Particle Accelerators

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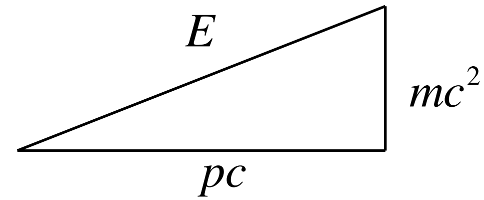
Comments

- This talk will focus primarily on the evolution of the highest energy particle accelerators
  - This has largely driven the development of the technology; *however*
  - High energy research machines are a tiny fraction (~1%) of the particle accelerators in use today.
- I'll be fairly technical
  - In the end, you should have a fairly quantitative understanding of most of the accelerator jargon you'll hear in a typical high energy physics talk:
    - "Lattice"
    - "Beta function"
    - "Tune"
    - "Emittance"
    - "RF"
    - etc…

Relativity and Units

Remember forever!



- Basic Relativity

$$\beta \equiv \frac{v}{c}$$

$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

$$\text{momentum } p = \gamma m v$$

$$\text{total energy } E = \gamma m c^2$$

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

$$E^2 = \sqrt{\left(mc^2\right)^2 + \left(pc\right)^2}$$

Some Handy Relationships

$$\beta = \frac{pc}{E}$$

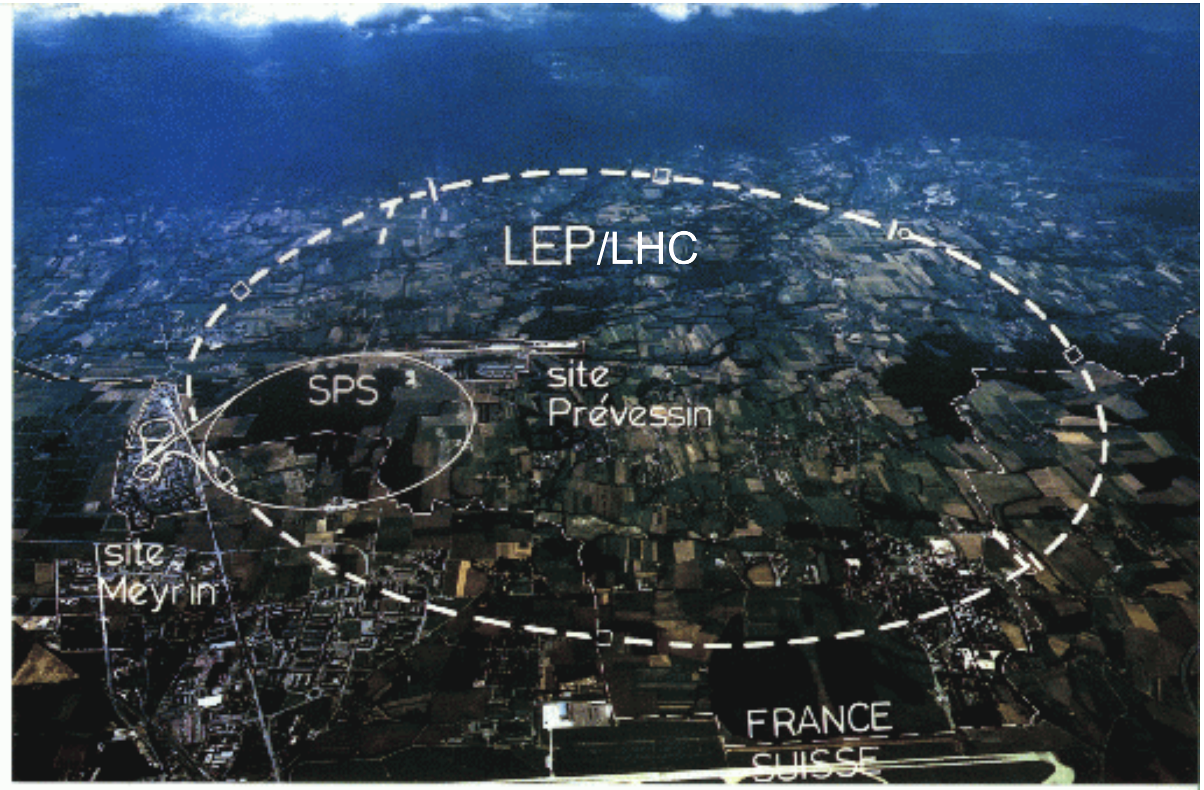
$$\gamma = \frac{E}{mc^2}$$

$$\beta\gamma = \frac{pc}{mc^2}$$

These units make these relationships really easy to calculate

- Units
  - For the most part, we will use SI units, except
    - Energy: eV (keV, MeV, etc) [1 eV = 1.6x10^{-19} J]
    - Mass: eV/c^2 [proton = 1.67x10^{-27} kg = 938 MeV/c^2]
    - Momentum: eV/c [proton @ ß=.9 = 1.94 GeV/c]
  - In the US and Europe, we normally talk about the kinetic energy (*K*) of a particle beam, although we'll see that momentum really makes more sense.

State of the Art: Large Hadron Collider (LHC)

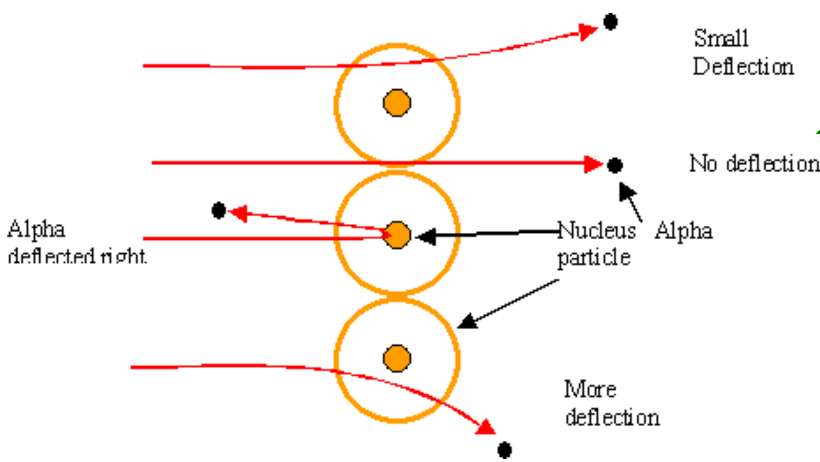


- Built at CERN, straddling the French/Swiss border
- 27 km in circumference
- Currently colliding beams of 6.5 TeV/beam
  - Design energy of 7 TeV
- That's where we are. Now let's see how we got here…

Rewind: Some Pre-History

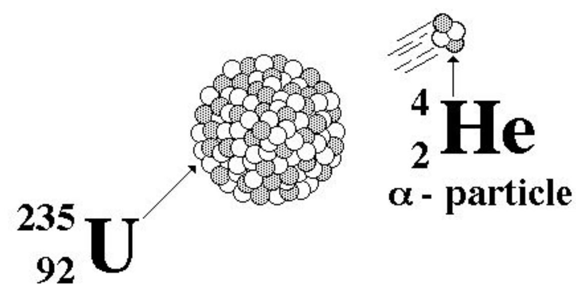
- The first artificial acceleration of particles was done using "Crookes tubes", in the latter half of the 19th century
  - These were used to produce the first X-rays (1875)
  - At the time no one understood what was going on

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



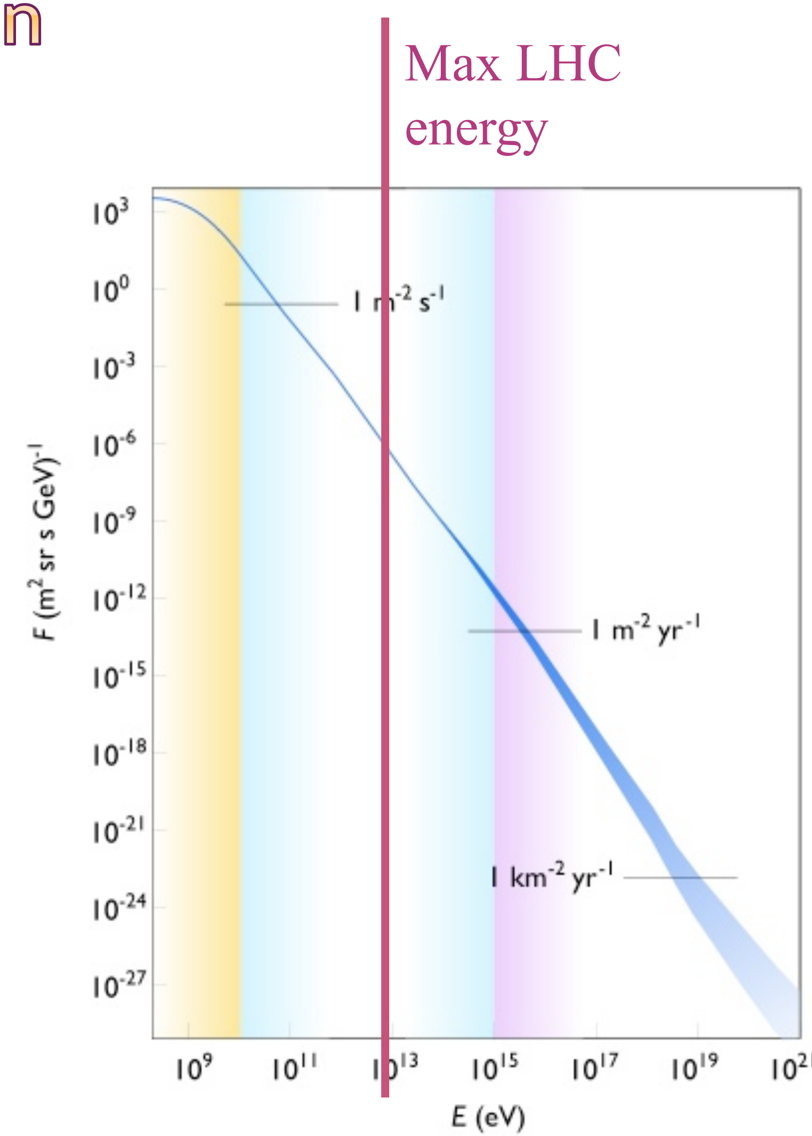
Study the way radioactive particles "scatter" off of atoms

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



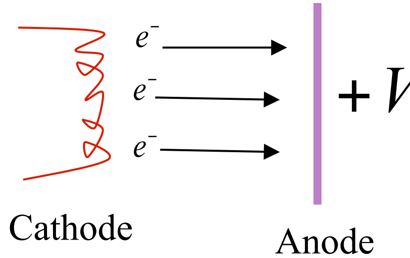
Natural Particle Acceleration

- 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
  - Not enough “luminosity”
- However, low energy cosmic rays are extremely useful for detector testing, commissioning, etc.



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:

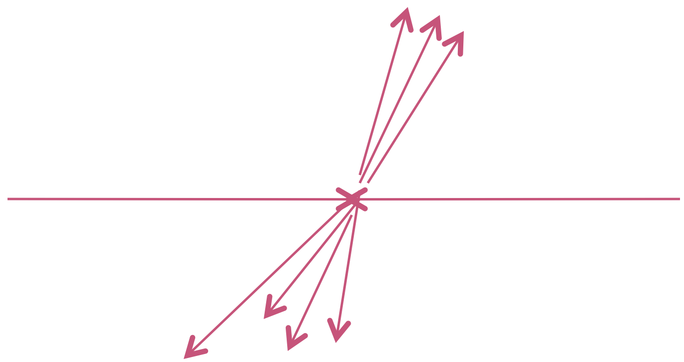
- CRT display ~keV
- X-ray tube ~10's of keV
- Van de Graaf ~MeVs

Old FNAL Cockroft-Walton = 750 kV

Solutions:

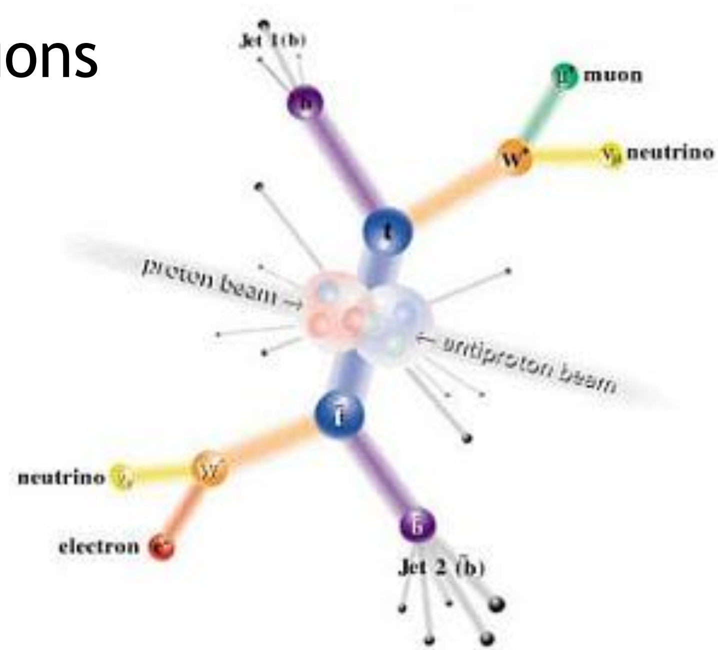
- Alternate fields to keep particles in accelerating fields -> Radio Frequency (RF) acceleration
- Bend particles so they see the same accelerating field over and over -> cyclotrons, synchrotrons

Interlude: Electrons vs. Protons



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

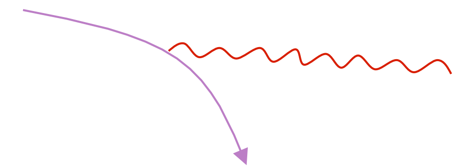
- Protons are made of quarks and gluons
  - Interaction take place between these constituents.
  - Only a small fraction of energy available, not well-defined.
  - Rest of particle fragments -> big mess!



So why not 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.

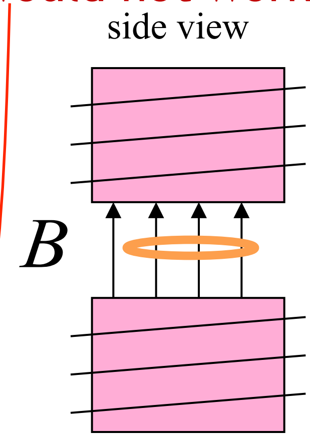
Since the beginning, the "energy frontier" has belonged to proton (and/or antiproton) machines, while electrons are used for precision studies and other purposes.

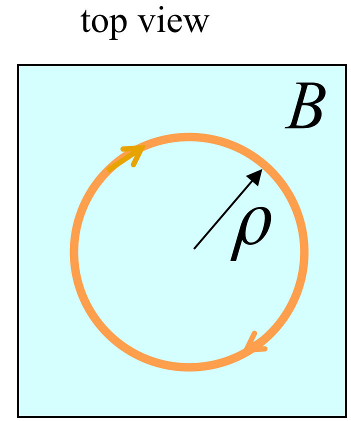
Now, back to the program…

The Cyclotron (1930's)

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

would not work for electrons!





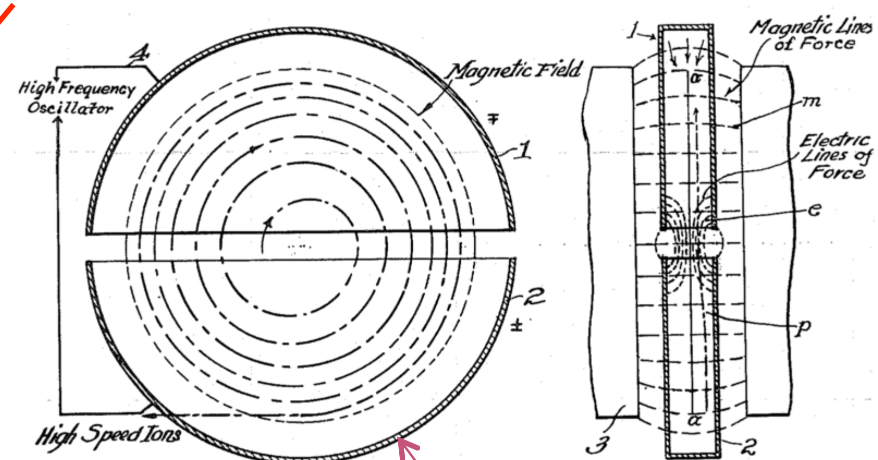
$$\rho = \frac{p}{qB} \approx \frac{mv}{qB} \quad (v \ll c)$$

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

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

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

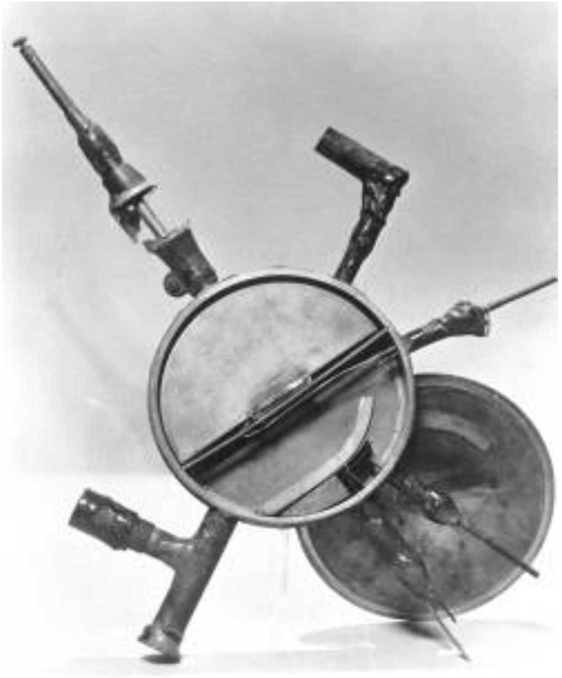
"Cyclotron Frequency"



For a proton:
$f_C = 15.2 \times B[T]$ MHz
i.e. "RF" range

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.

Round and Round We Go: the First Cyclotrons



- ~1930 (Berkeley)
  - Lawrence and Livingston
  - K=80 keV
  - Fit in your hand

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

Onward and Upward!

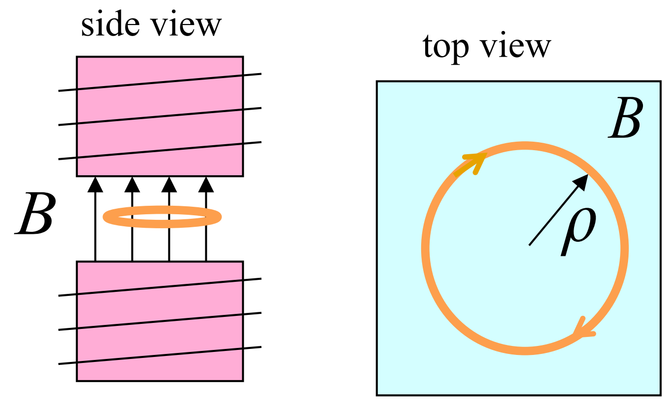
- Cyclotrons were limited by three problems
  - Constant frequency breaks down at ~10% speed of light
    - Solved with variable frequency "synchro-cyclotrons"
      ➔ phase stability (more about this later)
  - As energy goes up, magnet gets huge
  - Beams are not well focused and get larger with energy
- Two major advances allowed accelerators to go beyond the energies and intensities possible at cyclotrons
  - "Synchrotron" – in which the magnetic field is increased as the energy increases (proportional to momentum), such that particles continue to follow the same path .
  - "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.
- Note: still plenty of uses for cyclotrons (simple, inexpensive, rapid cycling)
  - Medical treatments
  - Isotope production
  - Nuclear physics

Understanding Beam Motion: Beam “rigidity”

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

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

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



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

$$(B\rho) = \frac{p}{e}$$

constant for fixed energy!

T-m²/s=V

$$(B\rho)c = \frac{pc}{e}$$

units of eV in our usual convention

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

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

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	βγ	$(pc)/(mc^2)$	1.017	7461.5
rigidity	(Bρ) [T-m]	$p[\mathrm{GeV}]/(.2997)$	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.

Weak Focusing

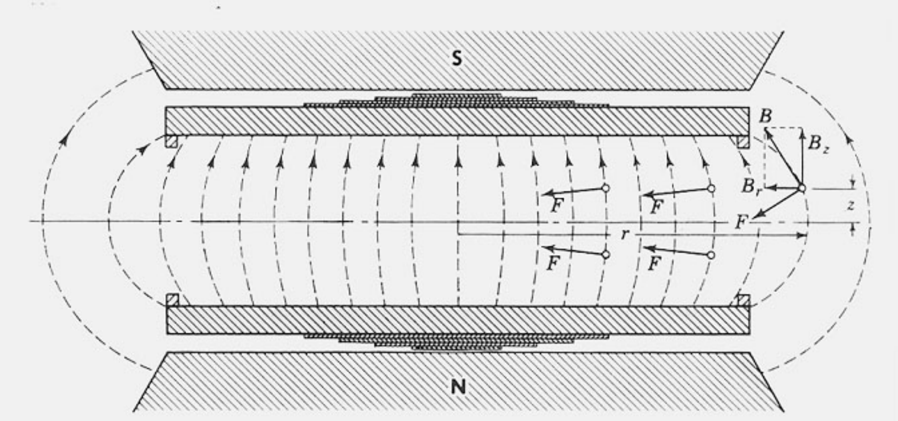
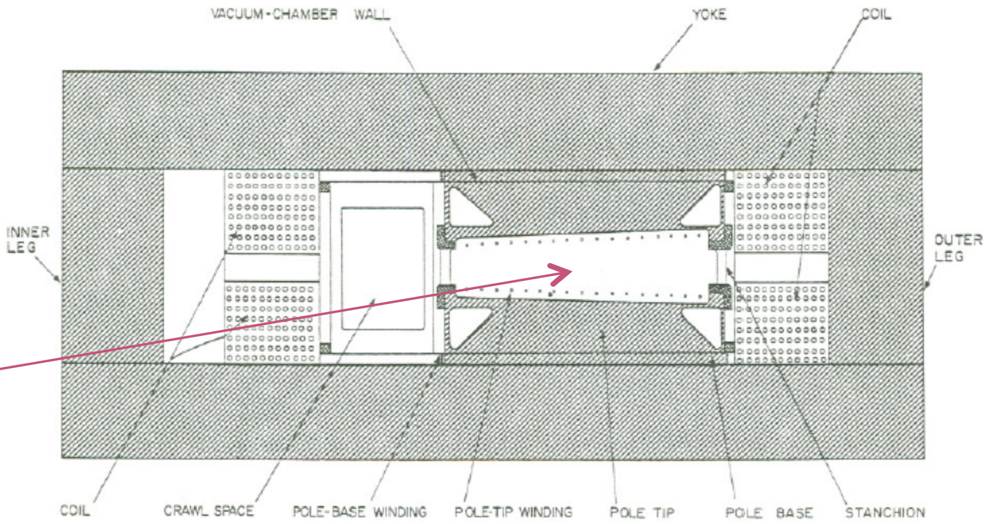


Fig. 6-7. Radially decreasing magnetic field between poles of a cyclotron magnet, showing shims for field correction.

- 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 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”!

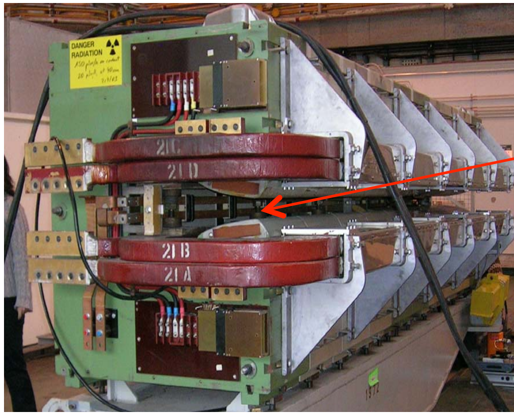


Strong Focusing

- Strong focusing utilizes alternating magnetic gradients to precisely control the focusing of a beam of particles
  - The principle was first developed in 1949 by Nicholas Christofilos, a Greek-American engineer, who was working for an elevator company in Athens at the time.
  - Rather than publish the idea, he applied for a patent, and it went largely ignored.
  - The idea was independently invented in 1952 by Courant, Livingston and Snyder, who later acknowledged the priority of Christophilos' work.
  - Courant and Snyder wrote a follow-up paper in 1958, which contains the vast majority of the accelerator physics concepts and formalism in use to this day!
- Although the technique was originally formulated in terms of magnetic gradients, it's much easier to understand in terms of the separate functions of dipole and quadrupole magnets.

Combined Function vs. Separated Function

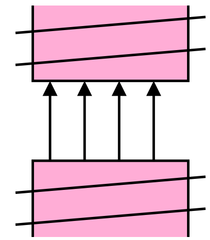
Strong focusing was originally implemented by building magnets with non-parallel pole faces to introduce a linear magnetic gradient



CERN PS (1959, 29 GeV)

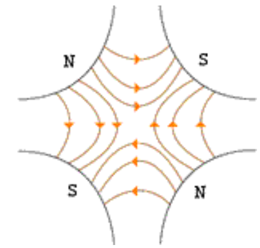
$$B_y(x) = B_0 + \frac{\partial B_y}{\partial x} x$$

=



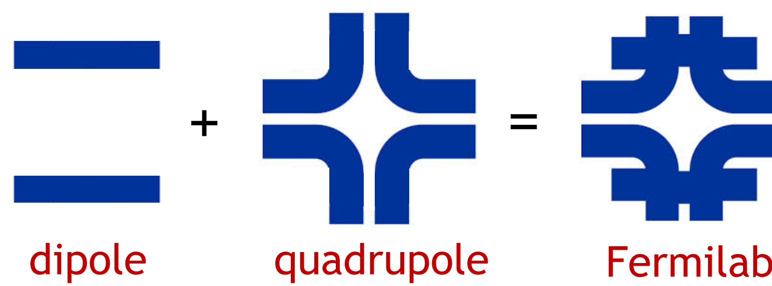
dipole

+



quadrupole

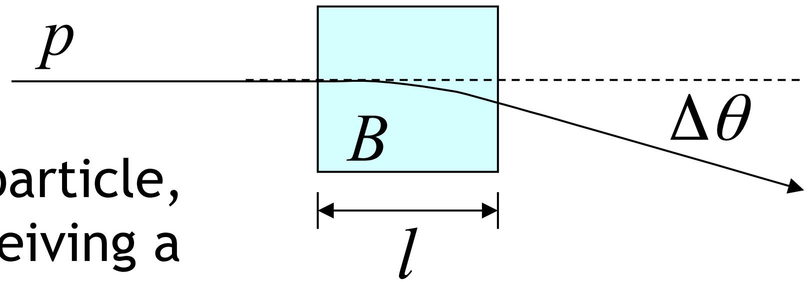
Later synchrotrons were built with physically separate dipole and quadrupole magnets. The first "separated function" synchrotron was the Fermilab Main Ring (1972, 400 GeV)



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

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", which is proportional to the integrated field

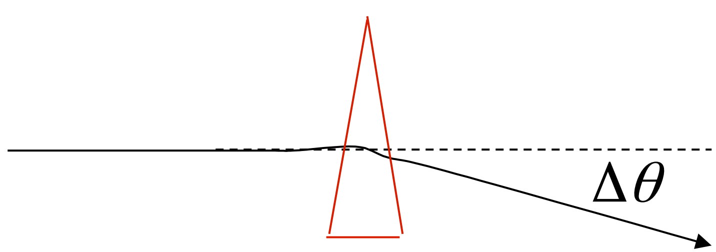


$$\boxed{p_\perp \approx qvBt = qvB(l/v) = qBl}$$

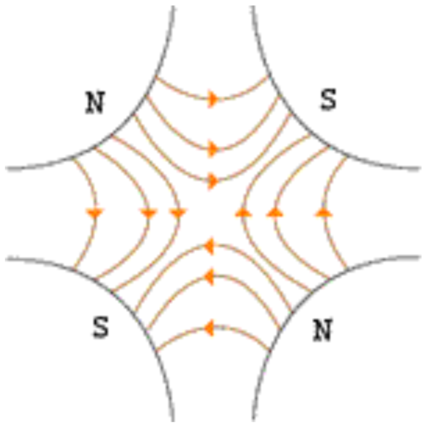
and it will be bent through small angle

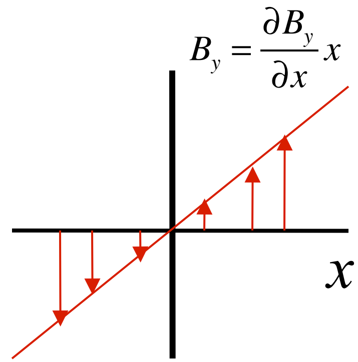
$$\boxed{\Delta\theta \approx \frac{p_\perp}{p} = \frac{Bl}{(B\rho)}}$$

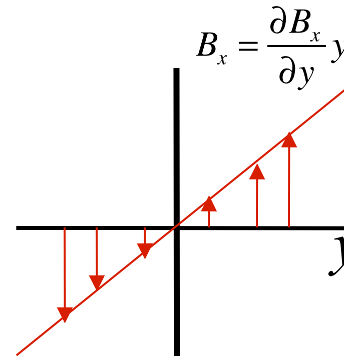
- In this "thin lens approximation", a dipole is the equivalent of a prism in classical optics.



Quadrupole Magnets* as Lenses



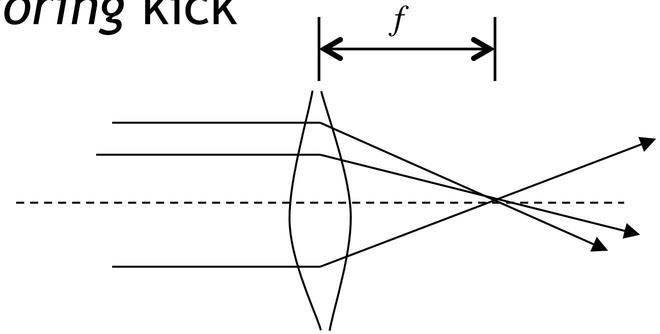




Note: $\vec{\nabla} \times \vec{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} \equiv B'$

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

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

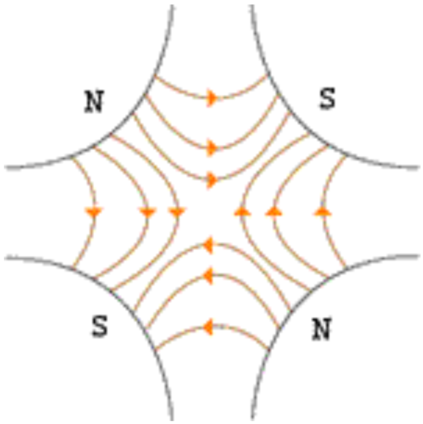


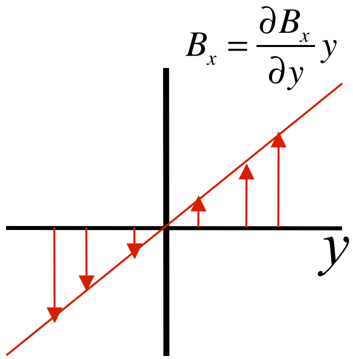
just like a "thin lens" with focal length

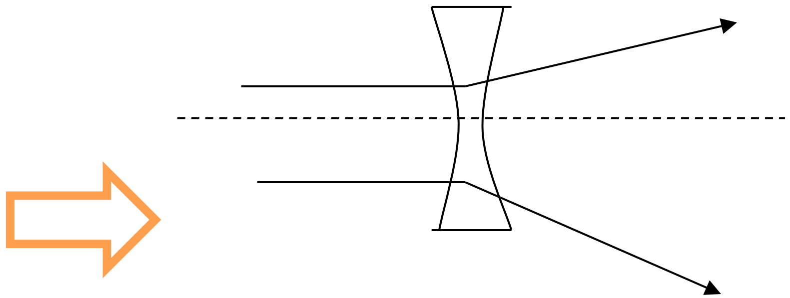
$$\boxed{f = \frac{x}{\Delta\theta} = \frac{(B\rho)}{B'l}}$$

*or quadrupole term in a gradient magnet

What About the Other Plane?



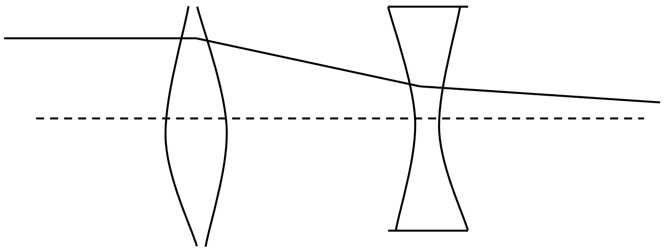


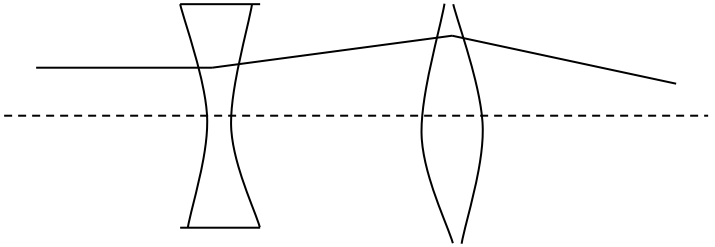


$$f = -\frac{(B\rho)}{B'l}$$

Defocusing!

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

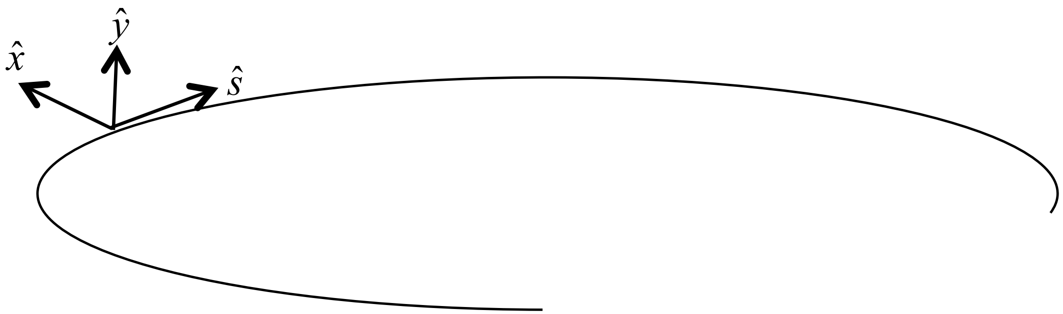




➔pairs give net focusing in *both* planes -> “FODO cell”

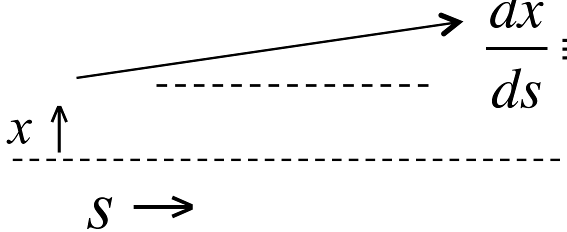
Formalism: Coordinates and Conventions

- We generally work in a right-handed coordinate system with x horizontal, y vertical, and s along the *nominal* trajectory (x=y=0).

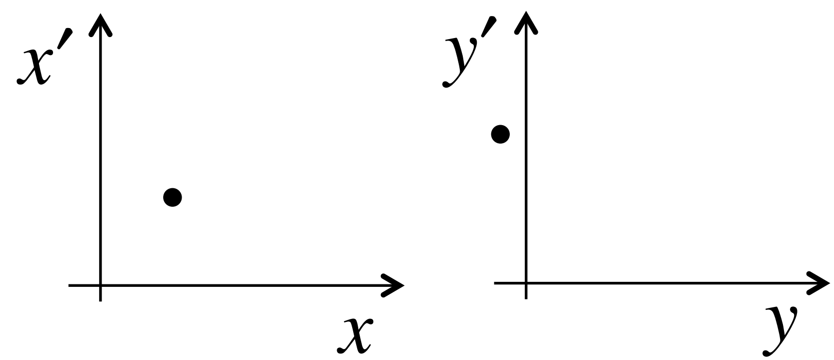


Note: s (rather than t) is the independent variable

Particle trajectory defined at any point in s by location in x,x' or y,y' "phase space"



$$\frac{dx}{ds} \equiv x' \approx \theta$$



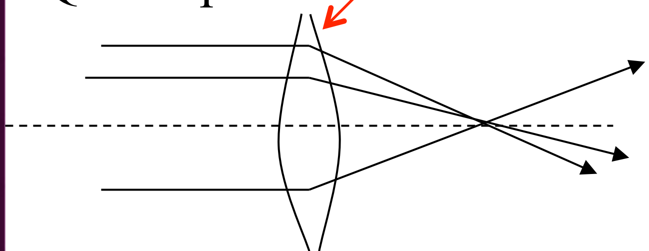
unique initial phase space point ➔ unique trajectory

Transfer Matrices

- Dipoles *define* the trajectory, so the simplest magnetic "lattice" consists of quadrupoles and the spaces in between them (drifts). We can express each of these as a linear operation in phase space.

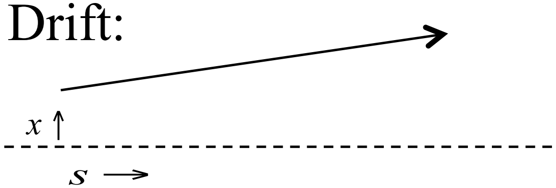
$$\Delta\theta = \Delta x' = -\frac{x}{f}$$

Quadrupole:



$$x = x(0)$$
$$x' = x'(0) - \frac{1}{f}x(0) \quad \Rightarrow \begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}$$

Drift:



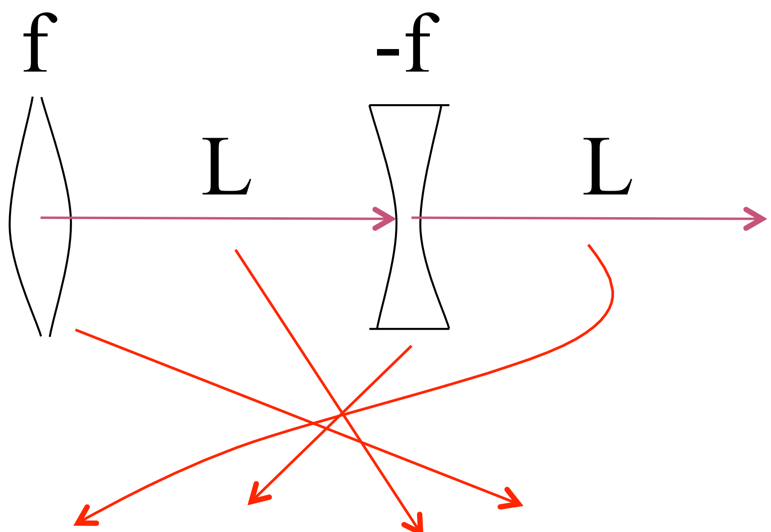
$$x(s) = x(0) + sx'(0)$$
$$x'(s) = x'(0) \quad \Rightarrow \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}$$

- By combining these elements, we can represent an arbitrarily complex ring or line as the product of matrices.

$$\mathbf{M} = \mathbf{M}_N \ldots \mathbf{M}_2 \mathbf{M}_1$$

Example: Transfer Matrix of a FODO cell

- At the heart of every beam line or ring is the basic “FODO” cell, consisting of a focusing and a defocusing element, separated by drifts:



Remember: motion is usually drawn from left to right, but matrices act from right to left!

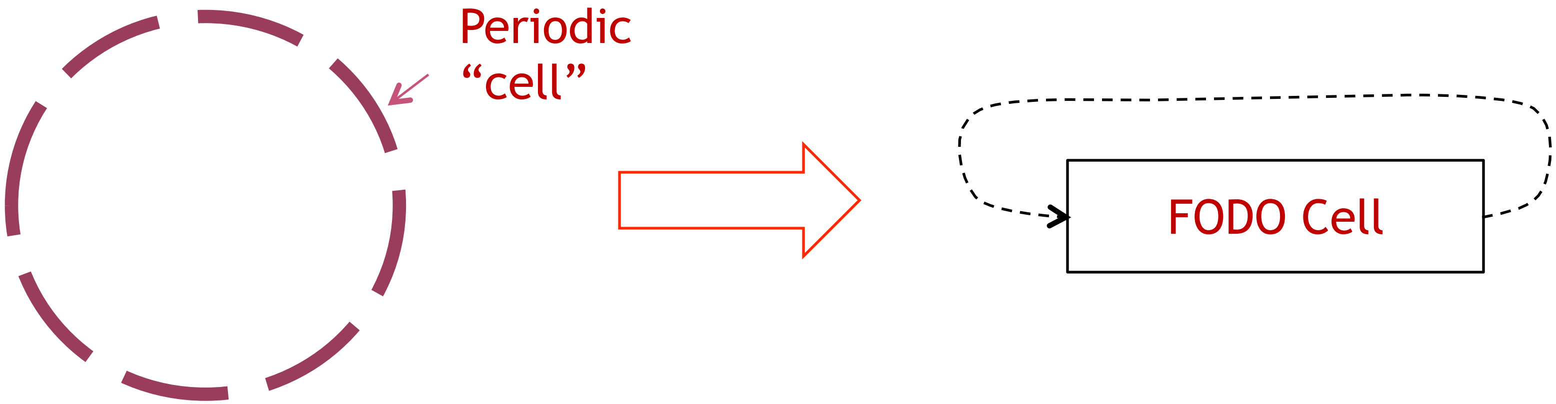
$$\Rightarrow \mathbf{M} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ +\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{f} - \left(\frac{L}{f}\right)^2 & 2L + \frac{L^2}{f} \\ -\frac{L}{f^2} & 1 + \frac{L}{f} \end{pmatrix}$$

Sign of *f* flips in other plane

- Can build this up to describe any beam line or ring

Periodic Systems

- You might think, "Start with a beam line, then make a ring out of it."
  - Difficult to solve general case, because it depends on the initial conditions
- Therefore, we initially solve for stable motion in a *periodic* system
- We can think of a ring made of identical FODO cells as just the same cell, over and over.

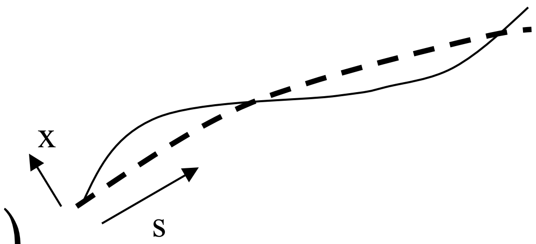


$$\mathbf{M}_{ring} = \mathbf{M}_{cell}\mathbf{M}_{cell}\cdots\mathbf{M}_{cell} = \mathbf{M}_{cell}^{N}$$

- Our goal is to decouple the problem into two parts
  - The "lattice": a mathematical description of the machine itself, based only on the magnetic fields, *which is identical for each identical cell*
  - The "emittance": mathematical description for the ensemble of particles circulating in the machine.
- Extend to beam lines by using boundary conditions ("matching")

General Solution: Betatron Motion

- We find (after a lot of algebra) that we can describe particle motion in terms of initial conditions and a "beta function" β(s), which is only a function of location along the nominal path, and follows the periodicity of the machine.



$\beta(s)$

Lateral deviation in one plane

$$x(s) = A\sqrt{\beta(s)}\cos\left(\psi(s)+\delta\right)$$

Phase advance

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

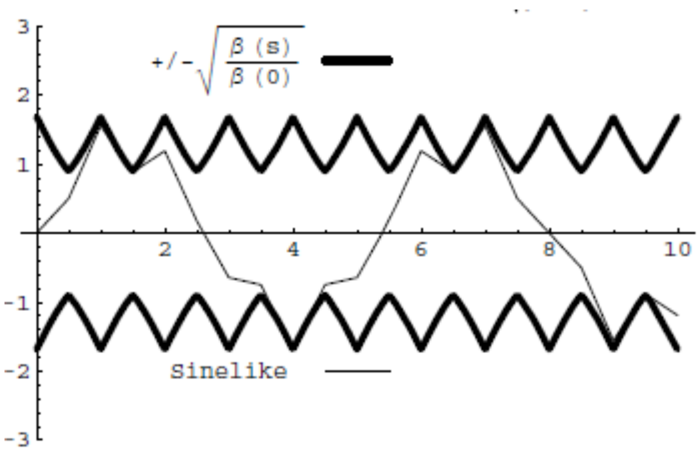
The "betatron function" $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.

- In other words, particles undergo "pseudo-harmonic" motion about the nominal trajectory, with a variable wavelength.
- Note: β has units of [length], so the amplitude has units of $[\text{length}]^{1/2}$

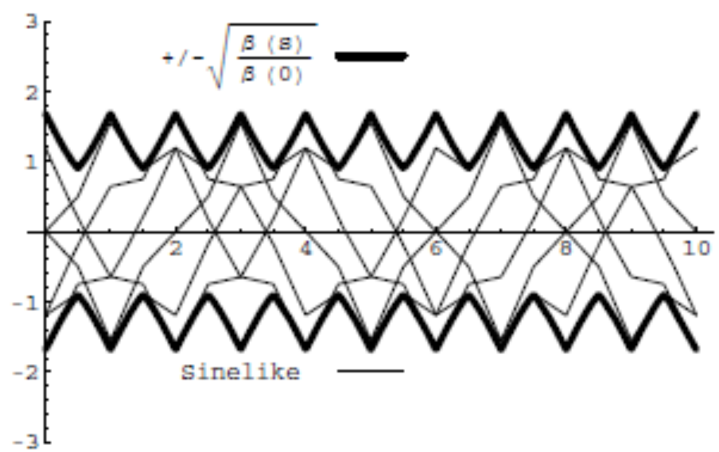
Conceptual Understanding of β

- It's important to remember that the betatron function represents a *bounding envelope* to the beam motion, not the beam motion itself

Normalized particle trajectory



Trajectories over multiple turns (or trajectories of multiple particles!)



$$x(s) = A\left[\beta(s)\right]^{1/2}\sin\left(\psi(s)+\delta\right)$$

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

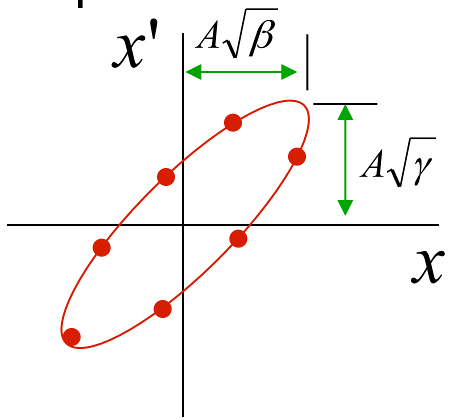
β(*s*) is also effectively the local wave number which determines the rate of phase advance

Closely spaced strong quads ➔ small β ➔ small aperture, lots of wiggles

Sparsely spaced weak quads ➔ large β ➔ large aperture, few wiggles

Characterizing Particle Ensembles: Emittance

- A particle returning to the same point over many terms traces an ellipse, defined by the "beta function", β, and two additional lattice parameters, α and γ.



$$\alpha = -\frac{1}{2}\frac{d\beta}{ds}$$

$$\beta x'^2 + 2\alpha x x' + \gamma x^2 = A^2 = \text{constant}$$

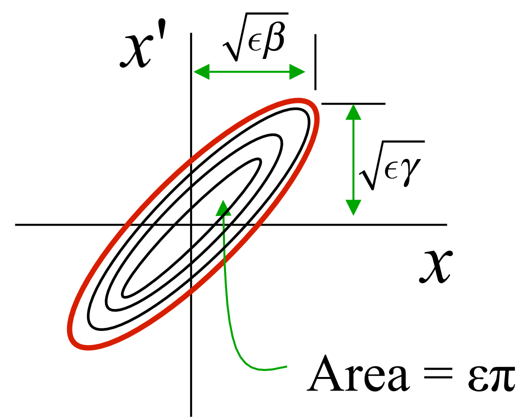
$$\gamma = \frac{1+\alpha^2}{\beta}$$

NOT to be confused with relativistic β and γ!

- An ensemble of particles can characterized by a bounding ellipse, known as the "emittance"
  - Definitions vary: RMS, 95%, 99%, etc

$$\beta x' + 2\alpha x x' + \gamma x^2 = \epsilon$$

Units of length



Emittance, Beam Size, and Adiabatic Damping

- If we use the Guassian definition emittance, then the beam size is

$$\sigma_x = \sqrt{\beta_x \epsilon}$$

- Emittance is constant at a constant energy, but as particles accelerate, the emittance decreases

$$\epsilon \propto \frac{1}{\beta\gamma}$$

Relativistic β and γ
(yes, I know it's confusing)

- This is known as "adiabatic damping". We therefore define a "normalized emittance"

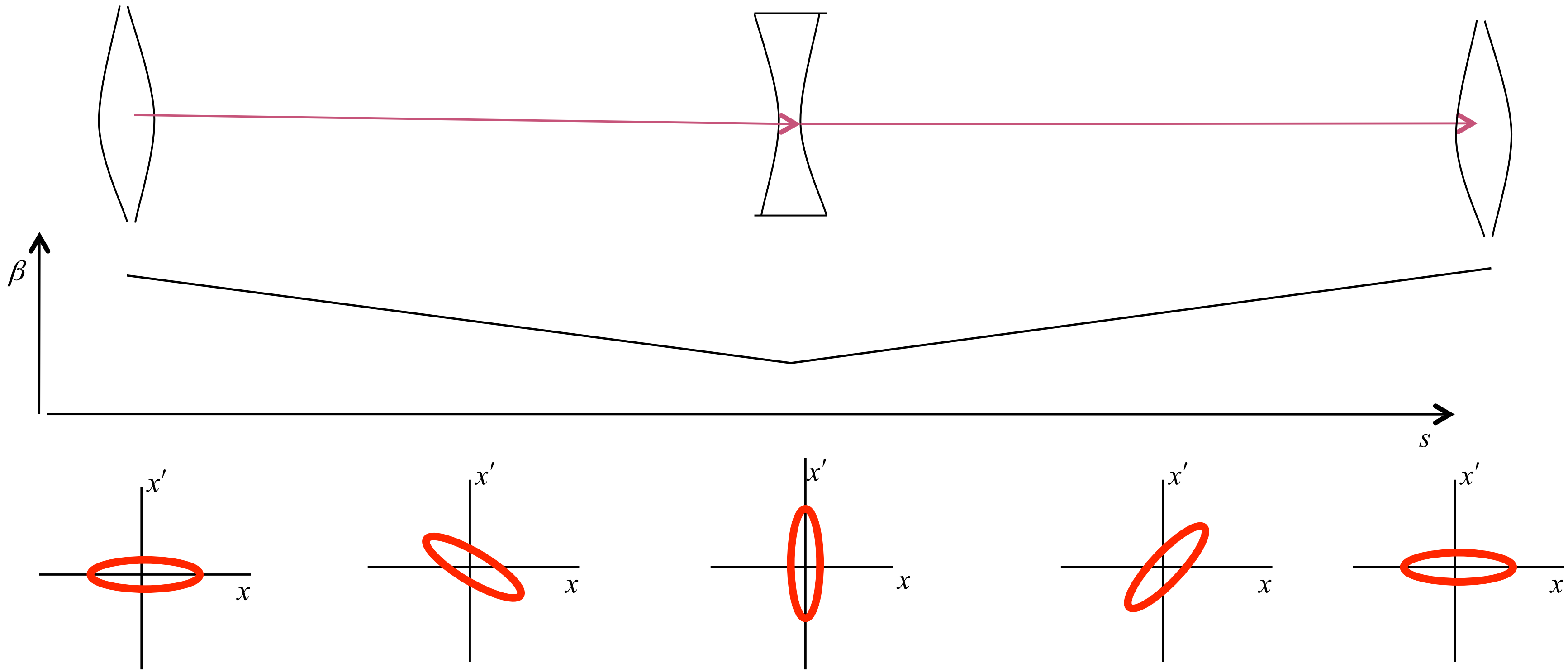
$$\epsilon_N \equiv \beta\gamma\epsilon$$

- which is constant with energy. Thus, at a particular energy

$$\sigma_x = \sqrt{\frac{\beta_x \epsilon_N}{\beta\gamma}} \propto \frac{1}{\sqrt{p}}$$

Emittance and Beam Distributions

- As we go through a lattice the shape in phase space varies, by the bounding emittance remains constant

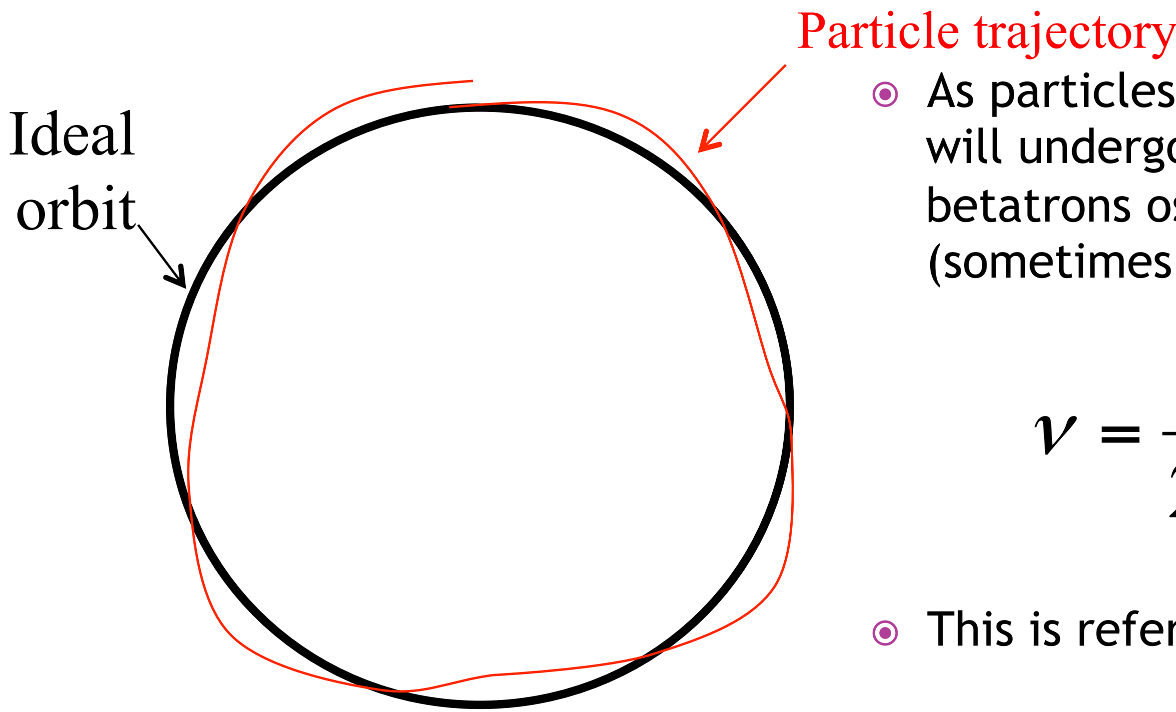


β = max α = 0 ➔maximum	β = decreasing α >0 ➔focusing	β = min α = 0 ➔minimum	β = increasing α < 0 ➔defocusing

large spatial distribution
small angular distribution

small spatial distribution
large angular distribution

Betatron Tune



- As particles go around a ring, they will undergo a number of betatrons oscillations *ν* (sometimes *Q*) given by

$$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

- This is referred to as the "tune"

- We can generally think of the tune in two parts:

Integer : magnet/ aperture optimization → 6.7 ← Fraction: Beam Stability

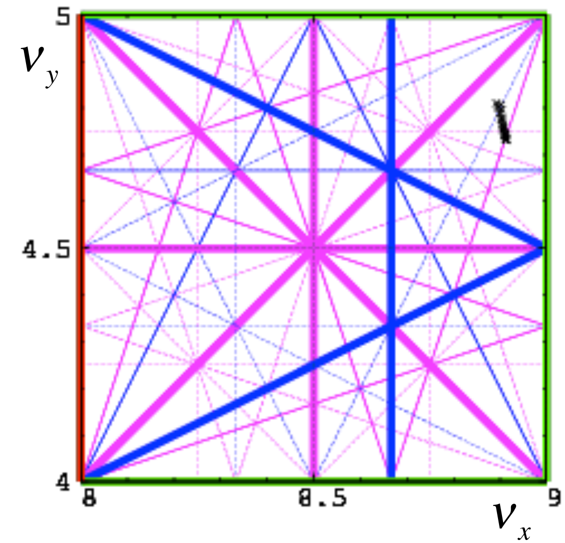
Tune, Stability, and the Tune Plane

- If the tune is an integer, or low order rational number, then the effect of any imperfection or perturbation will tend be reinforced on subsequent orbits.
- When we add the effects of coupling between the planes, we find this is also true for *combinations* of the tunes from both planes, so in general, we want to avoid

$$k_x \nu_x \pm k_y \nu_y = \text{integer} \Rightarrow \text{(resonant instability)}$$

"small" integers

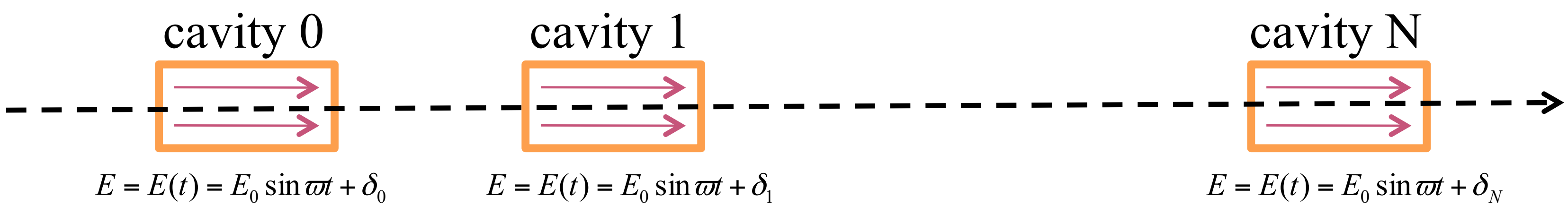
➔Avoid lines in the "tune plane"



- Many instabilities occur when something perturbs the tune of the beam, or part of the beam, until it falls onto a resonance, thus you will often hear effects characterized by the "tune shift" they produce.
  - For example: the maximum tune shift sets the absolute luminosity limit in a collider

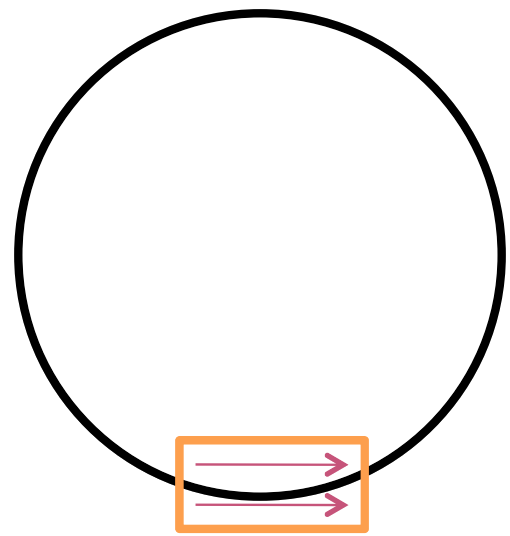
Longitudinal Motion

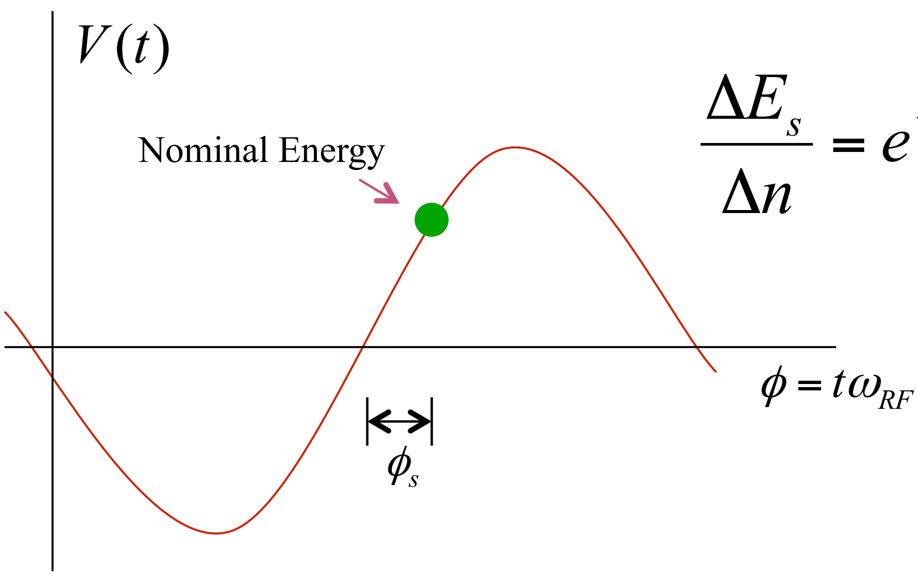
- We will generally accelerate particles using structures that generate time-varying electric fields (RF cavities), either in a linear arrangement



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





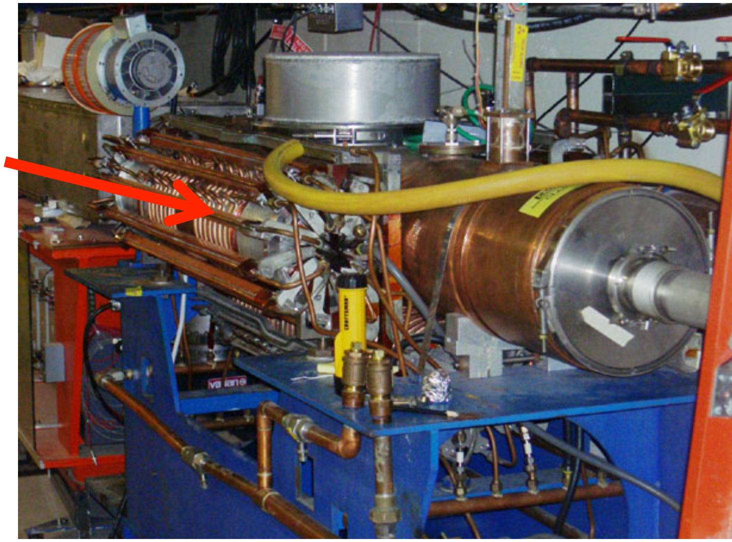
$$\frac{\Delta E_s}{\Delta n} = eV_0 \sin \phi_s$$

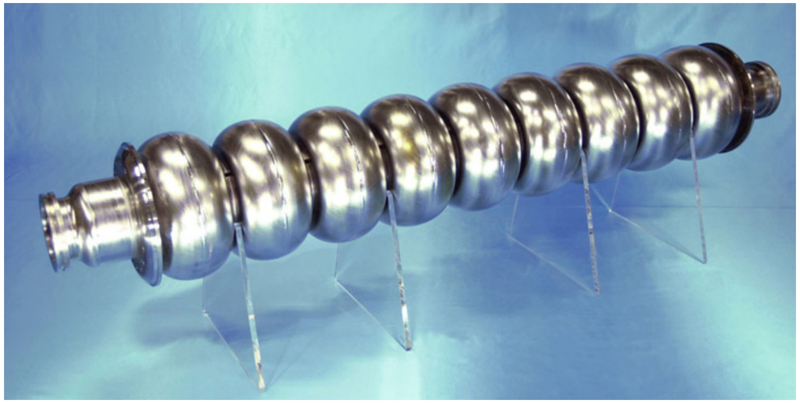
Examples of Accelerating RF Structures

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

37->53MHz Fermilab Booster cavity

Biased ferrite frequency tuner

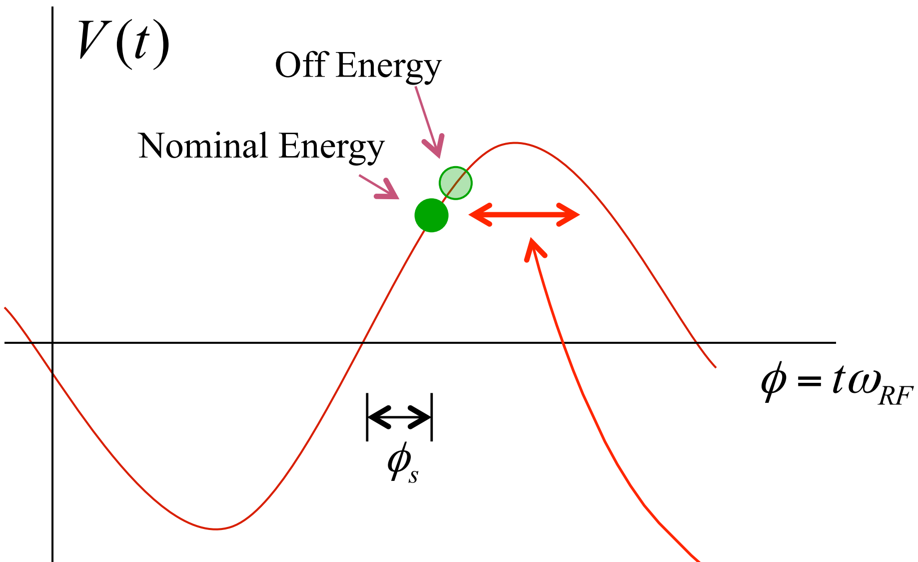




ILC prototype elipical cell “π-cavity” (1.3 GHz): field alternates with each cell

Phase Stability

- A particle with a slightly different energy will arrive at a slightly different time, and experience a slightly different acceleration



$$\frac{\Delta\tau}{\tau} = \eta\frac{\Delta p}{p}$$

"slip factor" = dependence of period on momentum
- negative for linacs
- positive for (relativistic) cyclotrons
- goes from negative to positive in synchrotrons ("transition")

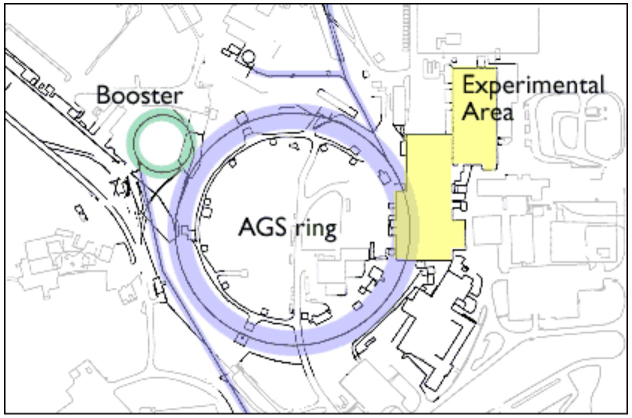
Stable point depends on sign.

- Longitudinal motion about stable phase referred to as "synchrotron motion".
  - Takes many revolutions to complete one longitudinal cycle in a synchrotron, so multiple RF cavities are just seen as a vector sum.

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

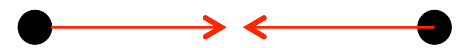
Brookhaven Alternating Gradient Synchrotron (AGS)
- 1960
- 808 m circumference
- 33 GeV protons
- Discovered charm quark, CP violation, muon neutrino

Getting the Most Energy: The Case for Colliders

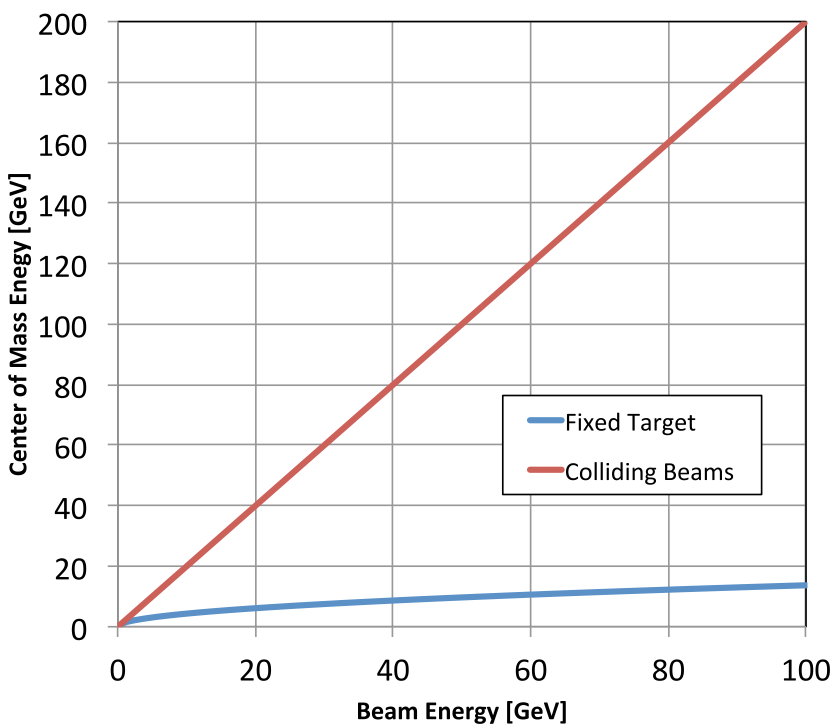
- If beam hits a stationary proton, the "center of mass" energy is

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

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



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



- 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!!*

Getting to the highest energies requires colliding beams

Luminosity

The relationship of the beam to the rate of observed physics processes is given by the "Luminosity"

Rate $\rightarrow$ $$R = L\sigma$$

"Luminosity"

Cross-section ("physics")

Standard unit for Luminosity is cm^{-2}s^{-1}
Standard unit of cross section is "barn"=10^{-24} cm^{2}
Integrated luminosity is usually in barn^{-1},where

$$\mathrm{b}^{-1} = (1\,\mathrm{sec}) \times (10^{24}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$$

nb^{-1} = 10^{9} b^{-1}, fb^{-1}=10^{15} b^{-1}, etc

For (thin) fixed target:

$$R = N\rho_n t\sigma \Rightarrow L = N\rho_n t$$

Target thickness

Incident rate

Target number density

Example: MiniBooNe primary target:

$$L \approx 10^{37}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Luminosity of Colliding Beams

- For equally intense Gaussian beams

Collision frequency

Particles in a bunch

$$L = f\frac{N_b^{\;2}}{4\pi\sigma^2}R$$

Geometrical factor:
- crossing angle
- hourglass effect

Transverse size (RMS)

- Using $\sigma^2 = \frac{\beta^*\epsilon_N}{\beta\gamma} \approx \frac{\beta^*\epsilon_N}{\gamma}$ we have

prop. to energy

$$L = f_{rev}\frac{1}{4\pi}nN_b^2\frac{\gamma}{\beta^*\epsilon_N}R$$

Normalized emittance

Revolution frequency

Number of bunches

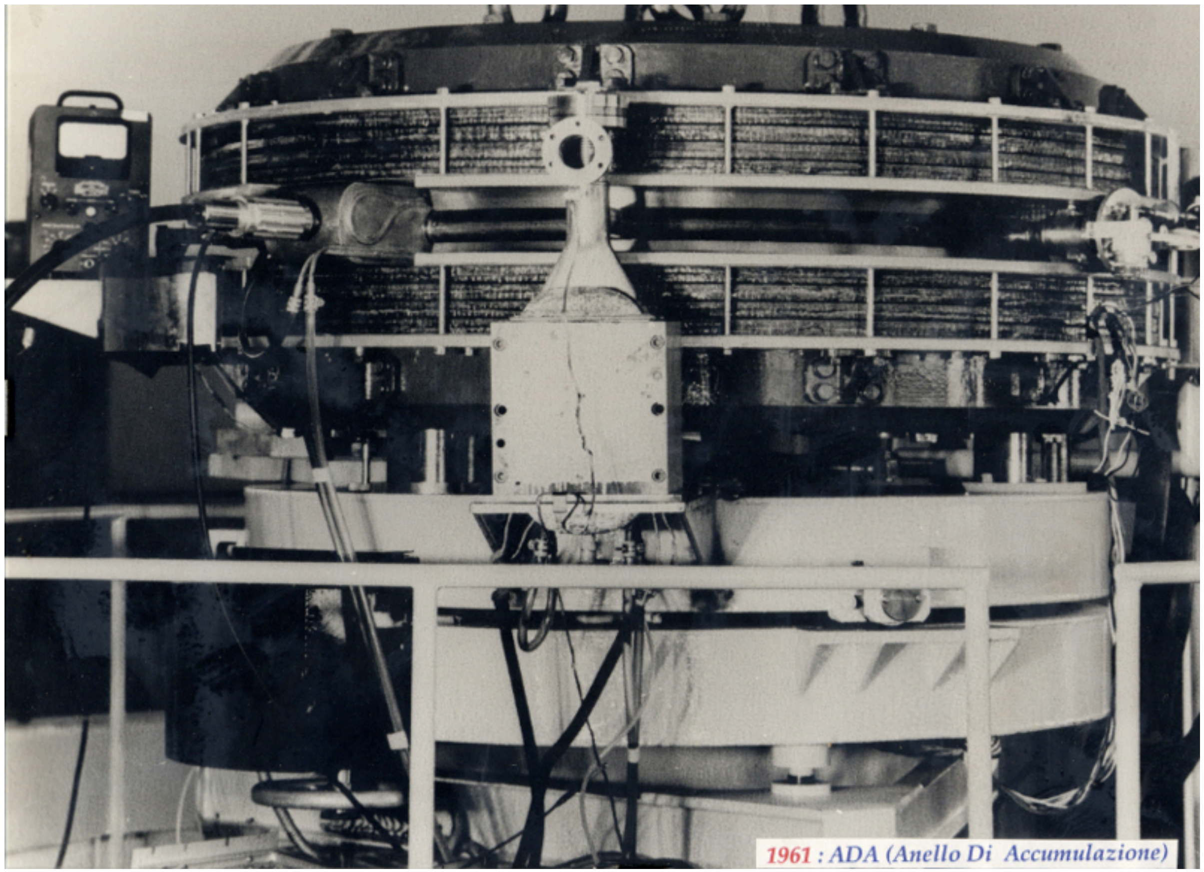
Particles in bunch

Betatron function at collision point ➔ want a small β*!

Record e+e- Luminosity (KEK-B):	$2.11\text{x}10^{34}$ cm^{-2}s^{-1}
Record p-pBar Luminosity (Tevatron):	$4.06\text{x}10^{32}$ cm^{-2}s^{-1}
Record Hadronic Luminosity (LHC):	$7.0\text{x}10^{33}$ cm^{-2}s^{-1}
LHC Design Luminosity:	$1.00\text{x}10^{34}$ cm^{-2}s^{-1}

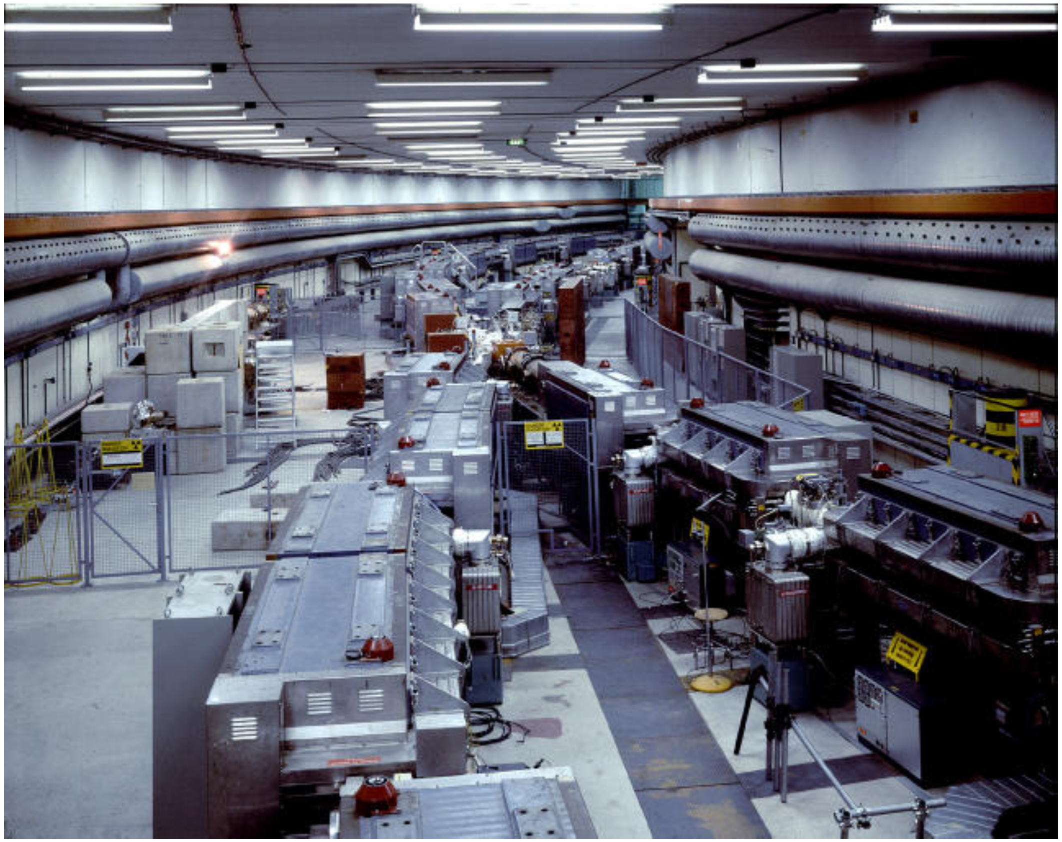
First e^+e^- Collider

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



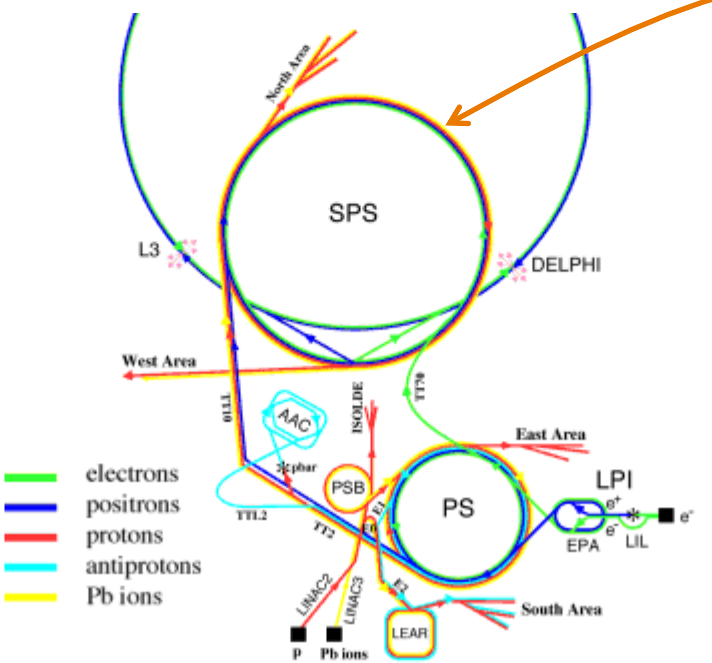
- It's easier to collide e+e-, because synchrotron radiation naturally "cools" the beam to smaller size.

First Proton Collider: CERN Intersecting Storage Rings (ISR)

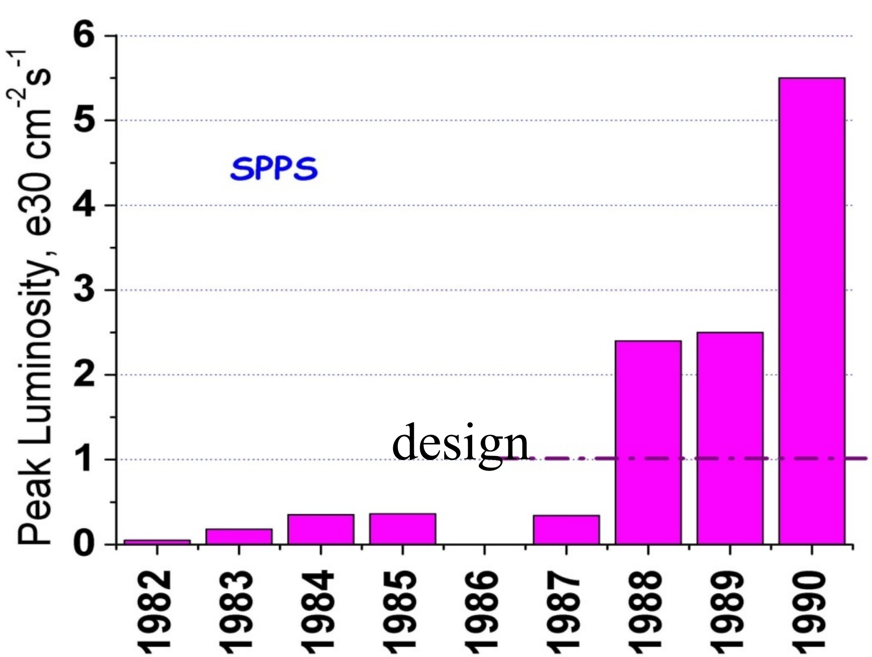


- 1971
- 31 GeV + 31 GeV colliding proton beams.
  - Highest CM Energy for 10 years
- Set a luminosity record that was not broken for 28 years!

$Sp\bar{p}S$: First Proton-Antiproton Collider



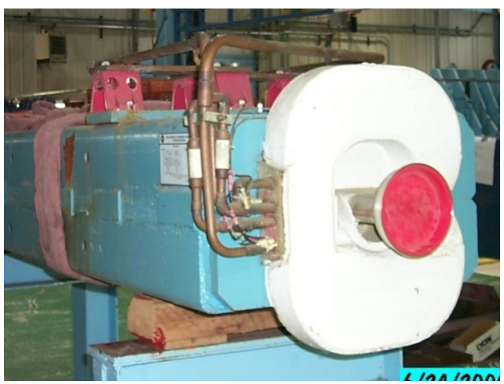
- Protons from the SPS were used to produce antiprotons, which were collected
- These were injected in the opposite direction (same beam pipe) and accelerated
- First collisions in 1981
- Discovery of W and Z in 1983
  - Nobel Prize for Rubbia and Van der Meer



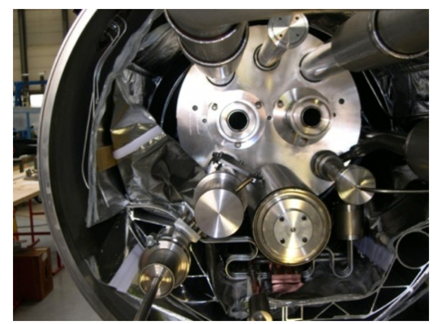
- Energy initially 270+270 GeV
- Raised to 315+315 GeV
  - Limited by power loss in magnets!

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



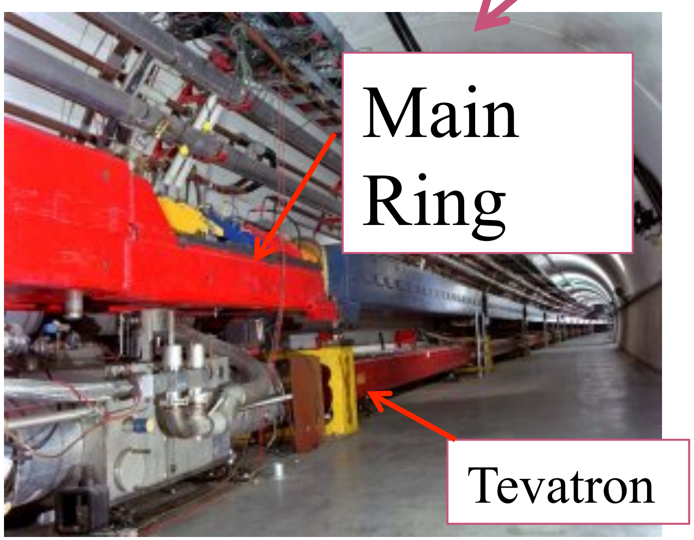
Superconducting magnets are complex and represent a great deal of stored energy which must be handled if something goes wrong



$$E \propto B^2$$

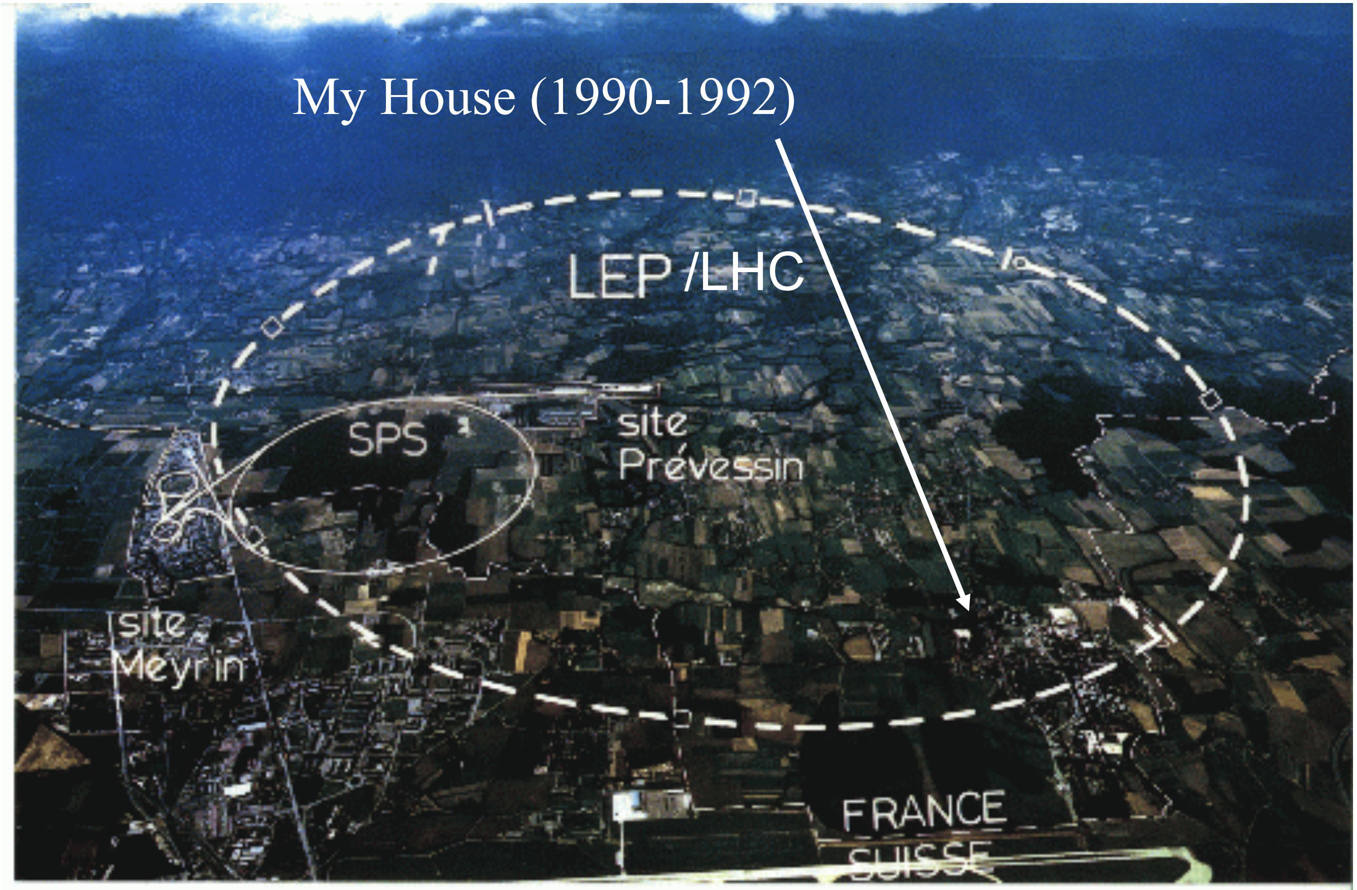
- R&D into superconducting technology is absolutely critical in the quest for the highest energies (made Tevatron and LHC possible!)
- Machine protection is one of the biggest challenges.

Tevatron: First Superconducting Synchrotron



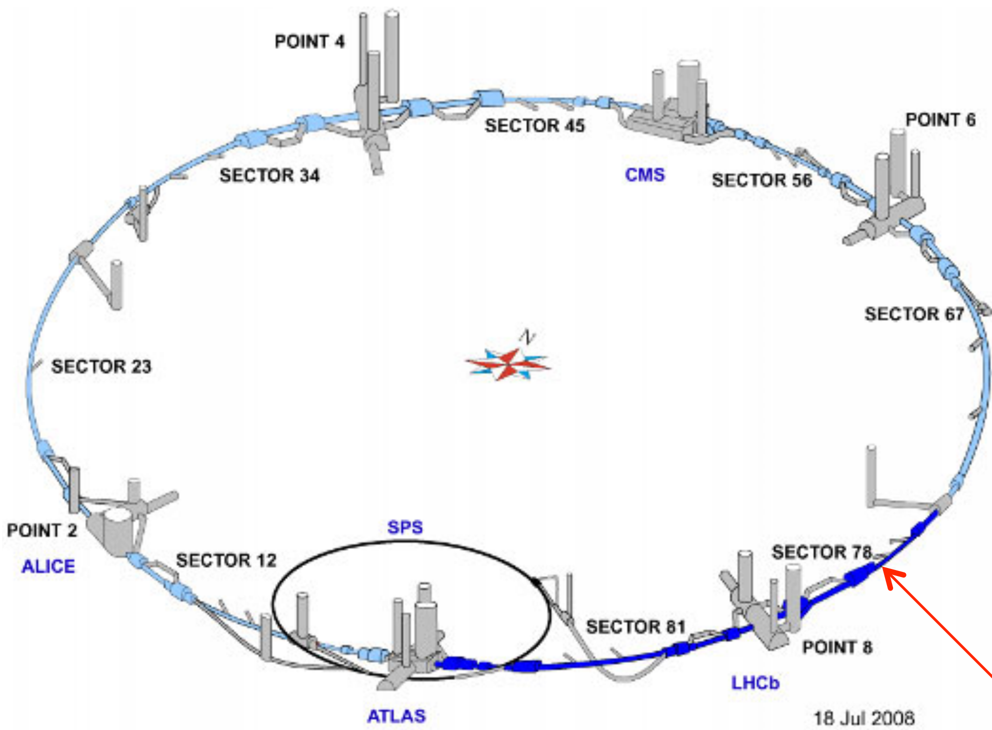
- 1968 – Fermilab Construction Begins
- 1972 – Beam in Main Ring
  - (normal magnets)
- Plans soon began for a superconducting collider to share the ring.
  - Dubbed "Saver Doubler" (later "Tevatron")
- 1985 – First proton-antiproton collisions in Tevatron
  - Most powerful accelerator in the world *for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

Back the present: Large Hadron Collider



- Straddles French/Swiss border near Geneva, Switzerland
- 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
  - 7 times Fermilab Tevatron
  - 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!

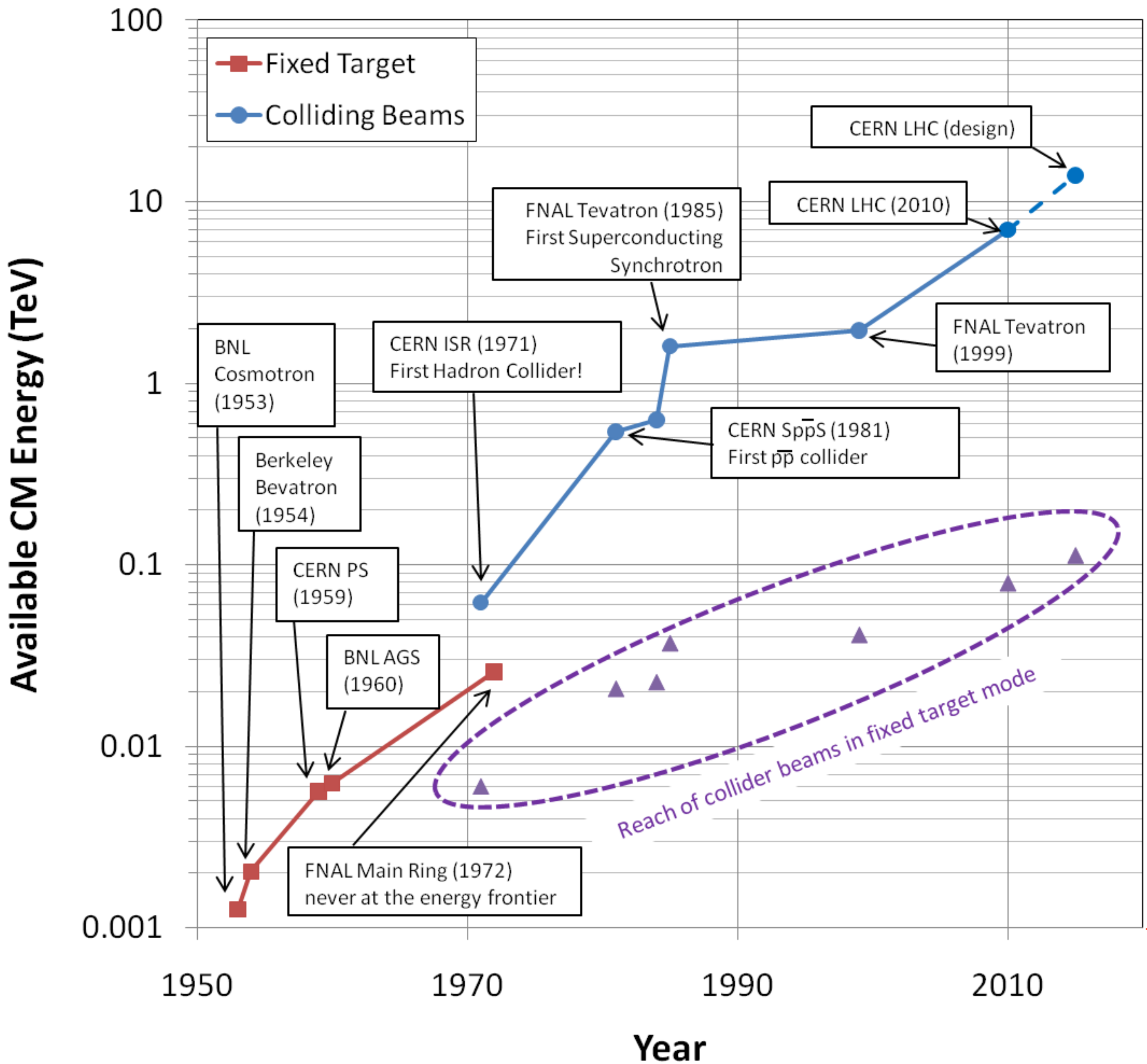
- 27 km in circumference
- 2 major collision regions: CMS and ATLAS
- 2 "smaller" regions: ALICE and LHCb

Partial LHC Timeline

- 2008
  - September 10th: First circulating beam
  - September 19th: BAD accident brings beam down for over a year (remember what I said about machine protection!)
- 2009
  - November 20th: Particles circulate again
- 2010
  - March 30th: 3.5 + 3.5 TeV collisions
    - Energy limited by flaw which caused accident
- 2012
  - April 5th: Energy increased to 4 + 4 TeV
  - July 4th: Announced the discovery of the Higgs
- 2013
  - Feb. 14th: Start 2 year shutdown to address design flaw and allow full energy operation
- 2015
  - Mar. 7: protons injected
  - May 20: 6.5+6.5 TeV protons collided

The LHC will (probably) be the flagship of the Energy Frontier for at least the next 20 years!

Evolution of the Accelerator Energy Frontier



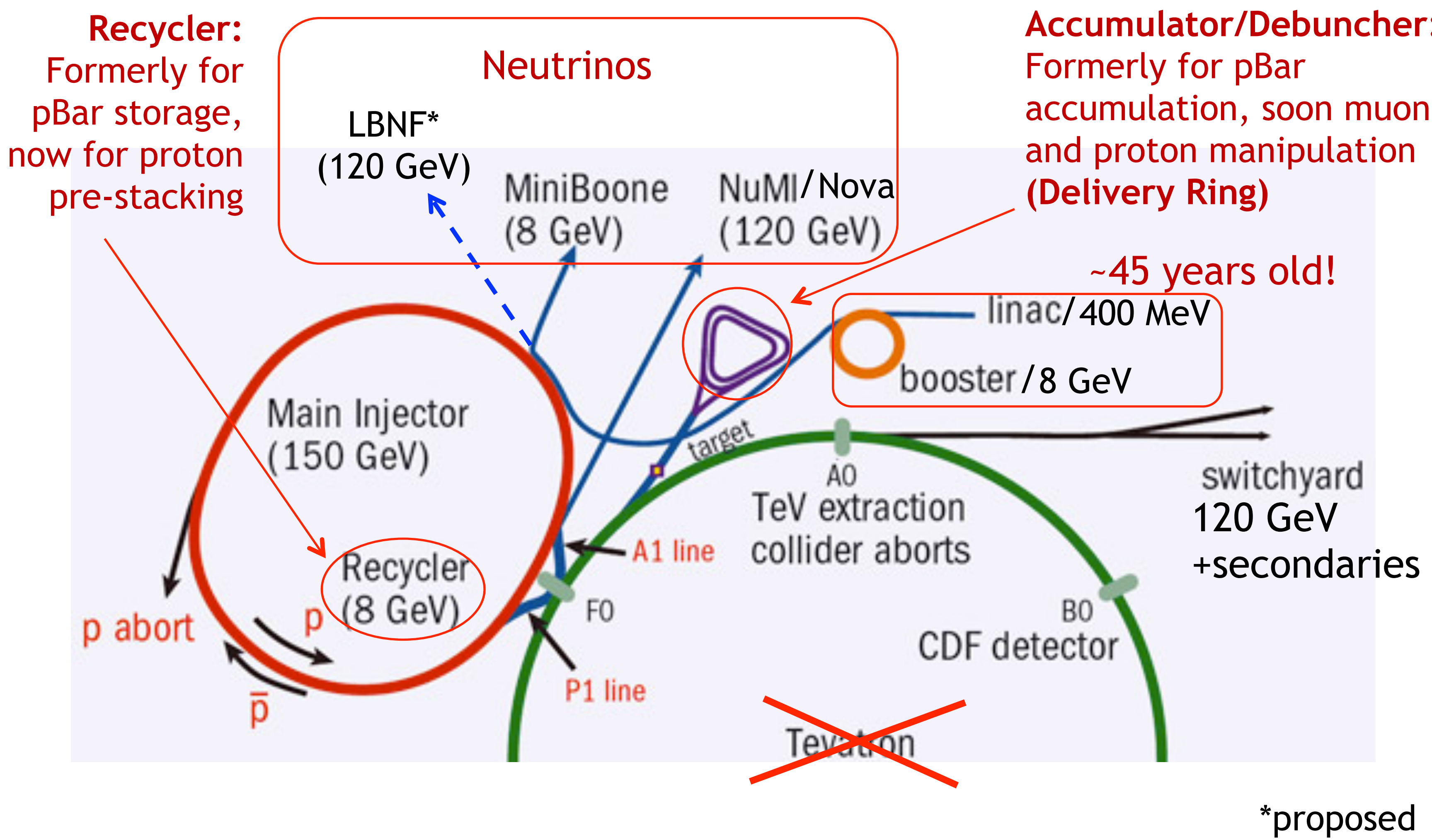
~a factor of 10 every 15 years

That trend will not continue

proton mass

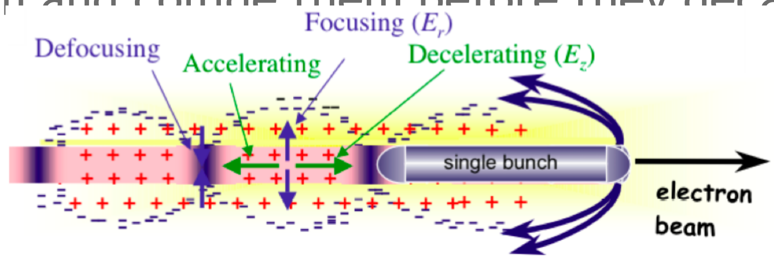
Fermilab Accelerator Complex Today

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

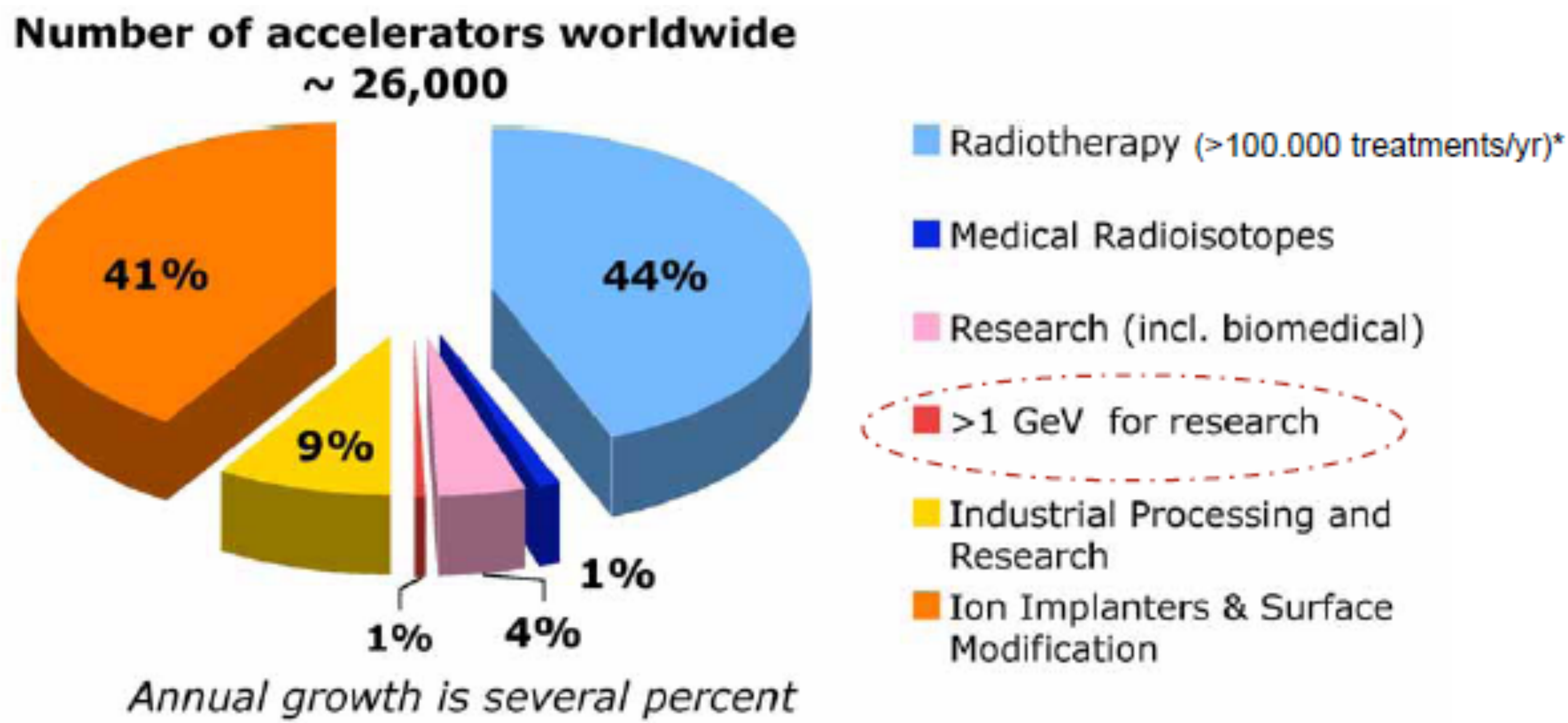


Possible Future Accelerators

- Circular Hadron Colliders
  - "Future Circular Collider": 100 km 50+50 TeV proton collider, based at CERN
- Linear e^+e^- colliders
  - "International Linear Collider" (ILC): Up to 500+500 GeV e^+e^- collider
    - Not energy frontier!
  - "Compact Linear Collider" (CLIC): Up to 1.5 TeV+1.5 TeV e^+e^- collider
- Muon collider?
  - Muons are point-like, like electrons, but don't radiate as much (good)
  - but they are unstable (bad)
  - R&D to find a way to cool them and collide them before they decay
  - Up to 5 TeV+5 TeV $\mu^+\mu^-$
- Even more exotic?
  - Plasma wakefield?
  - Dielectric wakefield?
  - Huge fields, but also huge technical challenges



Research Machines: Just the Tip of the Iceberg



Sales >3.5 B$/yr

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

Example: Spallation Neutron Source (Oak Ridge, TN)

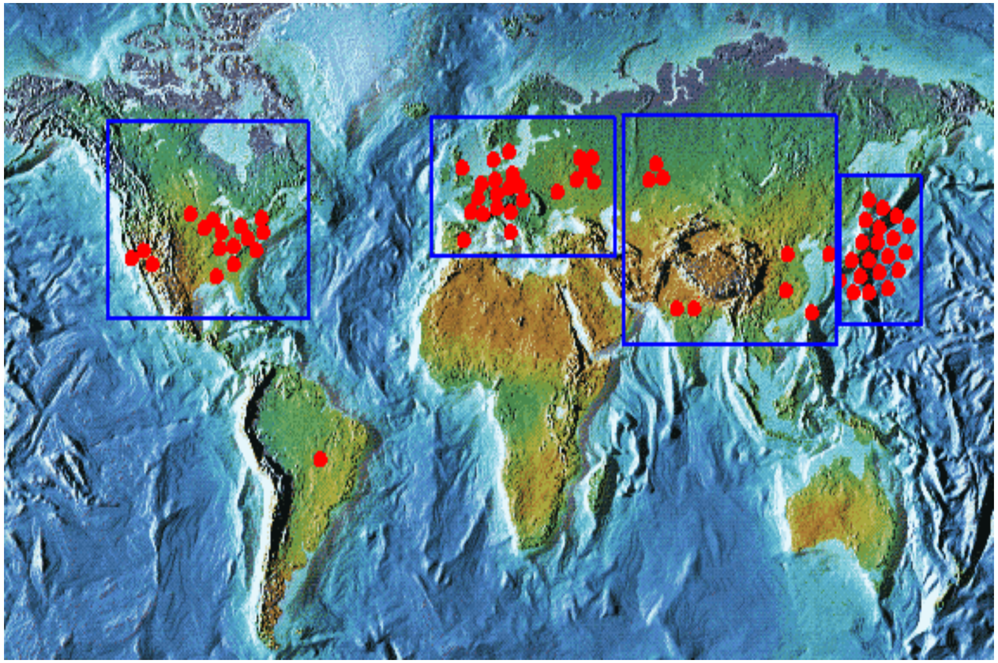
A 1 GeV Linac loads 1.5E14 protons into a non-accelerating synchrotron ring.

These are fast extracted onto a Mercury target

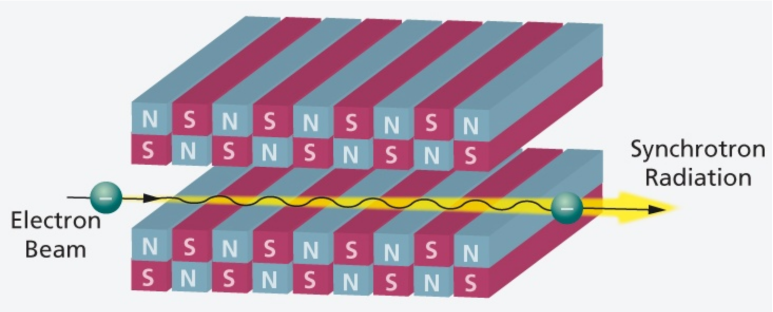
This happens at 60 Hz -> 1.4 MW

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…

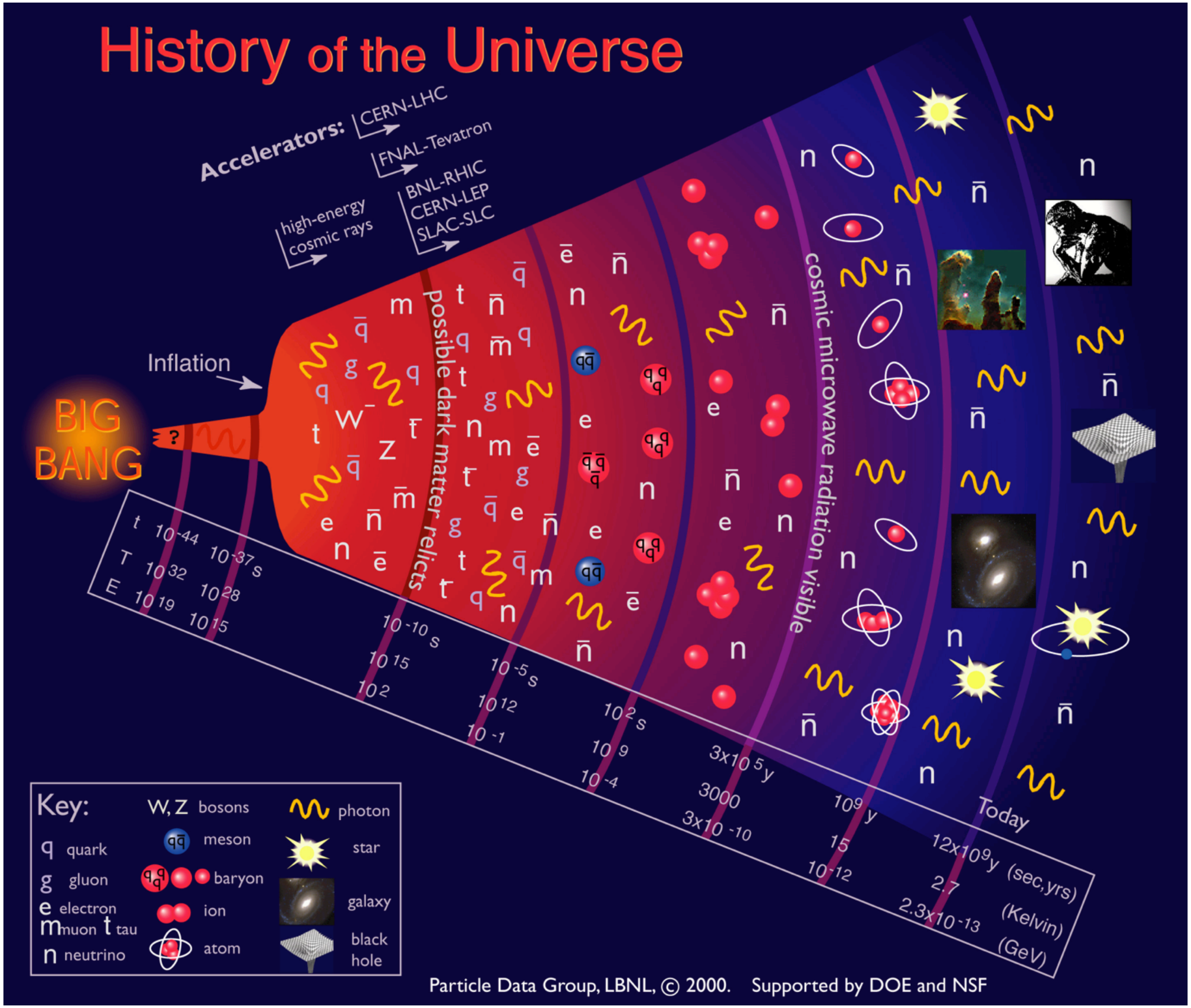
In a "Lichtenberg figure", a low energy electron linac is used to implant a layer of charge in a sheet of lucite. This charge can remain for weeks until it is discharged by a mechanical disruption.

Further Reading (in Order of Increasing Depth)

- My lectures at the 2014 Hadron Collider Physics Summer School
  - More details about Fermilab and the LHC (including "The Incident)
  - http://tinyurl.com/prebys-hcpss-2014
- Fermilab "Accelerator Concepts" ("Rookie Book")
  - http://www-bdnew.fnal.gov/operations/rookie_books/Concepts_v3.6.pdf
  - Particularly chapters II-IV
- Edmund Wilson, "Particle Accelerators"
  - Concise reference on a number of major topics
  - Available in paperback (important if you are paying)
  - Good reference for a non-accelerator physicist
- Edwards and Syphers "An Introduction to the Physics of High Energy Accelerators"
  - **My personal favorite**
  - Concise. Scope and level just right to get a solid grasp of the topic
  - Crazy expensive, for some reason.
- Helmut Wiedemann, "Particle Accelerator Physics"
  - Probably the most complete and thorough book around (originally two volumes)
  - Well written
  - Scope and mathematical level very high
- USPAS Course: http://uspas.fnal.gov/

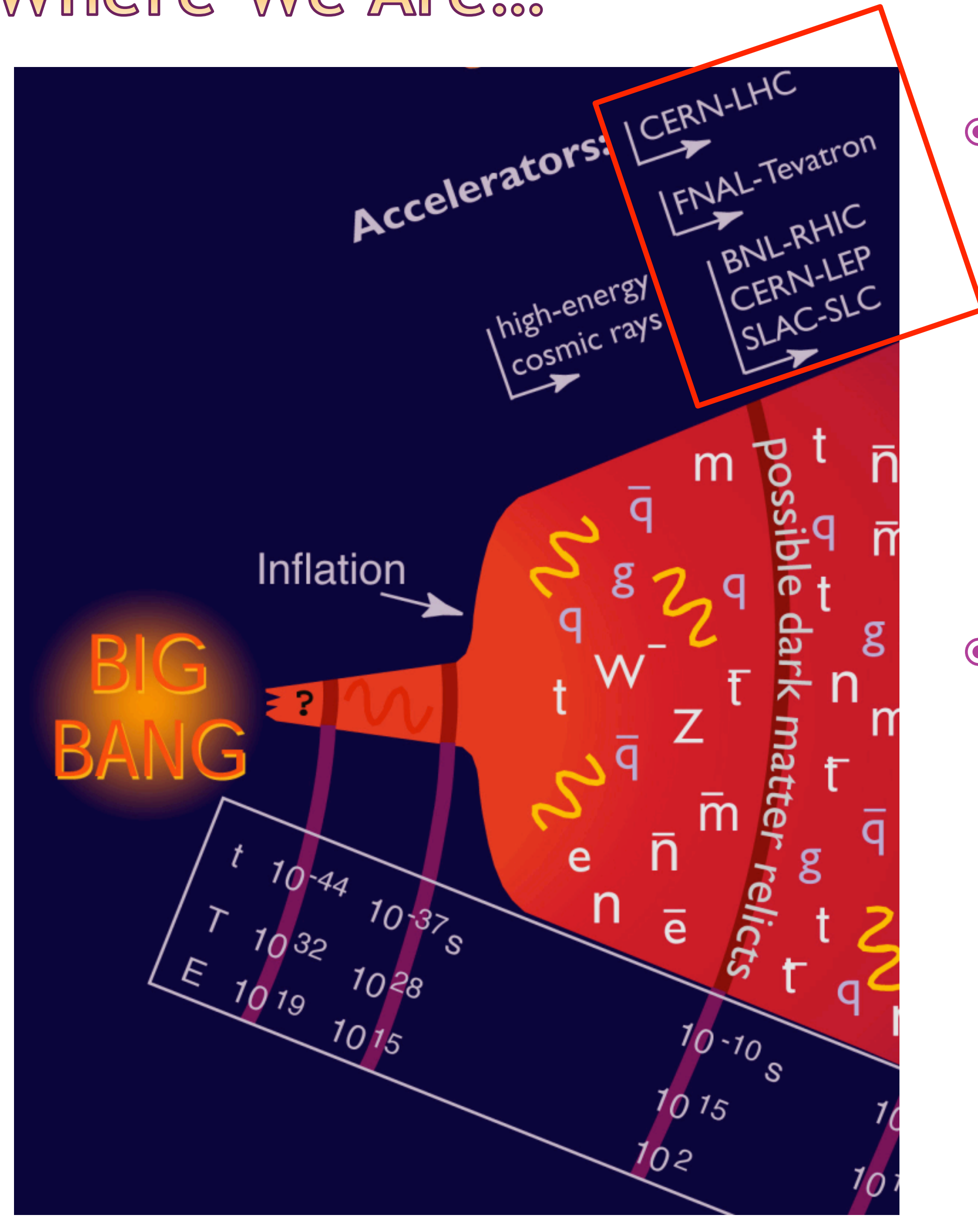
BACKUP SLIDES

Motivation



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.

Limits to Luminosity*

Total beam current, limited by machine protection(!), e⁻ cloud and other instabilities

"Brightness", limited by
- Space charge blowup at low energy
- Max beam-beam tune-shift

$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right]$$

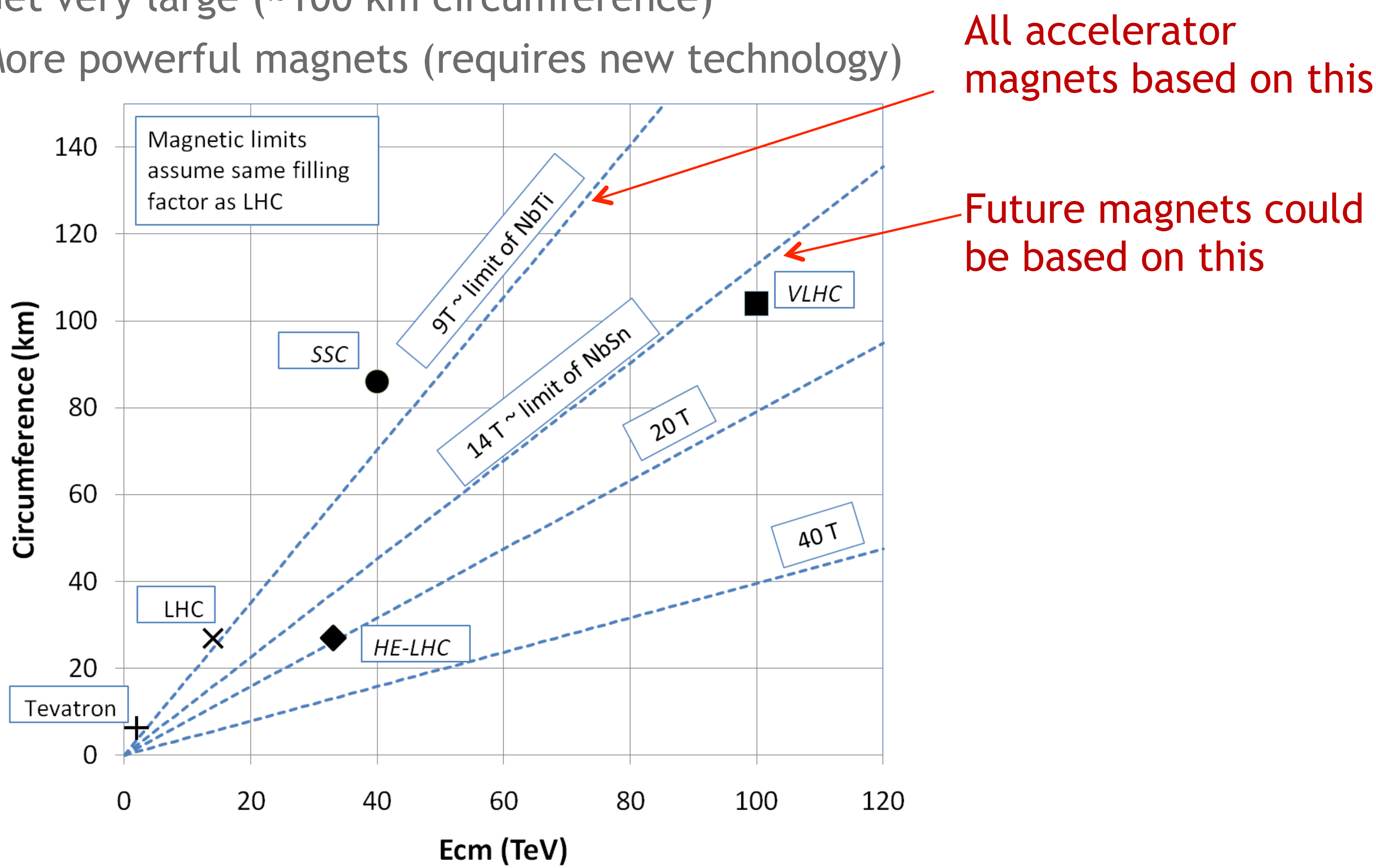
β*, limited by
- magnet technology
- chromatic effects

Geometric factor, related to crossing angle…

*see, eg, F. Zimmermann, "CERN Upgrade Plans", EPS-HEP 09, Krakow, for a thorough discussion of luminosity factors.

What next?

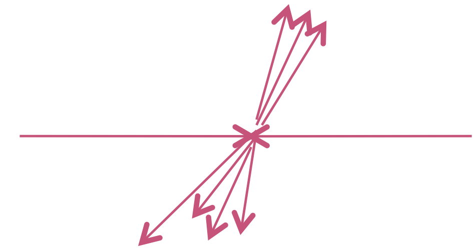
- The energy of Hadron colliders is limited by feasible size and magnet technology. Options:
  - Get very large (~100 km circumference)
  - More powerful magnets (requires new technology)



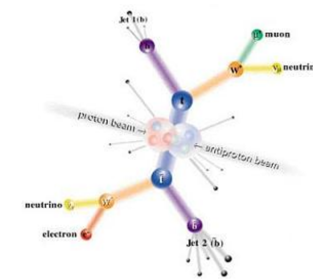
Future Circular Collider (FCC)

- 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).

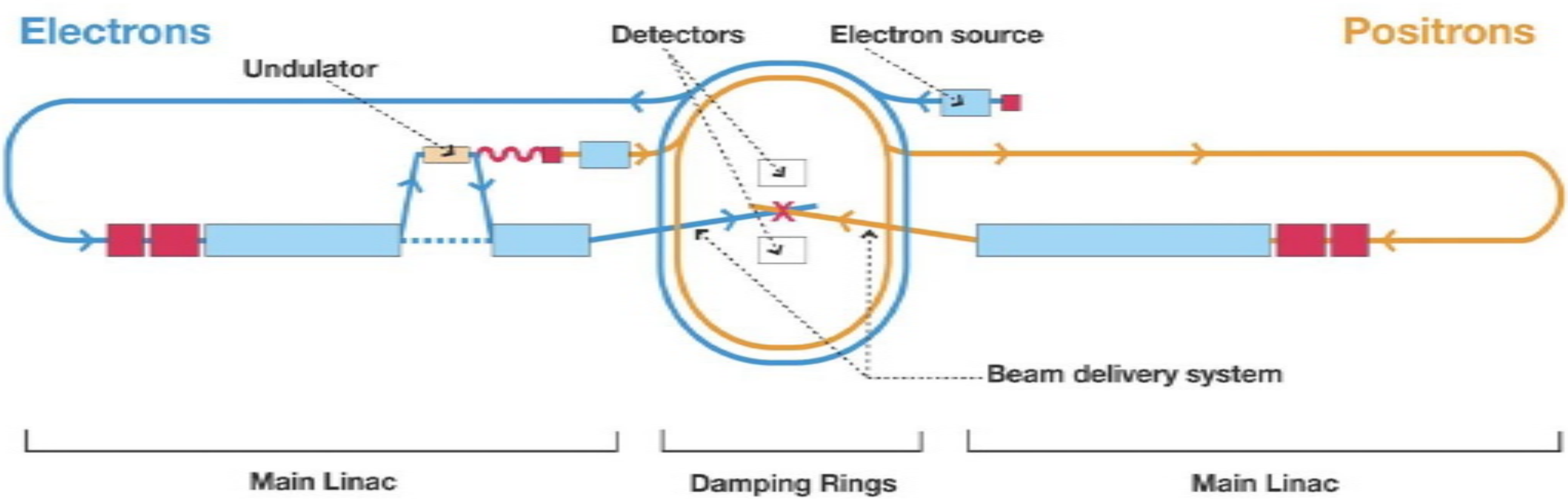


  - A lepton collider of >1 TeV/beam could compete with the discovery potential of the LHC
    - A lower energy lepton collider could be very useful for precision tests, but I'm talking about direct *energy frontier* discoveries.
  - Unfortunately, building such a collider is VERY, VERY hard
    - Eventually, circular e^+e^- colliders will radiate away all of their energy each turn
      - LEP reached 100 GeV/beam with a 27 km circuference synchrotron!

  ➔ Next e^+e^- collider will be linear

International Linear Collider (ILC)

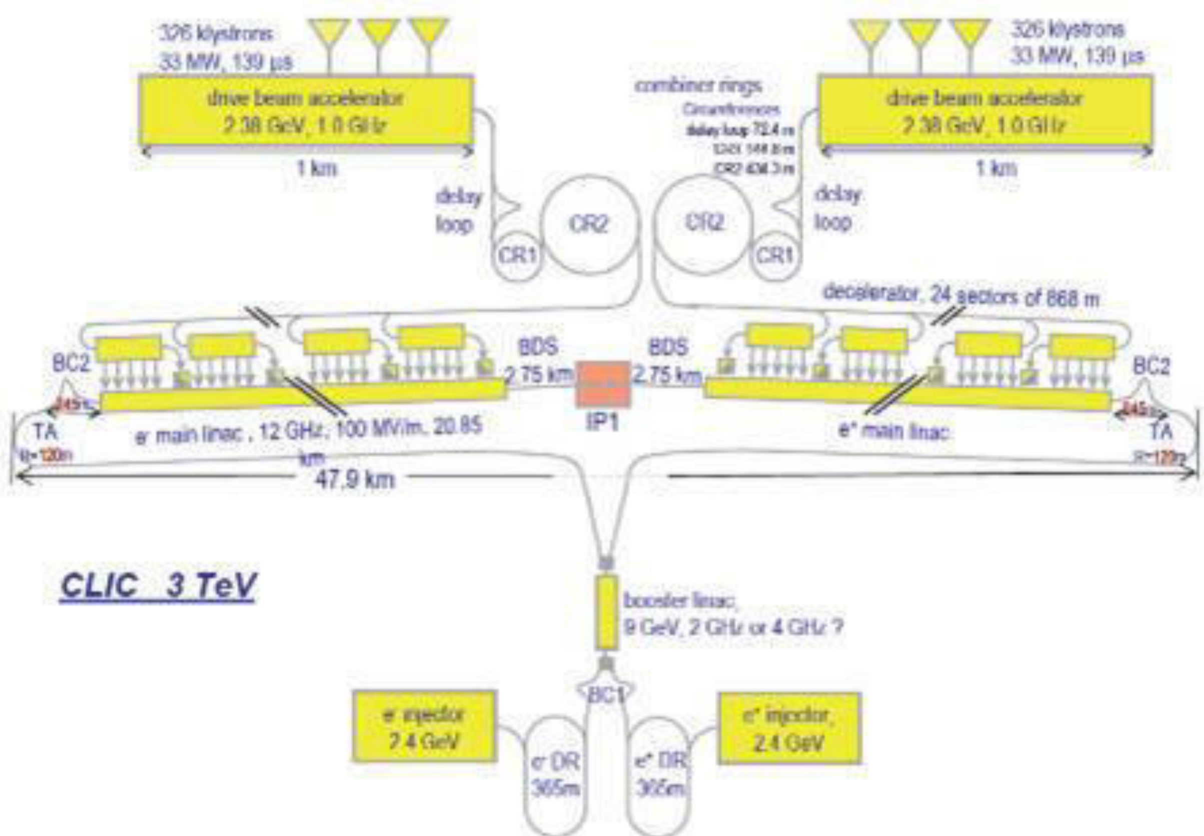
- LEP was the limit of circular e^+e^- colliders
  - Next step must be linear collider
  - Proposed ILC 30 km long, 250 x 250 GeV e^+e^- (NOT energy frontier)



- 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)?

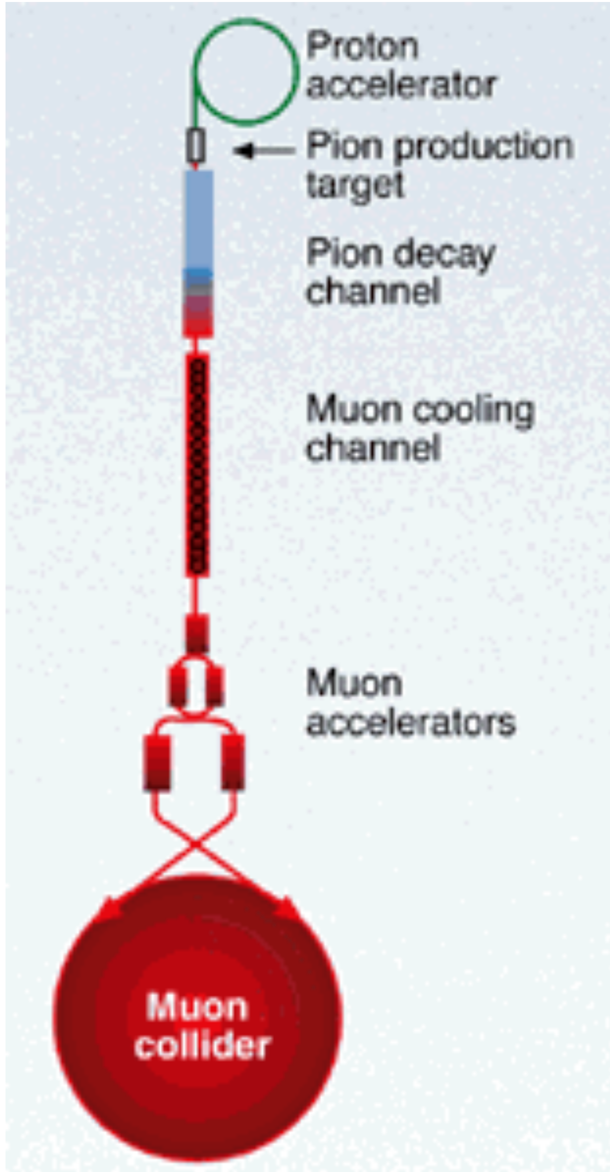
- Use low energy, high current electron beams to drive high energy accelerating structures



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

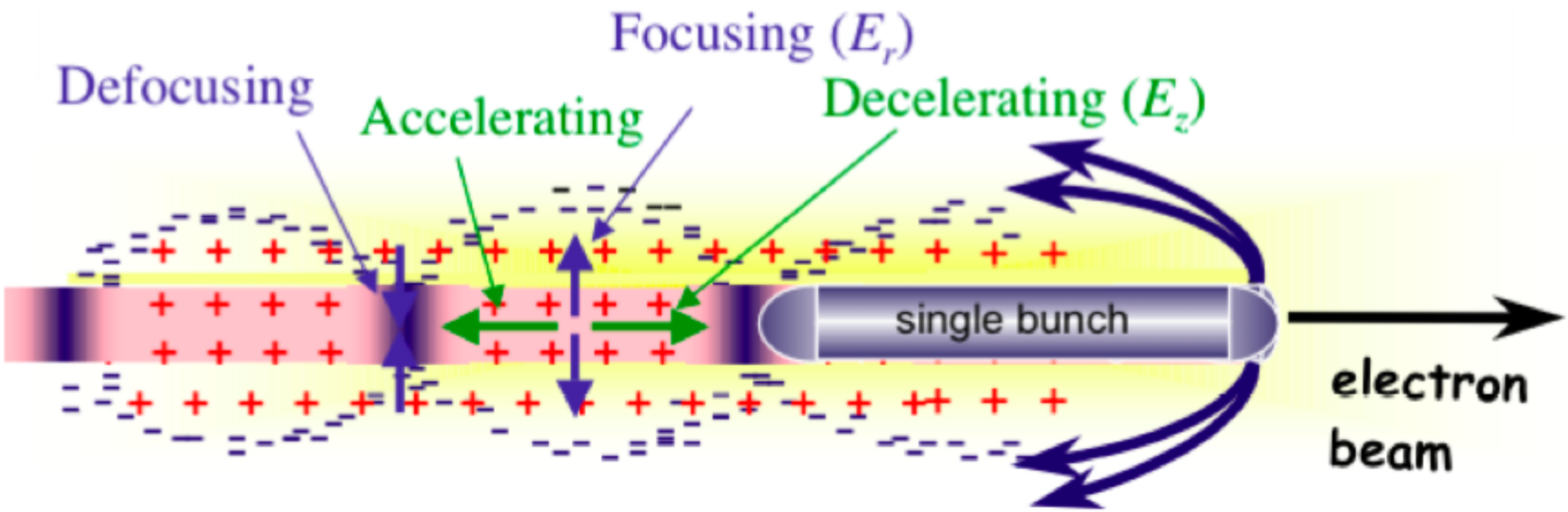
Muon colliders?

- 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.



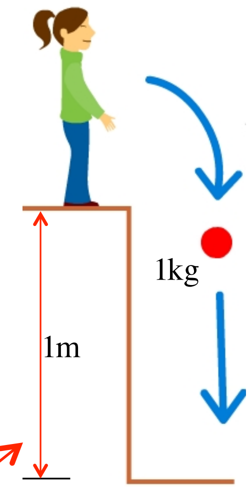
Wakefield accelerators?

- 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.

Units of energy: Electron Volts



- An "electron-volt" is the energy gained by a particle of unit charge is accelerated over 1V potential
- It is *really small*
  - 1eV =1.6x10^{-19} (=.00000000000000000016) Joules - our usual unit of energy.
  - A 1 kg weight dropped 1m would have 6x10^{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…

- Quantum mechanics tells us all particles have a wavelength

"Planck Constant"

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

momentum

as *v* approaches *c*

- 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…

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.

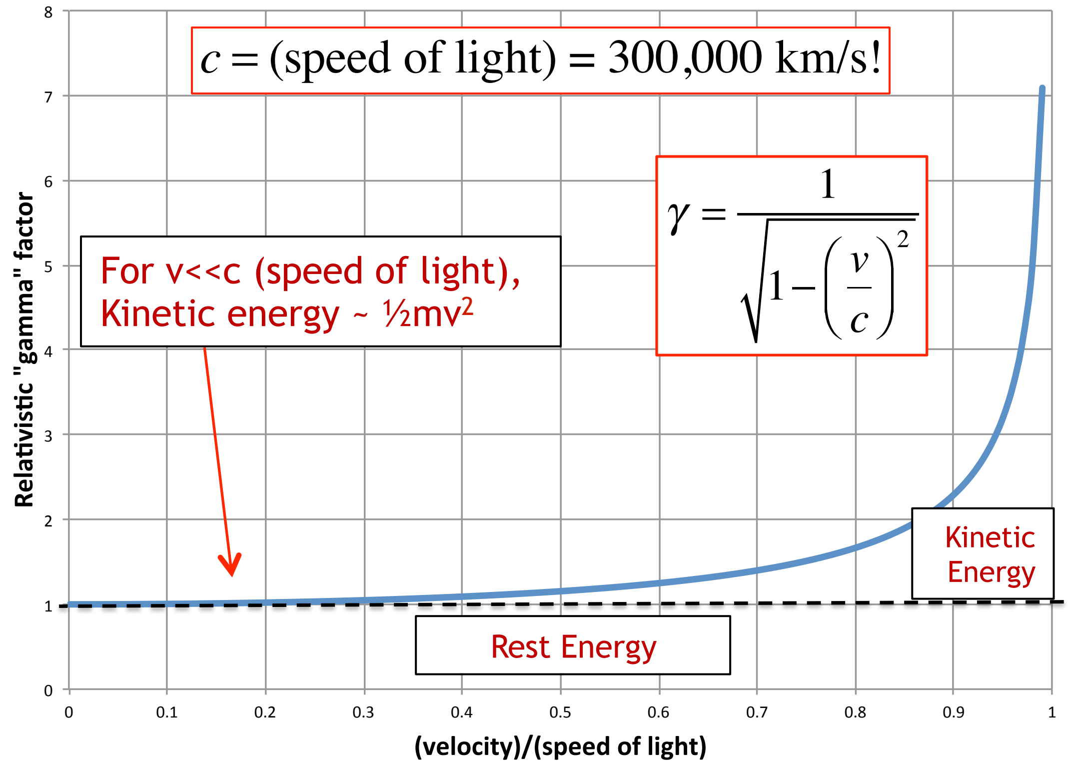
- If we could convert a kilogram of mass entirely to energy, it would supply all the electricity in the United States for *almost a day.*

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



Equations of Motion

- If we go through the equations, keeping only terms which are linear in *x* and *y*, we get

Local curvature due to dipole field (function of *s*)

$$\frac{\partial^2 x}{\partial s^2} + \left(\frac{1}{\rho(s)^2} + \frac{1}{(B\rho)} \frac{\partial B_y}{\partial x} \right) x = 0$$

$$\frac{\partial^2 y}{\partial s^2} - \frac{1}{(B\rho)} \frac{\partial B_x}{\partial y} y = 0$$

"Rigidity"

$\Rightarrow$

Periodic

$$x'' + K_x(s)x = 0$$

$$y'' + K_y(s)y = 0$$

Independent of energy for synchrotron!

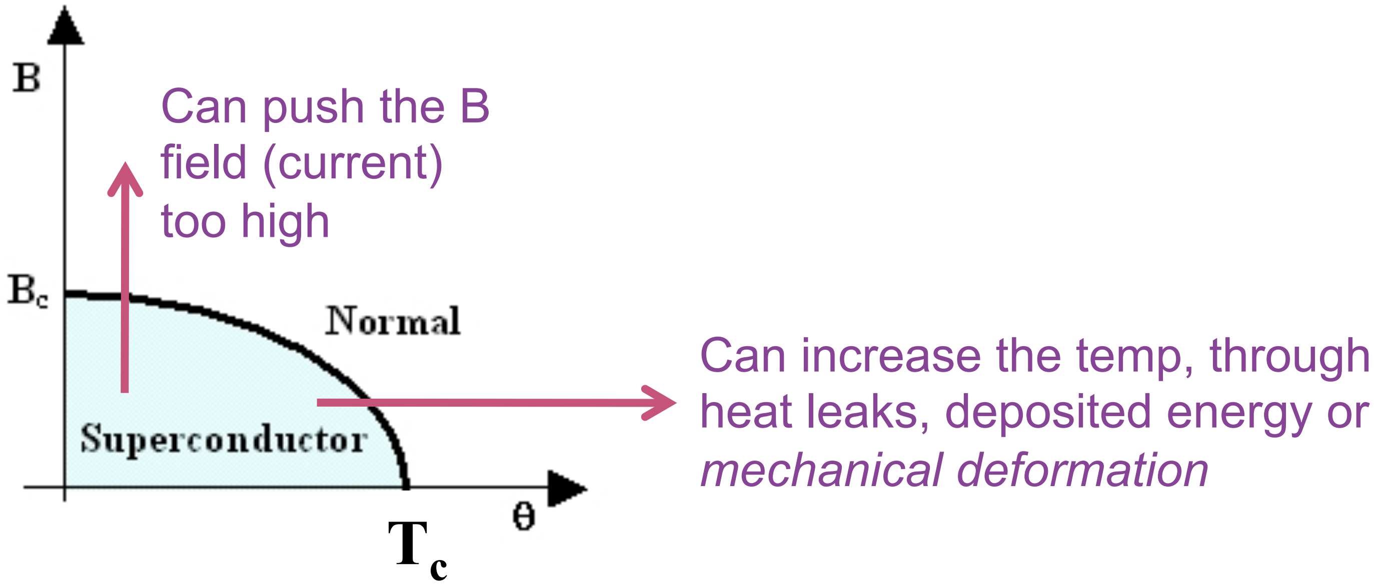
- Most generic treatment of small deviation from equilibrium in periodic system
  - "Hill's Equation", first used to study the stability of the lunar orbit
- Looks "kinda sorta" like a harmonic oscillator. If K is constant, then

$$x(s) = A\sin\left(\sqrt{K}x + \delta\right)$$ so try $$x(s) = Aw(s)\sin\left(\psi(s) + \delta\right)$$

not surprisingly, this works!

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.

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

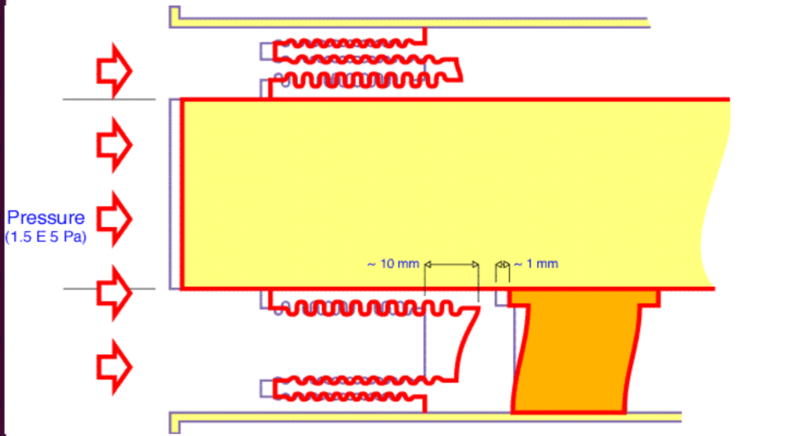
It begins…

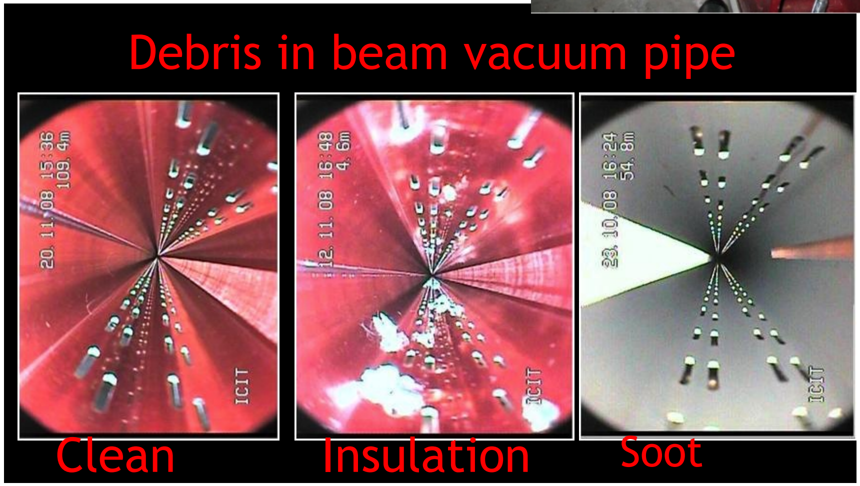
- 9:35 – First beam injected
- 9:58 – beam past CMS to point 6 dump
- 10:15 – beam to point 1 (ATLAS)
- 10:26 – First turn!
- …and there was much rejoicing

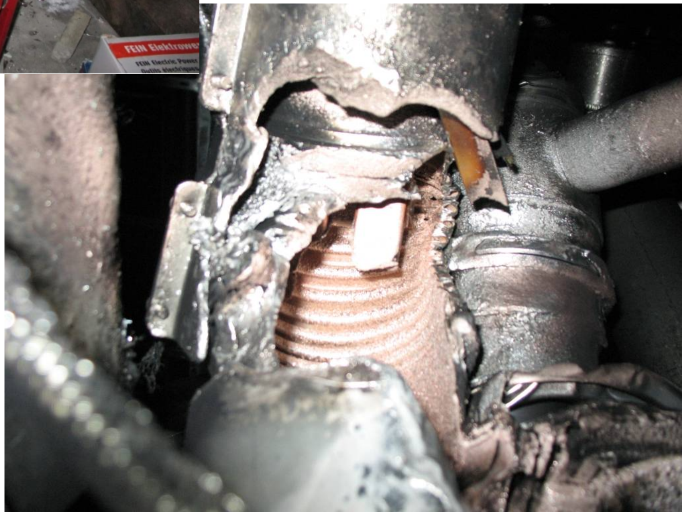
Commissioning proceeded smoothly and rapidly until September 19th, when *something* very bad happened

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



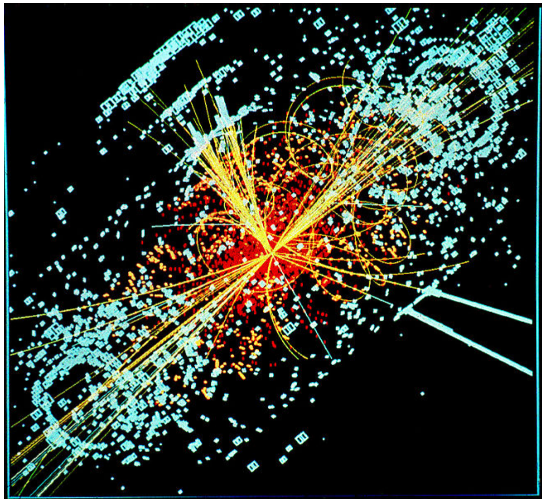




Secondary arcs

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

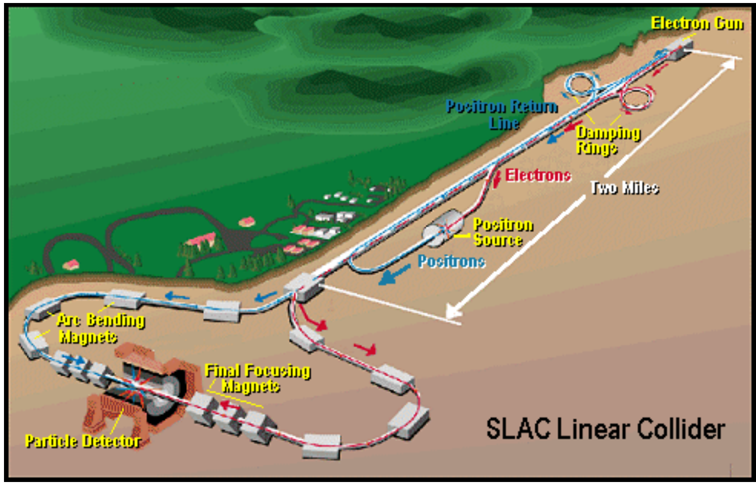
Some other important accelerators (past):

LEP (at CERN):

- 27 km in circumference
- e+e-
- Primarily at $2E=M_Z$ (90 GeV)
- Pushed to E_{CM}=200GeV
- 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**

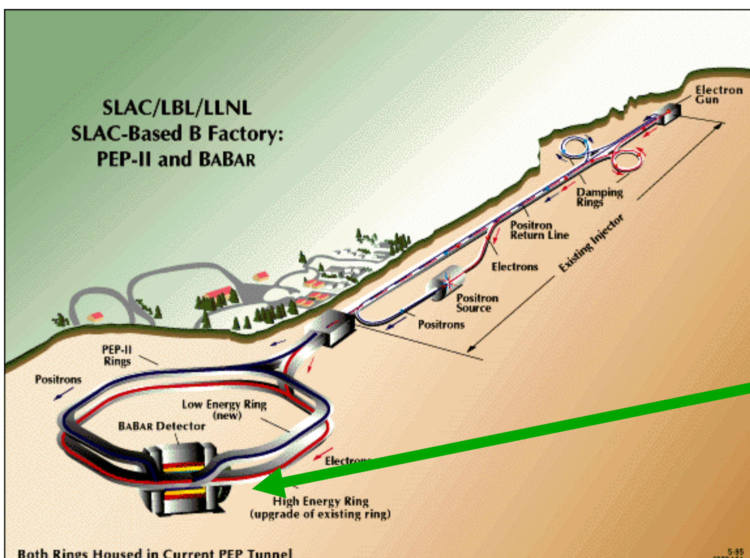


B-Factories

- 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):

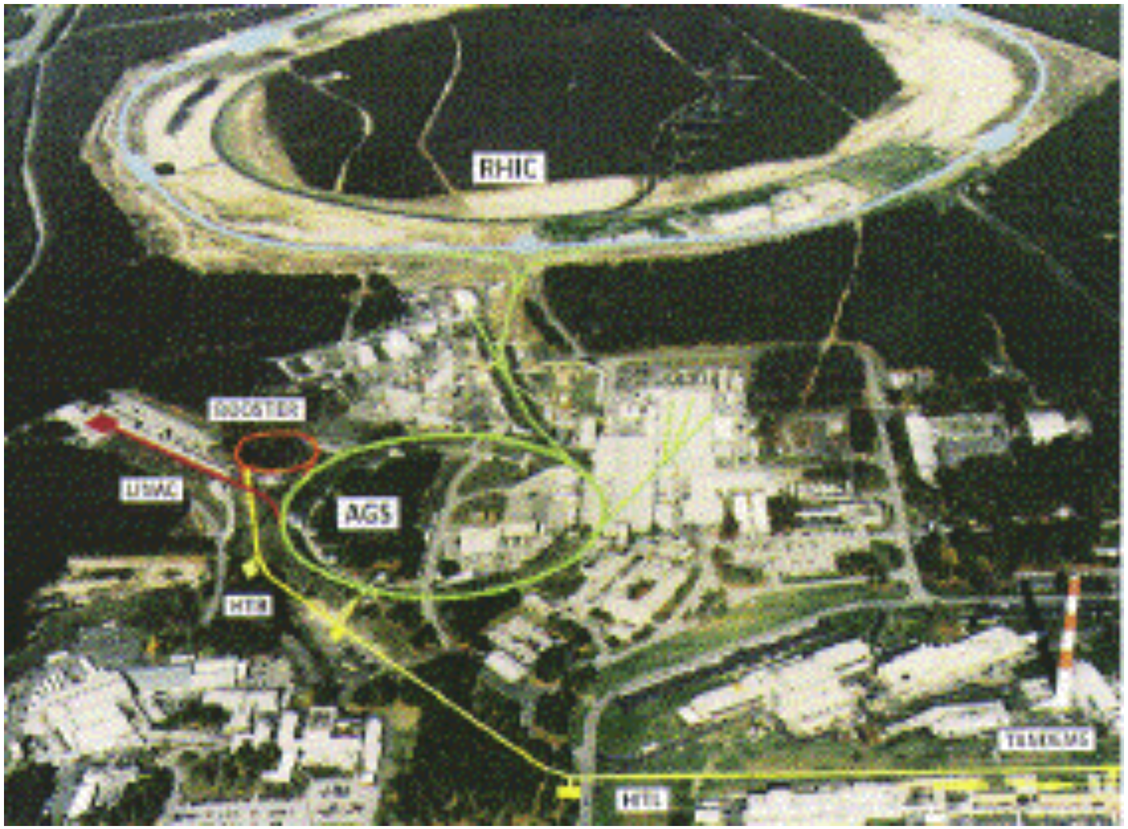
- Located at KEK (Japan)
- 8GeV e- x 3.5 GeV e+
- Peak luminosity >1e34



PEP-II (BaBar Experiment)

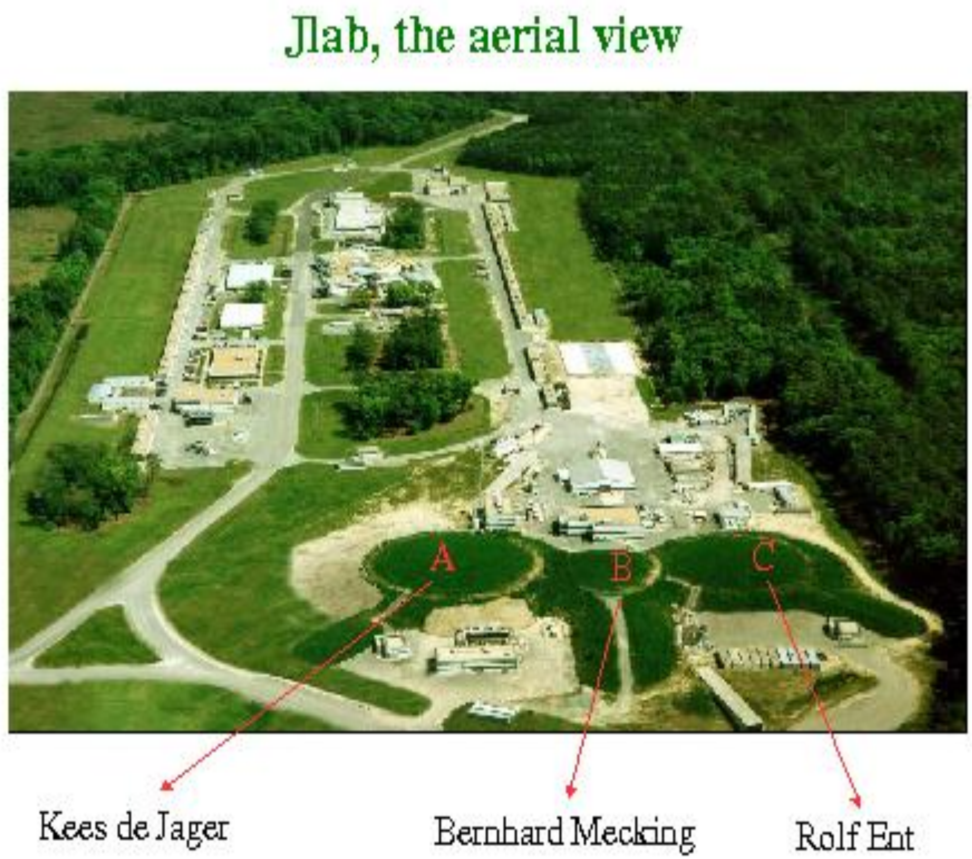
- Located at SLAC (USA)
- 9GeV e- x 3.1 GeV e+
- Peak luminosity >1e34

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)



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