Physics with Accelerators

R. Dixon

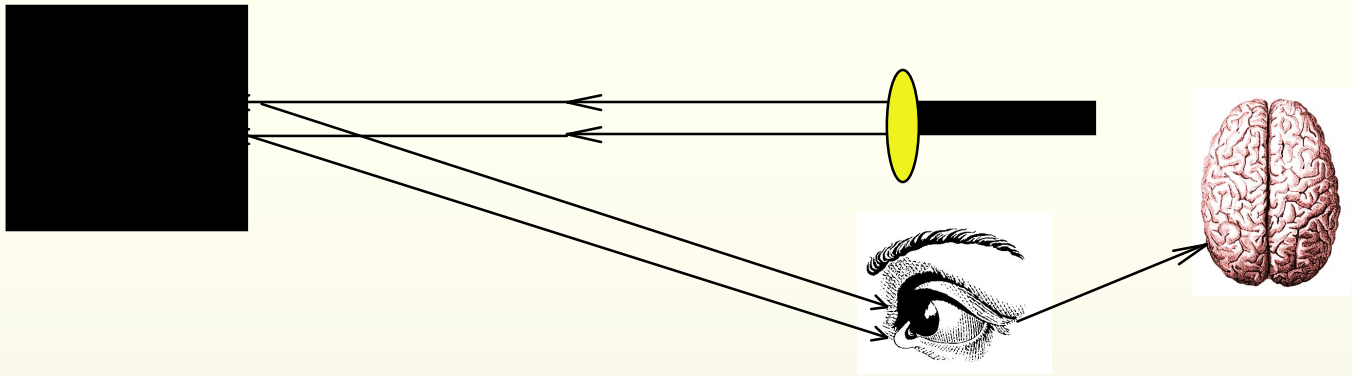
Acknowledgements

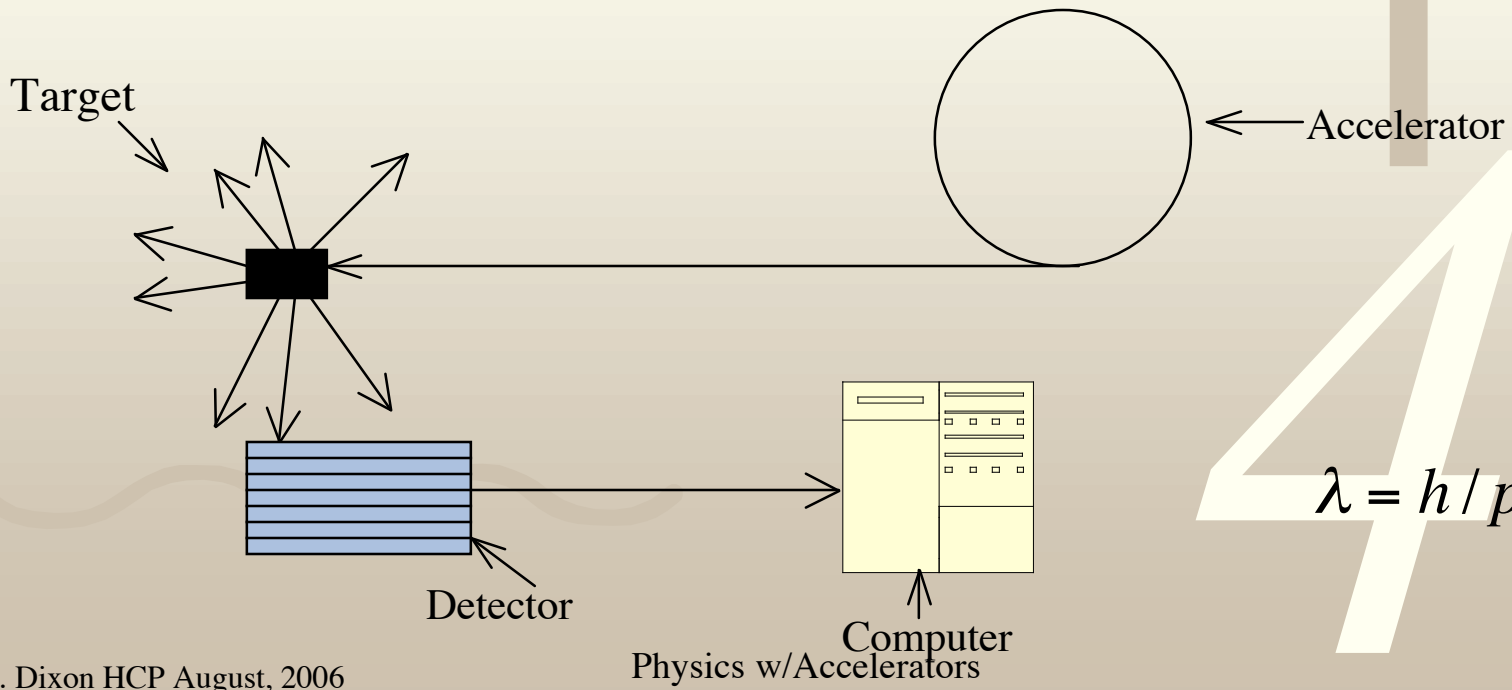
- Jean Slaughter
- Mike Syphers
- Ron Moore
- Operations Rookie Book and web page

Overview

- Historical Perspective
- Synchrotrons for Particle Physics
  - Just enough Technical Background
- Experimental Point of View
  - Fixed-Target
  - Collider
- Future Accelerators

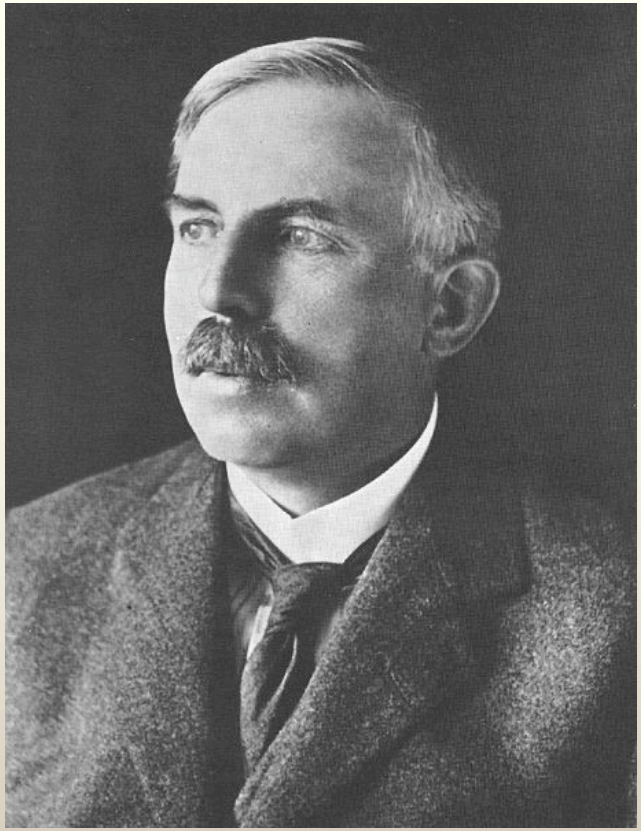
Basic Scattering



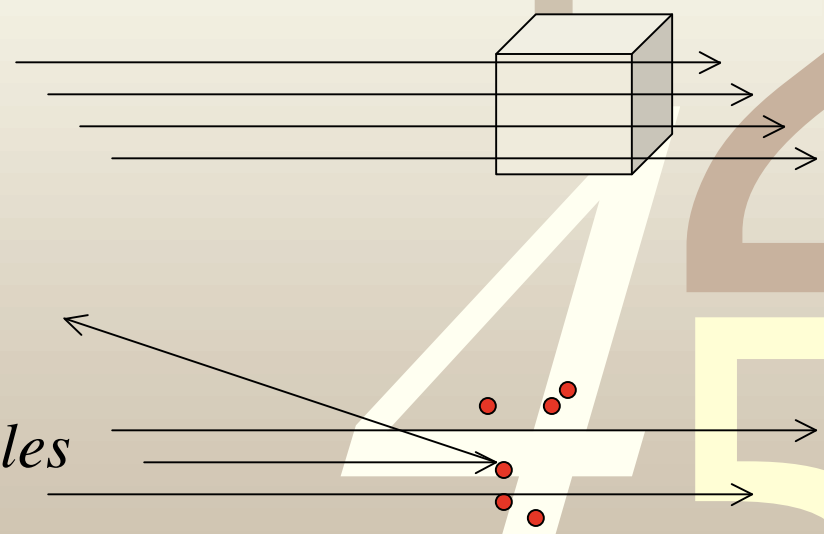


$$\lambda = h / p$$

Rutherford and the Nucleus

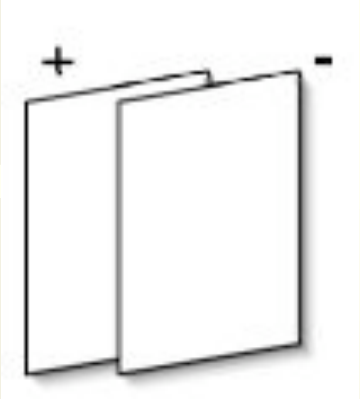


- Discovery of the Nucleus



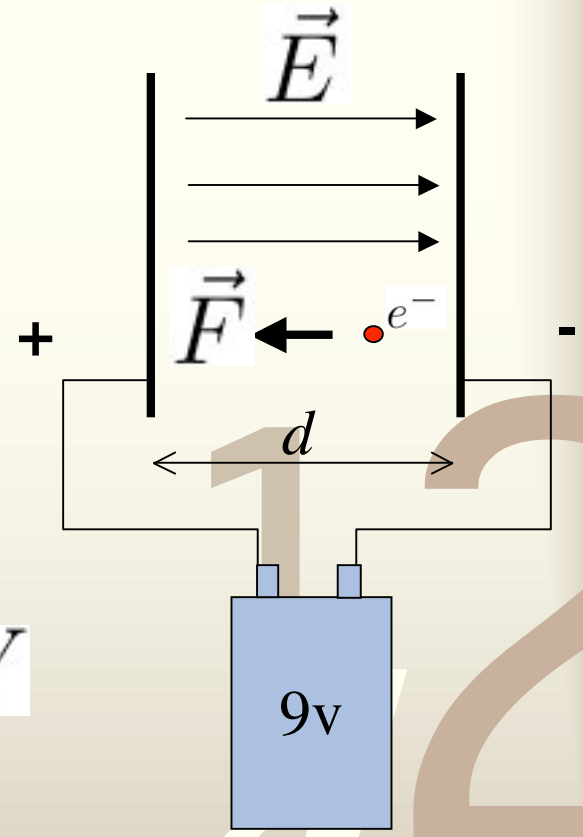
1871 -1937

How to Accelerate Charged Particles



$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$



As the electron accelerates from the right hand plate to the left, the change in energy is the work done,

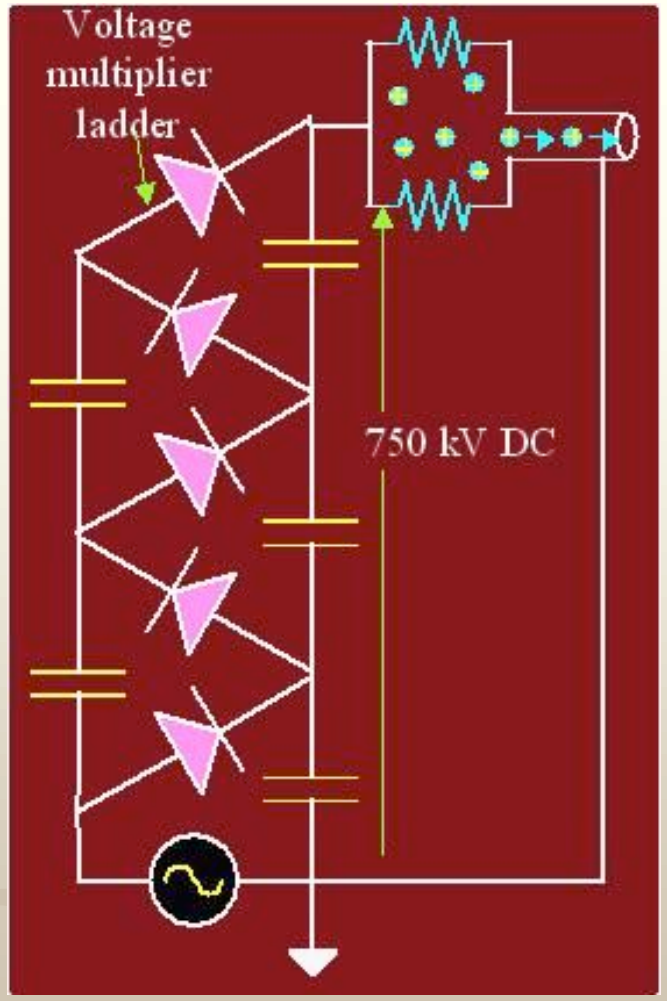
$$\Delta E = F \times d = qV$$

The charge on an electron is $q = -e = -1.6 \times 10^{-19}$ Coul
(on a proton, $+1.6 \times 10^{-19}$ Coul $= +e$)

So, we say that an electron/proton accelerated through 1 volt gains an amount of energy $\Delta E = 1$ eV (1 **electron volt**) ($= 1.6 \times 10^{-19}$ J)

In example above, the electron would gain energy of amount 9 eV.

Cockroft-Walton Generator



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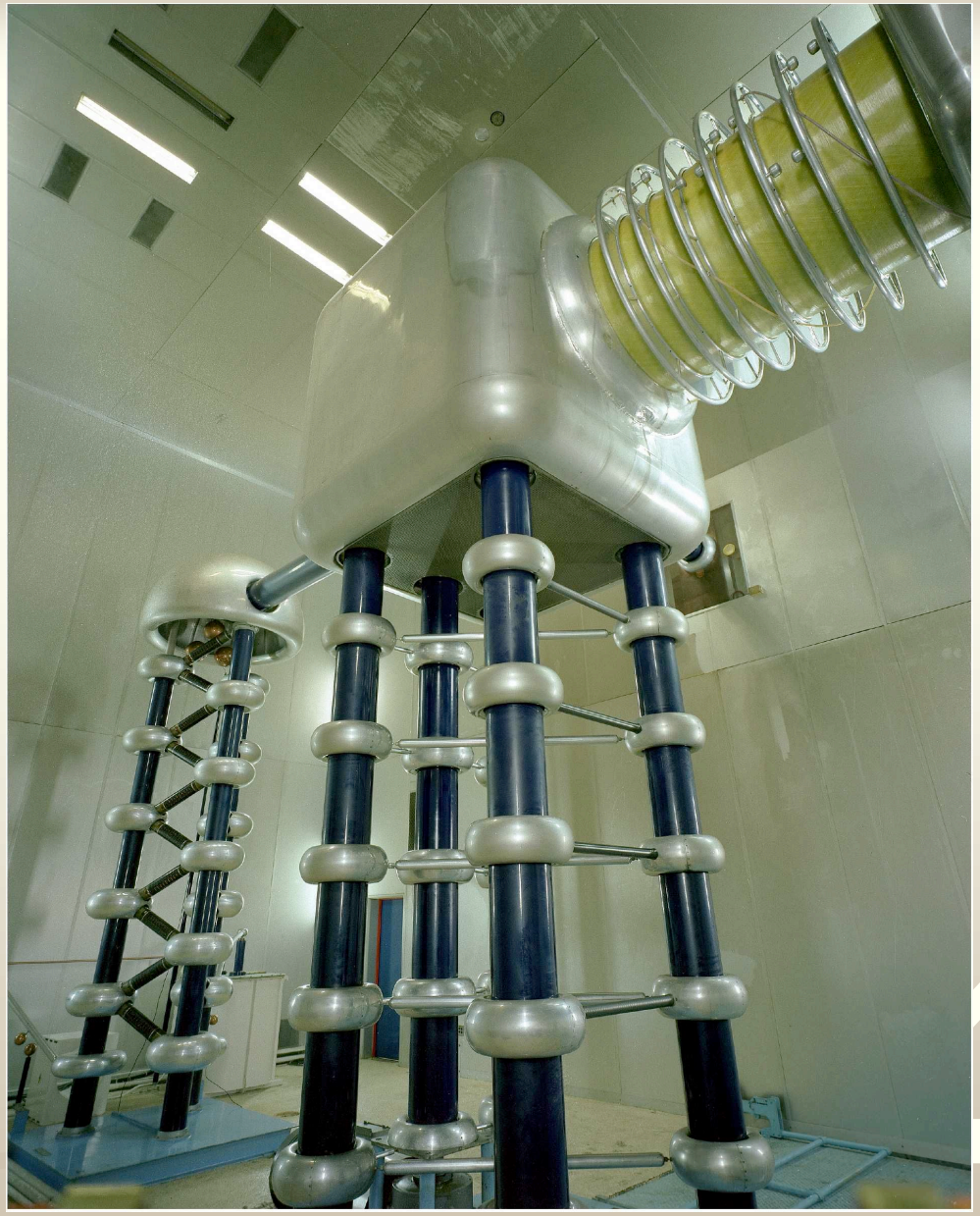


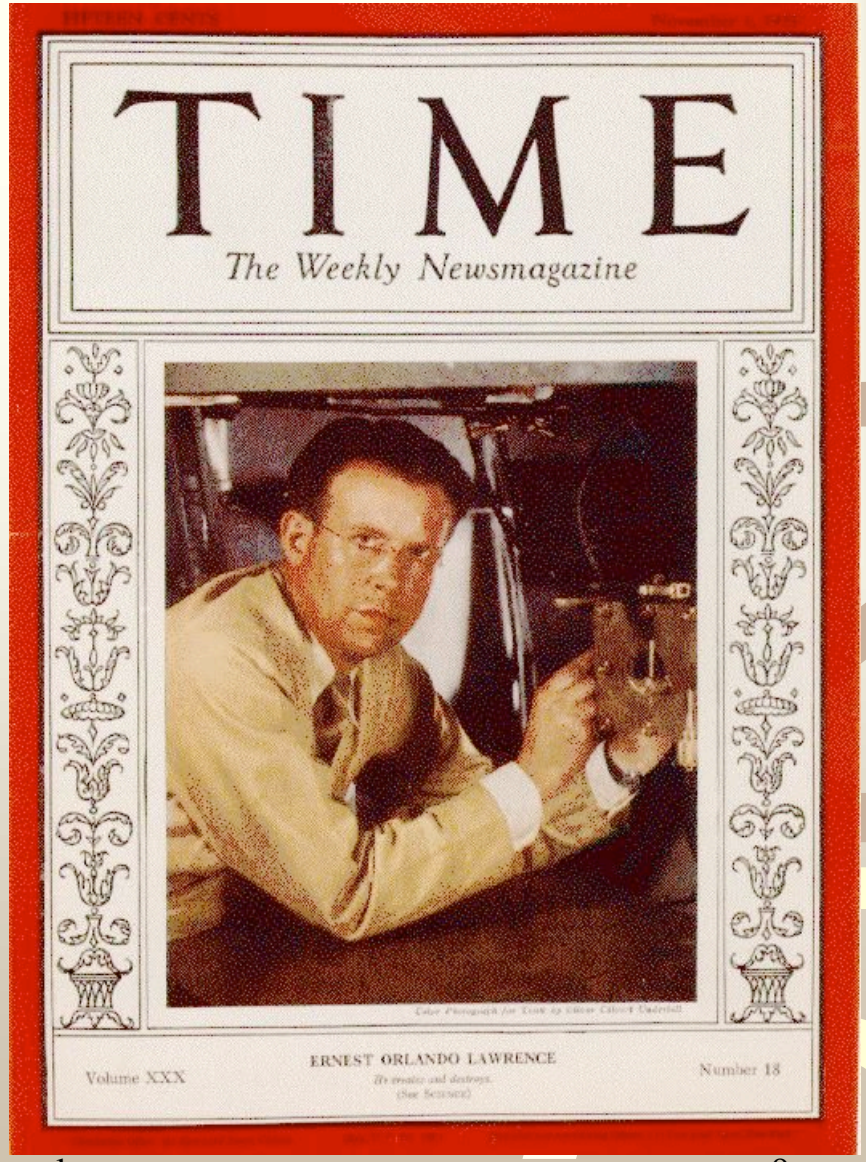
Hydrogen Source

Circular Accelerators

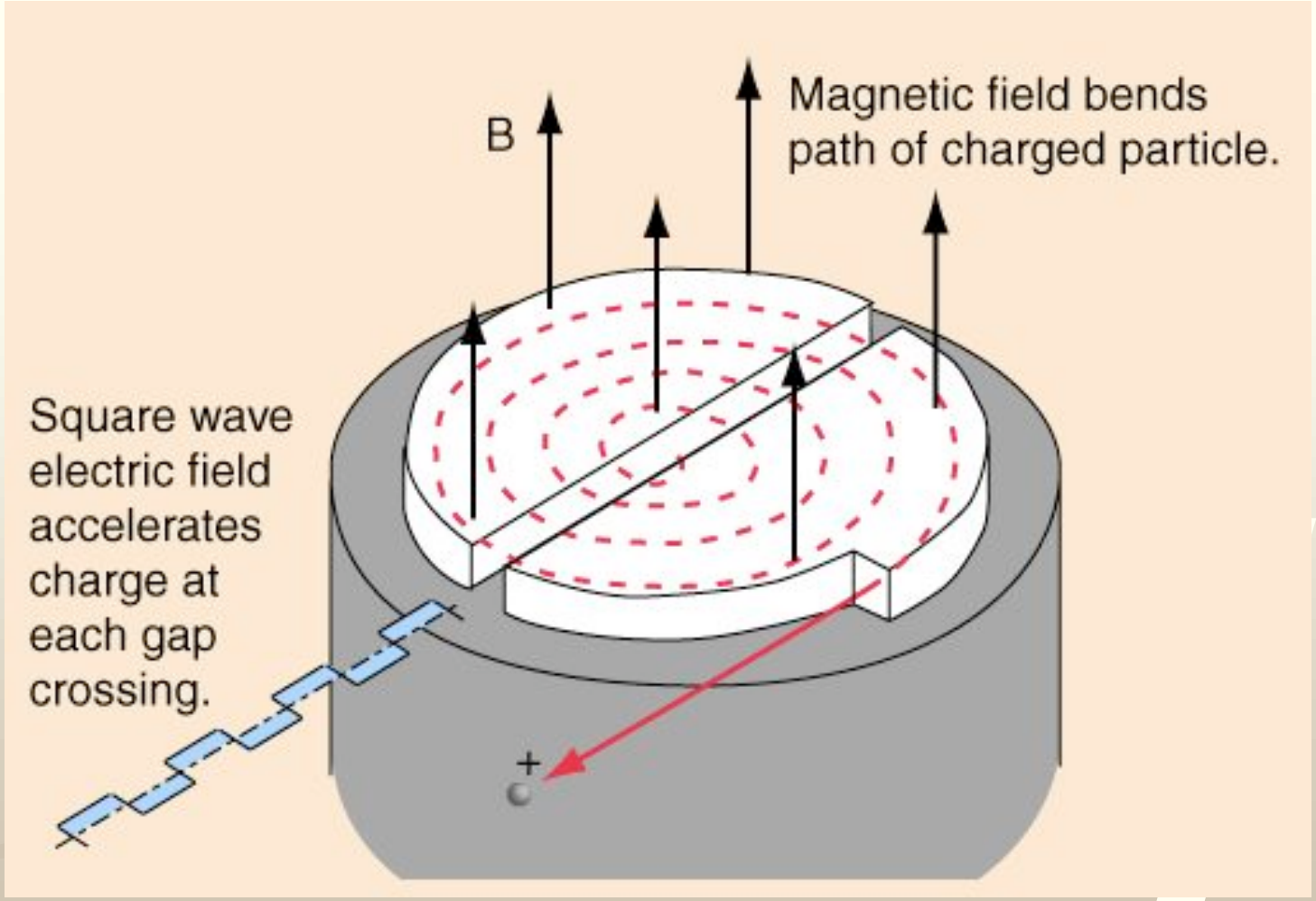
- Ernest Lawrence

  1901 - 1958

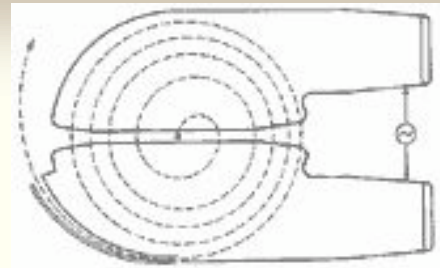
  - Cyclotron
  - ==> Synchrotron
  - ==> Storage Rings

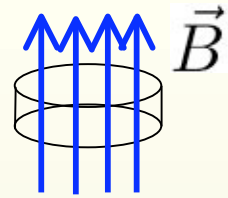


Cyclotron


B
Magnetic field bends path of charged particle.
Square wave electric field accelerates charge at each gap crossing.
+

The Cyclotron





4.5 in.

E.O. Lawrence, 1931

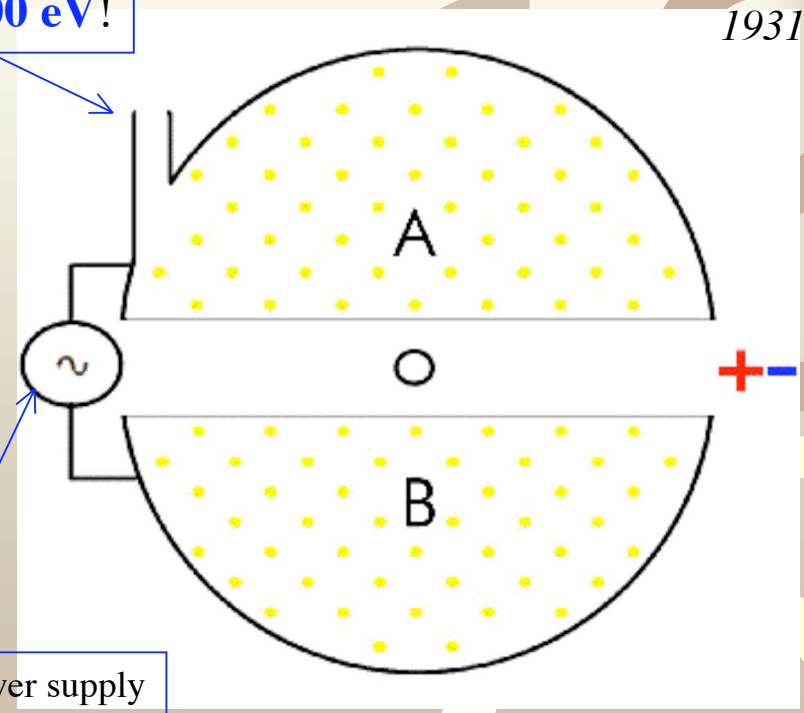
- A charged particle in a magnetic field, B, moves in a circular path of radius r at a speed v. The time to orbit once is

  $T = 2\pi r/v$.
- The force due to the magnetic field is

  $F = evB$
- The centripetal force is

  $F = mv^2/r$
- Equating these, we find $r/v = m/eB$
- And so, $T = 2\pi m / eB$
- Oscillate the voltage with a frequency f and adjust the magnetic field until $T = 1/f$.
- As the particle passes the gap, it gets accelerated, circulates on a slightly larger orbit, but the time to go around remains fixed.
- Eventually, the orbit gets big enough that the particle leaves the device.

$K.E. = \mathbf{80{,}000\ eV}$!



1,800 V power supply

The First Cyclotron, Berkeley -- 1930's

The Last Cyclotron--2006

Chris Olsen-- FNAL

Cyclotron Beams

- Bunched at Frequency determined accelerating voltage
- Extraction perfectly simple
  - Spill structure dependent on structure of accelerating voltage and uniformity of ion source
  - Minimal extraction losses
- Energy limited by size of magnet

184-inch Cyclotron, Berkeley -- 1940's

Cyclotron Physics

- Study of the nucleus
  - Cross-sections
    - Basic understanding
    - Reactors
    - Weapons
- Radioisotope production
  - Medical
  - Misc-- Fluid beds

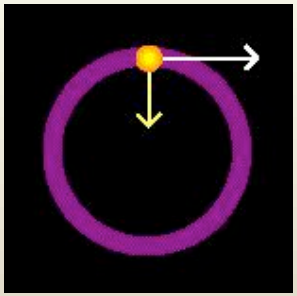
Evolution of the Circular Accelerators

- Energy increase cyclotrons ==> large volume magnetic field-- expensive
- Ramp field to keep orbit constant
  - Synchrocyclotron
  - Betatron
  - Synchrotron
    - Weak focusing
    - Alternating Gradient

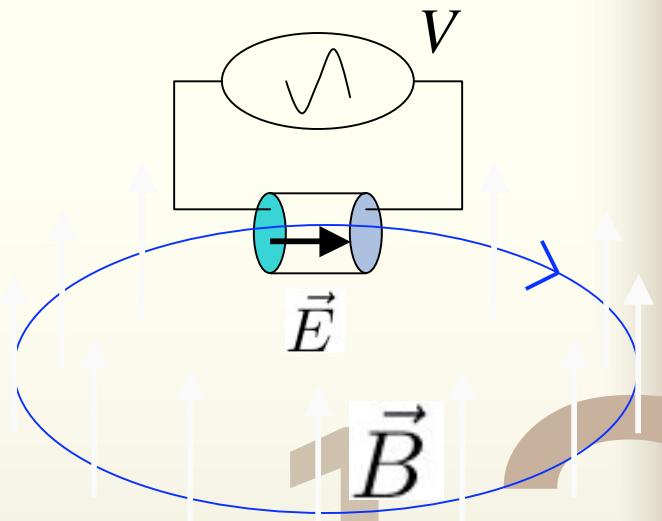
Synchrotrons

- As the electromagnet fields are slowly increased, the particle will be accelerated by the cavity enough to keep its momentum in step with the magnetic field and keep the orbit radius constant:

$$mv^2/R = evB \quad \Longrightarrow R = mv / eB$$
$$= p / eB$$



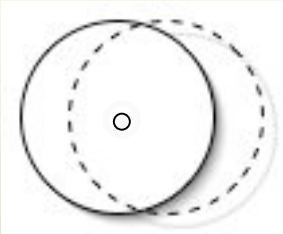
that is, we synchronize the magnetic field with the changing momentum (due to acceleration) to keep the particles on a constant orbit.

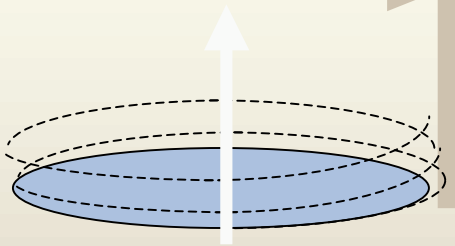


What frequencies do we need?
Let's say v ~ c,
and say R = 1 m
then,
$f = v / 2\pi R$
$= (3 \times 10^8 \text{ m/s}) / (2\pi\ 1\text{m})$
$= 5 \times 10^7 / \text{s} = 50 \text{ MHz}$

The Need for Focusing

- Particles move in circular orbits in a uniform magnetic field
- What happens if we deflect a particle as it is going around?
- Deflections in a Uniform magnetic field:
  - Horizontal -- stable Vertical -- NOT

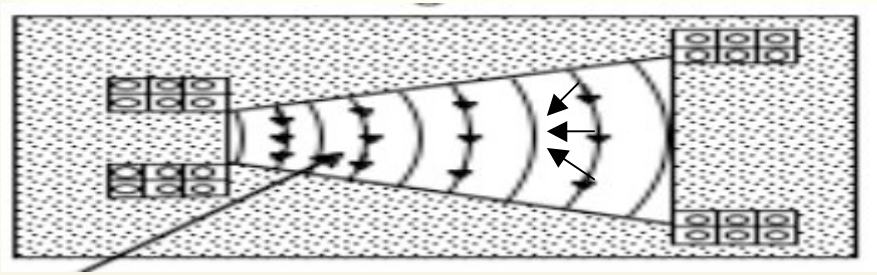




- Also, particles in a real beam start out heading in every which direction! (sort of like a flashlight beam, spreading out away from the source)

Focusing

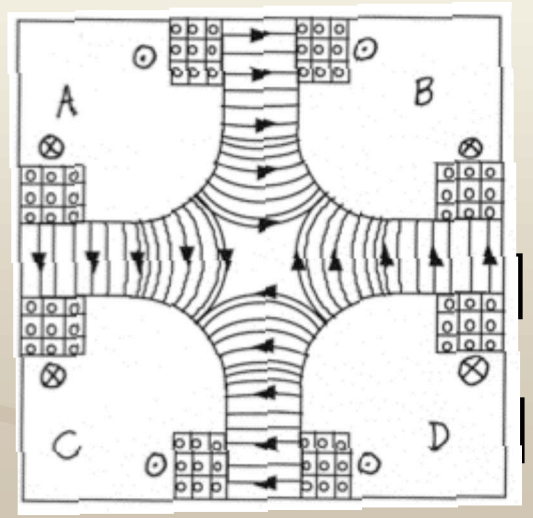
- Weak Focusing



Focuses in verticle direction only

Example: Zero Gradient Synchroton at ANL

- Strong Focusing

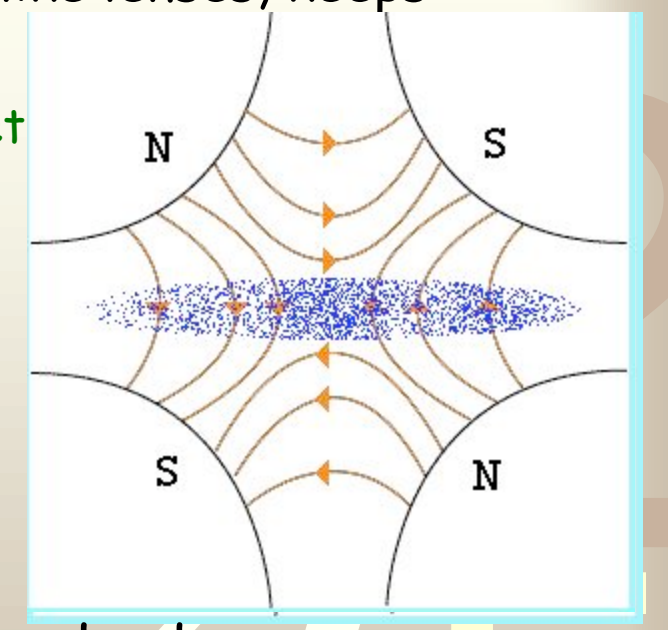


Quadrupole Magnets

Focusing

- So, as particles move around the accelerator, we use other electromagnets to steer and focus them
- Arrangement of focusing magnets, much like lenses, keeps the particle beam contained…
  - Focusing lens: a "quadrupole" magnet
  - Since $\underline{F} = e\underline{v} \times \underline{B}$, then this magnet will focus in one direction (L/R), but will defocus in the other (up/down)

B~bx



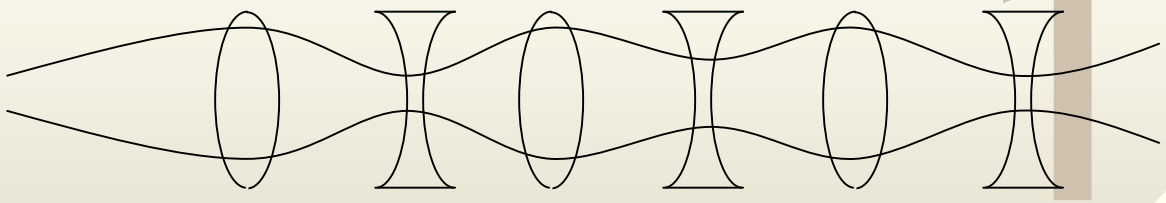
So, ***alternate*** lenses: + - + - + - …

End up with net focusing both L/R and U/D

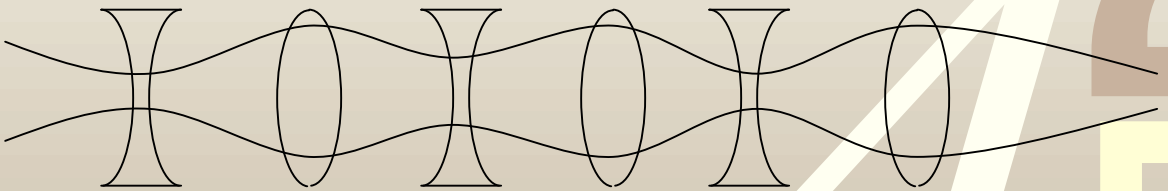
Alternating Gradient Focusing

- By alternating the polarity of the Quadrupole magnets, they serve to alternately focus and defocus the beam, keeping it stable in all directions simultaneously

Left/Right

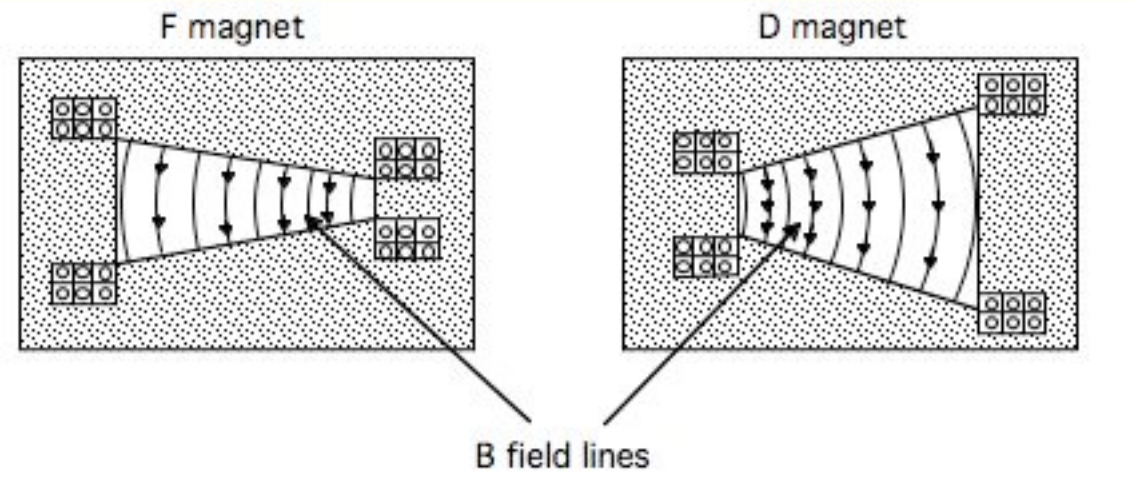


Up/Down

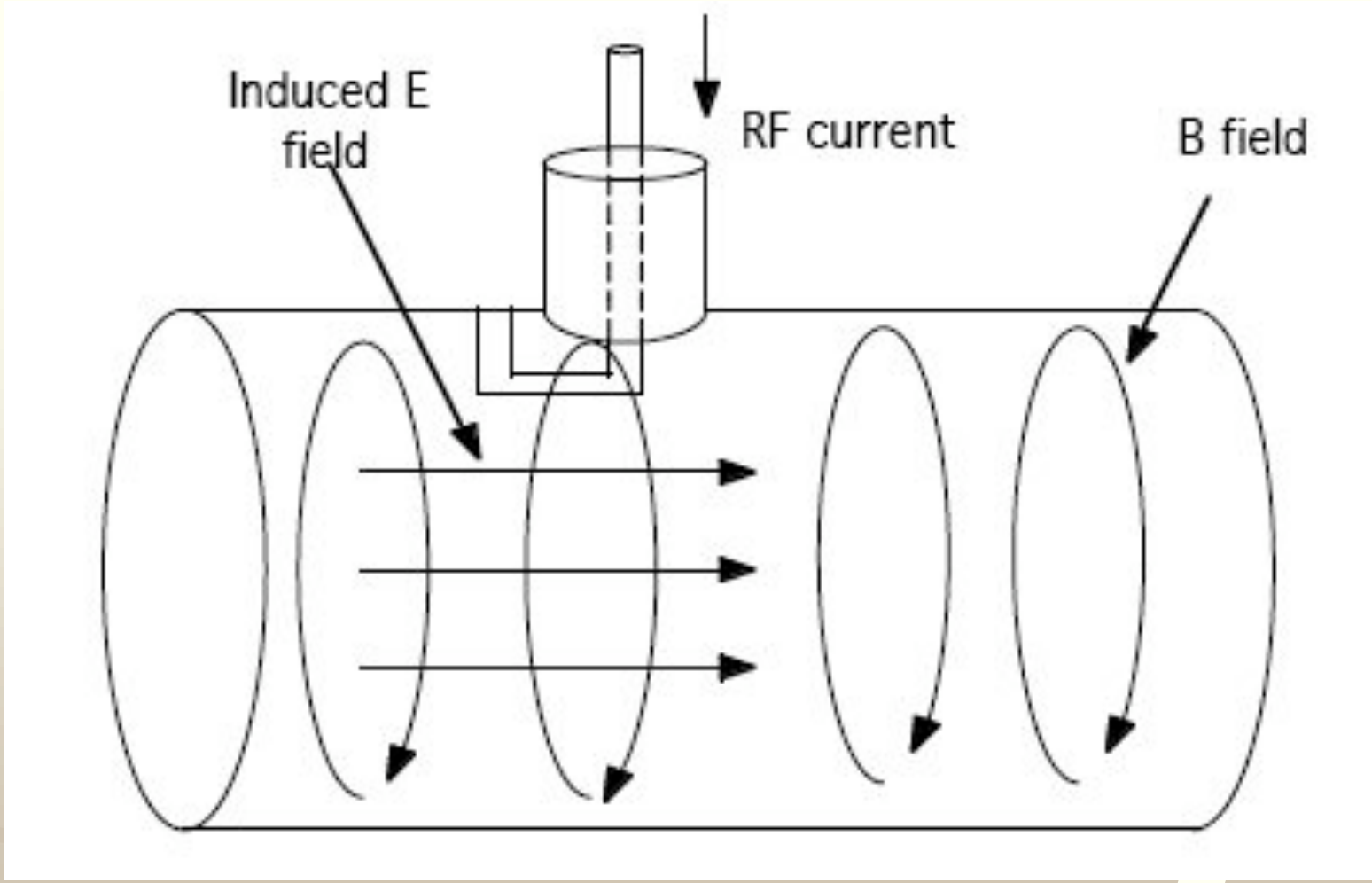


- ==> Alternating Gradient Synchrotron (AGS)

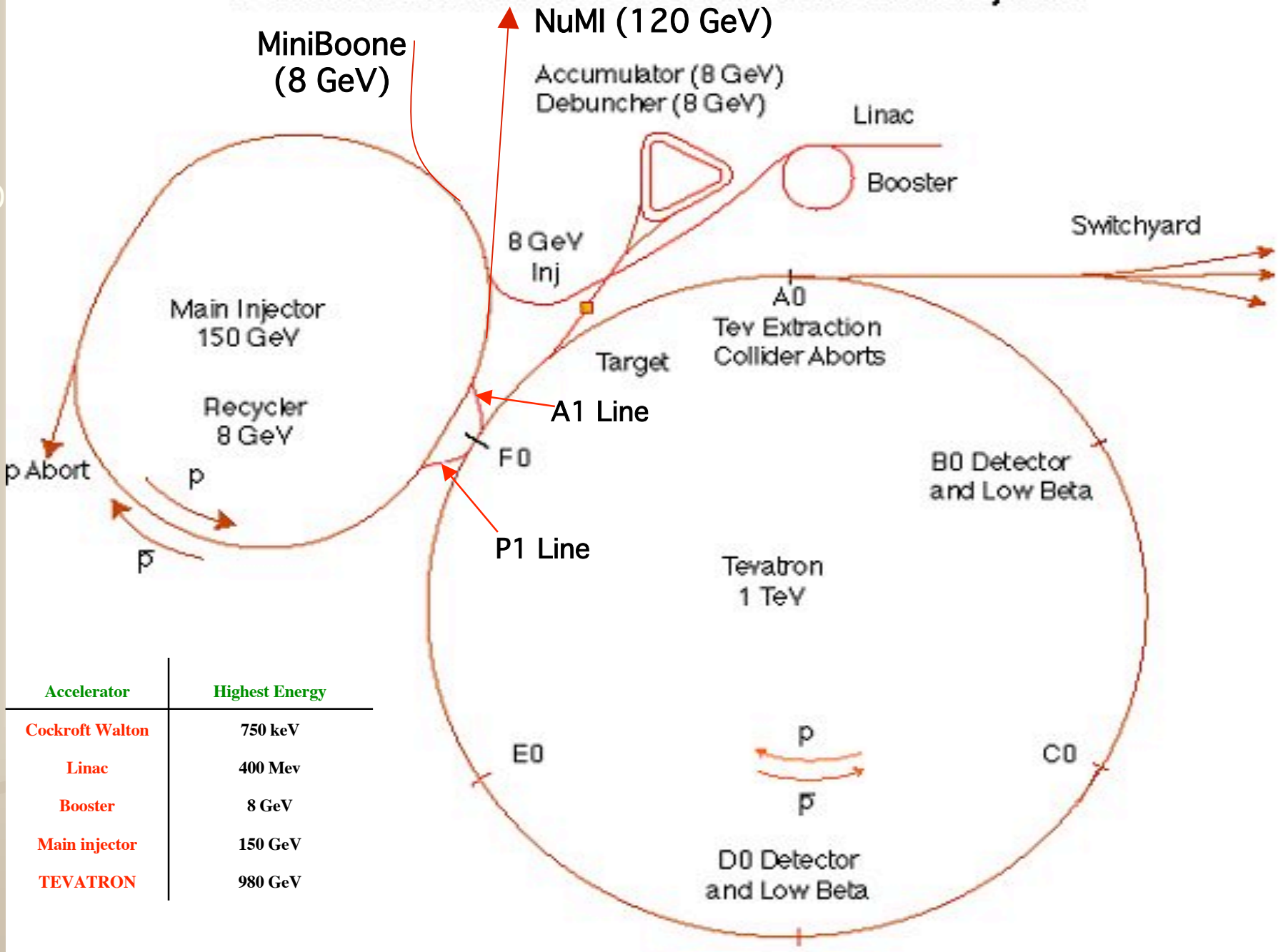
Combined Function Synchrotrons



RF Cavity

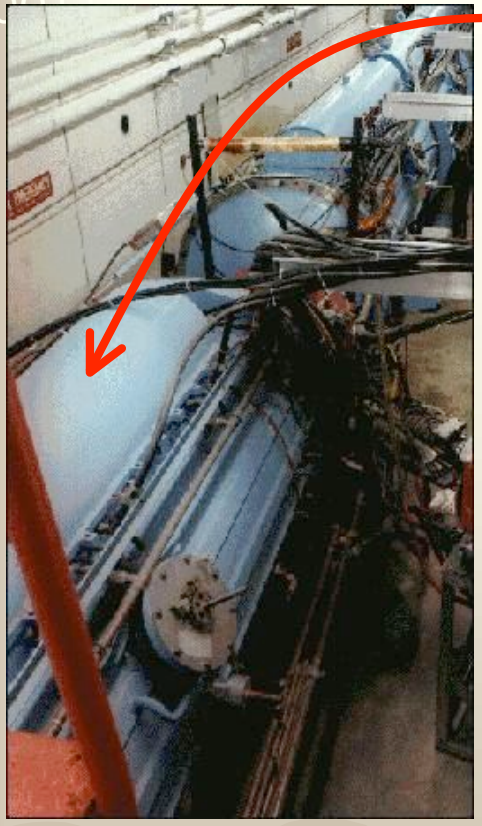


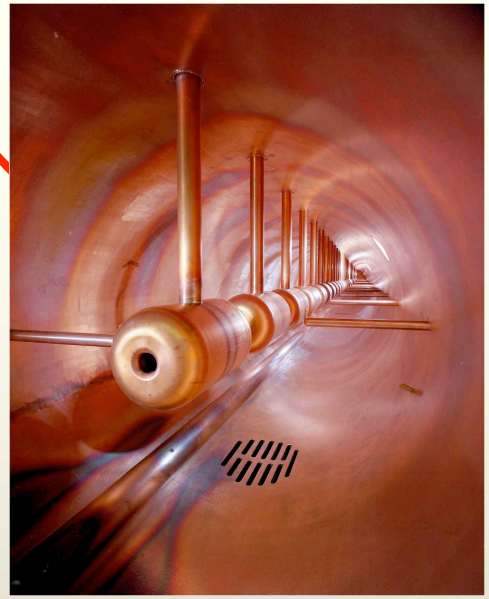
FermilabTevatron Accelerator With Main Injector



Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

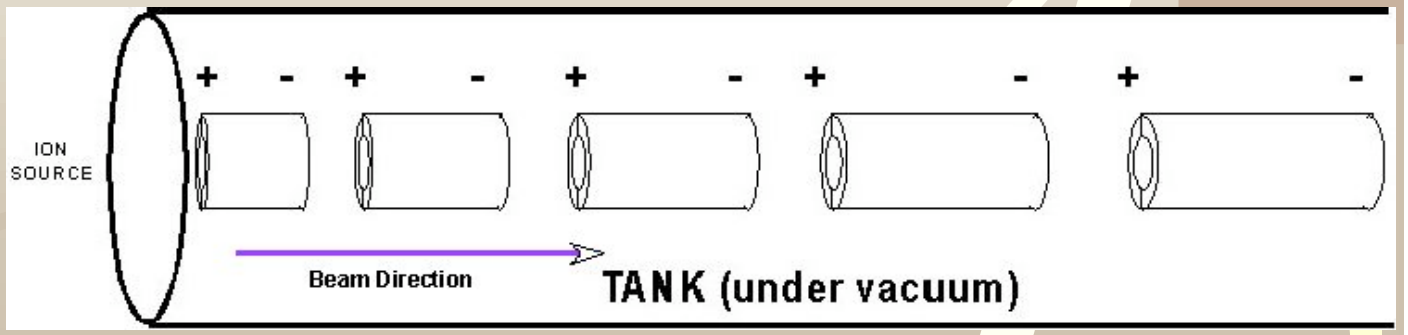
Linear Accelerator (Linac)





Upstream end of Linac:

- Field inside oscillates at 200 MHz
- Particles are accelerated in the 'gaps'
- Gaps get spaced further apart as particle speed increases



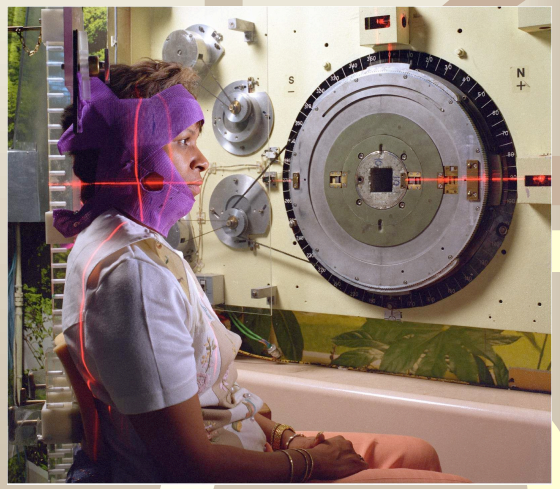
Linac (cont'd)

Downstream end of Linac:

- particle speed approaching 0.7*c*
- gap spacing not changing much; use different cavity structure

- here, field oscillates at 800 MHz
- Total Linac length:
- Final kinetic energy: 400 MeV

Mid-way, can take particles out and direct toward target; forms neutrons; used for cancer therapy!

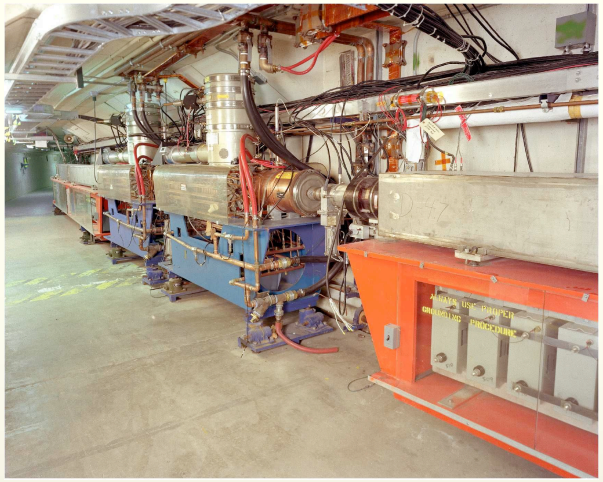


Synchrotrons at Fermilab

Booster

R = 75 m

h = 84



R = 500 m

h = 588

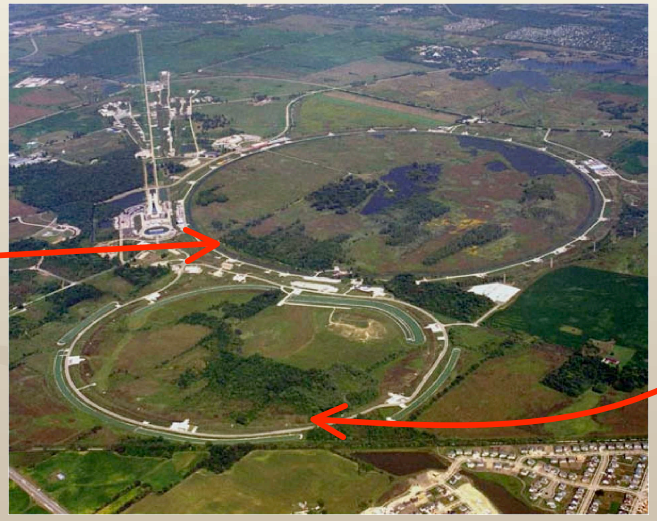
All use 53 MHz systems

h = # possible 'bunches' in the accelerator

Tevatron

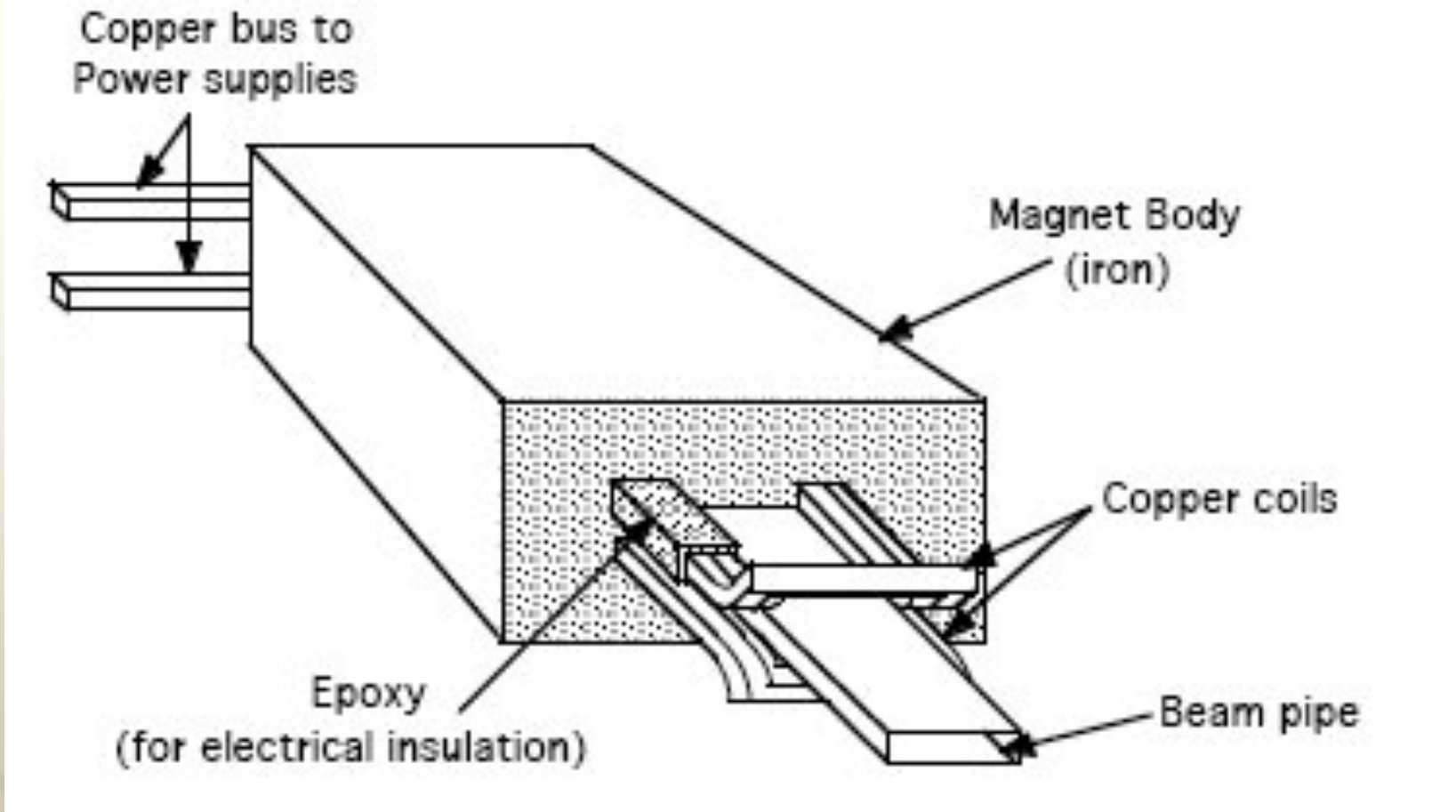
R = 1000 m

h = 1113



Main Injector

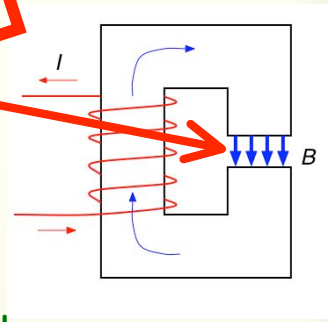
Dipole Magnet



Dipole Magnets

- Bending Magnets
  - A simple electromagnet might look like:

10 - 100 Gauss

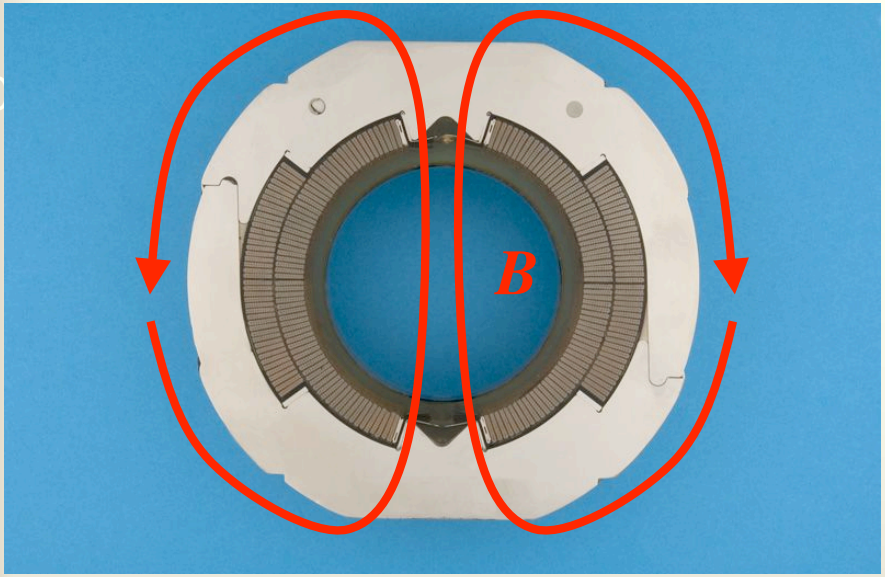


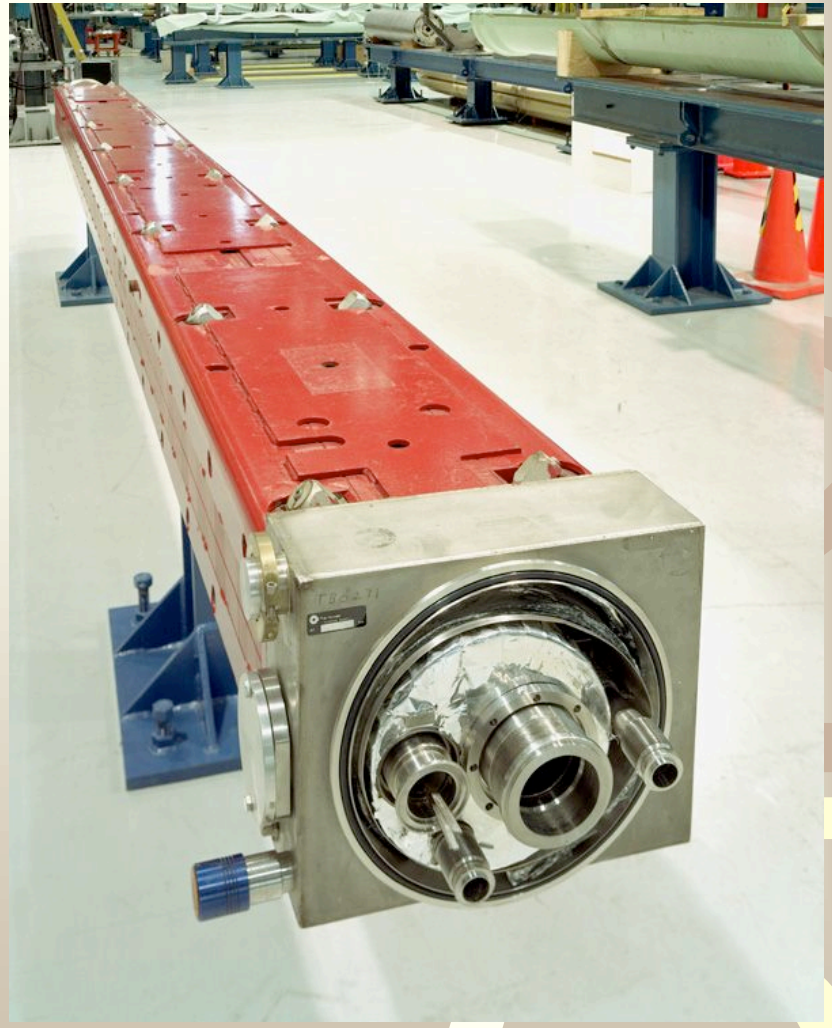
  - Accelerator magnet: lots of current and lots of iron!
    - Iron-dominated magnets can obtain field strengths up to ~2 Tesla

20,000 Gauss!!

  - Superconducting coils can generate much higher fields
    - Tevatron: 1st superconducting accelerator: $B \sim 4.4$ T
    - Nowadays, technology limit for accel. mag. is about 10-15 T

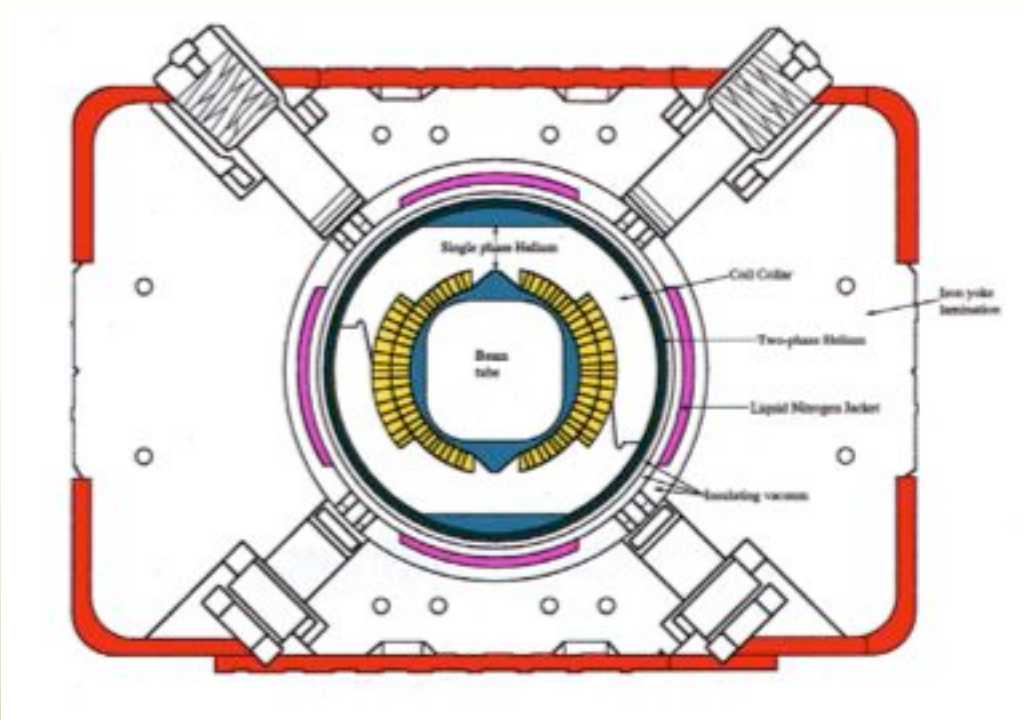
Superconducting Tevatron Magnet





- Outside is at room temperature;
  inside is at 4°K!
- Field is 4.4 Tesla @ ~4,000 A
- Each magnet is ~20 ft long,
  and weighs about 4 tons
- ~1000 magnets in the Tevatron
  (~800 dipoles, ~200 quadrupoles)

Tevatron Magnet



Cross section of a Tevatron Magnet

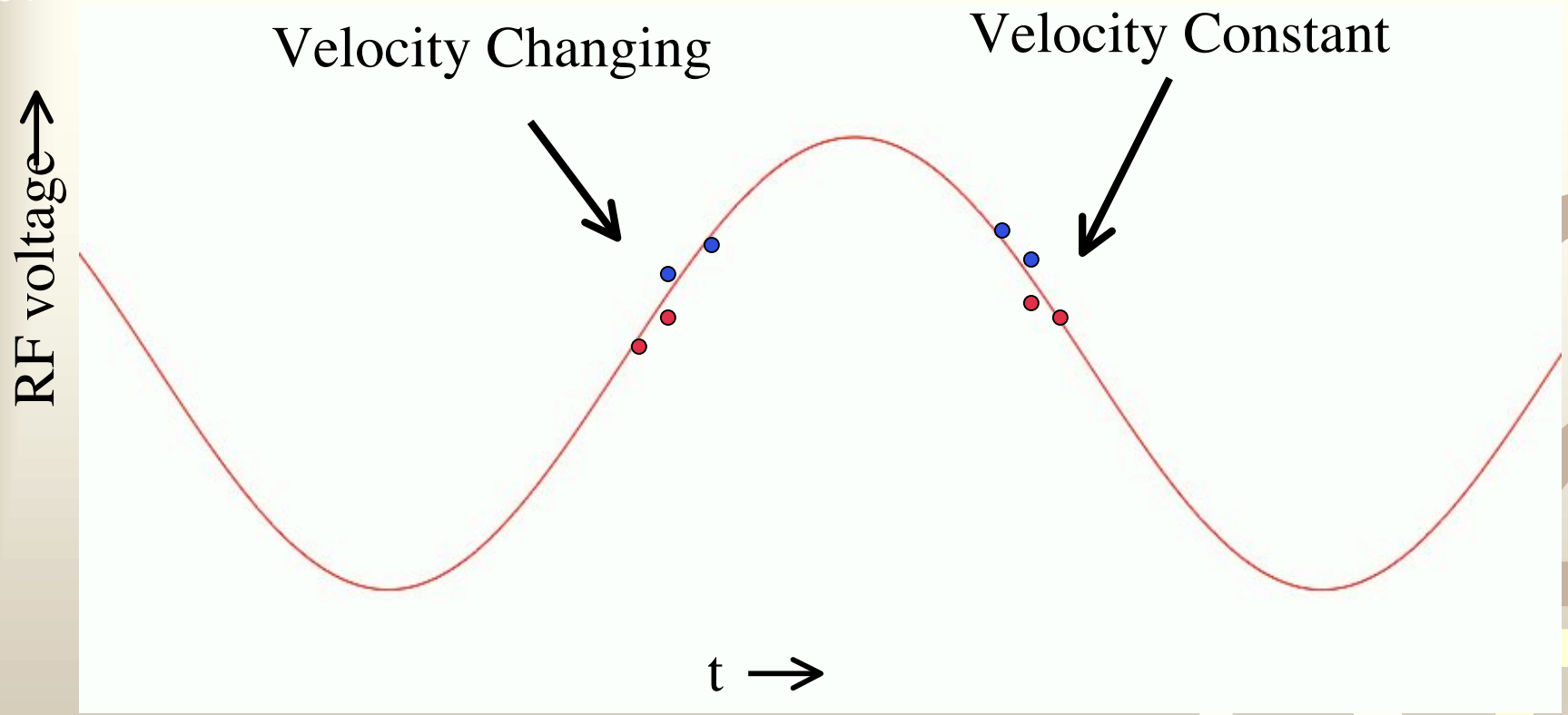
Cold bore/warm iron

Some Basic Accelerator Hardware

- Acceleration Cavities
  - "pillbox - like" cavity, with radius a, has natural frequency $f_{nat} = 2.4c / 2\pi a$.
  - For $f_{nat} \sim 50$ MHz, we see $a \sim 2$ m. (rather big)
  - So, we design other cavity "structures" which are more compact, but which have similar natural freq's

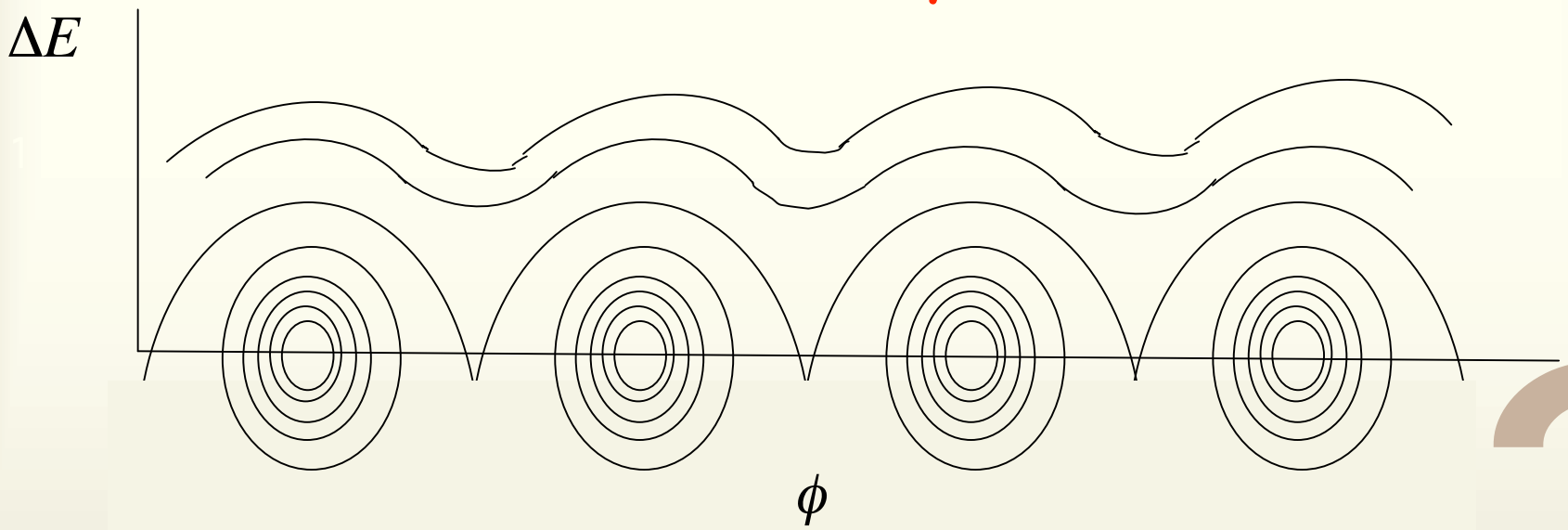
A 106 MHz cavity used in the Fermilab Main Injector synchrotron.

Phase Stability



Stable area = RF Bucket

Stability



$$(E_s)_{n+1} = (E_s)_n + eV \sin\phi_s$$

$$\Omega_s = \sqrt{-\frac{\eta \omega_{rf} c^2 eV \cos\phi}{\tau v^2 E_s}}$$

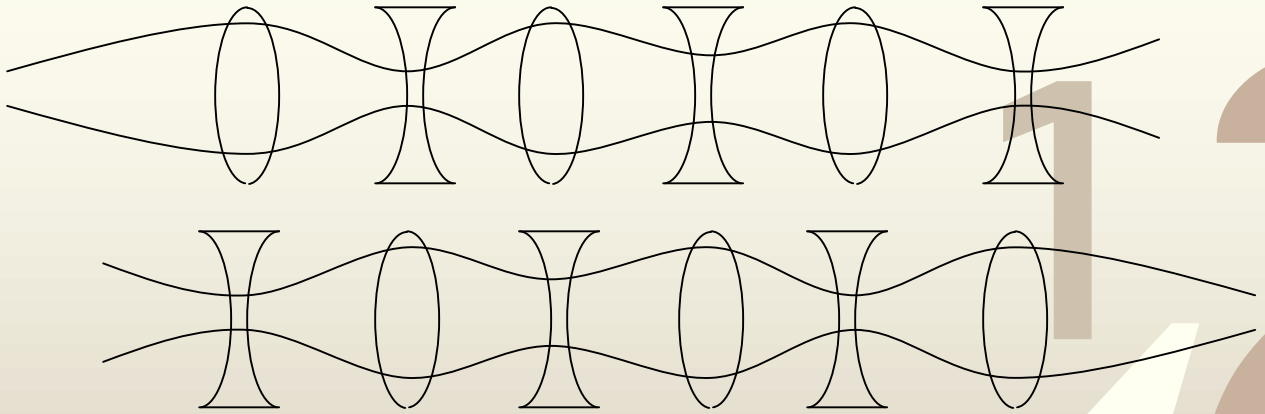
$$\eta \equiv \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

Alternating Gradient Focusing

- By alternating the polarity of the Quadrupole magnets, they serve to alternately focus and defocus the beam, keeping it stable in all directions simultaneously

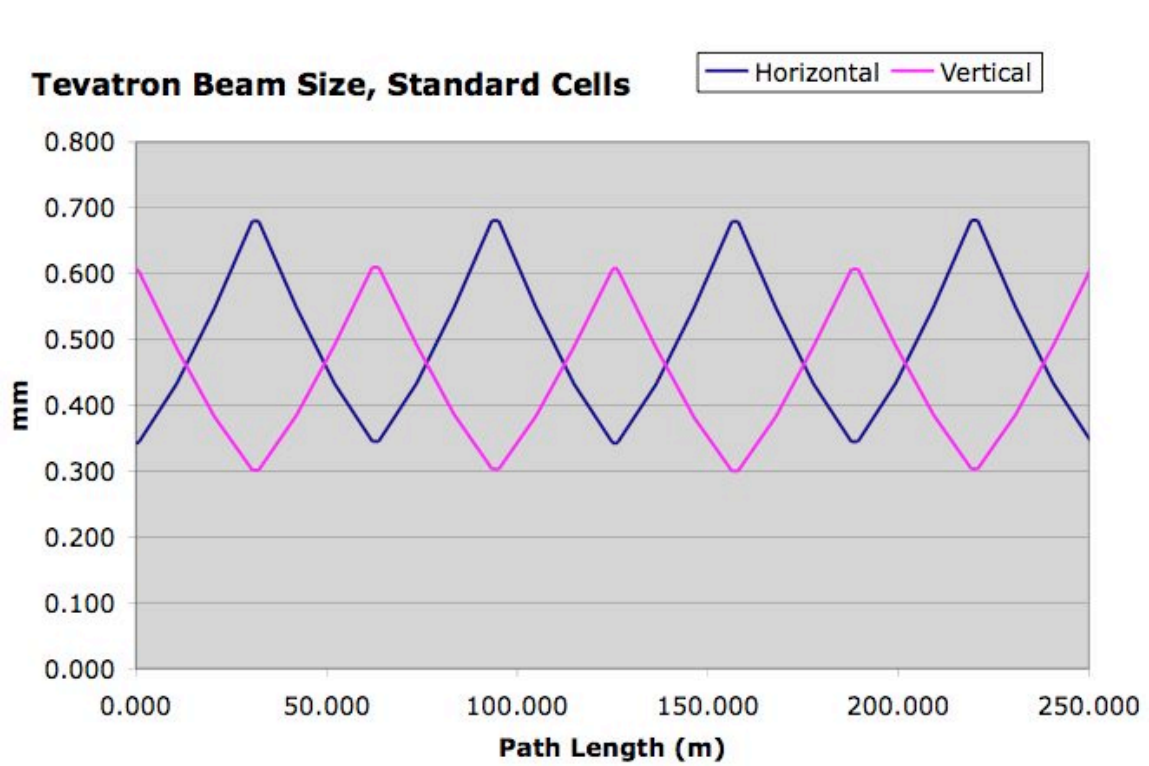
Left/Right

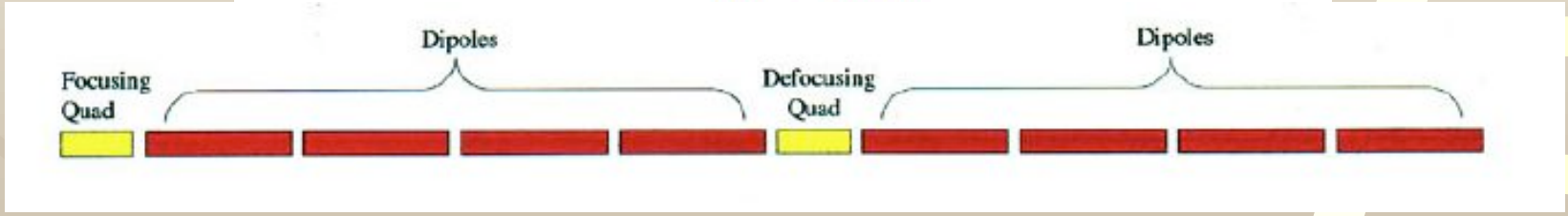
Up/Down



- Smaller magnets are used to fine-tune the beam trajectory, and to perform special orbit manipulations
  - Note: The beam in the Tevatron, for example, is only ~1 mm wide! Its orbit is controlled to a fraction of a mm! Yet, the orbit itself is 6.28 km (4 mi) around!

Tevatron Lattice Standard Cell





Equation of Motion

- Beam travel along s
- Transverse beam direction is x
- Then focusing system satisfies:

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

- This is an harmonic oscillator where the spring contant depends on s
- Solution:

$$x(s) = A\sqrt{\beta(s)}\cos[\Psi(s) + \delta]$$

- Assumes motion is periodic with period K(s)= K(s+C) and A is related to the Courant-Snyder parameters by:

$$A^2 = \gamma(s)x(s)^2 + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2$$

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The real story from Mike Sypher's notes

Real work cannot be done with PowerPoint

Phase Space

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

$$x' = \tfrac{1}{2}A\beta^{-1/2}\beta'\sin(\psi+\delta) + A\beta^{1/2}\cos(\psi+\delta)\psi'$$

$$= -A\alpha\beta^{-1/2}\sin(\psi+\delta) + A\beta^{-1/2}\cos(\psi+\delta)$$

$$\beta x' = -A\alpha\beta^{1/2}\sin(\psi+\delta) + A\beta^{1/2}\cos(\psi+\delta)$$

$$= -\alpha x + A\beta^{1/2}\cos(\psi+\delta)$$

$$\Rightarrow \beta x' + \alpha x = A\beta^{1/2}\cos(\psi+\delta)$$

$$\therefore \boxed{x^2 + (\beta x' + \alpha x)^2 = A^2\beta} \quad \text{(circle)}$$

or,

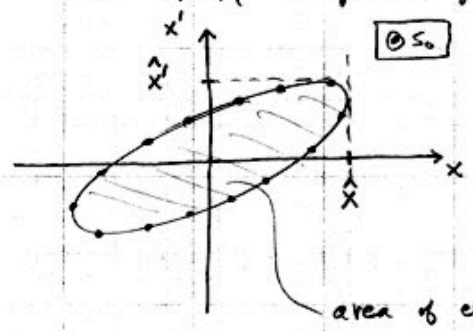
$$x^2 + \beta^2 x'^2 + 2\alpha\beta x x' + \alpha^2 x^2 = A^2\beta$$

$$x^2(1+\alpha^2) + 2\alpha\beta x x' + \beta^2 x'^2 = A^2\beta$$

$$\frac{1+\alpha^2}{\beta}x^2 + 2\alpha x x' + \beta x'^2 = A^2$$

$$\boxed{\gamma x^2 + 2\alpha x x' + \beta x'^2 = A^2} \quad \text{(ellipse)}$$

note: γ, α, β are functions of s; A^2 is not!



So, @ s_0, we have

$$\hat{x} = A\sqrt{\beta_0}$$

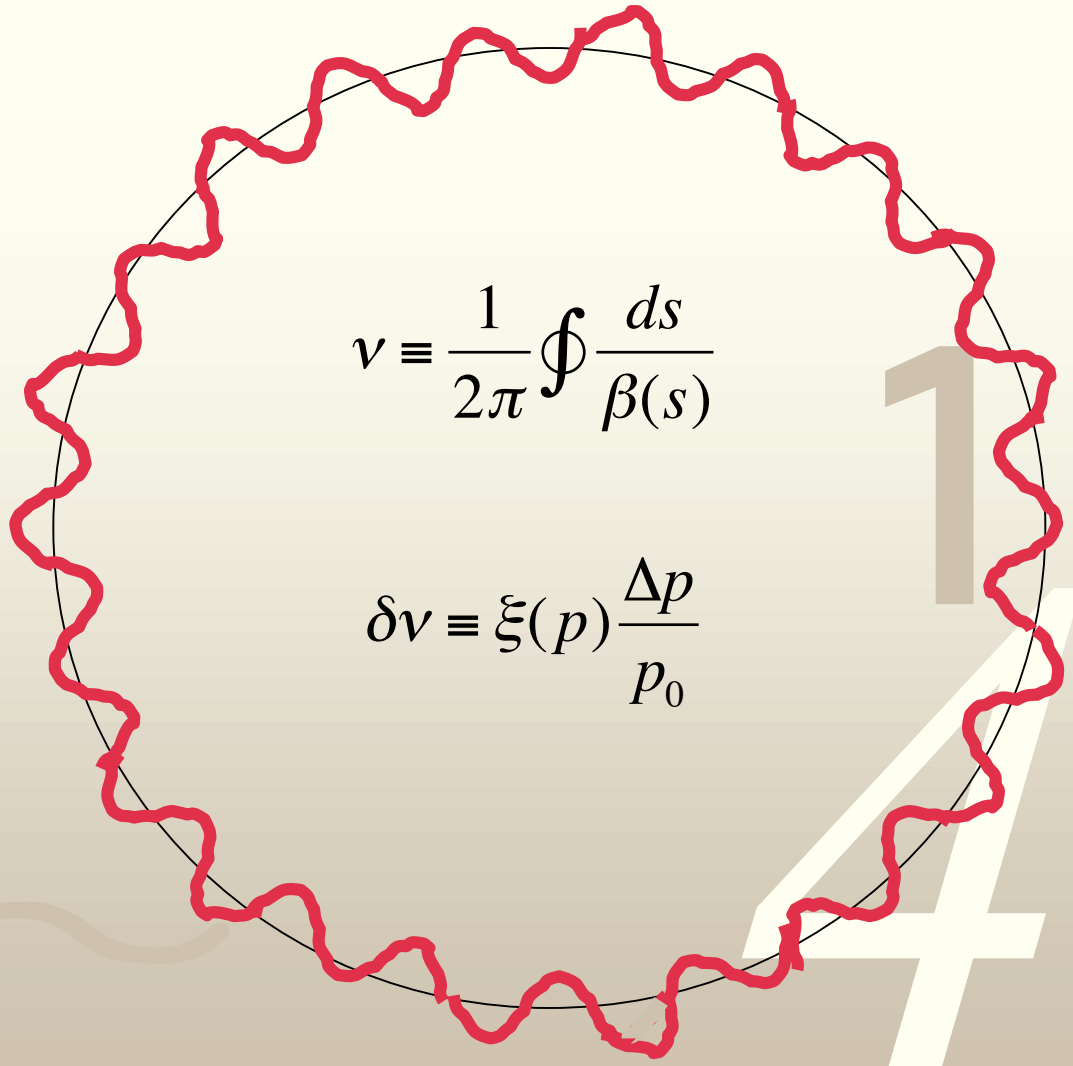
$$\hat{x}' = A\sqrt{\gamma_0}$$

area of ellipse $= \pi A^2$

independent of s

Tune and Chromaticity

- Number of oscillations in one turn is the tune
- Chromaticity, ξ , describes the way the tune varies with momentum

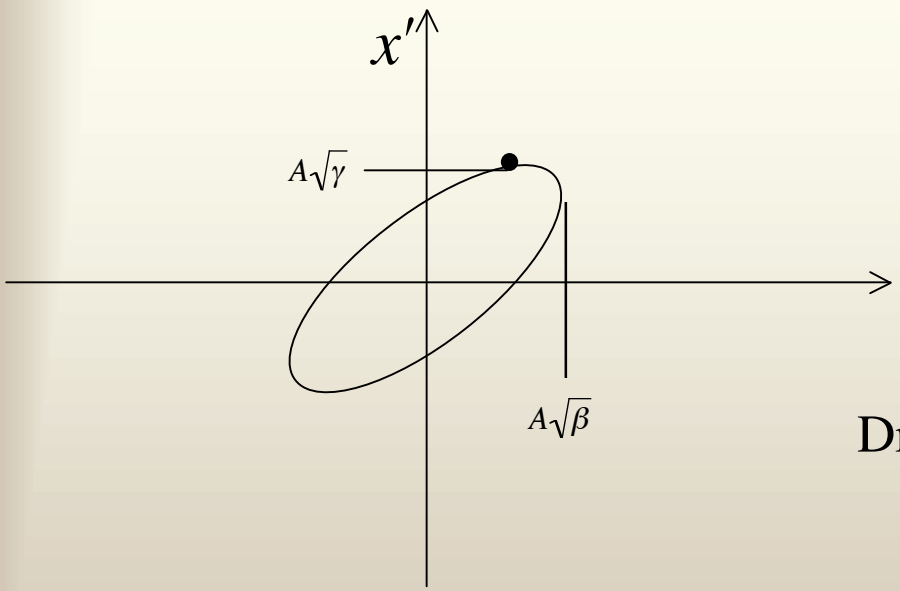


$$\nu \equiv \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

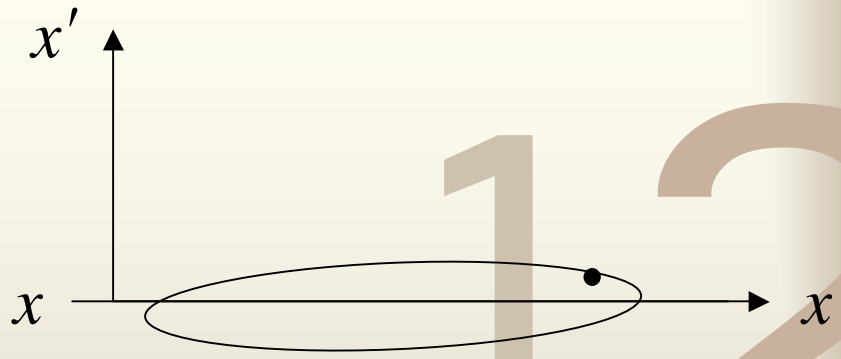
$$\delta\nu \equiv \xi(p)\frac{\Delta p}{p_0}$$

Courant-Snyder Parameters

If we look at a particle at any point in the accelerator, it will lie on an ellipse in phase space. As it goes around the accelerator, the ellipse will change shape, and the particle will move around the ellipse

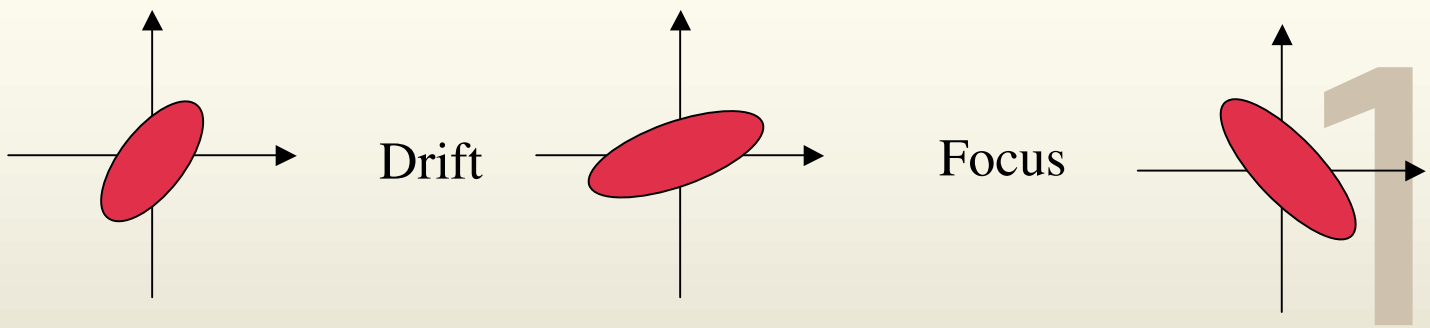


Drift →



Beam of Many Particles

- Now consider all the particles on smaller ellipses traveling around the accelerator



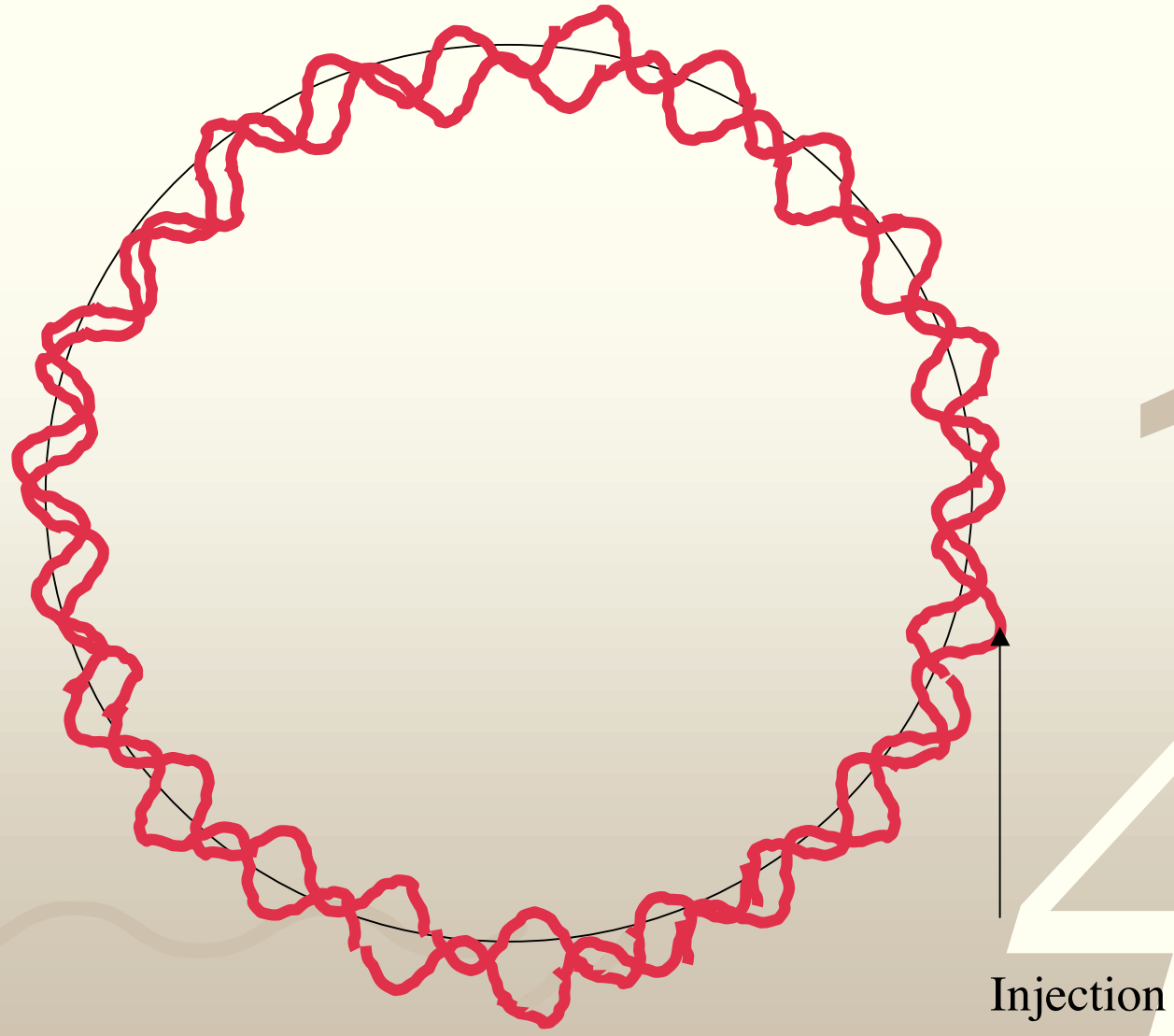
- Area of the ellipse remains constant (Ideally)
- Note that the ideal particle stays in the center

$$\pi a^2 = \beta\varepsilon \qquad x_{\max} = \sqrt{\frac{\varepsilon\beta_{\max}}{\pi}} \qquad x'_{\max} = \sqrt{\frac{\varepsilon\gamma_{\max}}{\pi}}$$

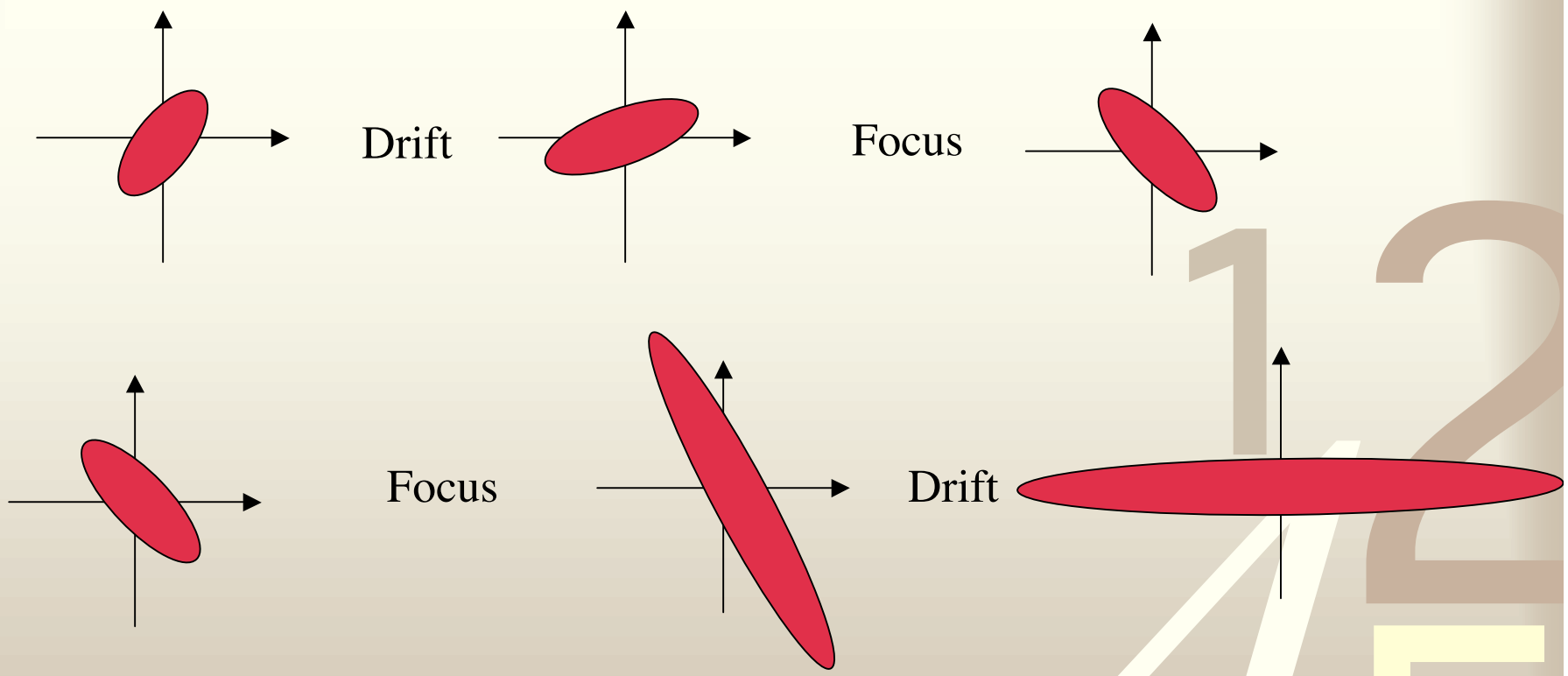
Injection

- Closing the orbit
  - Center of the beam must stay as close to the ideal orbit as possible to close on itself
  - ==> Beam must be kicked onto ideal orbit
    - H^- injection avoids this requirement
- Matching the optics
  - Proper orientation of injected ellipse

Matching Orbits



Matching Optics



Beam Stability

- Remember tune

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

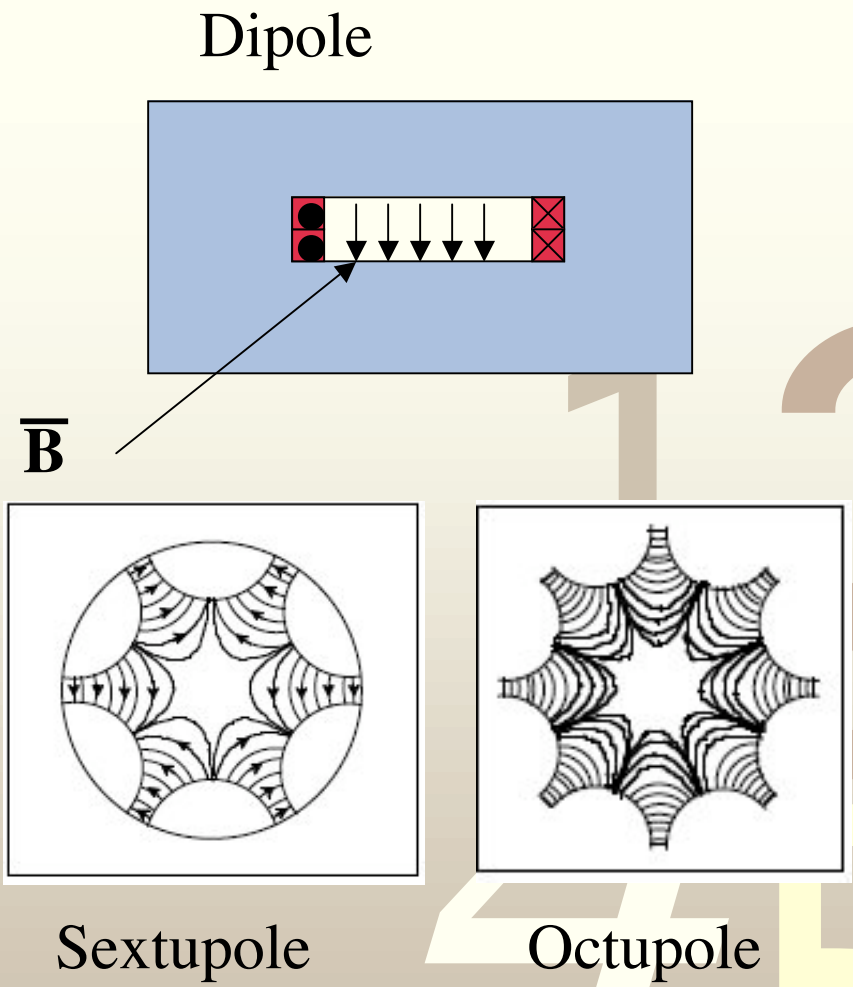
- If tune is an integer particle takes the same path around the accelerator every time
- If tune is a half integer, the path is the same every other time, and so on . . .

Magnetic Field Expansion

- Ideally B(x)=Constant
- Since we can't achieve the ideal case in practice we have:

$$B(x) = b_0 + b_1 x + b_2 x^2 + \ldots$$

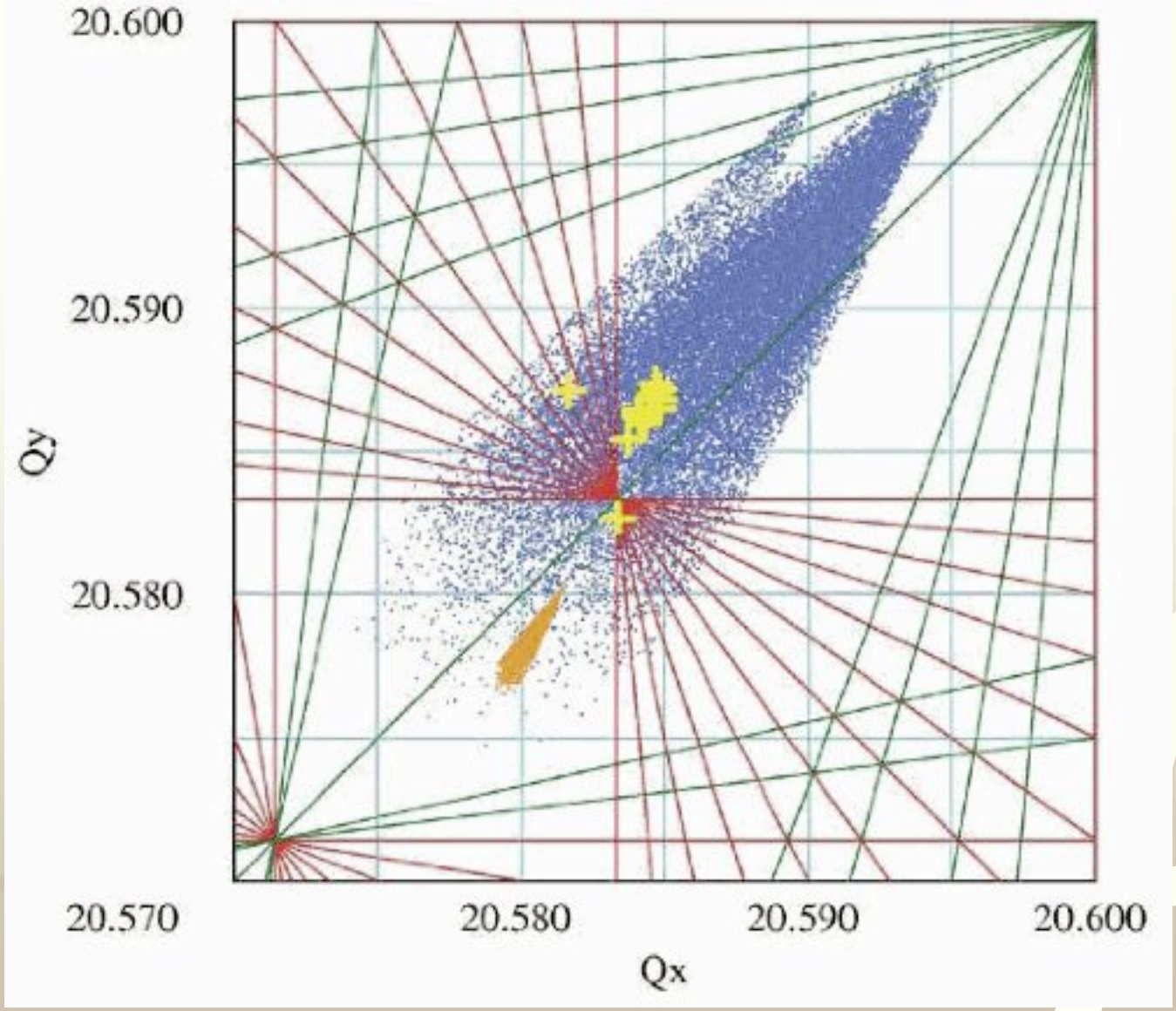
- What will this do to the beam?



Resonances

- For tunes where the that end up on the same orbit every time, every other time, etc., the particles see the same field imperfections over and over
  - Causes an instability
  - Particle path begins to follow a separatrix and begins to experience larger and larger oscillations
  - This instability can be used to extract the beam

Tune Plane of the Tevatron



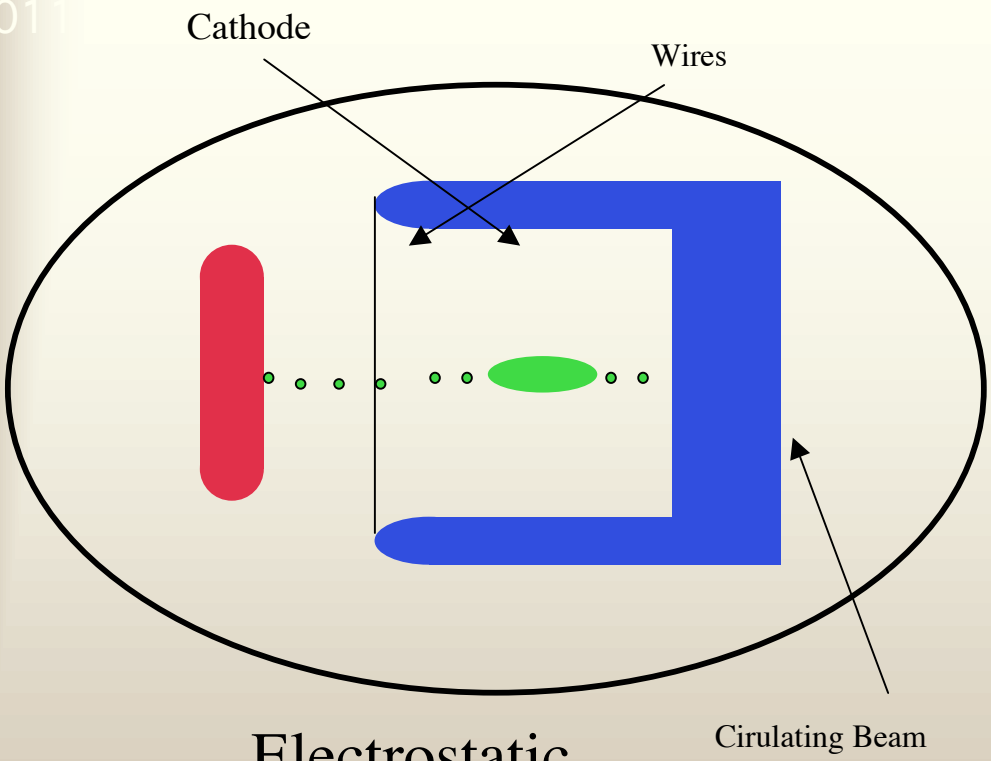
Extraction from Accelerators

- Beam spirals out (Cyclotrons)
- Energy Loss Targets (Weak Focusing Machines)
  - Beam Loss
- Fast Kickers
  - Single turn
- Resonant Extraction
  - High efficiency/low beam loss

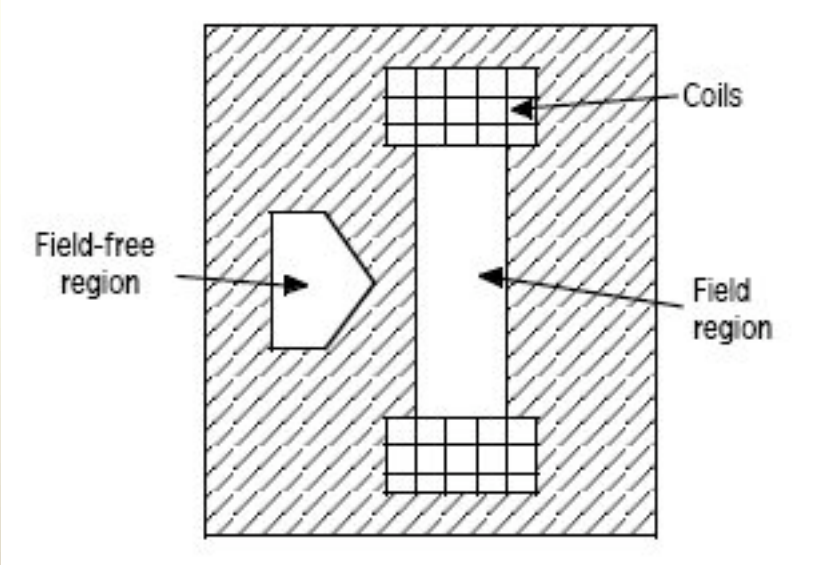
Resonant Extraction

- Tevatron used half interger resonance
  - Resonance excited by quadrupoles and octupoles controlled by feedback loop monitoring the spill
  - Beam loss minimized by adjusting the step size to the width of the septum
  - Once tune enters the stopband (unstable region), beam is lost

Extraction Devices



Electrostatic Septum



Lambertson Magnet