The Fermilab Accelerator Complex: Status and Challenges

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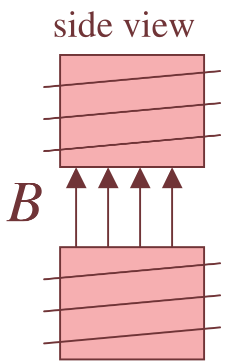
Outline

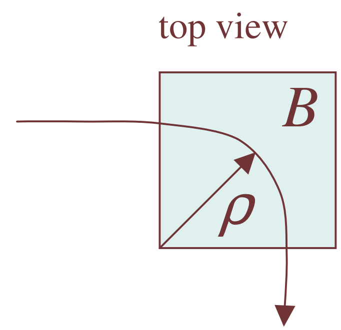
- Basic Accelerator Physics Concepts
  - Horizontal motion (lattice functions, emittance)
  - Tune plane
  - Longitudinal motion (phase stability, longitudinal emittance)
- The Accelerator Complex
  - Proton Source (Preac, Linac, Booster)
  - Main Injector
  - Pbar source (target, debuncher, accumulator)
  - Tevatron
  - Recycler
  - Operational modes
- The Challenges
  - Run II
  - MiniBooNE
  - NUMI

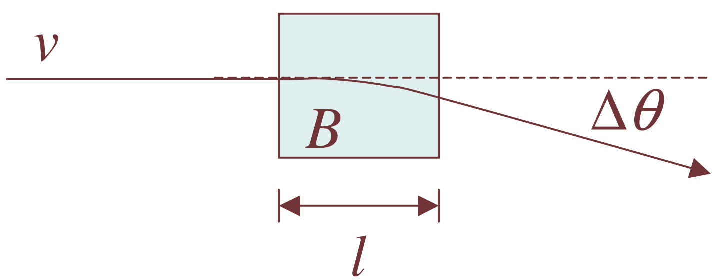
Dipole Field, Thin Lens Approximation.



A uniform magnetic field will bend particles in path of constant curvature:

$$\rho = \frac{\mathrm{p}}{eB} \Rightarrow \boxed{\rho[\mathrm{m}] = \frac{p[\mathrm{MeV/c}]/300}{B[\mathrm{T}]}}$$





“kink” at ≈ center of magnet

For small deflections:

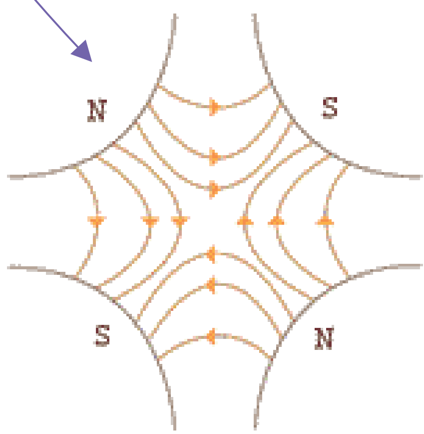
$$F = evB$$

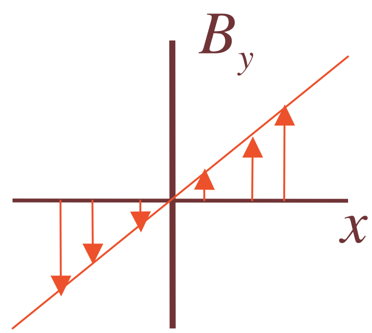
$$\Delta p \approx Ft = F\left(\frac{l}{v}\right) = Bl \equiv \text{"kick"}$$

$$\Delta\theta \approx \frac{\mathrm{p}}{\Delta p}$$

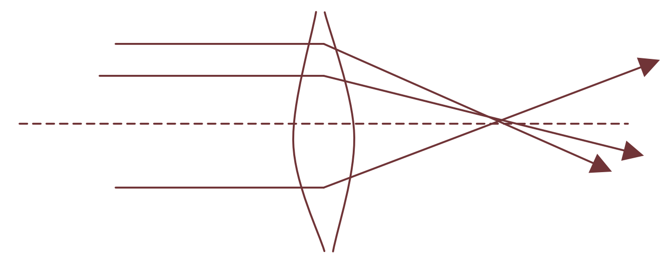
1 T-m = 300 MeV/c

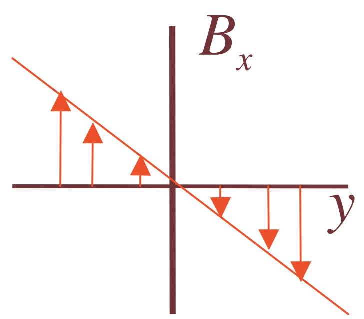
Quadrupole Fields (focusing elements)



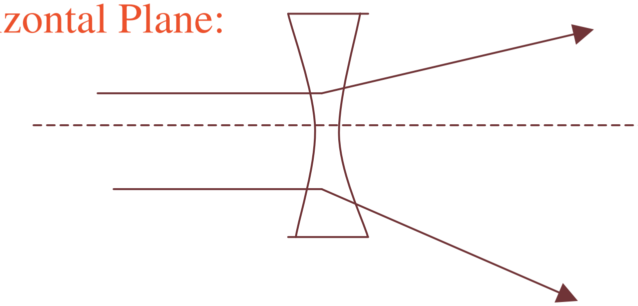


Vertical Plane:

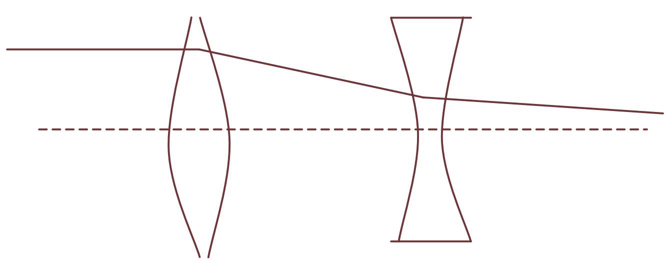


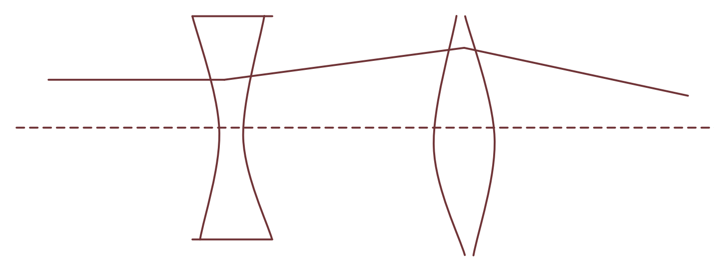


Horizontal Plane:



Luckily…



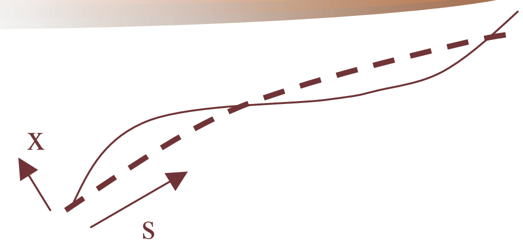


…pairs give net focusing in *both* planes!

"FODO cell"

Betatron Motion

For a particular particle, the deviation from an idea orbit will undergo "pseudo-harmonic" oscillation as a function of the path along the orbit:



Lateral deviation in one plane

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

Phase advance

$$\psi(s) = 2\pi \int_0^s \frac{ds}{\beta(s)}$$

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

Closely spaced strong quads -> small β -> small aperture

Sparsely spaced weak quads -> large β -> large aperture

β(s) is has the fundamental cell periodicity of the lattice $\Rightarrow \beta(s+L) = \beta(s)$

length of one, e.g., FODO cell

However, in general the phase (and therefore particle motion) does not, and indeed *must not*, follow the periodicity of the ring…

Tune and Tune Plane

We define the "tune" Q (or ν) as the number of complete betatron oscillations around the ring.

$$\nu = \frac{\psi(C+s)-\psi(s)}{2\pi} = 2\pi\int_s^{C+s}\frac{ds'}{\beta(s')} \approx \frac{C}{\langle\beta\rangle}$$

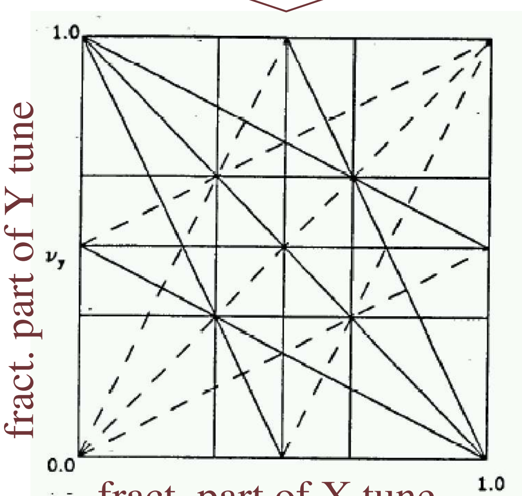
For example, the horizontal tune of the Booster is about: 6.7

Magnet Count/Aperture optimization

Beam Stability

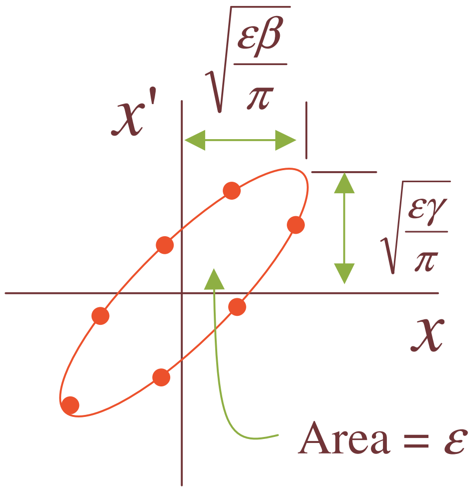
In general… $k_x\nu_x \pm k_y\nu_y = m \Rightarrow$ (resonant instability)

"small" integers



Many deviations from the ideal lattice are characterized in terms of their resulting "tune-shift". In general, the beam will become unstable if it shifts onto a resonance.

Emittance



As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space, defined by

$$\gamma_T x^2 + 2\alpha_T x x' + \beta_T x'^2 = \frac{\varepsilon}{\pi}$$

$$\gamma_T \beta_T - \alpha_T^{\ 2} = 1$$

Twiss Parameters

An ensemble of particles will have a "bounding" ε. This is referred to as the "emmitance" of the ensemble. Various definitions:

Electron machines: $\varepsilon = \frac{\pi \sigma_x^{\ 2}}{\beta_T}$ Contains 39% of Gaussian particles

Usually leave π as a unit, e.g. E=12 π-mm-mrad

Proton machines: (FNAL) $\varepsilon = \frac{6\pi \sigma_x^{\ 2}}{\beta_T}$ Contains 95% of Gaussian particles

Normalized Emittance

As the beam accelerates "adiabatic damping" will reduce the emittance as:

$$\varepsilon = \varepsilon_0 \frac{\gamma_0 \beta_0}{\gamma \beta}$$

The usual relativistic γ and β !!!!

so we define the "normalized emittance" as: $\boxed{\varepsilon_N = \gamma \beta \varepsilon_0}$

We can calculate the size of the beam at any time and position as: $x(s) = \sqrt{\dfrac{\varepsilon \beta_T(s)}{\pi \beta \gamma}}$

Example: Booster

			beam size [mm] (95%)	
Plane	ε_N [π-mm-mrad]	β_T [m]	Injection	Extraction
Horz	12	33.7	19.9	6.5
Horz	12	6.1	8.5	2.8
Vert	12	20.5	15.5	5.1
Vert	12	5.3	7.9	2.6

Slip Factor/Transition

A particle which deviates from the nominal momentum will travel a different path length given by….

$$\frac{\Delta L}{L} \equiv \alpha_C \frac{\Delta p}{p}$$

"Momentum compaction factor"

It will also travel at a slightly different velocity, given by

$$\frac{\Delta v}{v} = \frac{1}{\gamma^2}\frac{\Delta p}{p}$$

… so the time it takes to make one revolution will change by an amount

"slip factor"

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

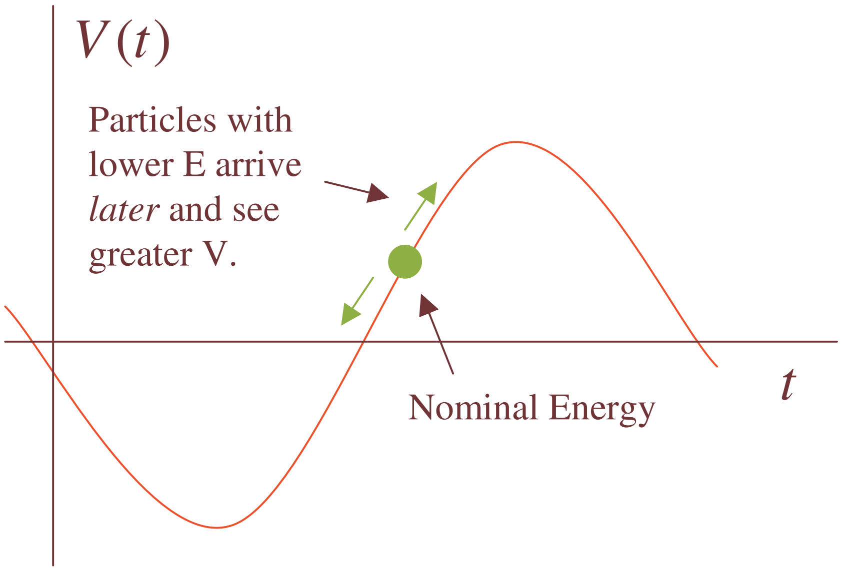
This changes sign at "transition", defined by

$$\gamma_t = \frac{1}{\sqrt{\alpha_C}}$$

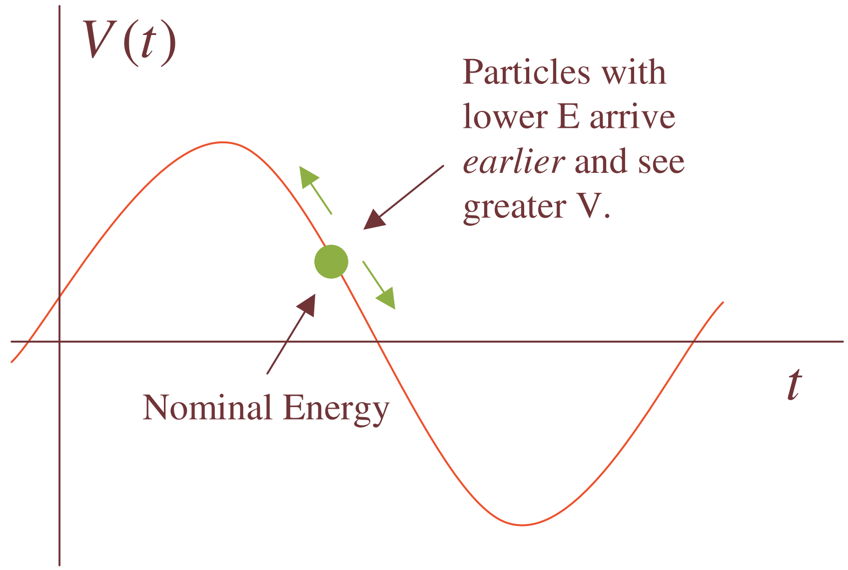
Usually $\gamma_T \approx \nu$. In booster $\gamma_T = 5.45$

Phase Stability

As particles circulate around a ring, they pass through standing RF waves in accelerating cavities. The stability depends on the relative energy received by off-energy particles

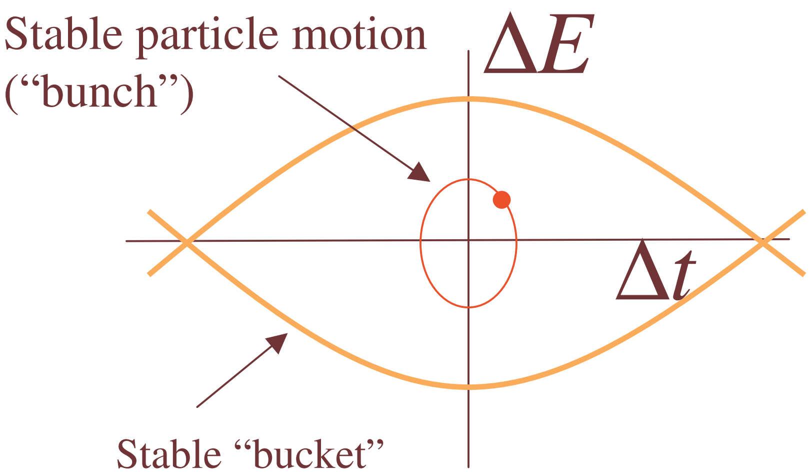


Below Transition

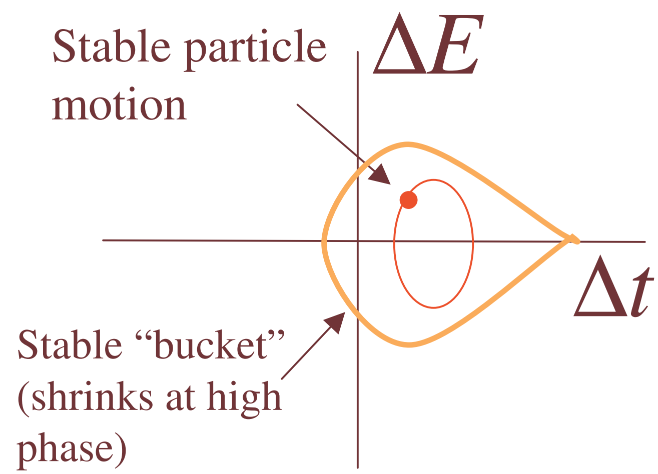


Above Transition

Longitudinal Phase Space



$\phi=0$ (no acceleration):

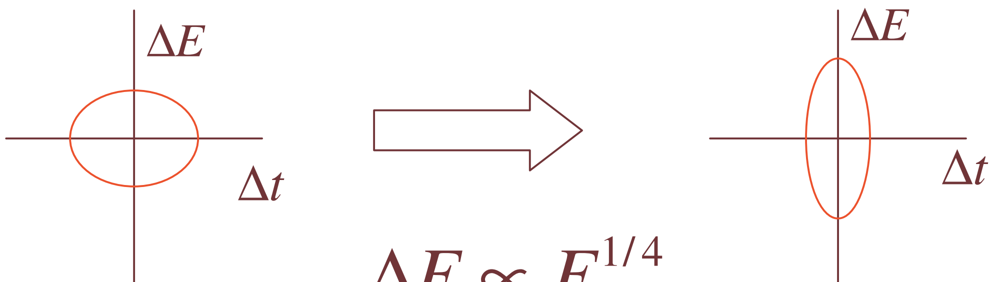


$\phi=60°$ (acceleration):

- Generally, hold RF *amplitude* constant, and adjust *phase* to control acceleration.
- If amplitude control is needed, it is accomplished by adjusting the *relative phase* of two sets of RF cavities.

Longitudinal Emittance

As the particles accelerate



$$\Delta E \propto E^{1/4}$$
$$\Delta t \propto E^{-1/4}$$

$$\Delta t \Delta E \equiv \varepsilon_L = (\text{constant})$$

Longitudinal Emittance.
Usually expressed in eV-s

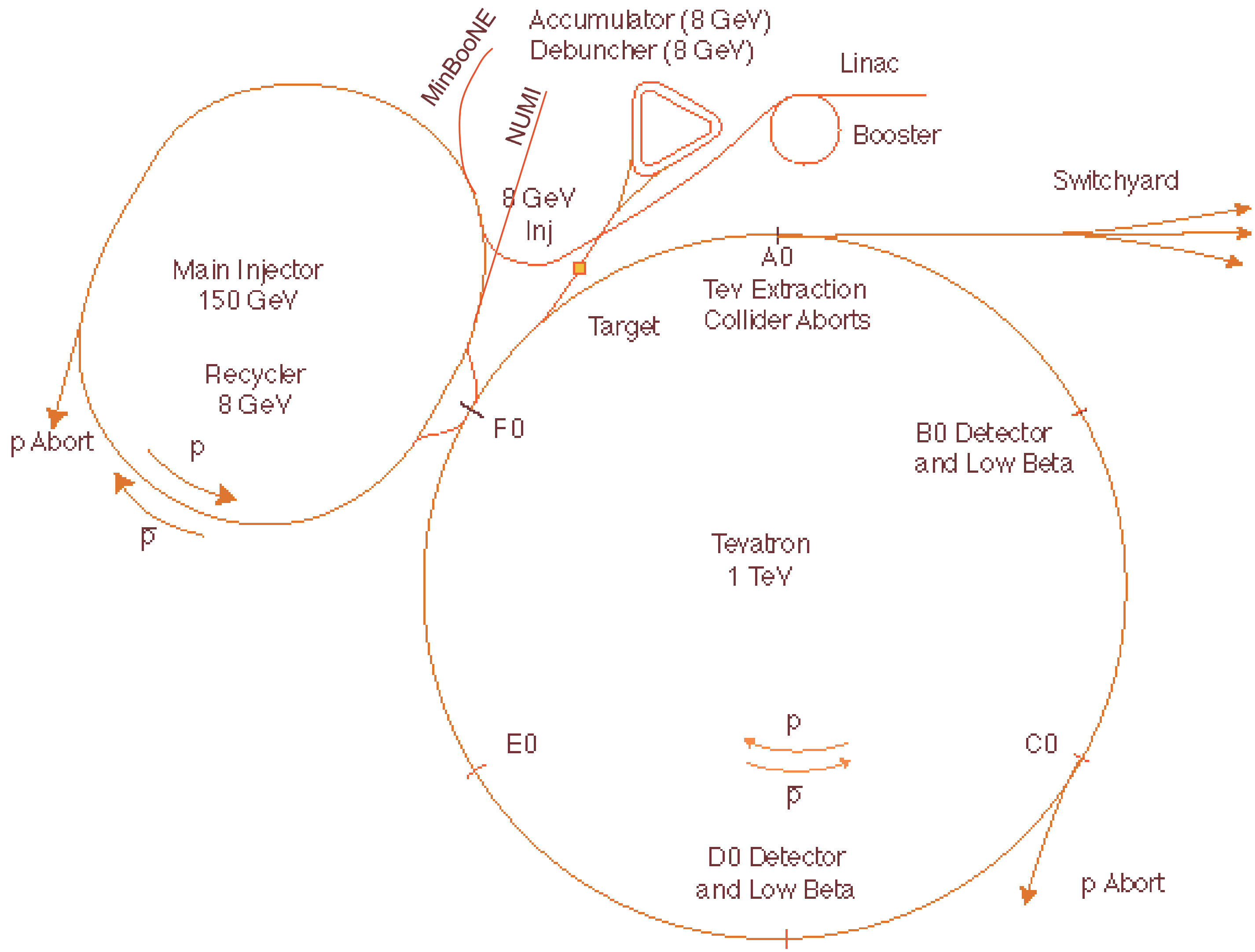
Typical values out of the booster are about .15 eV-s

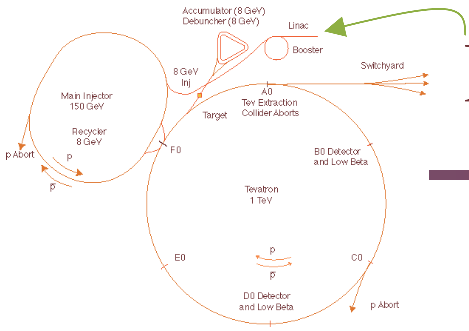
Fermilab Accelerators

History

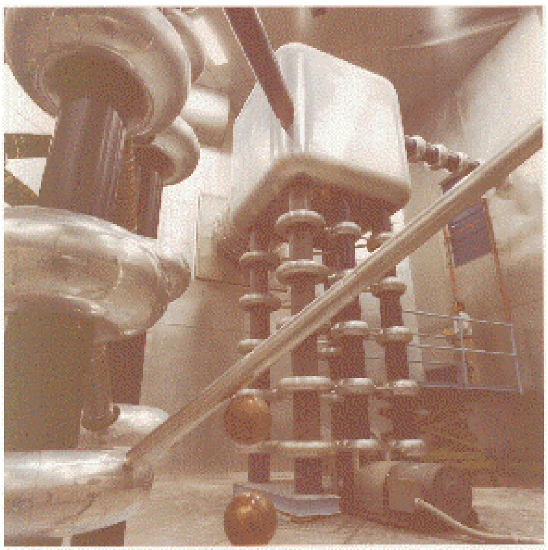
- Early 1960's – plans solidify for a high energy national accelerator laboratory.
- 1966 – The AEC chooses the Weston, IL site from amongst hundreds proposed.
- 1968 – Construction begins.
- 1972 – First 200 GeV beam in the Main Ring.
- 1983 – First (512 GeV) beam in the Tevatron ("Energy Doubler"). Old Main Ring serves as "injector".
- 1985 – First proton-antiproton collisions observed at CDF (1.6 TeV CoM).
- 1995 – Top quark discovery. End of Run I.
- 1999 – Main Injector complete.
- 2001 – Run II begins.

The Fermilab Accelerator Complex

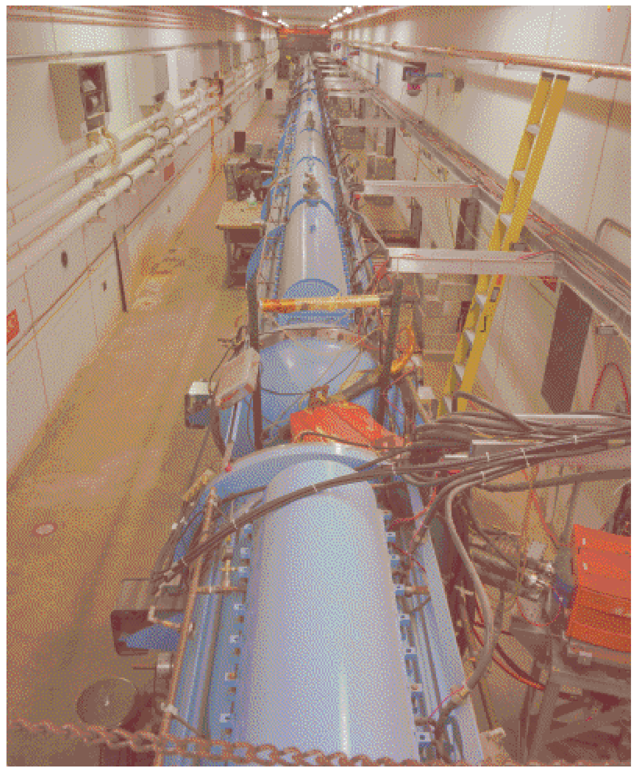




Preac(cellerator) and Linac

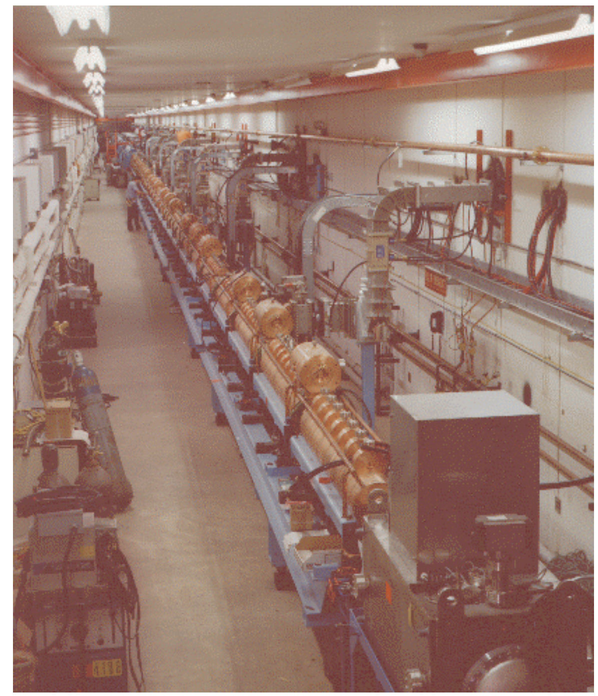


"Preac" - Coolest looking thing at Fermilab. Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV. (Actually, there are two of these, H- and I-)



"Old linac"- 200 MHz "Alvarez tubes" accelerate H- ions from 750 keV to 116 MeV

"New linac"- 800 MHz "π cavities" accelerate H- ions from 116 MeV to 400 MeV



Preac/Linac can deliver about 45 mA of current for about 35 usec at a 15 Hz repetition rate

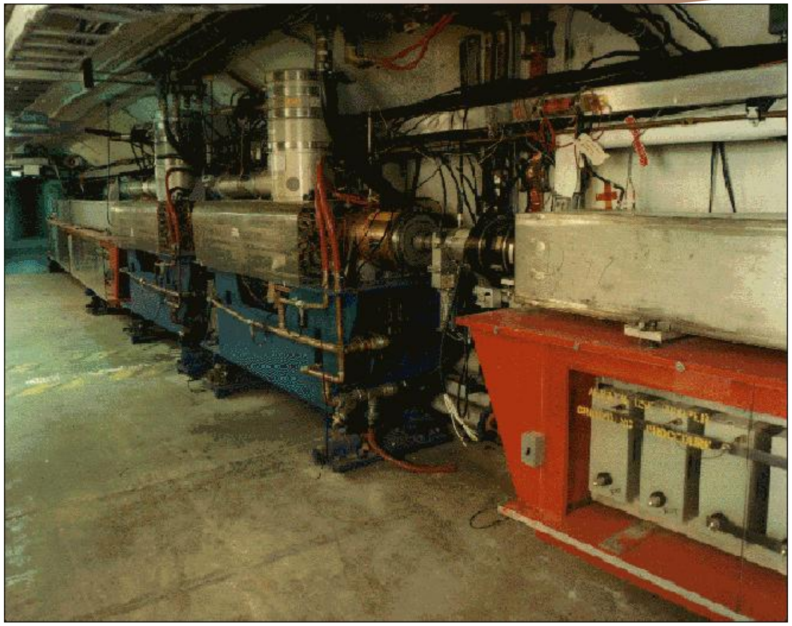
Booster

• 400 MeV Linac H- beam is injected into booster over several (up to 15) “turns”. The ion beam allows one to “cheat” Liouville’s theorem and inject (negative) beam on top of existing (positive) beam.

• The main magnets of the Booster form a 15 Hz offset resonant circuit , so the Booster field is continuously “ramping”, whether there is beam in the machine or not. Ramped elements limit the average rep rate to somewhat lower.

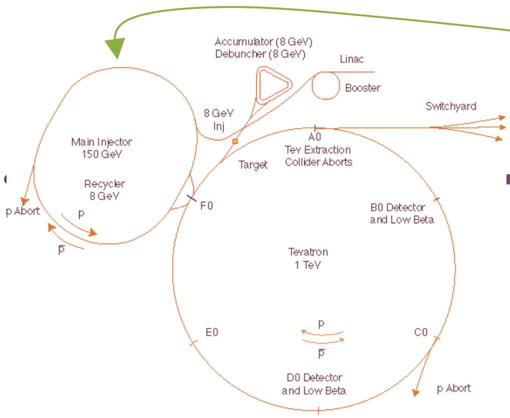
•From the Booster, beam can be directed to

- The Main Injector
- MiniBooNE (switch occurs in the MI-8 transfer line).
- The Radiation Damage Facility (RDF) – actually, this is the old main ring transfer line.
- A dump.



• One full booster “batch” sets a fundamental unit of protons throughout the accelerator complex (max 5E12).

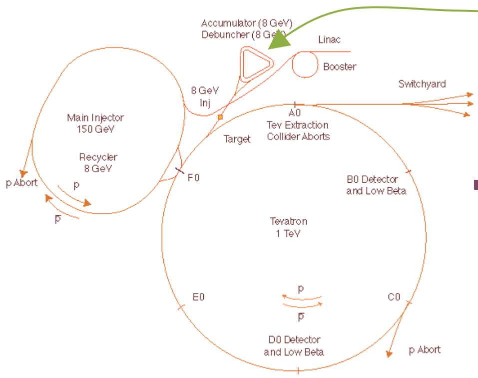
•This is divided amongst 84 53 MHz RF buckets, which sets another fundamental sub-unit (max 6E10).



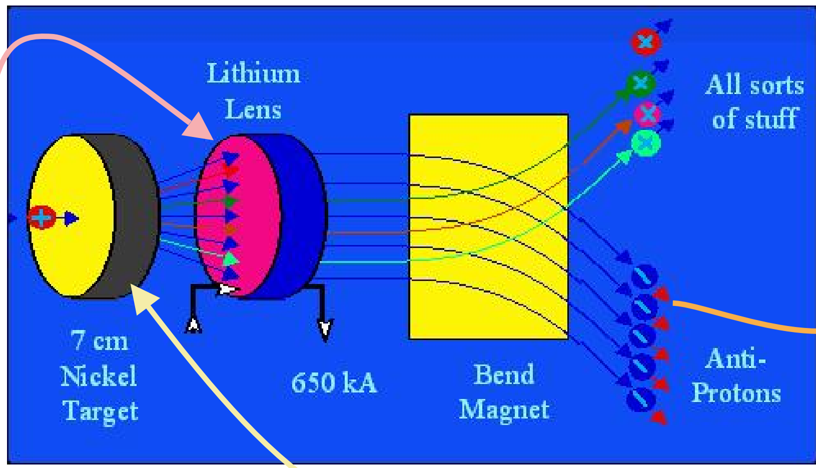
Main Injector

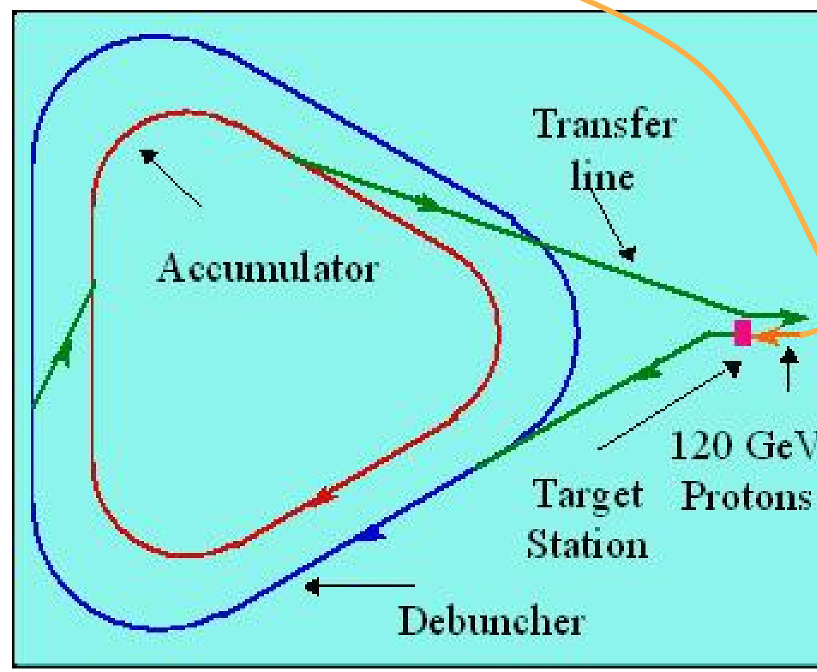
- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The Recycler (which shares the same tunnel)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - (soon) The fixed target area.
  - (soon) The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.
- The Main Injector can also accept 150 GeV antiprotons from the Tevatron and *decelerate* them to 8 GeV for transfer to the Recycler.

- The Main Injector is exactly 7 times the circumference of the Booster. Allowing one empty “slot” for switching, it can hold six booster batches, in the absence of exotic stacking schemes (slip stacking, RF barrier).
- It’s envisioned that one batch will be used for stacking and the rest for NUMI and/or switchyard 120.



Antiproton Source



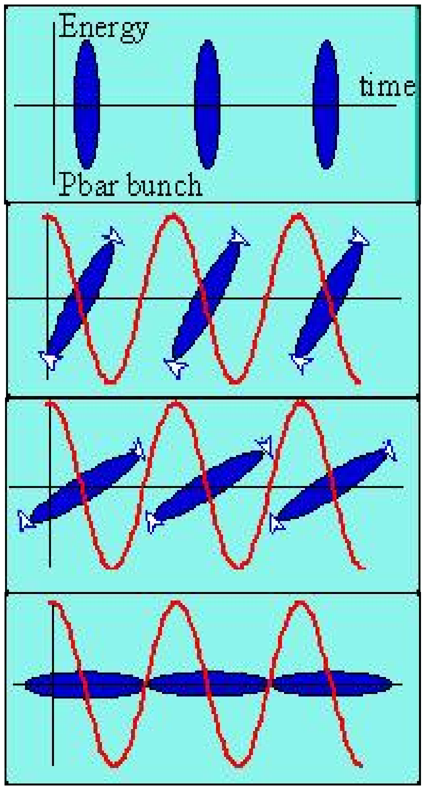


- 120 GeV protons strike a target producing many things, including antiprotons.
- a Lithium lens focuses these particles.
- a bend magnet selects the negative particles around 8 GeV. Everything but antiprotons decays away.

- The antiproton ring consists of 2 parts – the debuncher and the accumulator.

Antiproton Source – Debunching and Cooling

Debunching



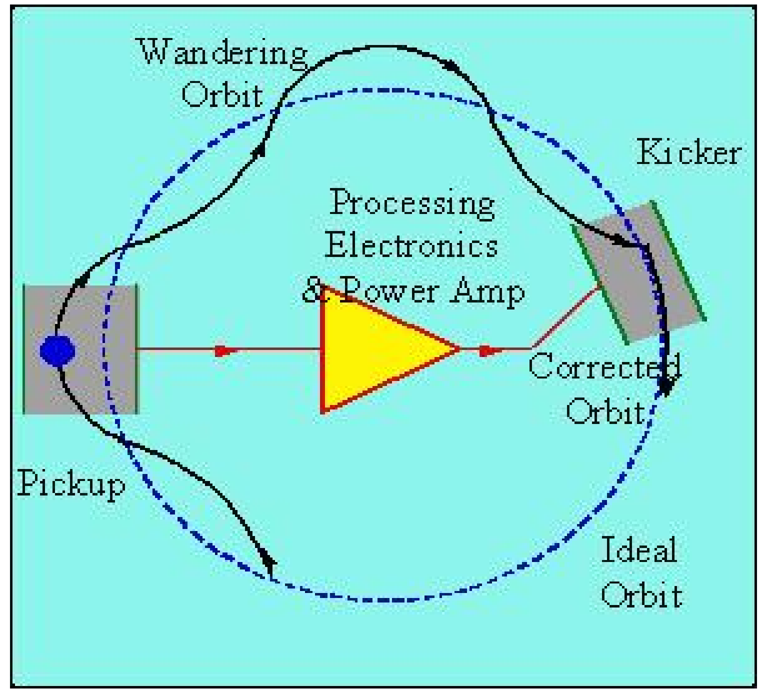
Particles enter with a *narrow* time spread and *broad* energy spread.

High (low) energy pbars take more (less) to go around…

…and the RF is phased so they are decelerated (accelerated),

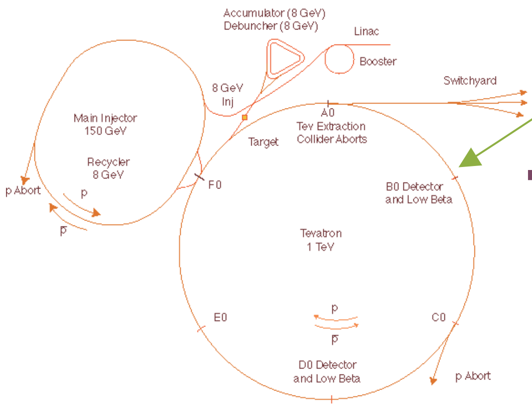
resulting in a *narrow* energy spread and *broad* time spread.

Cooling



Pickups detect deviations from an ideal orbit, which are used to "kick" the orbit back to the nominal. This reduces the transverse emittance in a statistical way.

The anti-proton source can typically "stack" at about 7E10 pbars/h, up to a maximum of about 120E10, at which point anti-protons are transferred to the Tevatron (via the M.I.).



Tevatron

- The Tevatron was the world's first superconducting accelerator.
- It accepts protons AND pbars at 150 GeV from the Main Injector. Typically:
  - 36 proton bunches with 180E9 protons in each. (Run IIa goal: 270E9)
  - 36 pbar bunches with 12E9 pbars in each. (Run IIa goal: 33E9)
- These are accelerated to 980 GeV.
- Collisions ("low beta") are initiated at the B0 (CDF) and D0 detector regions.
- These "stores" are kept for typically 16 hours, while more antiprotons are made for the next "shot".

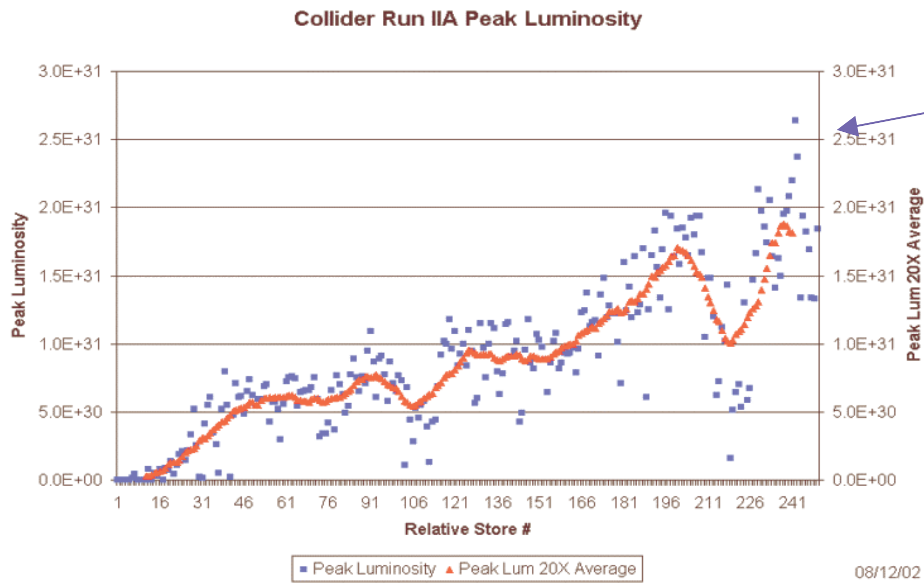
Recycler

- The Recycler is an 8 GeV storage ring in the same tunnel as the Main Injector.
- The main lattice elements (dipoles and quadrupoles) are made out of permanent magnets).
- The Recycler can accept 8 GeV antiprotons from
  - The antiproton accumulator.
  - The Main Injector (after deceleration).
- The Recycler can deliver these antiprotons to the Main Injector for acceleration.
- The goal of the recycler is
  - To store antiprotons from the accumulator, thereby increasing the total antiproton production capacity.
  - To recover antiprotons from a Tevatron store for use in subsequent stores.
- At the moment, the recycler is not being used in standard operation.

Primary Modes of Operation

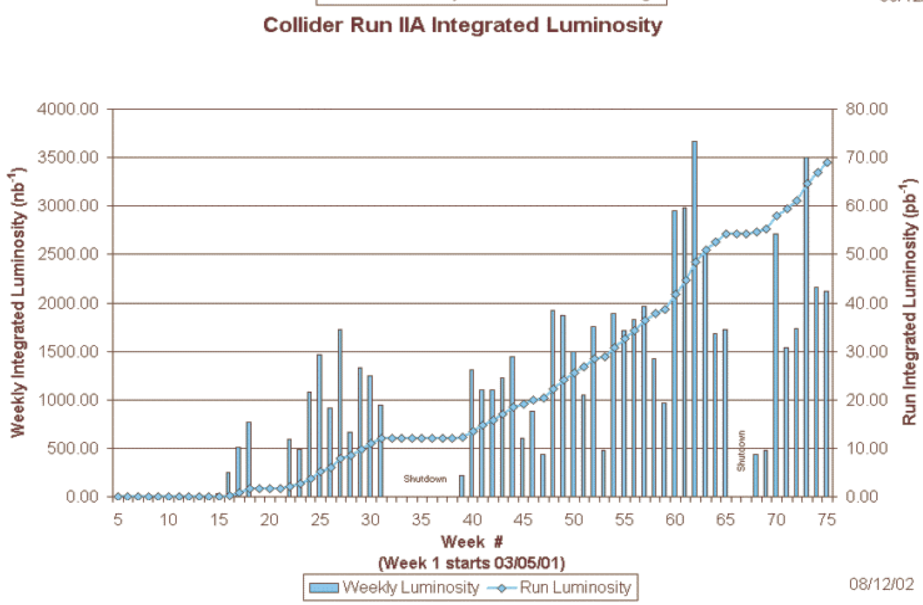
- **Stacking:** full booster batches (~5E12 p) are accelerated to 120 GeV by the Main Injector, and delivered to the pbar target about once every 3 seconds (limited by the rate at which they can be debunched and cooled. It takes 10-16 hours to get enough pbars for a "shot".
- **Shot setup:** various beamline tuning takes place. Most importantly, pbar transfer lines are tuned with *reverse protons*.
- **Proton Injection:** about 7 53 MHz booster bunches are injected into the M.I., accelerated to 150 GeV and "coalesced" into a single bunch, which is injected into the Tevatron (x 36).
- **Antiproton Injection:** part of the "core" of the accumulator is manipulated to a separate extraction orbit and about 11 53 MHz bunches are extracted to the M.I., where they are accelerated to 150 GeV, coalesced and injected into the tevatron at 150 GeV.
- **Acceleration/collision:** The protons and pbars are accelerated together to 980 GeV over a few minutes. The beam is scraped, and the beta is reduced ("squeezed") at the collision regions. Physics begins. During this time, the rest of the accelerator complex is *totally free to do other things* (primarily stacking).
- **MiniBooNE Operation:** While the M.I. Is ramping, a chain of 8 GeV Booster batches is switched to the MiniBooNE beamline.
- **NUMI Operation:** along with the stacking batch, 5 additional batches are loaded into the Main injector. These are accelerated along with the stacking batch and extracted to the NUMI line after it has been extracted.

How is Run II Going?



Record: 2.7E31

Run IIa Goal: 8.3E31



Original Run IIa Goals:

- 2E32 Peak Luminisity
- 2 fb^{-1} in two years

Why Haven't Run IIa Goals been Met?

- Number of pbars!!!
  - NOT (primarily) due to protons on target or pbar production rate.
  - Typically only around 50% of pbars from the accumulator make it to collisions.
  - Some of this is due to large emittances out of the accumulator. This gets worse with larger stacks.
  - Some is due to aperture and matching problems throughout the system.
- Long range beam interactions in the Tevatron:
  - Limit total number of protons.
  - Due to aperture and helix problems.
- General reliability problems:
  - It's a very complicated system
  - If we lose the antiprotons, it takes *at least* 12 hours to recover.

The Plan

- New cooling has been installed in the accumulator and is being tested. Initial results look good.
- Studies continue to understand all the transfer efficiencies of the machines.
- Continue to improve helix and aperture in Tevatron to reduce long range beam interaction.
- Integrate recycler into accelerator operation some time in 2003.

(Near) Future Challenges

- *Two* important neutrino experiments are coming on line soon:
  - **MiniBooNE** will use the 8GeV Booster beam and a detector 500 m away to look for neutrino oscillations in the range $\Delta m^2 \sim 1\ eV^2$ – the range indicated by the LSND experiment.
  - **NUMI** will use the 120 GeV Main Injector beam and a detector 750 km away to look for neutrino oscillations in the range of $\Delta m^2 \sim 10^{-5}\ eV^2$ – the range indicated by atmospheric and solar neutrino data.
- Both of these experiments place a major challenge on the Booster – arguably the *only* more or less original part of the Fermilab accelerator complex.

What's so Hard About Neutrino Physics (*from the Accelerator Standpoint*)?

- Probability that a proton on the AP target will produce an accumulated pbar:

  .000015 (1.5E-5)

- Probability that a proton on the MiniBooNE target will result in a detected neutrino:

  .000000000000004 (4E-15)

- Probability that a proton on the NUMI target will result in a detected neutrino at the MINOS far detector:

  .000000000000000025 (2.5E-17)

⇒ *Need more protons in a year than Fermilab has produced in its lifetime!!*

What Limits Total Proton Intensity?

- Maximum number of Protons the Booster can stably accelerate: 5E12
- Maximum average Booster rep. Rate: currently 2.5 Hz, soon 7.5 Hz
- (NUMI only) Maximum number of booster batches the Main Injector can hold: currently 6, possibly go to 11
- (NUMI only) Minimum Main Injector ramp cycle time (NUMI only): 1.4s+loading time
- Losses in the Booster:
  - Above ground radiation
  - Damage and/or activation of tunnel components

Our biggest worry at the moment!!!!

Proton Timelines

- Everything measured in 15 Hz "clicks"
- Minimum M.I. Ramp = 22 clicks = 1.4 s
- MiniBoone batches "don't count".
- Cycle times of interest
  - Stack cycle: 1 inj + 22 MI ramp = 23 clicks = 1.5 s
  - NuMI cycle: 6 inj + 22 MI ramp = 28 clicks = 1.9 s
  - Full Slipstack cycle (total 11 batches):

```
   6 inject
+ 2 capture (6 -> 3)
+ 2 inject
+ 2 capture (2 -> 1)
+ 2 inject
+ 2 capture (2 -> 1)
+ 1 inject
+ 22 M.I. Ramp
----------------------
39 clicks = 2.6 s
```

Summary of Proton Ecomomics

MiniBooNE baseline ≈ 5E20 p/year

Booster Hardware Issues

Radiation Issues

Scenario	Cycle (clicks)	Batches				Rep rate (ave. Hz)	Protons delivered (x E12 pps)*			Total	
		prepulse	Stack	MB	NuMI		Stack	MB	NuMI	E12	/RunII
Stack	23	2	1			2.0	3.3	0.	0.	3.3	1.
Stack/MB	23	2	1	8		7.2	3.3	26.1	0.	29.3	9.0
Stack/NuMI	28	2	1		5	4.3	2.7	0.	13.4	16.1	4.9
Stack/NuMI/MB	28	2	1	10	5	9.6	2.7	28.8	13.4	42.9	13.1
Slipstack/NuMI	39	2	2		9	5.0	3.8	0.	17.3	21.2	6.5
Slipstack/NuMI/MB	39	2	2	13	9	10.0	3.8	25.0	17.3	46.2	14.2

NUMI "baseline" = 13.4E12 pps x 2E7 s/year ≈ $\boxed{\text{2.7E20 p/year}}$

*assuming 5E12 protons per batch

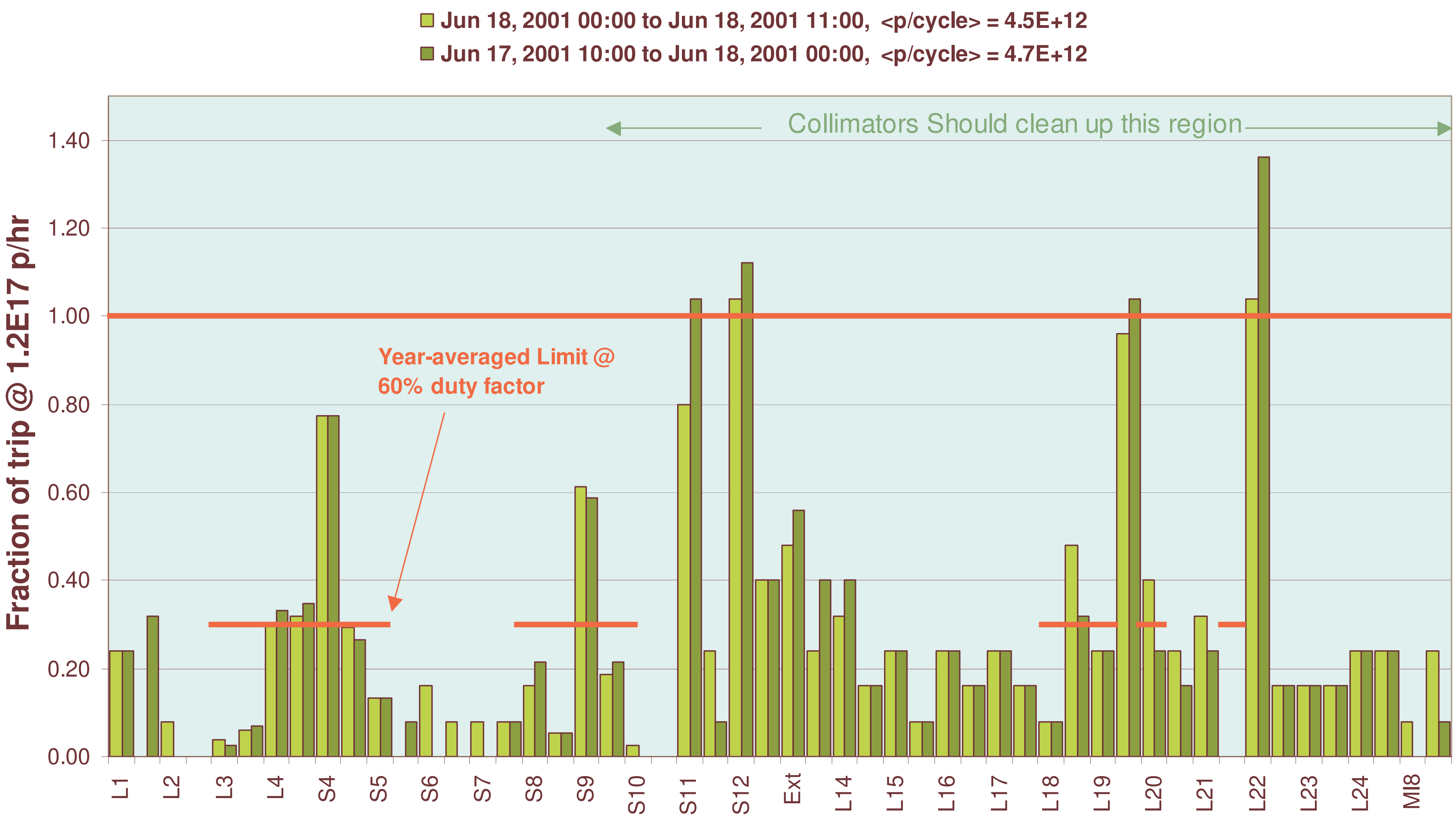
Booster Repetition Rate Limits

- Presently, the Booster is limited to an average rep. Rate of 2.5 Hz, which would only yield a small fraction of the desired MiniBooNE intensity. The primary limitation is the pulsed extraction septum magnet (MP02).
- A new power supply will go in in the next few weeks, which will raise this rate to 4.5 Hz, which would give about half the nominal MiniBooNE rate.
- A new magnet will go in during the January shutdown which will allow the Booster to go to 7.5 Hz – enough for MiniBooNE or NUMI.
- In order to run both MiniBooNE and NUMI, we need
  - More cables for the extraction septum.
  - Cooling for the RF cavities (or new RF cavities)
  - A new "bump" magnet, which steers beam out during injection.

Above Ground Radiation

- Main worry are the high occupancy areas in the Booster towers.
- Shielding has been added both in the tunnel and to the first floor of the Booster towers.
- Offices have been moved to reclassify some worrisome areas.

Best Performance + Shielding + BooNE Intensities



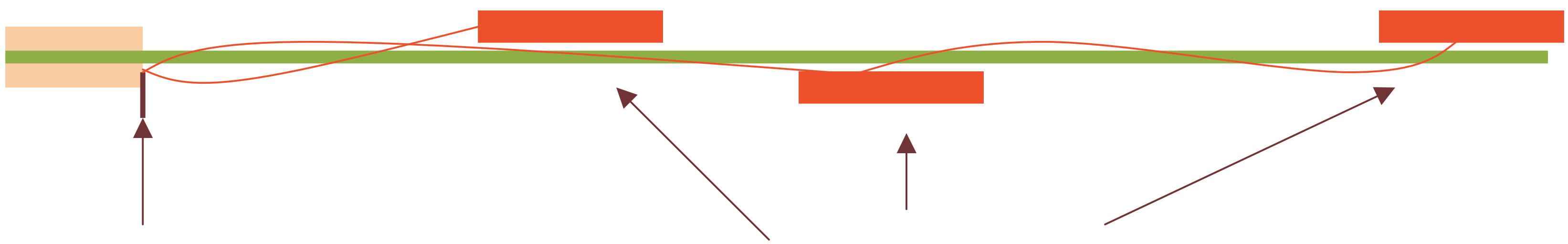
Scaled up from measurements during stacking-> looks *OK*

Booster Tunnel Losses

- Harder to quantify – no hard limits
- Major worry is activation of high maintenance components (e.g. RF cavities).
- Administrative limit set at twice the total power loss during "messy" stacking (for 9 times the beam!!!).
- If we had to run tomorrow, we could deliver roughly 20% of the nominal MiniBooNE intensity under this scenario.
- Steps are being taken to reduce beam losses and proton source consistency.

Collimators

Basic Idea…



A scraping foil deflects the orbit of halo particles…

…and they are absorbed by thick copper collimators.

All are moveable, and the Copper collimators are located in areas (period 6&7) where radiation is less of an issue. Once their operation has been established, these areas will be heavily shielded.

It is hoped that this collimation could reduce important losses by up to a factor of two – possibly more in critical areas.

Status: All collimators are in and have been exercised. Initial results look encouraging. A preliminary shielding design is complete and shielding should be installed over the next few months.

Other Improvements

- **Beam control:** programmable trim magnet control cards now allow control of the orbit throughout the cycle.
- **Improved beam monitoring:** a number of new beam diagnostics, including a real time tune measurement, had been or are being commissioned.
- **New monitoring and analysis tools:** we have been pledged support from computing division, which we plan to use to develop improved tools for monitoring and analyzing the performance of the proton source.

Summary

- The Fermilab accelerator complex is very complex and versatile.
- It presents many challenges which keep us busy now and in the foreseeable future.
- We're always looking for people to help out.