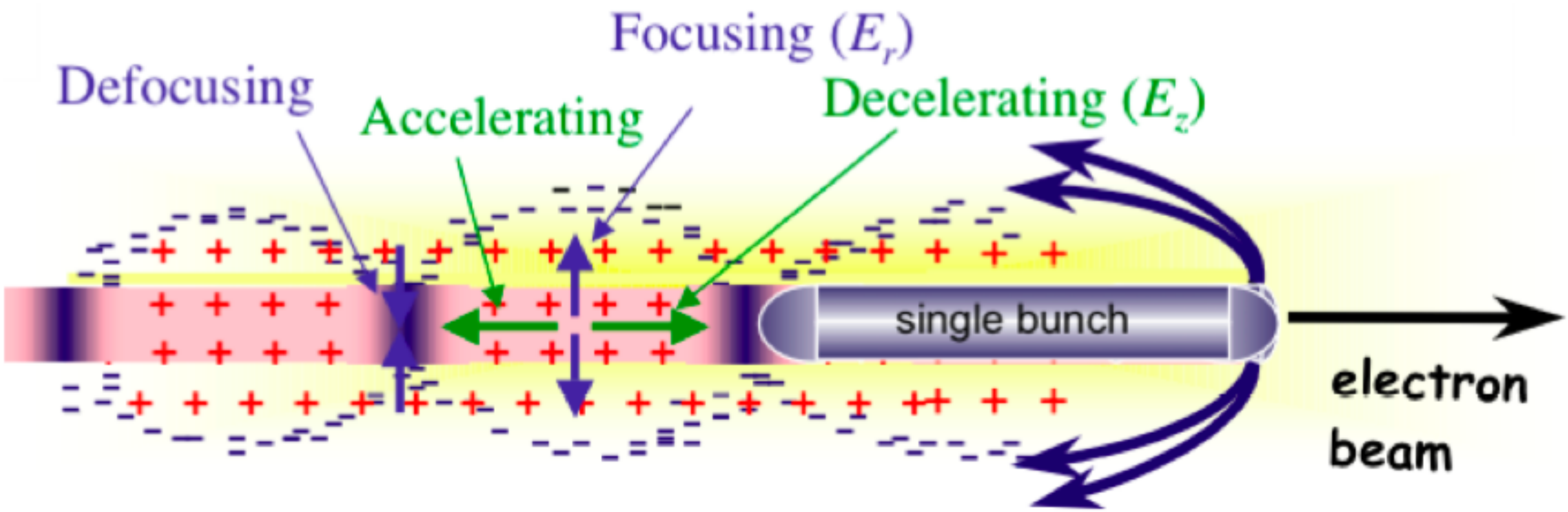
Muon colliders?

- 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.