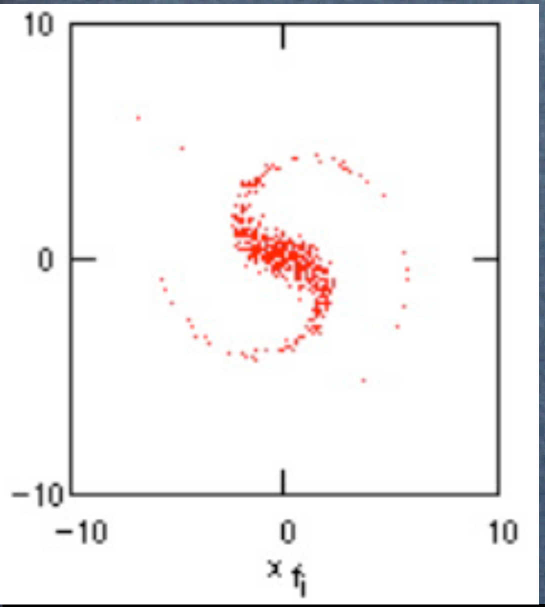
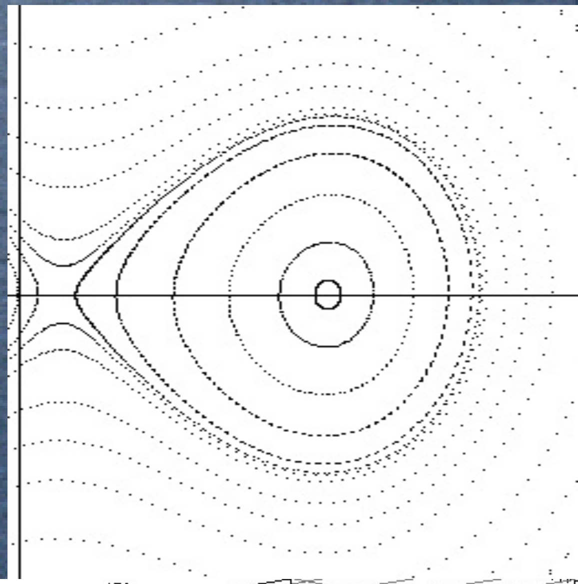
LPC
JTerm

FNAL
Jan09

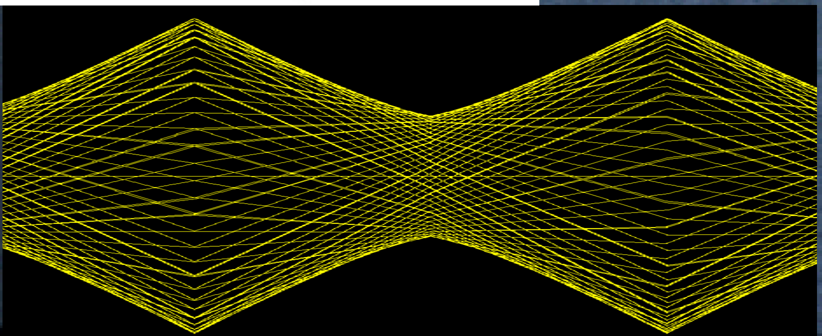
Fundamentals of Hadron Colliders

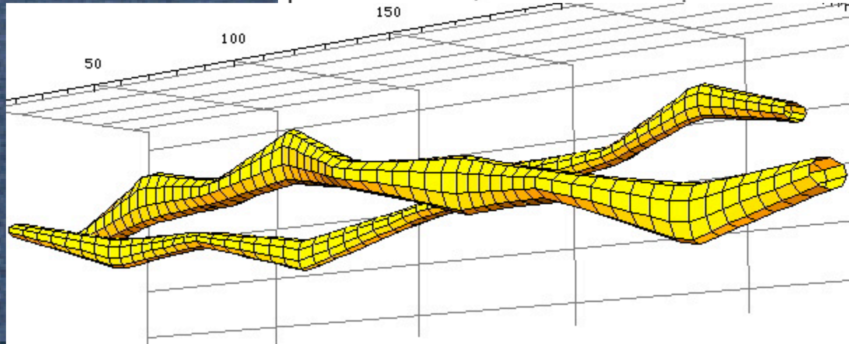
Mike Syphers, Fermilab
syphers@fnal.gov





Luminosity and its Realization
Acceleration, Transverse Focusing
Tevatron LHC
Challenges at High *E*/*L*
Luminosity Optimization





Introduction

- Can only introduce the subject, so mostly discuss the *physics* of particle accelerators, touching on the technology, relevant to large hadron colliding beams synchrotrons

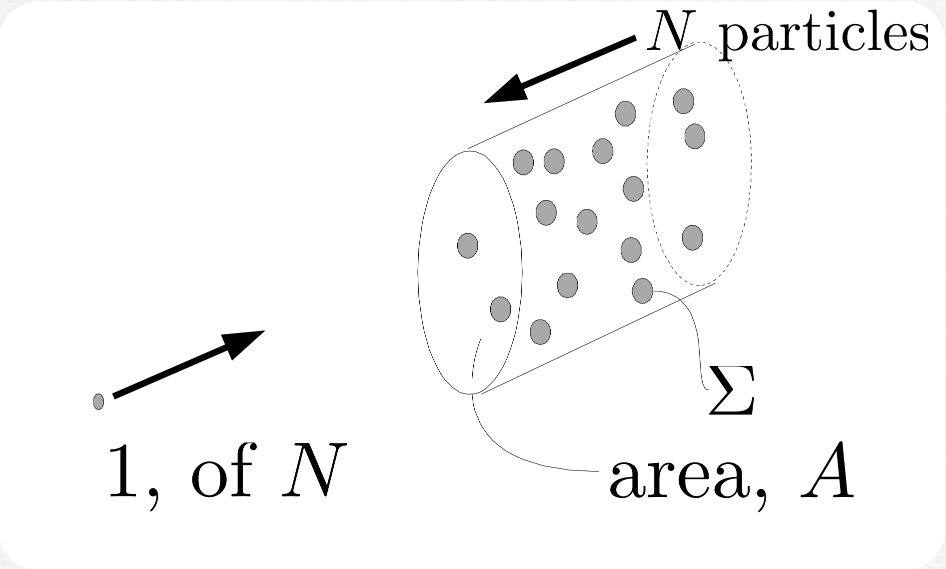
- Will cover:
  - luminosity; how to meet the requirements?
  - Accelerator Basics, the Tevatron and the LHC
  - Challenges at high energies

Collider Requirements

- ☐ Energy: collider vs. fixed target

$$m^* c^2 = \quad 2\, m_0 c^2\, \gamma_{beam} \qquad\qquad m^* c^2 = \sqrt{2}\, m_0 c^2\, \left[1 + \gamma_{beam}\right]^{1/2}$$

- ☐ Luminosity of Bunched-Beam Collider
  - look at frequency of collisions...



$$\mathcal{R} = \left(\frac{\Sigma}{A} \cdot N\right) \cdot (f \cdot N)$$

$$= \frac{f\,N^2}{A} \cdot \Sigma$$

$$\mathcal{L} \equiv \frac{f\,N^2}{A}$$

$$\boxed{(10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1} \text{ for LHC})}$$

Integrated Luminosity

☐ Suppose there are B bunches of particles circulating in each diretion in the accelerator; then,

$f_0 = \text{rev. frequency}$
$B = \text{no. bunches}$

$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

☐ In ideal case, particles are “lost” only due to “collisions”:

$$B\dot{N} = -\mathcal{L}\,\Sigma\,n$$

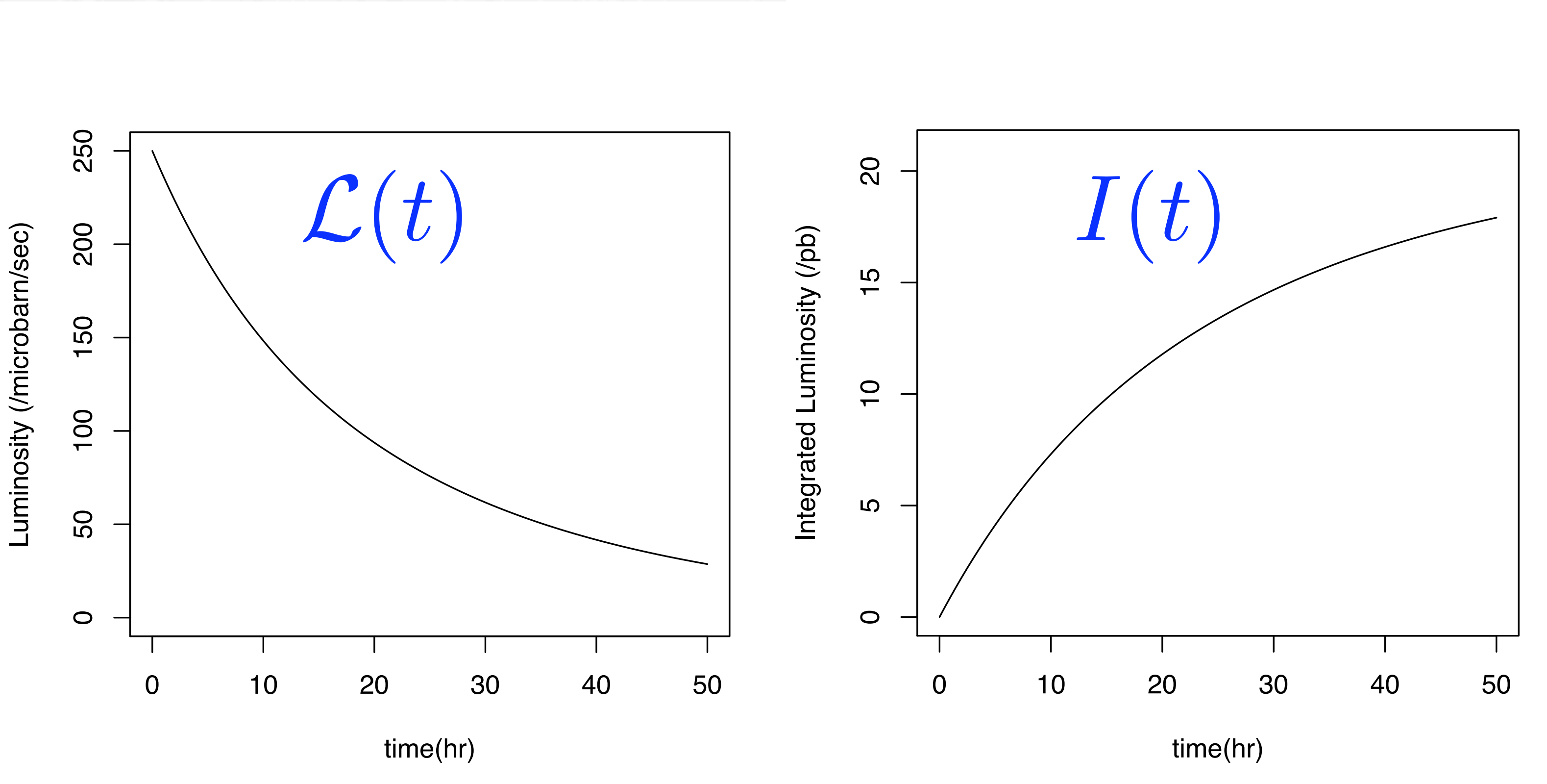
(n = no. of detectors receiving luminosity $\mathcal{L}$)

☐ So, in this ideal case, $\mathcal{L}(t) = \dfrac{\mathcal{L}_0}{\left[1 + \left(\frac{n\mathcal{L}_0\Sigma}{BN_0}\right)t\right]^2}$

Ultimate Number of Collisions

- Since $\mathcal{R} = \mathcal{L} \cdot \Sigma$ then, #events = $\int \mathcal{L}(t)dt \cdot \Sigma$
- So, our integrated luminosity is

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt = \frac{\mathcal{L}_0 T}{1 + \mathcal{L}_0 T(n\Sigma/BN_0)} = I_0 \cdot \frac{\mathcal{L}_0 T/I_0}{1 + \mathcal{L}_0 T/I_0}$$



asymptotic limit:

$$\boxed{I_0 \equiv \frac{BN_0}{n\Sigma}}$$

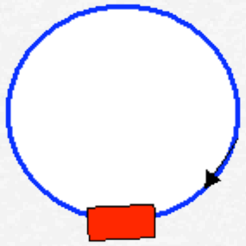
so, ...

$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

(will come back to luminosity at the end)

How to Make Collisions?

- Simple Model of Synchrotron:



  - Accelerating device + magnetic field to bring particle back to accelerate again

- Field Strength -- determines size, ultimate energy of collider

bend radius:

$$\rho = \frac{p}{e\,B}\ ;\quad R = \rho/f \quad (f \approx 0.8 - 0.9)$$

(fraction of circumference with bending)

  - ex:

$$B = 1.8\ \mathrm{T},\quad p = 450\ \mathrm{GeV/c}\quad f = 0.85 \rightarrow R \approx 1\ \mathrm{km}$$

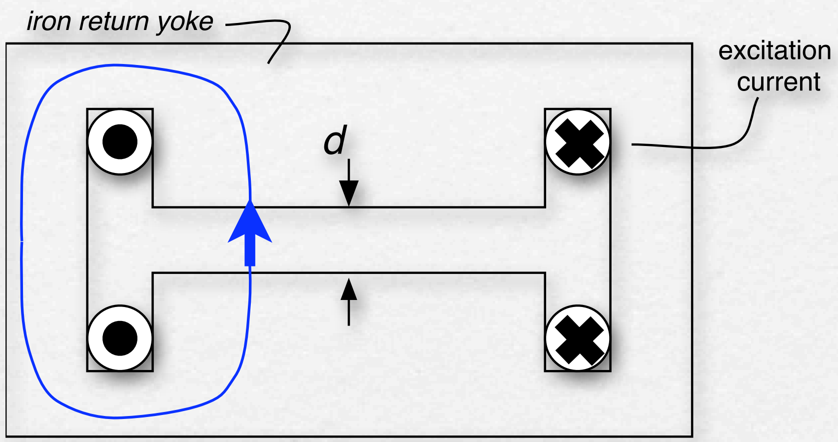
Magnets

- ☐ iron-dominated magnetic fields

$$B = \frac{2\mu_0 N \cdot I}{d}$$

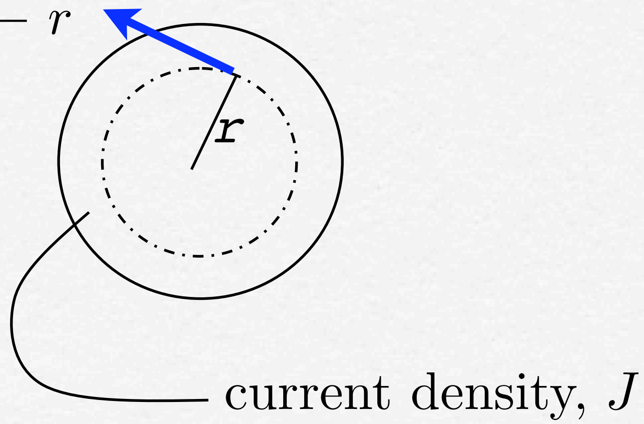
  - iron will "saturate" at about 2 Tesla

N turns per pole of current I



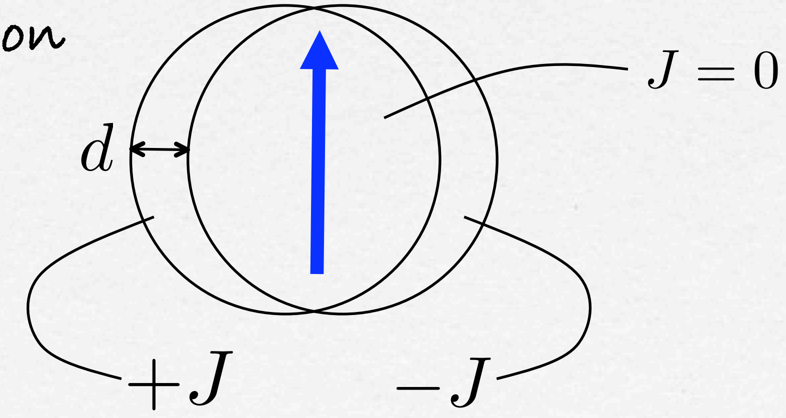
- ☐ Superconducting magnets
  - field determined by distribution of currents

$$B_\theta = \frac{\mu_0 J}{2}\, r$$



"Cosine-theta" distribution

$$\boxed{B_x = 0, \quad B_y = \frac{\mu_0 J}{2}\, d}$$



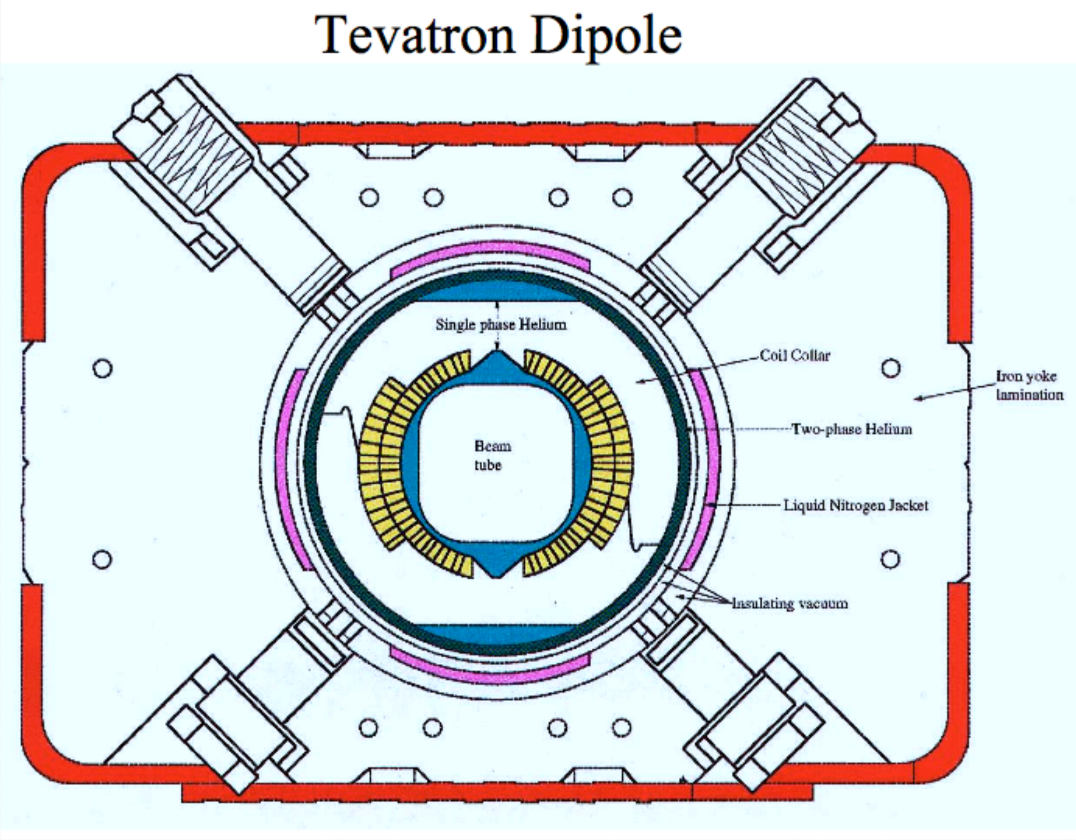
Superconducting Designs

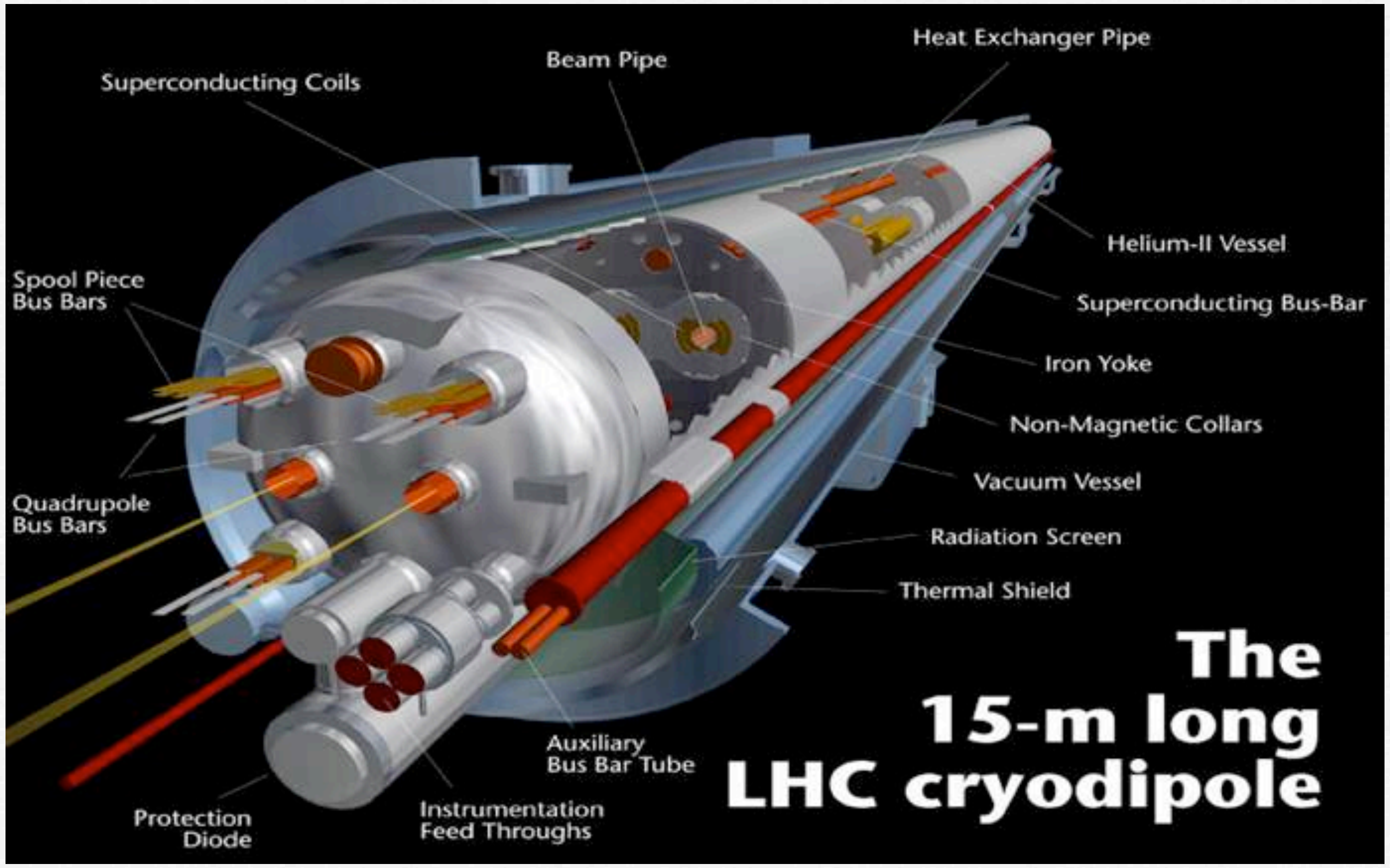
☐ Tevatron

- 1^{st} SC accelerator
- 4.4 T; 4°K

Numerical Example:

$$\begin{aligned} B &= \frac{\mu_0 J}{2} d \\ &= \frac{4\pi \text{ T m/A}}{10^7} \frac{1000 \text{ A/mm}^2}{2} \cdot (10 \text{ mm}) \cdot \frac{10^3 \text{mm}}{\text{m}} \\ &= 6 \text{ T} \end{aligned}$$





The 15-m long LHC cryodipole

☐ LHC -- 8 T; 1.8°K

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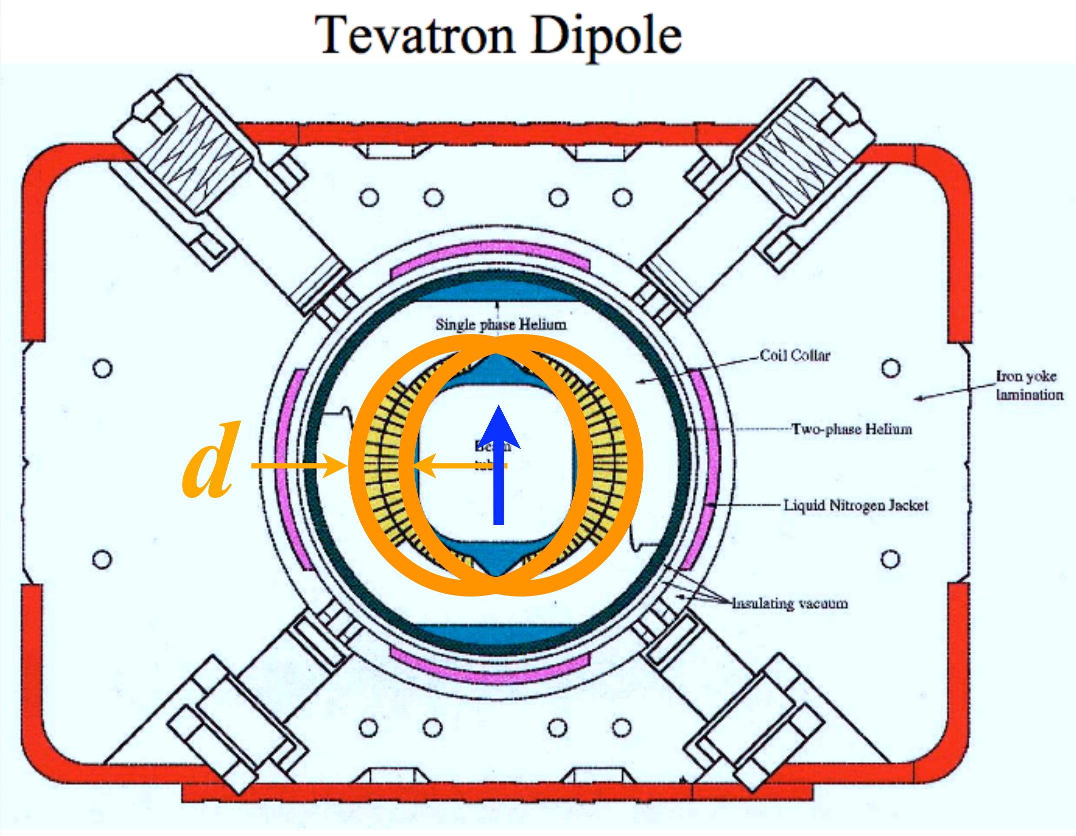
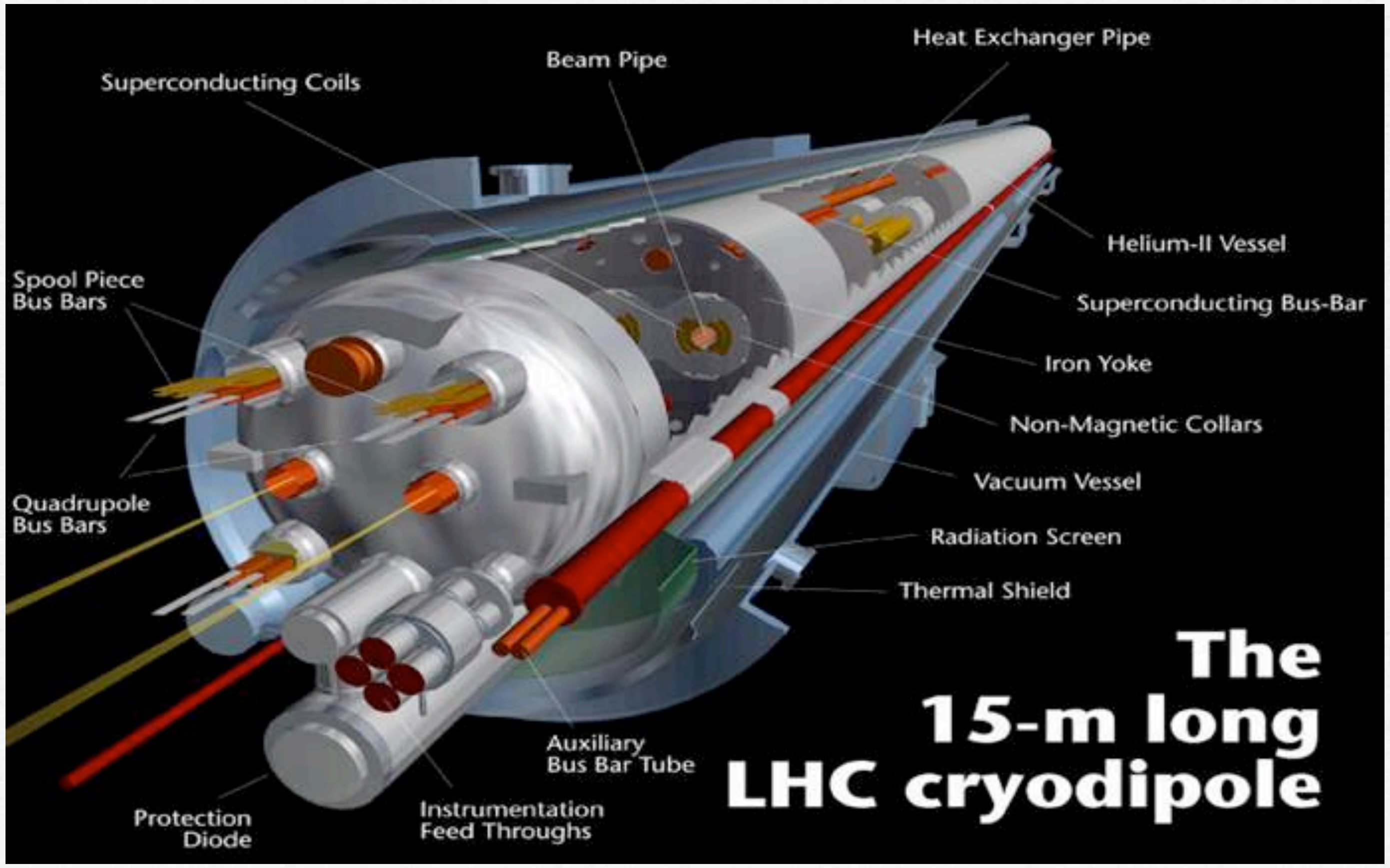
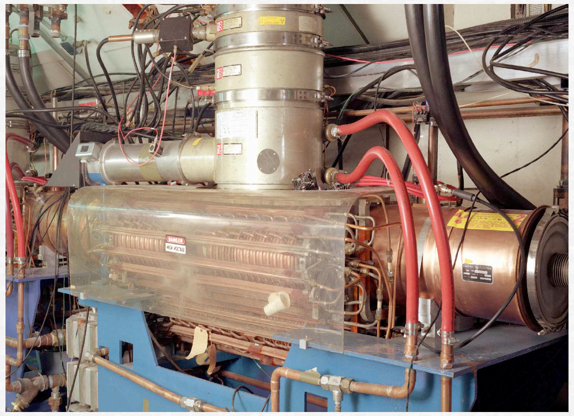

Tevatron Dipole



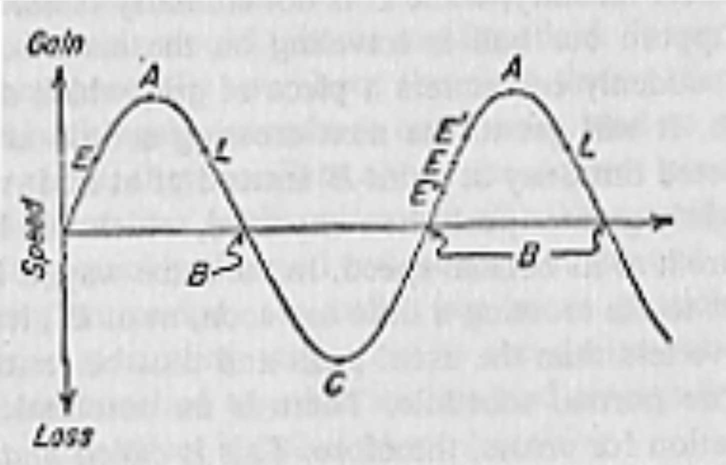
The 15-m long LHC cryodipole

- ☐ LHC -- 8 T; 1.8°K

Acceleration



- imagine: particle circulating in field, B, with orbit frequency ω. Along orbit, arrange particle to pass through a cavity with max. voltage V, oscillating at frequency $h \times f_{rev}$ (where h is an integer); suppose particle arrives near time of zero-crossing
  - net acceleration/deceleration $= eV\sin(\omega\Delta t)$



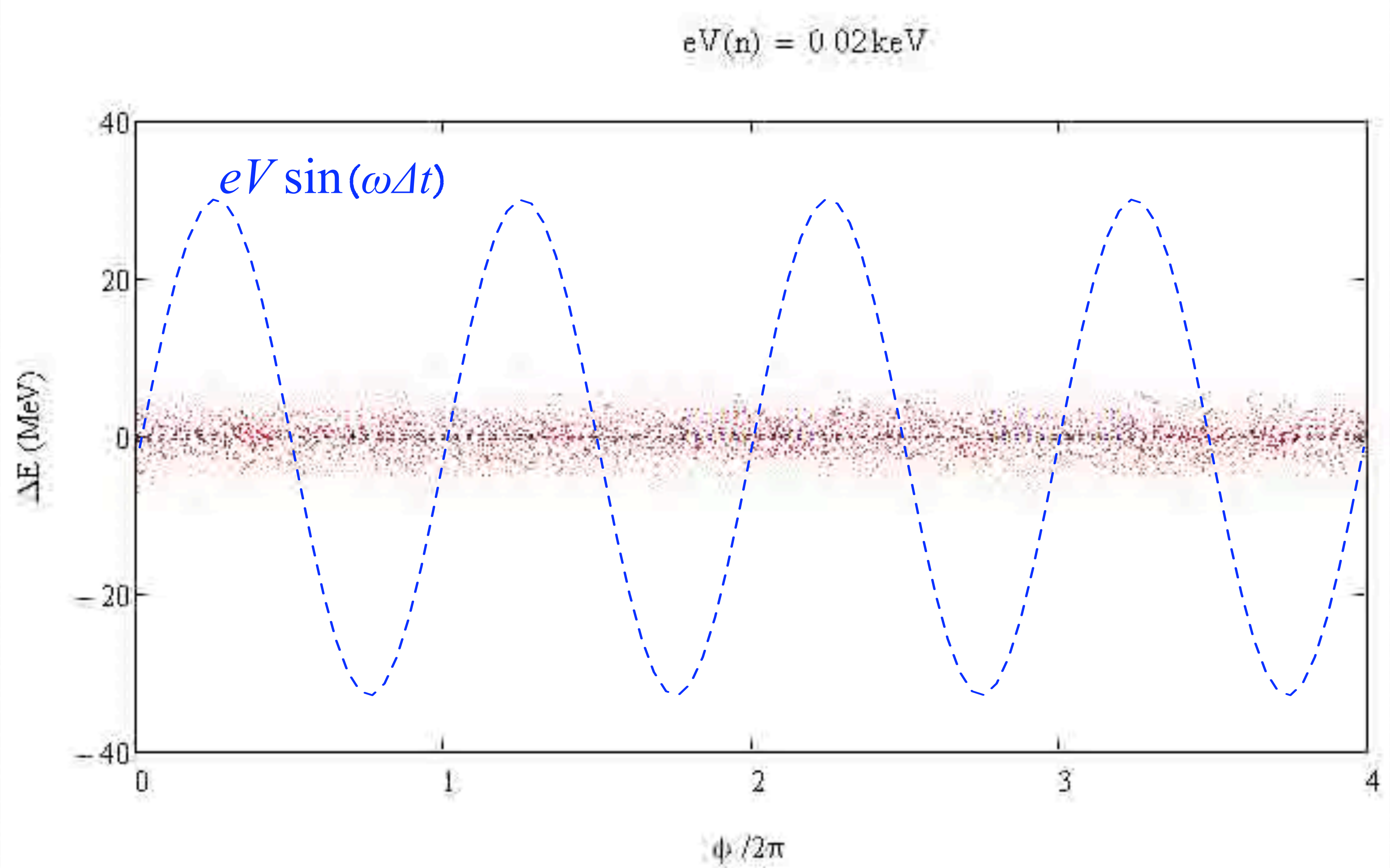
- if arrives late, more voltage is applied; arrives early, gets less
  - thus, a restoring force --> energy oscillation

"Synchrotron Oscillations"

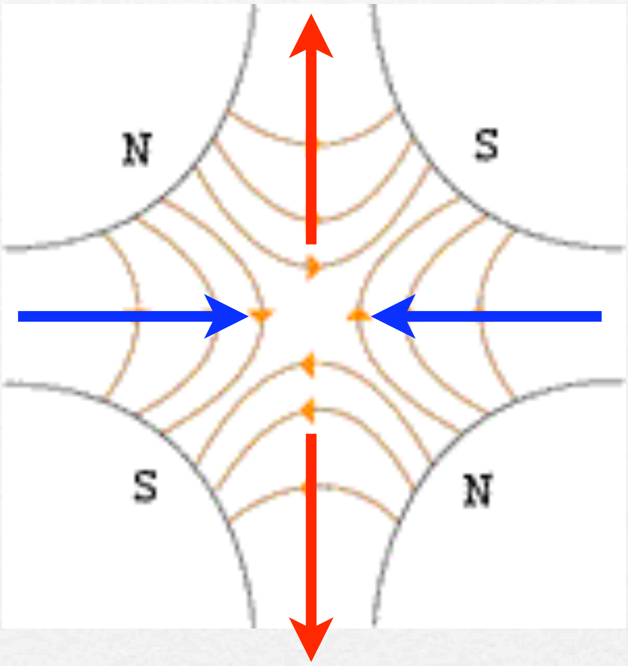
- next, slowly raise the strength of B; if raised adiabatically, oscillations continue about the "synchronous" momentum, defined by $p/e = B{\cdot}R$ for constant R, as B increases
- Nonlinear restoring force of the RF generates stable phase space regions
  - bunched beam $h = f_{rf} / f_{rev}$ = # of possible bunches

Bunched Beam

- ☐ Ex: Bunch by adiabatically raising voltage of RF cavities

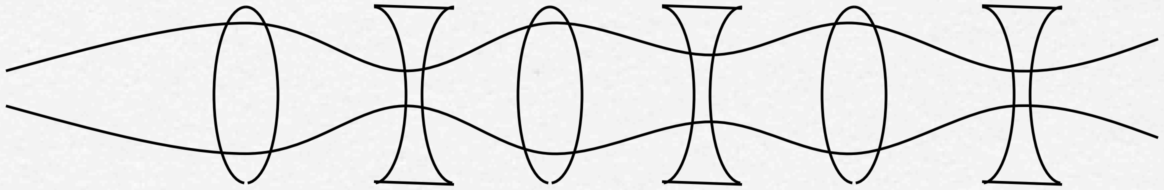


Keeping Focused

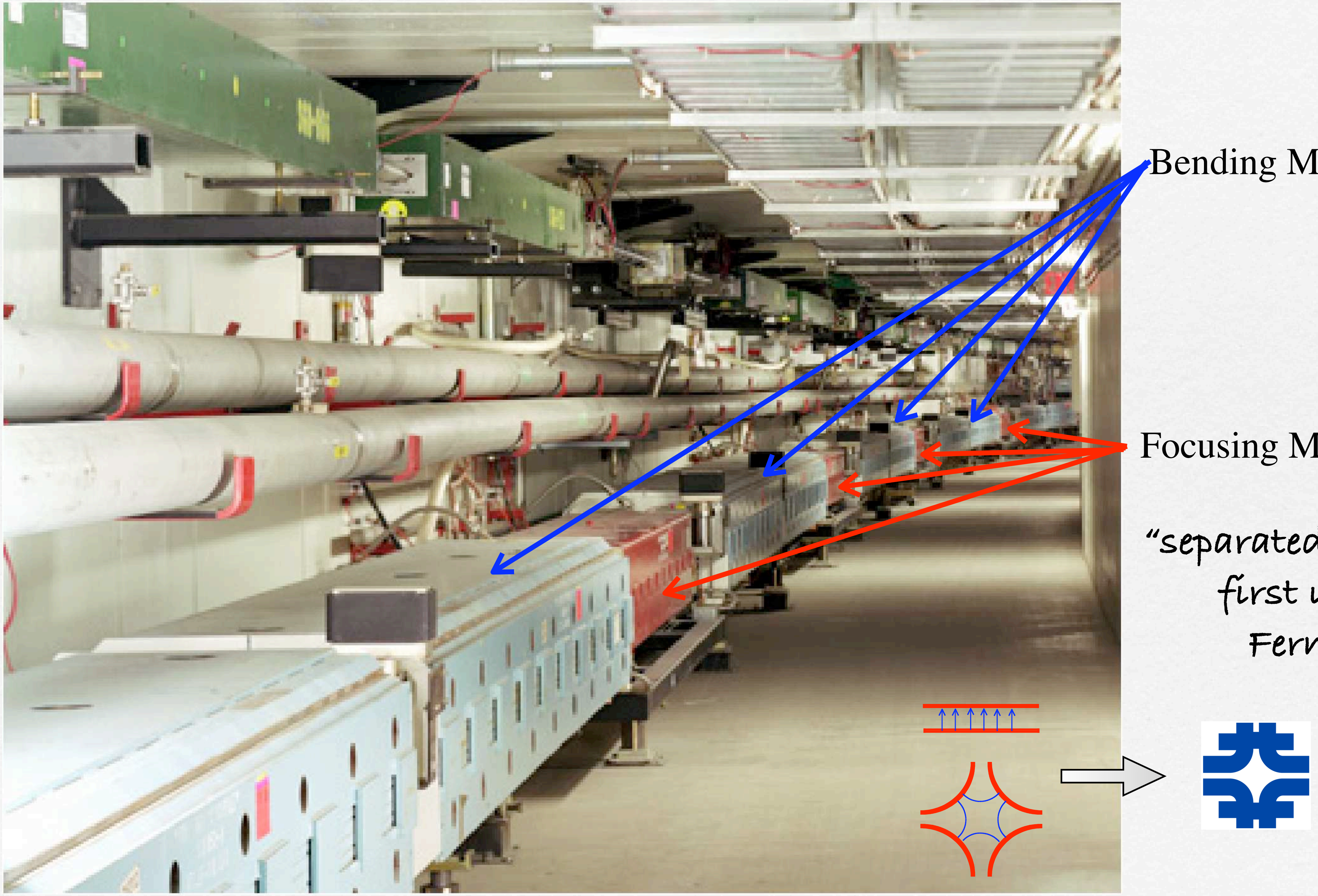


- ☐ In addition to increasing the particle's energy, must keep the beam focused transversely
- ☐ Standard focusing scheme: alternating system of focusing and defocusing lenses
- ☐ Quadrupole Field will focus in one transverse plane, but defocus in other; if alternate, can have net focusing in both
  - for equally spaced infinite set, net focusing requires $F > L/2$

    F = focal length, L = spacing
  - FODO cells:



Example: FNAL Main Injector



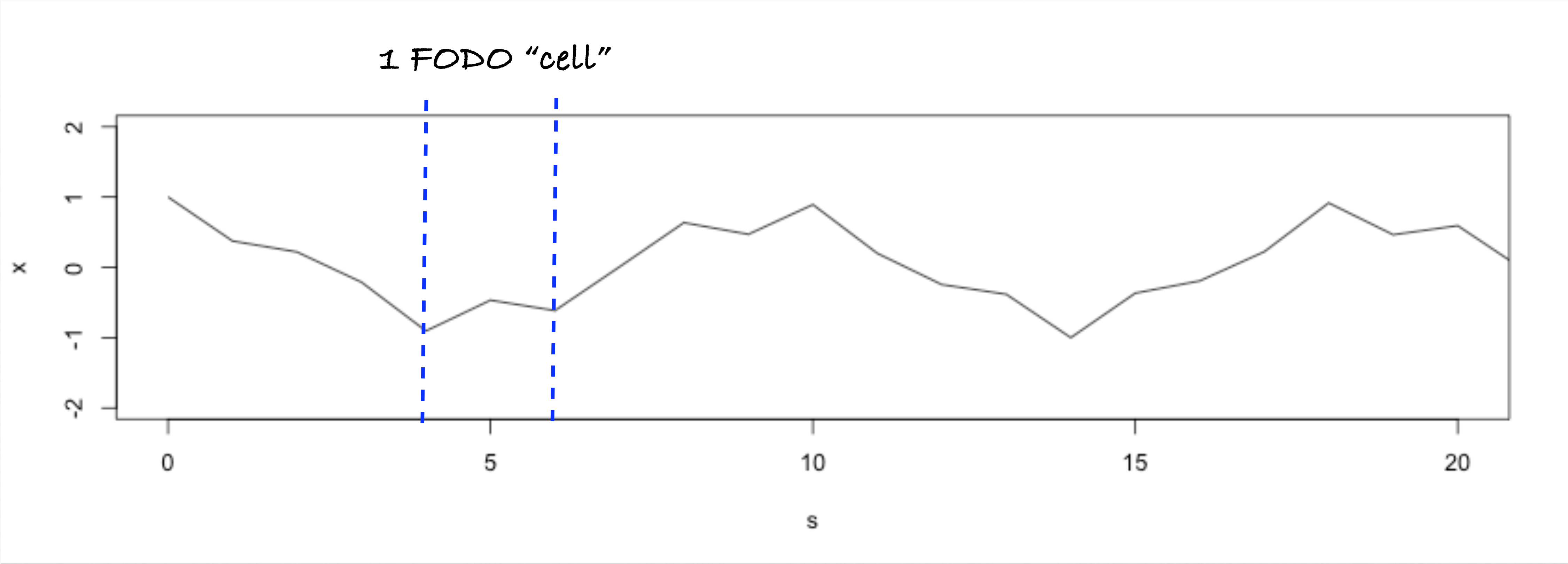
Bending Magnets

Focusing Magnets

"separated function"
first used at
Fermilab

Fermilab Logo

Particle Trajectories



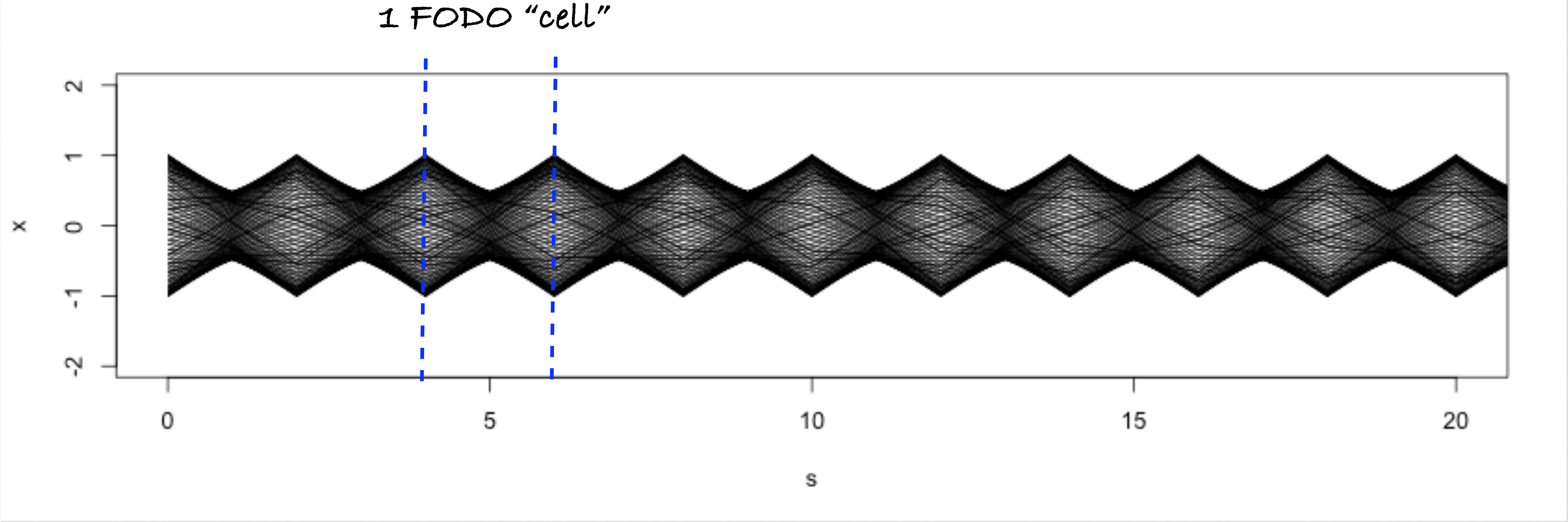
- ☐ Analytical Description: $\frac{dx'}{ds} = \frac{d^2x}{ds^2} = -\frac{eB'(s)}{p}x$ $\left[K(s) = \frac{e}{p}\frac{\partial B_y}{\partial x}(s)\right]$
  - Equation of Motion: (Hill's Equation)

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

  - Nearly simple harmonic; so, assume soln.: $\boxed{x(s) = A\sqrt{\beta(s)}\sin[\psi(s)+\delta]}$

Particle Trajectories

1 FODO "cell"



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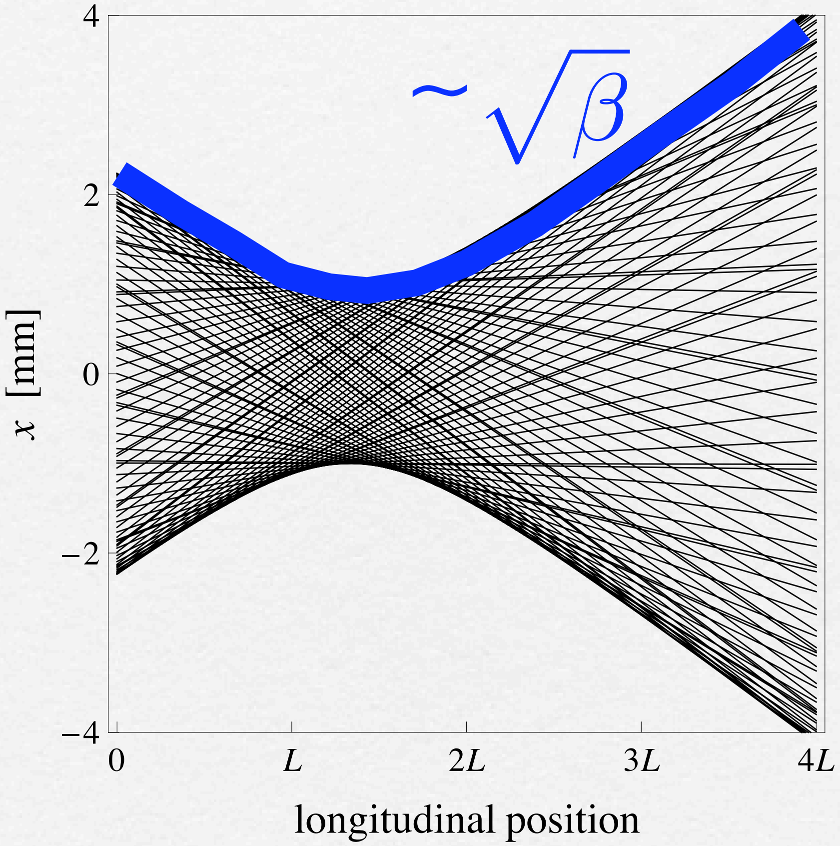
Hill’s Equation and the “Beta Function”

- We see that an “amplitude function” exists, so taking $x'' + K(s)x = 0$ and assuming $x(s) = A\sqrt{\beta(s)}\sin[\psi(s) + \delta]$
  - can show that $\boxed{\beta'' + 4K\beta = const.}$



- In a “drift” region (no focusing fields),
  - beta function is a parabola in drift regions
  - if pass through a waist at s = 0, then,

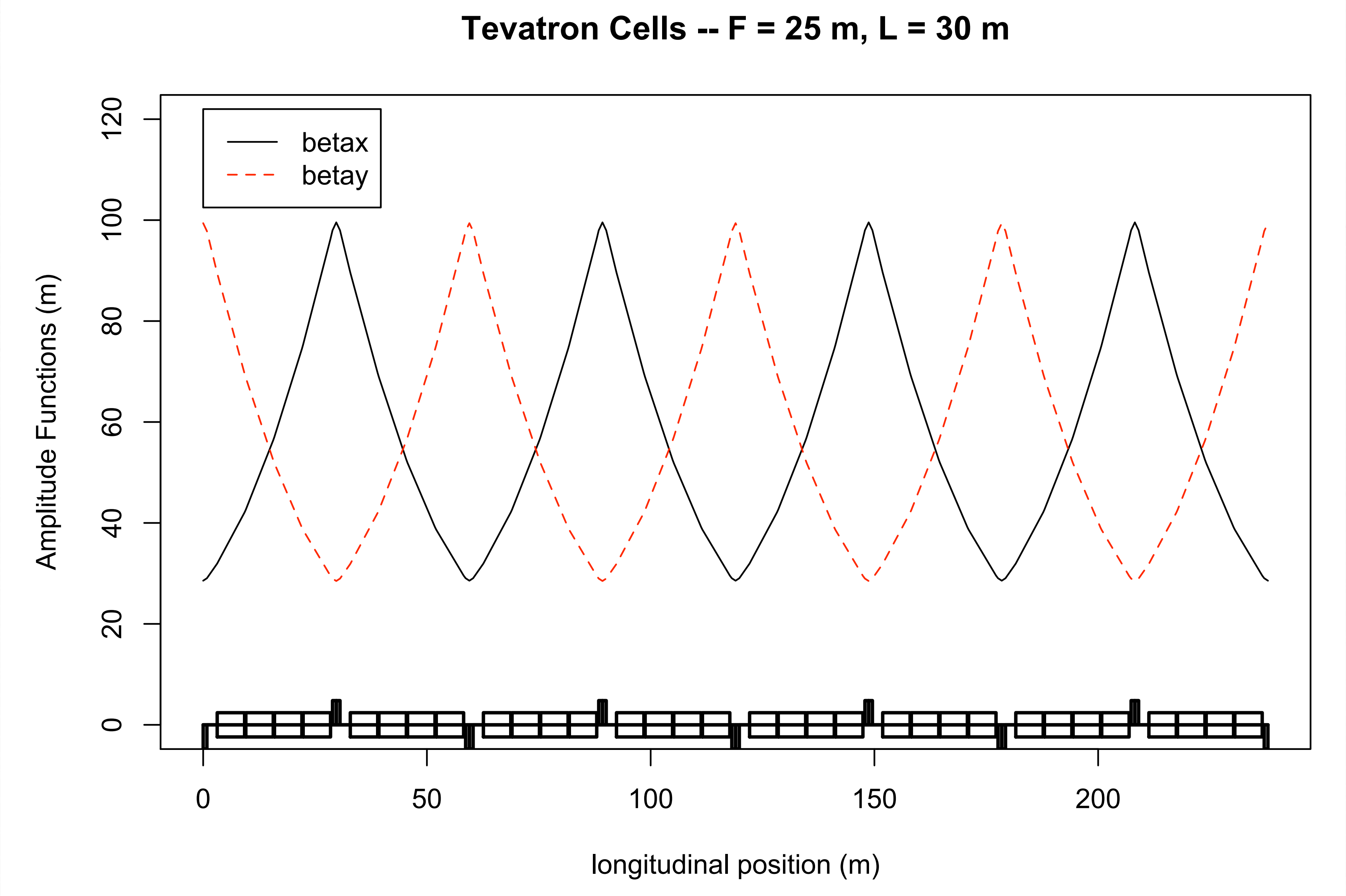
$$\boxed{\beta(s) = \beta^* + \frac{s^2}{\beta^*}}$$

- So, optical properties of synchrotron (β) are now decoupled from particle properties (A, δ) and accelerator can be designed in terms of optical functions; beam size will be proportional to $\beta^{1/2}$

FODO Cells (arcs)

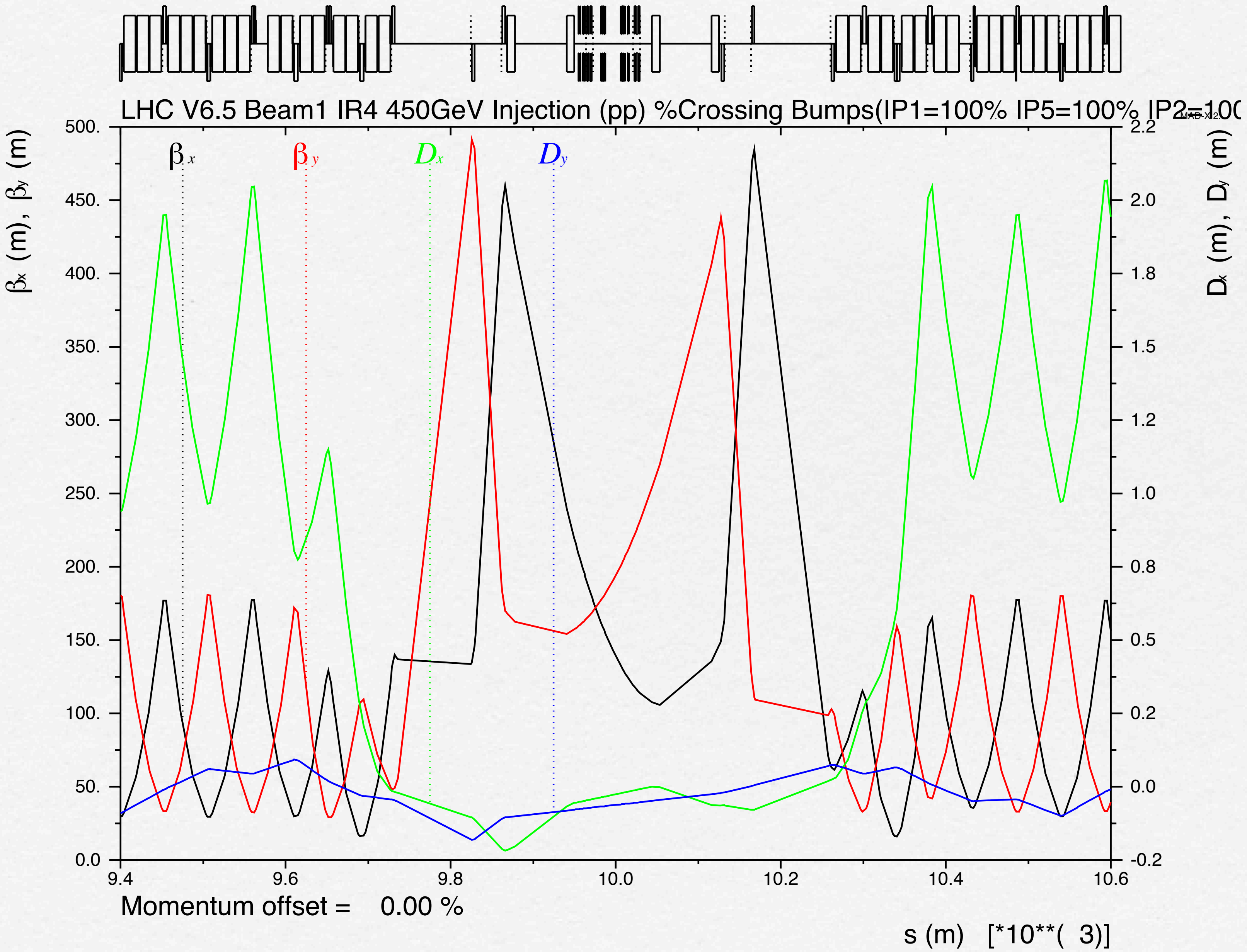
Ex: Tevatron Cell

$$\beta_{max,min} = 2F\sqrt{\frac{1 \pm L/2F}{1 \mp L/2F}}$$



Long Straight Section

- a "matched insertion" that propagates the amplitude functions from their FODO values, through the new region, and reproduces them on the other side
- Here, we see an LHC section used for beam scraping



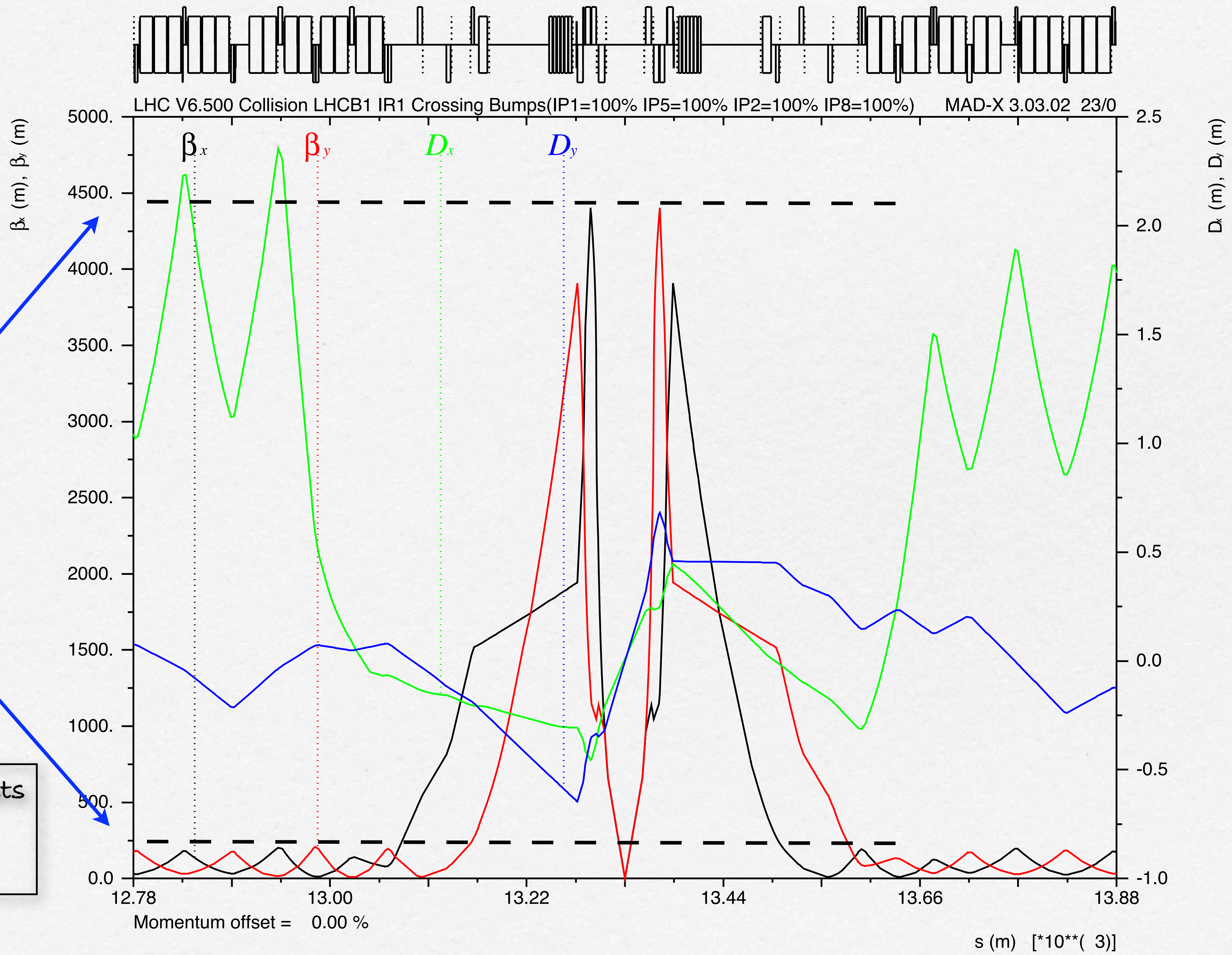
Interaction Region

LHC
high
lumi
IR

Note scales!

Triplets

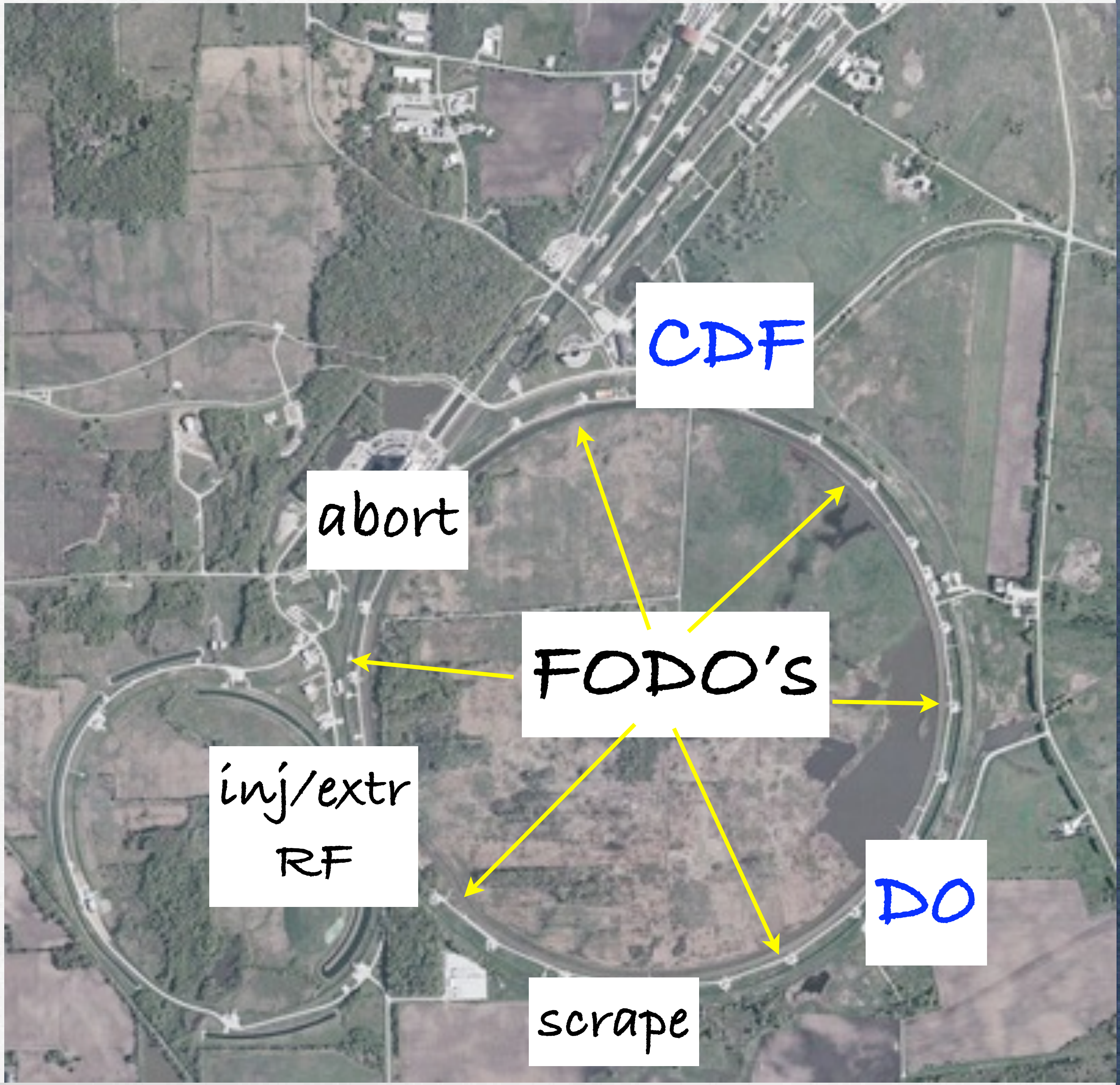
FODO



beam is ~10x larger in triplet magnets
than in the arcs of the ring;
~100x larger than at focal point

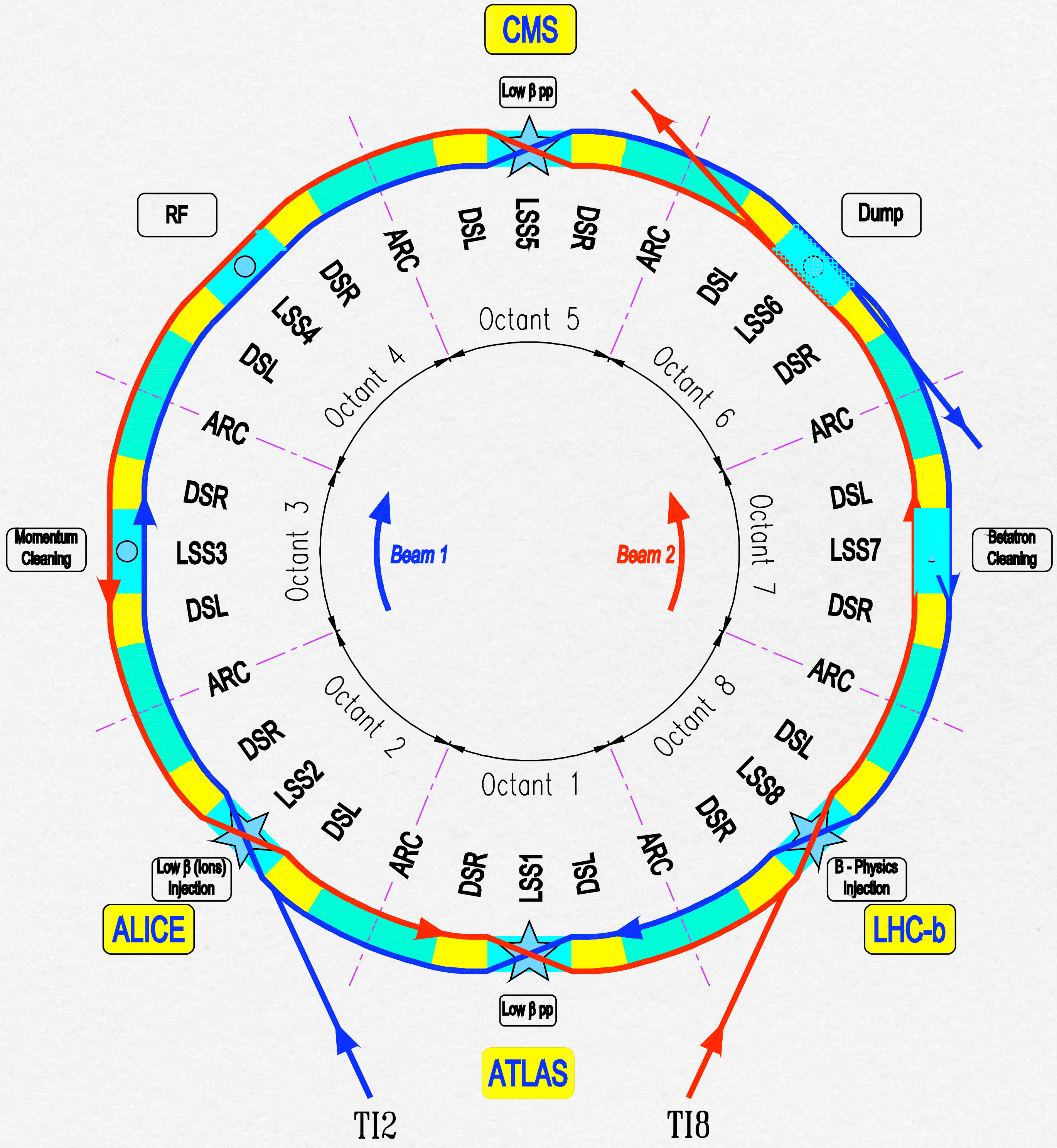
Put it all Together

- ☐ make up a synchrotron out of FODO cells for bending, a few matched straight sections for special purposes...

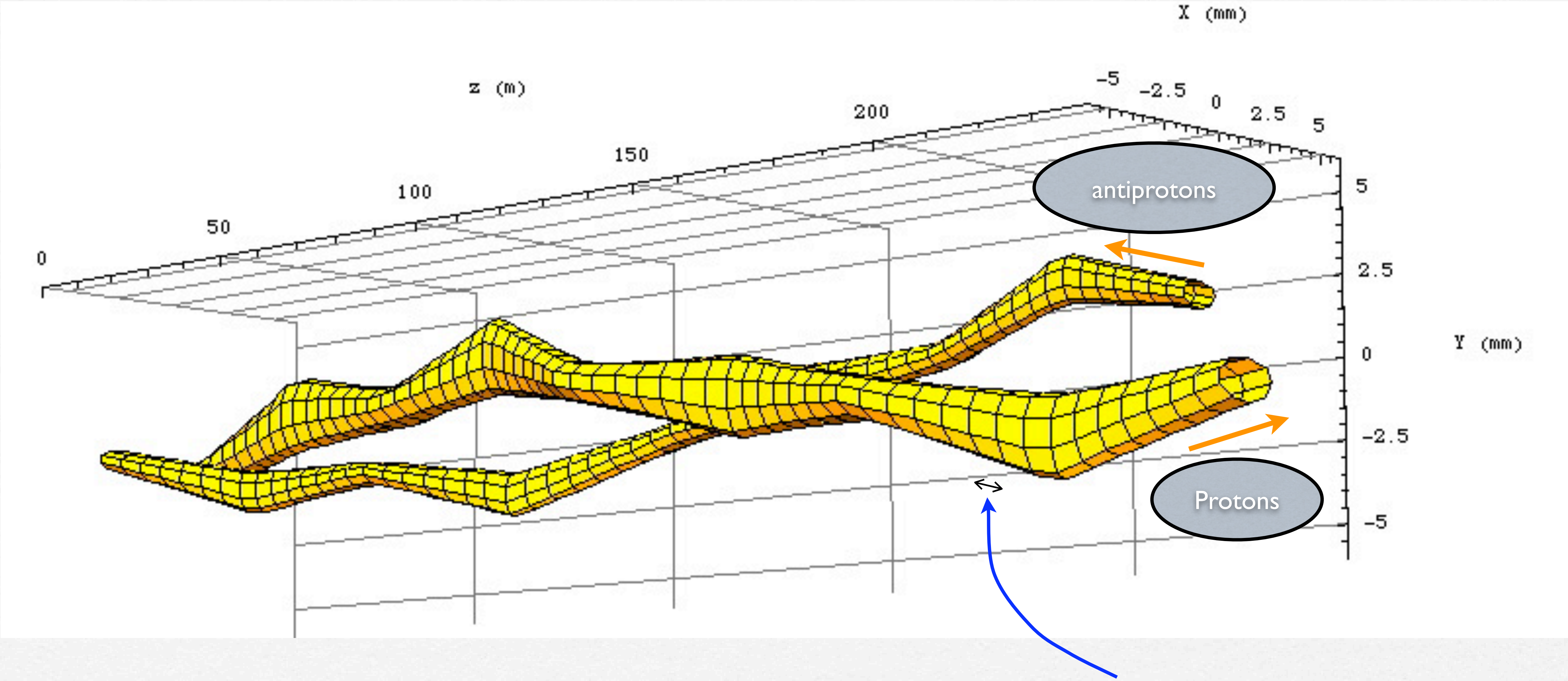


LHC Layout

- Mostly FODO cells, with beams separated horizontally in common cryostats
- straight regions for detectors, injection, RF, beam scraping, instrumentation, beam dumps, etc.
- Symmetry insures equal path lengths for two beams



Tevatron: 2 Beams in 1 Pipe



antiprotons

Protons

bunch length

Helical orbits through 4 standard arc cells of the Tevatron; beam envelopes are shown

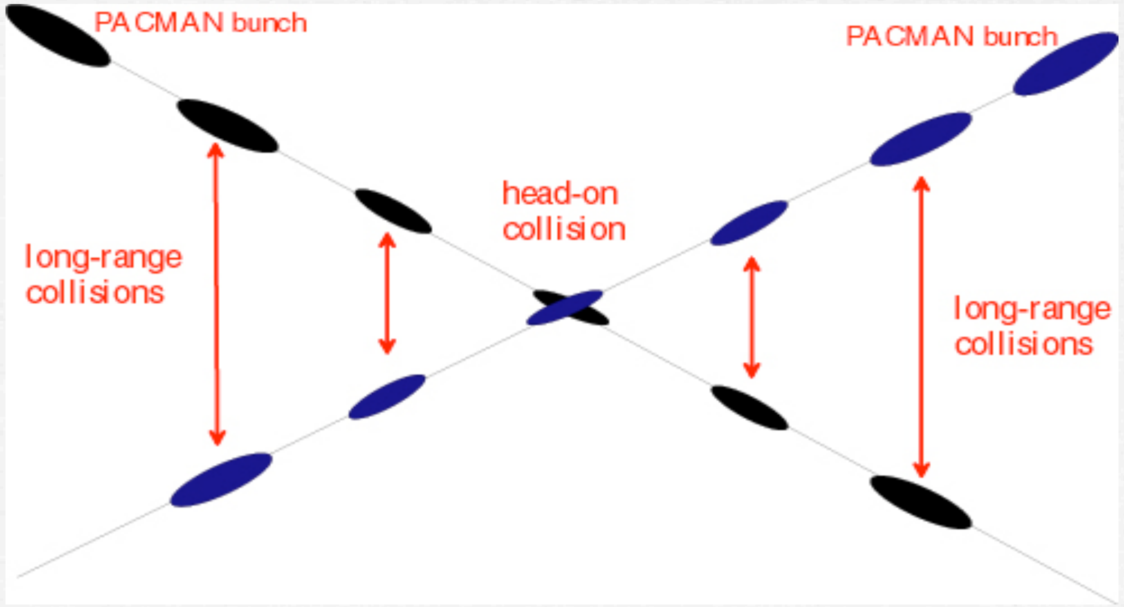
36 bunches in each beam,
separated by ~400 ns

LHC: 2 Beams in 2 Pipes

- Many more (~3000) bunches in each (separated) LHC beam; but, for about 120 m near the IP, contained in the same beam pipe
- This would give ~30 bunch interactions through this region
- Want a single Head-on collision ***at*** the interaction point (IP), but will still have long-range interactions on either side
- Beam size grows away from IP, and so does separation; can tolerate beams separated by ~10 sigma

$$d/\sigma = \theta \cdot (\beta^*/\sigma^*) \approx 10$$

$$\longrightarrow \qquad \theta = 10 \cdot (0.017)/(550) \approx 300\ \mu\text{rad}$$



Beam Stored Energy

☐ Tevatron

- $10^{13} \cdot 10^{12}$ eV $\cdot 1.6 \cdot 10^{-19}$ J/eV $\sim$ 2 MJ

☐ LHC

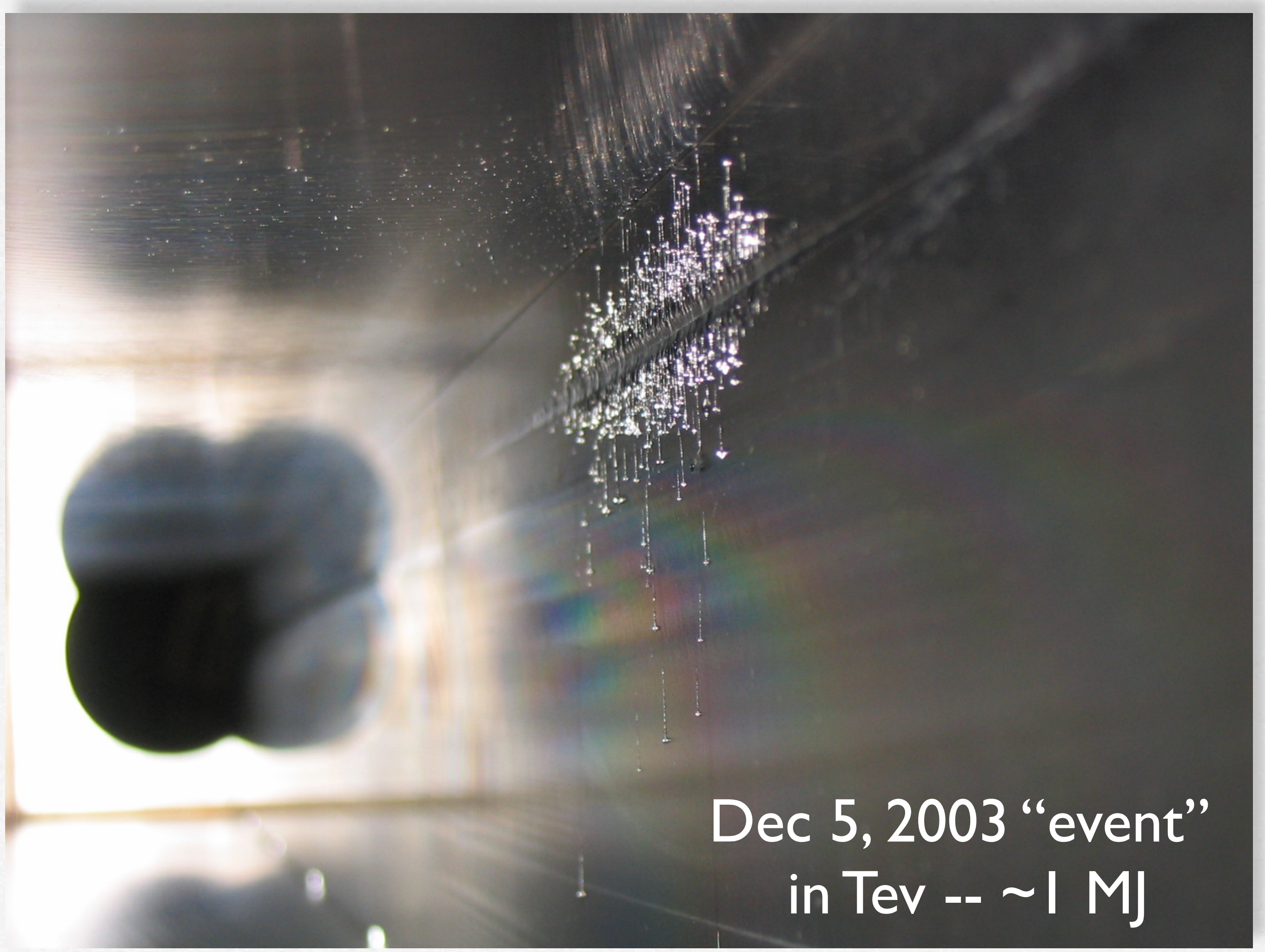
- $3 \cdot 10^{14} \cdot 7 \cdot 10^{12}$ eV $\cdot 1.6 \cdot 10^{-19}$ J/eV $\sim$ 300 MJ per beam!

☐ Power at IP's -- rate of lost particles x energy: $\mathcal{L} \cdot \Sigma \cdot E$

- Tevatron (at 4K) -- ~4 W at each detector region
- LHC (at 1.8K) -- ~1300 W at each detector region

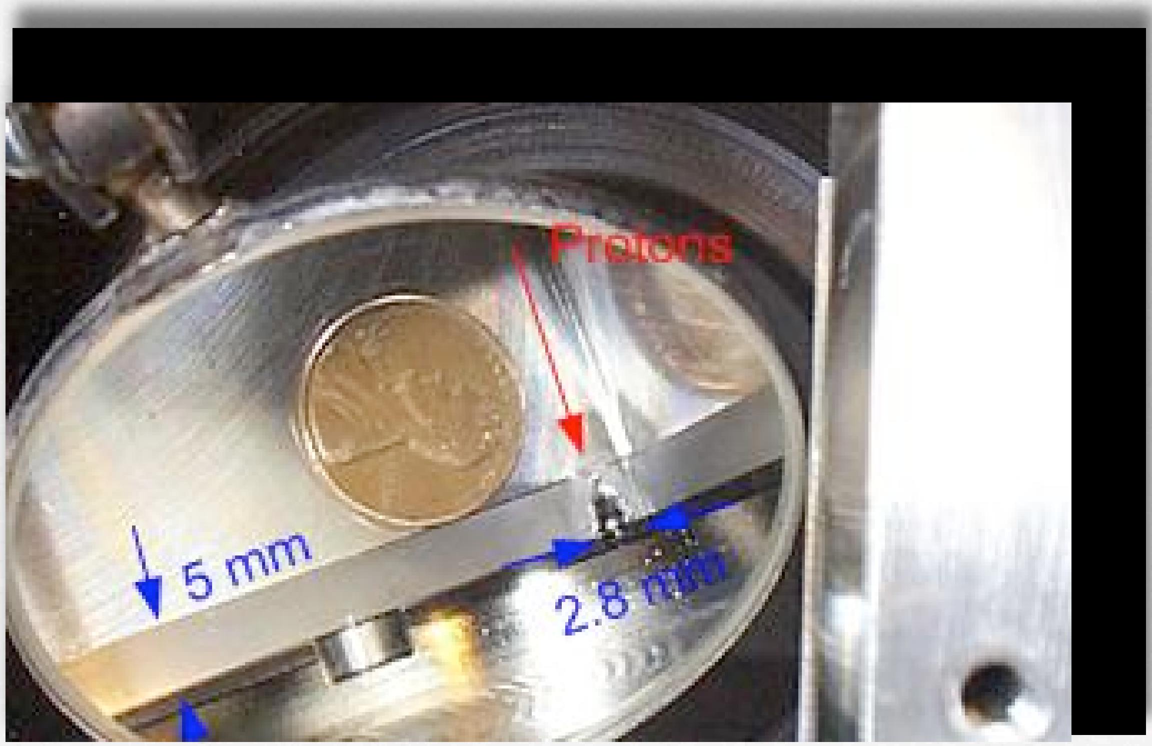
Collimation Systems

- ☐ Tevatron -- several collimators/scrapers
- ☐ LHC -- ~ 100 collimators



Dec 5, 2003 “event” in Tev -- ~1 MJ

Careful control of collimators, beam trajectory, beam envelope are required



Back to Luminosity...

- Can now express in terms of beam physics parameters; ex.: for short, round beams...

$$\mathcal{L} = \frac{f_0 B N^2}{4\pi\sigma^{*2}} = \frac{f_0 B N^2 \gamma}{4\epsilon\beta^*}$$

(rms beam size $\sigma \propto \sqrt{\beta}$)

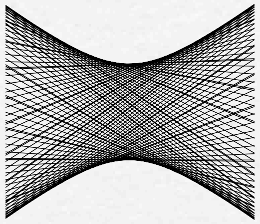
- If different average bunch intensities, and/or different transverse beam sizes for the two beams,

$$\mathcal{L} = \frac{f_0 B N_1 N_2}{2\pi(\sigma_1^{*2} + \sigma_2^{*2})} = \frac{f_0 B N_1 N_2 \gamma}{2\beta^*(\epsilon_1 + \epsilon_2)}$$

and assorted other variations...

Hour Glass

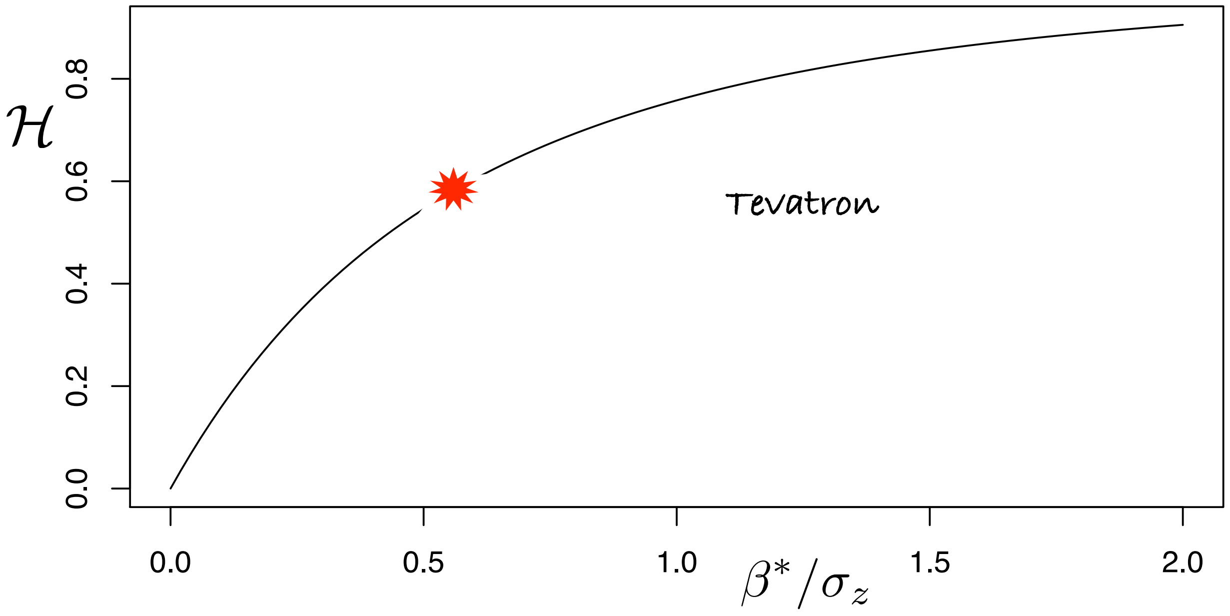
- If bunches are too long, the rapid increase of the amplitude function away from the interaction "point" reduces luminosity



$$\longrightarrow \mathcal{L} = \mathcal{L}_0 \cdot \mathcal{H}$$

- Tevatron:
  - $\sigma_s \approx 2\beta^*$
- LHC:
  - $\sigma_s << \beta^*$

$$\mathcal{H} = \sqrt{\pi}\left(\frac{\beta^*}{\sigma_z}\right) e^{(\beta^*/\sigma_z)^2}\left[1 - \mathrm{erf}(\beta^*/\sigma_z)\right]$$



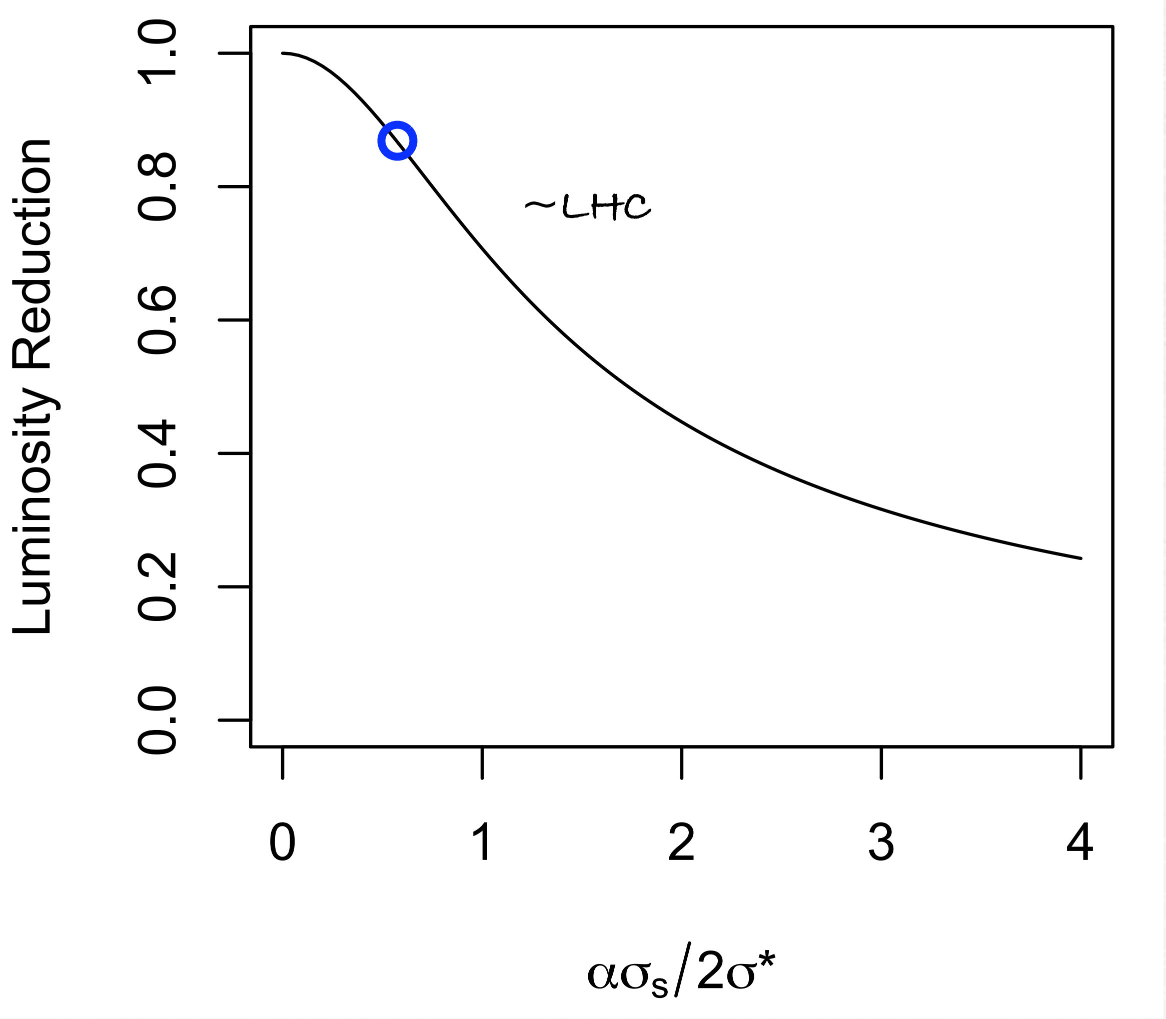
Crossing Angle

☐ Though the hourglass effect will not be an issue in the LHC, we saw that a crossing angle is required -- will also reduce luminosity from previous expressions

-- however, since bunches are indeed shorter in LHC, effect due to crossing angle in LHC is only ~15%:

$$\mathcal{L} = \mathcal{L}_0 \cdot \frac{1}{\sqrt{1 + (\alpha\sigma_s/2\sigma^*)^2}}$$

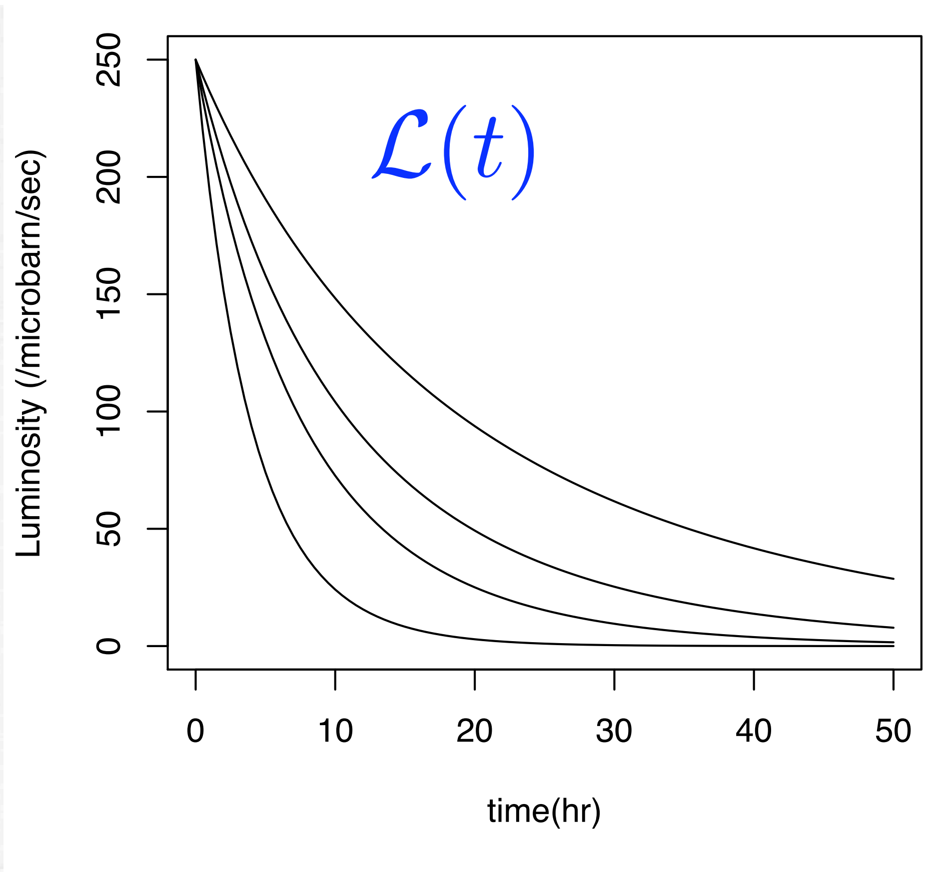
α = full crossing angle

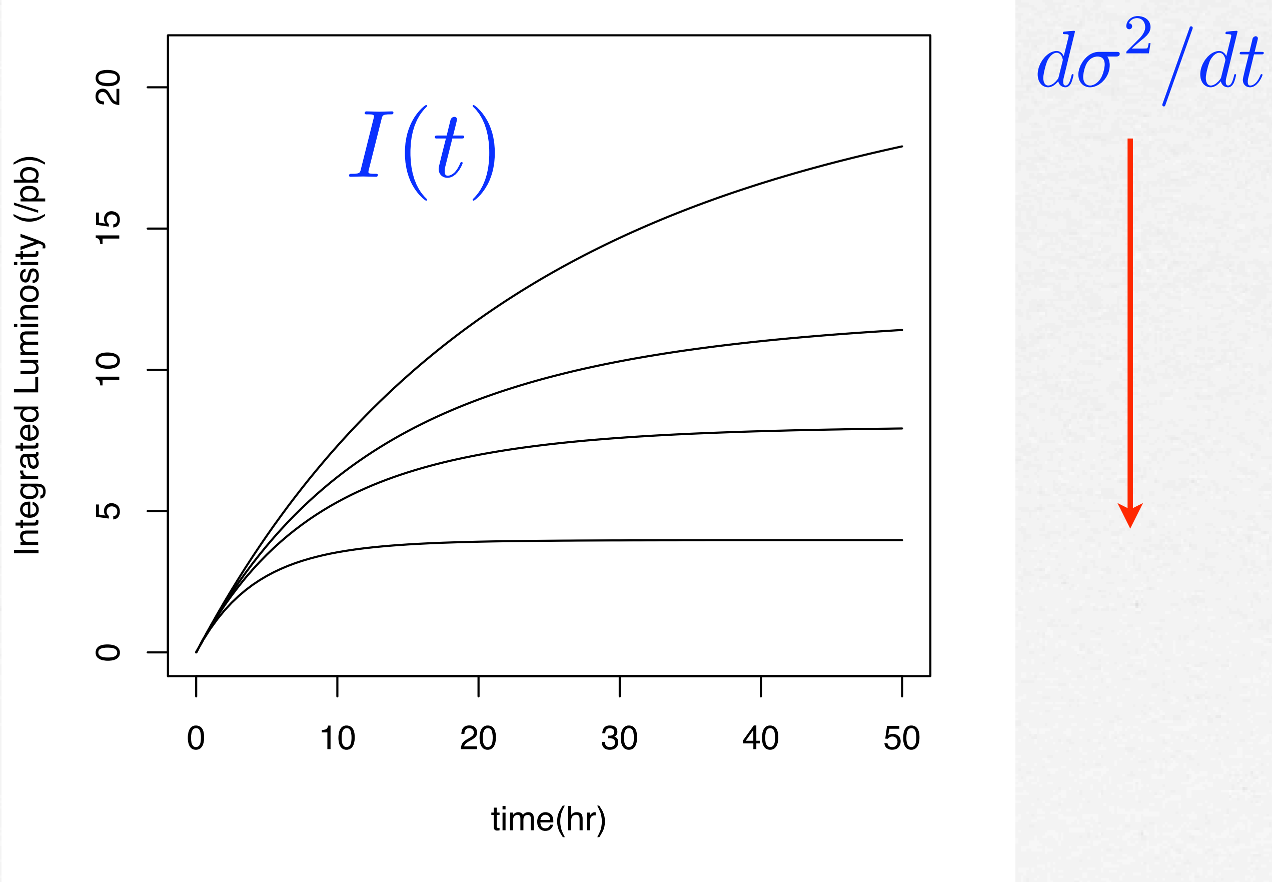


Back to Integrated Luminosity...

- need to include effect of particle loss due to other means
  - ex: scattering off residual gas
- suppose diffusion effects cause $d\sigma^2/dt$ (they do!), and particles eventually strike collimators:

Tevatron example:

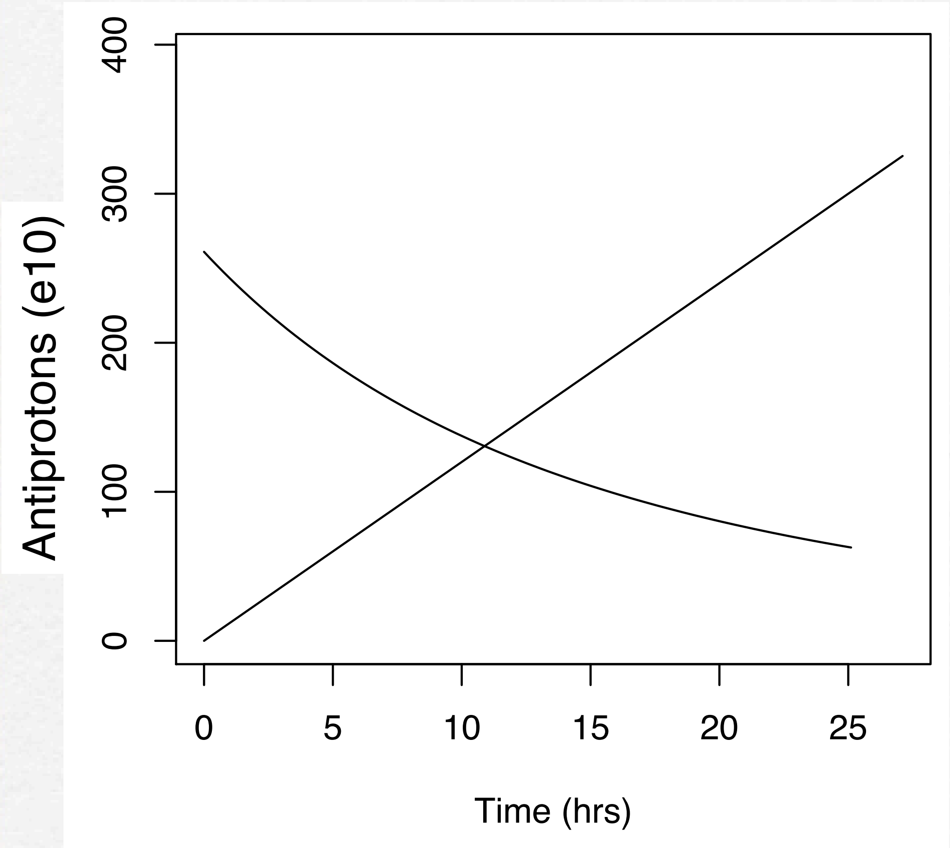


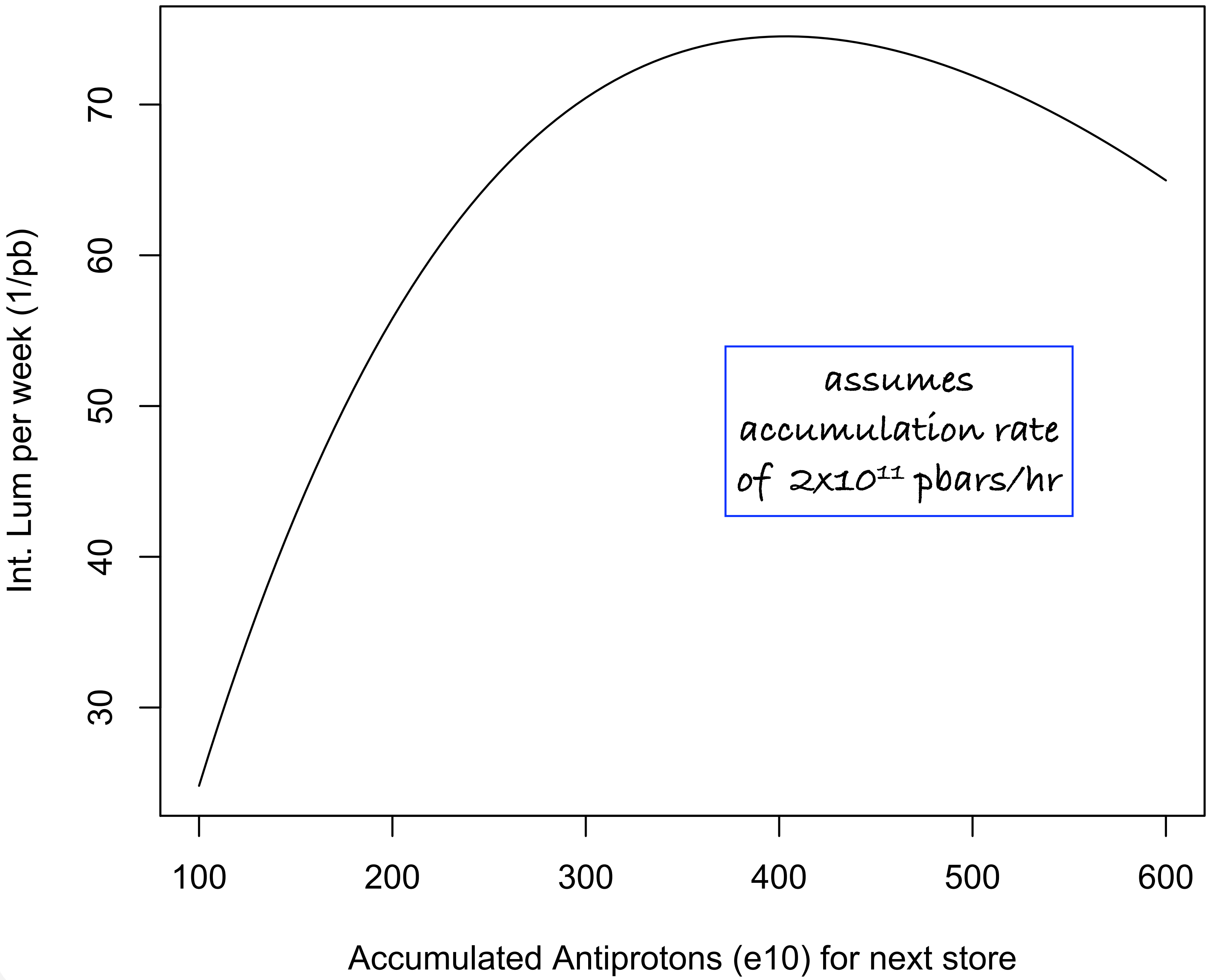


Optimization of Integrated Luminosity

- The ultimate goal for the accelerator -- provide largest total number of collisions possible
- So, optimize initial luminosity, according to turn-around time, emittance growth rates, etc. to produce most integrated luminosity per week (say)
  - example: recent Tevatron running

Luminosity Optimization



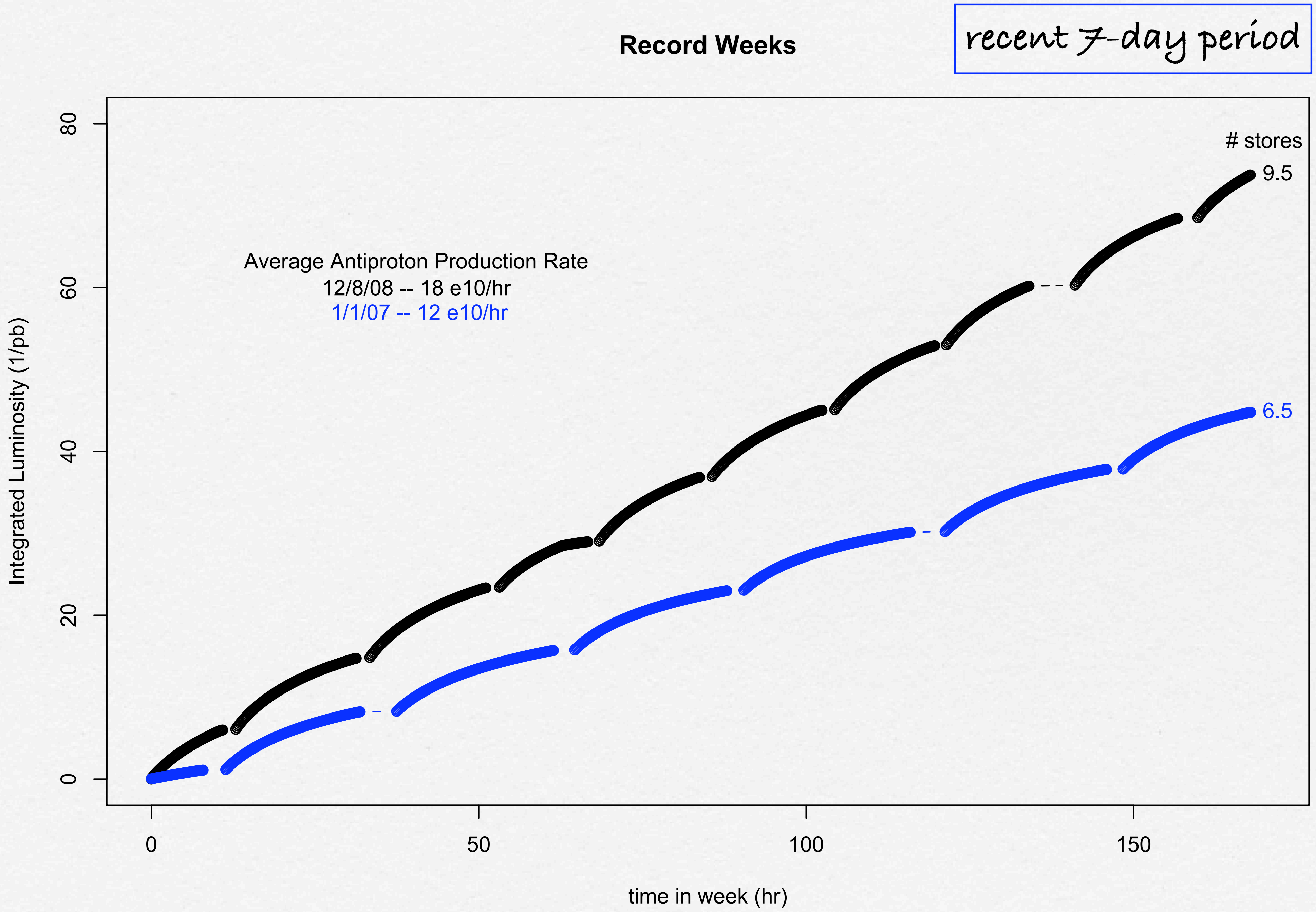


assumes accumulation rate of 2x10^{11} pbars/hr

☐ For Tevatron, balance rate at which integrate luminosity against the rate at which we can produce antiprotons

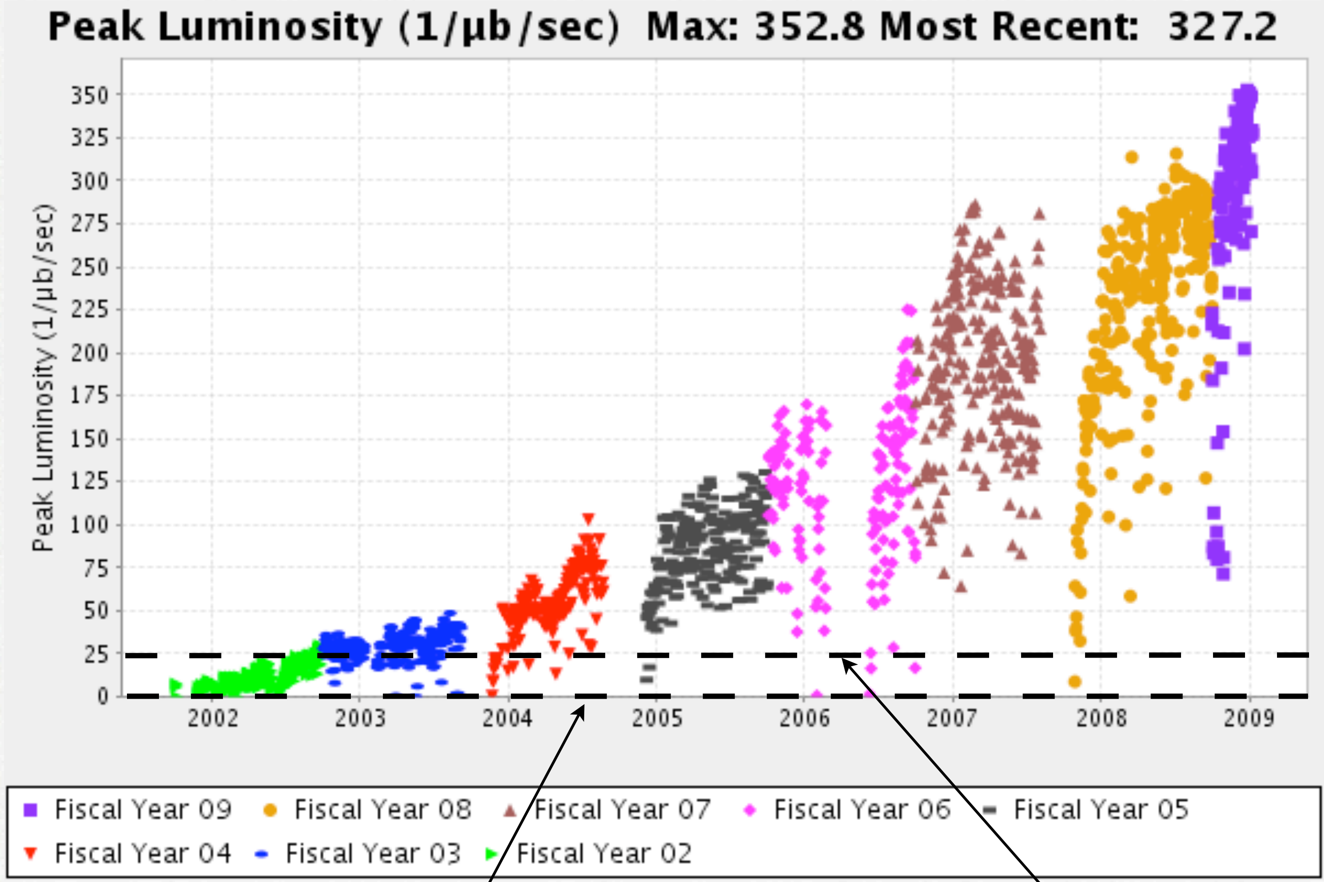
Tevatron Operation

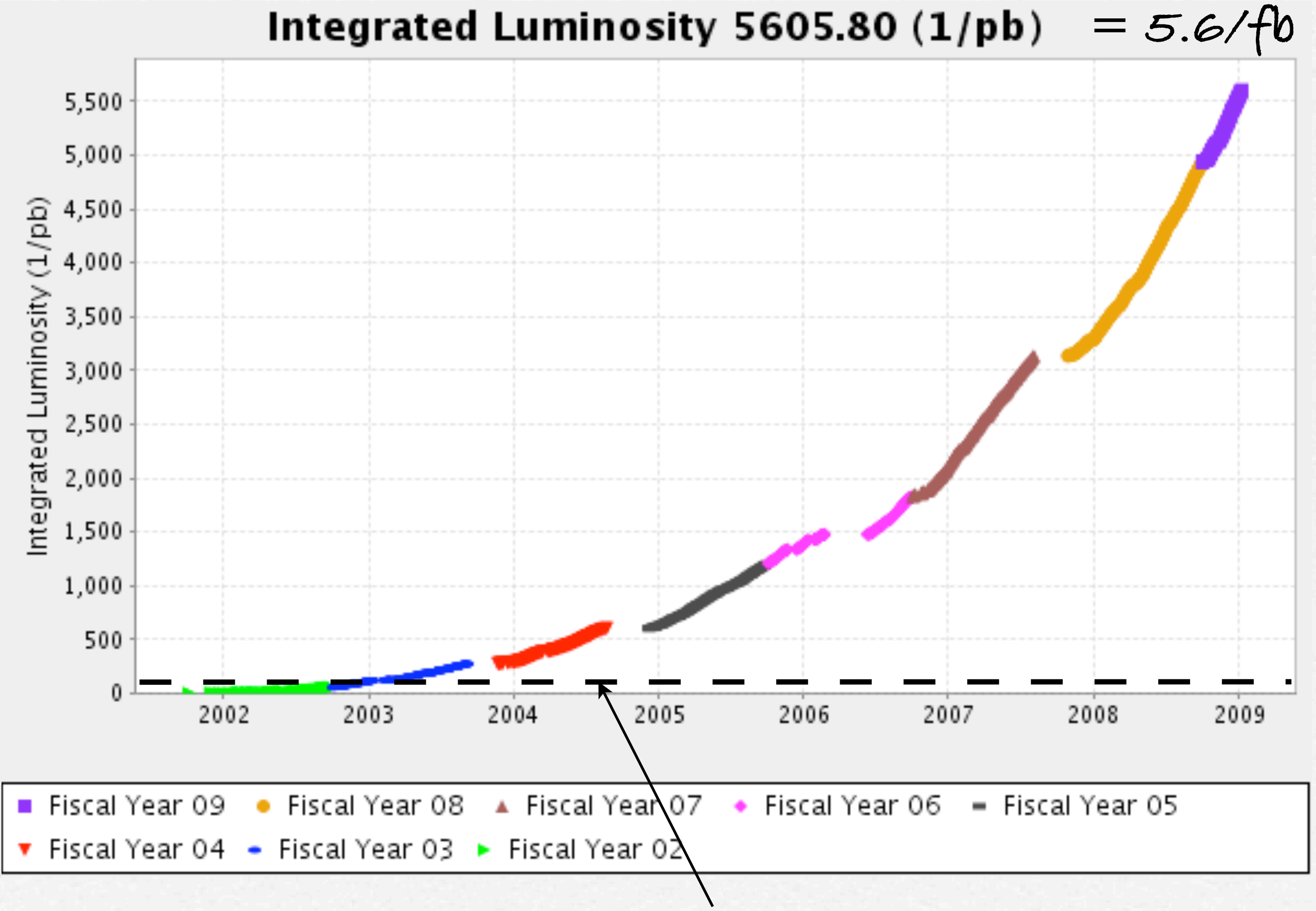
Here, need to balance the above with the production rate of antiprotons to find optimum running conditions



Tevatron Performance

- E_{cm} = **1.96 TeV**; operating >***350 times*** original design luminosity
- Upgrades since 1986 --
  - Linac upgrade; new Main Injector; Interaction Region magnets; improved magnet cooling; more bunches (6 -> 36); “Recycler” (antiproton storage); electron cooling; new stochastic cooling systems; new Beam Position Monitoring systems, other diagnostics; much maintenance -- alignment, magnet fixes, etc.; much more ...





= 5.6/fb

Tevatron I design goal (1/μb/s)
(Eng. run, 1980’s)

best achieved in Run I (25/μb/s)
(5/92 - 2/96)

Final level reached in Run I (~100/pb)
(5/92 - 2/96)

Integrating Luminosity at LHC

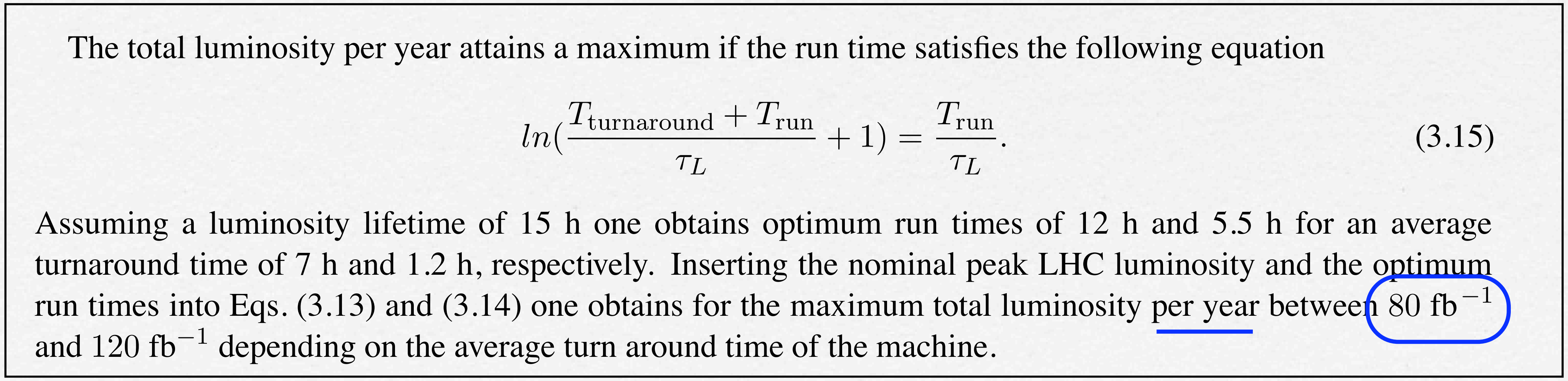
☐ For LHC, protons are readily available; beams are designed to be of equal intensity

☐ So, will balance the decay of luminosity...

$$\mathcal{L}(t) = \frac{\mathcal{L}_0}{\left[1+\left(\frac{n\mathcal{L}_0\Sigma}{BN_0}\right)t\right]^2}\cdot\mathcal{F}(t)$$

☐ ... against the time it takes to regenerate initial conditions, beam growth rates and loss mechanisms, etc.

From LHC Design Report:



The total luminosity per year attains a maximum if the run time satisfies the following equation

$$ln\left(\frac{T_{\rm turnaround}+T_{\rm run}}{\tau_L}+1\right) = \frac{T_{\rm run}}{\tau_L}. \tag{3.15}$$

Assuming a luminosity lifetime of 15 h one obtains optimum run times of 12 h and 5.5 h for an average turnaround time of 7 h and 1.2 h, respectively. Inserting the nominal peak LHC luminosity and the optimum run times into Eqs. (3.13) and (3.14) one obtains for the maximum total luminosity per year between 80 fb^{-1} and 120 fb^{-1} depending on the average turn around time of the machine.

What’s been left out?

- ☐ Lots…
  - synchrotron radiation
  - Coupling of degrees-of-freedom transverse x/y, trans. to longitudinal
  - Space charge interactions (mostly low-energies)
  - Wake fields, impedance, coherent instabilities
  - Beam cooling techniques
  - RF manipulations
  - Resonant extraction
  - Crystal collimation
  - Magnet, cavity design
  - Beam Instrumentation and diagnostics
  - much more…

Further Schooling...

- ☐ US Particle Accelerator School:
  - http://uspas.fnal.gov
  - Twice yearly, January / June

- ☐ CERN Accelerator School:
  - http://cas.web.cern.ch
    - Spring (specialized topics)
    - autumn (intro/intermediate)

email: *syphers@fnal.gov*

Further Reading

- ☐ D. A. Edwards and M. J. Syphers, An Introduction to the Physics of High Energy Accelerators, John Wiley & Sons (1993)
- ☐ S. Y. Lee, Accelerator Physics, World Scientific (1999)
- ☐ E. J. N. Wilson, An Introduction to Particle Accelerators, Oxford University Press (2001)

and many others...

- ☐ Conference Proceedings --
  - Particle Accelerator Conference (2007, 2005, ...)
  - European Particle Accelerator Conference (2006, 2004, ...)
  - Asian Particle Accelerator Conference (2007, 2004, ...)