HCPSS 2014

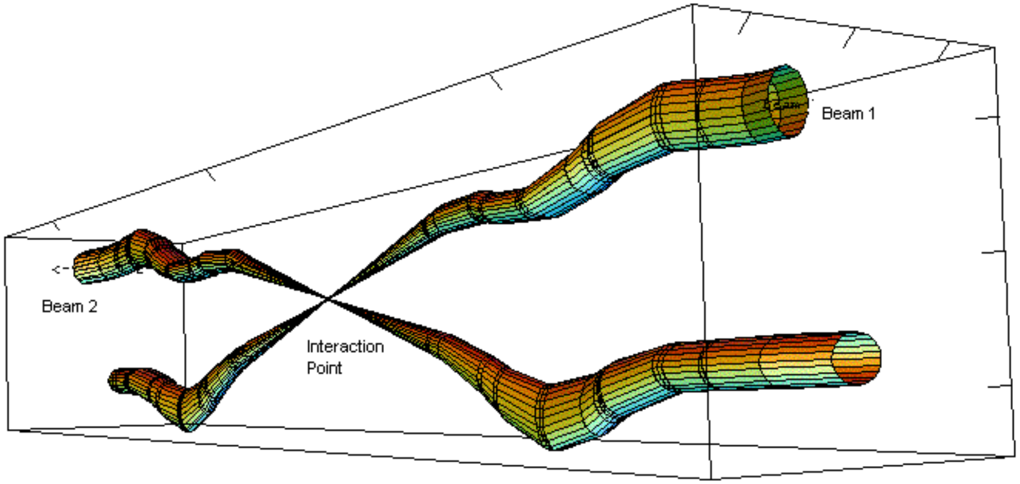
Hadron Collider Physics Summer School

August 11 - 22, 2014 Fermi National Accelerator Laboratory

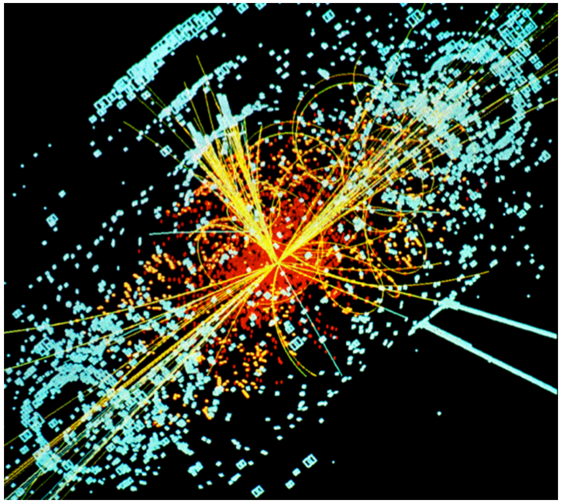
FERMILAB-CERN
HADRON COLLIDER PHYSICS
Summer School 2014

Hadron Colliders

Eric Prebys, FNAL



Relative beam sizes around IP1 (Atlas) in collision



LHC Interaction Region

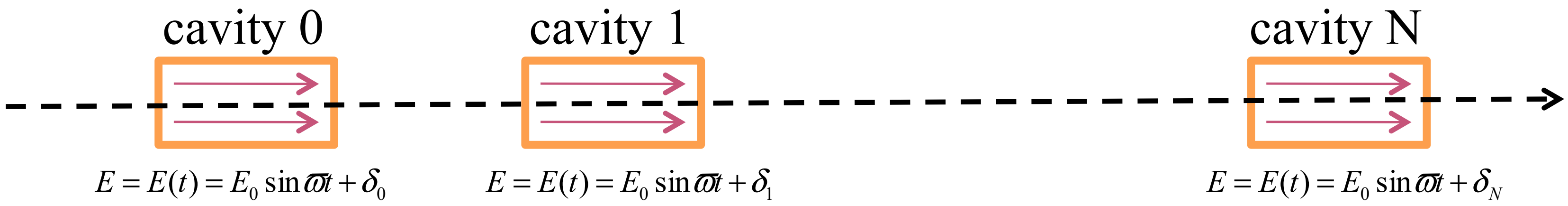
Lecture 2

Review and plan

- Yesterday:
  - Basics of transverse motion and strong focusing
- Today
  - Longitudinal motion
  - “Tricks of the trade”
  - Colliders and luminosity

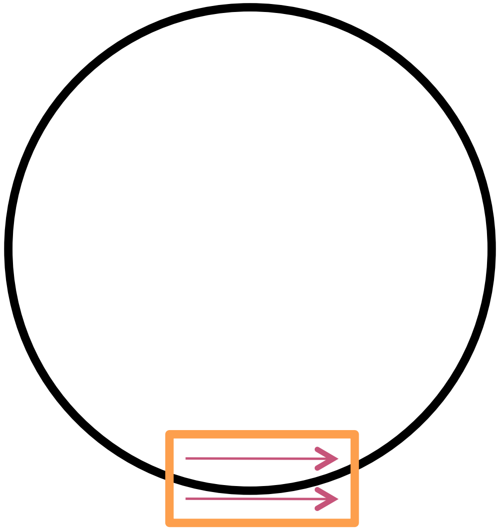
Longitudinal Motion

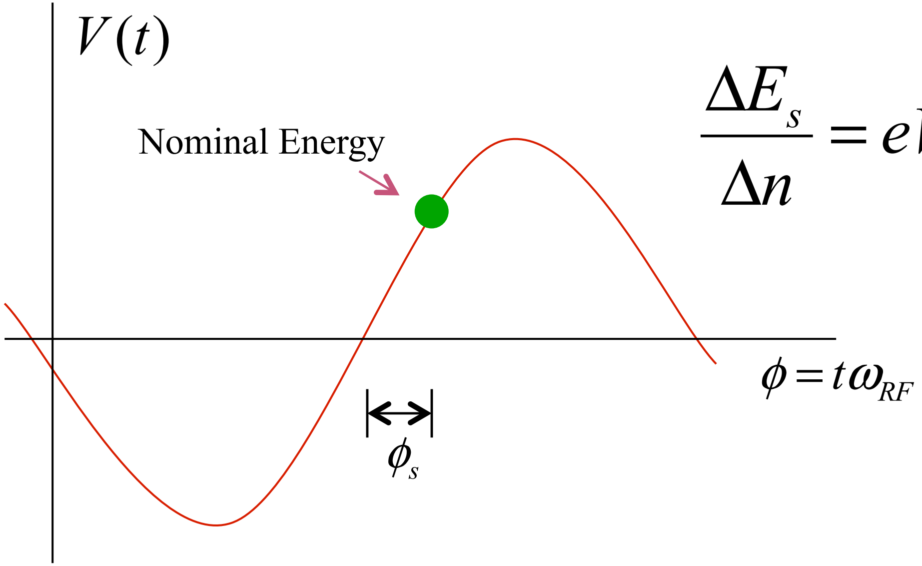
- We will generally accelerate particles using structures that generate time-varying electric fields (RF cavities), either in a linear arrangement



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



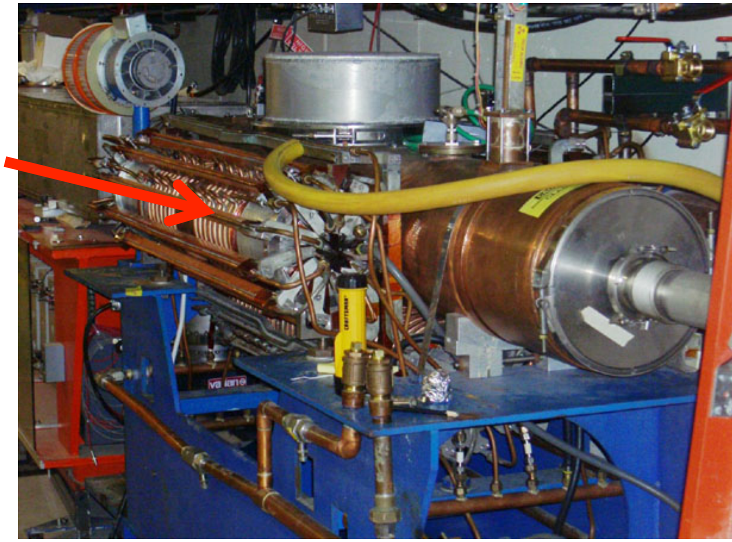


$$\frac{\Delta E_s}{\Delta n} = eV_0 \sin \phi_s$$

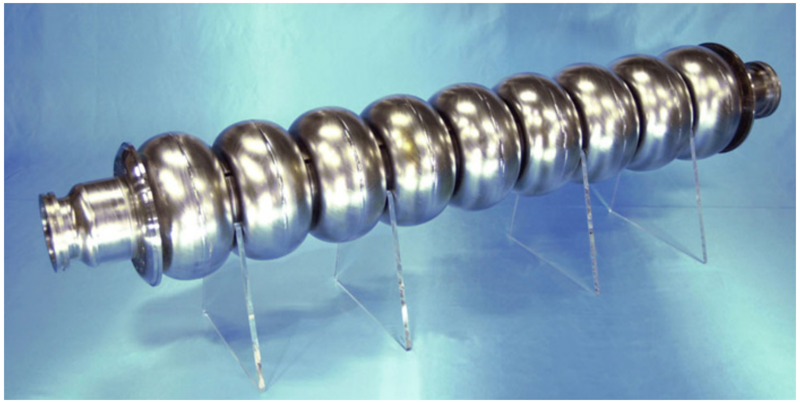
Examples of Accelerating RF Structures

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

37->53MHz Fermilab Booster cavity



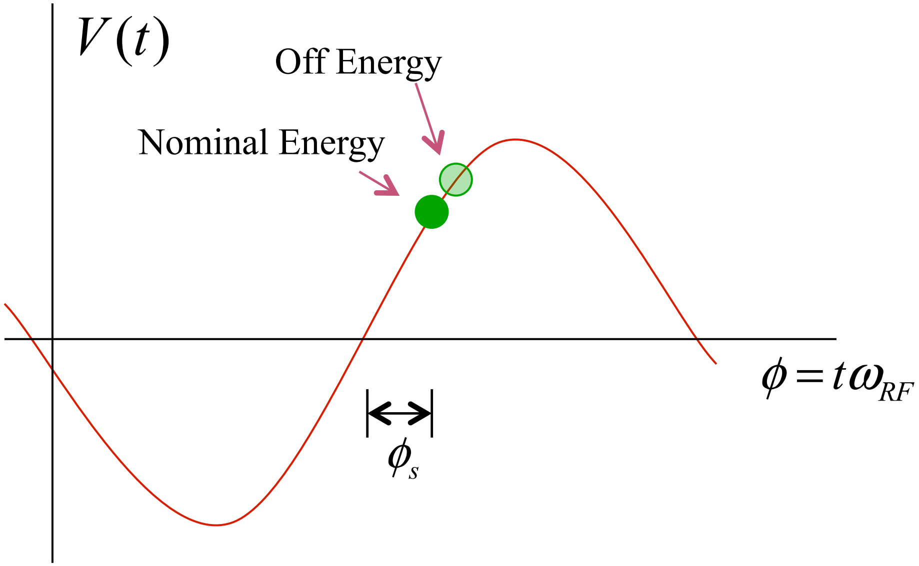
Biased ferrite frequency tuner



ILC prototype elipical cell “p-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



- The relationship between arrival time and difference in energy depends on the details of the machine

$$\frac{\Delta\tau}{\tau} = \eta \frac{\Delta p}{p} = \eta \frac{1}{\beta^2} \frac{\Delta E}{E}$$

use $\frac{\Delta p}{p} = \frac{1}{\beta^2} \frac{\Delta E}{E}$

"slip factor" = dependence of period on momentum

Slip Factor

- As cyclotrons became relativistic, high momentum particles take longer to go around.
  - This led to the initial understanding of phase stability during acceleration.
- In general, two effects compete

Path length

Velocity

Can prove this with a little algebra

$$\tau = \frac{L}{v} \Rightarrow \frac{\Delta\tau}{\tau} = \frac{\Delta L}{L} - \frac{\Delta v}{v} = \alpha_C \left(\frac{\Delta p}{p} \right) - \frac{1}{\gamma^2} \left(\frac{\Delta p}{p} \right) = \left(\alpha_C - \frac{1}{\gamma^2} \right) \frac{\Delta p}{p} \equiv \eta \frac{\Delta p}{p}$$

“momentum compaction factor” we just talked about

Momentum dependent “slip factor”

- The behavior of the slip factor depends on the type of machine

Special Cases of Slip Factor

- In a linac

$$\alpha_C = 0 \rightarrow \eta = -\frac{1}{\gamma^2}$$

negative, asymptotically approaching 0

- In a cyclotron

$$L = 2\pi\rho \propto p \rightarrow \alpha_C = 1 \rightarrow \eta = 1 - \frac{1}{\gamma^2}$$

0 for v<<c, then goes positive.
Compensating for this ➔
“synchro-cyclotron”

- In a synchrotron, the momentum compaction depends on the lattice, but is *usually* positive

$$\eta = \alpha_C - \frac{1}{\gamma^2}$$

Starts out negative, then goes positive for $\gamma > \frac{1}{\sqrt{\alpha_C}} \equiv \gamma_t$

“transition”

In a normal lattice, for very non-intuitive reasons

$$\gamma_t \approx \nu(\text{tune})$$

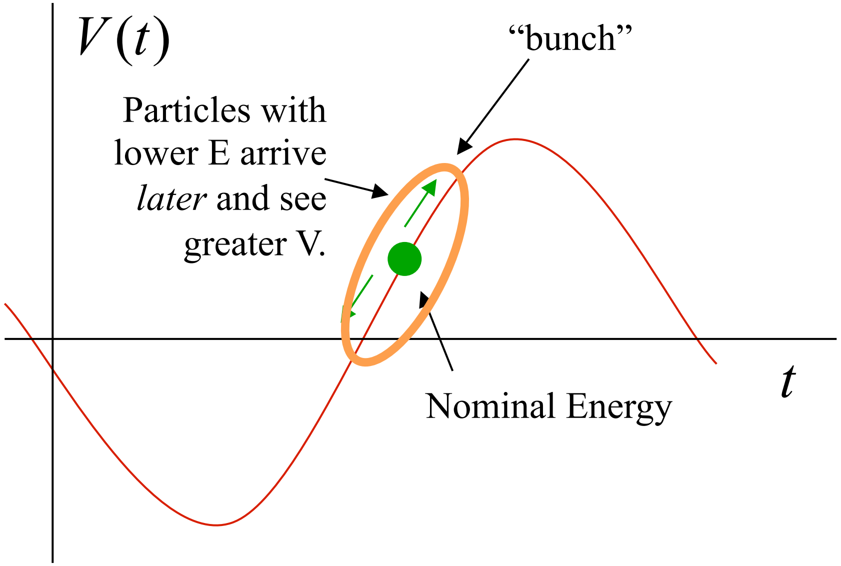
electron machines are almost always above transition. Proton machines go through transition

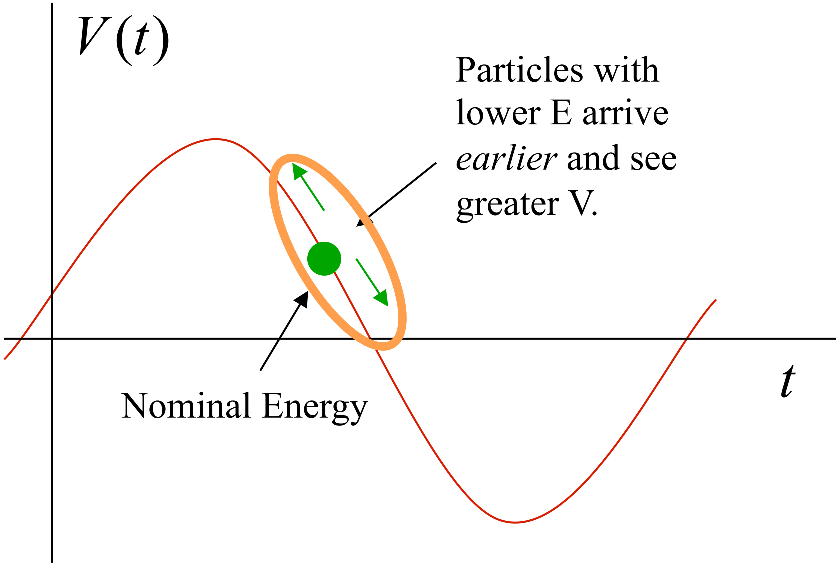
Transition and phase stability

- The sign of the slip factor determines the stable region on the RF curve.

Below γ_t: velocity dominates

Above γ_t : path length dominates

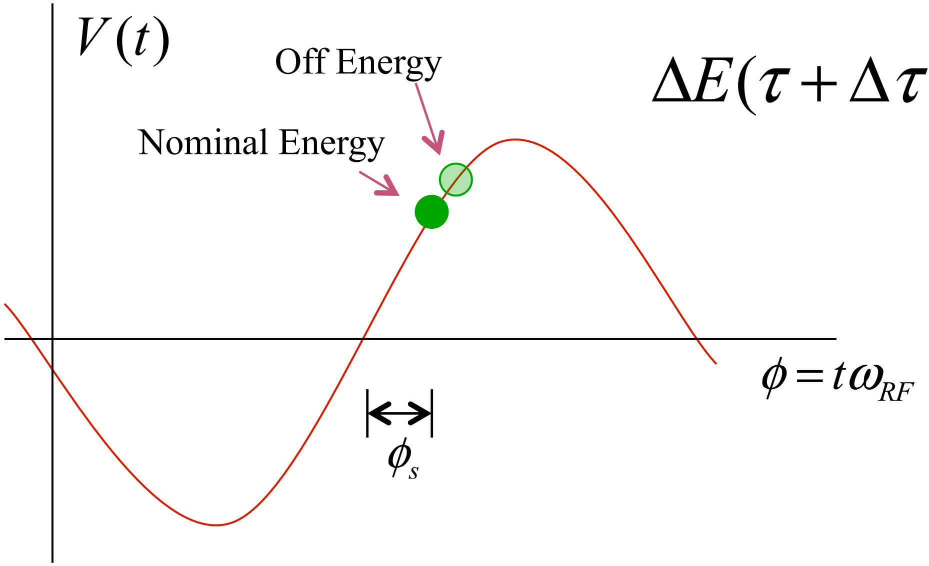




- Somewhat complicated phase manipulation at transition, which can result in losses, emittance growth, and instability
  - Easy with digital electronics, but they've been doing this since way before digital electronics.

Synchrotron motion and synchrotron tune

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



$$\Delta E(\tau + \Delta\tau) \approx eV_0(\sin\phi_s + \varpi_{RF}\cos\phi_s\Delta\tau)$$
$$= \Delta E_s + \varpi_{RF} eV_0 \cos\phi_s \Delta\tau$$

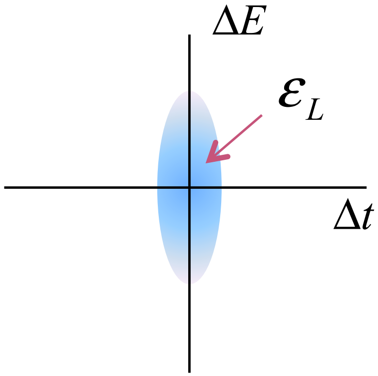
$$\frac{\Delta\tau}{\tau} = \eta\frac{\Delta p}{p} = \eta\frac{1}{\beta^2}\frac{\Delta E}{E}$$

- If $\eta\cos\phi_s < 0$ then particles will stably oscillate around this equilibrium energy with a “synchrotron frequency” and “synchrotron tune”

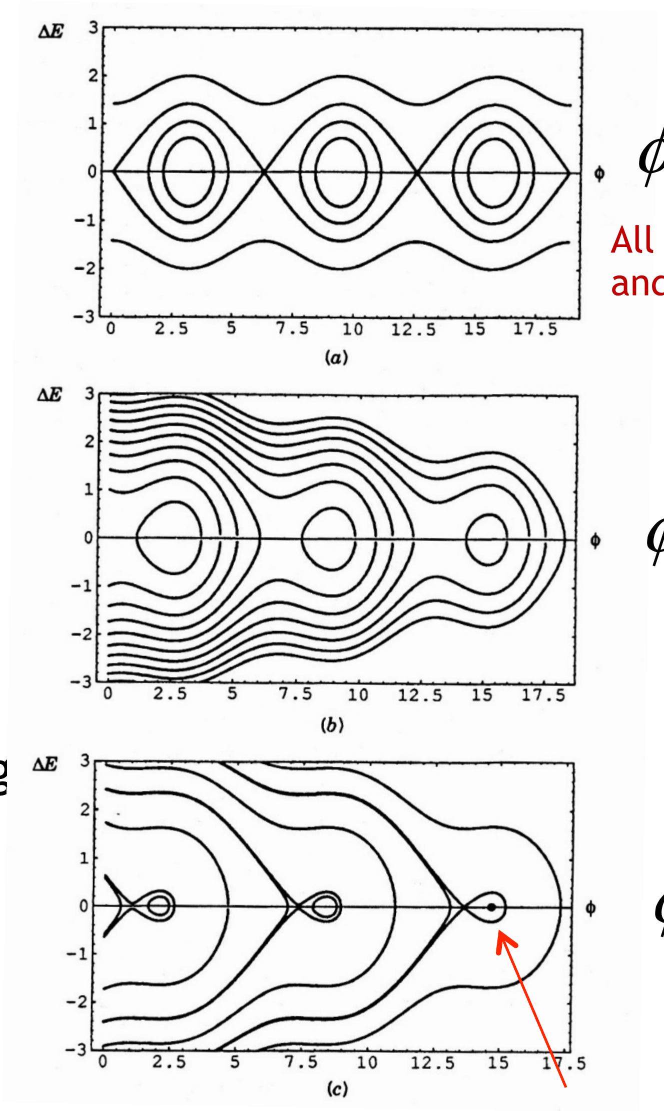
$$\Omega_s = \sqrt{-\frac{\eta\varpi_{RF} eV_0 \cos\phi_s}{\tau\beta^2 E_s}};\ \nu_s = \frac{\Omega_s\tau}{2\pi} << 1$$

Accelerating phase and longitudinal emittance

- The accelerating voltage grows as sinϕ_s, but the stable bucket area shrinks
- Just as in the transverse plane, we can define a phase space, this time in the Δt-ΔE plane



Area = "longitudinal emittance" (usually in eV-s)



$\phi_s = 0$

All beam bunched and stable

$\phi_s = 30°$

$\phi_s = 60°$

Stable "bucket"

- As particles accelerate or accelerating voltage changes

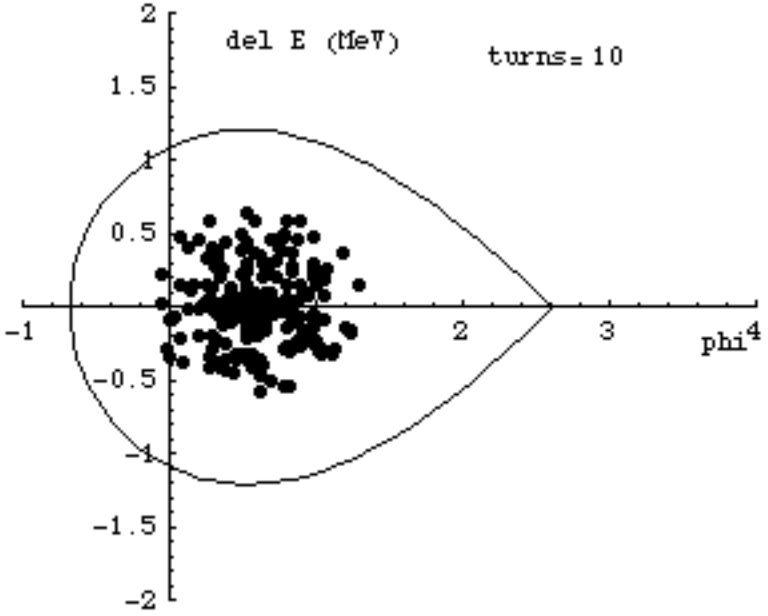
$$\Delta E_{\max} \propto \left(V_0 \beta^2 \gamma^3\right)^{\frac{1}{4}}$$

$$\Delta t_{\max} \propto \left(V_0 \beta^2 \gamma^3\right)^{-\frac{1}{4}}$$

$$\epsilon_L \propto \Delta E_{\max} \Delta t_{\max} = \text{ constant}$$

Phase stability at transition

- At transition, η=0, so beam would quickly become longitudinally unstable. It's therefore important to get through transition quickly*

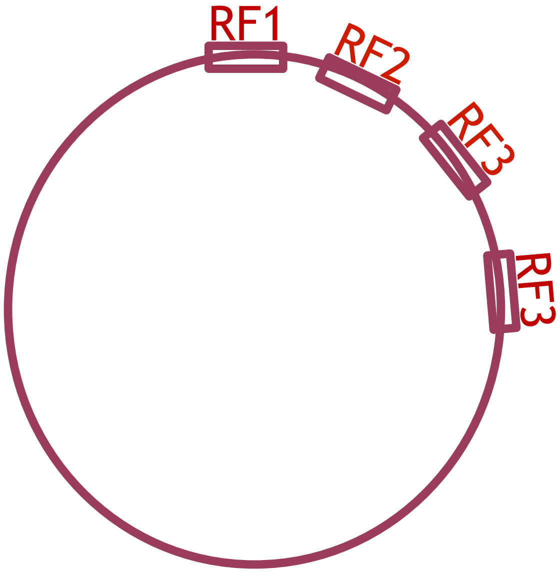


- There are also "gamma-t jump" systems which can quickly shift the transition gamma to below the current energy.

*animations courtesy G. Dugan, Cornell

RF Manipulations

- Synchrotron (longitudinal) oscillations generally take many revolutions to complete one cycle (ν<<1).
- That means that if there are multiple RF cavities around the ring, the orbiting particle will see the *vector sum* of the cavities.



$$\frac{\Delta E}{dn} = \sum_{i=1}^{N} V_i \sin(\phi_i)$$
$$= V_{eff} \sin\left(\phi_{eff}\right)$$

ϕ_i is the phase angle at the arrival of the particle at cavity *i*

- We will clearly get the maximum energy gain if all phases are the same, so (assuming all voltages are the same)

$$\frac{\Delta E}{dn} = NV_0 \sin\left(\phi_s\right)$$

Do we always want the maximum acceleration?

- There are times when we want to change the amplitude of the RF quickly.
- Because cavities represent stored energy, changing their amplitude quickly can be difficult.
- Much quicker to change phase
- Standard technique is to divide RF cavities into two groups and adjust the relative phase. In the simplest case, we put half the RF cavities into group "A" and half into group "B". We can adjust the phases of these cavities relative to our nominal synchronous phase as

$$\begin{aligned} V_{eff}\sin\left(\phi_{eff}\right) &= \frac{N}{2}V_0\sin\left(\phi_s+\delta\right)+\frac{N}{2}V_0\sin\left(\phi_s-\delta\right) \\ &= \frac{N}{2}\left(\sin\phi_s\cos\delta+\cos\phi_s\sin\delta+\sin\phi_s\cos\delta-\cos\phi_s\sin\delta\right) \\ &= NV_0\cos\delta\sin\phi_s \\ V_{eff} &= NV_0\cos\delta;\phi_{eff}=\phi_s \end{aligned}$$

- So

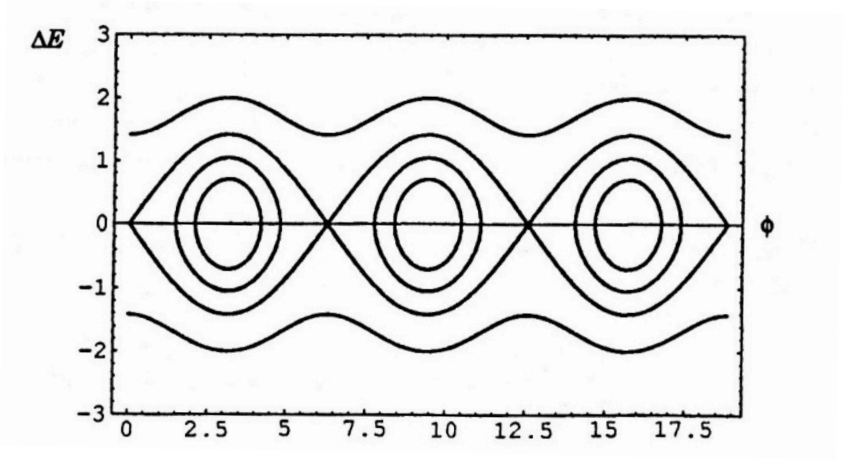
$$\delta=0\Rightarrow V_{eff}=NV_0$$

$$\delta=\frac{\pi}{2}\Rightarrow V_{eff}=0$$

Like "turning RF off"

RF capture

- We can capture beam by increasing the RF voltage with no accelerating phase



- As we accelerate beam, Δt decreases. Recall $\Delta E \Delta t \equiv \epsilon_L = \text{constant}$

$$\Delta E_{RMS} = \mathrm{E}_s^{\frac{1}{4}}$$

$$\Delta t_{RMS} = \mathrm{E}_s^{-\frac{1}{4}}$$

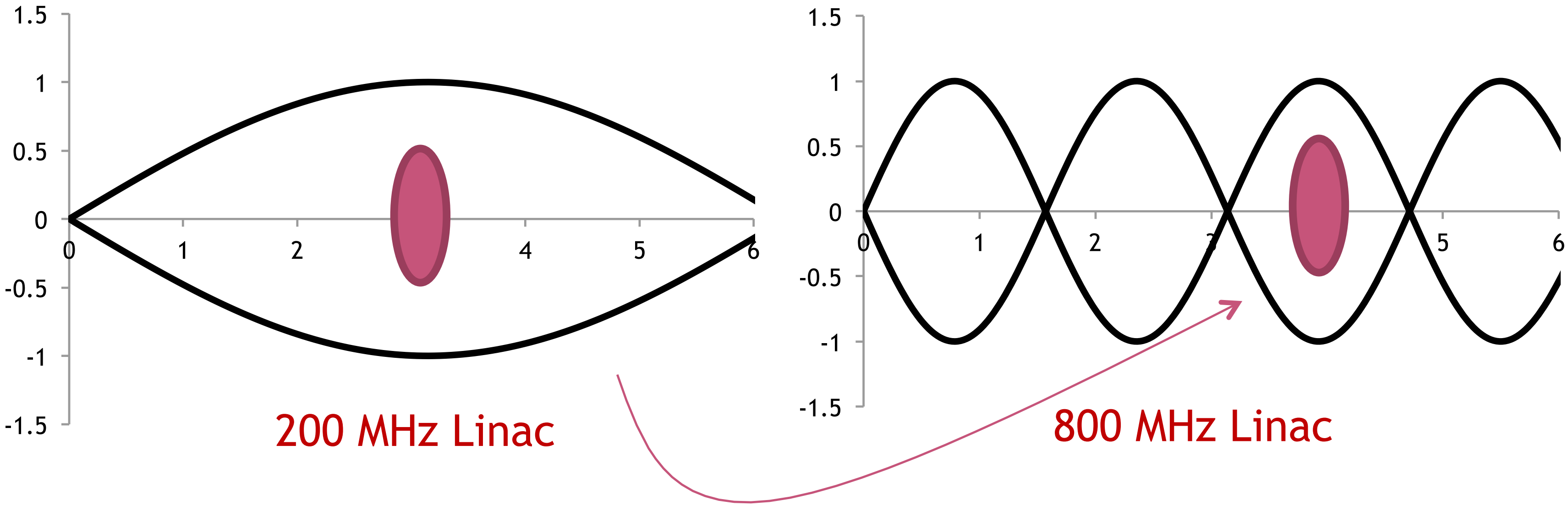
- So as beam accelerates, bunches get narrower

Bucket to Bucket Transfer

- In general, the accelerating gradient of an RF structure is

$$\frac{V}{L} \propto \frac{V_{breakdown}}{\lambda_{RF}} \propto \omega_{RF} V_{breakdown}$$

- So when bunches get short enough, it's advantageous to transfer to a higher frequency. For example, in the Fermilab Linac



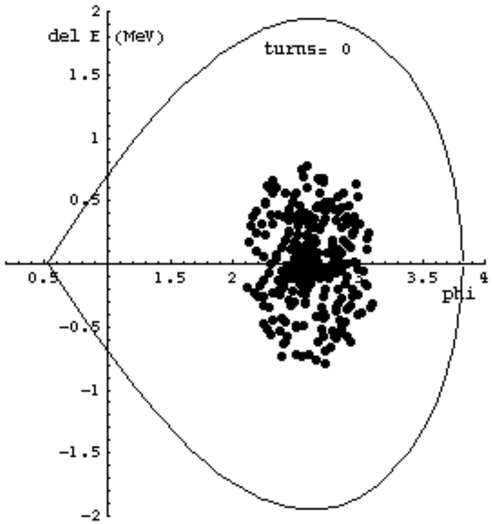
200 MHz Linac

800 MHz Linac

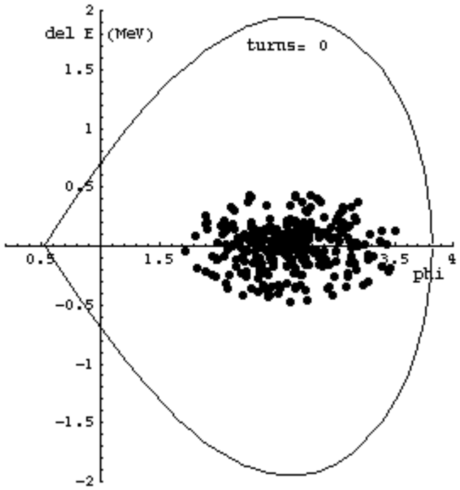
Transfer beam to every 4th bucket

Effect of mismatching

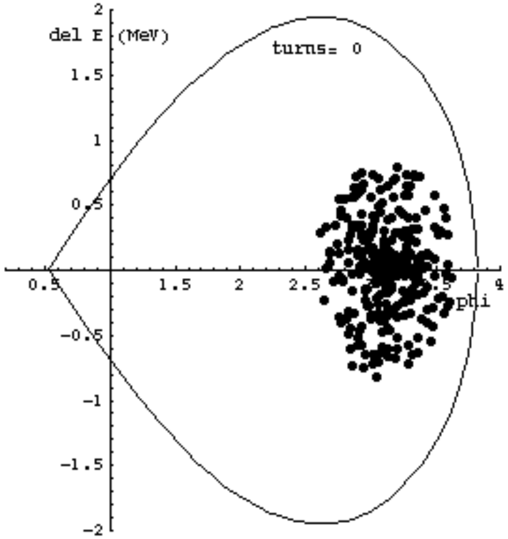
- In bucket-to-bucket transfers, it's very important to match both the shape and the phase of the longitudinal bunch. Failing to do so could result in effectively increasing the emittance.



matched



shape (β_L) mismatch



phase mismatch

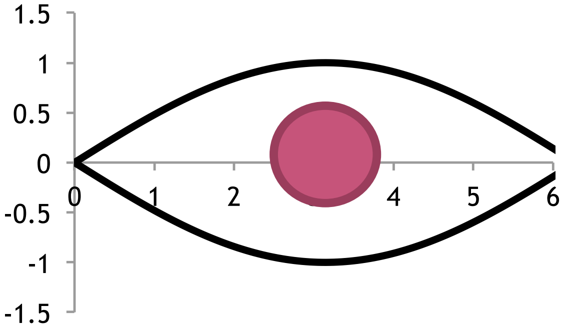
Bunch Rotation

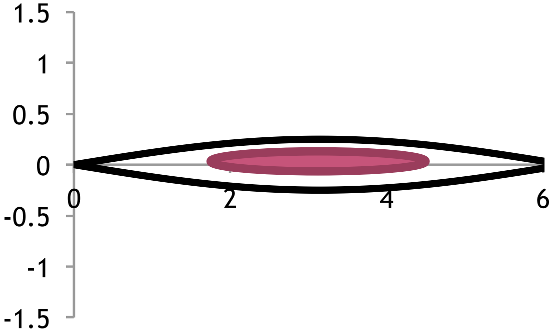
- If we *slowly* change the RF voltage (or effective voltage by phasing), we can adiabatically change the bunch shape

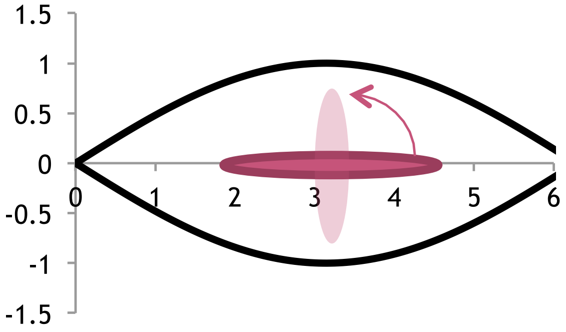
$$\Delta E_{RMS} \propto V_0^{\frac{1}{4}}$$

$$\Delta t_{RMS} \propto V_0^{-\frac{1}{4}}$$

- If we suddenly change the voltage, then the bunch will be mismatched and will rotate in longitudinal phase space



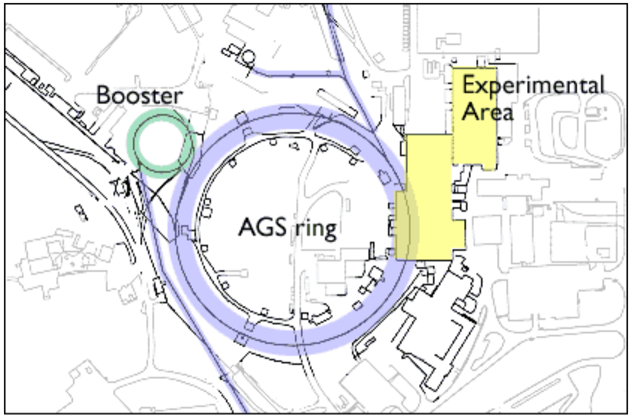




Some Important Early Synchrotrons

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

CERN Proton Synchrotron (PS)
- 1959
- 628 m circumference
- 28 GeV protons
- Still used in LHC injector chain!



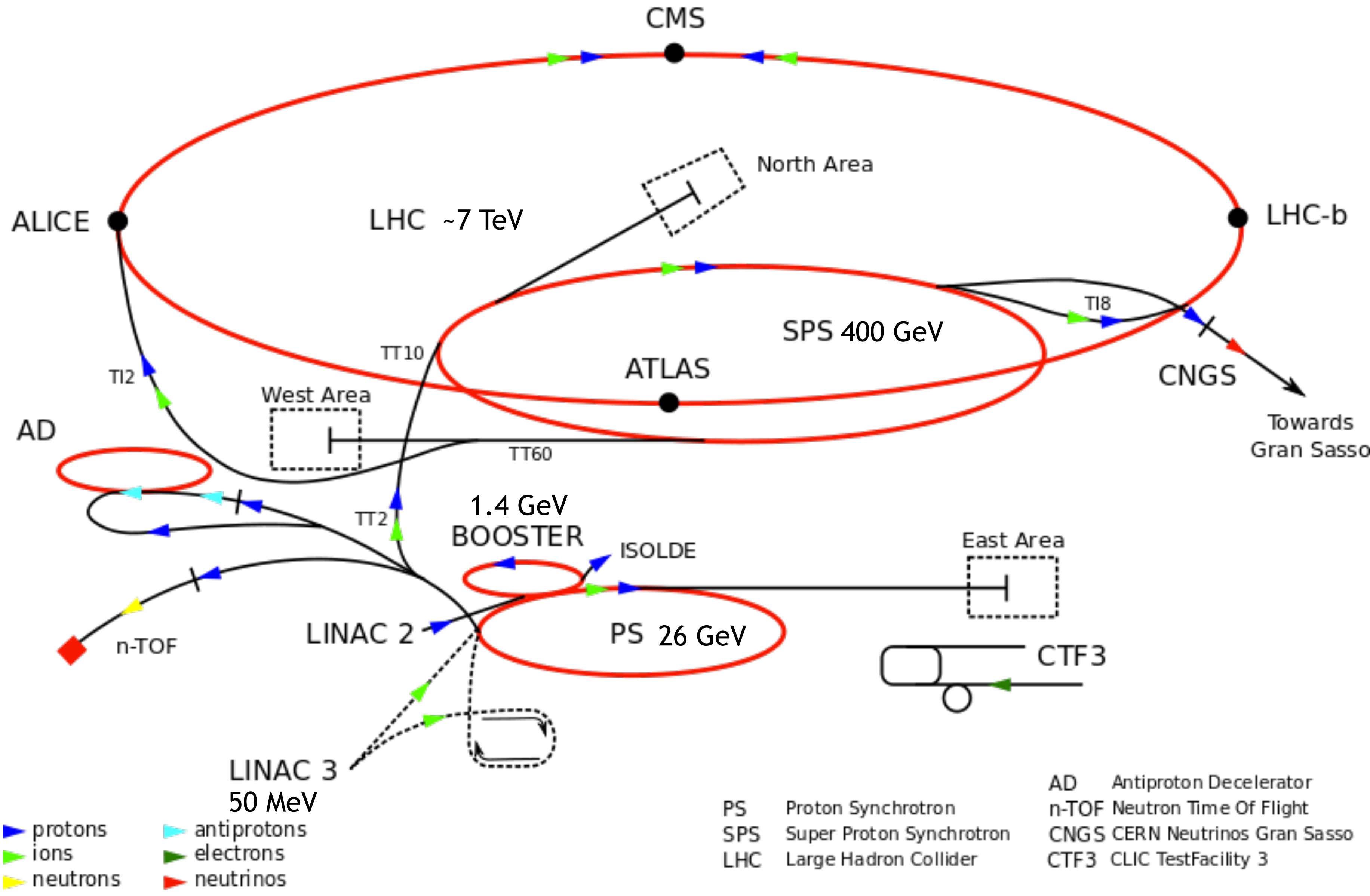
The Alternating Gradient Synchrotron complex

CERN Proton Synchrotron (PS)
- 1960
- 808 m circumference
- 33 GeV protons
- Discovered charm quark, CP violation, muon neutrino

Digression: tricks of the trade

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

CERN Accelerator Complex

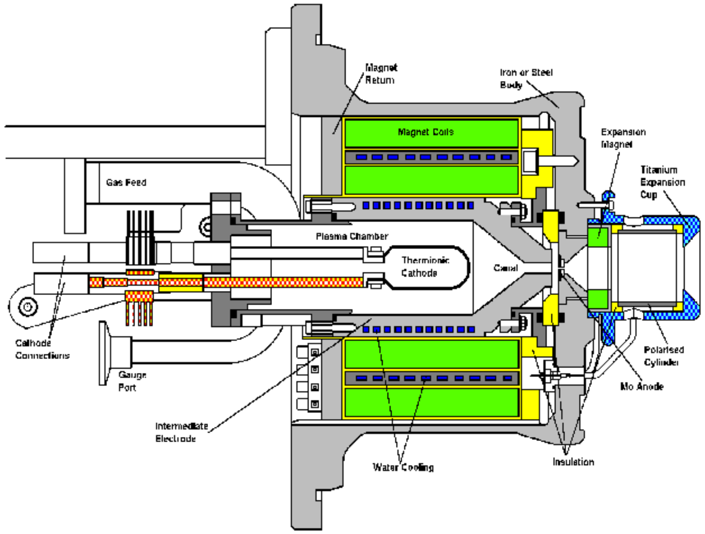


PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider

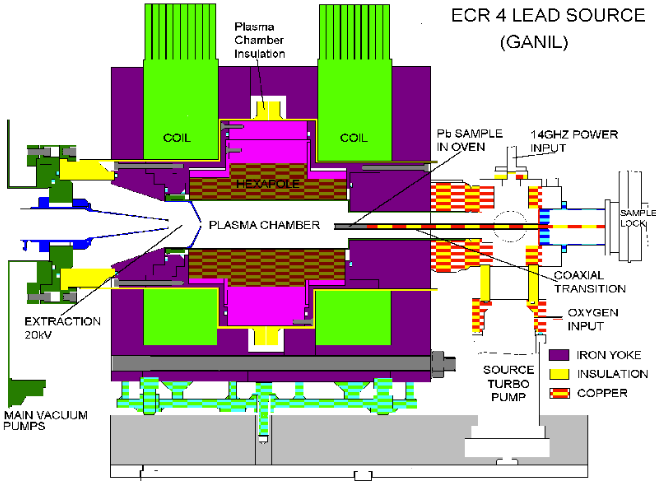
AD	Antiproton Decelerator
n-TOF	Neutron Time Of Flight
CNGS	CERN Neutrinos Gran Sasso
CTF3	CLIC TestFacility 3

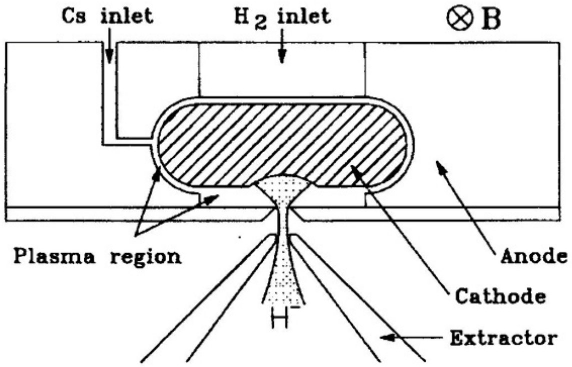
Getting started: Ion sources

CERN proton source



CERN Lead source



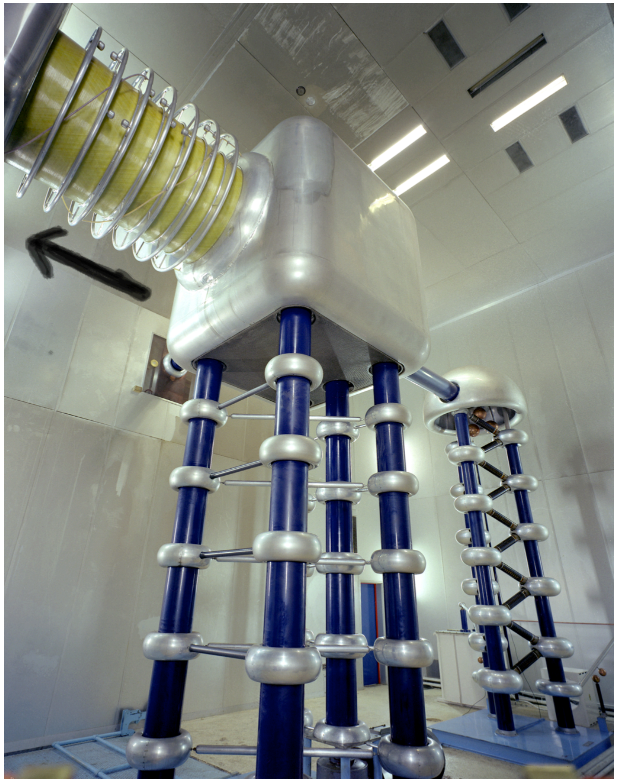


FNAL H- source. Mix Cesium with Hydrogen to add electron. (why? we'll get to that)

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

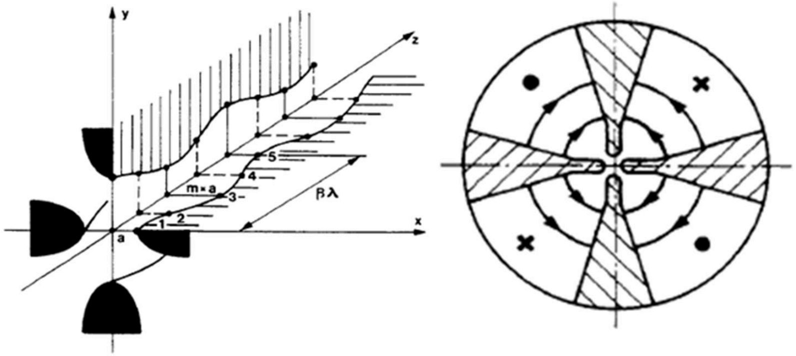
Initial acceleration

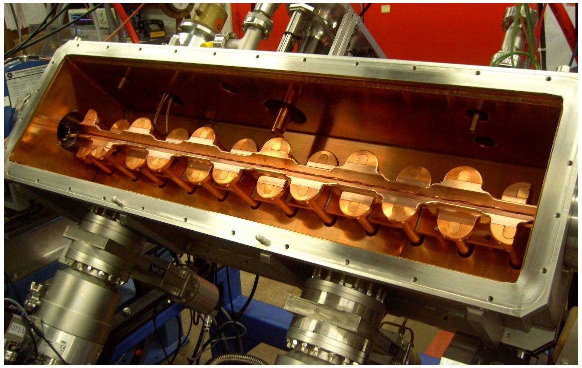
Old: Static



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

New: RF Quadrupole (RFQ)

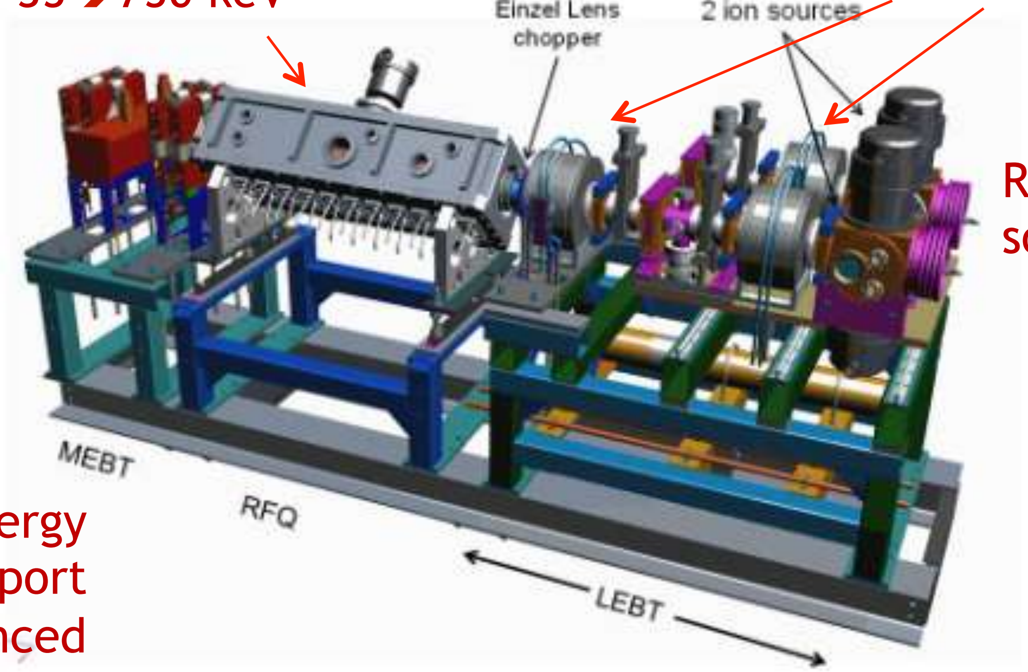




RF structure combines an electric focusing quadrupole with a longitudinal accelerating gradient.

Early stages

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



200 MHz RFQ: 35➔750 keV

Solenoidal focusing for low energy beam

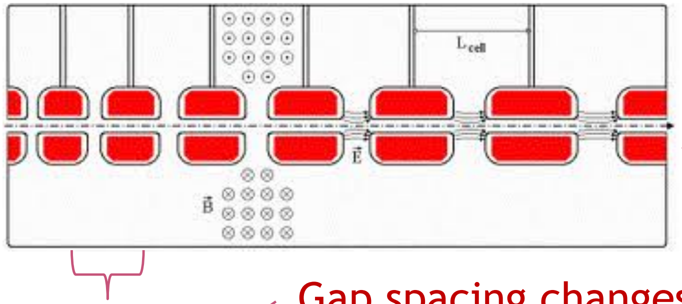
Redundant H^- sources: 0-35 keV

Medium Energy Beam Transport (MEBT, pronounced "mebbit"): 750 kEV

Low Energy Beam Transport (LEBT, pronounced "lebbit"): 35 keV

Drift Tube (Alvarez) Cavity

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

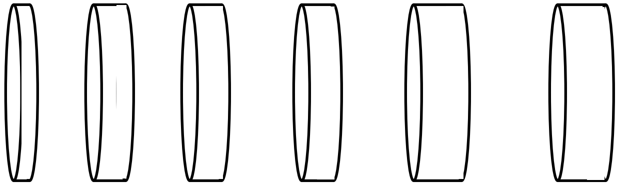


$$d = \frac{v}{f}$$

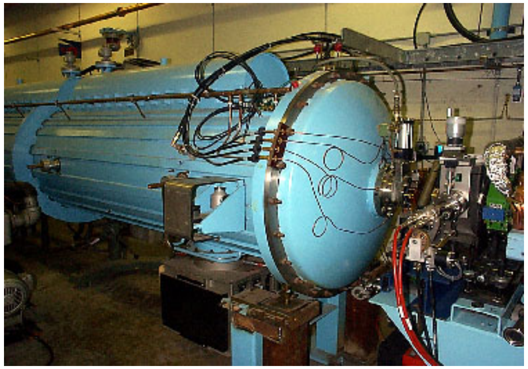
Gap spacing changes as velocity increases

$\approx$

Bunch of pillboxes



Drift tubes contain quadrupoles to keep beam focused



Fermilab low energy linac

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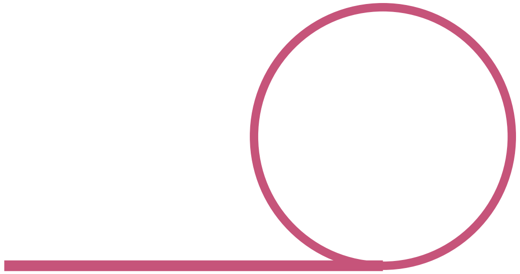
Inside

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

Linac -> synchrotron injection

- Eventually, the linear accelerator must inject into a synchrotron



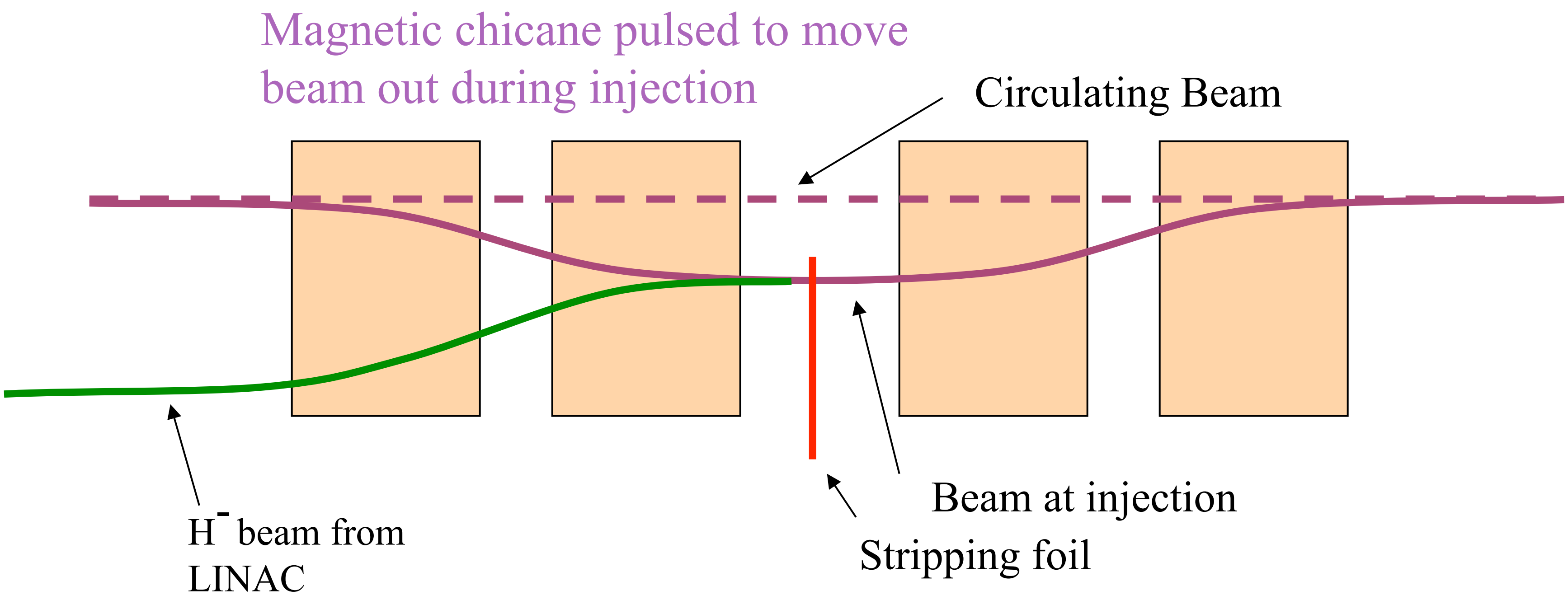
- In order to maximize the intensity in the synchrotron, we can
  - Increase the linac current as high as possible and inject over one revolution
    - There are limits to linac current
  - Inject over multiple (*N*) revolutions of the synchrotron
    - Preferred method
- Unfortunately, Liouville's Theorem says we can't inject one beam on top of another
  - Electrons can be injected off orbit and will "cool" down to the equilibrium orbit via synchrotron radiation.
  - Protons can be injected a small, changing angle to "paint" phase space, resulting in increased emittance

$$\epsilon_S \geq N \epsilon_{LINAC}$$

Synchrotron emittance

Linac emittance

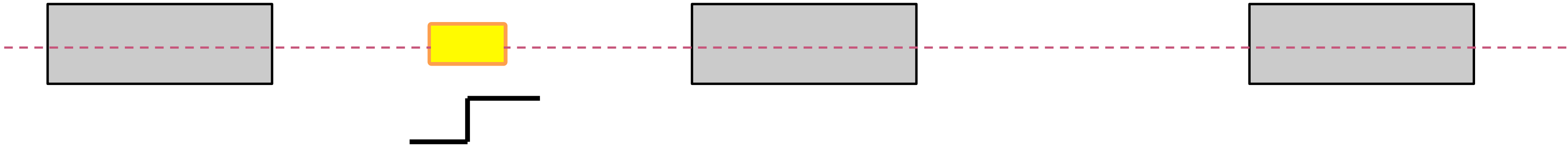
Ion (or charge exchange) injection



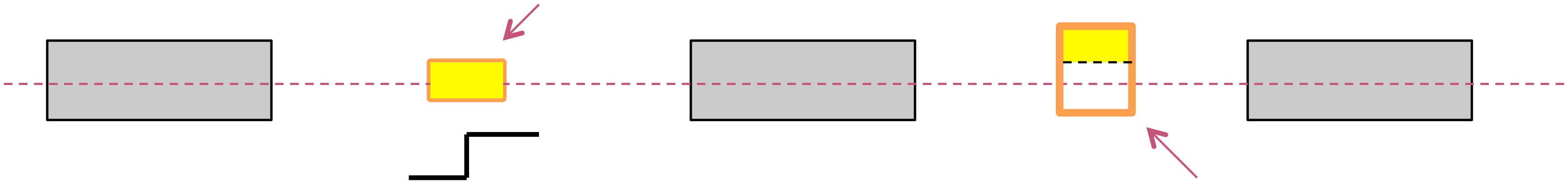
- Instead of ionizing Hydrogen, and electron is added to create H^-, which is accelerated in the linac
- A pulsed chicane moves the circulating beam out during injection
- An injected H^- beam is bent in the opposite direction so it lies on top of the circulating beam
- The combined beam passes through a foil, which strips the two electrons, leaving a single, more intense proton beam.
- Fermilab was converted from proton to H^- during the 70's
- CERN *still* uses proton injection, but is in the process of upgrading (LINAC4 upgrade)

Injection and extraction

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



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



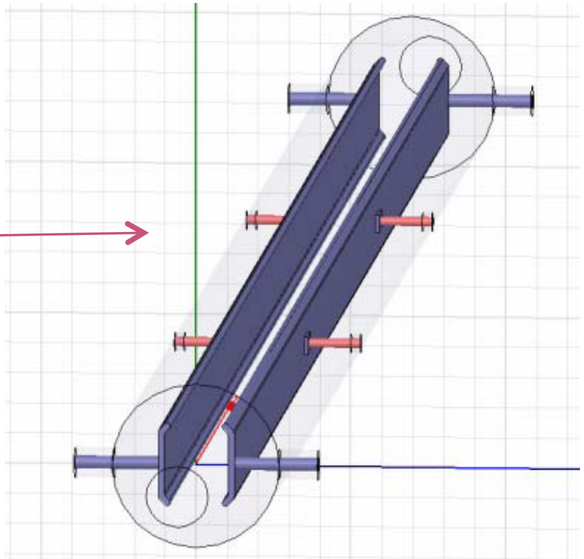
fast, weak "kicker"

slower (or DC) extraction magnet with zero field on beam path.

Extraction hardware

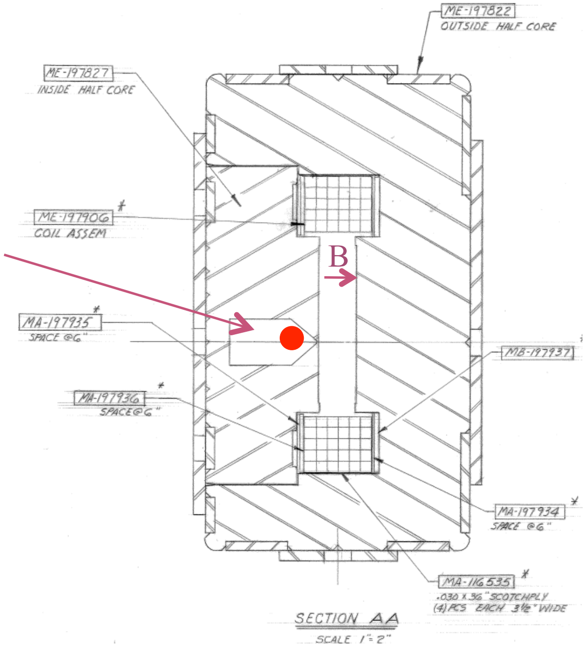
“Fast” kicker

- usually an impedance matched strip line, with or without ferrites



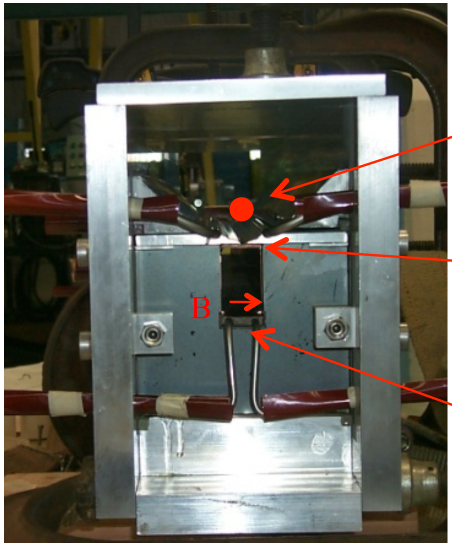
“Slow” extraction elements

“Lambertson”: usually DC



circulating beam (B=0)

Septum: pulsed, but slower than the kicker



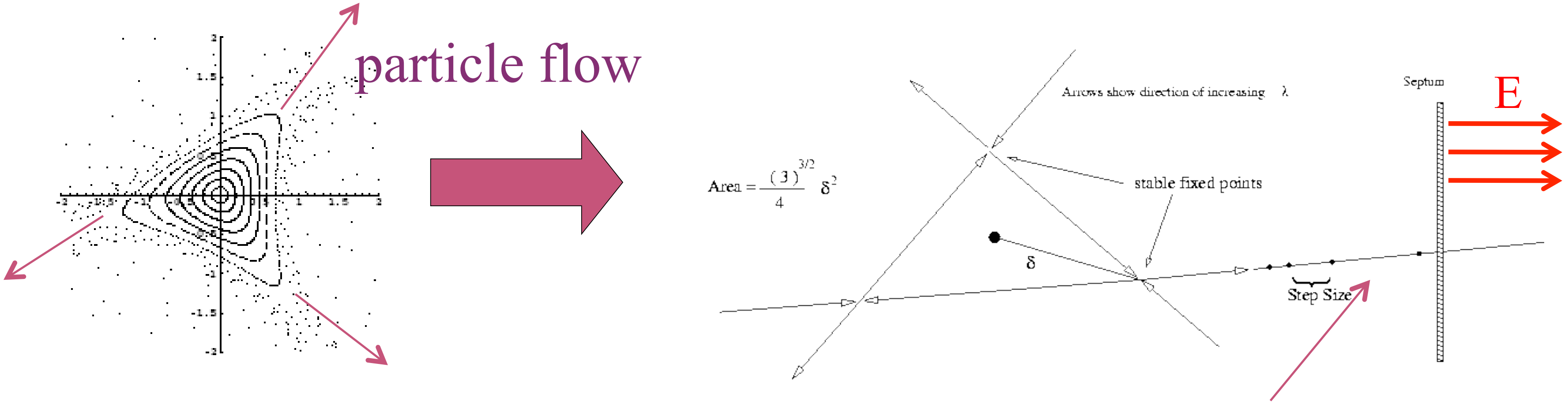
circulating beam (B=0)

current “blade”

return path

Slow Extraction (not important for colliders)

- Sometimes fixed target experiments want beam delivered *slowly* (difficult)
- To do this, we generate a harmonic resonance
  - Usually sextupoles are used to create a 3rd order resonant instability

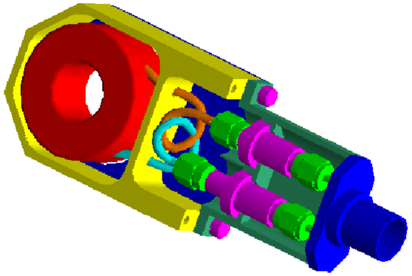


Particles will flow out of the stable region along lines in phase space into an electrostatic extraction field, which will deflect them into an extraction Lambertson

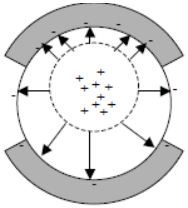
- Tune the instability so the escaping beam exactly fills the extraction gap between interceptions (3 times around for 3rd order)
  - Minimum inefficiency ~(septum thickness)/(gap size)
  - Use electrostatic septum made of a plane of wires. Typical parameters
    - Septum thickness: .1 mm
    - Gap: 10 mm
    - Field: 80 kV

Standard beam instrumentation

- Bunch/beam intensity are measured using inductive toriods

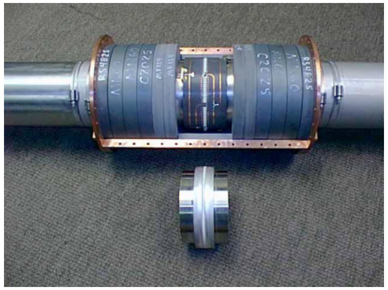


- Beam position is typically measured with beam position monitors (BPM's), which measure the induced signal on a opposing pickups



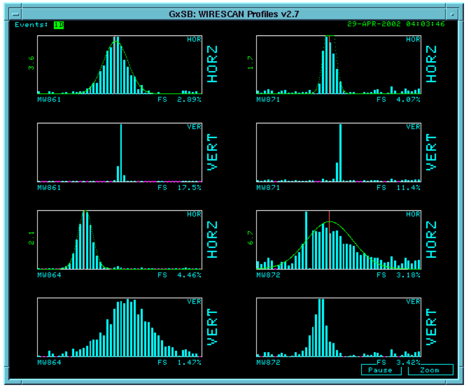
$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

- Longitudinal profiles can be measured by introducing a resistor to measure the induced image current on the beam pipe -> Resistive Wall Monitor (RWM)



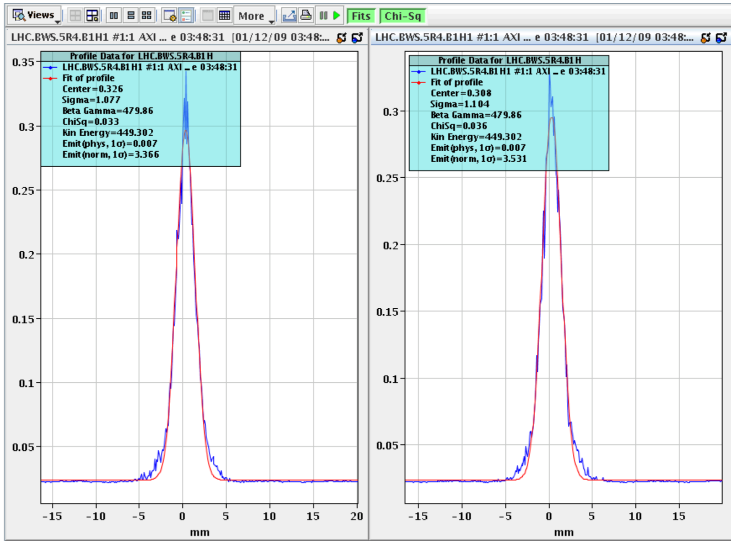
Beam instrumentation (cont'd)

- Beam profiles in beam lines can be measured using secondary emission multiwires (MW's)



Beam profiles in MiniBooNE beam line

- Can measure beam profiles in a circulating beam with a "flying wire scanner", which quickly passes a wire through and measures signal vs time to get profile



Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H1 #1:1 AXI _ e 03:48:31
Fit of profile
Center=0.326
Sigma=1.077
Beta Gamma=479.86
ChiSq=0.033
Kin Energy=449.302
Emit(phys, 1σ)=0.007
Emit(norm, 1σ)=3.366

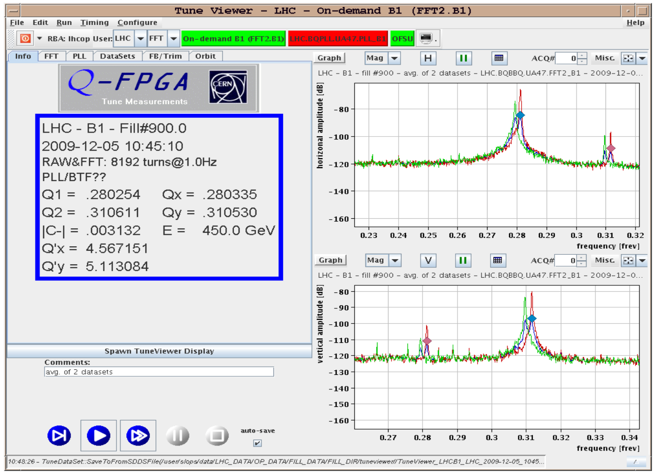
Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H1 #1:1 AXI _ e 03:48:31
Fit of profile
Center=0.308
Sigma=1.104
Beta Gamma=479.86
ChiSq=0.036
Kin Energy=449.302
Emit(phys, 1σ)=0.007
Emit(norm, 1σ)=3.531

Flying wire signal in LHC

- Non-destructive measurements include
  - Ionization profile monitor (IPM): drift electrons or ions generated by beam passing through residual gas
  - Synchrotron light
    - Standard in electron machines
    - Also works in LHC

Measuring lattice parameters

- The fractional tune is measured by Fourier Transforming signals from the BPM's
  - Sometimes need to excite beam with a kicker

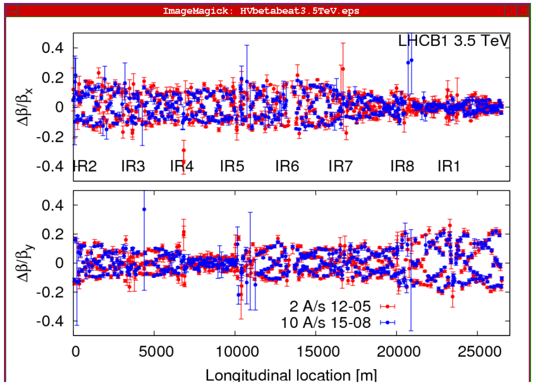


LHC - B1 - Fill#900.0
2009-12-05 10:45:10
RAW&FFT: 8192 turns@1.0Hz
PLL/BTF??
Q1 = .280254 Qx = .280335
Q2 = .310611 Qy = .310530
|C-| = .003132 E = 450.0 GeV
Q'x = 4.567151
Q'y = 5.113084

Comments: avg. of 2 datasets

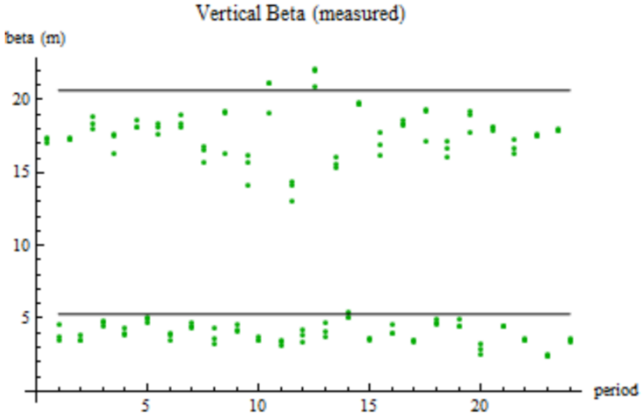
10:48:26 - TuneDataSet::SaveToFromSDDSFile(/user/slops/data/LHC_DATA/OP_DATA/FILL_DATA/FILL_DIR/tuneviewer//TuneViewer_LHCB1_LHC_2009-12-05_1045...

- Beta functions can be measured by exciting the beam and looking at distortions
  - Can use kicker or resonant ("AC") dipole



- Can also measure the by functions indirectly by varying a quad and measuring the tune shift

$$\Delta \nu = \frac{1}{4\pi}\frac{\boxed{\beta}}{f}$$

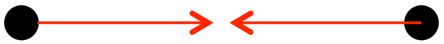


Moving on: The Case for Colliders

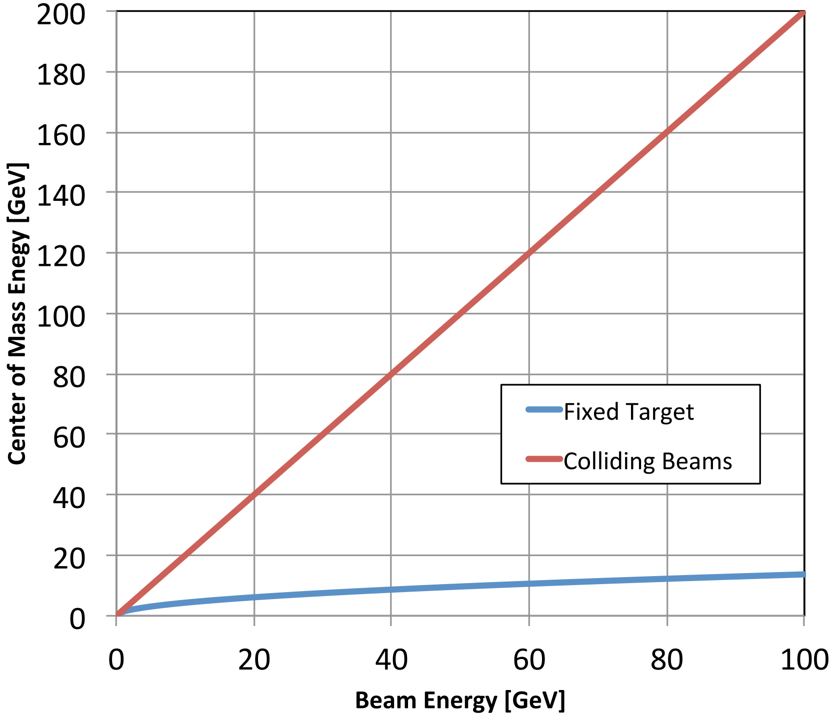
- If beam hits a stationary proton, the "center of mass" energy is

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

- 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 → $$R = L\sigma$$

"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:

Target thickness

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

Incident rate

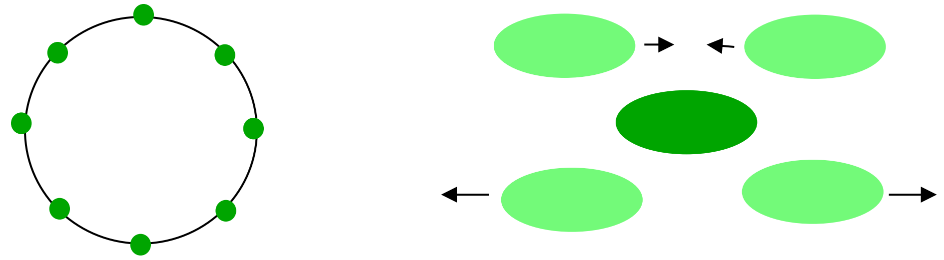
Target number density

Example: MiniBooNe primary target:

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

Colliding Beam Luminosity

Circulating beams typically "bunched"



(number of interactions)

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

Cross-sectional area of beam

Total Luminosity:

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

crossing rate

Number of bunches

Circumference of machine

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

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

Normalized emittance

Revolution frequency

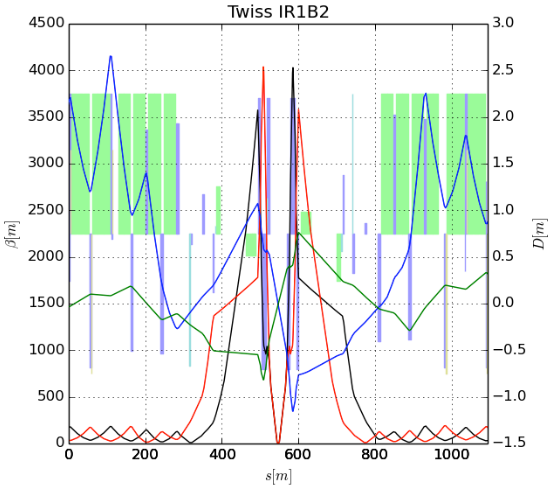
Number of bunches

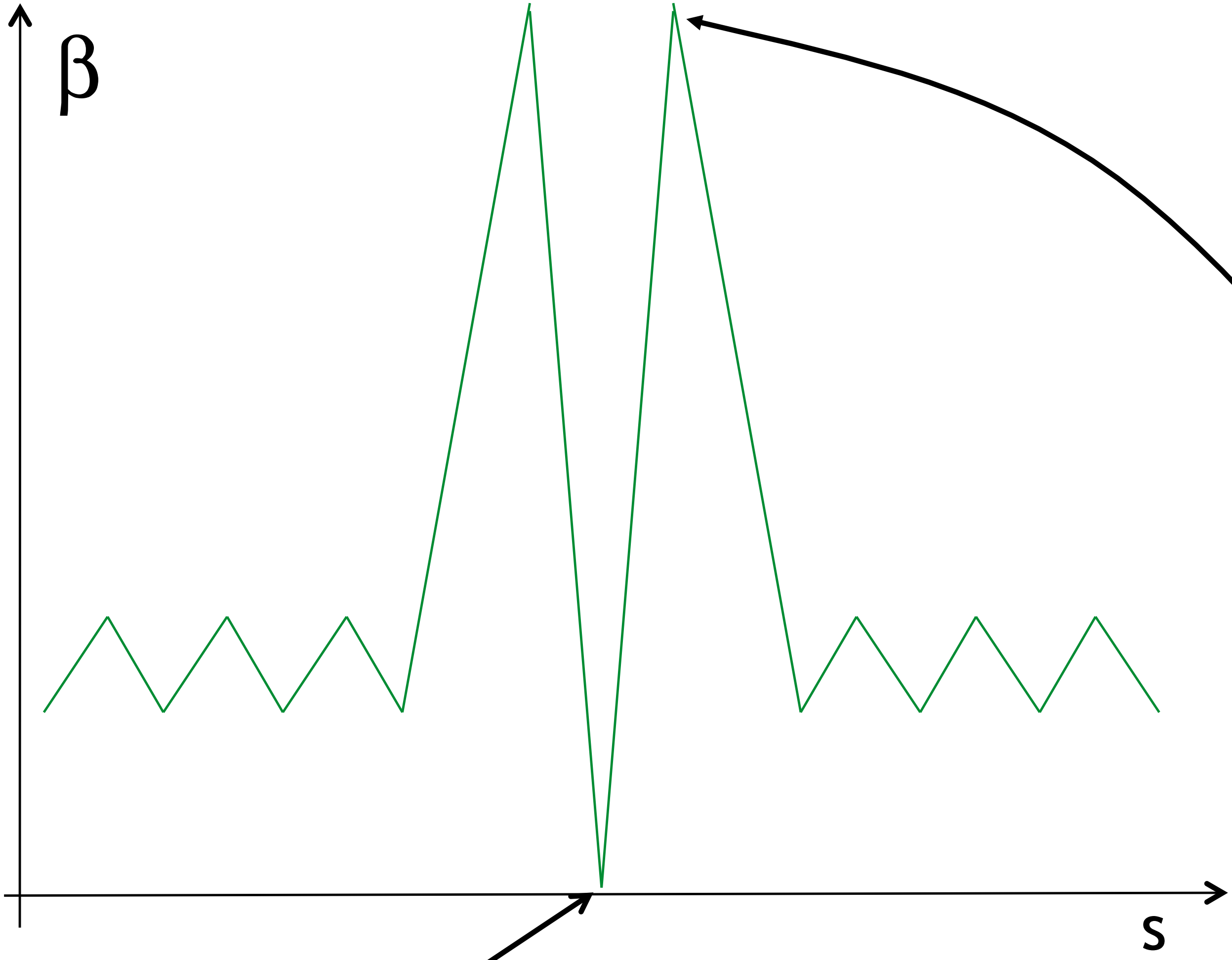
Betatron function at collision point ➔ want a small β*!

Particles in bunch

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

Limits to β*





$$\beta(\Delta s) = \beta^* + \frac{\Delta s^2}{\beta^*} \rightarrow \beta_{\max} \propto \frac{1}{\beta^*}$$

➔ small β* means large β (aperture) at focusing triplet

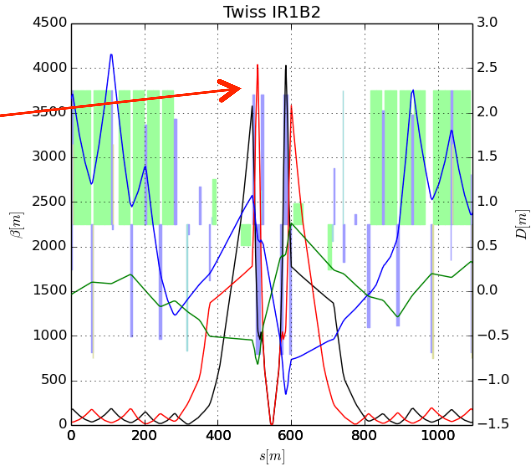
The “squeeze”?

- In general, synchrotrons scale all magnetic fields with the momentum, so the optics remain constant – with one exception.
- Recall that because of adiabatic damping, beam gets smaller as it accelerates.

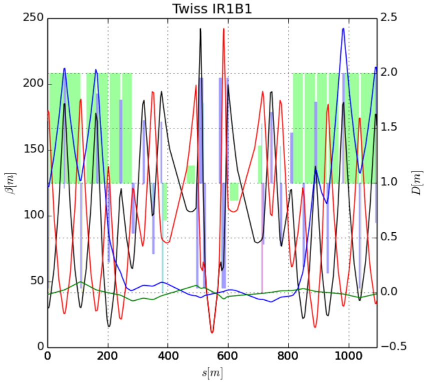
$$\sigma_x = \sqrt{\frac{\beta_x \epsilon}{\beta\gamma}} \propto \frac{1}{\sqrt{p}}$$

factor of ~4 for LHC

- This means all apertures must be large enough to accommodate the injected beam.
  - This a problem for the large β values in the final focus triplets



- For this reason, injection optics have a larger value of β*, and therefor a smaller value of β in the focusing triplets.
- After acceleration, beam is “squeezed” to a smaller β* for collision



Beam Parameters: LHC

Parameter	Symbol	Equation	Injection	Collision
proton mass	m [GeV/c^2]		0.93827	
kinetic energy	K [GeV]		400	7000
total energy	E [GeV]	$K+mc^2$	400.93827	7000.93827
momentum	p [GeV/c]	$\sqrt{E^2-\left(mc^2\right)^2}$	400.9371721	7000.937937
rel. beta	β	$\left(pc\right)/E$	0.999997262	0.999999991
rel. gamma	γ	$E/(mc^2)$	427.3165187	7461.539077
beta-gamma	βγ	$\left(pc\right)/(mc^2)$	427.3153486	7461.53901
rigidity	(Bρ) [T-m]	$p[\mathrm{GeV}]/(.2997)$	1337.8	23359.8
emittance	ϵ_N [m]		2.75x10^{-6}	2.75x10^{-6}
typical beta	β_T [m]		~100	
typical size	σ [mm]	$\sqrt{\frac{\beta_T\epsilon_N}{\beta\gamma}}$	.8	.2
collision beta	β^*[m]		11	.6
collision size	σ^* [mm]	$\sqrt{\frac{\beta^*\epsilon_N}{\beta\gamma}}$	.266	.015
max. beta	$\beta_{\max}$ [m]		240	4000
max size	$\sigma_{\max}$ [mm]	$\sqrt{\frac{\beta_{\max}\epsilon_N}{\beta\gamma}}$	1.3	1.3

Squeeze keeps this the same

Luminosity Lifetime

If we keep all other loss mechanisms minimal, the useful life of colliding beams is determined by the "burn rate", based on the total cross section

$$\frac{dN_b}{dt} = -\mathcal{L}\sigma_{total}$$

$$\mathcal{L} \propto N_b^2 \equiv kN_n^2$$

Not exponential!

$$\frac{d\mathcal{L}}{dt} = 2\mathcal{L}N_b\frac{dN_b}{dt} = -2kN_b\mathcal{L}\sigma_{total} = -2k^{1/2}\mathcal{L}^{3/2}$$

$$\equiv -\frac{\mathcal{L}}{\tau_{\mathcal{L}}}$$

Luminosity lifetime (not constant)

$$\tau_{\mathcal{L}} = \frac{1}{2kN_b\sigma_{total}} = \frac{N_b}{2\mathcal{L}\sigma_{total}}$$

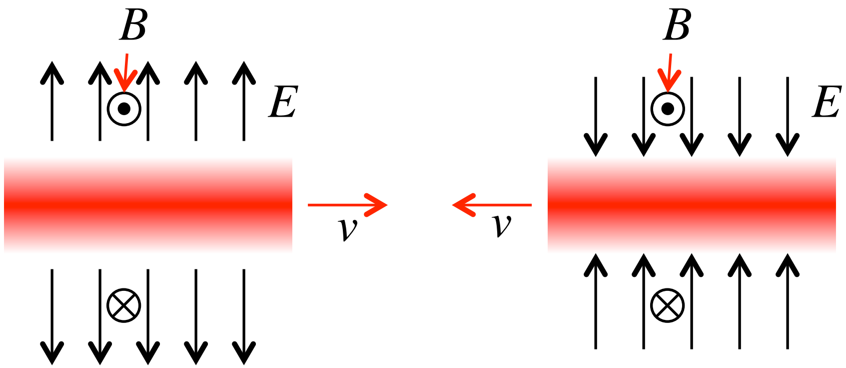
$$= \frac{\mathcal{L}}{N_b}$$

$$\boxed{\text{initial } \tau_{\mathcal{L}} = \frac{N_0}{2\mathcal{L}_0\sigma_{total}}}$$

Normally talk about the initial luminosity lifetime

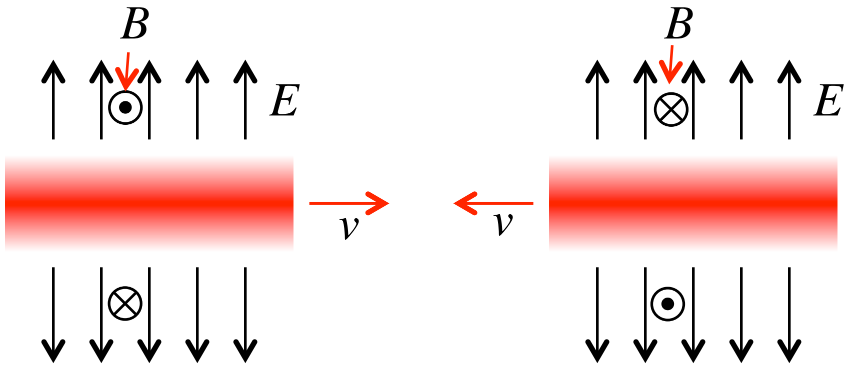
Beam-beam Interaction

If two *oppositely* charged bunches pass through each other…

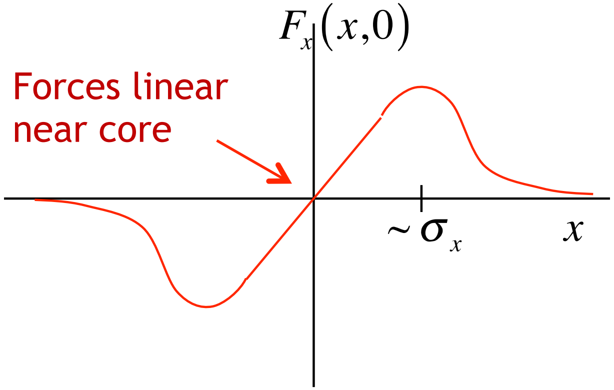


Both E and B fields are *attractive* to the particles in the other bunch

If two bunches with the *same* sign pass through each other…



Both E and B fields are *repulsive* to the particles in the other bunch



Forces linear near core

In either case, the forces add. This looks like a little quadrupole in each plane, causing the tune to spread out.

Luminosity and Tuneshift

The total tuneshift will ultimately limit the performance of any collider, by driving the beam onto an unstable resonance. Values of on the order ~.02 are typically the limit. However, we have the somewhat surprising result that the "beam-beam parameter" (scale of spread)

$$\xi = \frac{r_0}{2\pi\gamma}\left(\frac{N_b}{\epsilon}\right); \quad \mathrm{r}_0 \equiv \frac{e^2}{4\pi\epsilon_0 m_0 c^2}$$

"classical radius"

$$= 1.53\times 10^{-18} \text{ m for protons}$$

does *not* depend on β*, but only on

bunch size →

$$\frac{N_b}{\epsilon} \equiv \text{"brightness"}$$

emittance →

For a collider, we have

$$\mathcal{L} = \frac{f n_b N_b^2}{4\pi\sigma^2} = \frac{f n_b N_b^2}{4\pi\left(\frac{\beta^* \epsilon_N}{\gamma}\right)} = \frac{f n_b N_b \gamma}{r_0 \beta^*}\left(\frac{r_0}{4\pi}\frac{N_b}{\epsilon_N}\right)$$

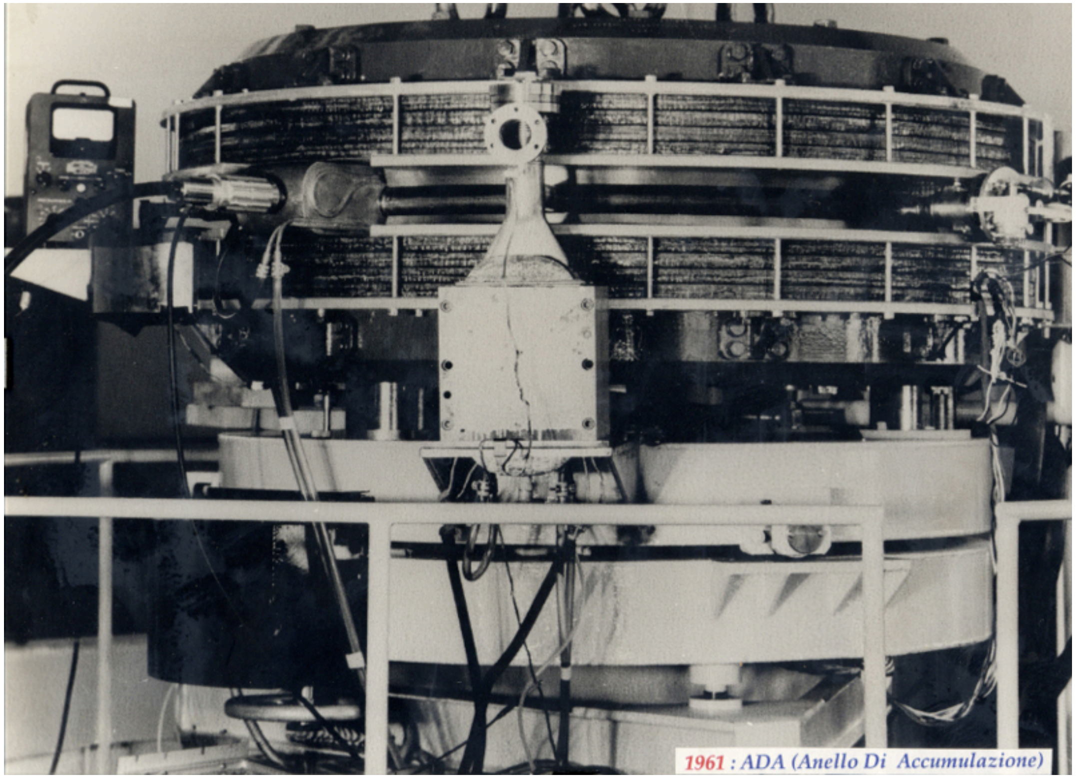
$$\boxed{= f\frac{n_b N_b \gamma}{r_0 \beta^*}\xi}$$

We assume we will run the collider at the "tuneshift limit", in which case we can increase luminosity by

- Making β* as small as possible
- Increasing N_b and ε proportionally.

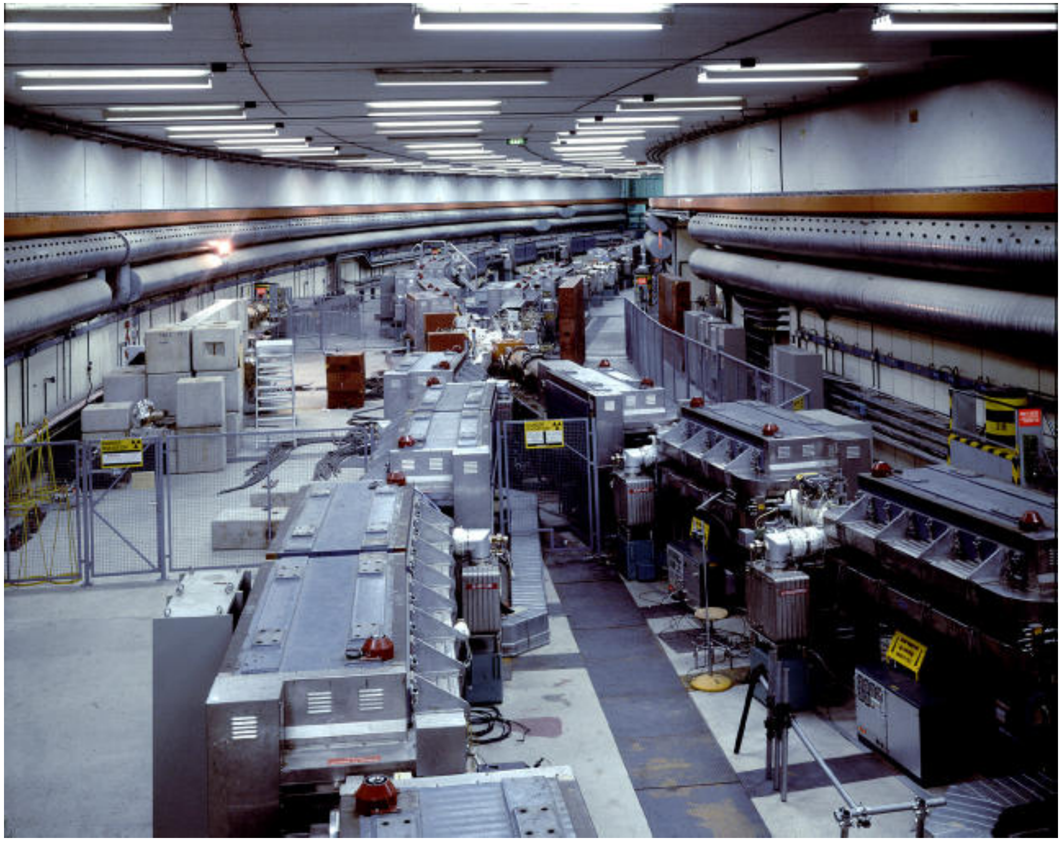
First e^+e^- Collider

- ADA (Anello Di Accumulazione) at INFN, Frascati, Italy (1961)
  - 250 MeV e^+ x 250 MeV e^-
  - L~10^{25} $cm^{-2}s^{-1}$



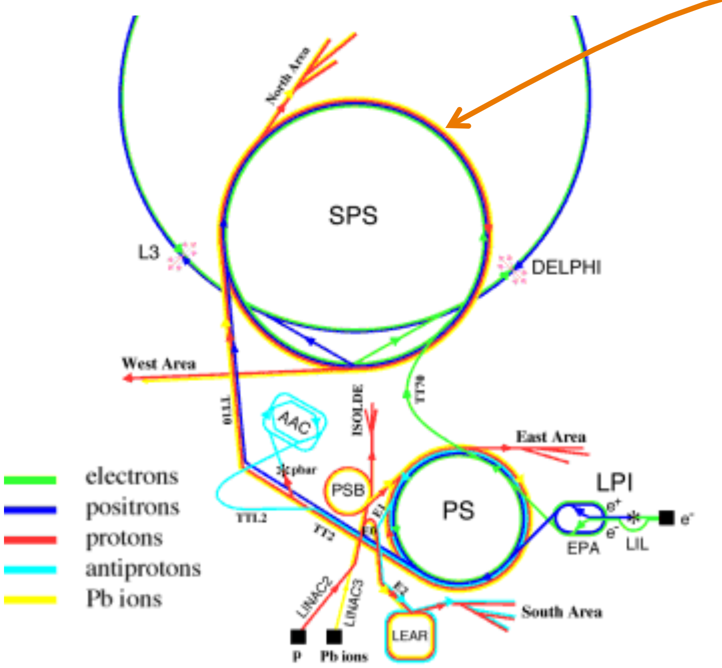
- It's easier to collide e+e-, because synchrotron radiation naturally "cools" the beam to smaller size.

History: CERN Intersecting Storage Rings (ISR)

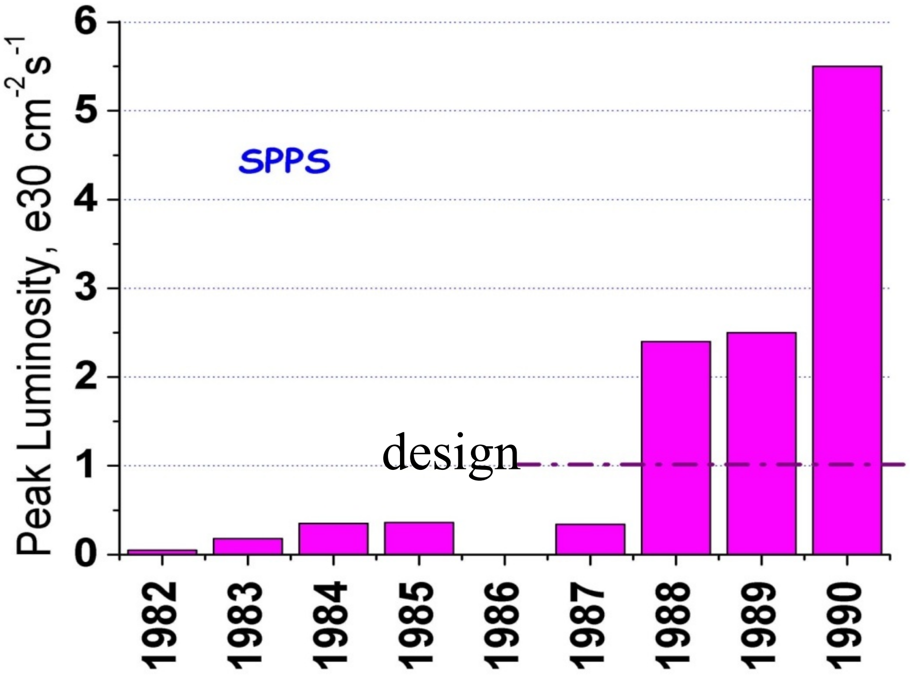


- First hadron collider (p-p)
- Highest CM Energy for 10 years
  - Until Sp$\bar{p}$S
- Reached it's design luminosity within the first year.
  - Increased it by a factor of 28 over the next 10 years
- Its peak luminosity in 1982 was 140x10^{30} cm^{-2}s^{-1}
  - a record that was not broken for 23 years!!

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



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

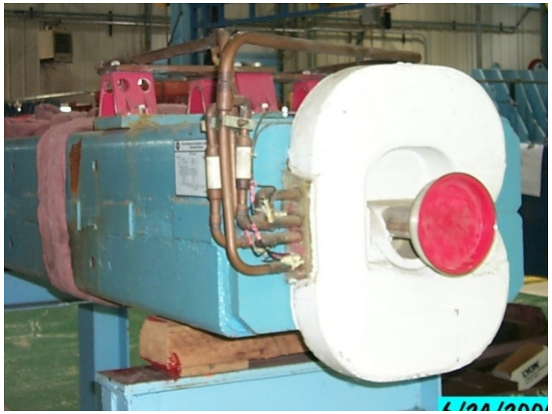


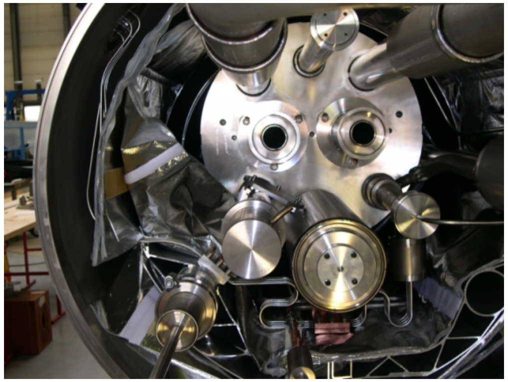
- Energy initially 270+270 GeV
- Raised to 315+315 GeV
  - Limited by power loss in magnets!
- Peak luminosity: $5.5\text{x}10^{30}\text{cm}^{-2}\text{s}^{-1}$
  - ~.2% of current LHC

Superconductivity: Enabling Technology

- The maximum Sp$\bar{p}$S energy was limited by the maximum power loss that the conventional magnets could support in DC operation
  - P = I^2R proportional to B^2
  - Maximum practical DC field in conventional magnets ~1T
  - LHC made out of such magnets would be roughly the size of Rhode Island!
- Highest energy colliders only possible using superconducting magnets
- Must take the bad with the good
  - Conventional magnets are simple and naturally dissipate energy as they operate

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

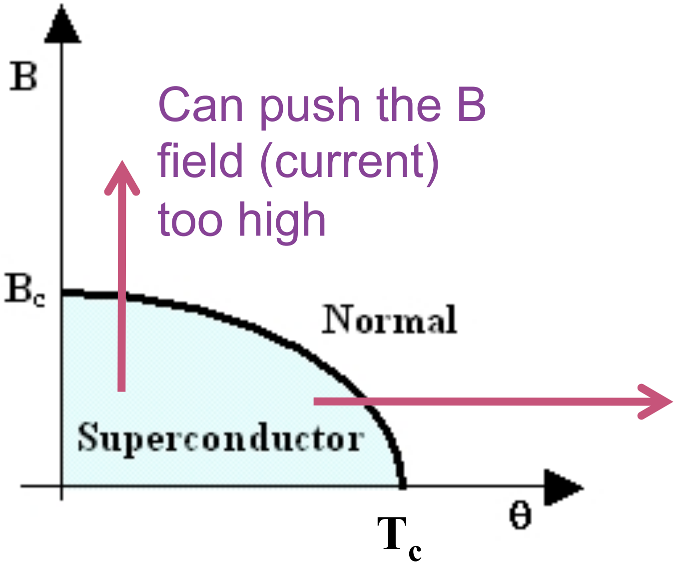




$$E \propto B^2$$

When is a superconductor not a superconductor?

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



Can push the B field (current) too high

Can increase the temp, through heat leaks, deposited energy or *mechanical deformation*

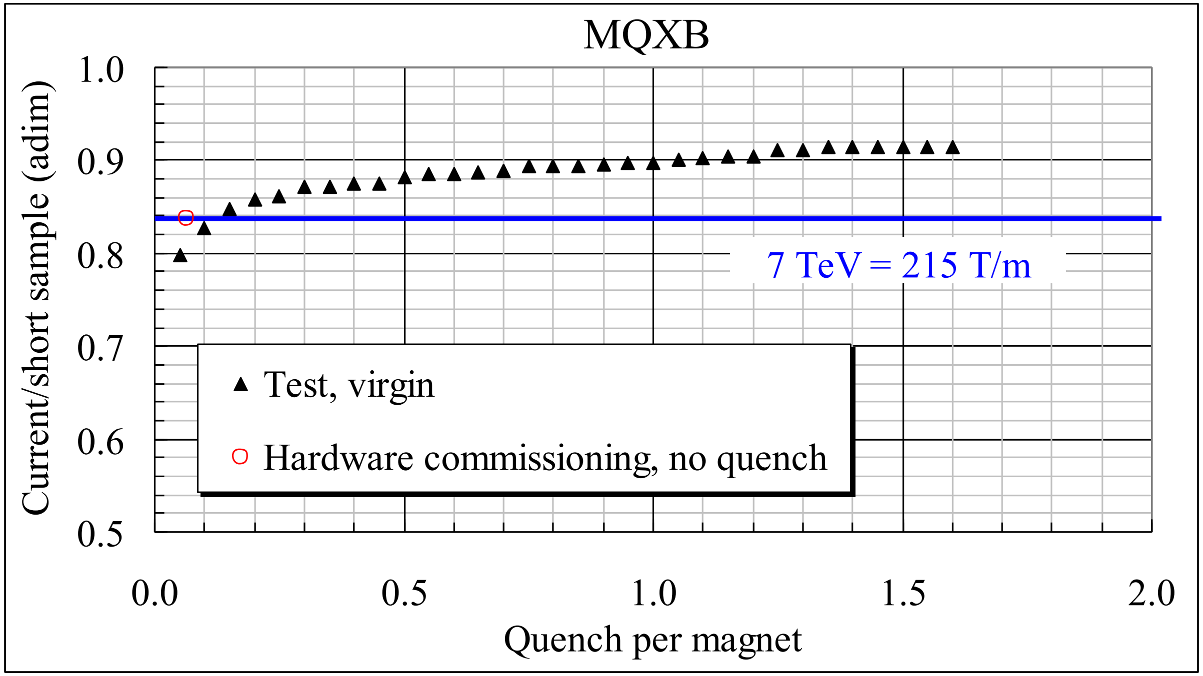
- When this happens, the conductor heats quickly, causing the surrounding conductor to go normal and dumping lots of heat into the liquid Helium➔“quench
  - all of the energy stored in the magnet must be dissipated in some way
- Dealing with quenches is the single biggest issue for any superconducting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

Quench Example: MRI Magnet*

*pulled off the web. We recover our Helium.

Magnet "training"

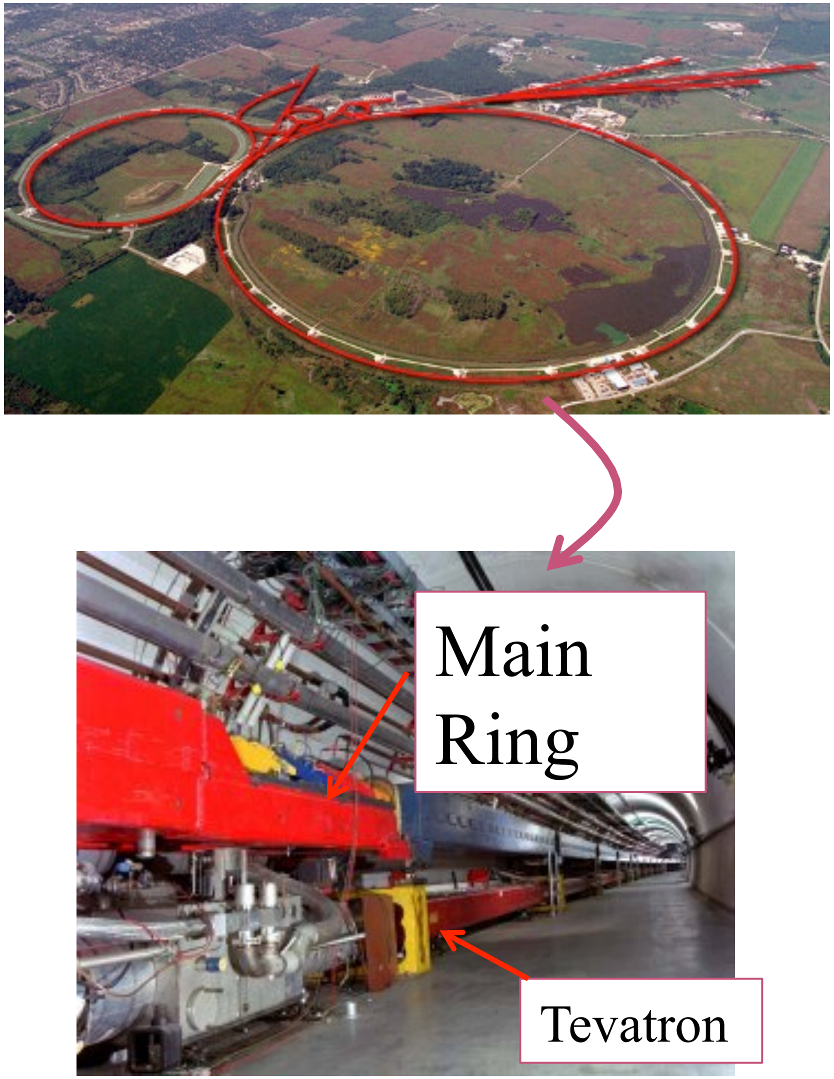
- As new superconducting magnets are ramped, electromechanical forces on the conductors can cause small motions.
- The resulting frictional heating can result in a quench
- Generally, this "seats" the conductor better, and subsequent quenches occur at a higher current.
- This process is knows as "training"



Milestones on the Road to a Superconducting Collider

- 1911 – superconductivity discovered by Heike Kamerlingh Onnes
- 1957 – superconductivity explained by Bardeen, Cooper, and Schrieffer
  - 1972 Nobel Prize (the second for Bardeen!)
- 1962 – First commercially available superconducting wire
  - NbTi, the "industry standard" since
- 1978 – Construction began on ISABELLE, first superconducting collider (200 GeV+200 GeV) at Brookhaven.
  - 1983, project cancelled due to design problems, budget overruns, and competition from…

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
- Reached L=4.06x10^{32} cm^{-2}s^{-1}
  - Breaking ISR p-p record
- 2011 – Tevatron shut down after successful LHC startup