Accelerator Physics and Technology

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Hadron Collider Physics Summer School
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- Today – Lecture 1
  - Basics of Accelerator Physics
  - High Energy Colliders: Past, Present, Future
- Tomorrow – Lecture 2
  - Key Accelerator Technologies
  - Technicalities of LHC Operation

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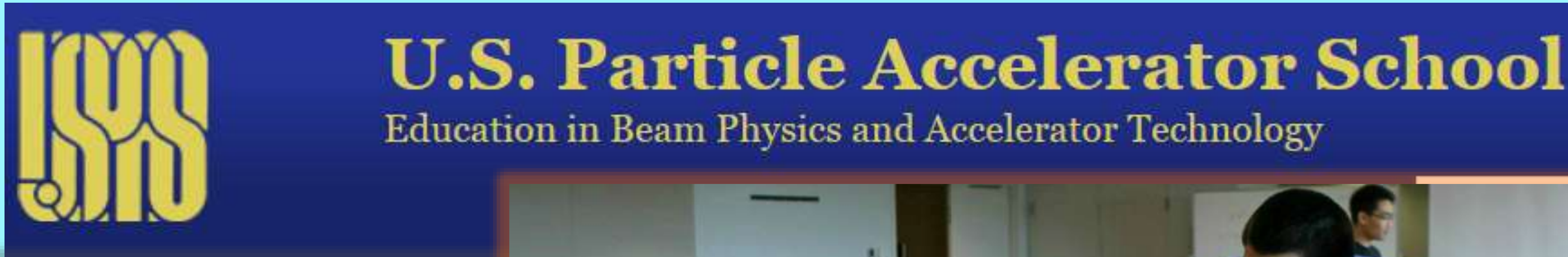
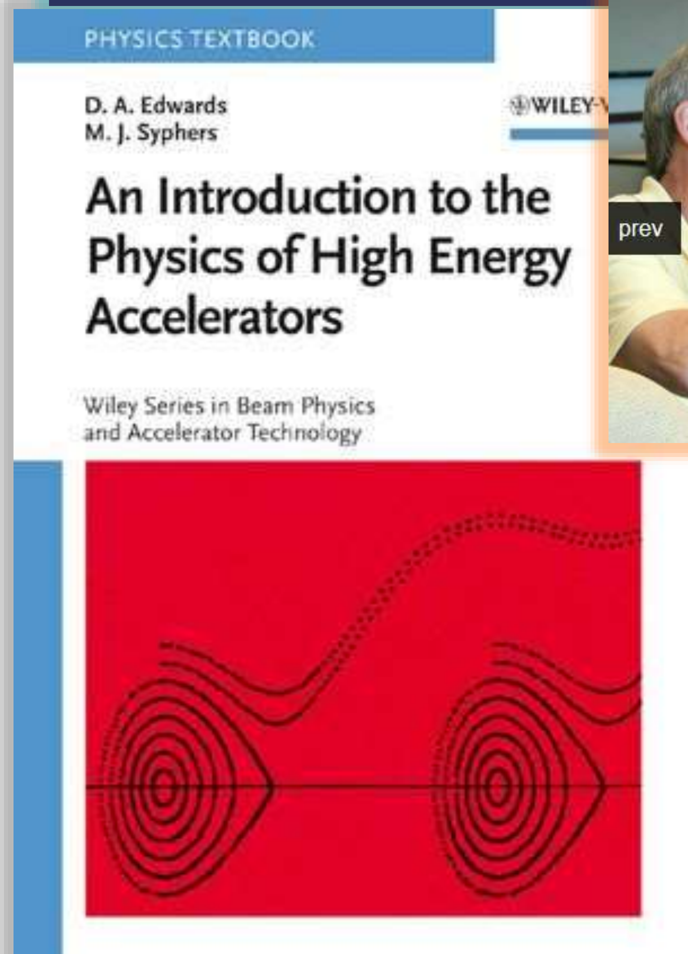
Heads-Up

- This talk will focus primarily on the evolution of the highest energy particle accelerators, particularly, hadron ones
  - 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.
- This talk will 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…*

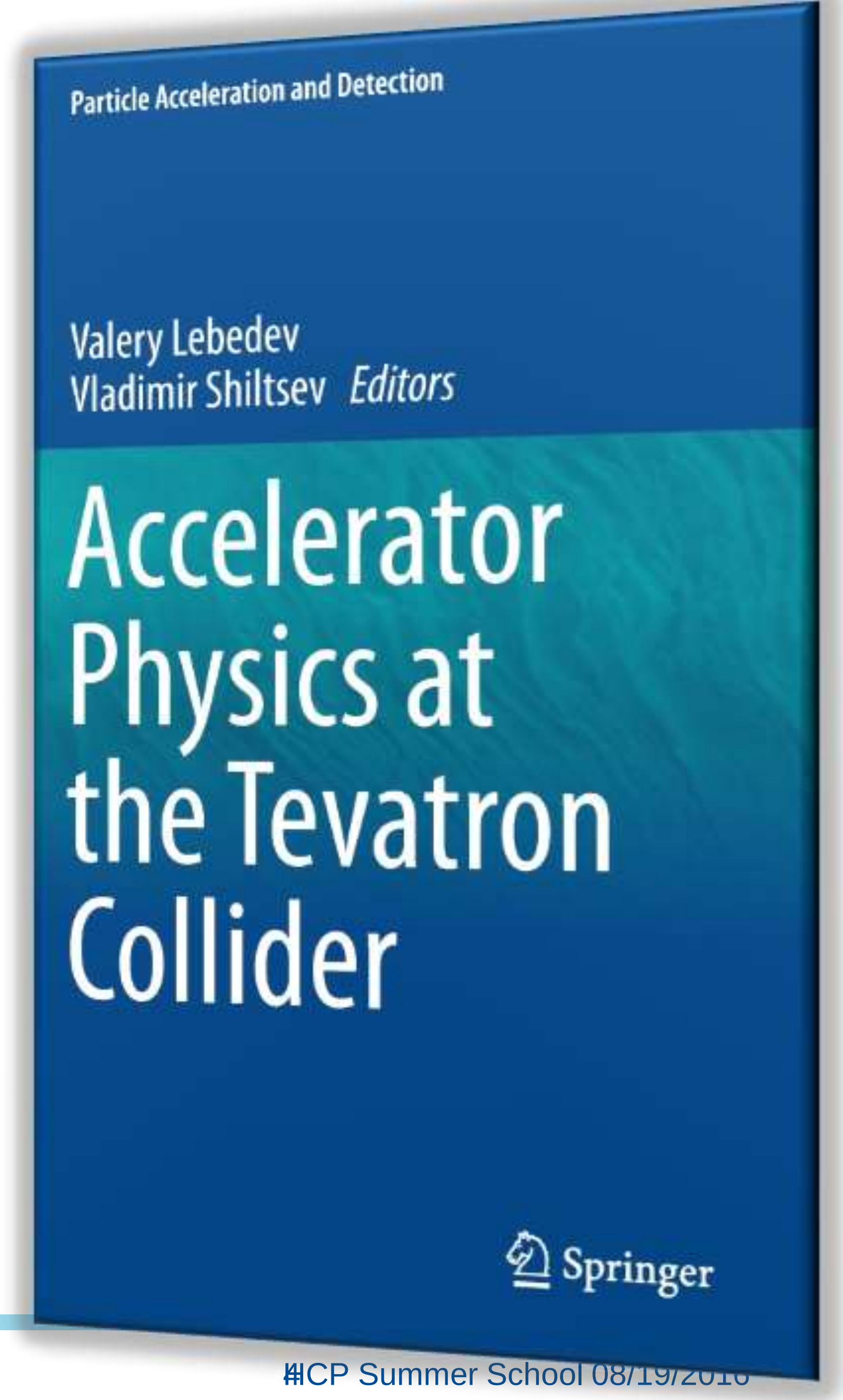
Best Way to Get Introduced to Accelerators





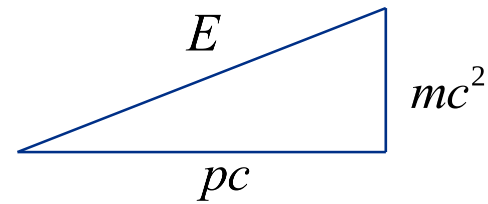
Further Reading on Accelerator Physics

- Accelerator Physics, S.Y. Lee (*World Scientific*, 1999)
- Hand Book of Accelerator Physics and Engineering – eds. A.Chao and M.Tigner (*World Scientific*, 1999)
- CAS CERN Accelerator, Accelerator Physics Courses http://cas.web.cern.ch/
- Particle Accelerators Physics, H.Wiedemann (*Springer*, 3rd ed., 2007)
- Accelerator Physics at the Tevatron Collider - by V.Lebedev and V.Shiltsev, (*Springer,* 2014)



Relativity and Units

Remember !



- 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

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

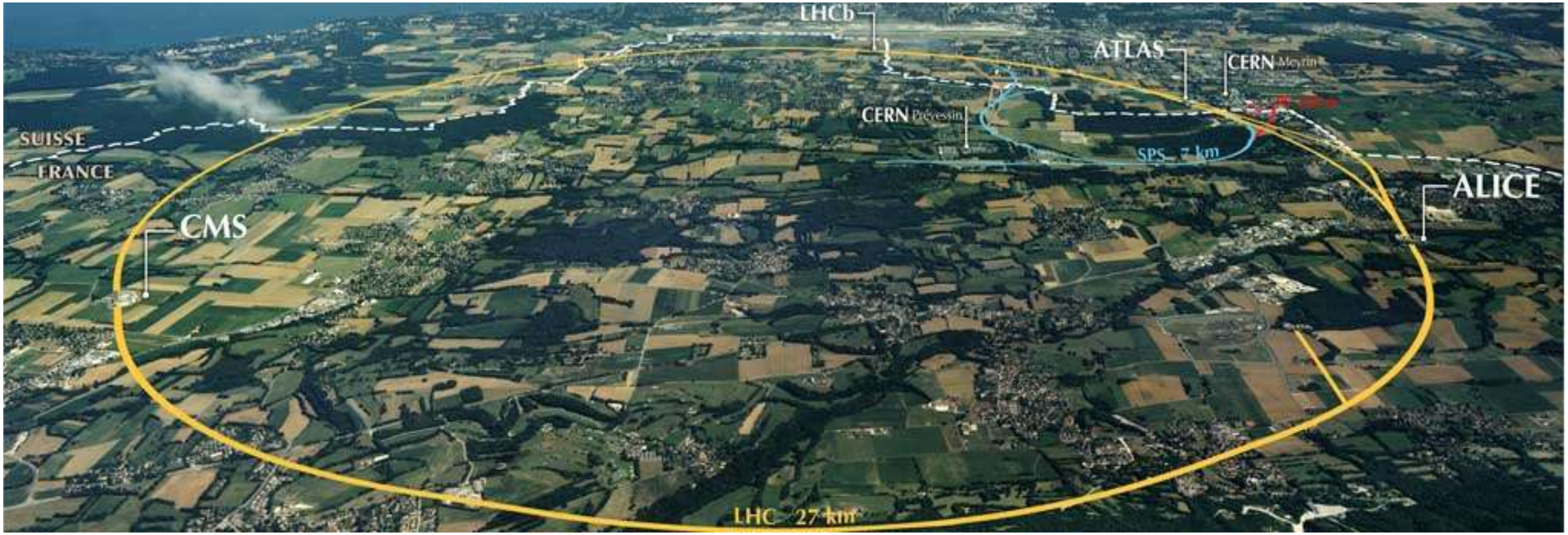
$$g = \frac{E}{mc^2}$$

$$bg = \frac{pc}{mc^2}$$

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 @ β= 0.9 = 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.

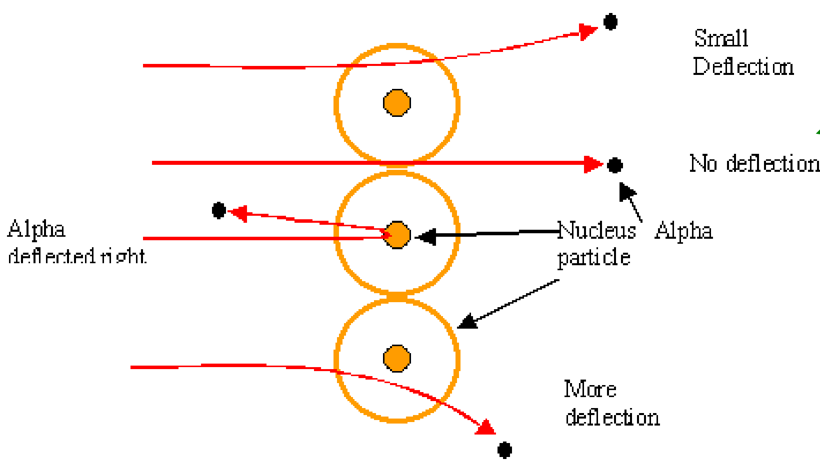
State of the Art: Large Hadron Collider (LHC)



- 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 = 7,000 GeV
- That's where we are. Now let's see how we got here…

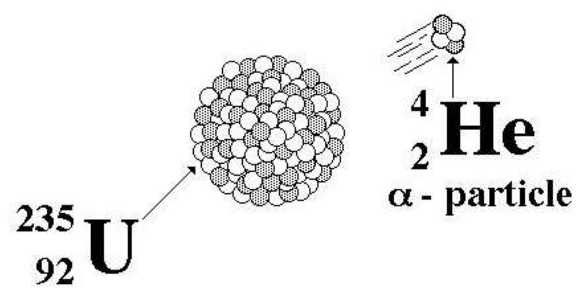
Rewind: Some Pre-History

- The first artificial acceleration of particles was done using “Crookes tubes”, in the latter half of the 19^{th} 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)



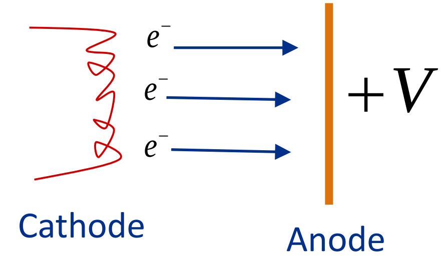
Study the way radioactive particles “scatter” off of atoms

- 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)



$$K = eEd = eV$$

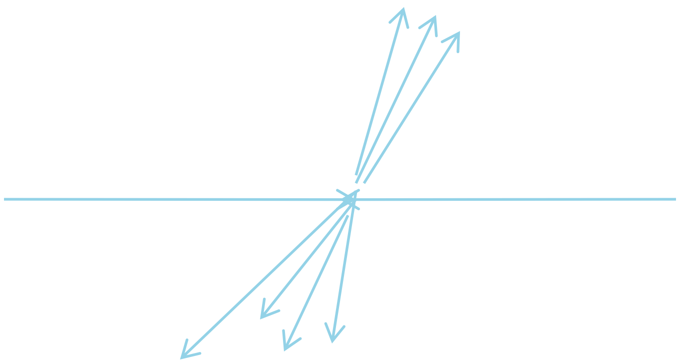
Limited by magnitude of electric field:

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

Solutions:

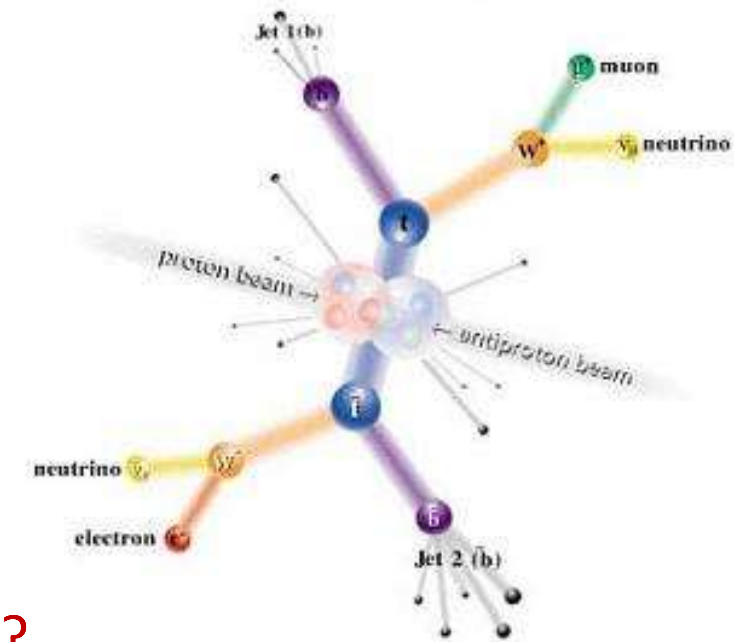
- Alternate fields to keep particles in accelerating fields -> Radio Frequency (RF) acceleration
- Bend particles so they see the same accelerating field over and over -> cyclotrons, synchrotrons

Interlude: Electrons vs. Protons



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

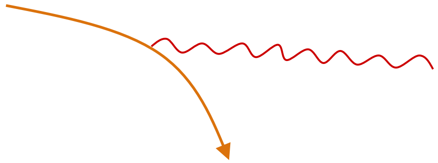
- Protons are made of quarks and gluons
  - Interaction take place between these constituents.
  - Only a small fraction of energy available, not well-defined.
  - Rest of particle fragments -> big mess!



So why not stick to electrons?

Synchrotron Radiation

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



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

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)

would not work for electrons!

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

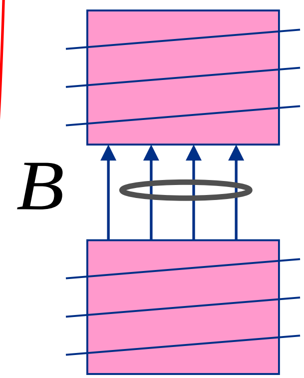
$$r = \frac{p}{qB} \approx \frac{mv}{qB} \quad (v << c)$$

$$f = \frac{v}{2pr}$$

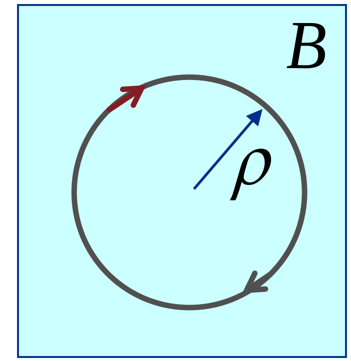
$$= \frac{qB}{2pm} \quad \text{(constant!!)}$$

$$W_s = \frac{f}{2p} = \frac{qB}{m}$$

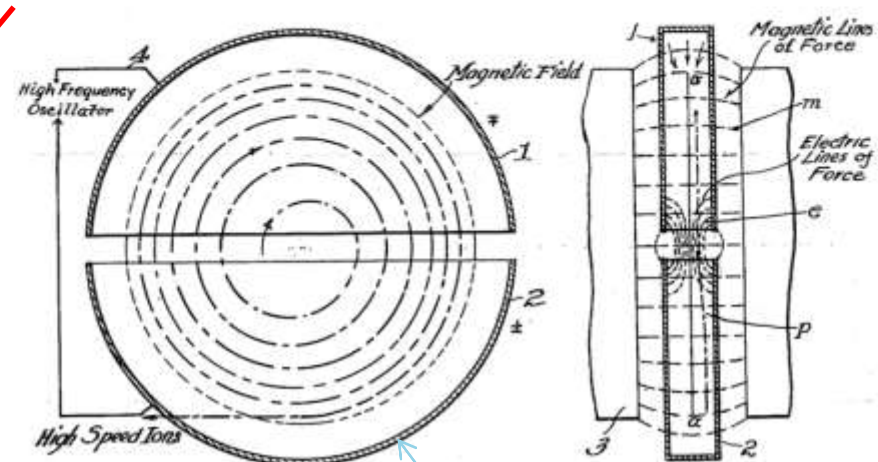
side view



top view



"Cyclotron Frequency"



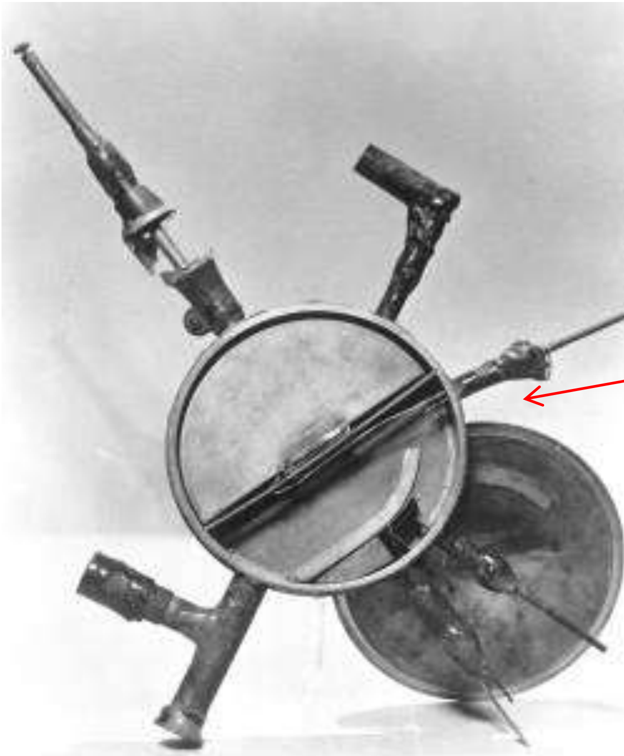
For a proton:

$$f_C = 15.2 ´ \ B[T] \ \text{MHz}$$

i.e. "RF" range

By applying a voltage which oscillates at f_c, we can accelerate 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)
  - E.O.Lawrence and Livingston
  - *K*=80 keV, 41 turns
  - Fit in your hand

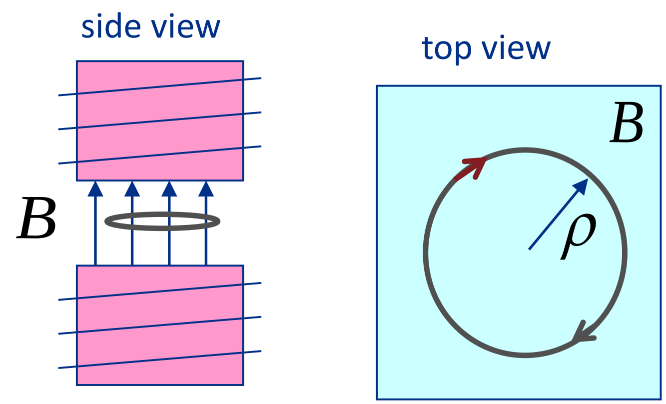
Nobel Prize 1939

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

Understanding Beam Motion: Beam "Rigidity"

- The relativistically correct form of Newton's Laws for a particle in an electromagnetic field is: $\vec{F} = \dfrac{d\vec{p}}{dt} = q\left(\vec{E} + \dfrac{\vec{v}}{c} \times \vec{B}\right); \vec{p} \equiv \gamma m \vec{v}$

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



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

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

constant for fixed energy!

T-m²/s=V

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

units of eV in our usual convention

Beam "rigidity" = constant at a given momentum (even when *B*=0!)

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

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/c²]		0.938	
kinetic energy	K [GeV]		.4	7000
total energy	E [GeV]	$K+mc^2$	1.3382	7000.938
momentum	p [GeV/c]	$\sqrt{E^2 - \left(mc^2\right)^2}$	0.95426	7000.938
rel. beta	β	$\left(pc\right)/E$	0.713	0.999999991
rel. gamma	γ	$E/(mc^2)$	1.426	7461.5
beta-gamma	βγ	$\left(pc\right)/(mc^2)$	1.017	7461.5
rigidity	(Bρ) [T-m]	p[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

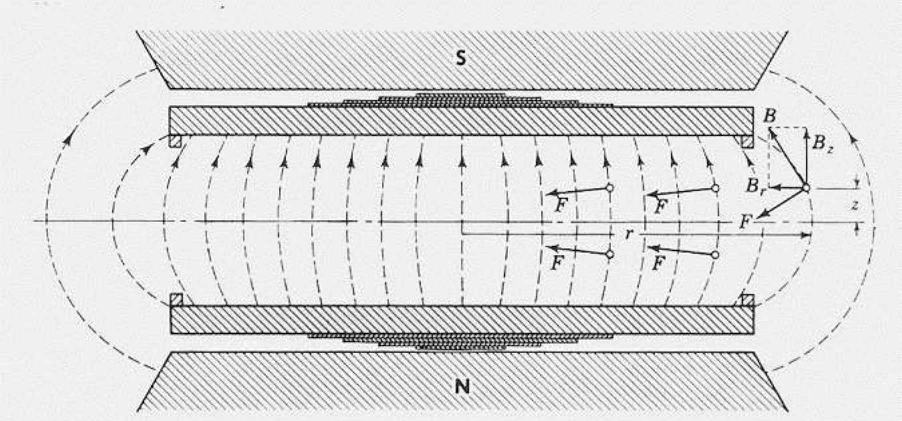
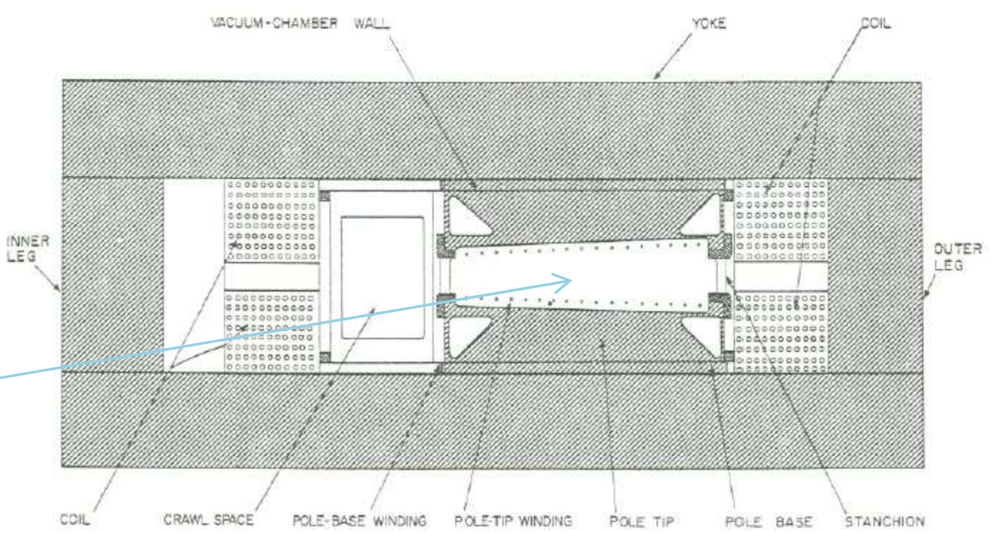


Fig. 6-7. Radially decreasing magnetic field between poles of a cyclotron magnet, showing shims for field correction.

- 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”!

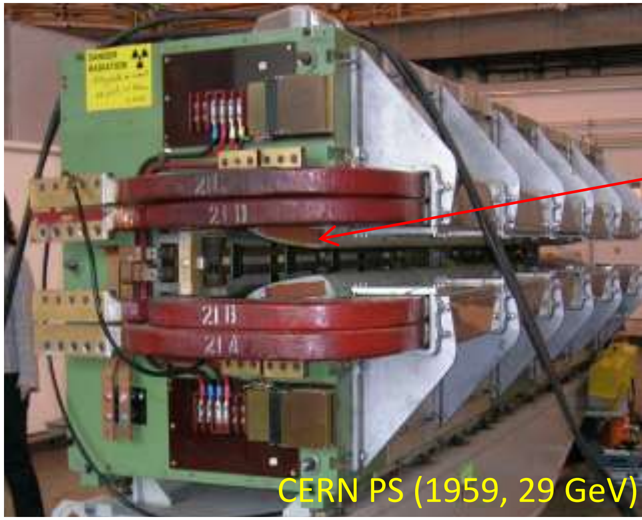


Strong Focusing

- 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

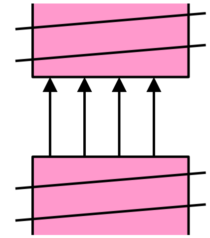
Strong focusing was originally implemented by building magnets with non-parallel pole faces to introduce a linear magnetic gradient



CERN PS (1959, 29 GeV)

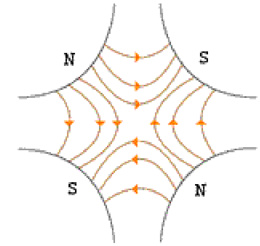
$$B_y(x) = B_0 + \frac{\partial B_y}{\partial x} x$$

=



dipole

+



quadrupole

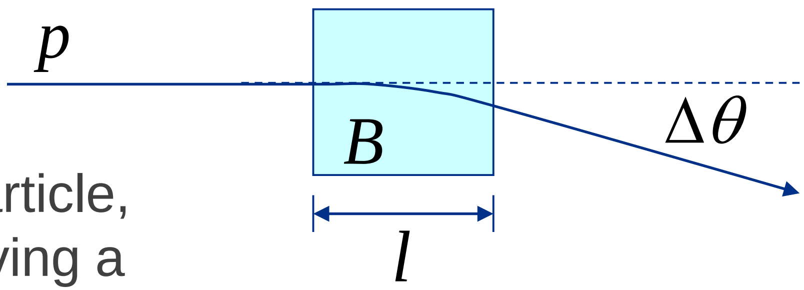
Later synchrotrons were built with physically separate dipole and quadrupole magnets. The first "separated function" synchrotron was the Fermilab Main Ring (1972, 400 GeV)

dipole quadrupole Fermilab

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

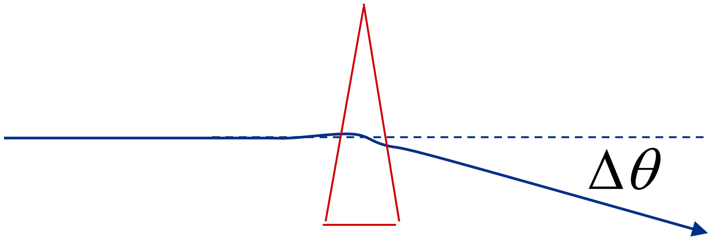


$$\boxed{p_\perp \approx qvBt = qvB(l/v) = qBl}$$

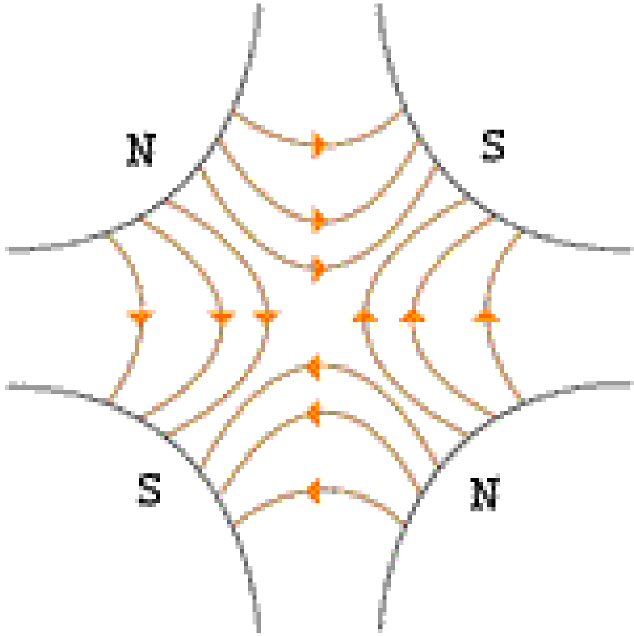
and it will be bent through small angle

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

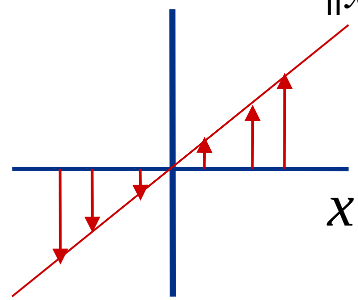
- In this "thin lens approximation", a dipole is the equivalent of a prism in classical optics.



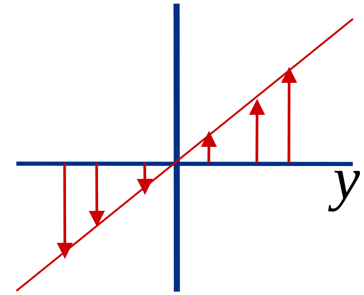
Quadrupole Magnets* as Lenses



$$B_y = \frac{\partial B_y}{\partial x} x$$



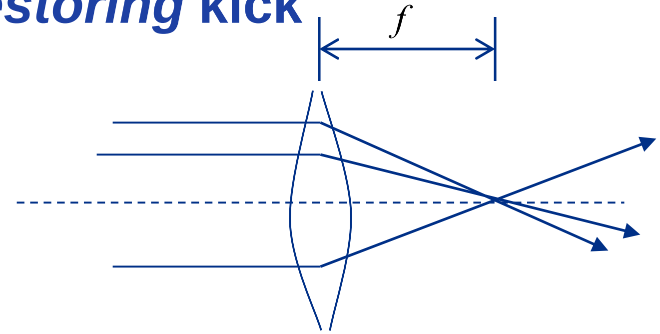
$$B_x = \frac{\partial B_x}{\partial y} y$$



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

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

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

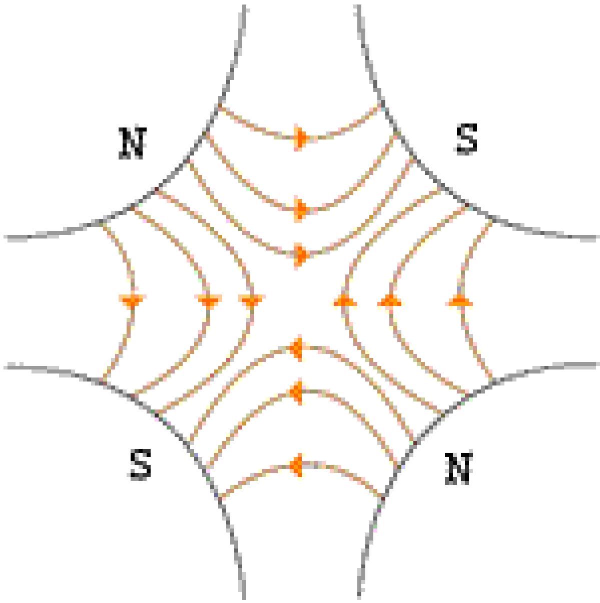


just like a “thin lens” with focal length

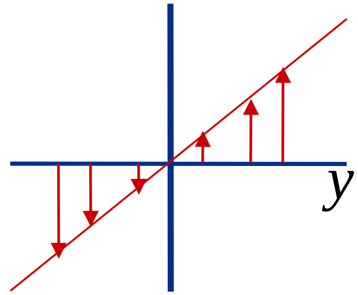
$$\boxed{f = \frac{x}{\Delta\theta} = \frac{(B\rho)}{B' l}}$$

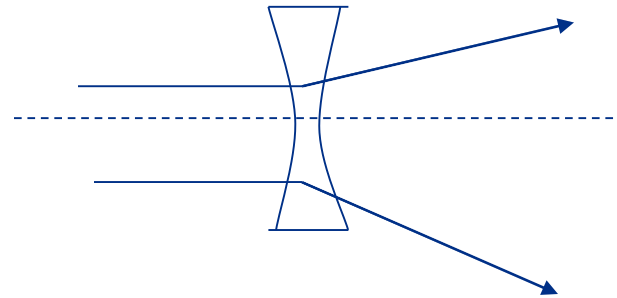
*or quadrupole term in a gradient magnet

What About the Other Plane?



$$B_x = \frac{\partial B_x}{\partial y} y$$

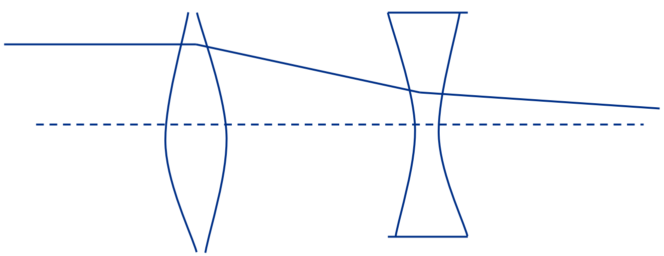


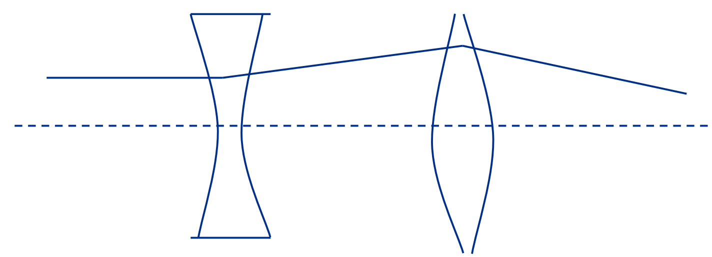


$$f = -\frac{(B\rho)}{B' l}$$

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"**

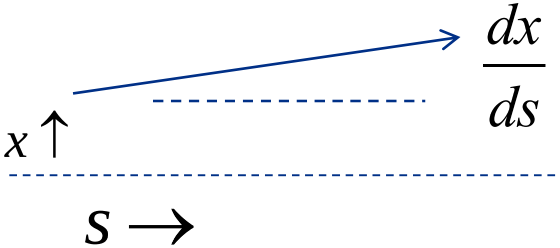
Focusing -- Drift (O) – Defocusing – Drift (O)

Formalism: Coordinates and Conventions

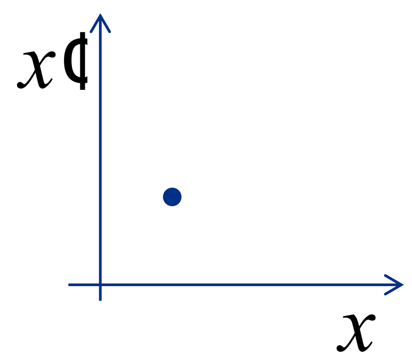
- We generally work in a right-handed coordinate system with *x* horizontal, *y* vertical, and *s* along the *nominal* trajectory (*x*=*y*=0).

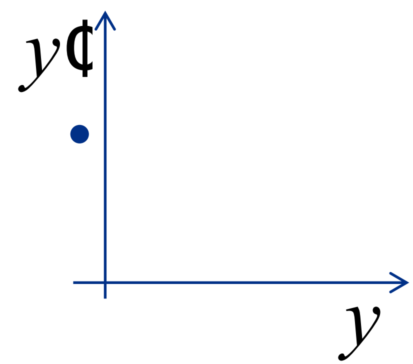
Note: *s* (rather than *t)* is the independent variable

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



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





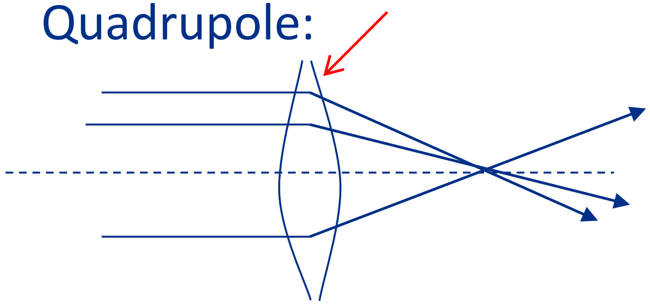
unique initial phase space point ➔ unique trajectory

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.

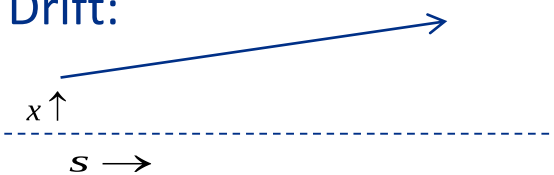
$$\Delta\theta = \Delta x' = -\frac{x}{f}$$

Quadrupole:



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

Drift:



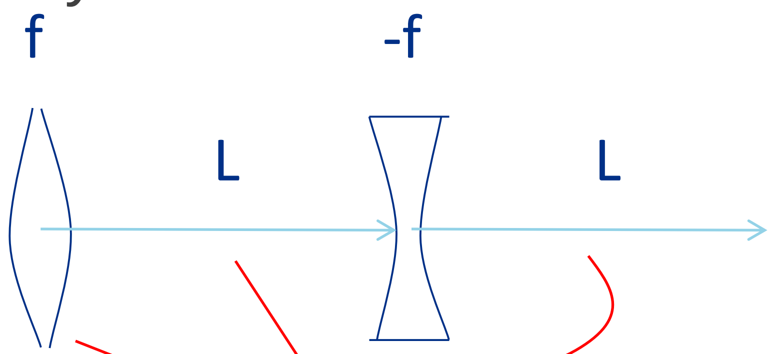
$$x(s) = x(0) + s x'(0)$$
$$x'(s) = x'(0)$$
$$\Rightarrow \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}$$

- 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!

Sign of *f* flips in other plane

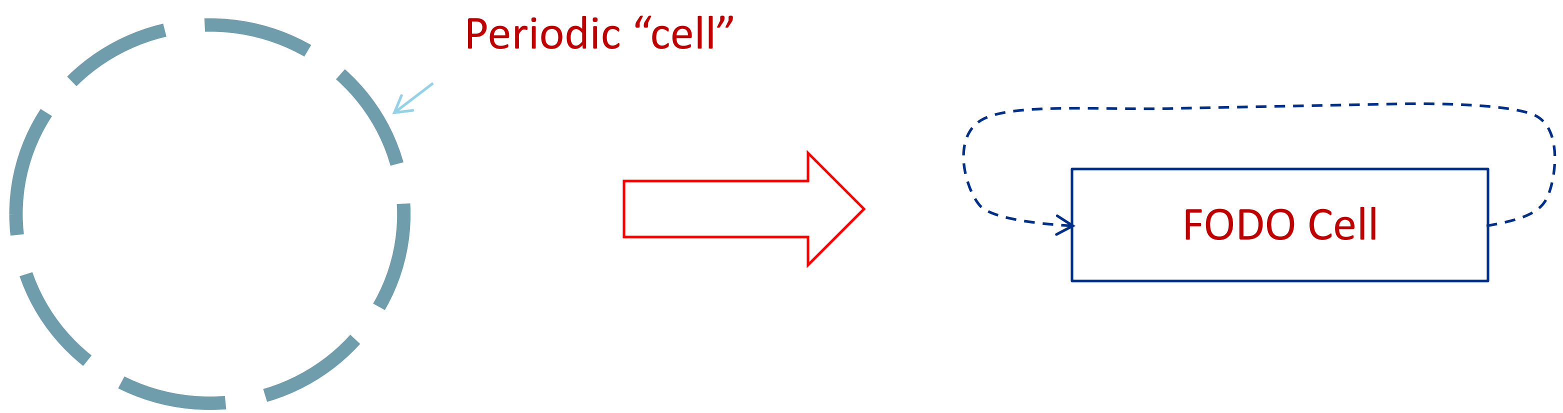
$$
\Rightarrow \mathbf{M} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ +\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{f} - \left(\frac{L}{f}\right)^2 & 2L + \frac{L^2}{f}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

Matrix unstable if ***f* < *L*/2**

- 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.



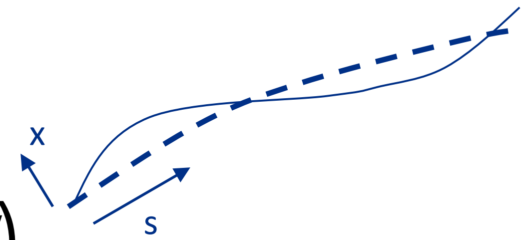
$$\mathbf{M}_{ring} = \mathbf{M}_{cell}\mathbf{M}_{cell}\cdots\mathbf{M}_{cell} = \mathbf{M}_{cell}^{N}$$

- 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.

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" $\beta(s)$,** which is only a function of location along the nominal path, and follows the periodicity of the machine.

$b(s)$



Lateral deviation in one plane

$$x(s) = A\sqrt{b(s)}\cos\left(y(s) + d\right)$$

Phase advance

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

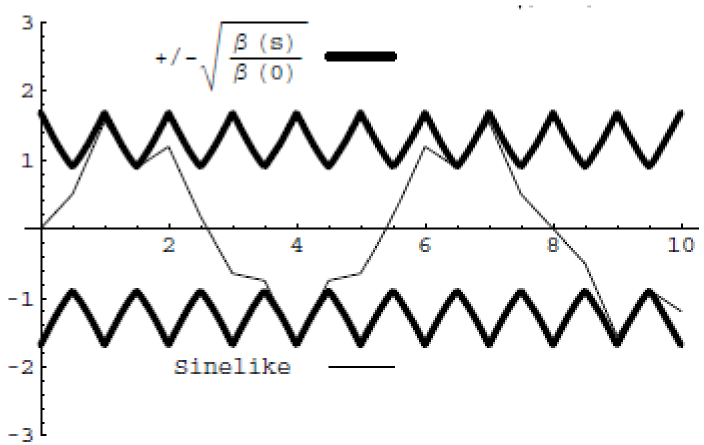
The "betatron function" $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.

- 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 [length]$^{1/2}$

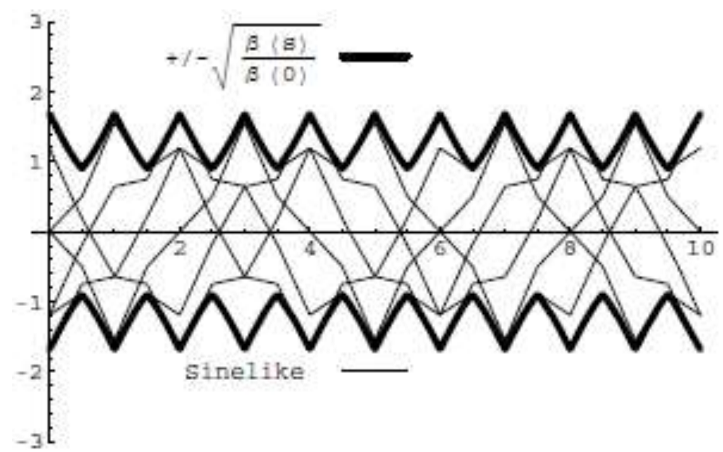
Conceptual Understanding of β

- 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!)



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

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

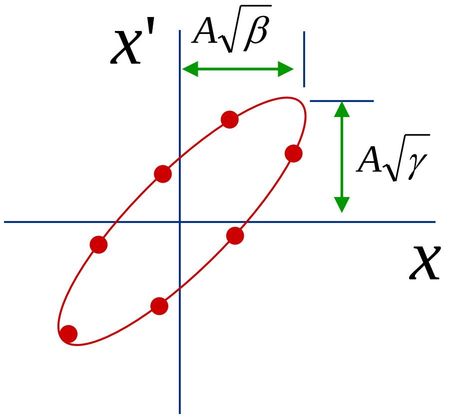
$\beta(s)$ is also effectively the local wave number which determines the rate of phase advance

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.



$$a = -\frac{1}{2}\frac{db}{ds}$$

$$b x¢^2 + 2a x x¢ + g x^2 = A^2 = \text{constant}$$

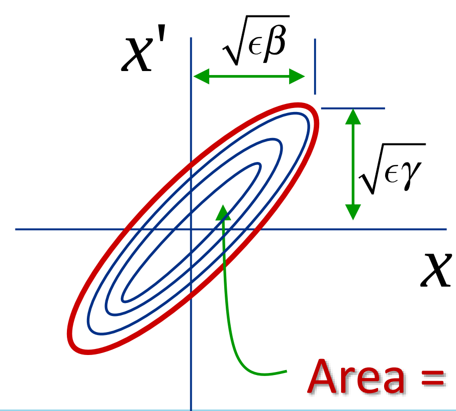
$$g = \frac{1+a^2}{b}$$

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

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

Units of length



Area = επ

Emittance, Beam Size, and Adiabatic Damping

- If we use the Guassian definition emittance, then the rms 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" (measure of truly conserved adiabatic invariant *Δp×Δx*)

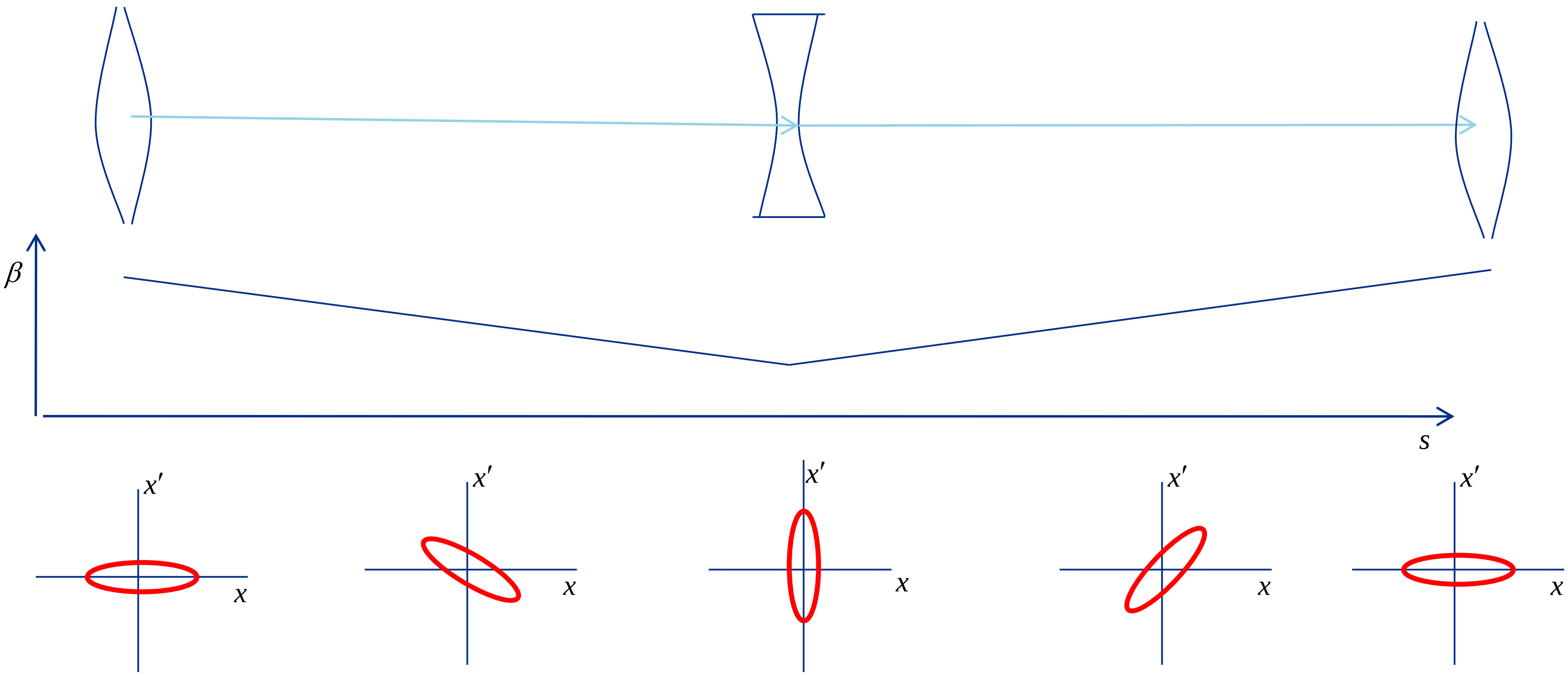
$$\epsilon_N \equiv \beta\gamma\epsilon$$

- 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

Numerical Example: LHC (γ »1, β=v/c ≈1)

$$\boxed{\varepsilon_{n\ (x,y)} = \gamma \cdot \sigma_{x,y} \sigma'_{x,y}}$$

$$\varepsilon_n = 2.9\ \underbrace{mm \cdot mrad}_{10^{-6} m}$$

$$\gamma = 6930$$

$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}} \qquad \sigma'_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma \cdot \beta_{x,y}}} = \frac{\sigma_{x,y}}{\beta_{x,y}}$$

Squeeze in ATLAS/CMS

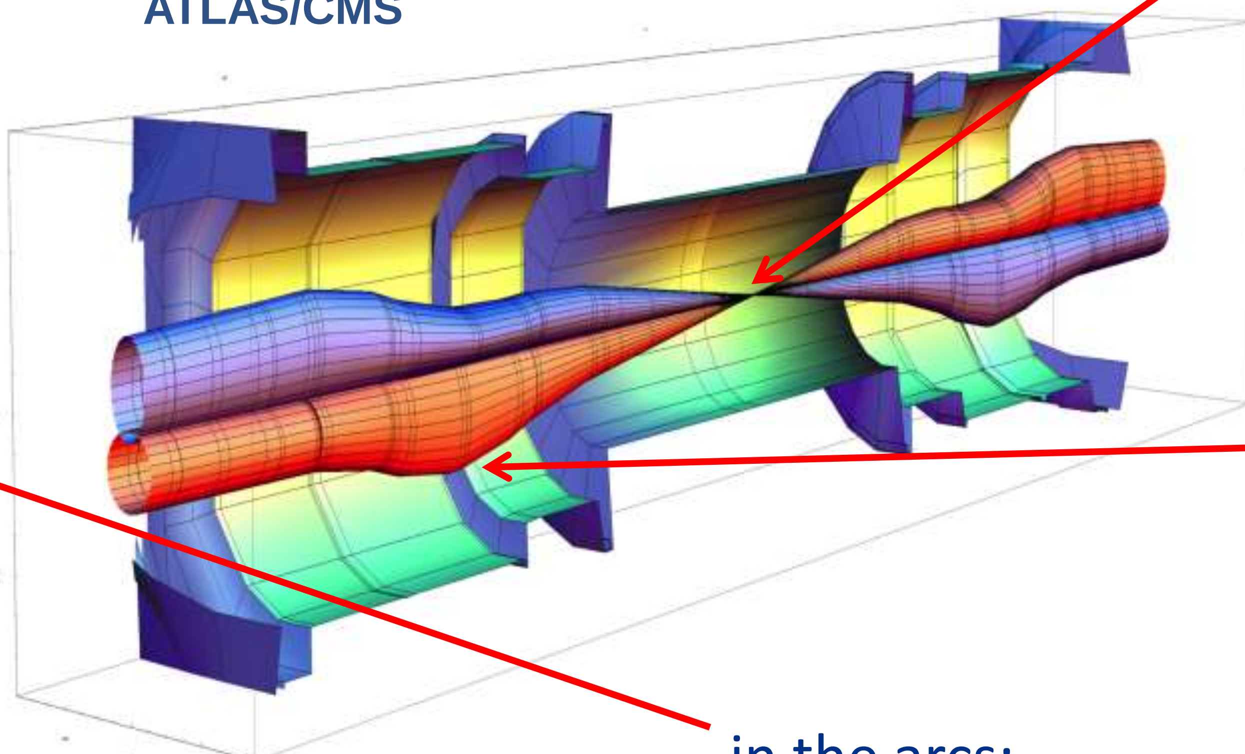
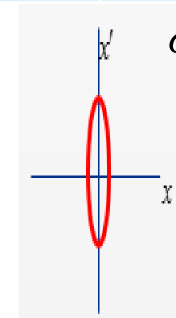


Image courtesy John Jowett

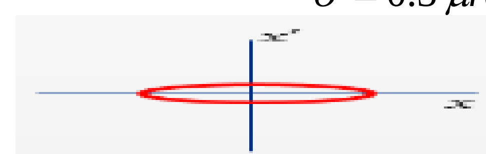
β*	***Sigma****
40 cm	13 um

$\sigma' = 30\ \mu rad$



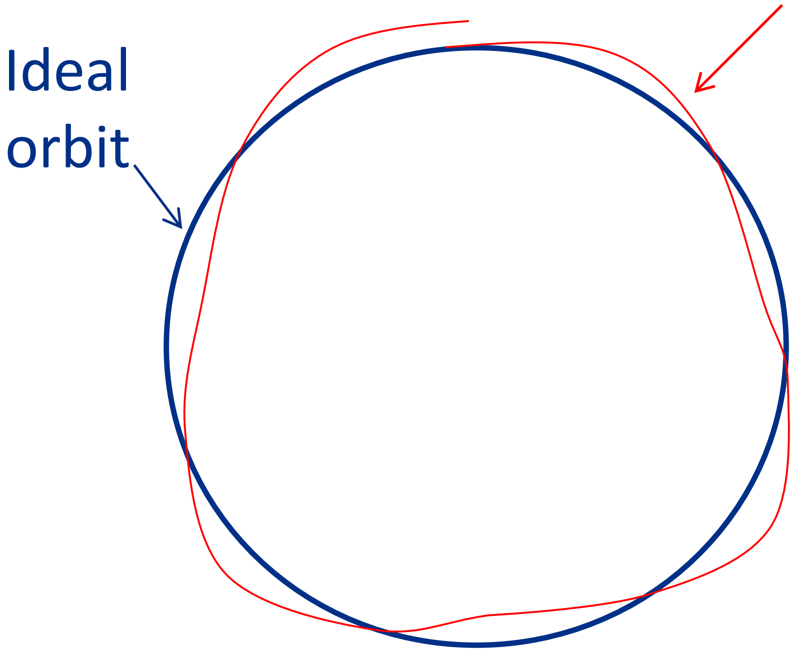
$\beta_{triplet}$	***Sigma triplet***
~4.5 km	1.5 mm

$\sigma' = 0.3\ \mu rad$



in the arcs:
β~200m, σ≈0.3mm

Betatron Tune



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

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

- This is referred to as the **<u>"tune"</u>**

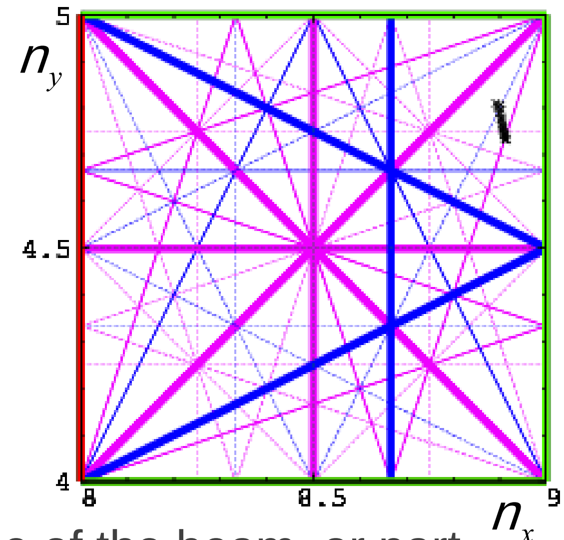
- We can generally think of the tune in two parts:

Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

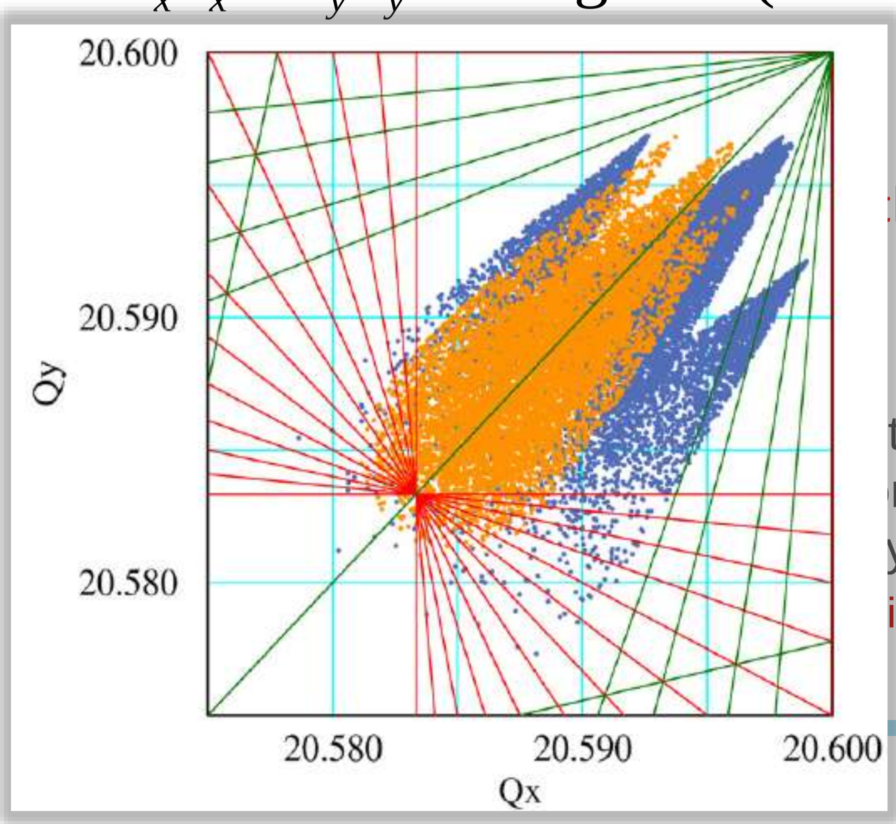
Tune, Stability, and the Tune Plane

- 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

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



➔Avoid lines in
he “tune plane”



thing perturbs the tune of the beam, or part
nance, thus you will often hear effects
y produce.

ift sets the absolute luminosity limit in a collider

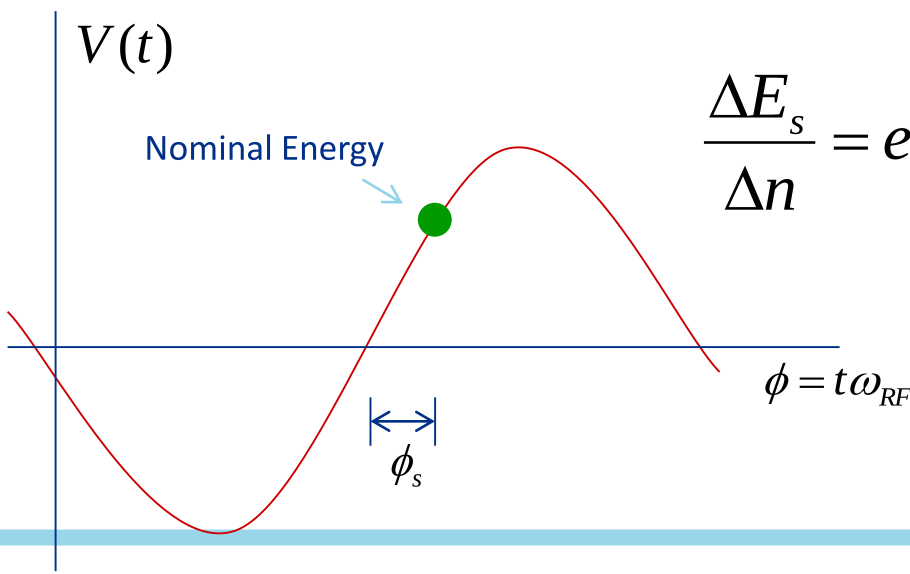
Longitudinal Motion

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

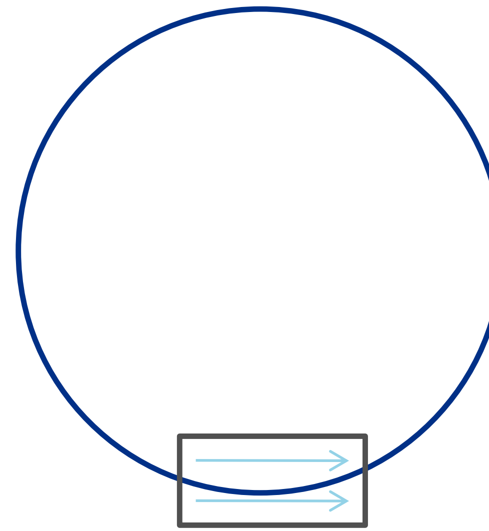
$E = E(t) = E_0 \sin \varpi t + \delta_0$ $\quad$ $E = E(t) = E_0 \sin \varpi t + \delta_1$ $\quad$ $E = E(t) = E_0 \sin \varpi t + \delta_N$

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

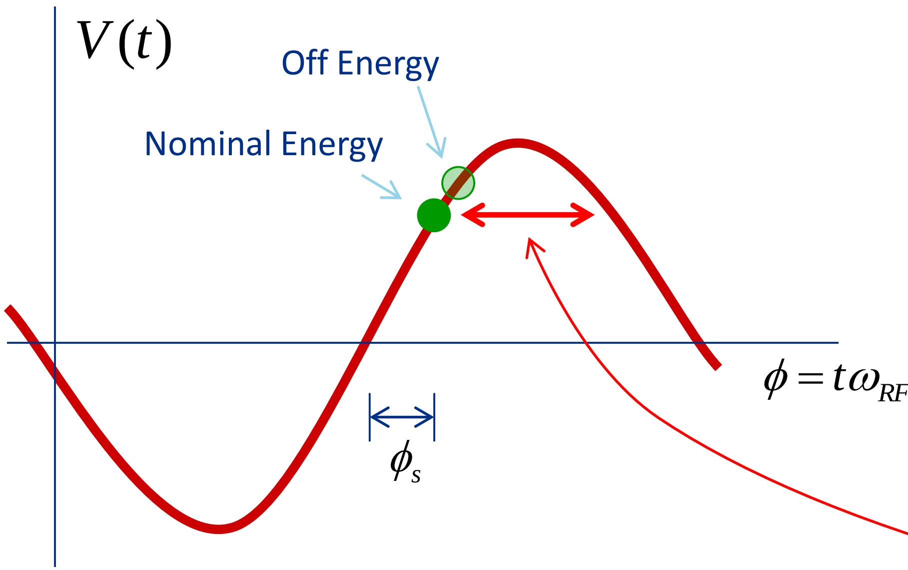


$$\frac{\Delta E_s}{\Delta n} = eV_0 \sin \phi_s$$



Phase Stability

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



$$\frac{Dt}{t} = h\frac{Dp}{p}$$

"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.

Example: LHC

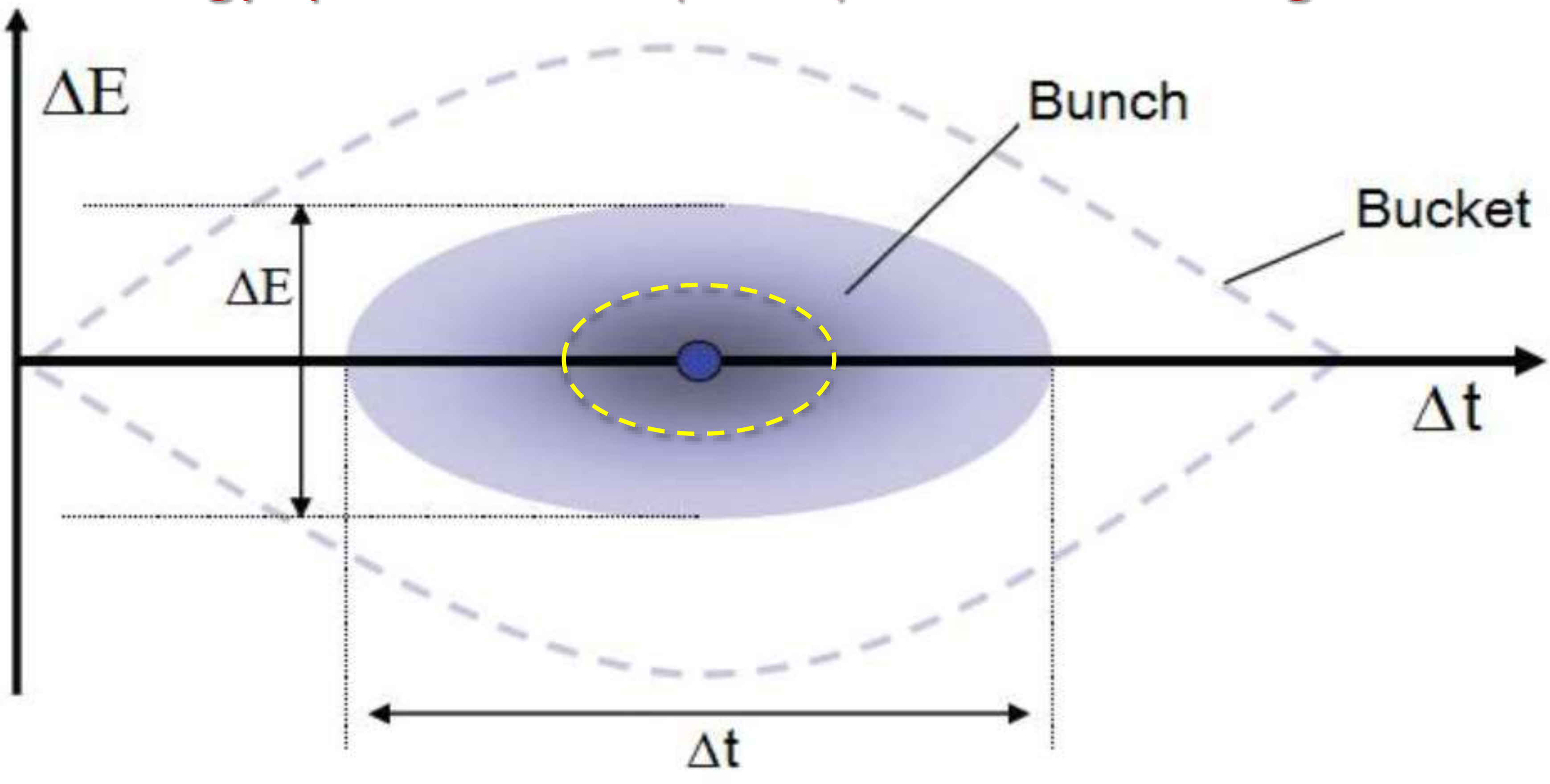
RF Frequency 400 MHz
(35640 times revolution frequency)

- RF Voltage = 8 cavities x 2 MV = 16 MV / turn (max)

In collisions dE/dn= 0 V/turn (synchronouse phase ~0)

Slow energy-position oscillations (23 Hz or ~500 turns)

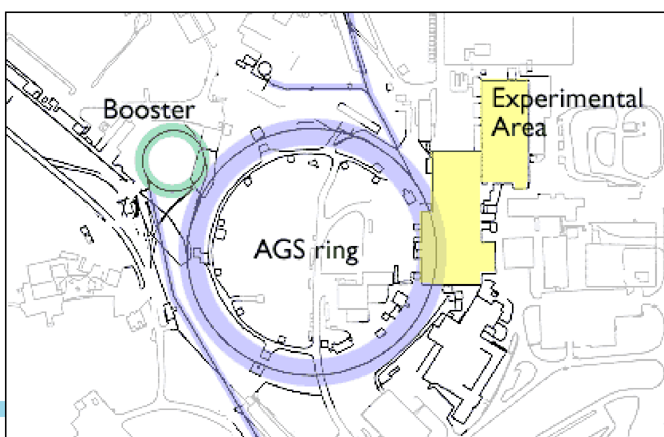
rms energy spread 1.3e-4 (1GeV) rms bunch length ~ 8cm



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

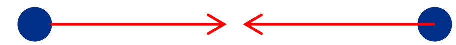
Brookhaven Alternating Gradient Synchrotron (AGS)
- 1960
- 808 m circumference
- 33 GeV protons
- Discovered charm quark, CP violation, muon neutrino

Getting the Most Energy: The Case for Colliders

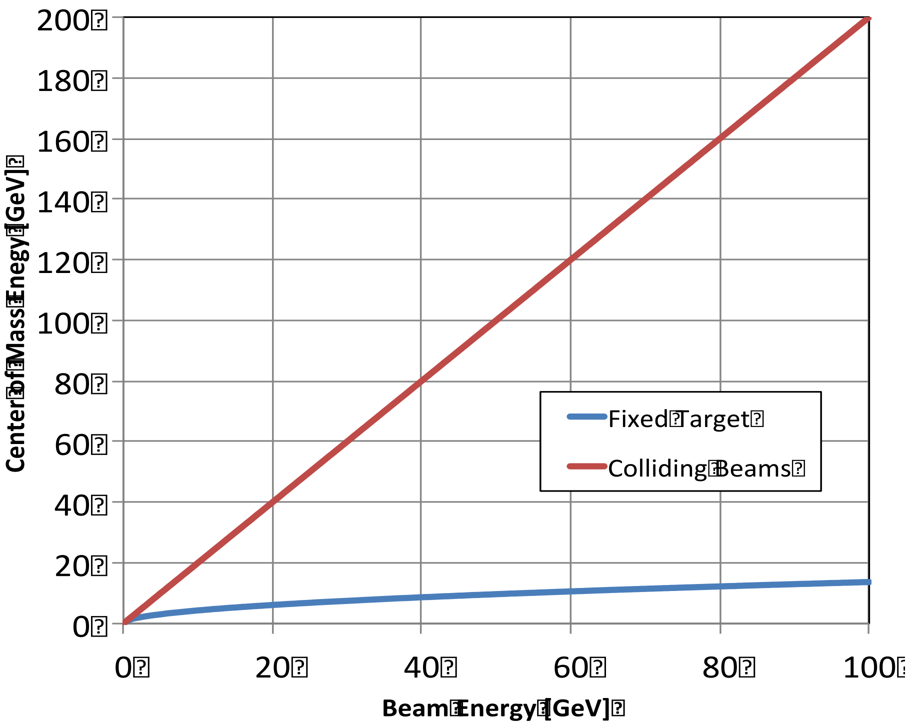
- If beam hits a stationary proton, the "center of mass" energy is

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

- 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"

$$\underbrace{R}_{\text{Rate}} = \underbrace{L}_{\text{"Luminosity"}} \underbrace{\sigma}_{\text{Cross-section ("physics")}}$$

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

Geometrical factor:
- crossing angle
- hourglass effect

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

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 $\boxed{\text{a small } \beta^*!}$

Record *e+e-* Luminosity (KEK-B):	2100 x10^{30} cm^{-2}s^{-1}
Record *p-pBar* Luminosity (Tevatron):	430 x10^{30} cm^{-2}s^{-1}
Record *p-p* Luminosity (LHC):	1000 x10^{30} cm^{-2}s^{-1}
Record *e-p* Luminosity (HERA):	75 x10^{30} cm^{-2}s^{-1}

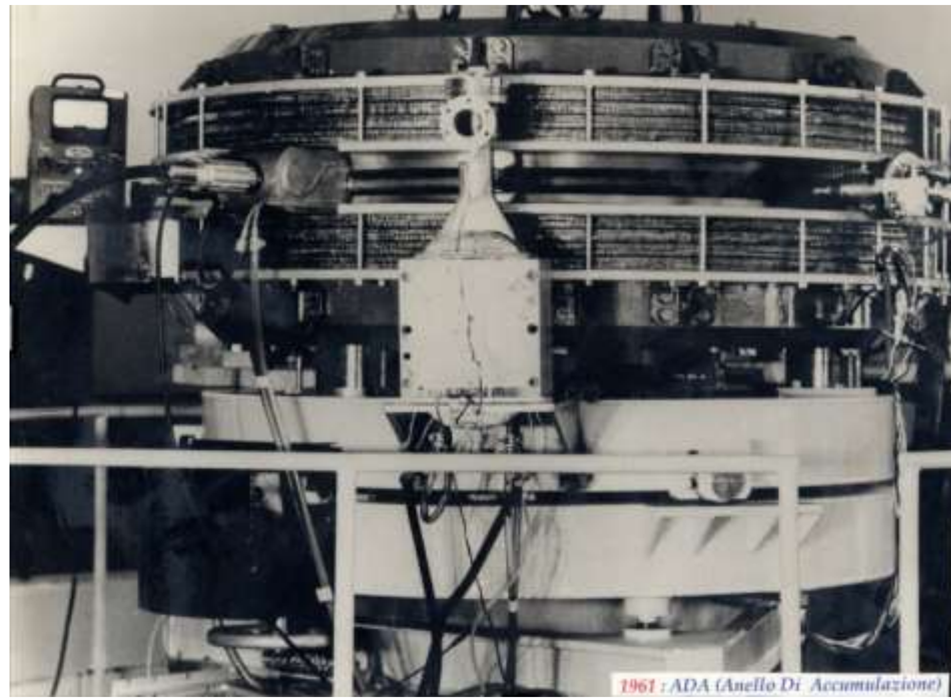
First e^-e^- / e^+e^- Colliders - 1964

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

- VEP-1 (*Встречные Электронные Пучки*) at Novosibirsk, USSR
  - 130 MeV e^- x 130 MeV e^-

  - 1963: Construction Finished
  - May 19, 1964: Luminosity

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

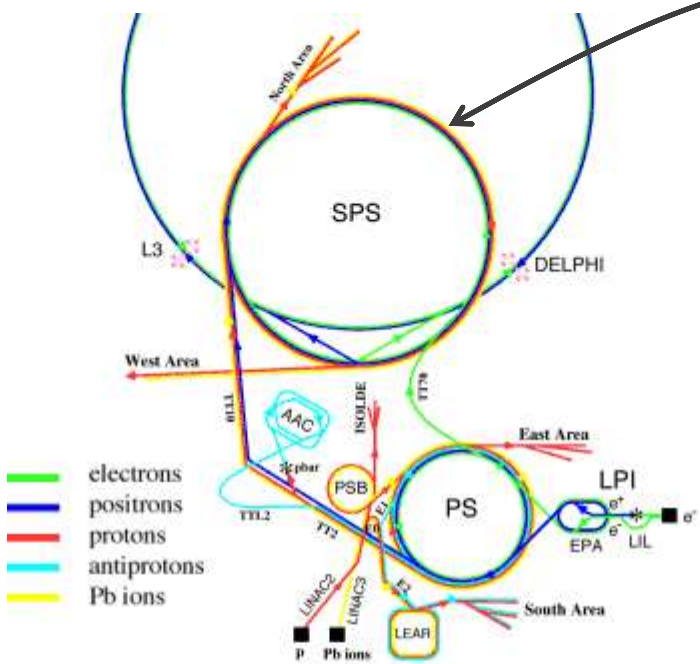


  - 1961 : Construction Finished
  - ~ May-June 1964: Luminosity Detected

First Proton Collider: CERN Intersecting Storage Rings (ISR) - 1971

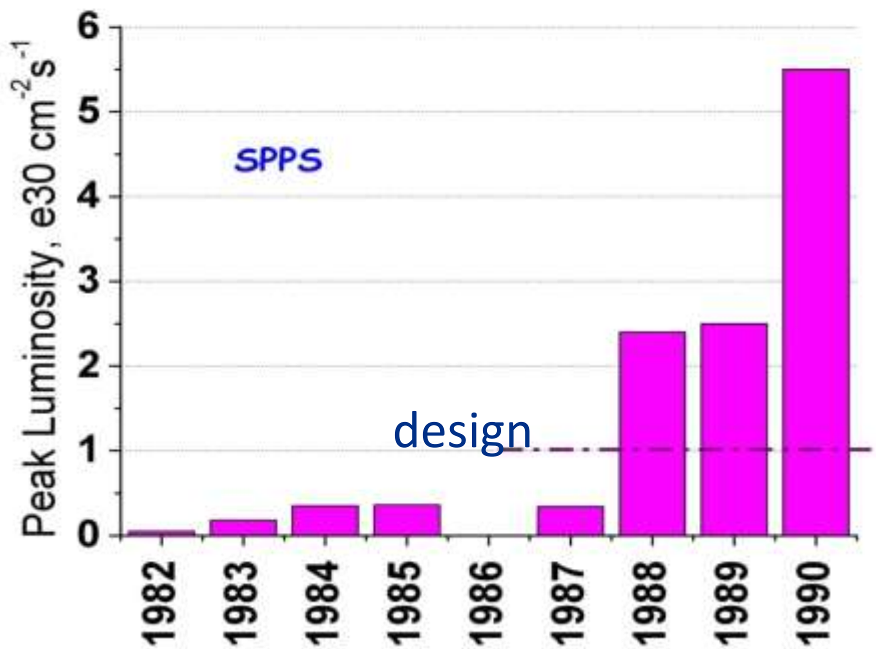
- 31 GeV + 31 GeV colliding proton beams.
  - Highest CM Energy for 10 years
- Set a luminosity record that was not broken for 28 years!

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 NC magnets (heating)!
  - ◆ (need SC magnets! 2T→ 5…8 T)



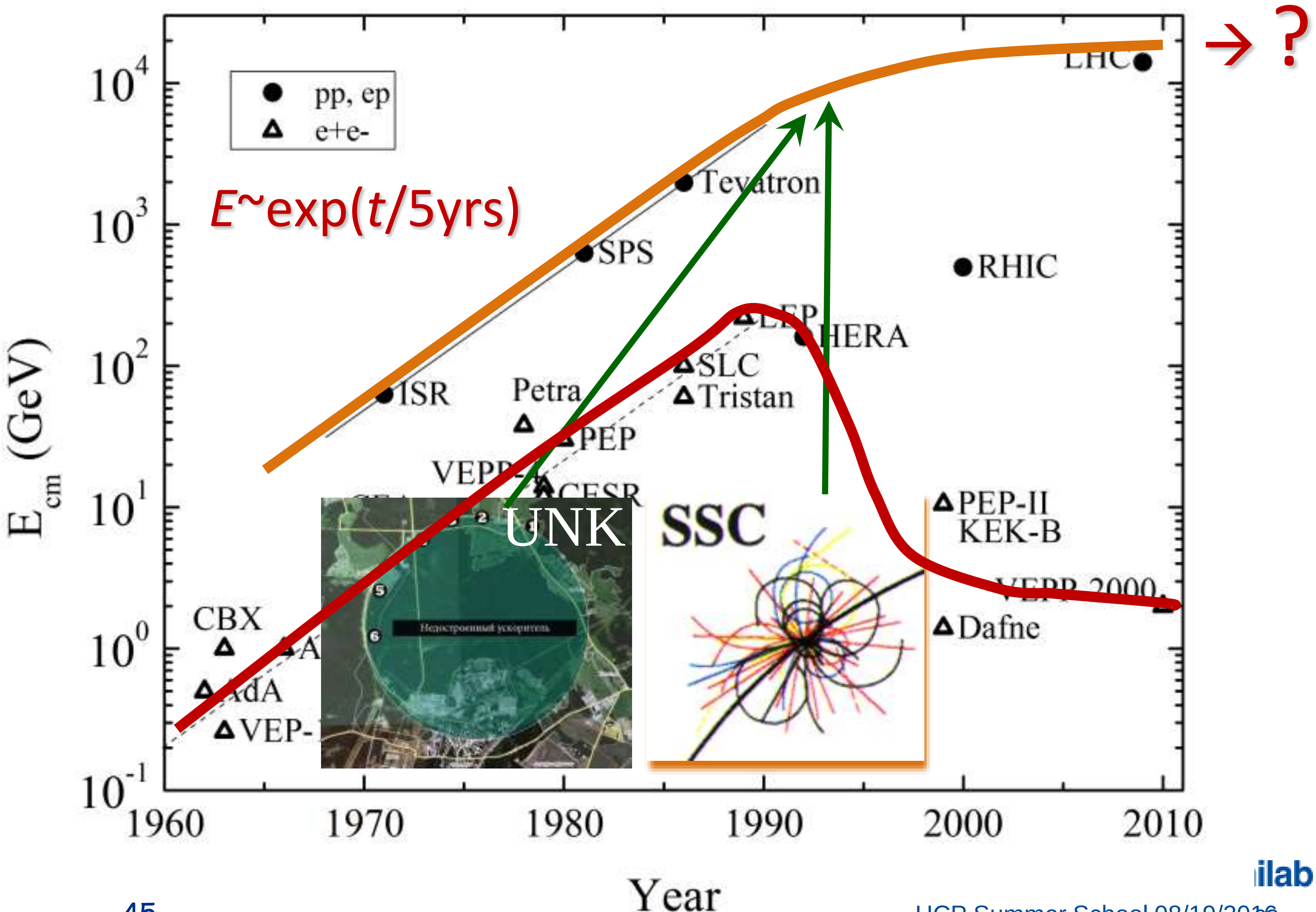
rmilab

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

Colliders :29 Built, 7 in Operation Now

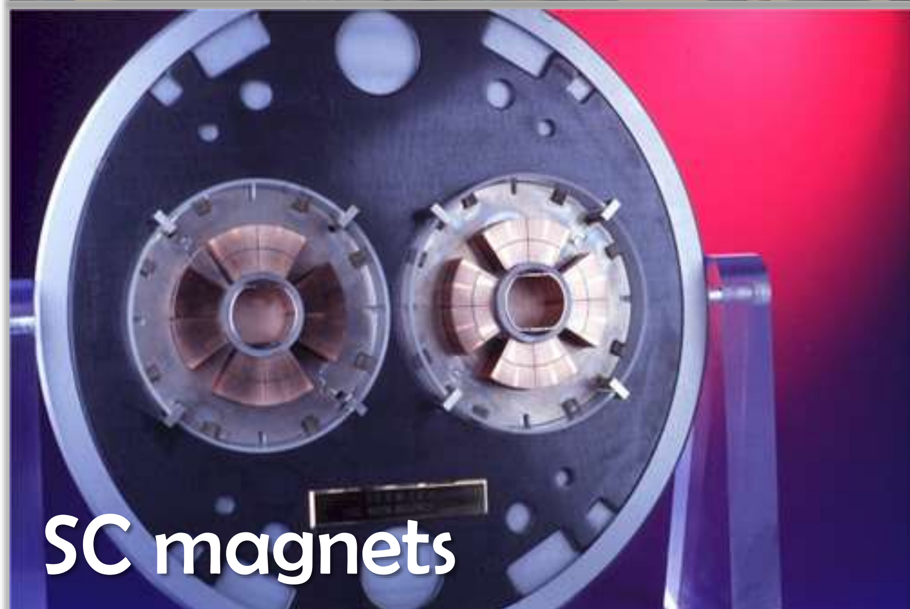
Colliders: Glorious Past



(*Future*) = (*Physics* × Feasibility)

- **PHYSICS** case of post-LHC high energy physics machine depends on the LHC discoveries:
  - it might call for a collider (if signals are clear)
  - otherwise, search for signs of new physics in the neutrino/rare decays (*Intensity Frontier*) or astrophysics
- **FEASIBILITY** of an accelerator is actually complex:
  - Feasibility of **ENERGY**
    - Is it possible to reach the *E* of interest / what's needed ?
  - Feasibility of **PERFORMANCE**
    - Will we get enough physics out there / luminosity ?
  - Feasibility of **COST**
    - Is it affordable to build and operate ?
- **What can we learn/take from the past/present?**

Four “Feasible” Technologies



… in addition to “traditional” technologies of tunneling, electric power and site infrastructures, etc …

! WARNING !

αβγ - Cost Estimate Model (17 data points):

2014 JINST 9 T07002

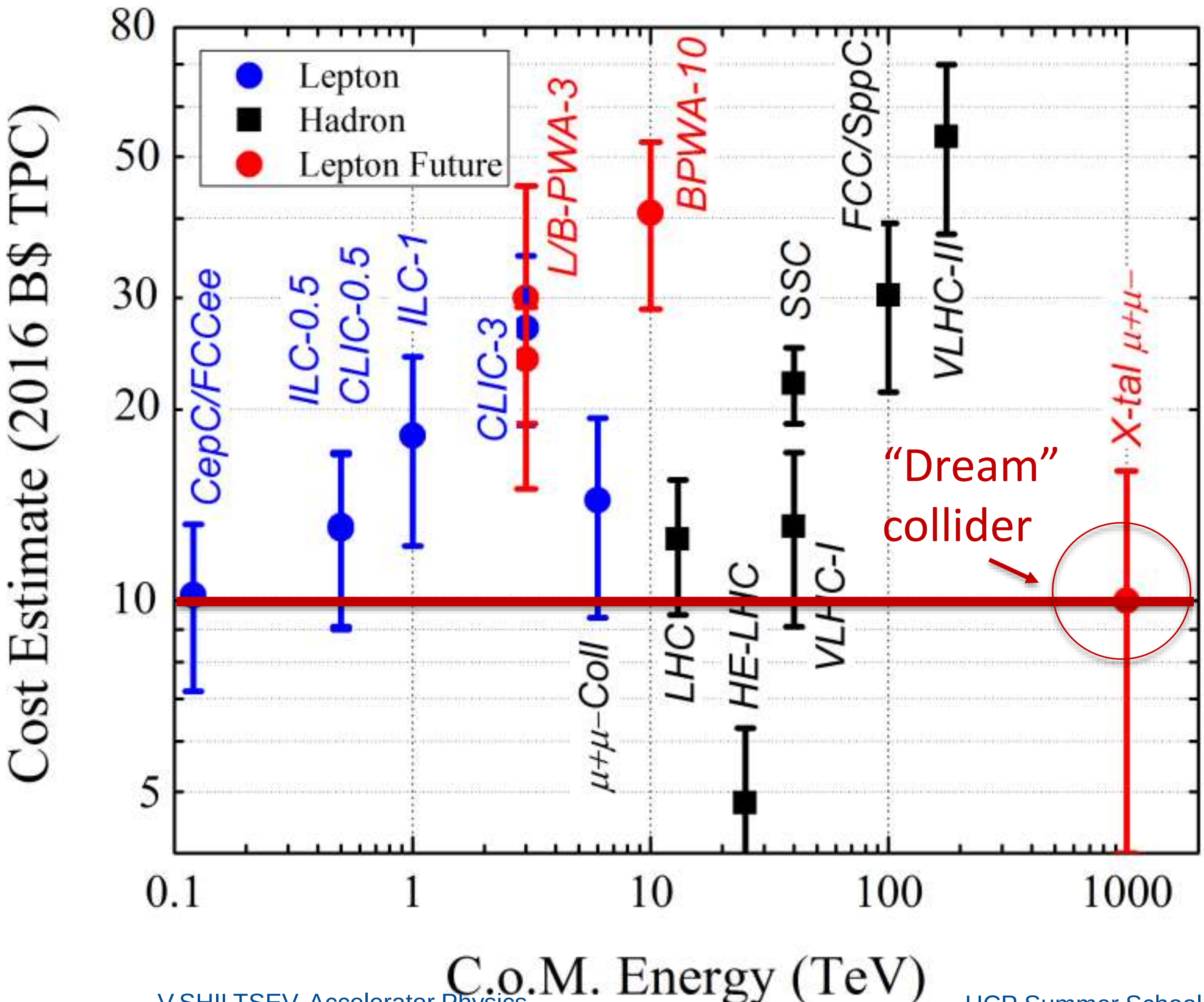
$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **±33% estimate, for a "green field" accelerators**

b) **"US-Accounting" = TPC !** (~ 2 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)
  - ***α*≈ 2B$/sqrt(*L*/10 km)**
  - ***β*≈ 10B$/sqrt(*E*/TeV)** for SC/NC RF
  - ***β*≈ 2B$ /sqrt(*E*/TeV)** for SC magnets
  - ***β*≈ 1B$ /sqrt(*E*/TeV)** for NC magnets
  - ***γ*≈ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!



Cost Estimate (2016 B$ TPC)
80
50
30
20
10
5
0.1
1
10
100
1000
C.o.M. Energy (TeV)
Lepton
Hadron
Lepton Future
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
L/B-PWA-3
BPWA-10
μ+μ−Coll
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
X-tal μ+μ−
"Dream" collider

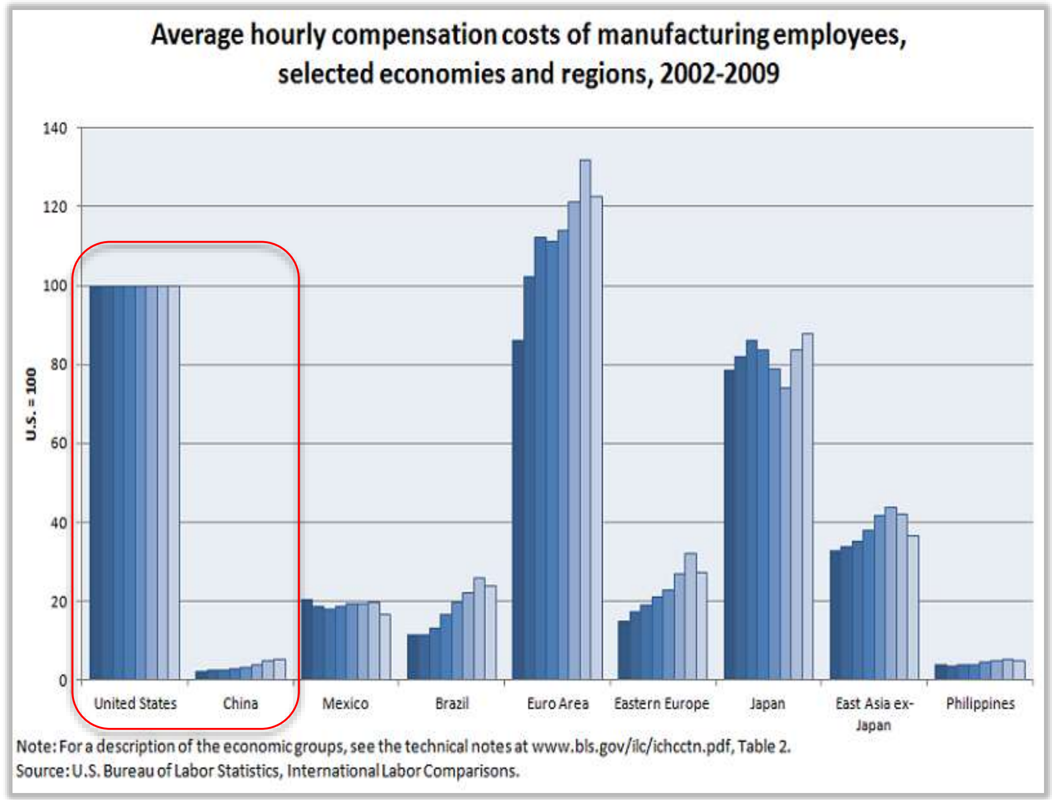
How to Proceed: Options

#1: *Re-use parts:*

- *eg tunnel, injectors, infrastructure (14 TeV LHC → 30 TeV HE-LHC)*

#2: *Reduce cost:*

- *eg cost of SRF or SC Magnets… by 2-5 (R&D)*



#3: *"Move to China!":*

- *Save ~x3*
- *Gap is shrinking → "do it now!"*

#4: *New technology:*

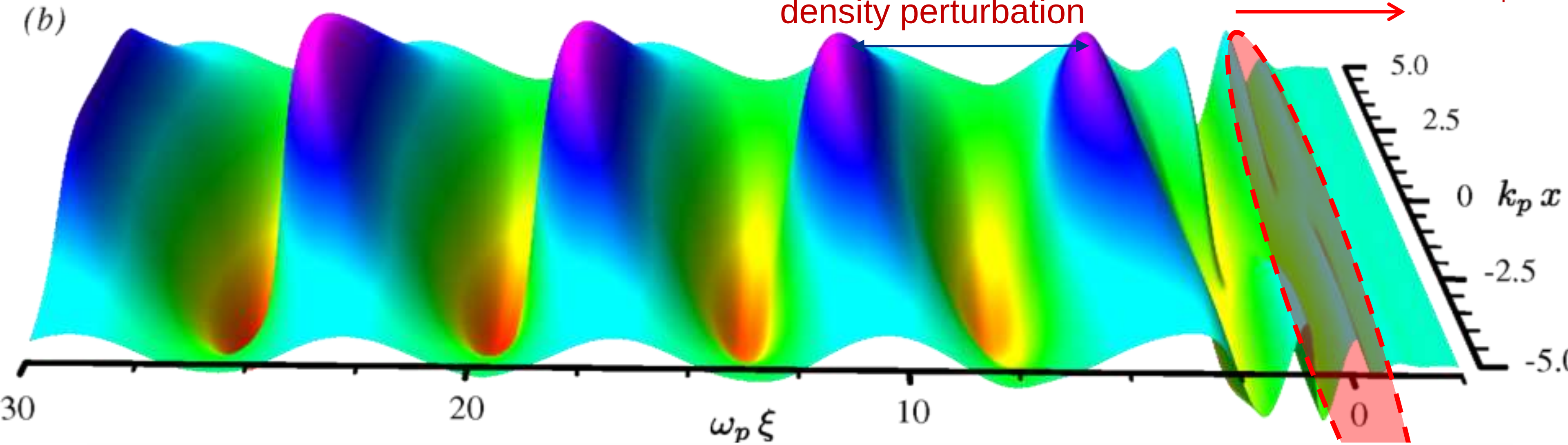
- *Risk*
- *Time*
- *Need extensive R&D*

#5: *Switch to leptons:*

- *Equivalent c.o.m. gain ~6-10*
- *Non-radiating (e+e- radiate even if linear : at E> 3-10 TeV only muons)*

Option 4: New Technology- Plasma

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:

Short intense e-/e+/p bunch

Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

Option B:

Short intense laser pulse

~10^{18}cm^{-3}, **50 GV/m** over 0.1m

First looks into "Plasma-Collider": **staging kills ! <*E*>~2 GV/m,ε**

“Phase-Space” is Further Limited

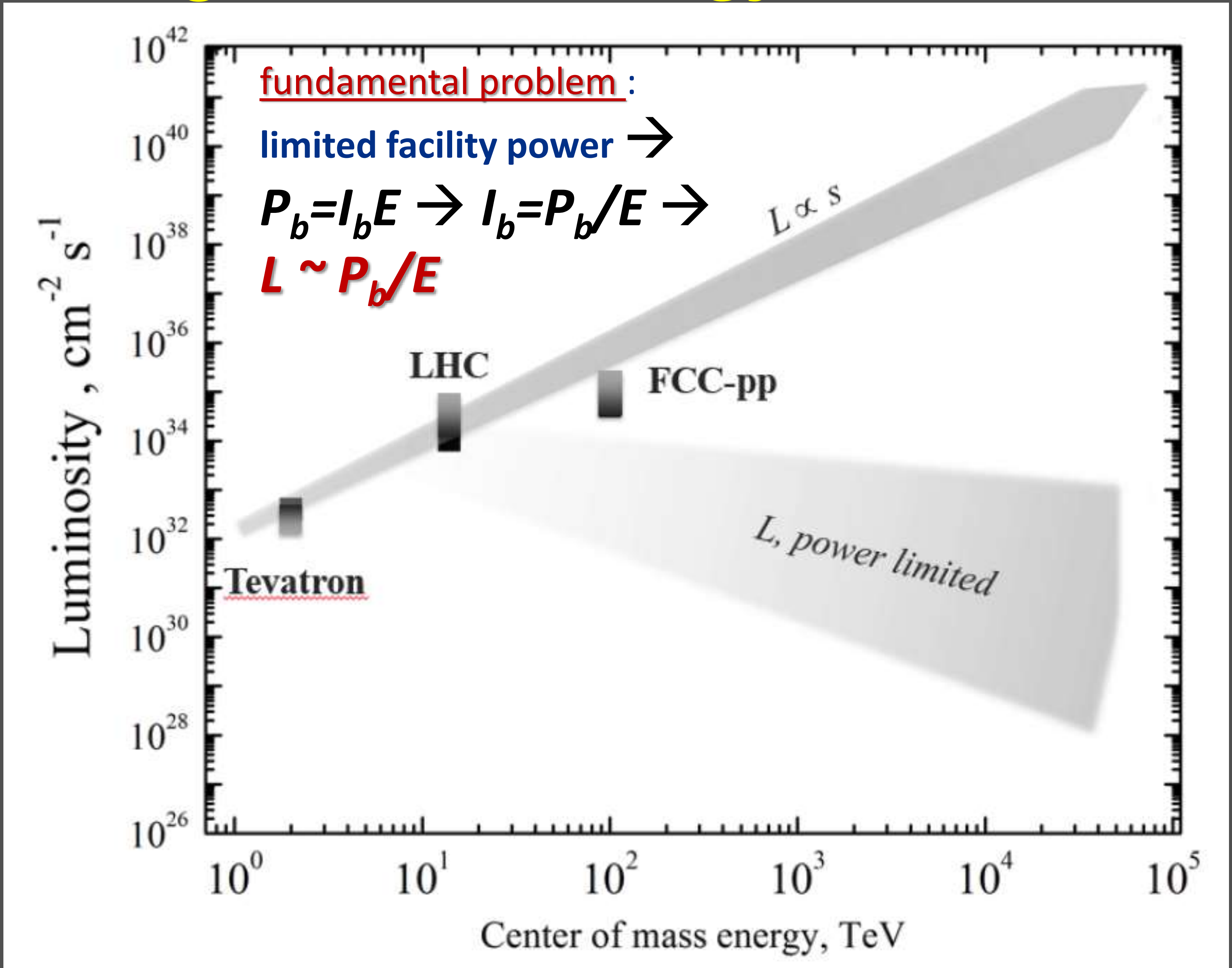
- **“Cost Feasibility”:** for (20-100) ×LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

Only one option for >30 GeV/m known now: <u>dense plasma (Xtals)</u>→ that excludes *protons*→ <u>only *muons*</u>

Paradigm Shift : *Energy* vs *Luminosity*



Questions ?