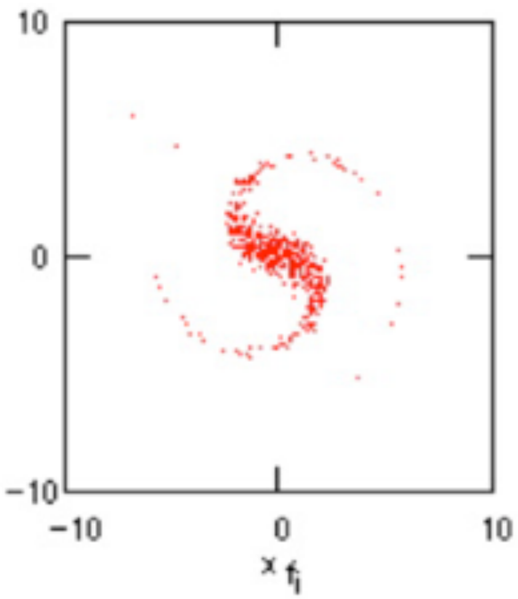
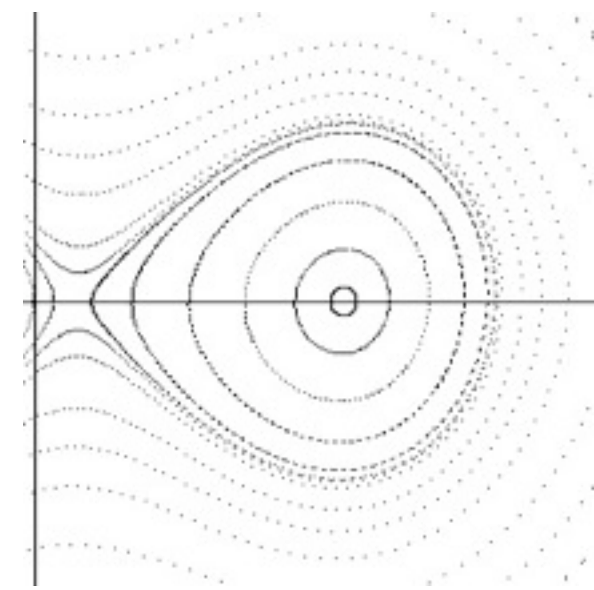
Hadron Collider Physics
Summer School 2012

syphers@msu.edu

An Introduction to Hadron Colliders

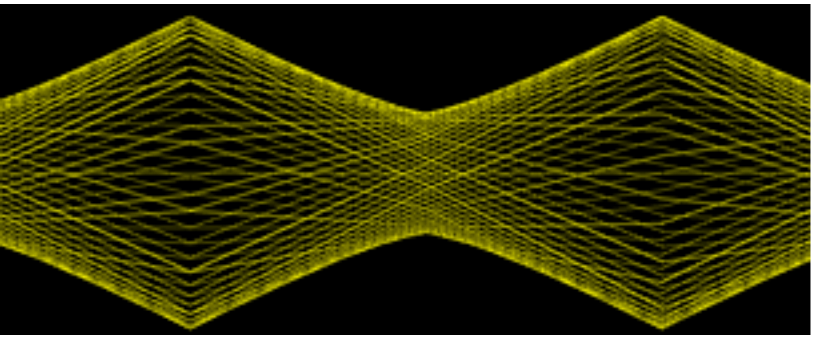
Lecture 3

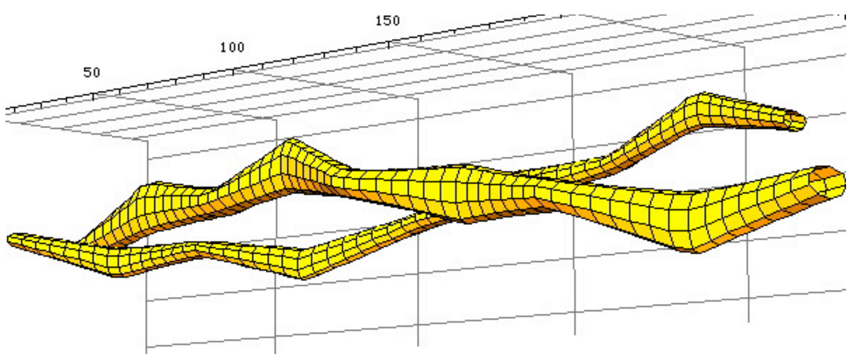




Mike Syphers

Michigan State University





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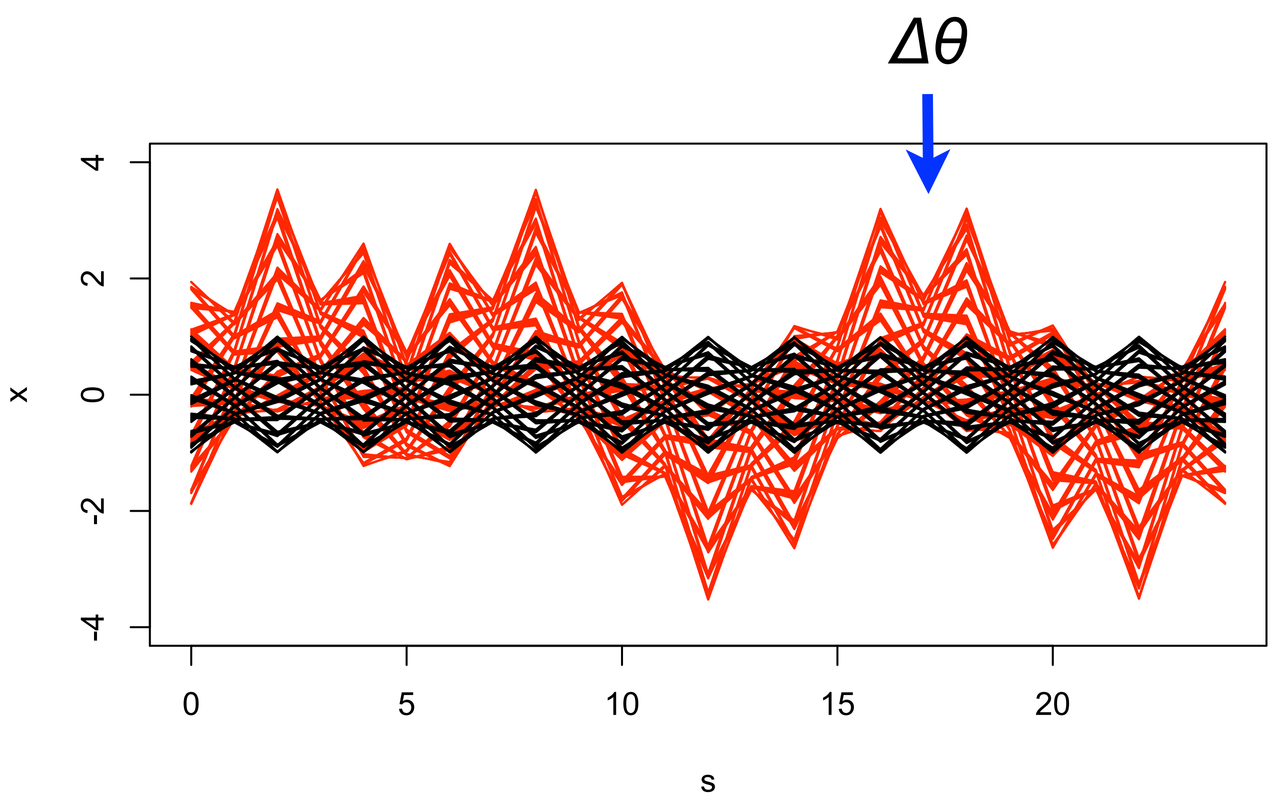
Corrections and Adjustments

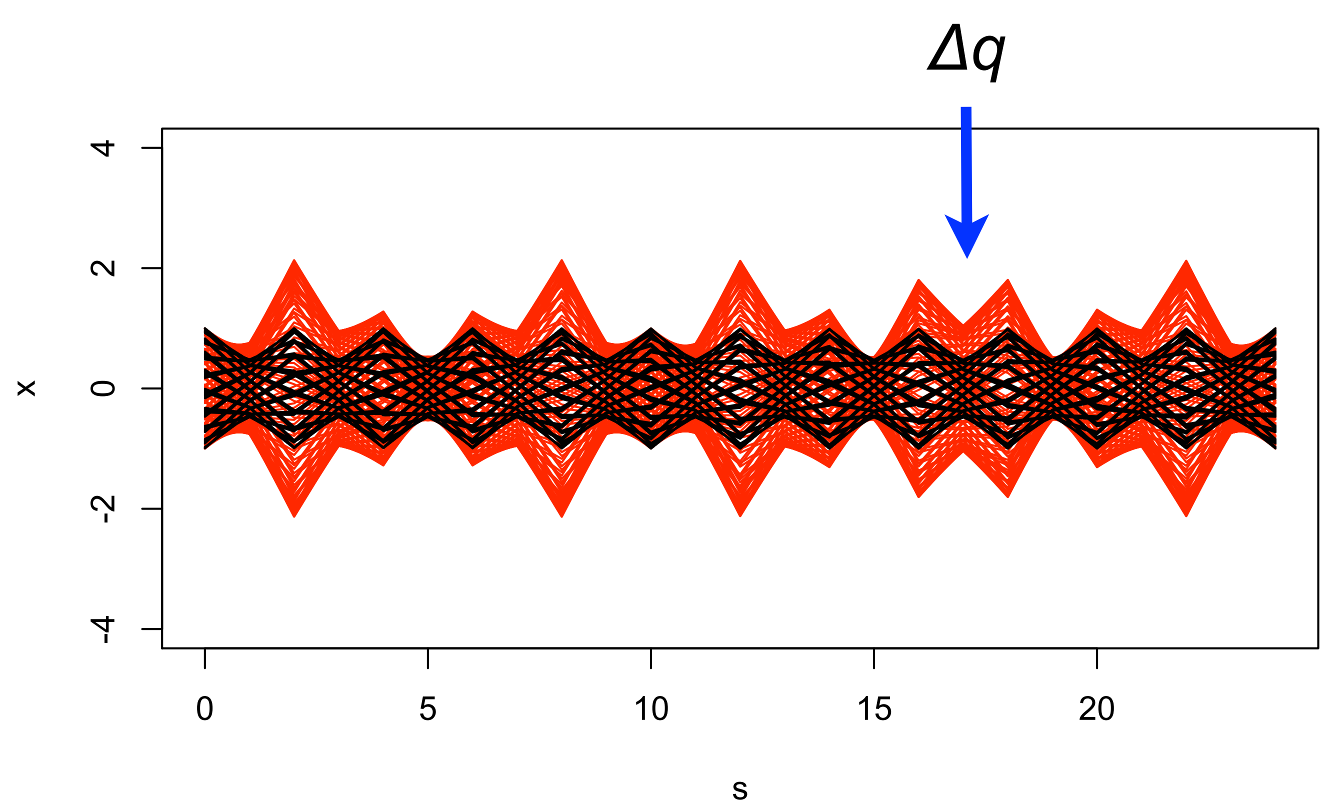
- Correction/adjustment systems required for fine control of accelerator:
  - correct for misalignment, construction errors, drift, etc.
  - adjust operational conditions, tune up
- Use smaller magnetic elements for "fine tuning" of accelerator
  - dipole steering magnets for orbit/trajectory adjustment
  - quadrupole correctors for tune adjustment
  - sextupole magnets for chromaticity adjustment

- Typically, place correctors and instrumentation near the major quadrupole magnets -- "corrector package"
  - control steering, tunes, chromaticity, etc.
  - monitor beam position (in particular), intensity, losses, etc.

Linear Distortions



Orbit distortion due to single dipole field error



Envelope Error (Beta-beat) due to gradient error

gradient error also generates a shift in the betatron tunes...

$$\Delta\nu = \frac{1}{4\pi}\beta_0 \Delta q$$

Resonances and Tune Space

- Error fields are encountered repeatedly each revolution -- can be resonant with tune

  - repeated encounter with a steering (dipole) error produces an orbit distortion:

$$\Delta x \sim \frac{1}{\sin \pi\nu}$$

    - » thus, avoid integer tunes

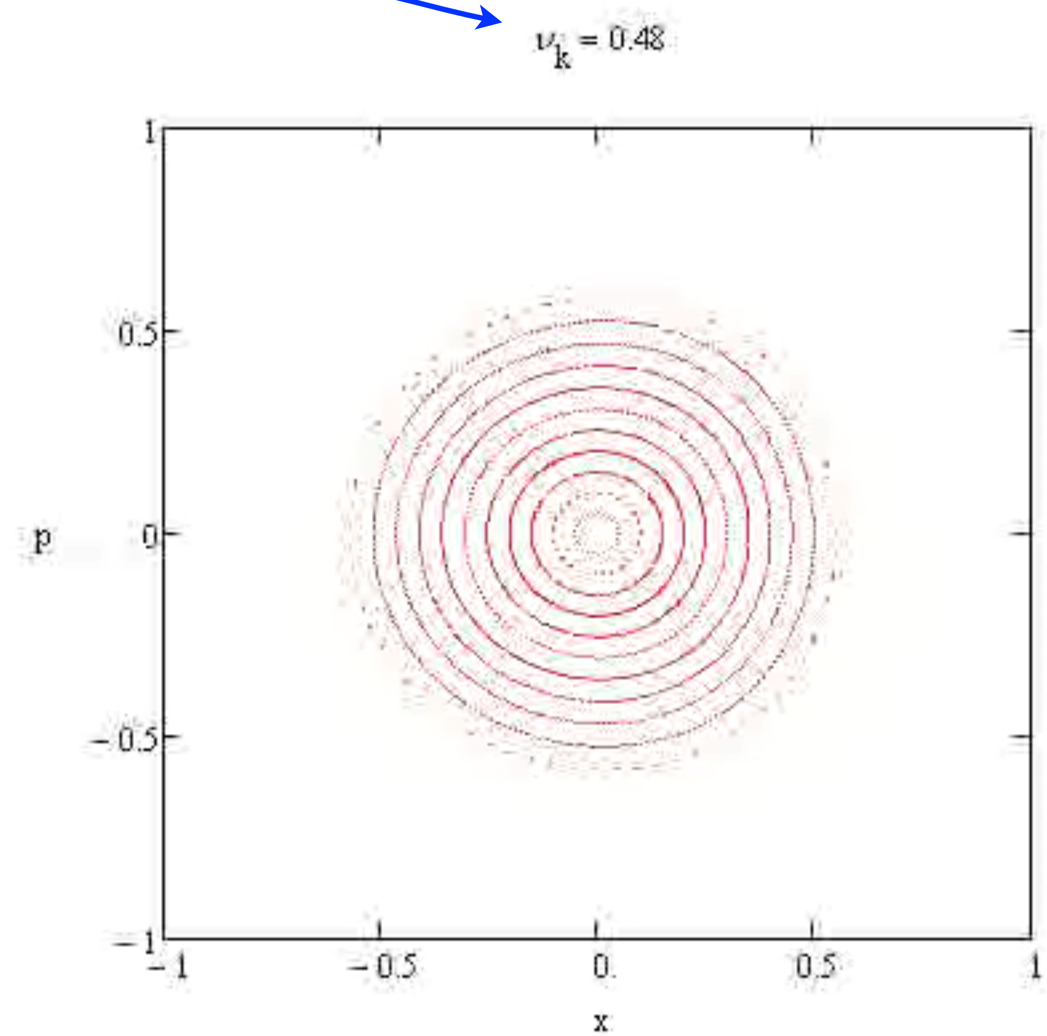
  - repeated encounter with a focusing (quad) error produces distortion of amplitude function:

$$\Delta\beta/\beta \sim \frac{1}{\sin 2\pi\nu}$$

    - » thus, avoid half-integer tunes

Nonlinear Resonances

- Phase space w/ sextupole field present ($B_y \sim x^2$)
  - tune dependent:
  - "dynamic aperture"



- Thus, avoid tune values:
  - k, $k/2$, $k/3$, ...

Tune Diagram

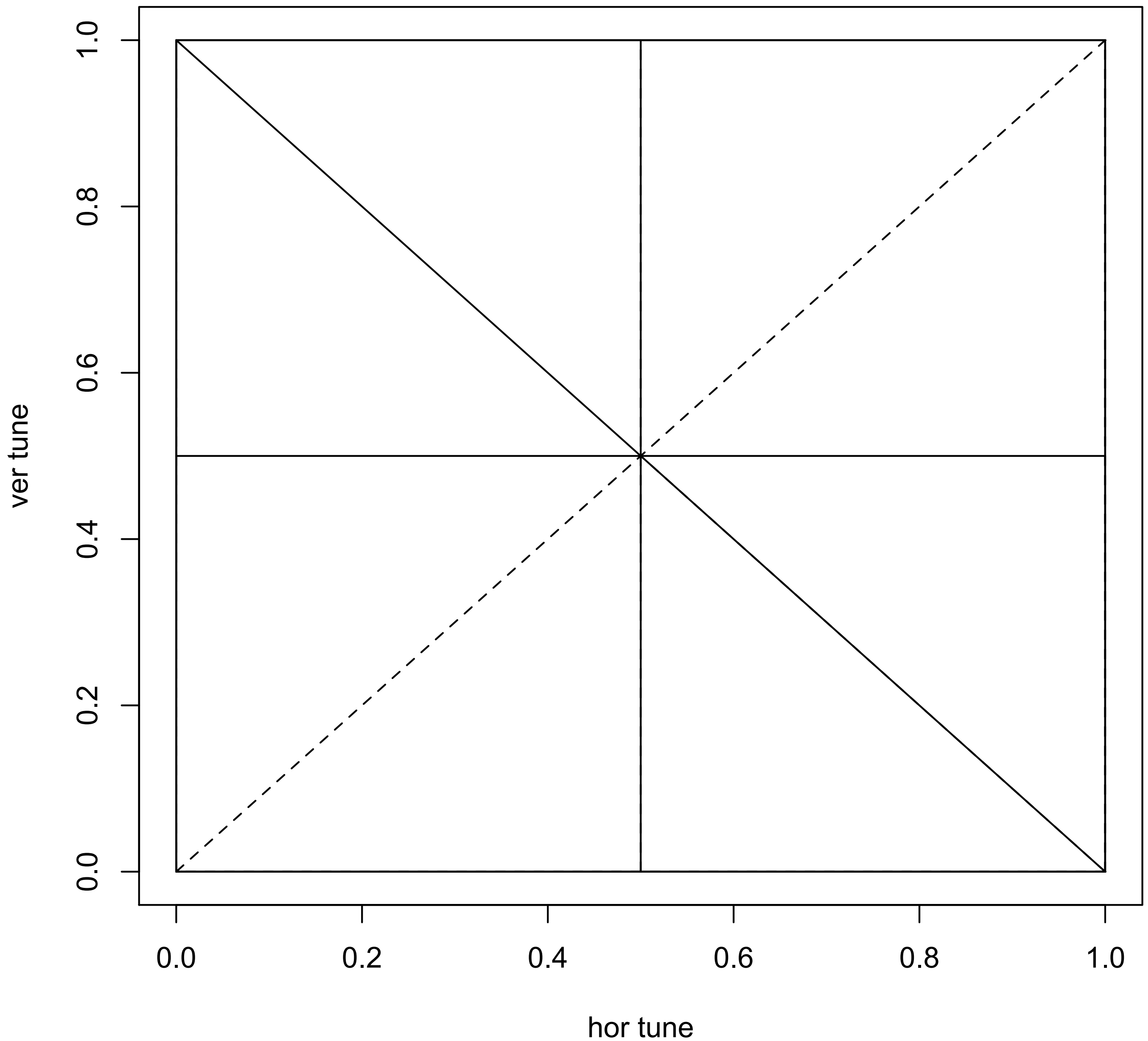
- Always "error fields" in the real accelerator

- Coupled motion also generates resonances (sum/difference resonances)
  - in general, should avoid: $$m\,\nu_x \pm n\,\nu_y = k$$

avoid ALL rational tunes???

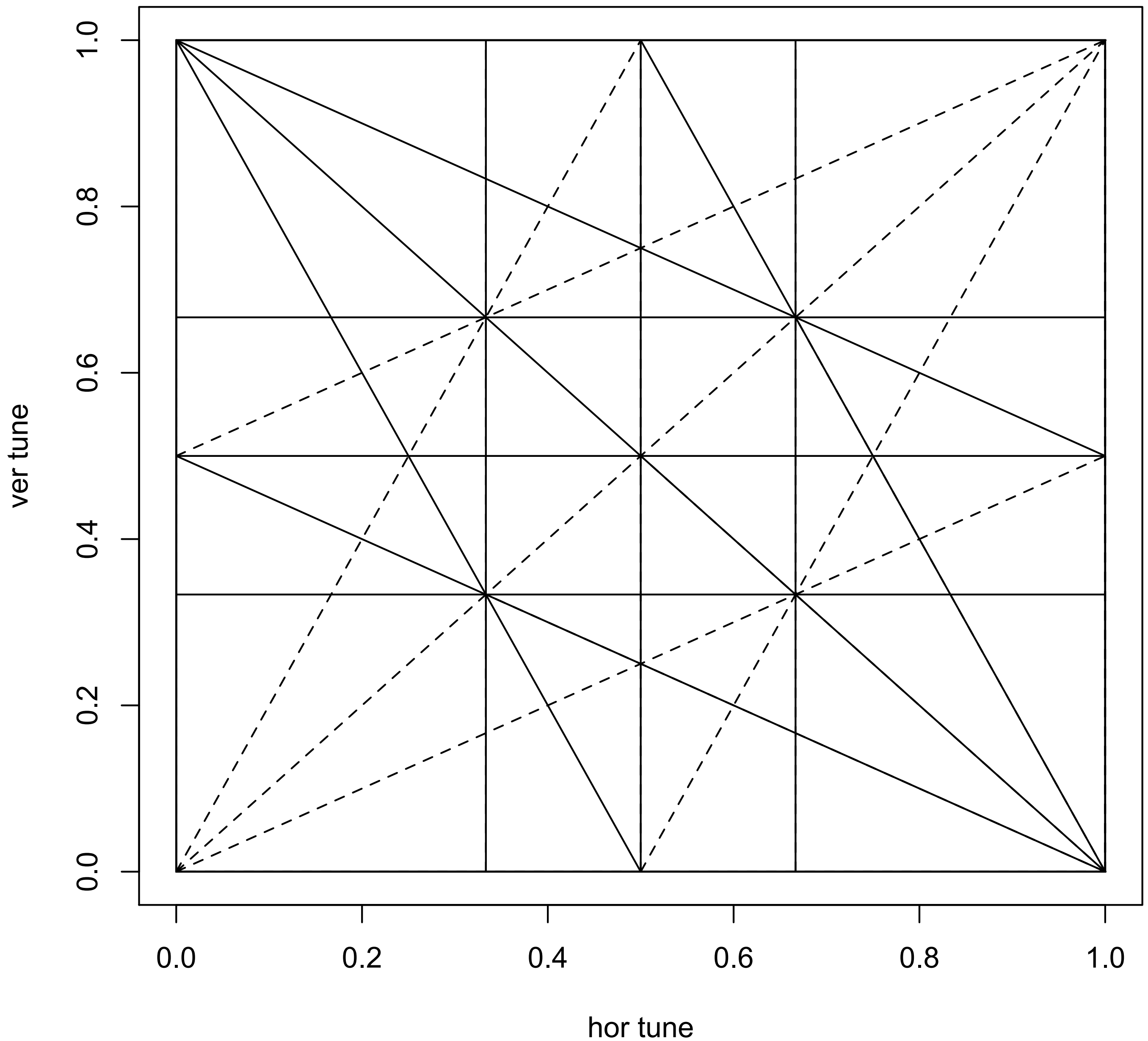
Tune Diagram

Through order
k =2



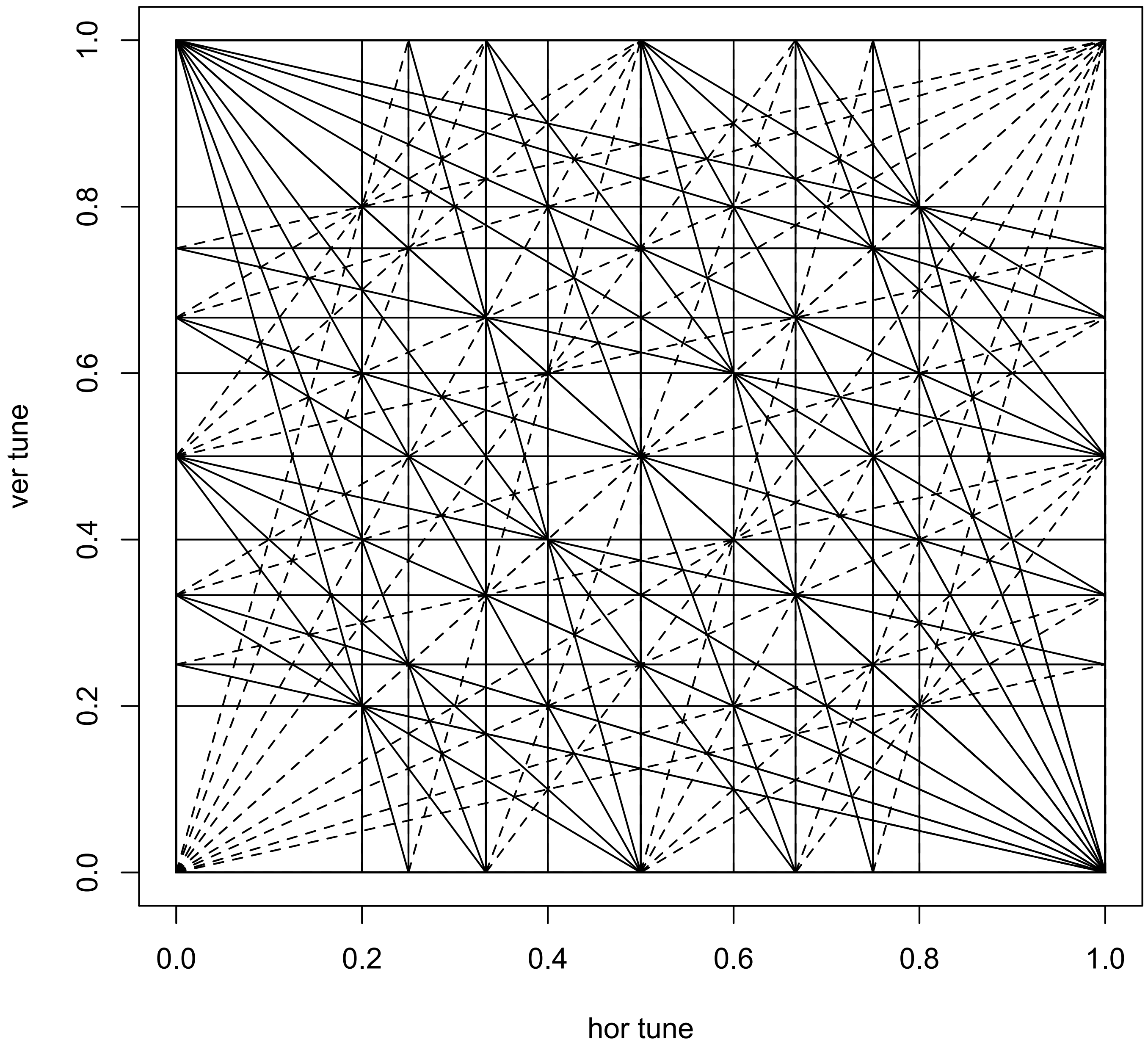
Tune Diagram

Through order
k =3

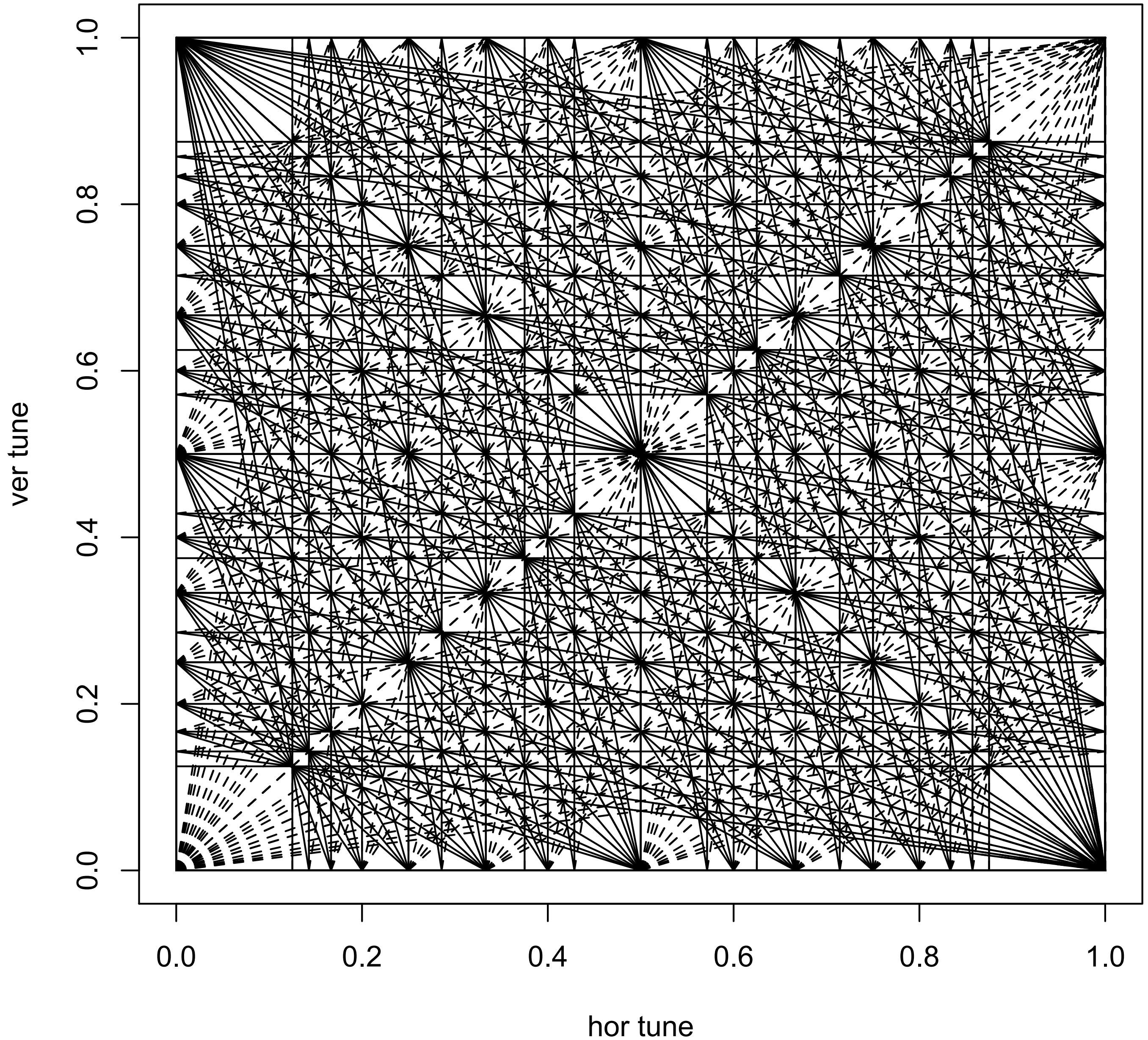


Tune Diagram

Through order k =5

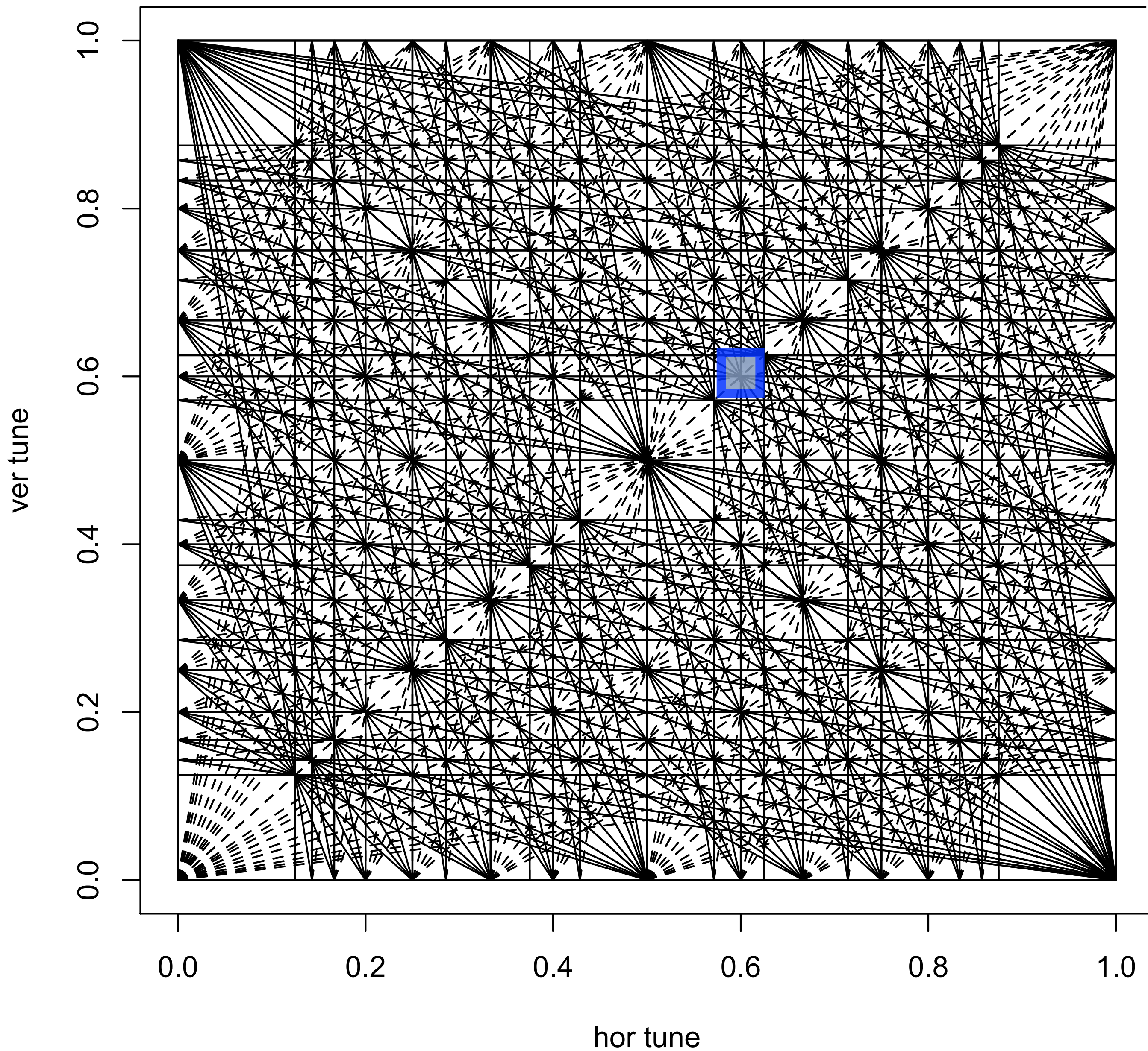


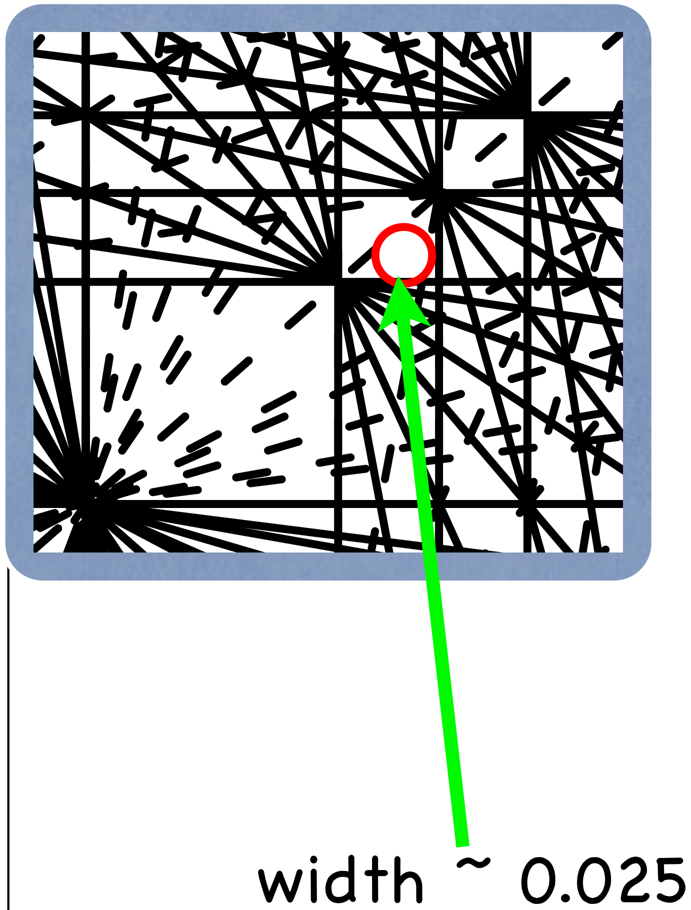
Tune Diagram



Through order
k =8

Tune Diagram

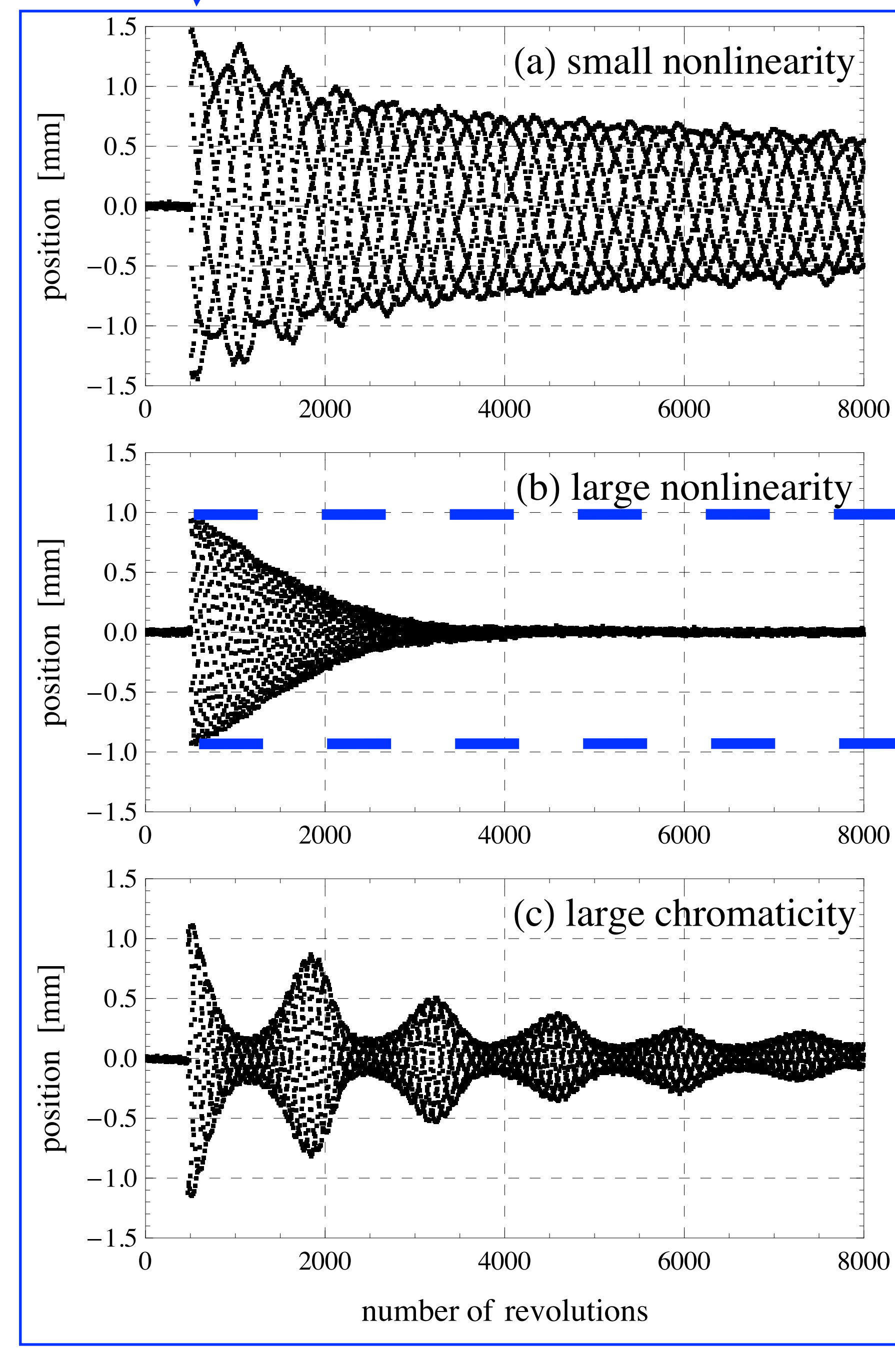




"Measuring" Nonlinearity, Tune Spread

- tune spread due to momentum/chromaticity
  - "natural" chromaticity due to particle rigidity
  - also, due to field errors in magnets ~ x^2 when in the presence of Dispersion
- tune spread due to nonlinear fields
  - field terms ~ x^2, x^3, etc. can be present around the synchrotron
- result: a "decoherence" of beam position signal at transverse position monitors

"kick" the beam



Beam-Beam Force

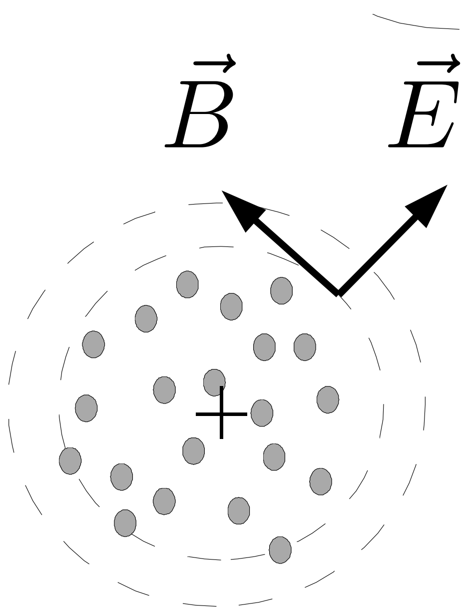
- As particle beams "collide" (very few particles actually "interact" each passage), the fields on one beam affect the particles in the other beam. This "beam-beam" force can be significant.
- On-coming beam can act as a "lens" on the particles, thus changing focusing characteristics of the synchrotron, tunes, etc.

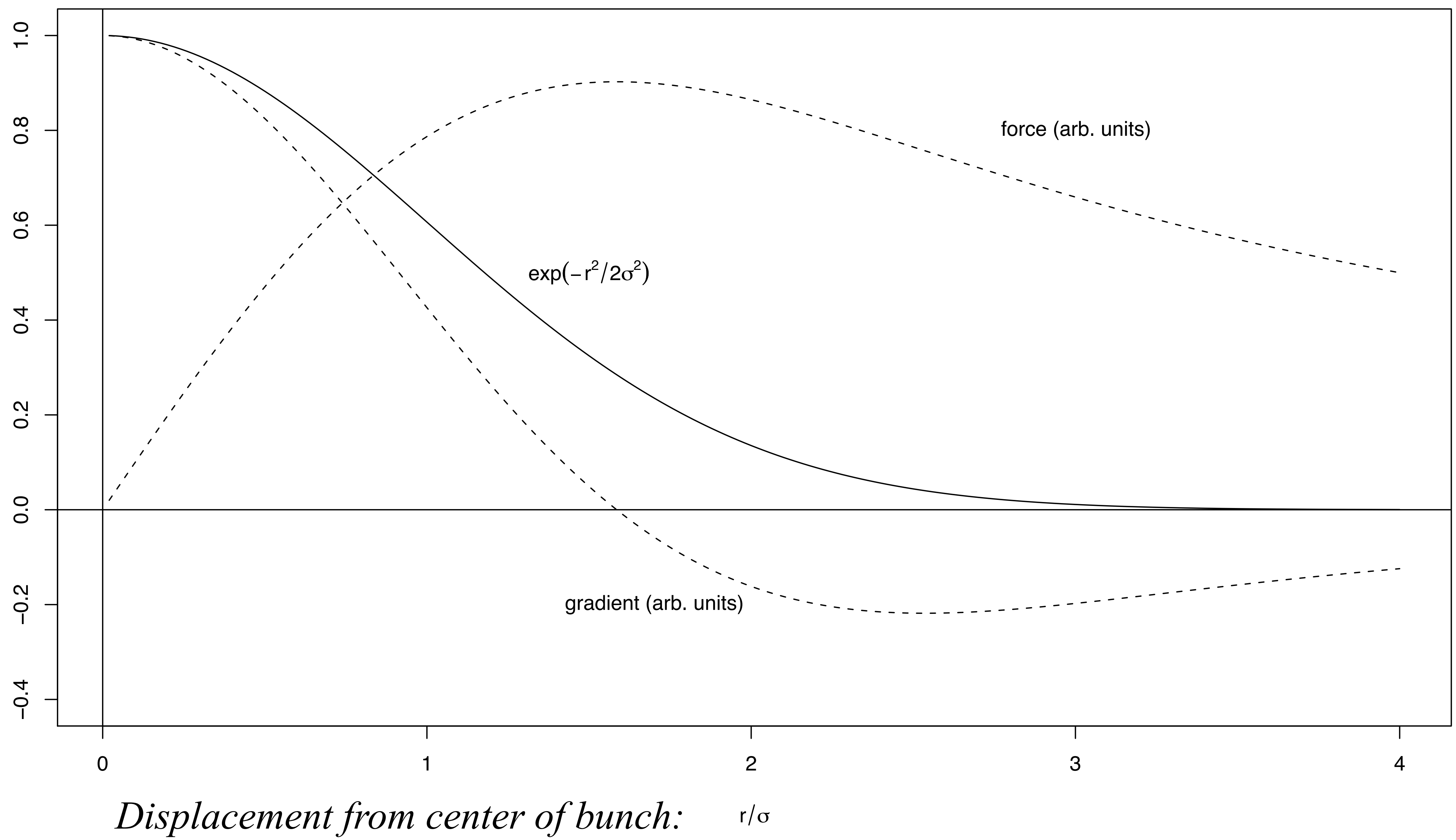
$$\text{Force} \propto \frac{1 - e^{-x^2/2\sigma^2}}{x} \approx \frac{x}{2\sigma^2}$$, for small x; ~ 1/*x* for large x

- Head-On: core sees ~ linear force; rest of beam, nonlinear force --> tune spread, nonlinear resonances, etc.
- Long-Range: force ~ 1/*separation* --> for large enough separation, mostly coherent across the bunch, but still some nonlinearity
- Bunch structure (train) means some bunches will experience different effects, increasing the tune spread, etc., of the total beam

The Beam-Beam Force

- Force, and its derivative (gradient), vary with position
  - $\partial B_y/\partial_x$ at particle's typical amplitude determines its oscillation frequency ...
    - » "beam-beam tune shift"





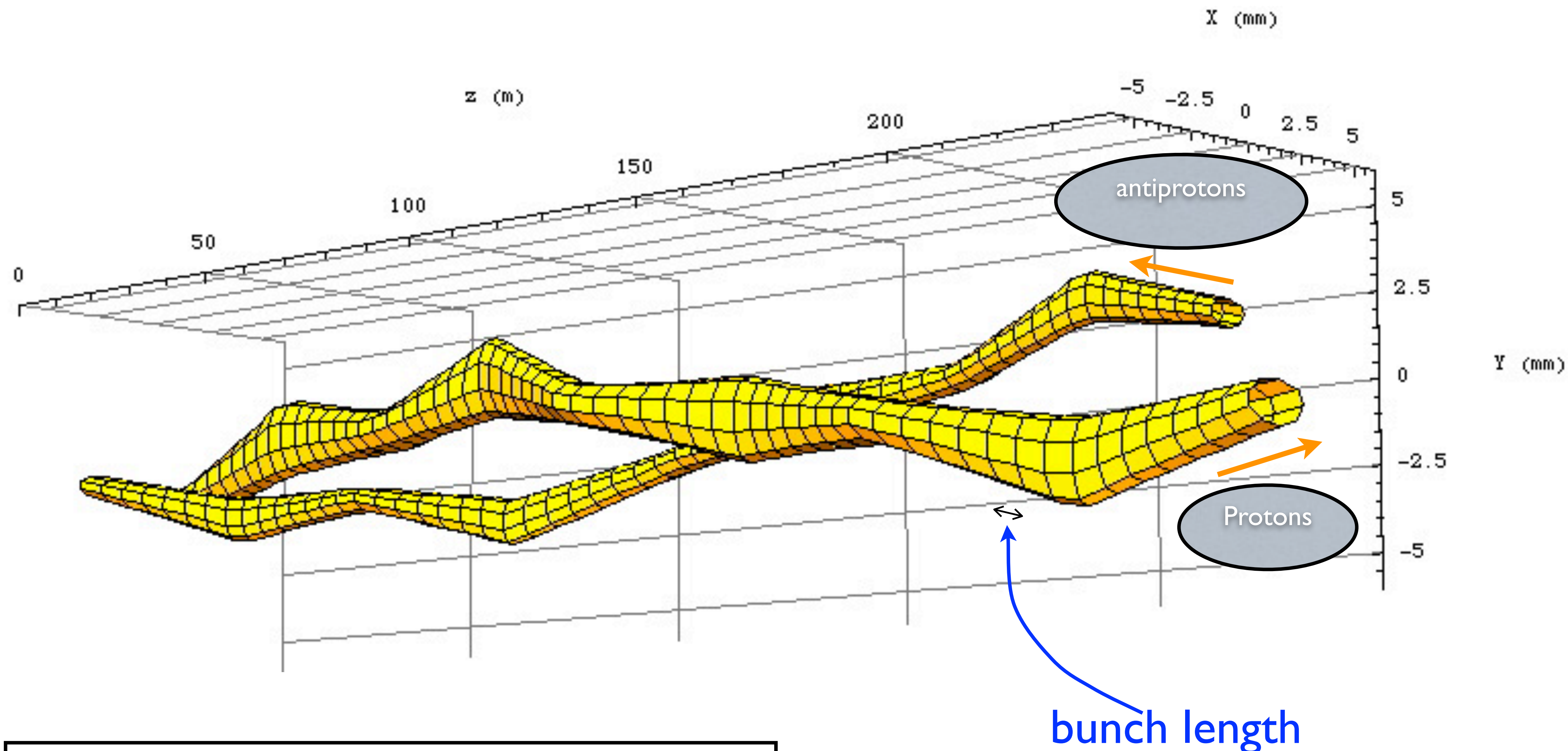
Different amplitude particles will have different "tunes"

Beam-Beam Mitigation

- Beams are "separated" (if not in separate rings of magnets) by electrostatic fields so that the bunches interact only at the detectors

  - "Pretzel" or "helical" orbits separate the beams around the ring
  - However, the "long-range" interactions can still affect performance
  - "electron lenses" and current-carrying wires can be employed which can mitigate the effects of beam-beam interactions, both head-on and long-range

Tevatron: 2 Beams in 1 Pipe

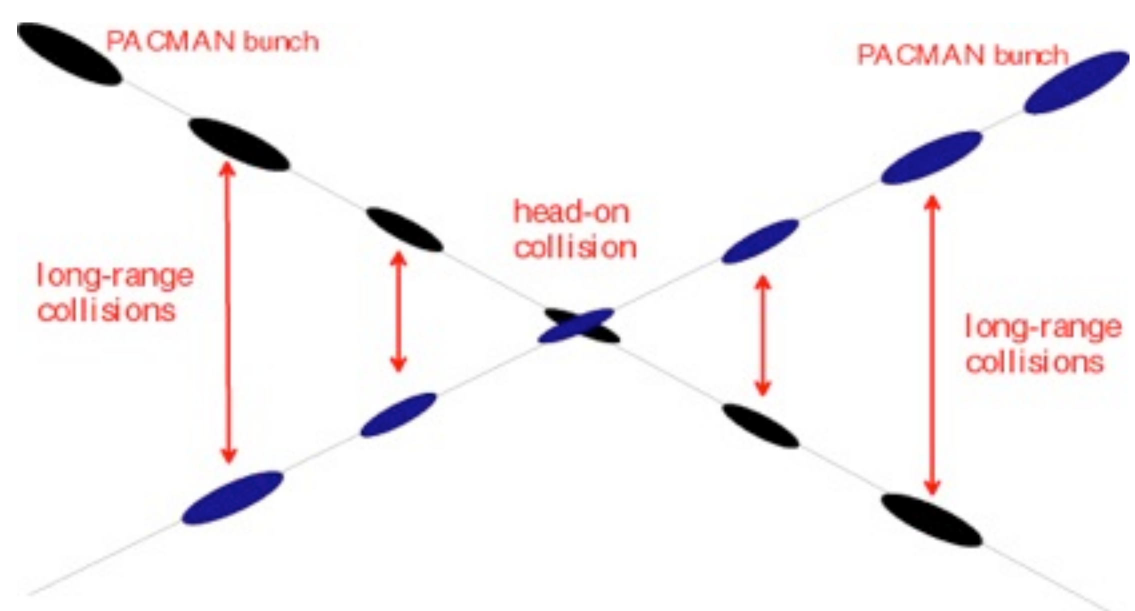


Helical orbits through 4 standard arc cells of the Tevatron

LHC: 2 Beams in 2 Pipes

- Across each interaction region, for about 120 m, the two beams are contained in the same beam pipe
- This would give ~ 30 bunch interactions through the region
- Want a single head-on collision ***at*** the 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

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



Emittance Control

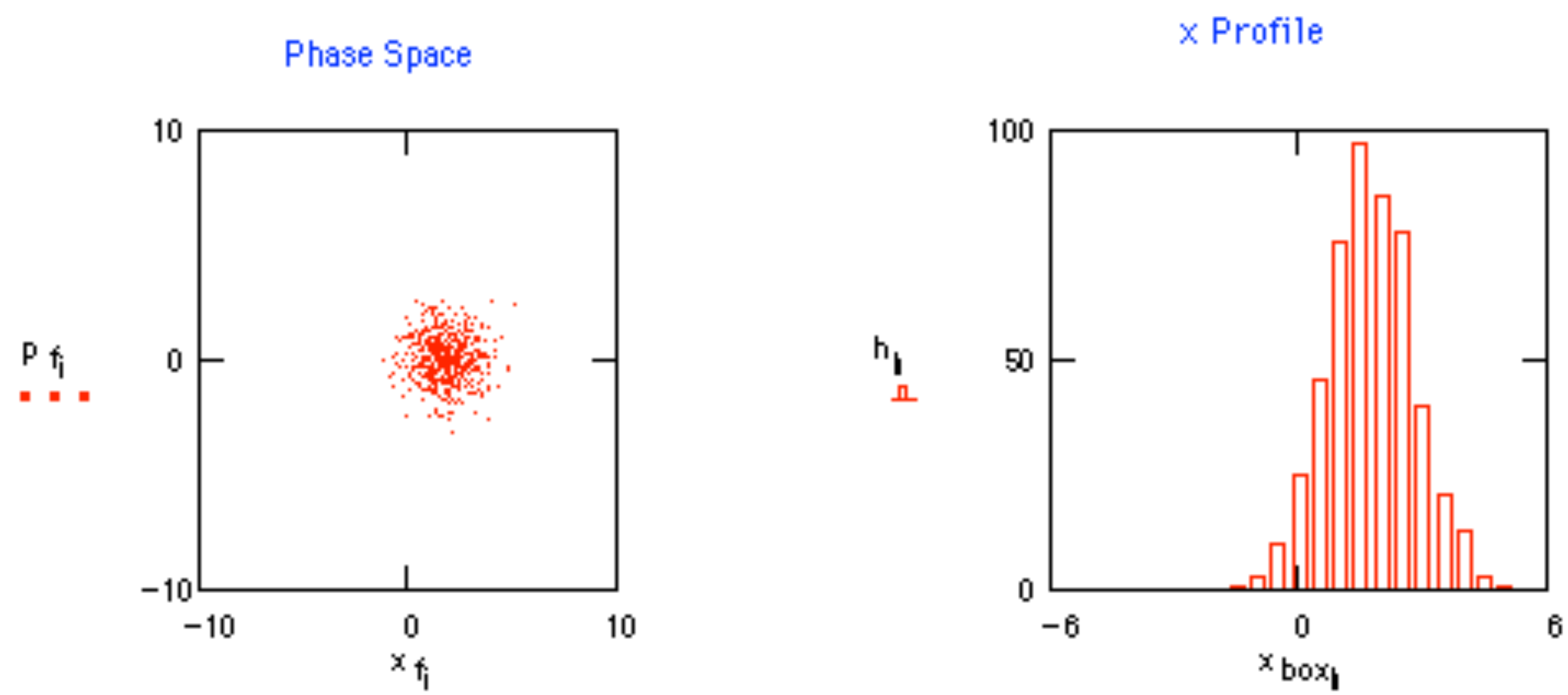
- Electrons radiate extensively at high energies; combined with energy replenishment from RF system, small equilibrium emittances result
  - in Hadron Colliders; emittance at collision energy determined by proton source, and its control through the injectors

- larger emittance -- smaller luminosity

- larger emittance growth rates during collisions result in particle loss
  - thus, lower integrated luminosity

Injection Errors

- Emittance growth from trajectory errors at injection -- more sensitive at higher energy injection (beam size is smaller)
- Similarly, energy/ phase mismatch at injection (injection into "center" of buckets)
- damper systems
  - fast corrections of turn-by-turn trajectory
  - correct offsets before "decoherence" sets in



mean(x_f) = 1.985   stdev(x_f) = 1.039

Emittance Increase: $\mathrm{stdev}(x_f)^2 = 1.08$

Predicted "typical" values:

(Steering Mismatch) $1 + \frac{1}{2}\cdot\Delta x^2 = 3$

FRAME = 0   (Amplitude function Mismatch) $\frac{r_\beta^2 + 1}{2\cdot r_\beta} = 1$

Diffusion

- Random sources (power supply noise; beam-gas scattering in vacuum tube; ground motion) will alter the oscillation amplitudes of individual particles

  - in simplest cases will grow like $\sqrt{N}$, amplitudes of the particle oscillations will eventually reach the limiting aperture

- Thus, beam lifetime will develop, affecting beam intensity, emittance, and thus luminosity

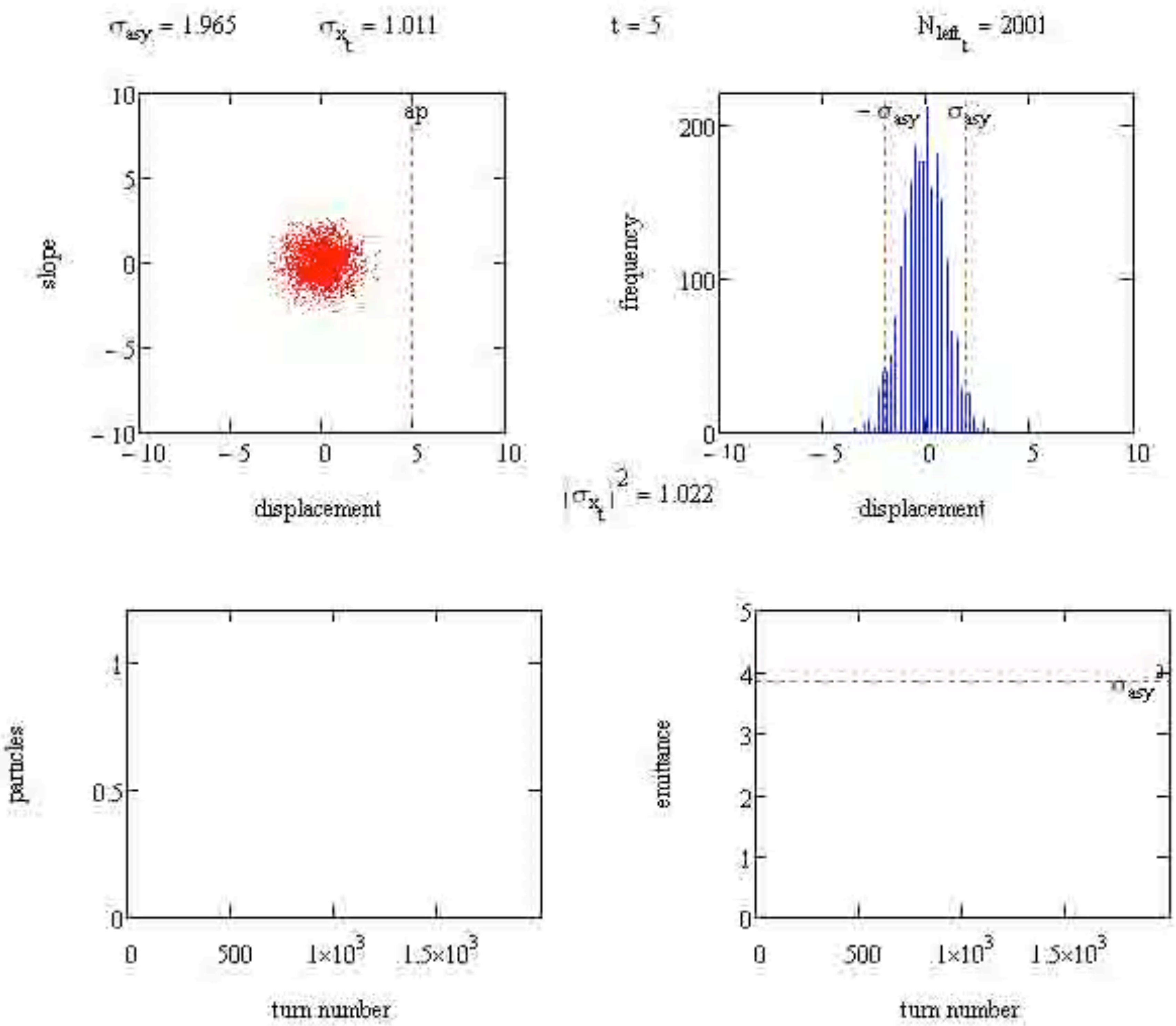
Diffusion Example

Phase Space

Beam Profile

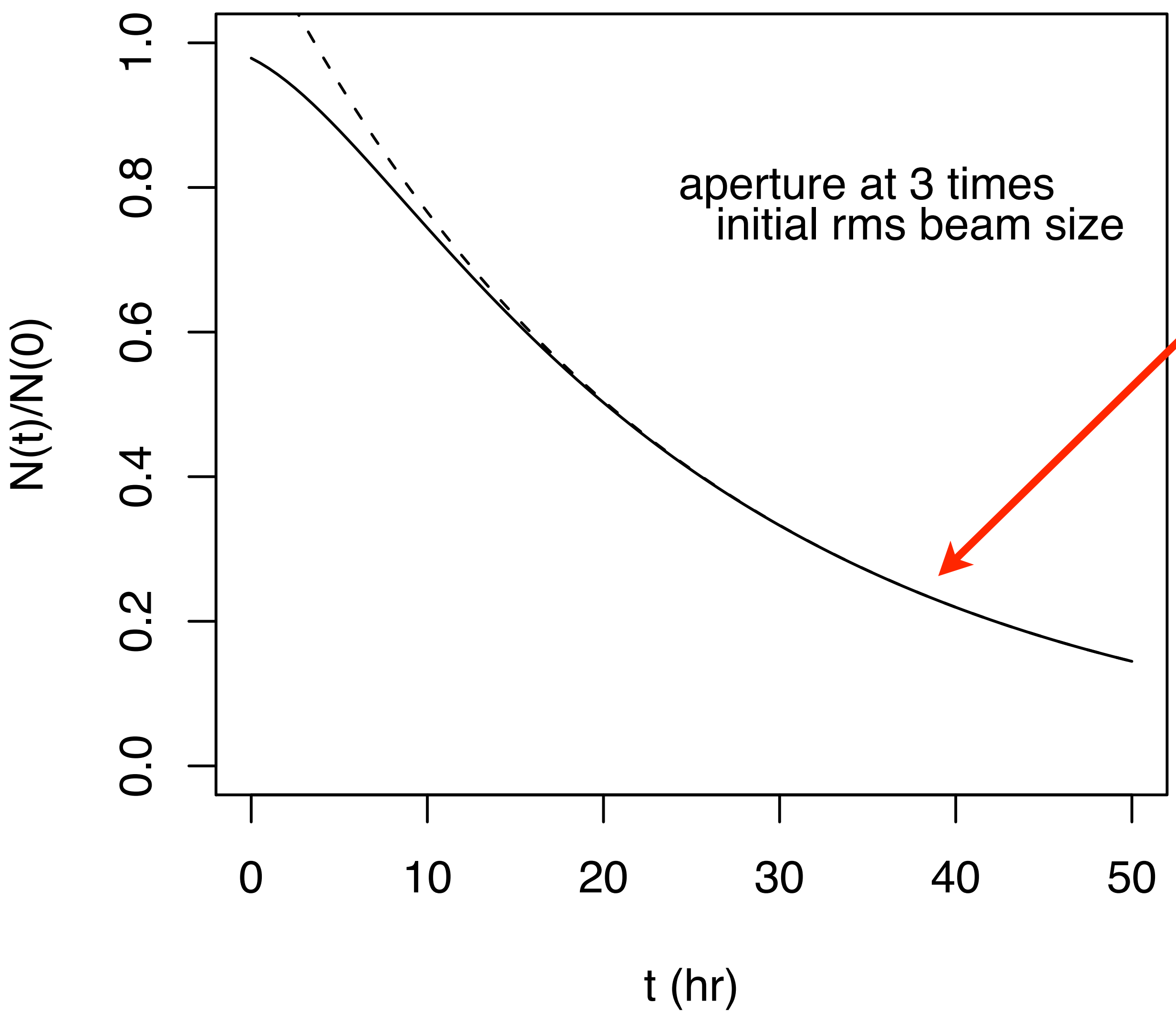
Beam Intensity

Beam Emittance



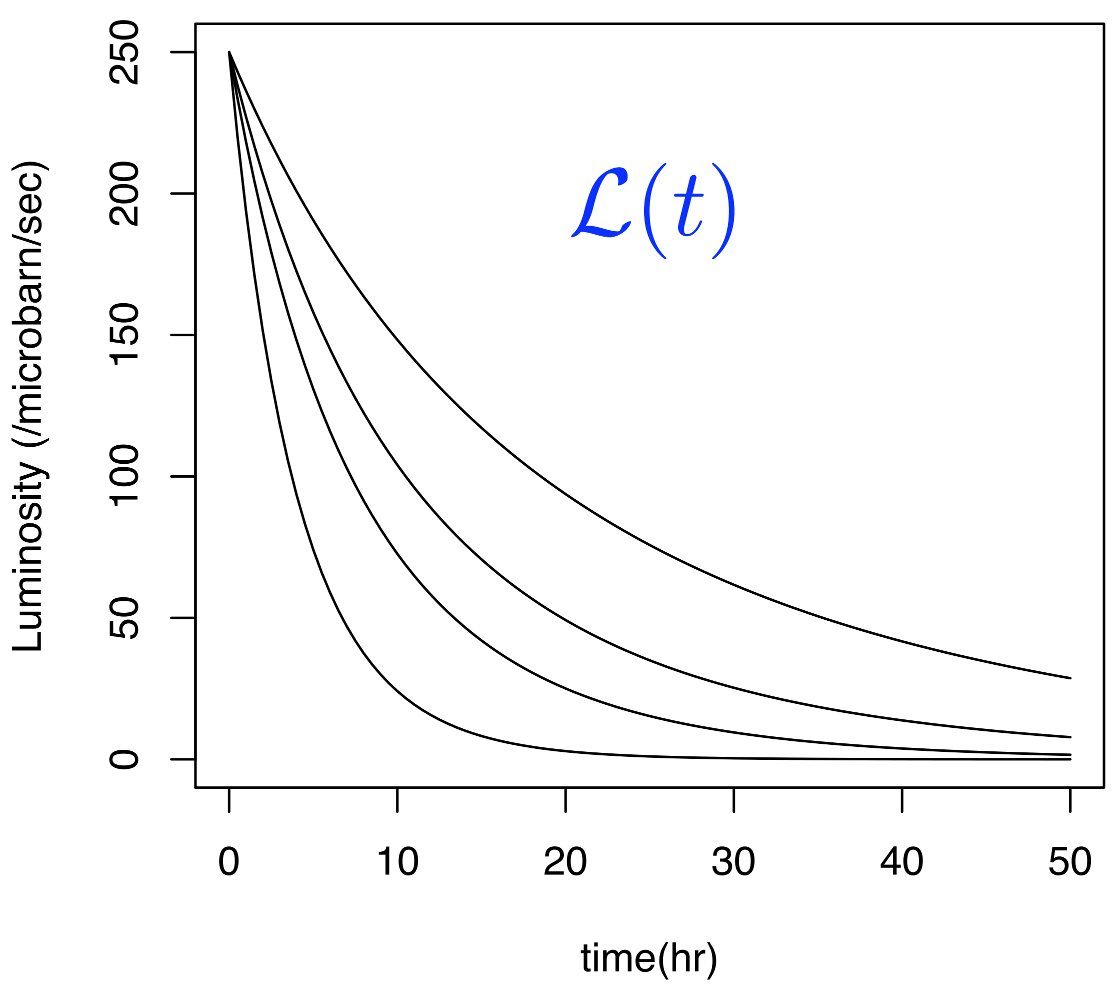
Effects on Luminosity ...

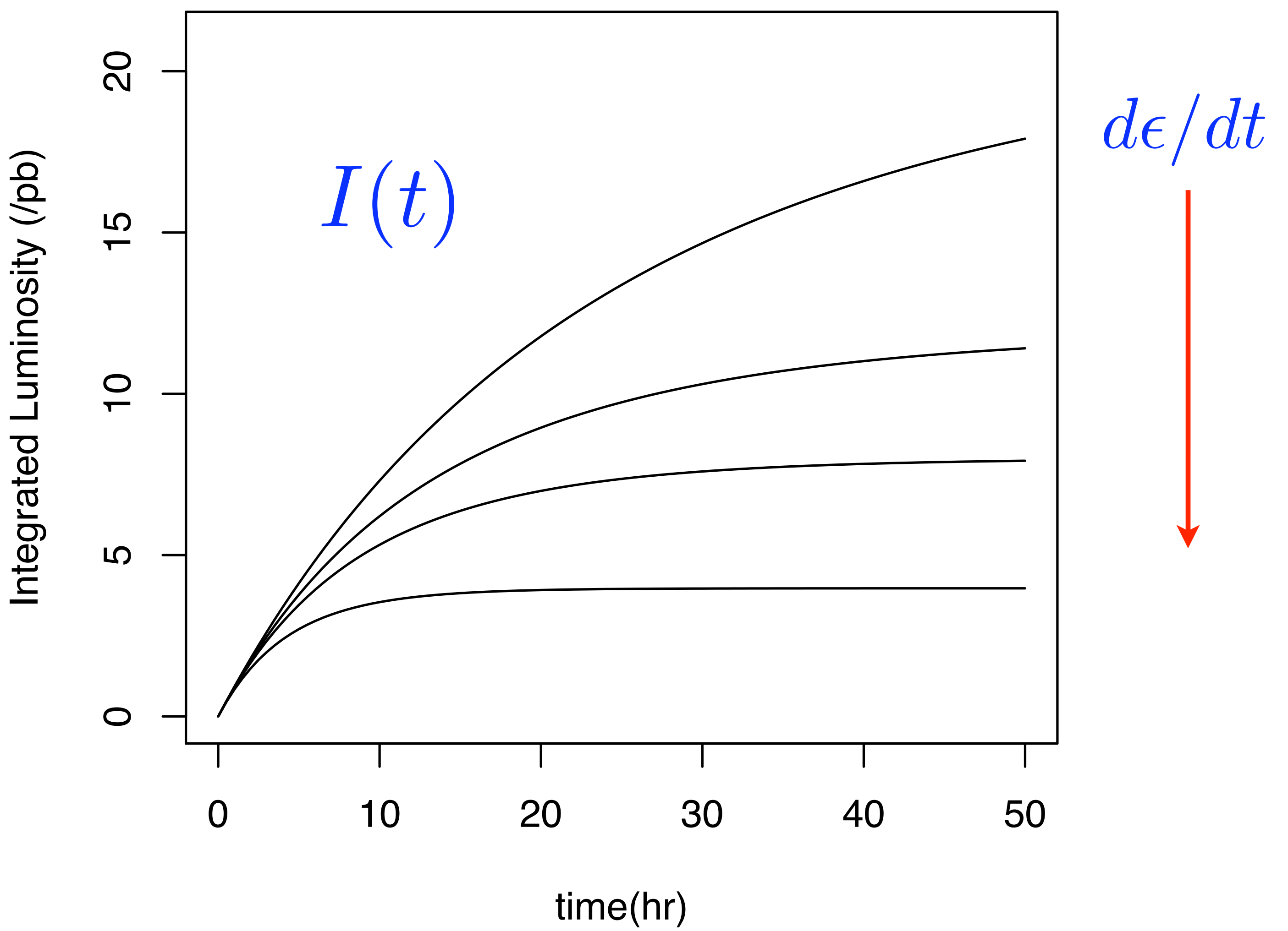
- Diffusion of transverse particle amplitudes leads to beam loss at locations other than at the IP
- In absence of luminosity interactions, beam attains an equilibrium lifetime
  - if beam initially nearly fills the aperture, this lifetime is achieved early



$$\tau = \frac{2a^2}{\lambda_1^2 d\langle x^2\rangle/dt} \approx \frac{2\hat{\epsilon}}{\dot{\epsilon}}$$

... and, on Integrated Luminosity





Tevatron conditions, in this example

DC Beam

- Noise from RF system (phase noise, voltage noise) will increase the beam *longitudinal* emittance

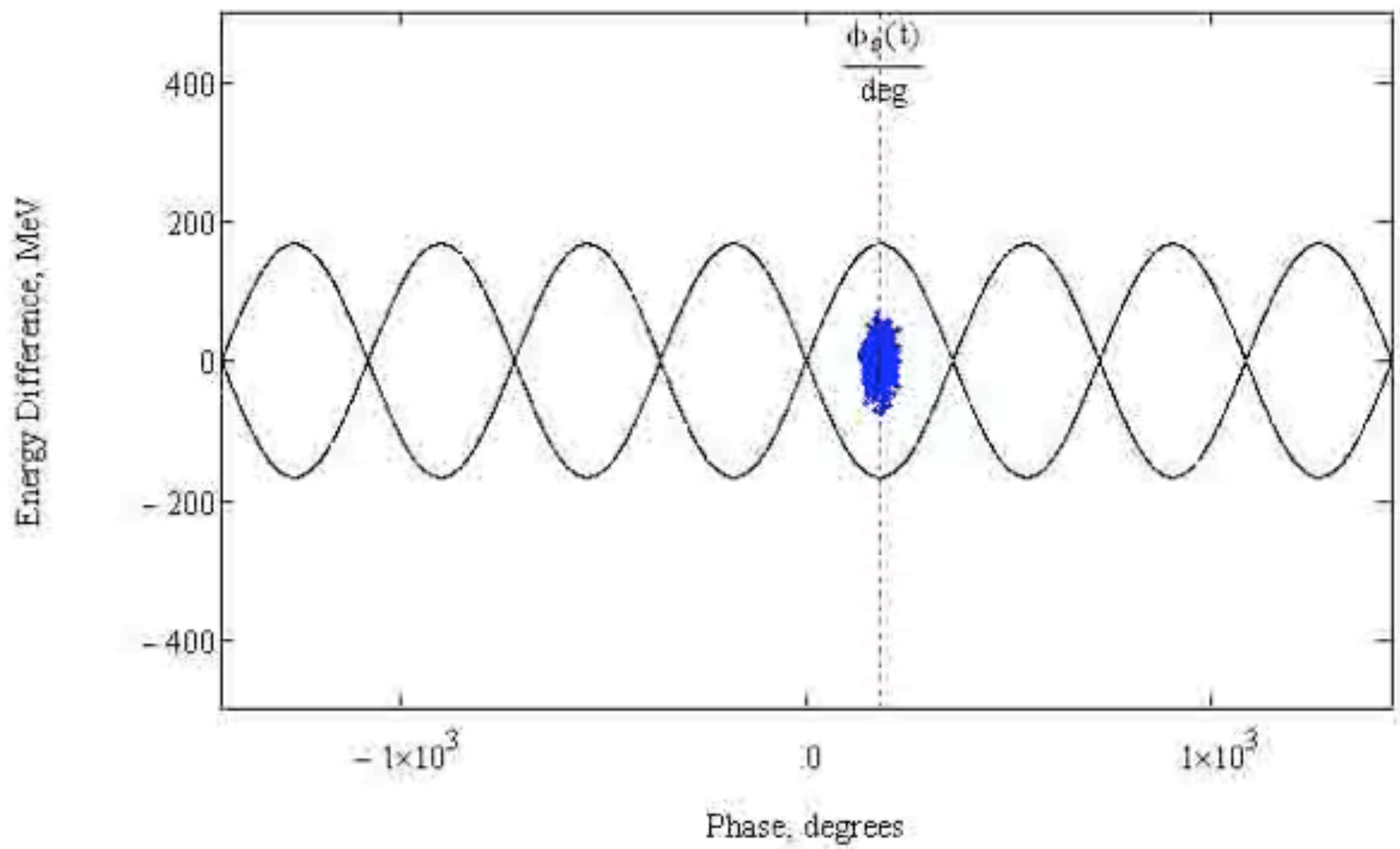
- Particles will “leak” out of their original bucket, and circulate around the circumference out of phase with the RF
  - “DC Beam”

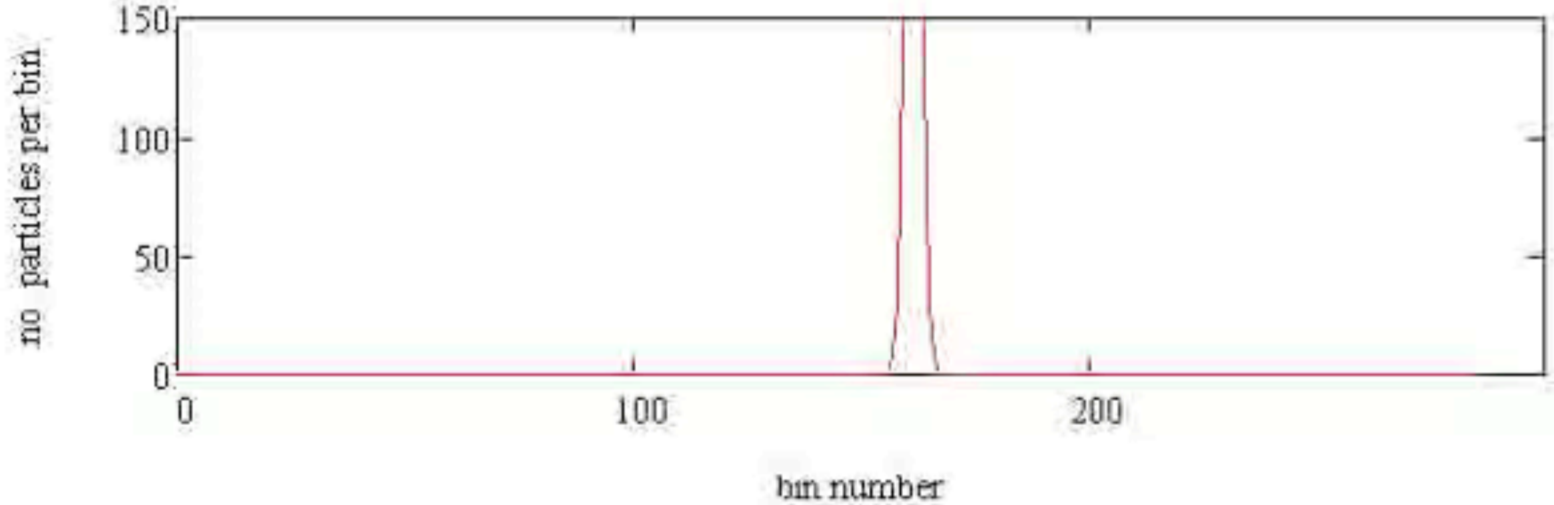
- Hence, collisions can occur between nominal bunch crossings; can be of concern for the experiments
- Perhaps more important, must remove DC beam that wanders into the abort gap(s) to permit clean removal of stored beams
  - typically “cleaned up” using fast, low-amplitude kicker magnets, electron lens deflectors, etc.

DC Beam Generation

model using
phase noise
in the RF system...

(parameters exaggerated)



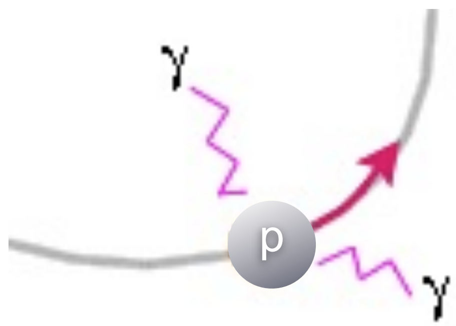


Energy Deposition

- 1-10 TeV is high energy, but actually less than one micro-Joule; multiply by 10^{13}-10^{14} particles, total energy quite high
- Beam Stored Energy:
  - Tevatron
    - » $10^{13} \cdot 10^{12}$ eV $\cdot$ $1.6 \cdot 10^{-19}$ J/eV ~ 2 MJ
  - LHC
    - » $3 \cdot 10^{14} \cdot 7 \cdot 10^{12}$ eV $\cdot$ $1.6 \cdot 10^{-19}$ J/eV ~ 300 MJ each 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
- Sources of energy deposition into the accelerator systems
  - Synchrotron Radiation
  - Particle diffusion (above)
  - Beam abort
  - Collisions!

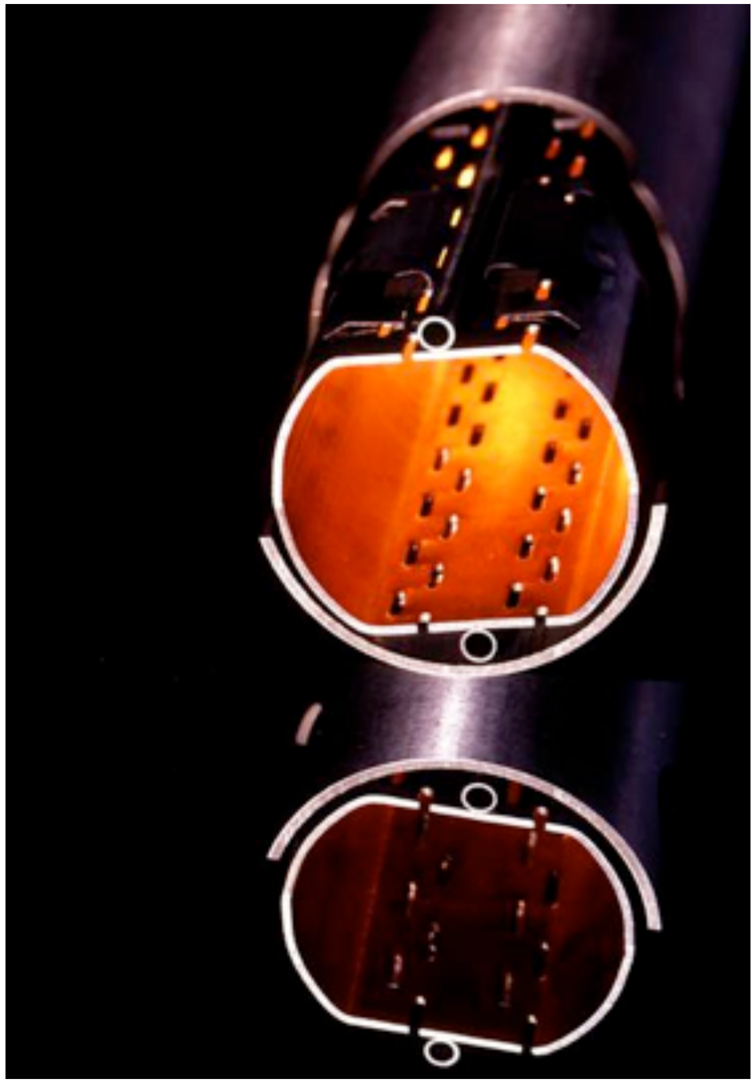
Synchrotron Radiation

- Energy loss per turn:



$$\Delta E_{s.r.} = \frac{4\pi r_0}{3(mc^2)^3} \; E^4 \; R \, \langle \frac{1}{\rho^2} \rangle$$

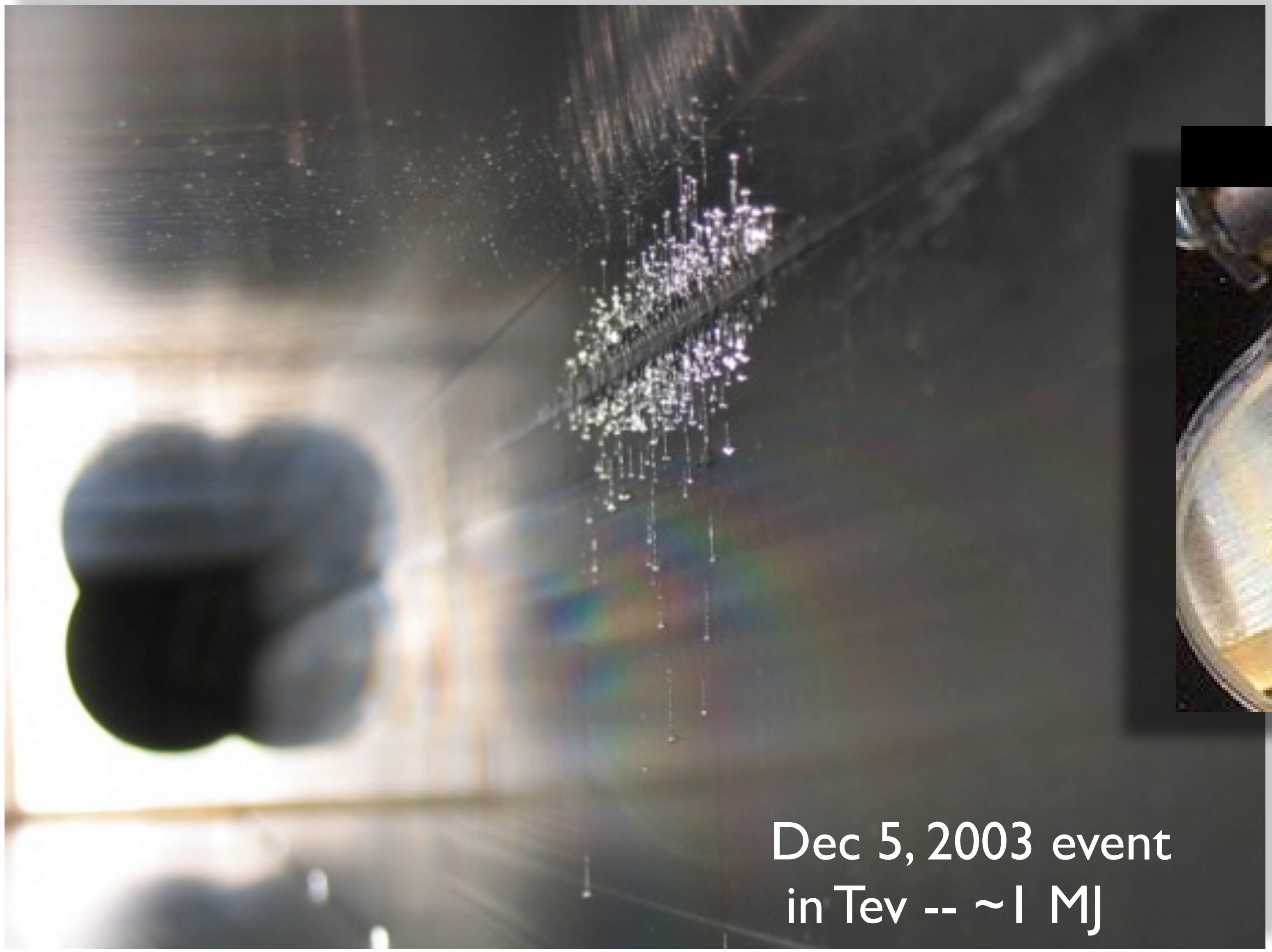
- For Tevatron:
  - » ~ 9 eV/turn/particle; ~ 1 W/ring
- for LHC:
  - » ~6700 eV/turn/particle; ~ 3.6 kW/ring



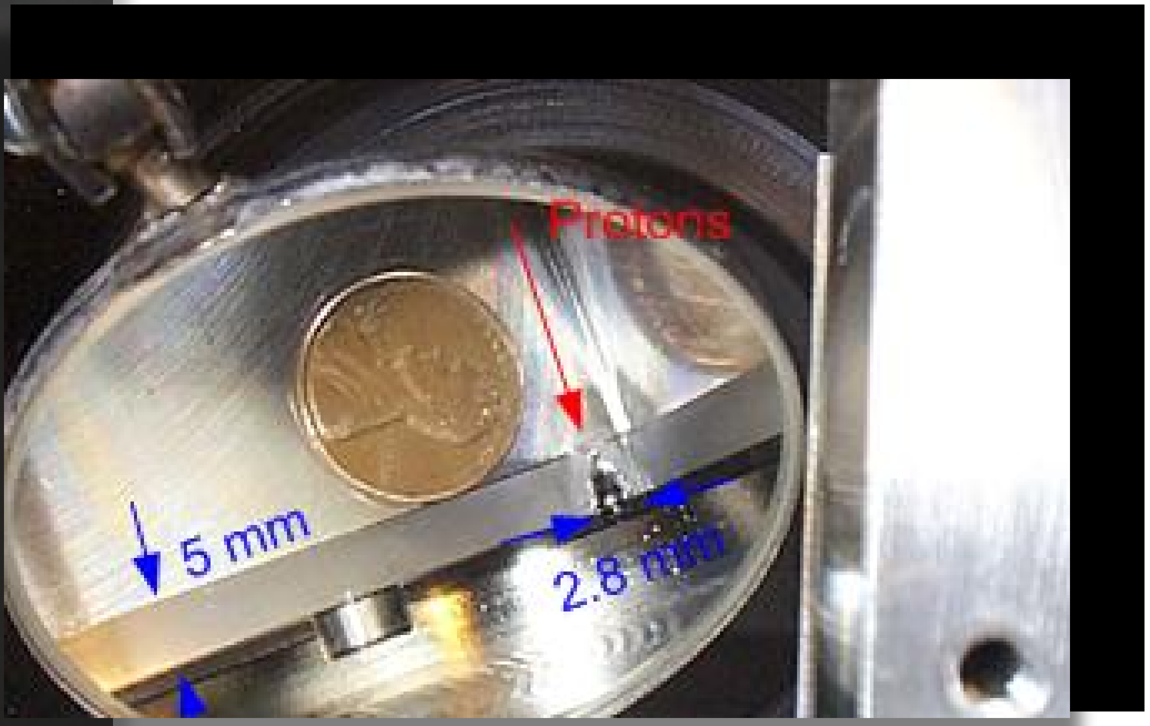
- Vacuum instability -- "electron cloud"
  - requires liner (beam screen) for LHC beam tube

Collimation Systems

- Tevatron -- several collimators/scrapers to contain enegy deposition
- LHC -- ~ 100 collimators



Careful control of collimators, beam trajectory, beam envelope required



Back to Luminosity...

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

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

- If different bunch intensities, different transverse beam emittances for the two beams,

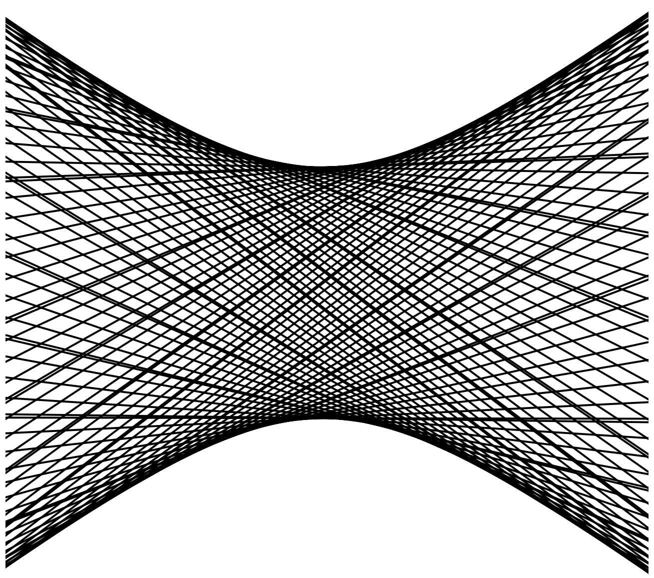
$$\mathcal{L} = \frac{f_0 B N_1 N_2}{2\pi(\sigma_1^{*2} + \sigma_2^{*2})} = \frac{f_0 B N_1 N_2 \gamma}{2\beta^*(\epsilon_1 + \epsilon_2)}$$

and assorted other variations...

Hour Glass

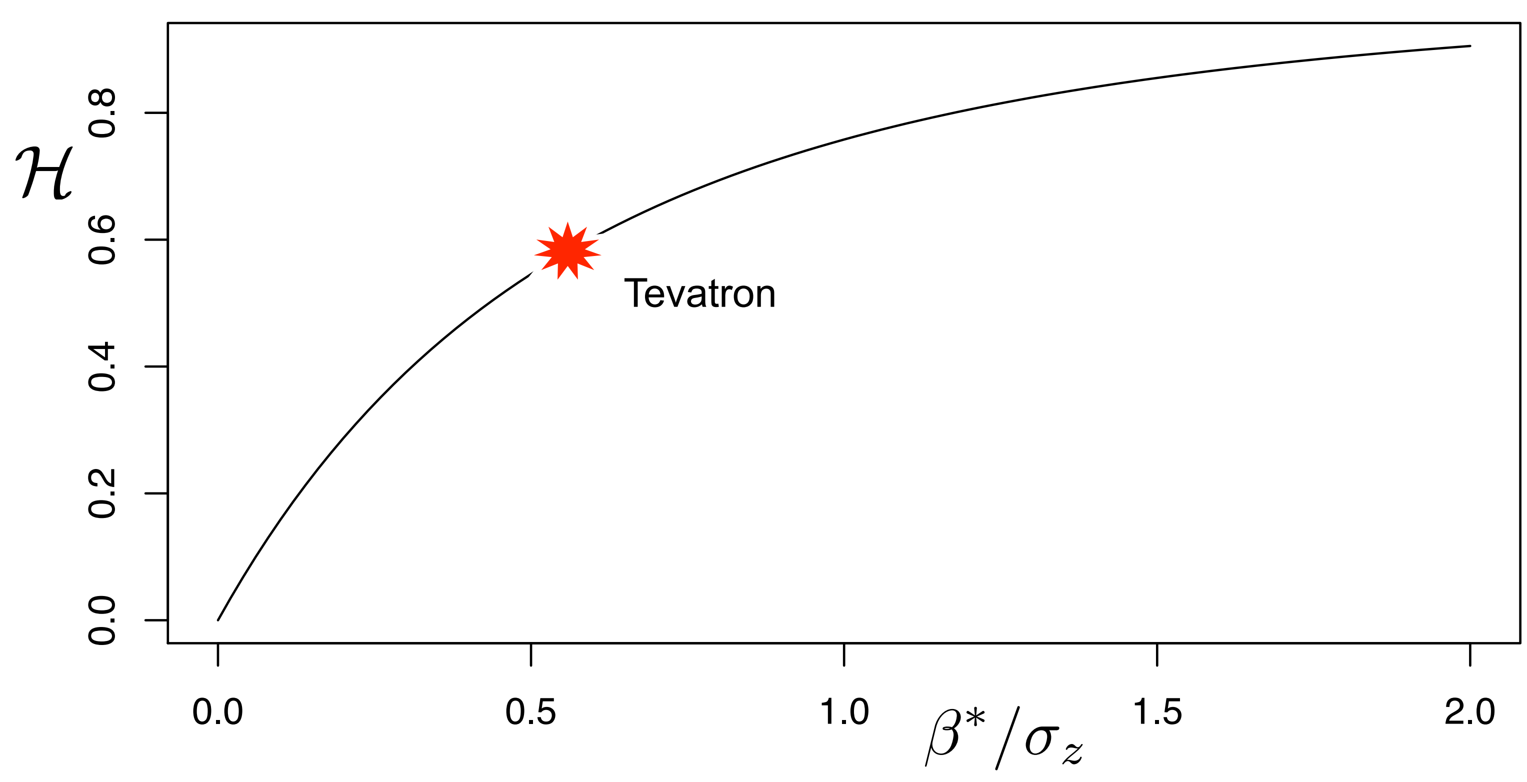
- If bunches are too long, the rapid increase of the amplitude function away from the interaction "point" reduces luminosity

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



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

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



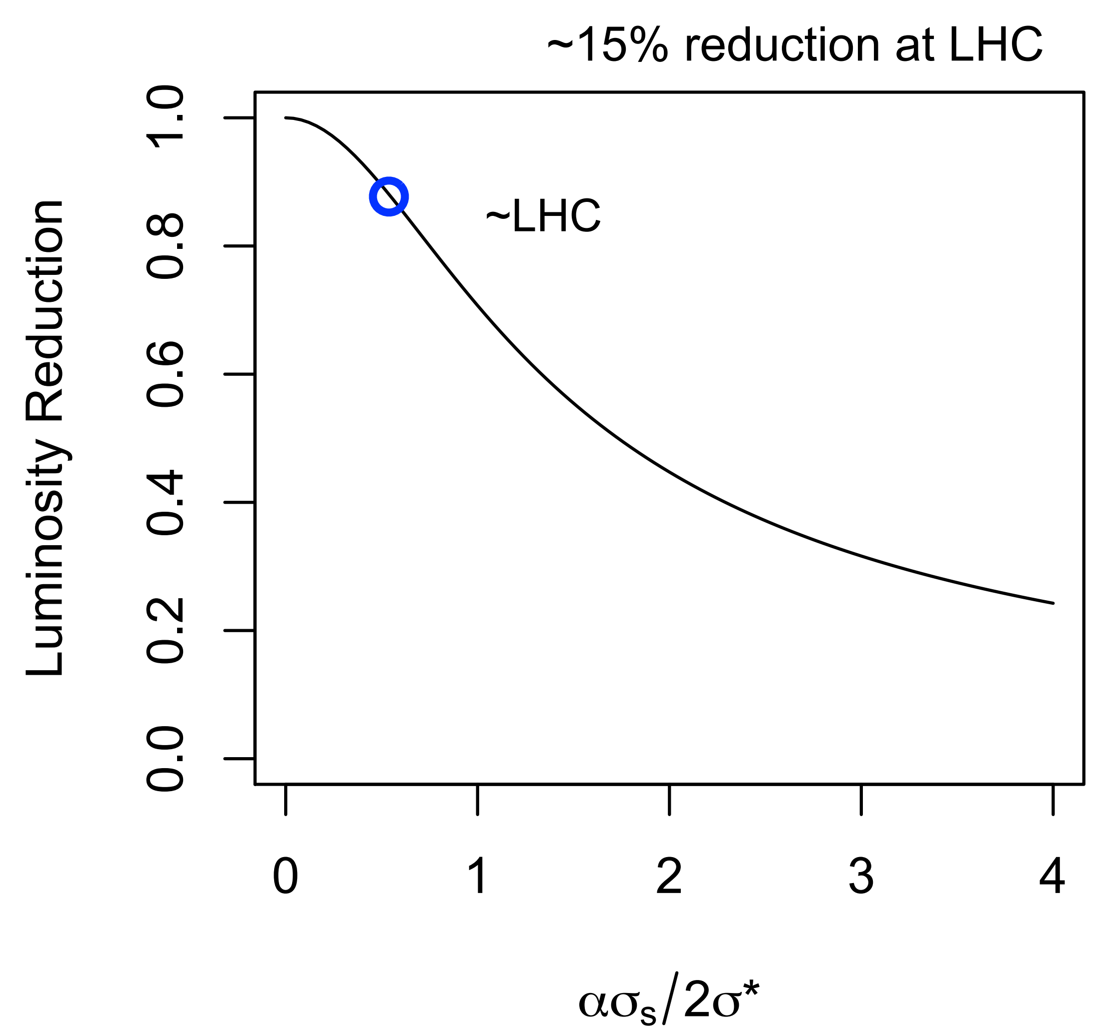
Crossing Angle

- in LHC, across each interaction region, for about 120 m, the two beams are contained in the same beam pipe (Tev had greater bunch spacing)
  - there would be ~(120/(7.5/2)) ~ 30 bunch interactions in this region
    - » thus, separate these collisions through a “crossing angle”
  - beams separated by ~10 sigma

$$d/\sigma = \alpha \cdot (\beta^*/\sigma^*) \approx 10$$
$$\longrightarrow \quad \alpha = 10 \cdot (0.017)/(550) \approx 300\ \mu\text{rad}$$

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

$$\alpha\sigma_s/2\sigma^* = (0.3\ \text{mrad})(70\ \text{mm})/(2{\cdot}17\ \mu\text{m}) = 0.62$$



Determining LHC Luminosity

- What parameters are given? are required? are doable?

$$f_0 = 3\times10^8 \text{ m/s} \; / \; 27 \text{ km} = 11 \text{ kHz} \qquad \gamma = 7 \text{ TeV}/0.938 \text{ GeV} \approx 7500$$

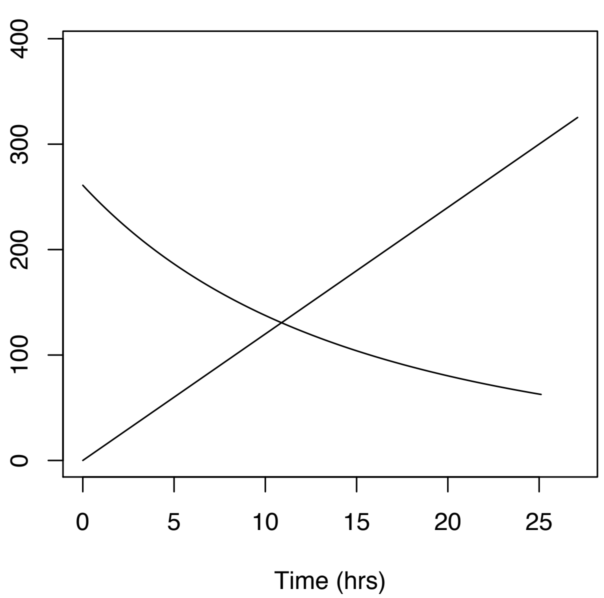
- Injector system creates emittances on scale of $\epsilon_N \approx 4\pi$ mm-mrad
- Minimum β in part determined by maximum β (aperture) in the triplet
- Can create $\beta^* \approx 0.5 - 1$ m ; want bunch length much less than this
  - say ~7.5 cm (rms)   ~38 cm (full)
    - if this is within +/- 90° of ideal RF phase, want ~0.75 m RF "period"
    - thus, use RF frequency of about 400 MHz
    - implies $h \sim$ 400 MHz / 11 kHz ~ 36000
    - if keep ~ 10 "empty buckets" between bunches, then $B \sim 3600$
      - » but, need space for abort gap(s) and empty bunches from transfers, etc. --> $B \sim 2800$
  - » also saw need for crossing angle of ~300 μrad to keep beams separated 10σ

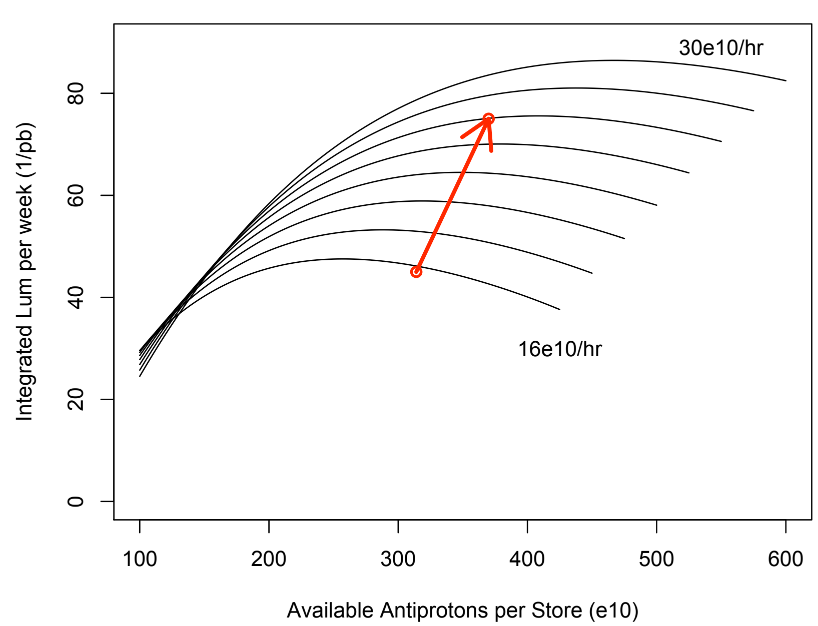
$$\mathcal{L} = \frac{f_0 B N^2 \gamma}{4\epsilon\beta^*} \cdot \frac{1}{\sqrt{1+\pi\gamma\alpha^2\sigma_s^2/4\epsilon\beta^*}} = \frac{11,000 \cdot 2800 \cdot 7500}{4(4\pi 10^{-6})(0.5)} \cdot 0.85 \cdot \frac{1}{\text{m}^2\text{sec}} \cdot N^2 = \frac{0.78\times10^{12}}{\text{cm}^2\text{sec}} \cdot N^2$$

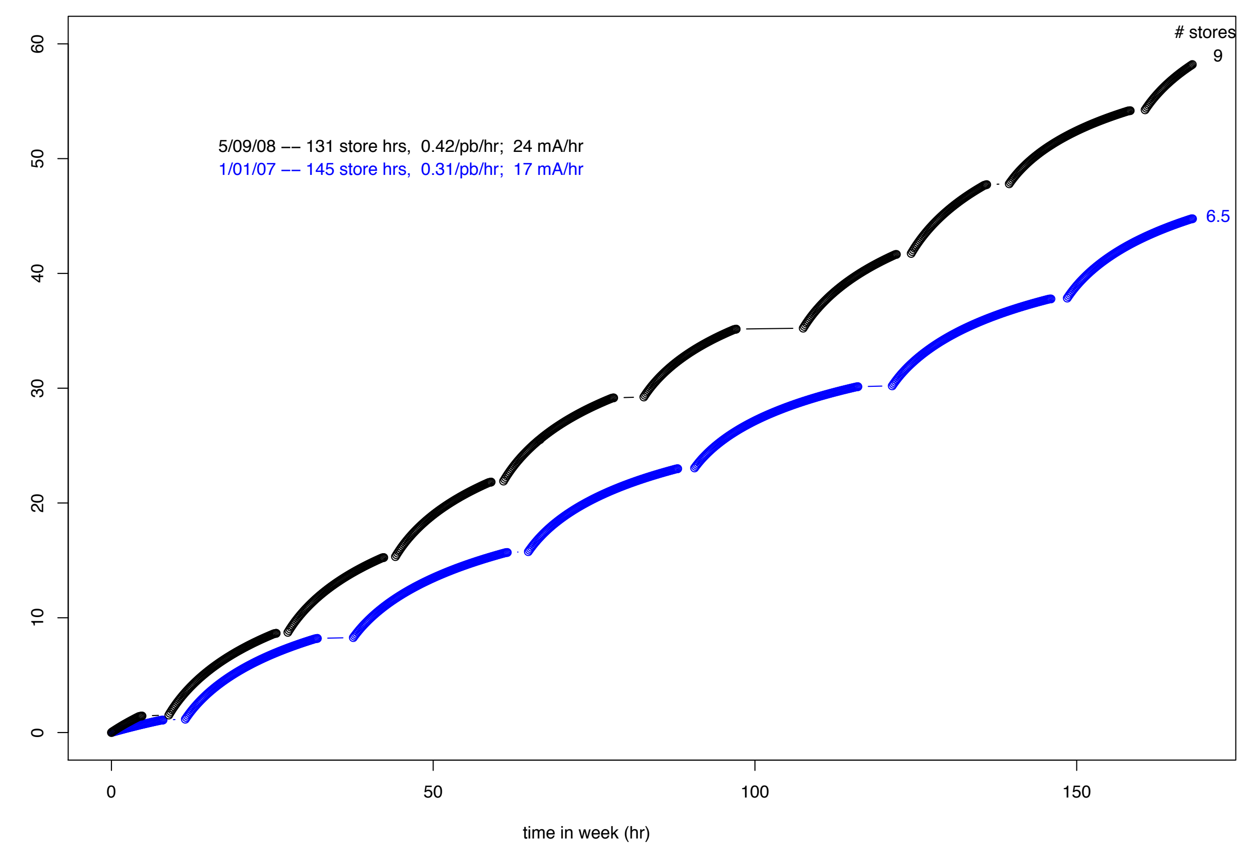
- Thus, need $N = 1.14 \times 10^{11}$ to make **10^{34}** luminosity √

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)
- Perhaps more straightforward for LHC than it was for Tevatron
  - in Tevatron operation, needed to balance the above with the production rate of antiprotons, longer turn-around times, to find optimum running conditions





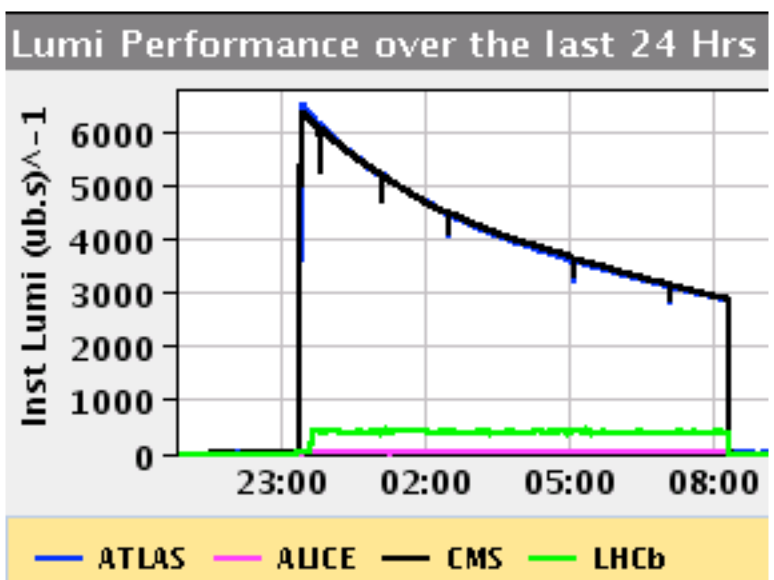


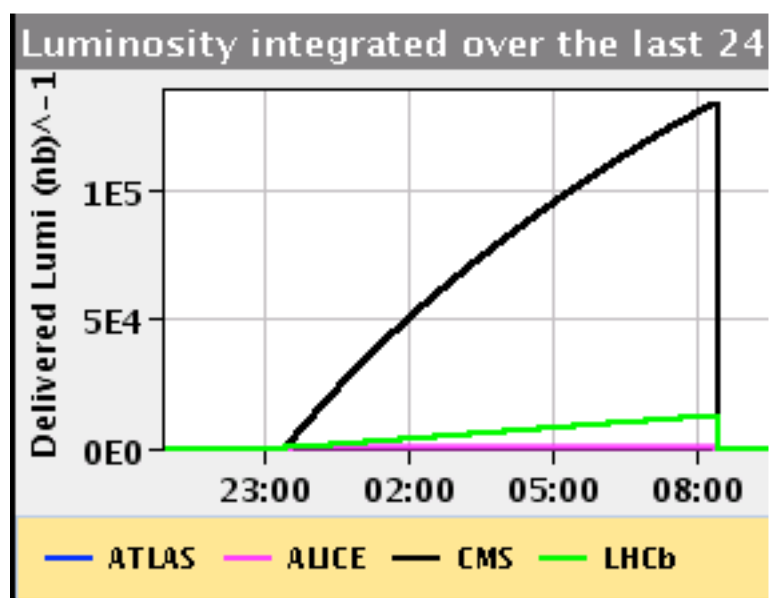
Integrating Luminosity at LHC

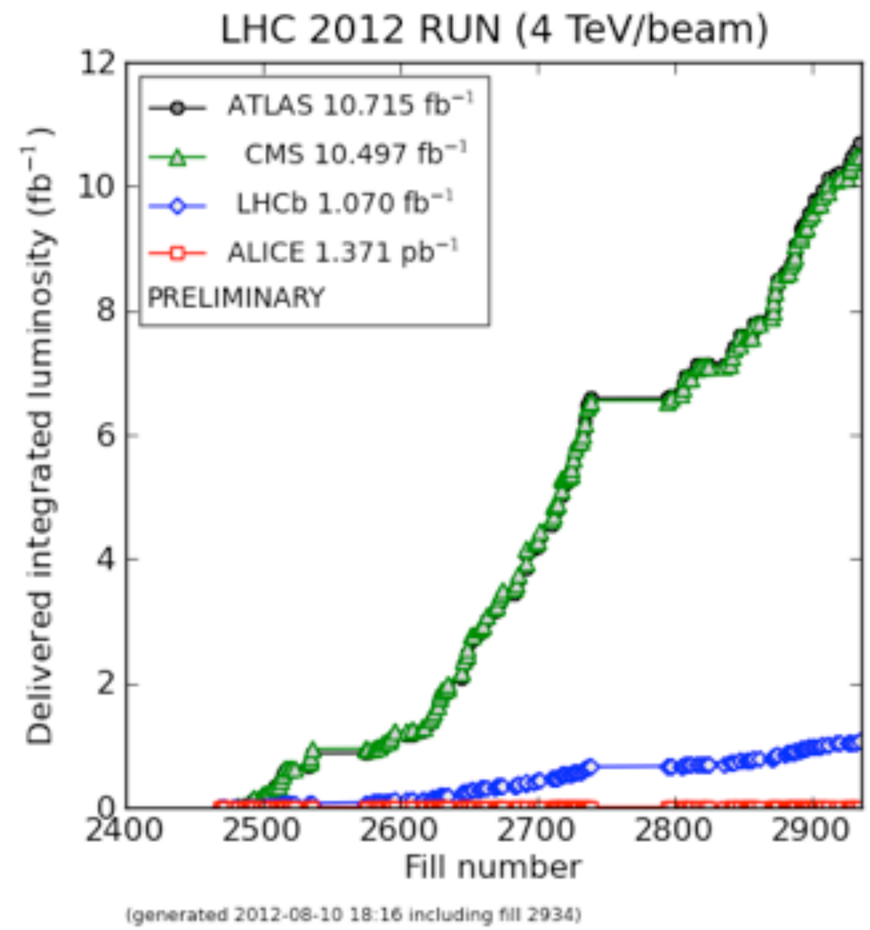
- For LHC, protons are readily available; beams are designed to be of equal intensity
- So, will balance the decay of luminosity...

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

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

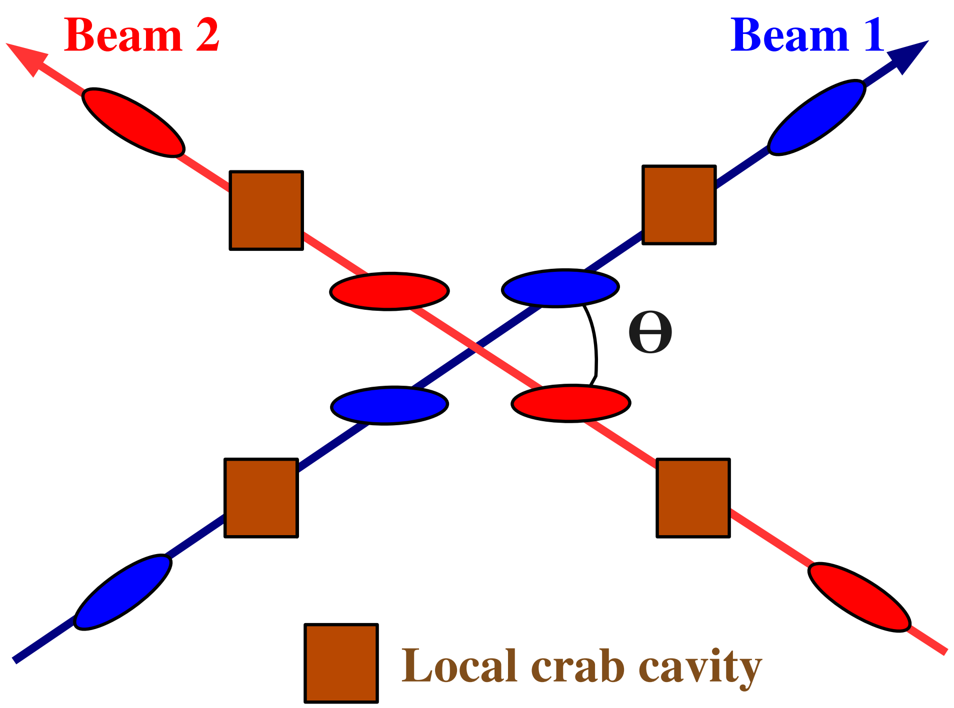






Future Directions

- LHC Luminosity Upgrade Directions
  - 10^{35} will imply 10x higher energy deposition at the IRs
    - » > 13 kW at each IR?
    - » will require new IR magnets to better handle higher energy deposition
  - higher synchrotron radiation in the arcs if intensities go up
    - » S.R. ~ $BN \times E^4$
  - crab cavities to re-gain luminosity lost from crossing angle
  - ...???



- Next directions for HEP?
  - linear colliders
  - muon colliders
  - wake field accelerators
  - ...???

The Livingston Plot

- In 1954, M. Stanley Livingston produced a curve in his book *High Energy Accelerators*, indicating exponential growth in particle beam energies over "past" ~25 years;
  - the 33 "Bev" (GeV) AGS at Brookhaven and 28 GeV PS at CERN were underway, and kept up the trend
- The advent of Strong Focusing (A-G focusing) was key to keeping this trend going...

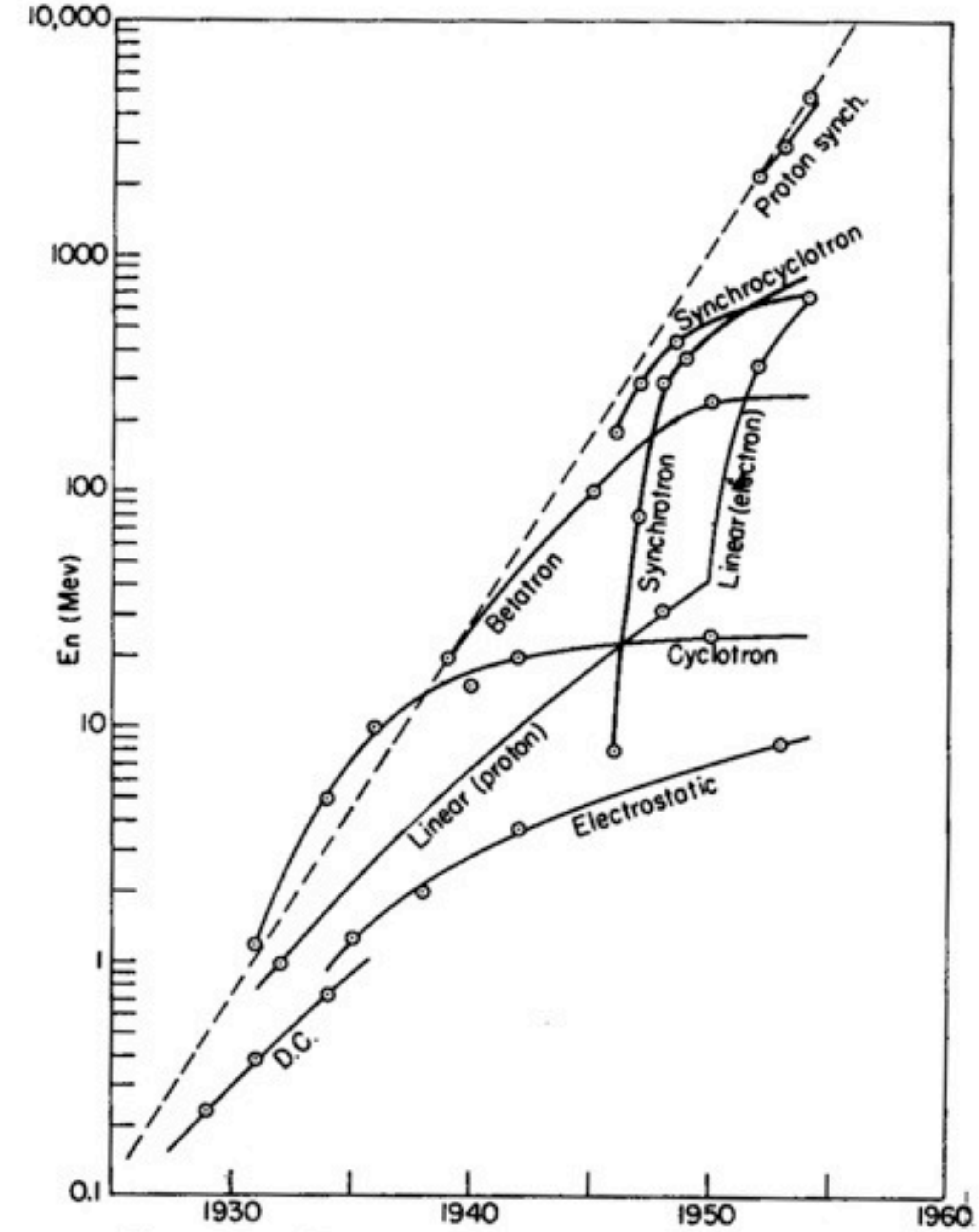
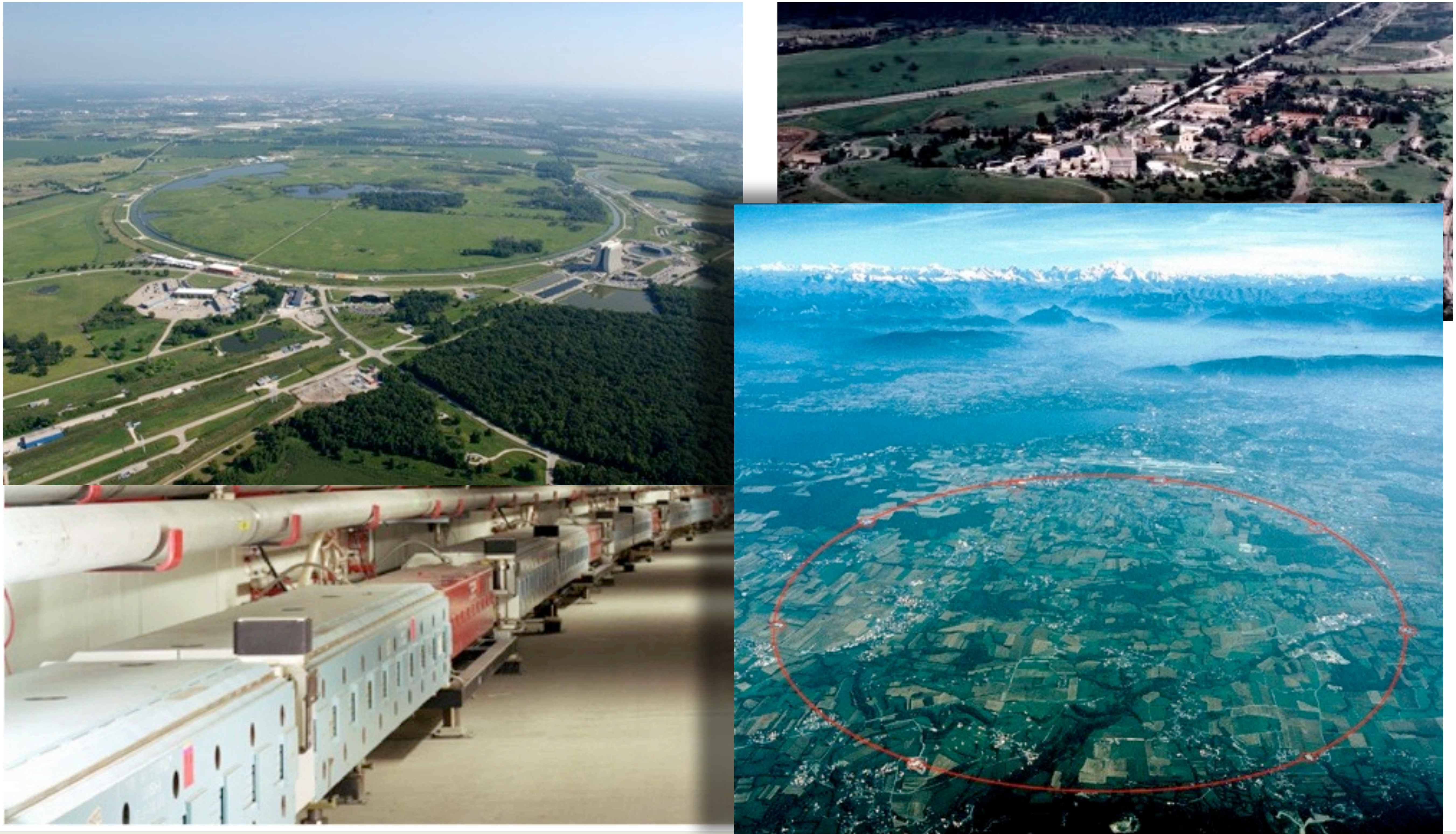


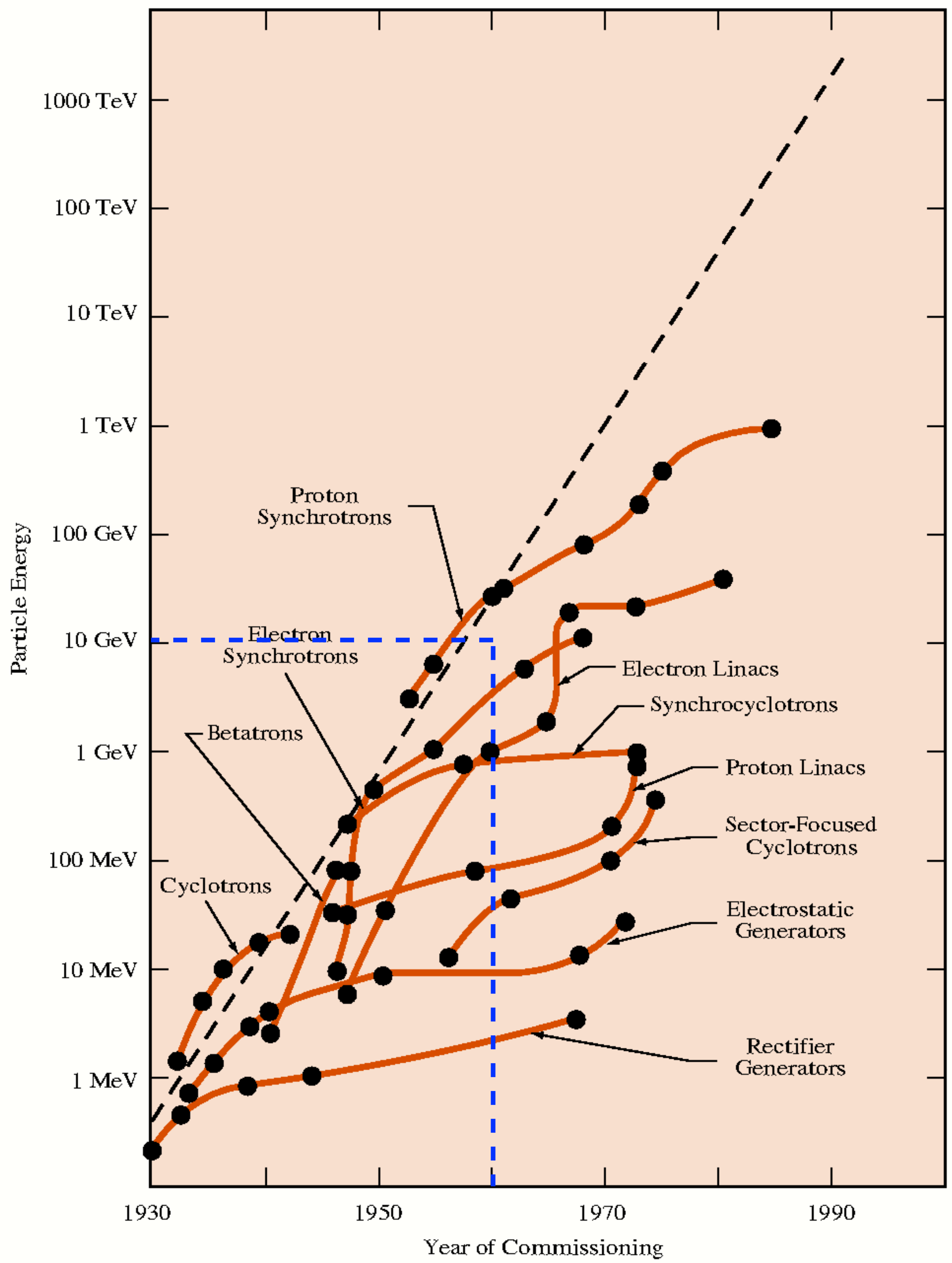
FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

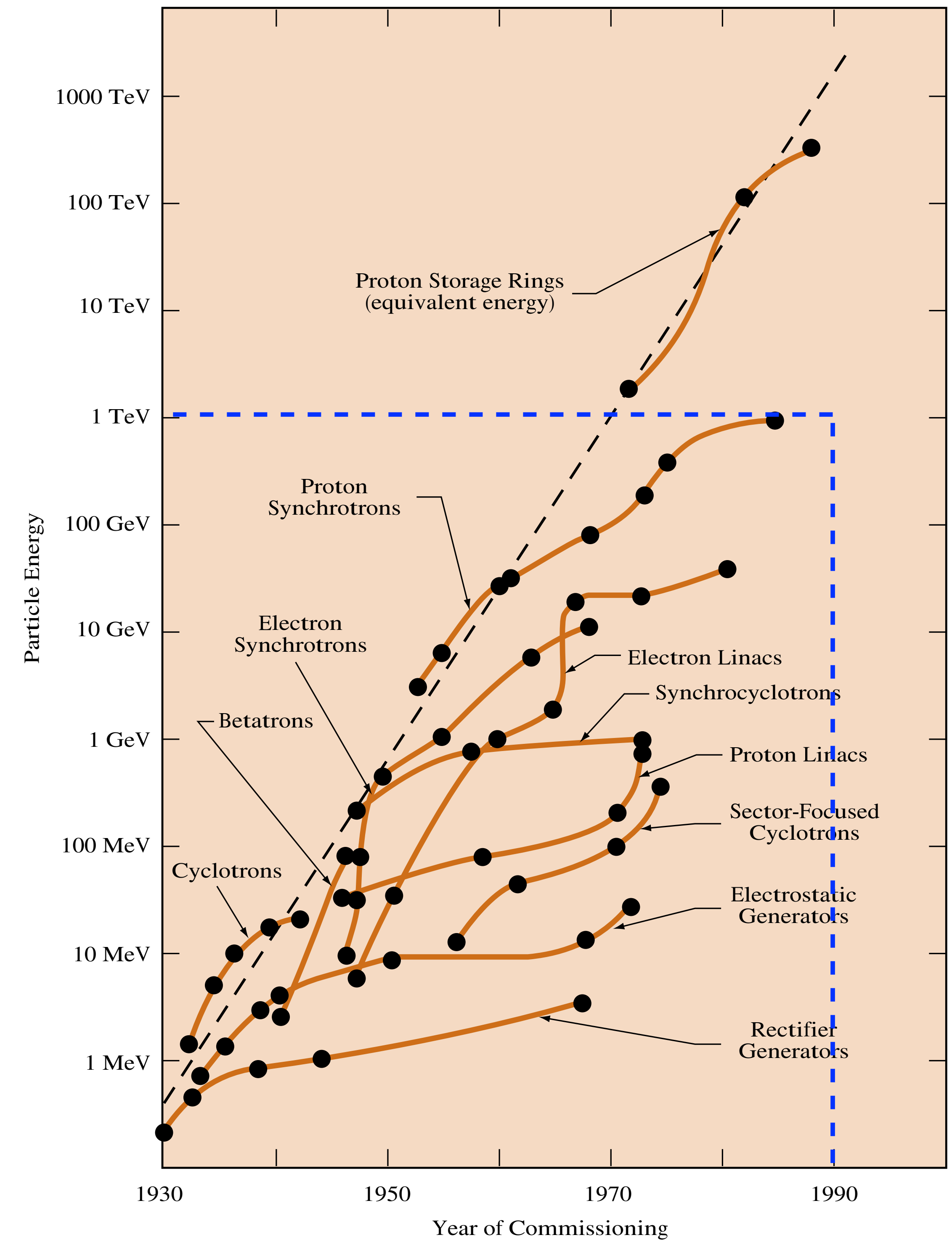
The Past 40 Years



Livingston Revisited

from W. Panofsky. *Beam Line* (SLAC) 1997





Possible Next Steps for High Energy Particles with standard RF technology

Some ideas, around 10-12 years ago...

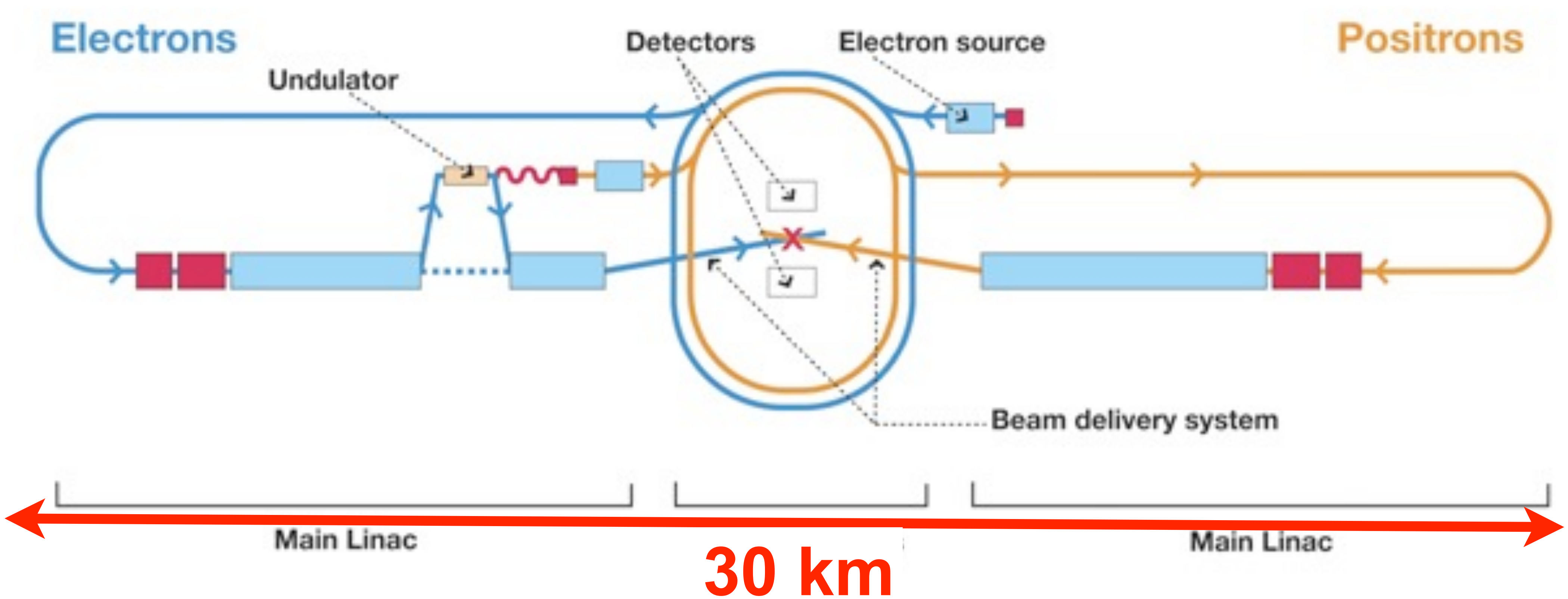
- Very Large Hadron Collider (VLHC) -- 20x20 to 100x100 TeV (pp)
- International Linear Collider -- 0.25 x 0.25 up to 0.5 x 0.5 TeV (e+e-)
- Muon Collider -- generate beams of muons, accelerate (quickly!) to few TeV and collide

- Snowmass 2001 -- VLHC (no) vs. ILC (yes); [*μ-μ*: too far away...]
  - ILC more "complementary" to LHC; natural next step
  - physics events easier to "disentangle" -- leptons vs. hadrons
  - ILC more affordable (???)

- Look at Linear Collider ...

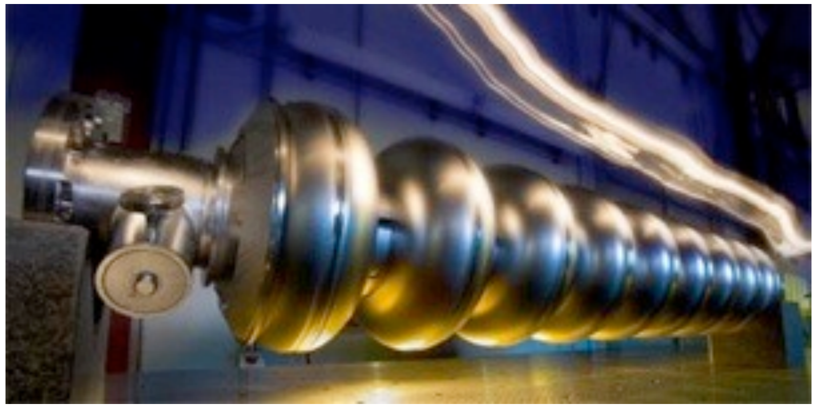
ILC Conceptual Layout

- Use (part of) Main Linac to accelerate beams for positron production
- Use Damping Rings to generate small beams at low energy (~10 GeV) *via* Synch. Radiation -- makes flat beams, longer bunches than desired
- Beams travel length of tunnel, turn around (bunch compression) and enter Main Linacs
- Exit Main Linacs with E~250 GeV; deliver to Experiments



Same limiting factors ...

- superconducting technology -- accel. cavities this time, not magnets
- high accelerating gradient (>30 MeV/m)
- Synchrotron Radiation
  - effects obvious in e+e-; hence, the **L** in **ILC**
  - real estate vs. electric field strength



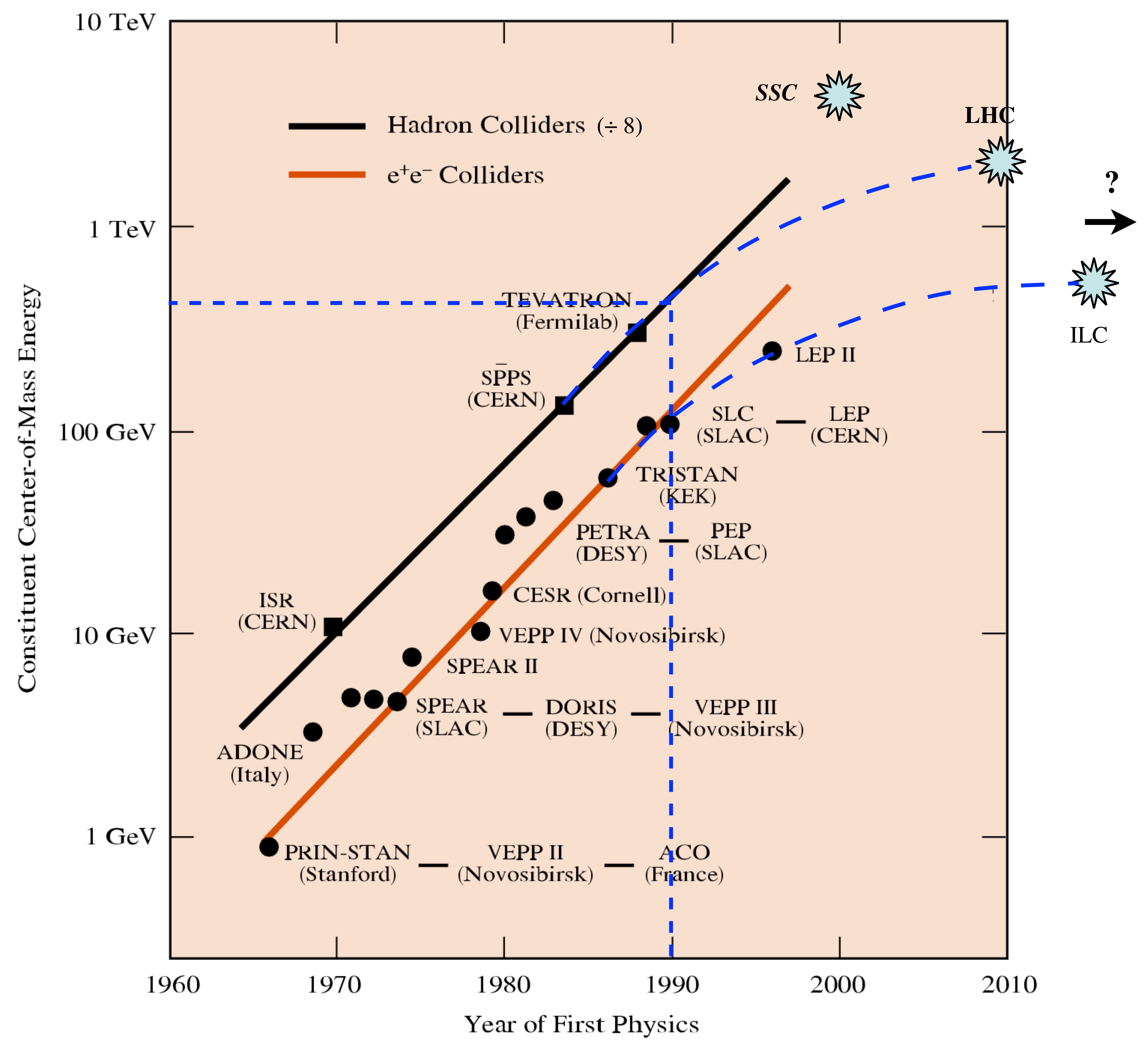
- stored energy an issue in LHC;   *beam power* issue in linac
- energy deposition at Interaction Points; backgrounds
- small apertures --> alignment tolerances (micron scale)
- requires very small beam sizes at collision point -- nm scale
  - damping rings -- S.R. put to good use
  - emittance exchange -- can eliminate need for damping rings?

very large price tag

The Livingston Curve Again

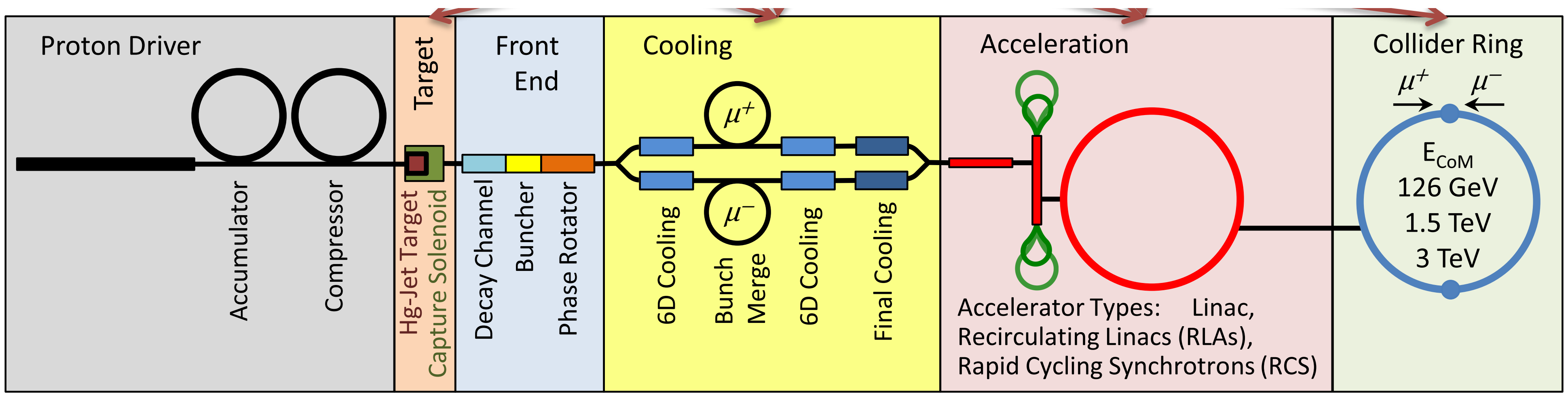
- In attempt to compare e- & p, switch to C-of-M view of constituents
- seeing a new roll-off happening
- driven by budgets, if constrained to present technology
- thus, need new technologies to make much higher energies affordable...

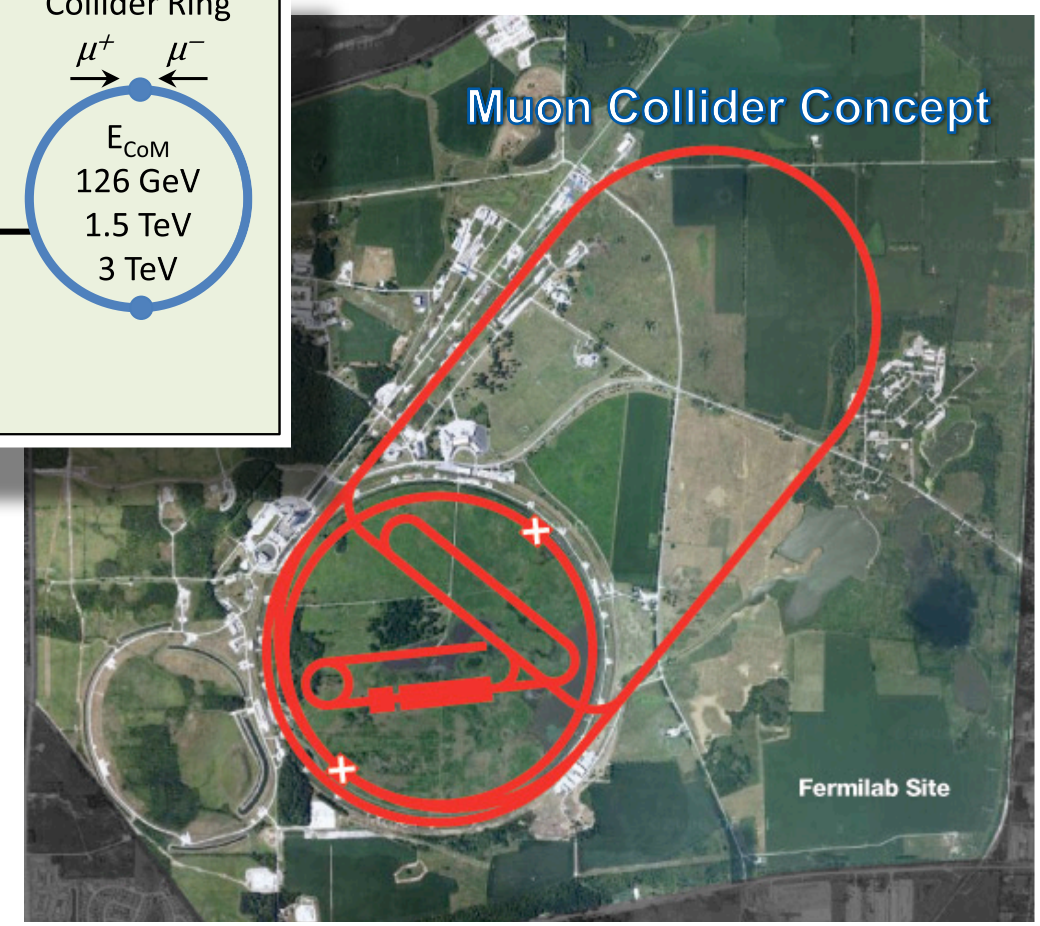
adopted from W. Panofsky. *Beam Line* (SLAC) 1997



Muon Collider

- Collide beams of +/- muons
  - use intense proton driver (linac?) to create pion beams --> muons
  - collect muons, cool to small emittances, accelerate to high energy
    - » all as the muons are decaying away...
  - store in ring for collisions
    - » at 150 GeV, tau = 3 ms   at 3 TeV, tau = 62 ms (~3000 turns in Tevatron-size ring)





If pursued in earnest, will likely require a very long-term phased approach

Lawrence Berkeley Lab Laser Wakefield Acceleration

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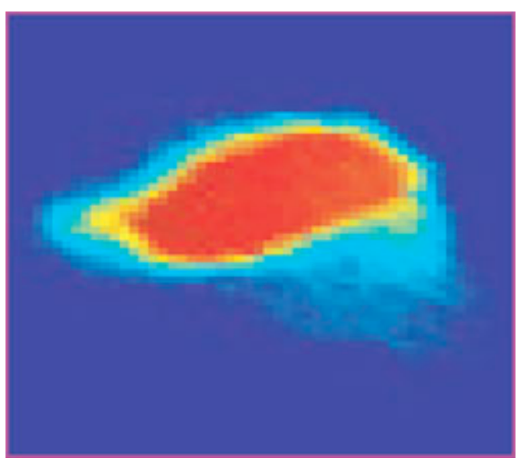
From Zero to a Billion Electron Volts in 3.3 Centimeters
Highest Energies Yet From Laser Wakefield Acceleration

Contact: Paul Preuss, (510) 486-6249, paul_preuss@lbl.gov

BERKELEY, CA — In a precedent-shattering demonstration of the potential of laser-wakefield acceleration, scientists at the Department of Energy's Lawrence Berkeley National Laboratory, working with colleagues at the University of Oxford, have accelerated electron beams to energies exceeding a billion electron volts (1 GeV) in a distance of just 3.3 centimeters. The researchers report their results in the October issue of *Nature Physics*.



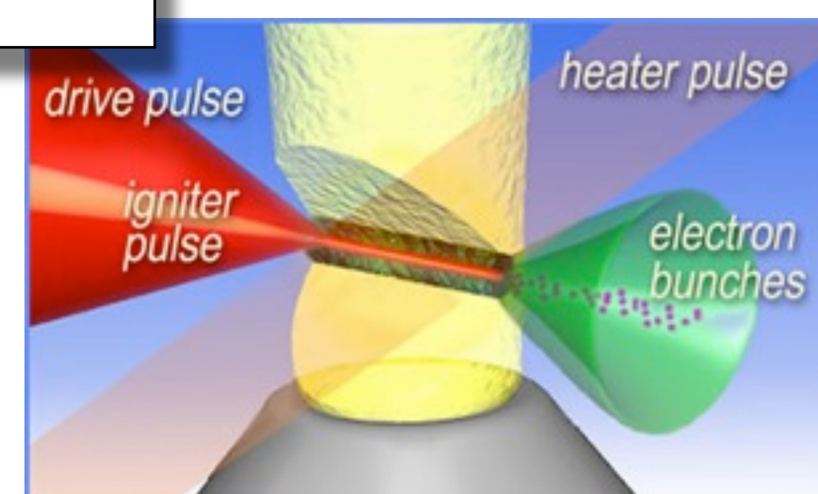
Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

By comparison, SLAC, the Stanford Linear Accelerator Center, boosts electrons to 50 GeV over a distance of two miles (3.2 kilometers) with radiofrequency cavities whose accelerating electric fields are limited to about 20 million volts per meter.

The electric field of a plasma wave driven by a laser pulse can reach 100 *billion* volts per meter, however, which has made it possible for the Berkeley Lab group and their Oxford collaborators to achieve a 50th of SLAC's beam energy in just one-100,000th of SLAC's length.

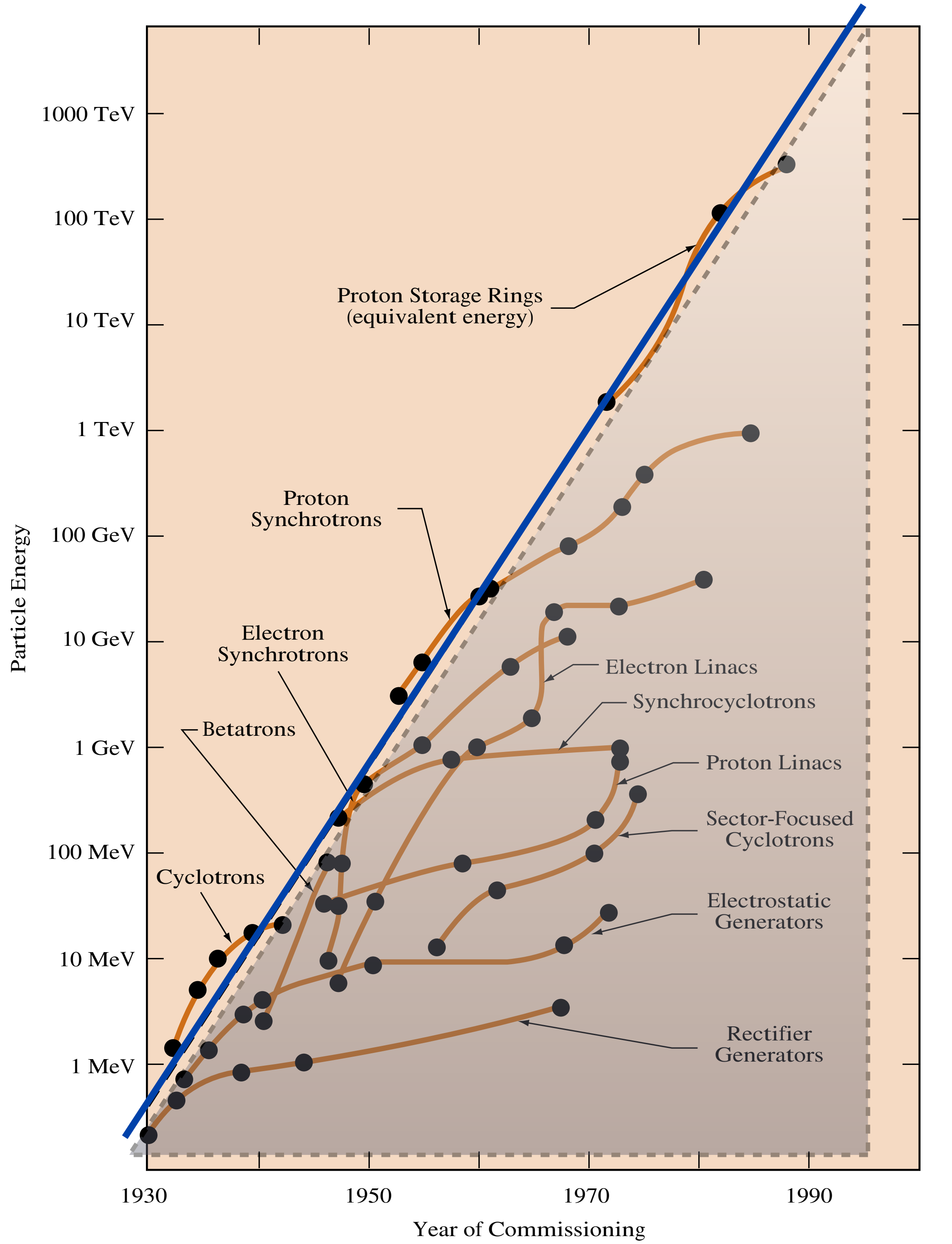
This is only the first step, says Wim Leemans of Berkeley Lab's Accelerator and Fusion Research Division (AFRD). "Billion-electron-volt beams from laser-wakefield accelerators open the way to very compact high-energy experiments and superbright free-electron lasers."

- 30 *G*eV/m, compared to 30 *M*eV/m in present SRF cavity designs
- ... and, *small* momentum spread (2-5%) as well



Looking Below the Curve

- Accelerator Facilities, and the need for scientists to develop, build, commission, operate, improve them have seen an enormous growth over the decades
- While peak accelerator energies continue to drive particle physics, much work to do and applications to develop at lower energies
- Many, many facilities and industrial uses are not shown here, but flood the area “below the curve”



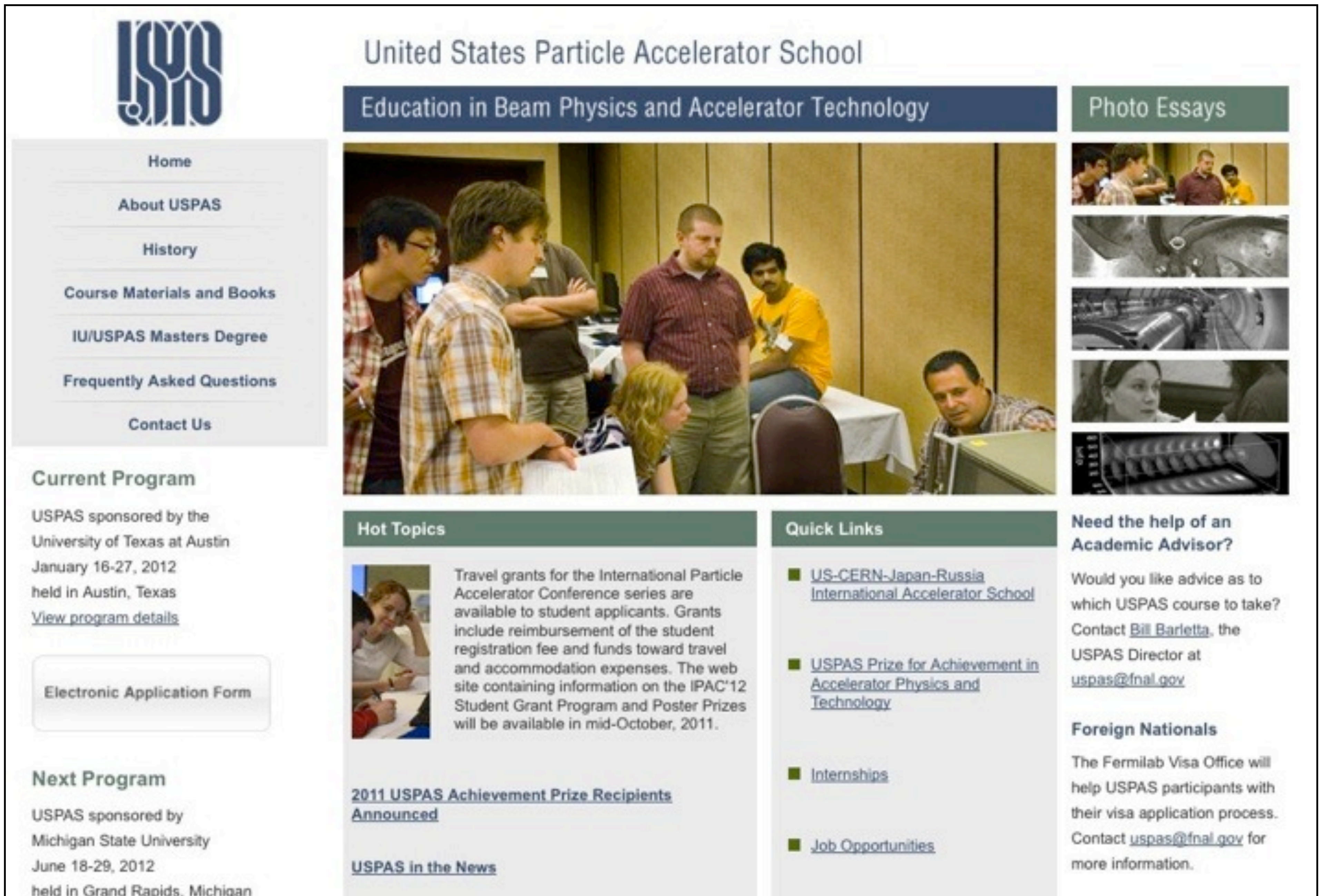
What's been left out?

- Hope have gotten a glimpse of the basic physics of particle accelerators and particle beams

- What, there's more??
  - 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
  - ...

US Particle Accelerator School

- Held twice yearly at venues across the country; offers graduate credit at major universities for courses in accelerator physics and technology



http://uspas.fnal.gov

Some Recent Schools:

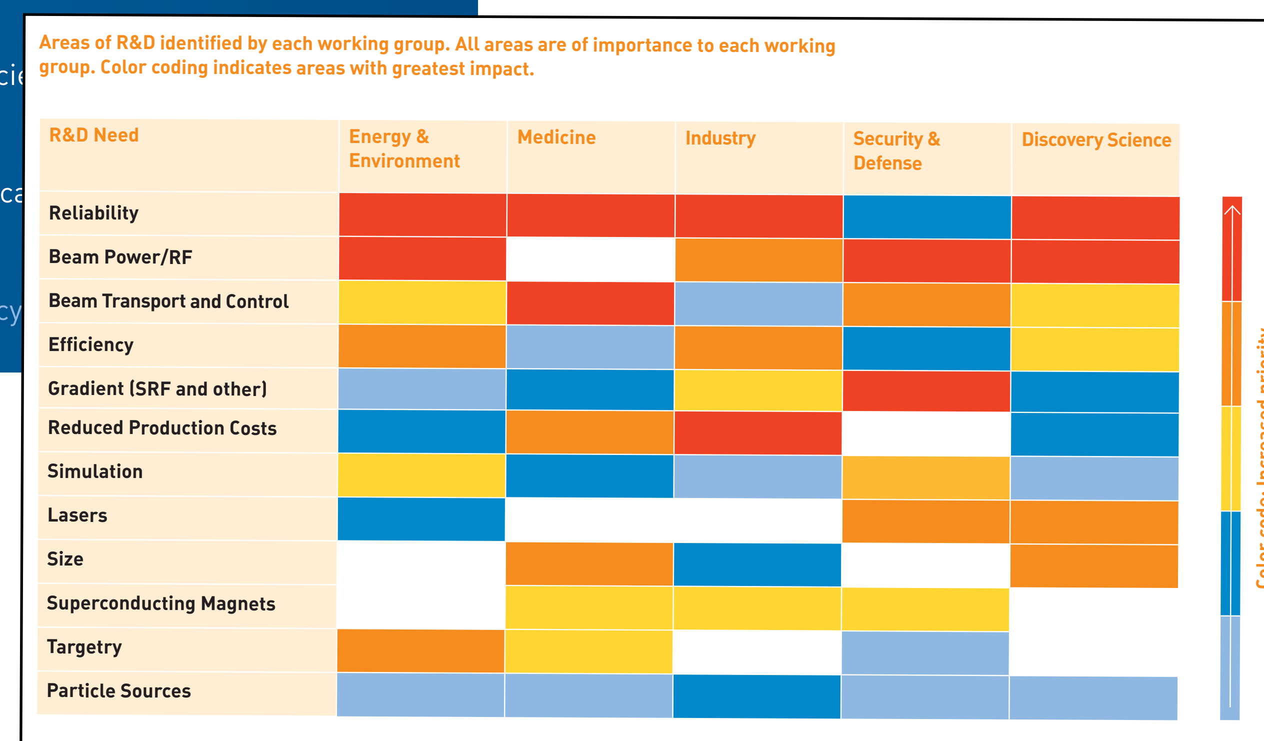
June 5-16, 2000	SUNY at Stony Brook
January 15-26, 2001	Rice University
June 4-15, 2001	University of Colorado at Boulder
January 14-25, 2002	UCLA
June 10-21, 2002	Yale University
January 6-17, 2003	Indiana University (held in Baton Rouge, LA)
June 16-27, 2003	University of California, Santa Barbara
January 19-30, 2004	The College of William and Mary
June 21 - July 2, 2004	University of Wisconsin - Madison
January 10-21, 2005	University of California, Berkeley
June 20 - July 1, 2005	Cornell University
January 16-27, 2006	Arizona State University
June 12-23, 2006	Boston University
January 15-26, 2007	Texas A&M University
June 4-15, 2007	Michigan State University
January 14-25, 2008	University of California, Santa Cruz
June 16-27, 2008	University of Maryland
January 12-23, 2009	Vanderbilt University
June 15-26, 2009	University of New Mexico
January 18-29, 2010	University of California, Santa Cruz
June 14-25, 2010	MIT
January 17-28, 2011	Old Dominion University
June 13-24, 2011	Stony Brook University

See also, CERN schol:

http://cas.web.cern.ch/cas/

Accelerators for America's Future

- Symposium and workshop held in Washington, D.C., October 2009
- 100-page Report available at web site



http://www.acceleratorsamerica.org/

A “Final” word...

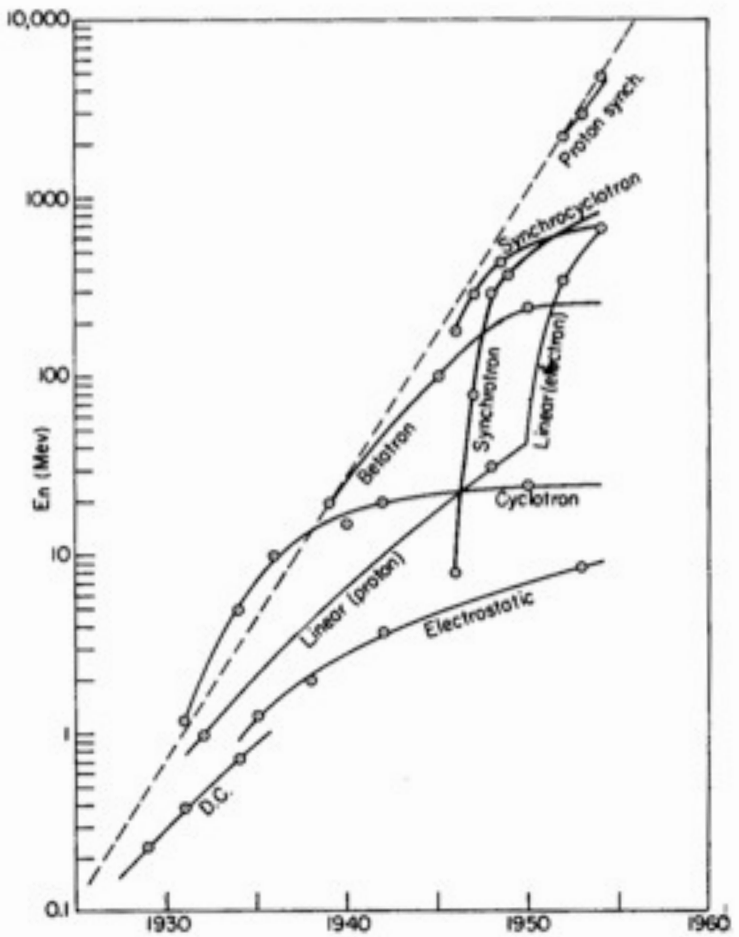


FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

of the plot is the approximately linear slope of this envelope, which means that energy has in fact increased exponentially with time. The rate of rise is such that the energy has increased by a factor of 10 every six years, from a start at 100 kv in 1929 to 3 billion volts in 1952.

It is interesting to extrapolate this curve into the future, to predict the energy of accelerators after another six years. We have reason to hope that either the Brookhaven or the CERN A-G proton synchrotrons will have reached 25 Bev by that

time. Further extrapolation of this exponentially rising curve would predict truly gigantic accelerators which would exceed any possible budgets, even those of government laboratories. So we will postpone such speculation until the present machines can demonstrate their value to science.

Those of us in the accelerator field are frequently asked, “When will this development of higher-and-higher-energy accelerators stop?” Yet it must be recognized that it is not the urge to higher voltage which inspires this growth, but the pressure of the continuously expanding horizons of science. As long as there are unsolved problems in Nature which might be answered by higher-energy particles, and as long as the scientific urge to know the answers continues, there will be a steady and persistent demand to develop the tools and instruments required.

A "Final" word...

ALTERNATE GRADIENT FOCUSING 151

152 HIGH-ENERGY ACCELERATORS

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M. Stanley Livingston, 1954

A-G proton synchrotrons will have reached 25 Bev by that

syphers@msu.edu

THANKS!

Further reading:

D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, John Wiley & Sons (1993)
E. J. N. Wilson, *An Introduction to Particle Accelerators*, Oxford University Press (2001)
S. Y. Lee, *Accelerator Physics*, World Scientific (1999)
T. Wangler, *RF Linear Accelerators*, John Wiley & Sons (1998)
H. Padamsee, J. Knobloch, T. Hays, *RF Superconductivity for Accelerators*, John Wiley & Sons (1998)

and many others…

Conference Proceedings --

Particle Accelerator Conference (2011, 2009, 2007, …)
European Particle Accelerator Conference (2010, 2008, 2006, …)
visit http://www.jacow.org