Phase Space and Antiproton Production at Fermilab

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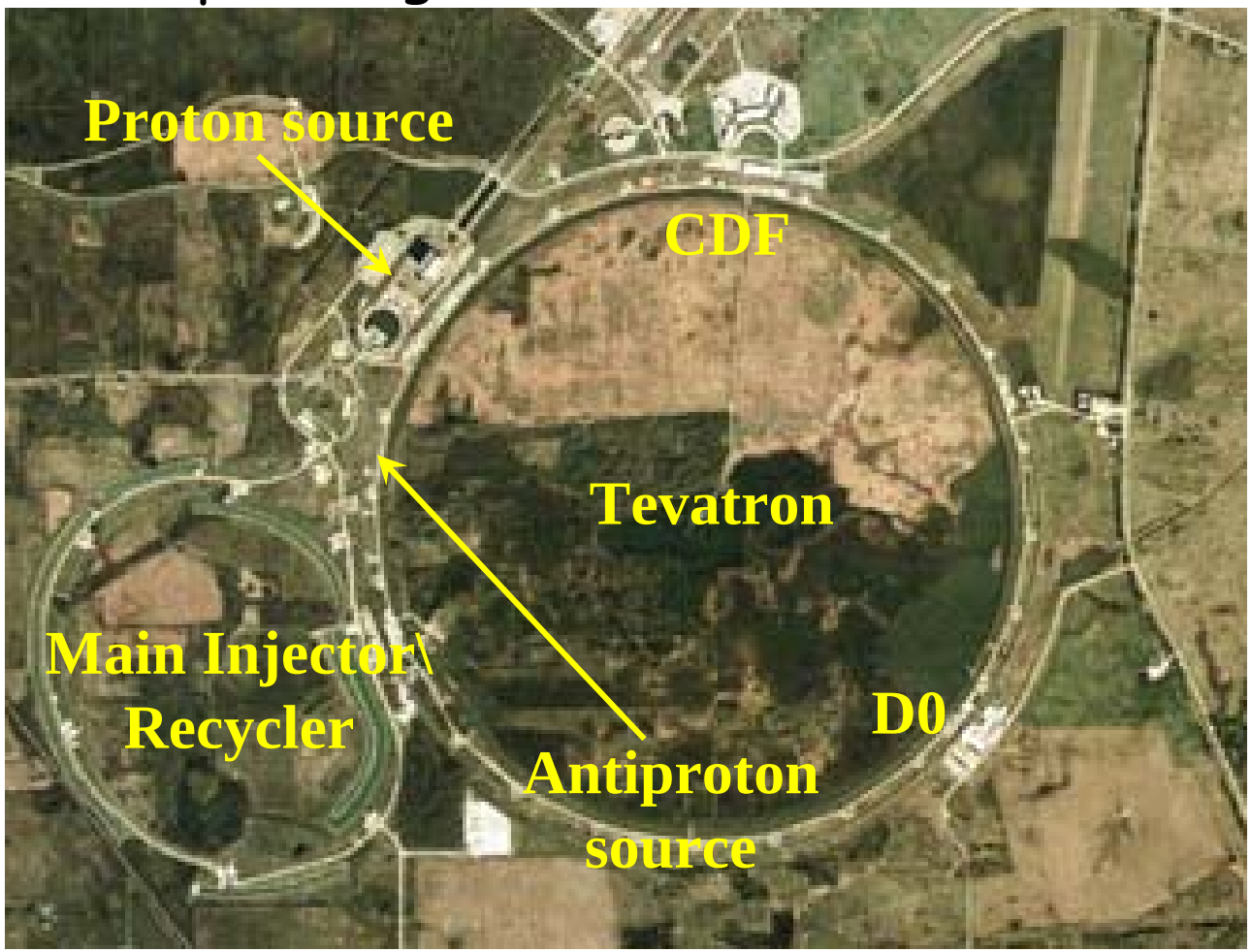
Introduction

- A key feature to the success of a high energy collider is the beam brightness or luminosity.
- The beam brightness is determined by particle motion or evolution though the accelerator chain.
- To first order, the motion of particles in an accelerator can be described by simple harmonic motion around an ideal trajectory or energy.
- This motion can be portrayed using the concept of phase space.
- This talk will use the Fermilab Tevatron collider as an example of the importance of phase space in high energy colliders
  - The use of antiprotons in the Tevatron pose additional challenges that are clearly illustrated with the concept of phase space.

Fermilab Complex

- The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV



Luminosity

$$L = \frac{3\gamma f_o}{\beta^*} BN_{\bar{p}} \frac{N_p}{\varepsilon_p} \frac{F\left(\beta^*, \theta_{x,y}, \sigma^L_{p,\bar{p}}, \varepsilon_{p,\bar{p}}\right)}{\left(1 + \varepsilon_{\bar{p}} / \varepsilon_p\right)}$$

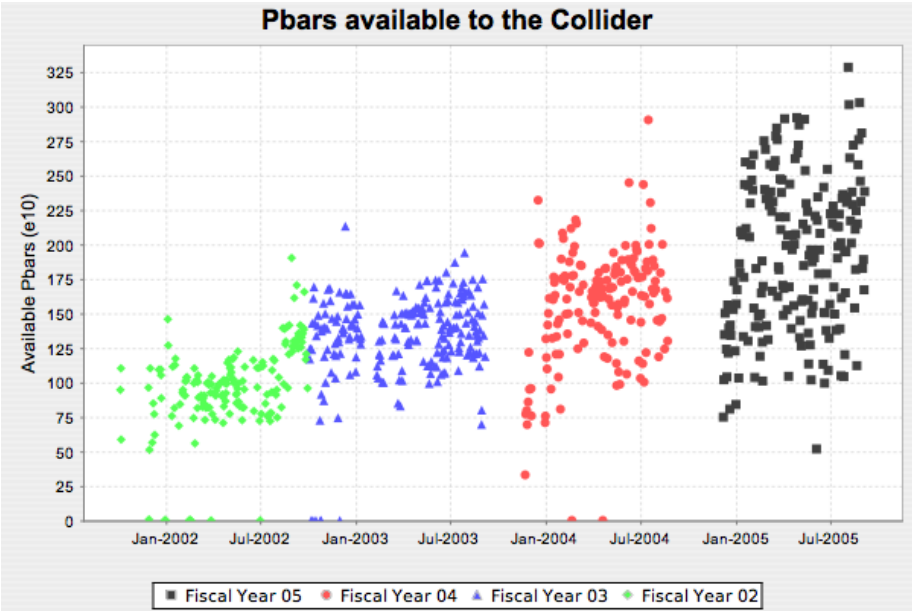
- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
    - Beam-Beam effects
  - Antiproton emittance
  - F<1

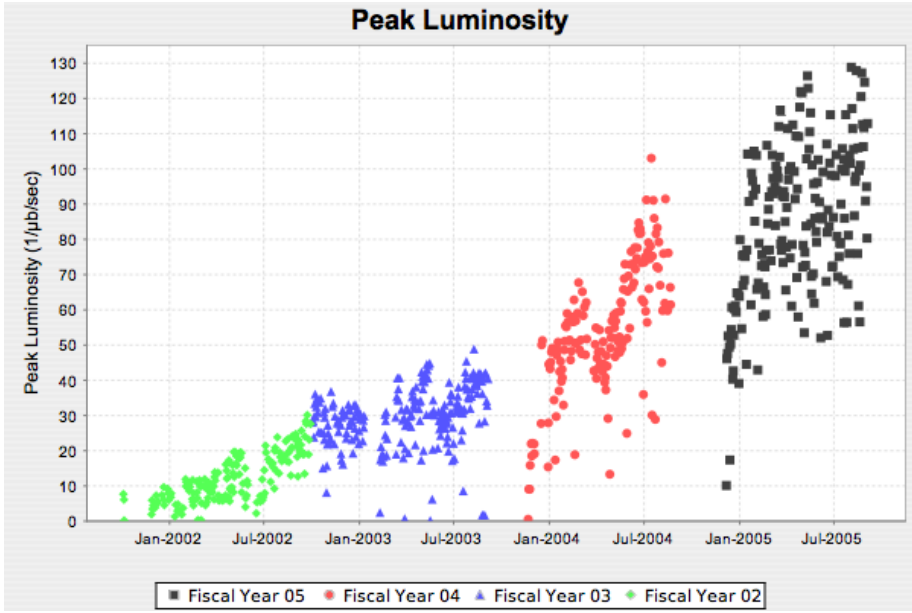
Antiproton Economics

$$\Phi_{\bar{p}}^{(\min)} = n_c \sigma_a L$$

- $n_c = 2$
- $\sigma_a = 70$ mb
- $L = 3.0\times10^{32}$ cm^{-2}-sec^{-1}
- $\Phi = 15\times10^{10}$ hr^{-1}

Antiprotons and Luminosity

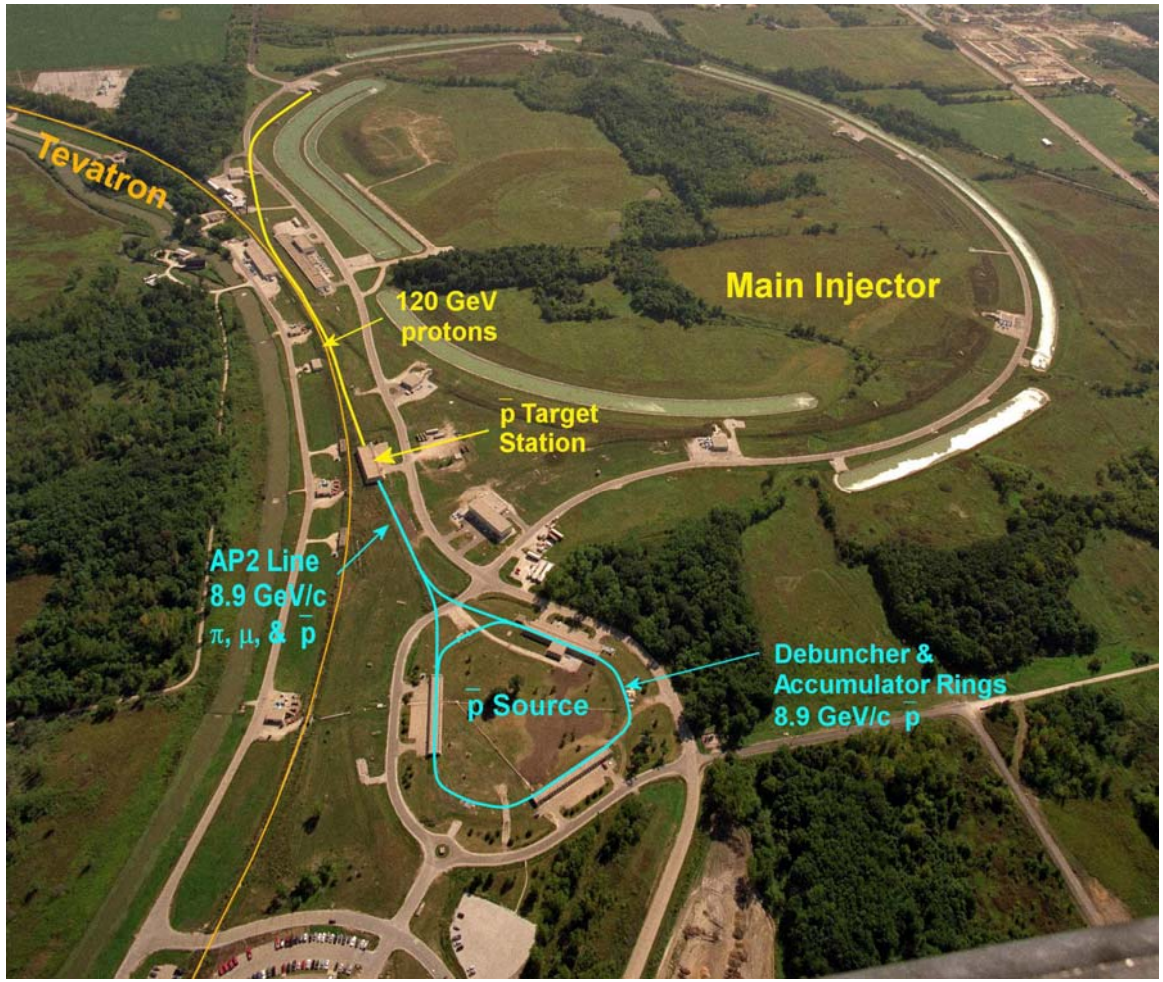




- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Antiproton Production

- 1×10^8 8 GeV pbars are collected every 2-4 seconds by striking 7×10^{12} 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON



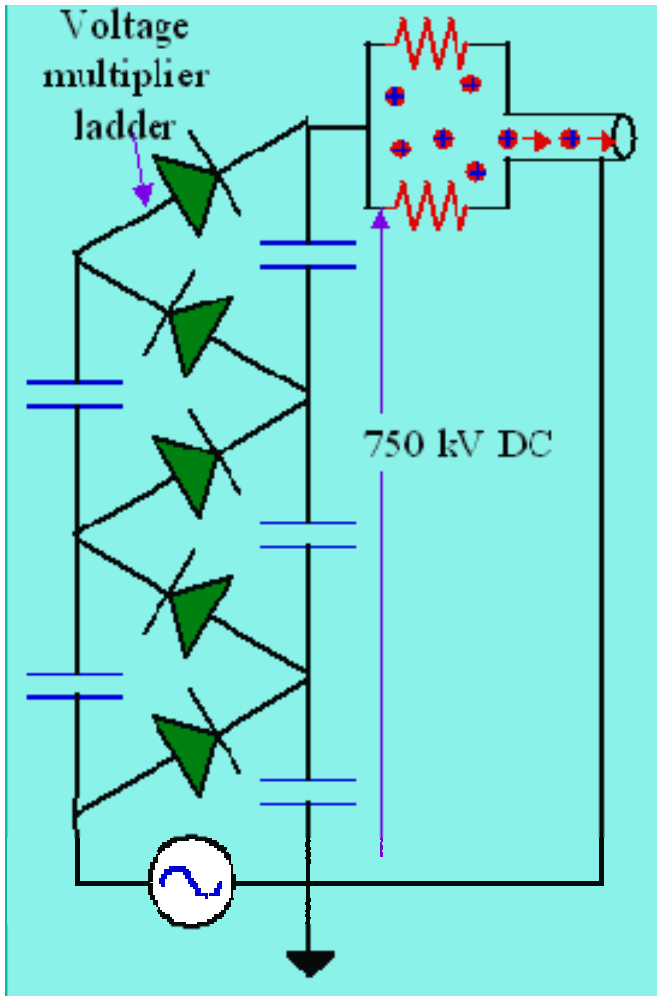
Stacking Rate

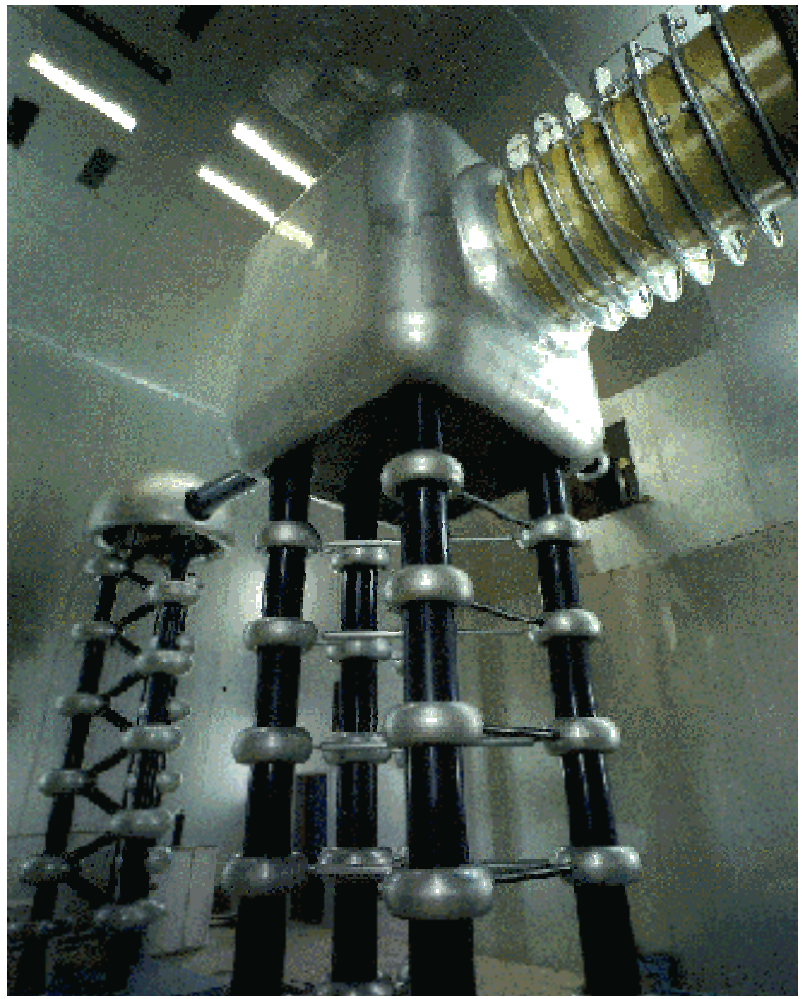
$$\Phi = \frac{N_p P}{T_{rep}}$$

- N_p is the number of protons on target
- P is the production ratio of the number of antiprotons produced to N_p
  - Typically about 15-20x10^{-6}
  - Mostly a function of the collection aperture
- T_{rep} is the cycle time
  - Mostly a function of the cooling rate

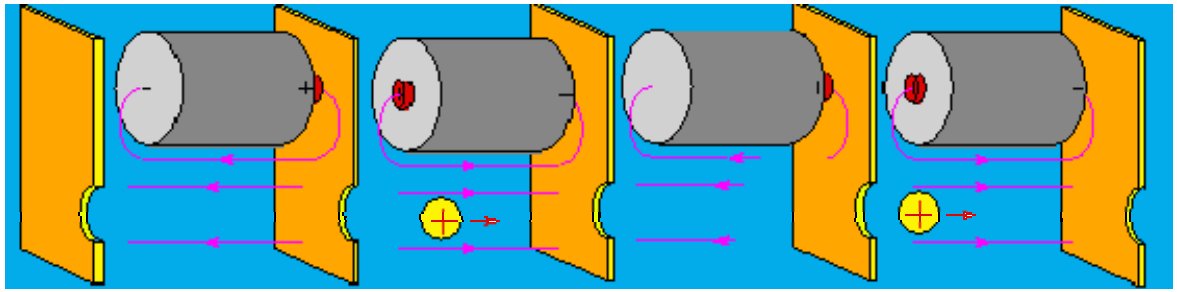
Number of Protons on Target

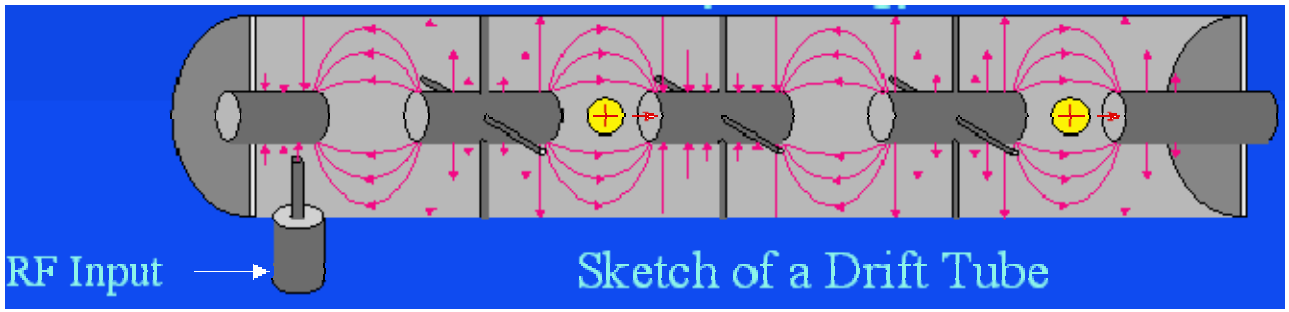
- First Stage of Acceleration
  - Can be thought of as a 750kV DC voltage source.
  - The maximum voltages is limited by how much the air can "stand off"

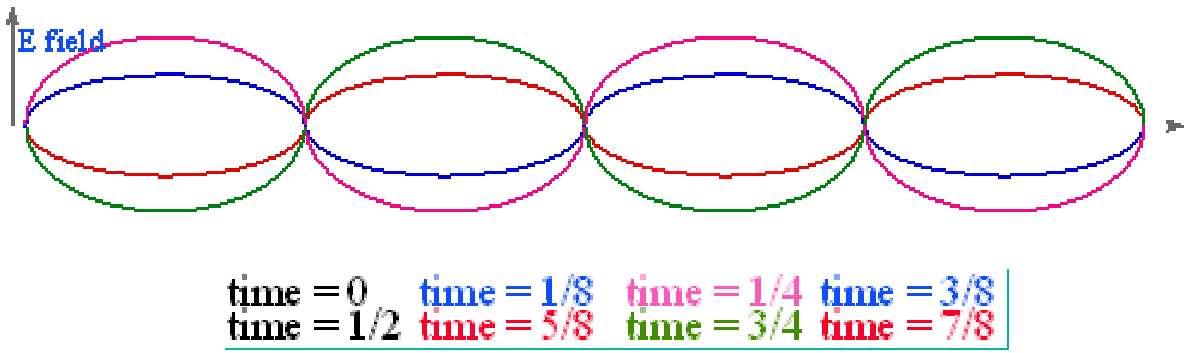




Second Stage of Acceleration – The Linac

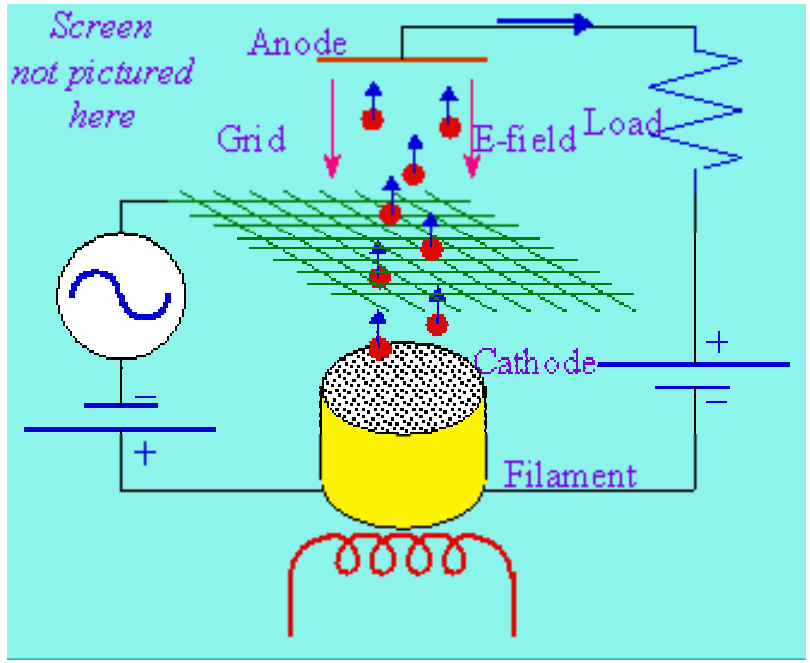






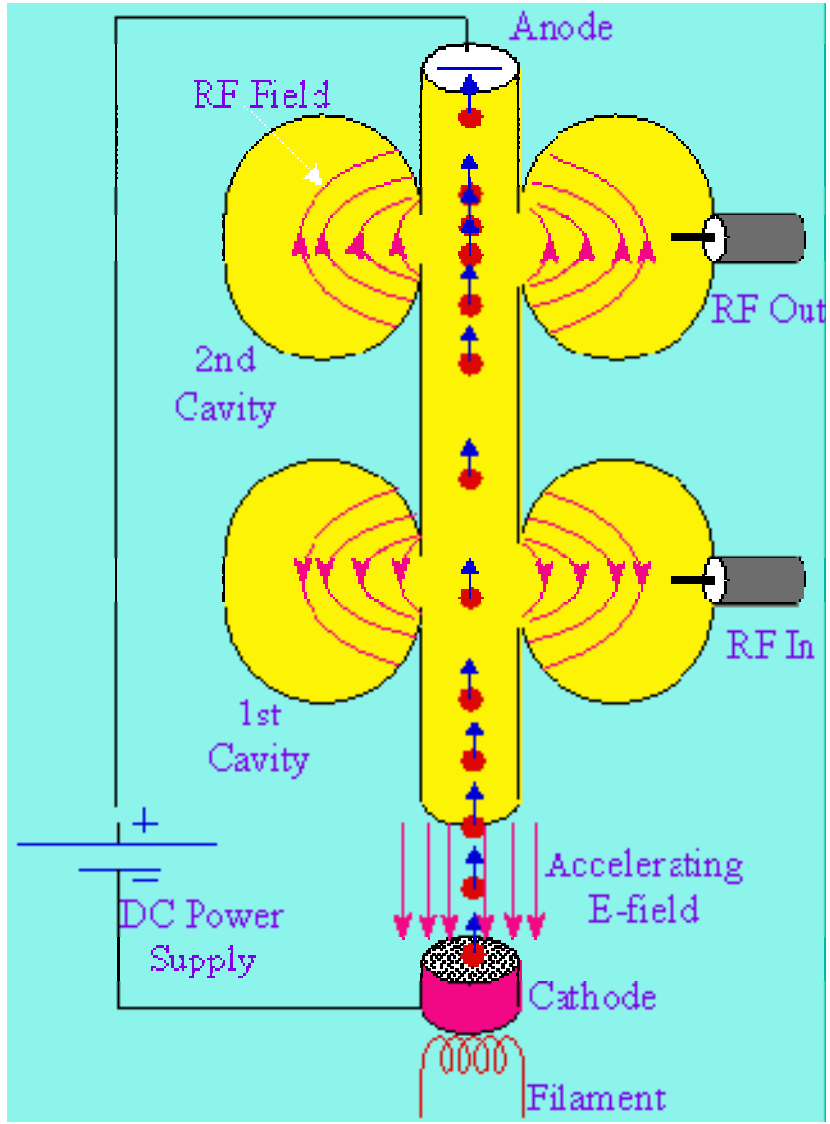
RF Power Amplifiers – The Tetrode

- The tetrode is in itself a miniature electron accelerator
- The filament boils electrons off the cathode
- The electrons are accelerated by the DC power supply to the anode
- The voltage between the grid to cathode controls how many electrons make it to the anode
- The number of electrons flowing to the anode determines the current into the load
- The tetrode can be thought of as a voltage controlled current source
- Tetrodes work well at low frequencies (< 400MHz)



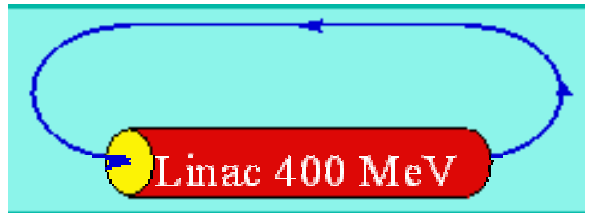
RF Power Amplifiers – The Klystron

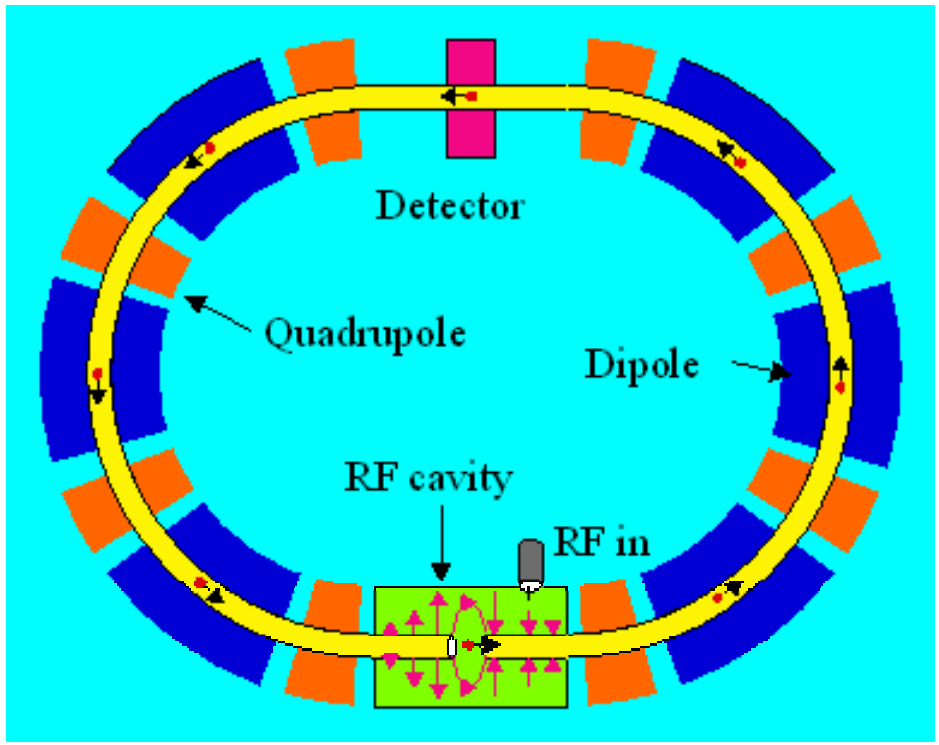
- The klystron is in itself a miniature electron accelerator.
- The filament boils electrons off the cathode.
- The electrons are accelerated by the DC power supply to the anode.
- The velocity (or energy) of the electrons is modulated by the input RF.
- Because of velocity modulation, some electrons are slowed down, some are sped up..
- The electrons drift to the anode.
- If the output cavity is placed in the right place, the electrons will bunch up at the output cavity which will excite an high intensity RF field in the output cavity.
- Klystrons need a minimum of 2 cavities but can have more for larger gain.
- A klystron's size is determined by the size of the bunching cavities.
  - The size of these cavities is inversely proportional to the frequency
  - Klystrons are used at high frequencies (> 600 MHz)



Synchrotrons

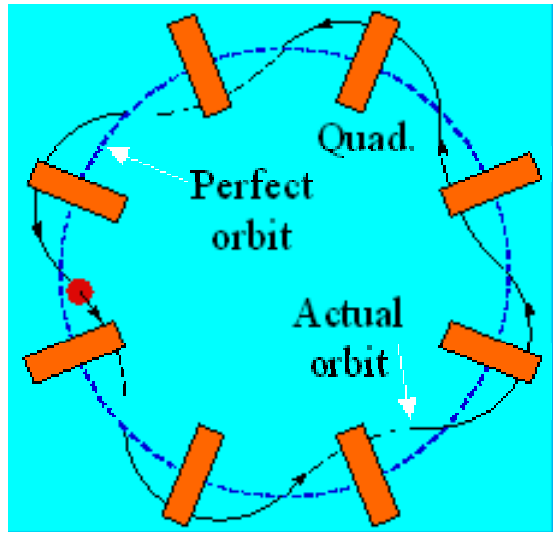
- RF cavities accelerate particles
- Dipoles are used to bend particles
  - The more energy the particles get, the stronger magnets have to be to keep the beam on track
  - As the particles go around faster, they arrive at the RF cavity sooner then they did on the previous turn
  - The frequency of the RF cavity must be increased so that the RF is pointing in the right direction when the beam arrives the next turn
  - The magnet strength and the RF frequency must be synchronized to keep the particles in the ring
- Quadrupoles are used to focus particles

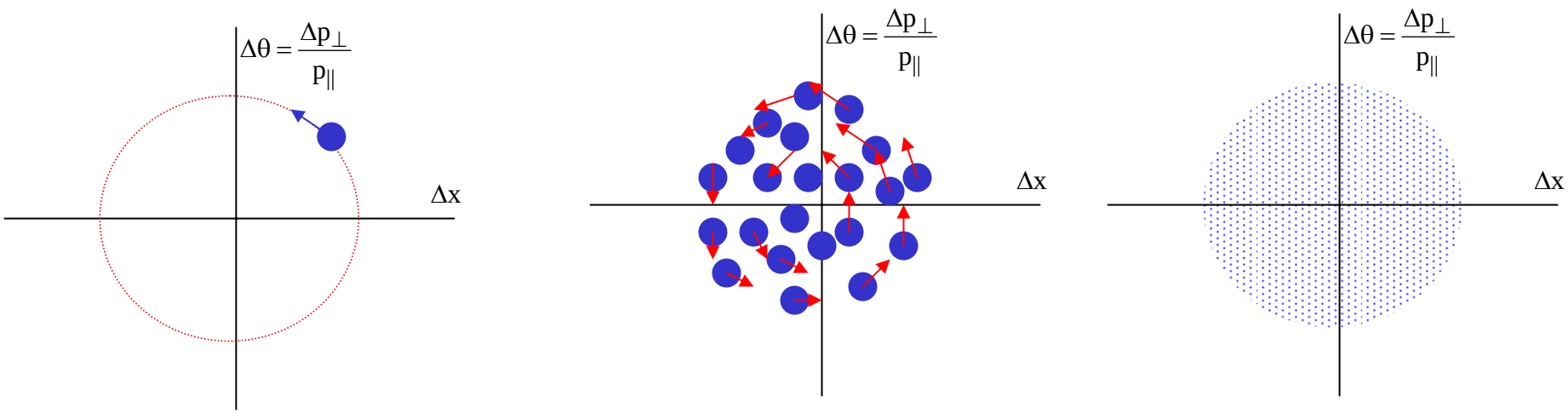




Transverse Phase Space

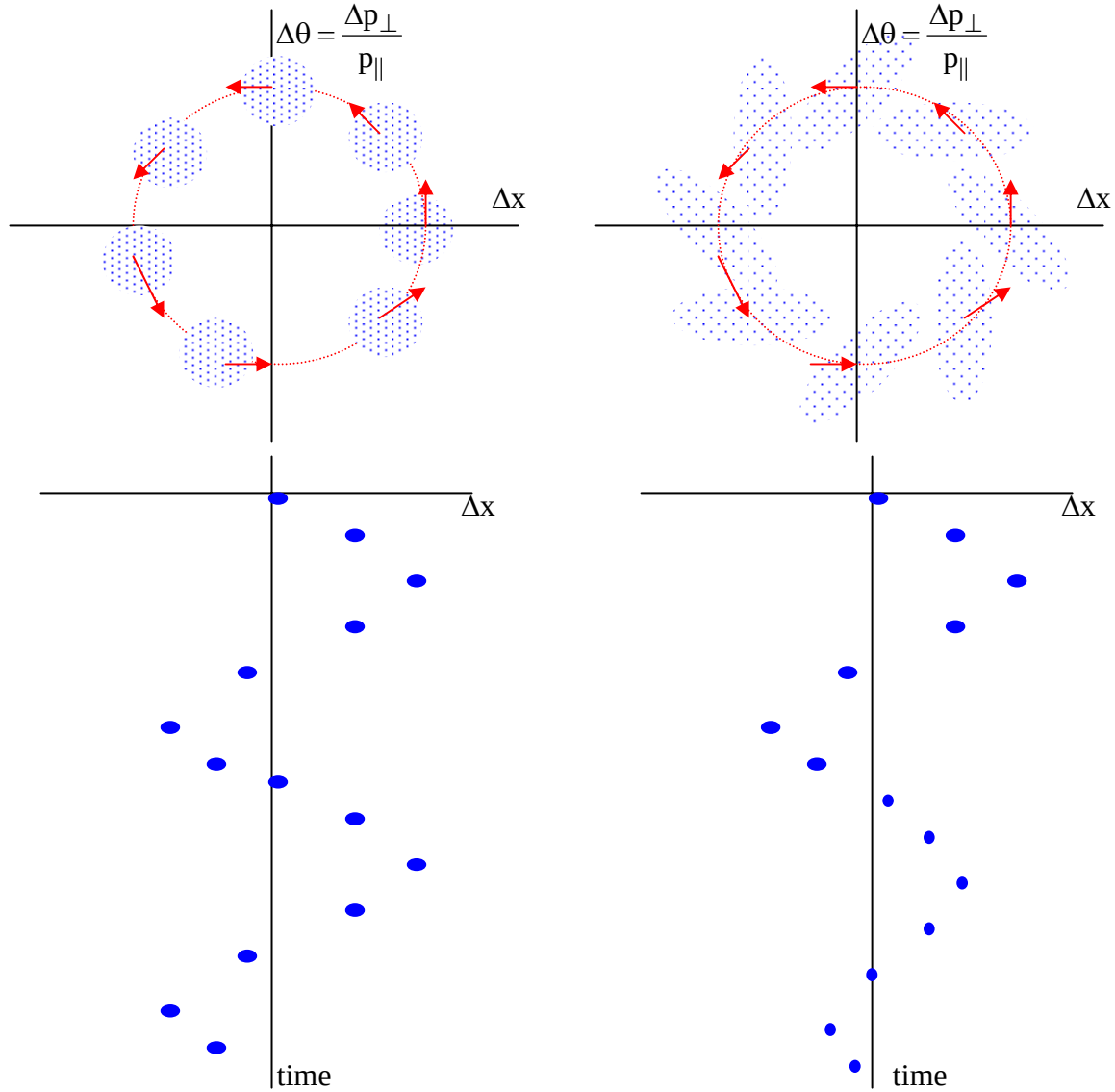
- Quadrupoles are needed for focusing particles
- Not all the particles are on the perfect orbit
- At any given location in the ring, each particle has a unique transverse position <u>and</u> angle w.r.t to the ideal orbit
- The number of times that a particle circles phase space during one complete trip around the ring is the tune of the machine.
- The transverse emittance is the area (mm-mrad) in phase space that contains a collection of particles.





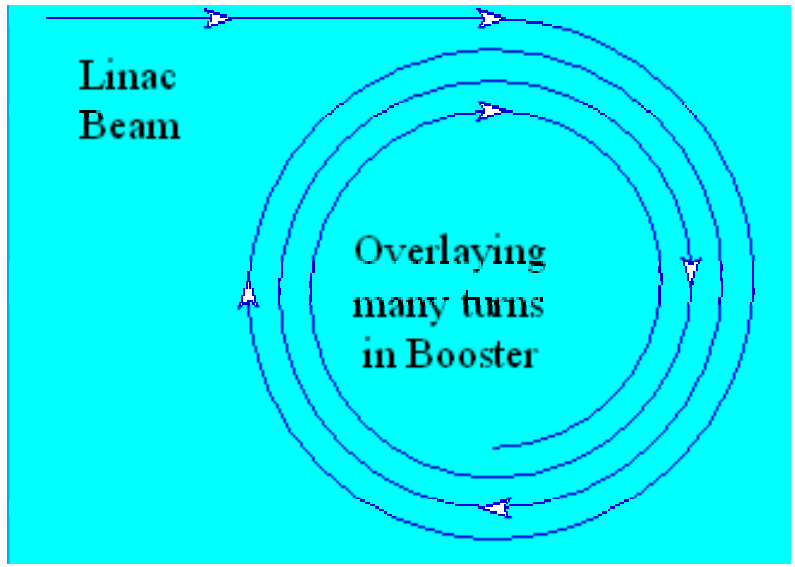
Injection Oscillations in Synchrotrons

- If beam is not injected onto the ideal orbit, the ensemble in phase space will oscillate about the ideal position
- Magnets are not perfect
  - Octupole components will act as a amplitude dependent quadrupole
  - The betatron tune will be a function of the particle's phase-space amplitude
  - The phase space will smear out after many turns
  - The oscillation will seem to damp
    - Landau damping
  - The emittance will grow
    - The density decreases



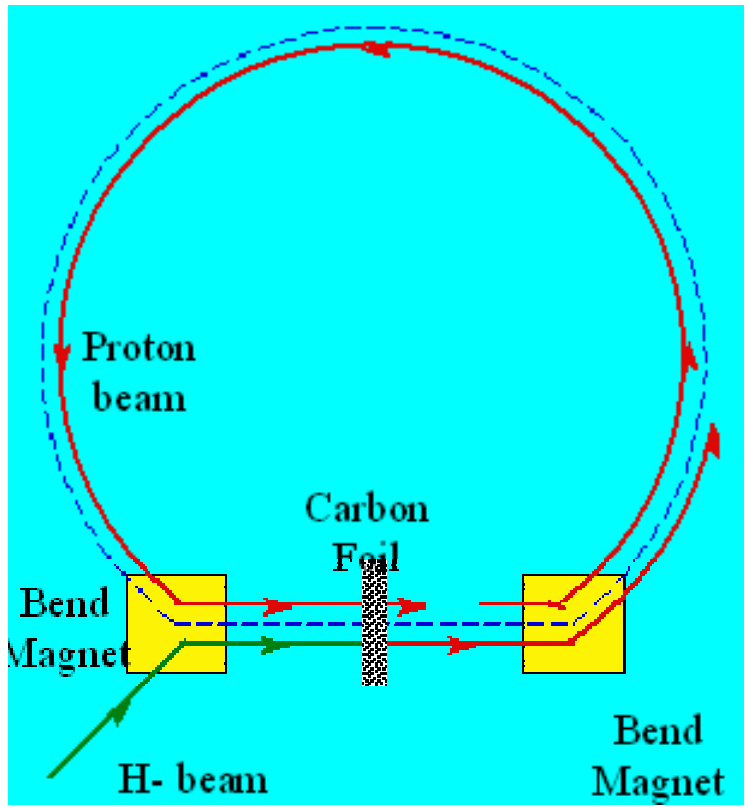
Multi-turn Injection

- Because the Linac is a single pass acclerator, the rate at which the klystrons can pour energy into the beam and still achieve the final beam energy (400 MeV) limits the beam current.
  - P=I x V
- The total charge in the Linac is the beam current x pulse length.
- To get a lot of charge, the pulse length in the Linac must be made very long (>20uS)
- Since the next accelerator circumference (the Booster) is only 2.2uS long, the Linac beam must be wrapped around the Booster many times (turns)



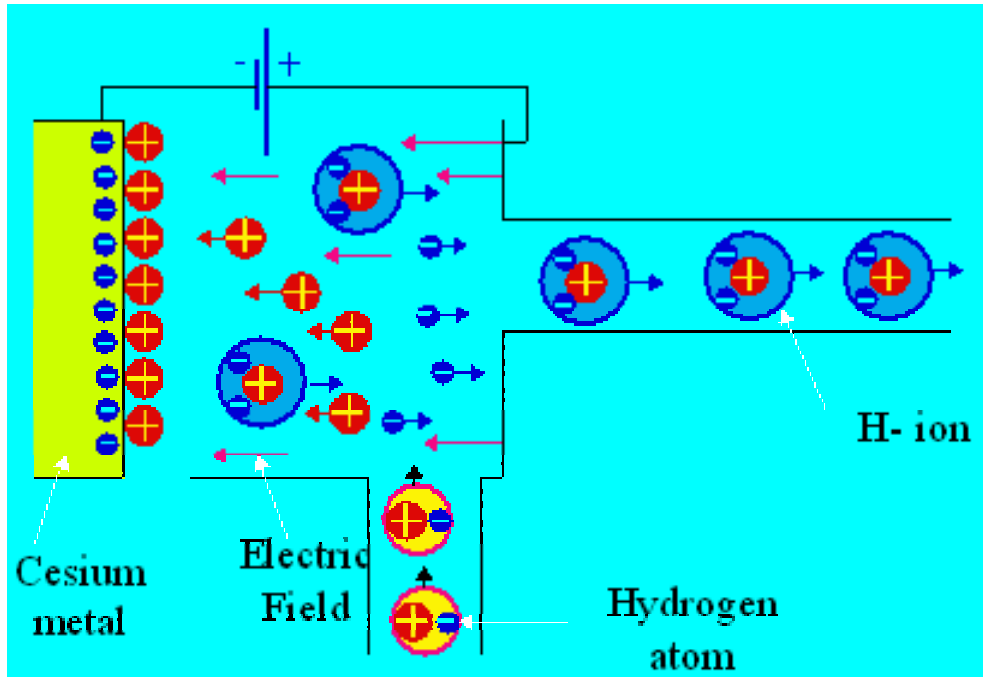
Multi-turn Injection

- We want dense beams
  - High intensity
  - Low emittance
- How is more than 1 turn added to the Booster without
  - "kicking" out the protons that are already in the Booster?
  - Or increasing the emittance?
- We cheat Liouville's theorem (sort-of)
  - The Linac actually accelerates H- ions (one proton, two electrons) which basically have the same mass as a proton but opposite charge.
  - Because of the opposite charges, the H- ions "merge" when passed through a single magnet
    - Care has to be taken to not magnetically strip the electrons from the H- ions
  - The "merged" beams would diverge again if passed through a second magnet.
  - Before the "merged" beams pass through a second magnet
    - they pass through a thin carbon file which strips of the weakly bound electrons from the H- ions.
    - Because the foil is thin, and the protons have high energy, the foil will not bother the protons.



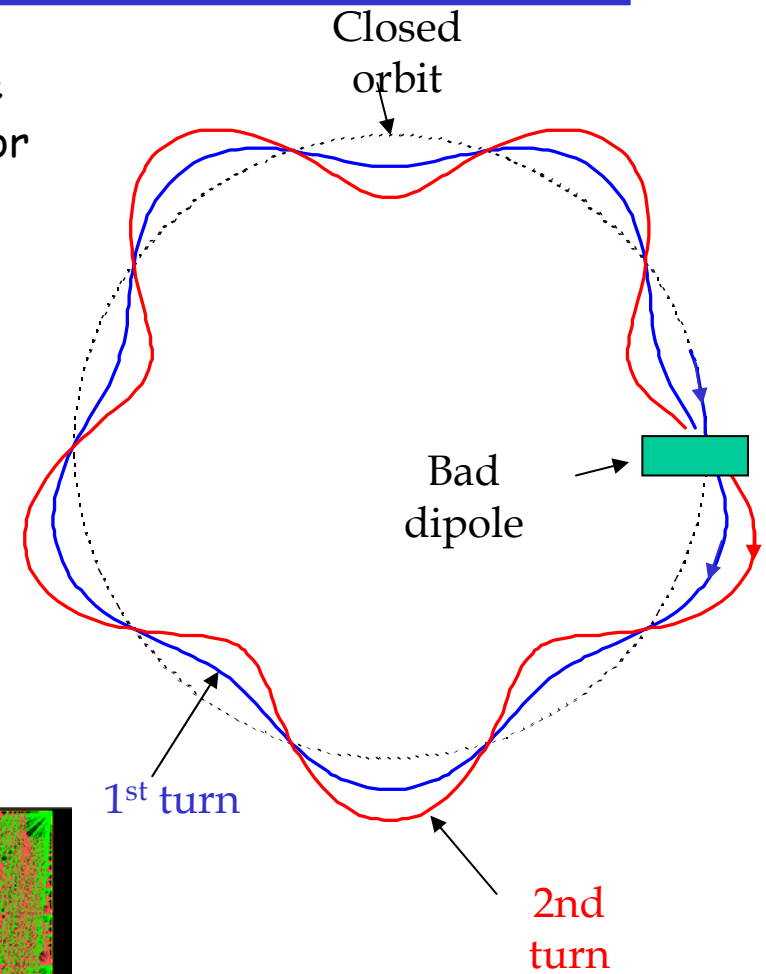
Production of H- Ions

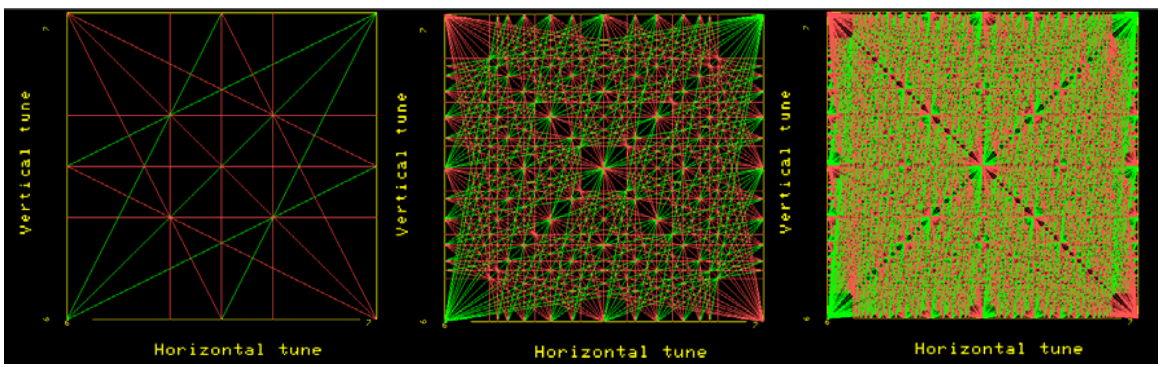
- Place a Hydrogen atom in an electric field and strip away the electron
- Protons will congregate on the Cesium metal surface
- The metal surface has free electrons and the Cesium makes it easier to steal electrons from the metal (low work function).
- Every once in awhile, an incoming proton will smack a proton with two electrons attached off the metal wall.
- Because of its negative charge, the H- ion will move away from the negative surface.



Resonance Lines and Tunes

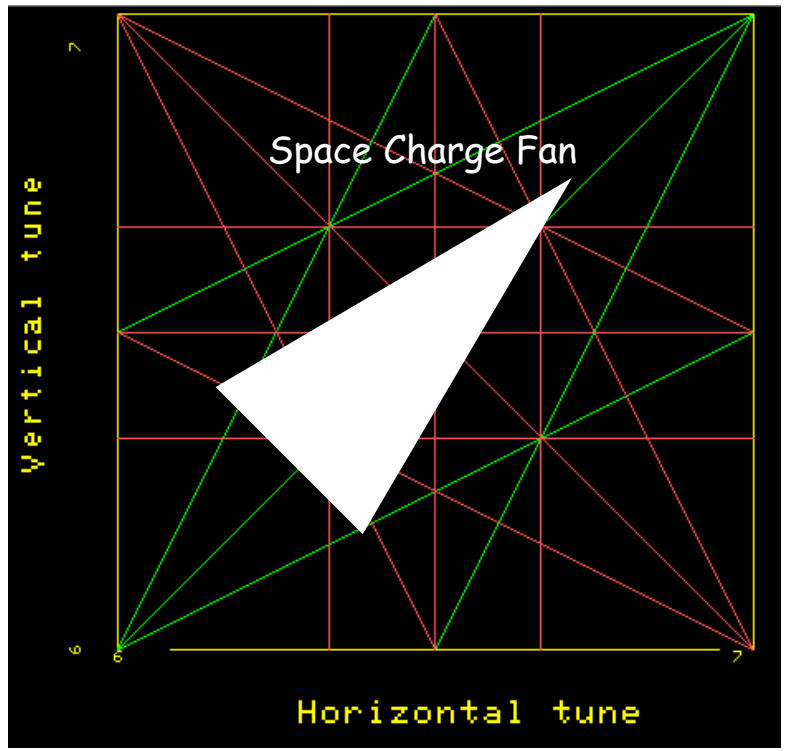
- The betatron tune is the number of "wiggles" a particle makes as it goes around the machine once
- The tune is proportional to the machine focusing or the quadrupole strength (lattice)
- If the tune is an integer:
  - A dipole error would amplify turn after turn
  - The amplification is proportional to the dipole error
- If the tune is an $\frac{1}{2}$ integer a quadrupole error would amplify every other turn, etc…
- For an infinite set of multipoles
  - The tune should **not** be a rational number
  - The growth rate is inversely proportional to the multipole order
  - The growth rate is proportional to the multipole strength



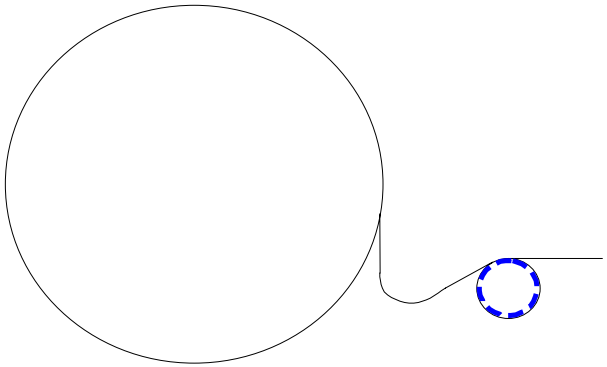


Space Charge Tune Shift

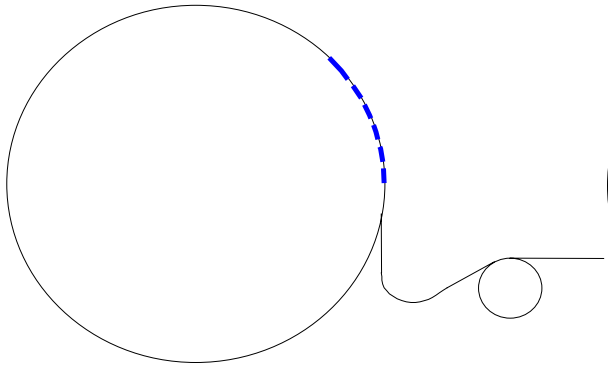
- The beam in the Booster is limited by space charge tune shift
  - Moving particles produce a magnetic field on the other particles which act as a de-focusing lens
  - De-focusing force is
    - proportional to
      - the beam current
      - 1/Energy
    - a function of the phase space amplitude
      - Not all the particles get the same tune shift
- Slip-stacking is a technique to double the number of particles
  - Done at relatively high energy so space charge is not a problem
  - Takes advantage of the enormous amount longitudinal "room" available in the Main Injector
    - Big circumference
    - Big momentum aperture



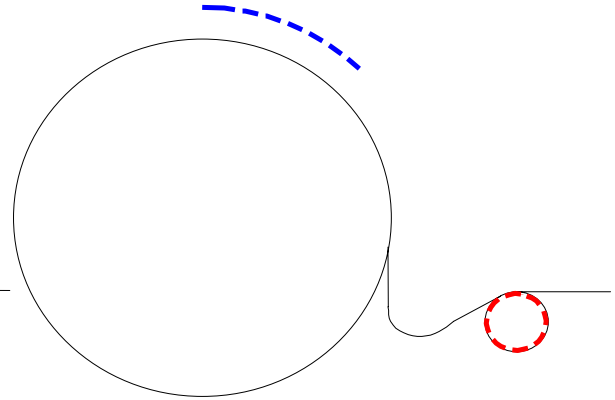
Slip Stacking



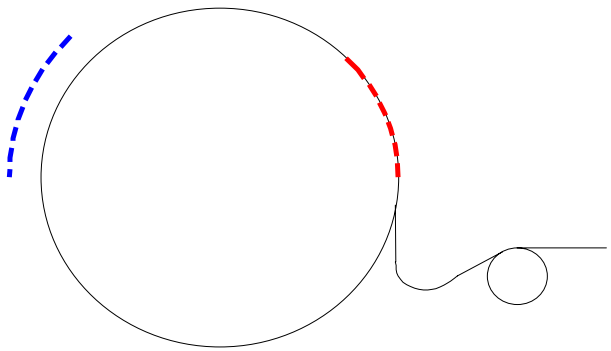
1. First Booster Batch accelerated in Booster



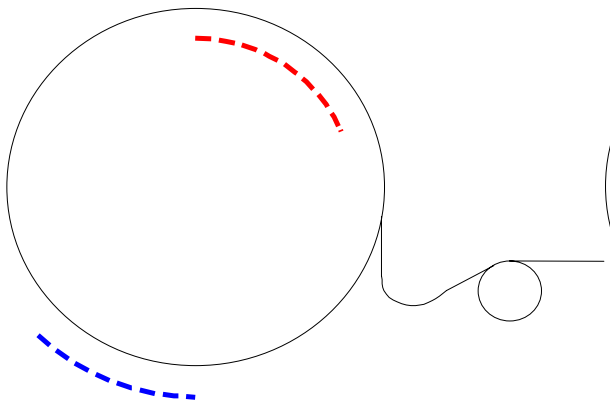
2. First Booster Batch injected onto MI central orbit with RF system A



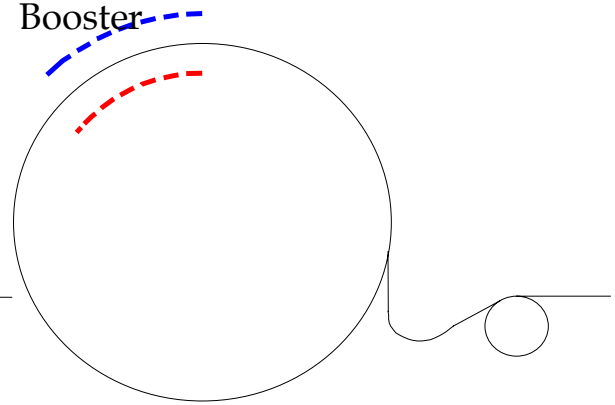
3. First Booster Batch slightly accelerated in MI with RF System A. Second Booster Batch accelerated in Booster



4. Second Booster Batch injected onto MI central orbit with RF system B

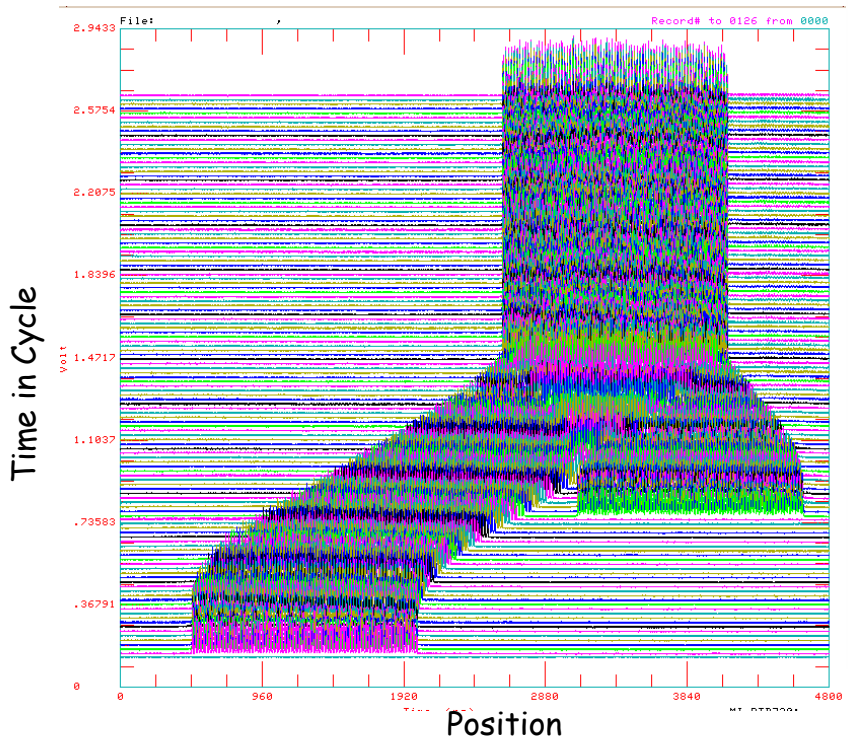


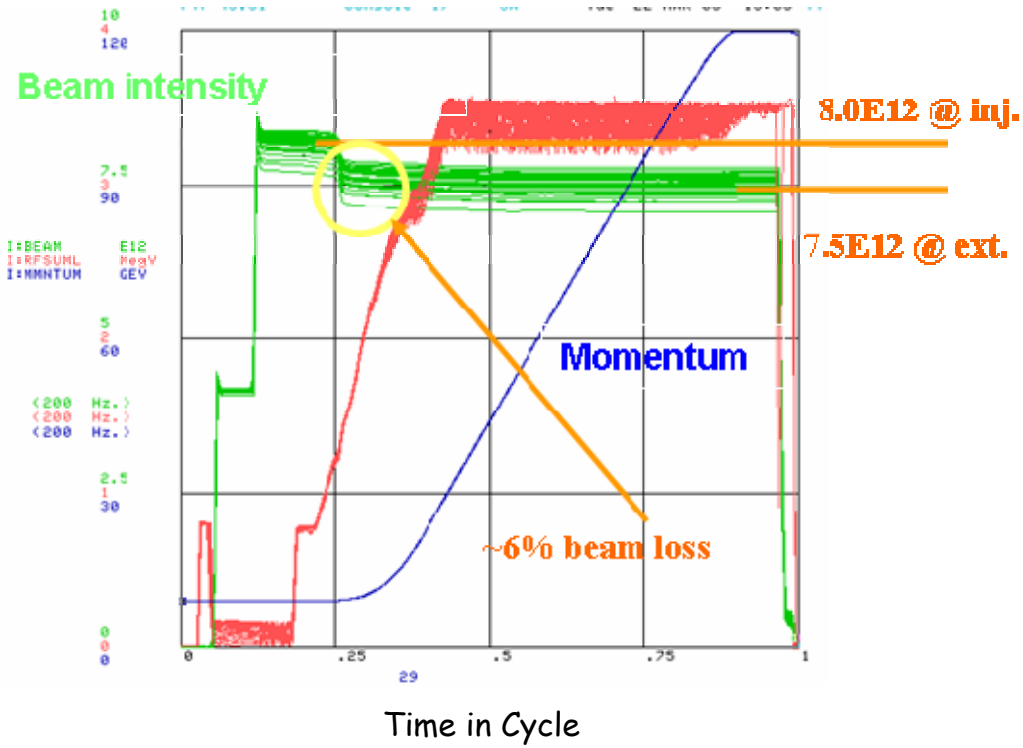
5. Second Booster Batch slightly decelerated in MI with RF System B



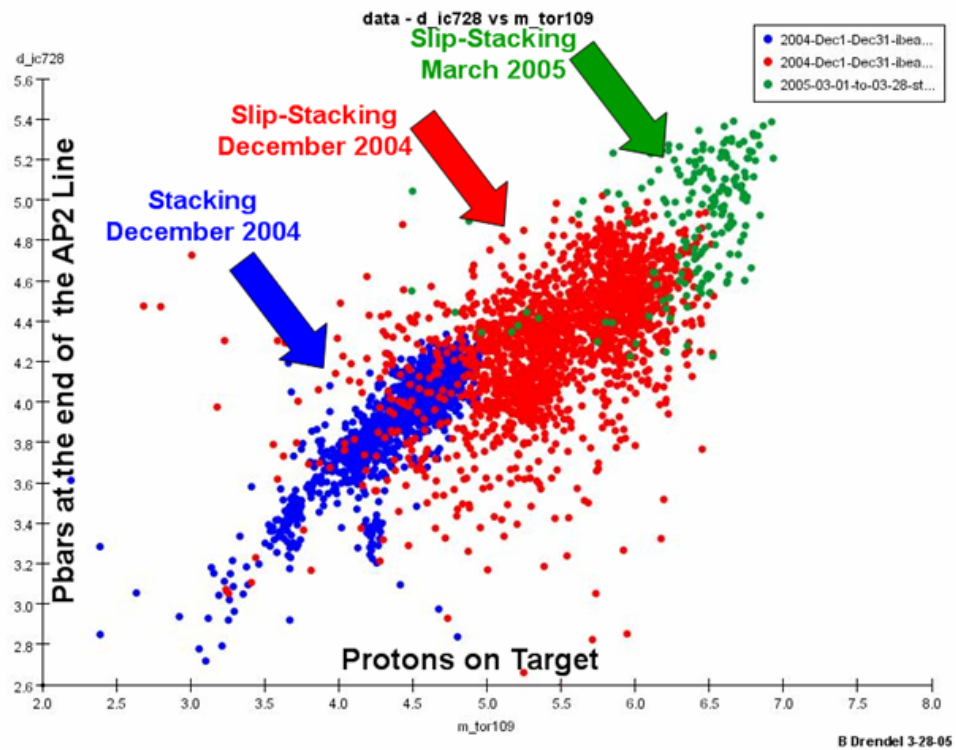
6. Wait till batches line up and snap on RF system C while turning of RF systems A & B

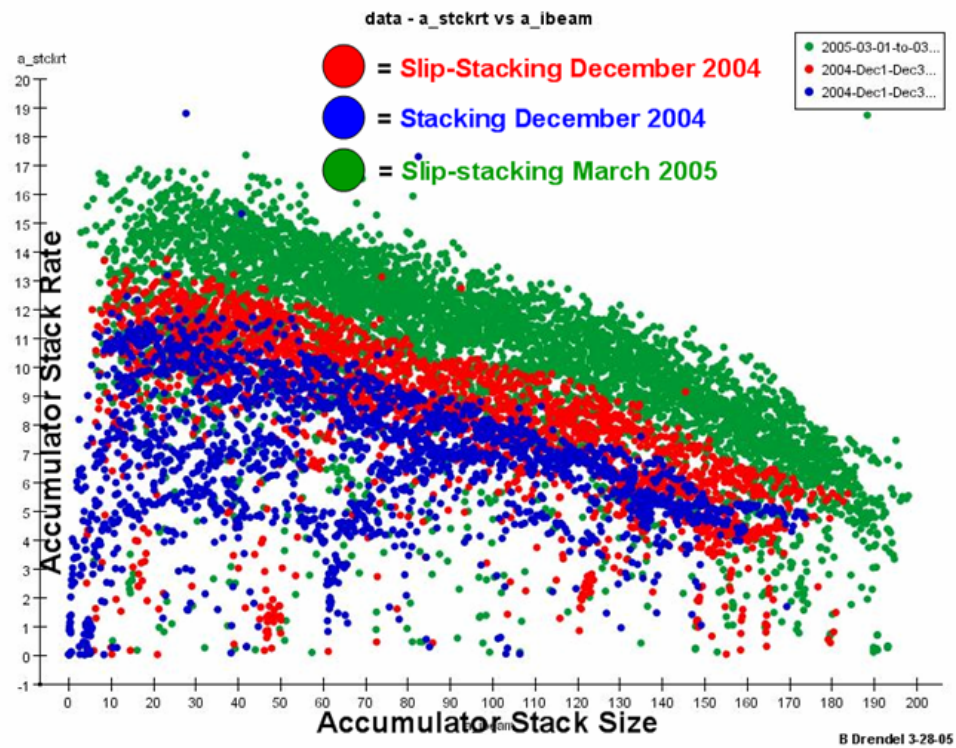
Antiproton Production – Slip Stacking





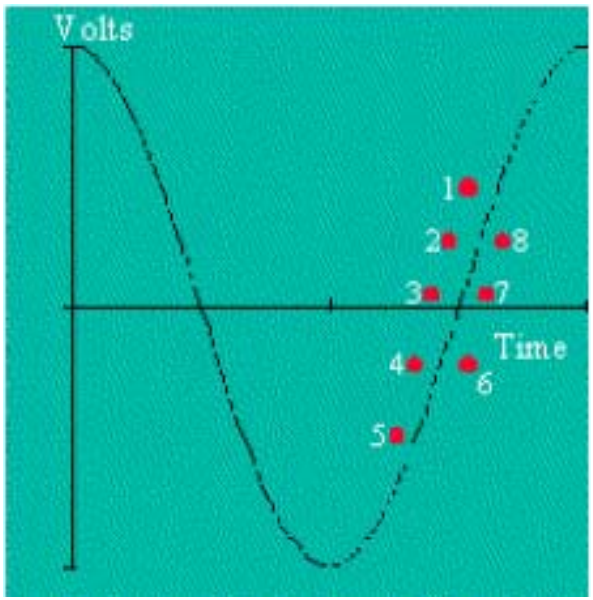
Antiproton Production – Slip Stacking



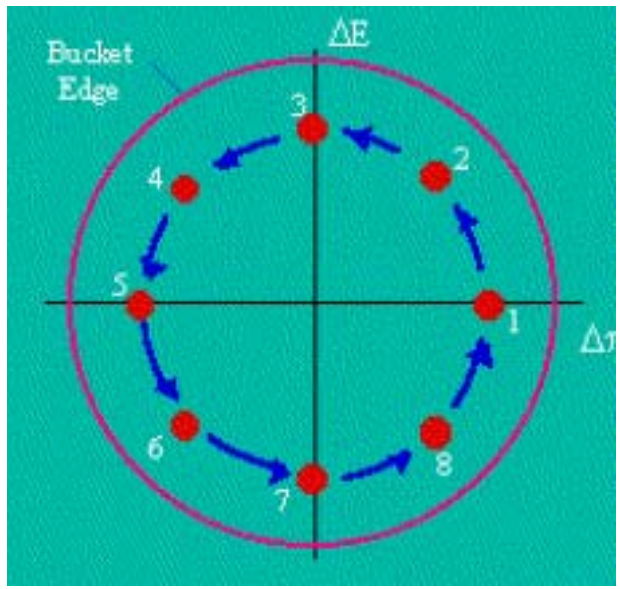


RF Basics

- The RF Voltage not only accelerates the beam but forms a barrier to keep particles from wandering away in time.
- The magnitude of the RF Voltage determines the size of this barrier or "bucket"

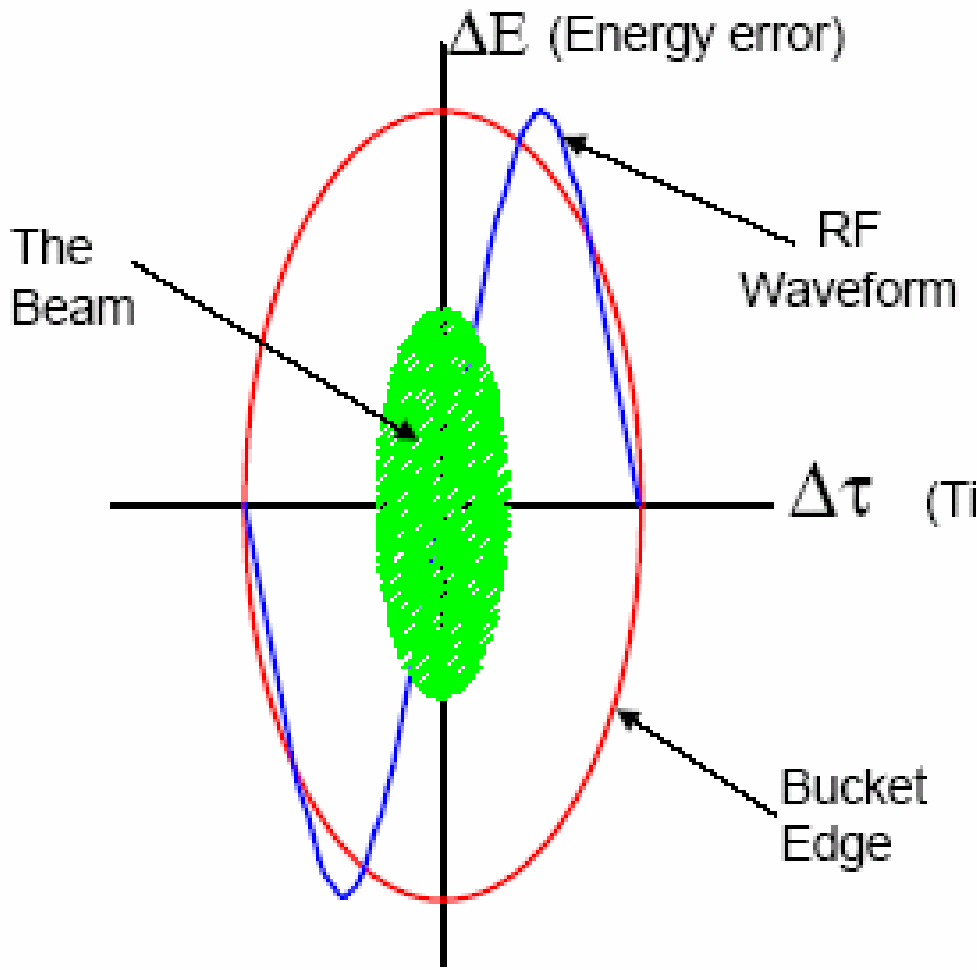


- A particle's energy error and time (phase) error are plotted on a "phase space" plot.
- The RF bucket causes a particle with a phase space error to wander about phase space in an ellipse. The shape of the ellipse is determined by the strength of the RF voltage.

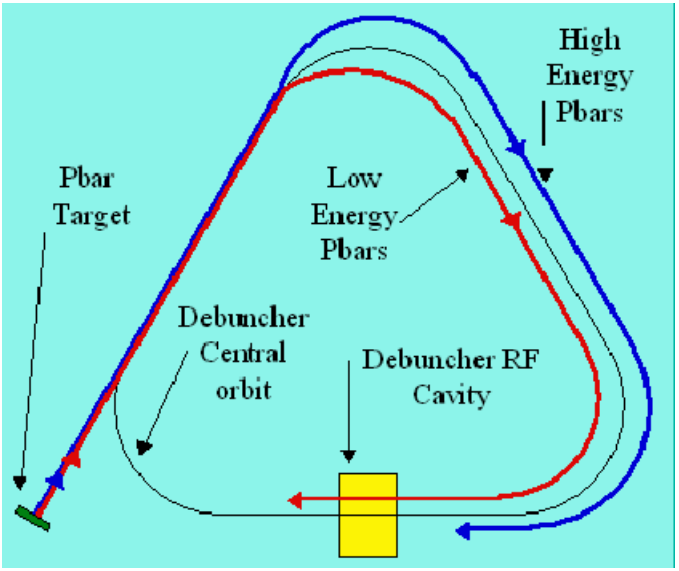


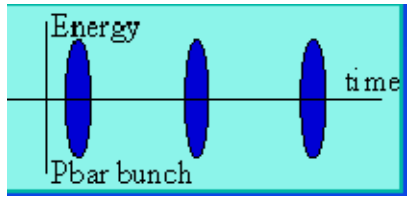
Longitudinal Phase Space

- The beam consists of many particles.
- Each particle has its own energy and phase error.
- The area in phase space that contains all the particles is called the longitudinal emittance (eV-Sec.)

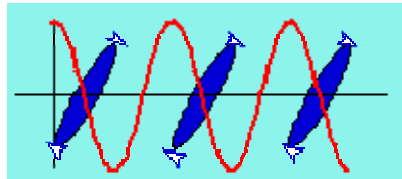


Antiproton Debunching

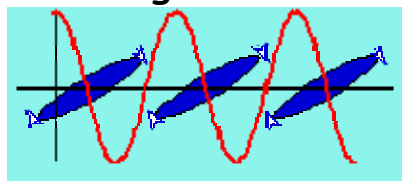




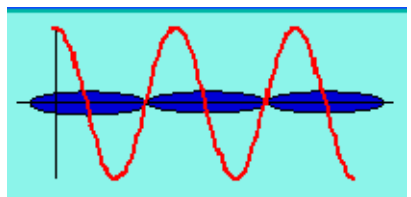
Pbars right after the target



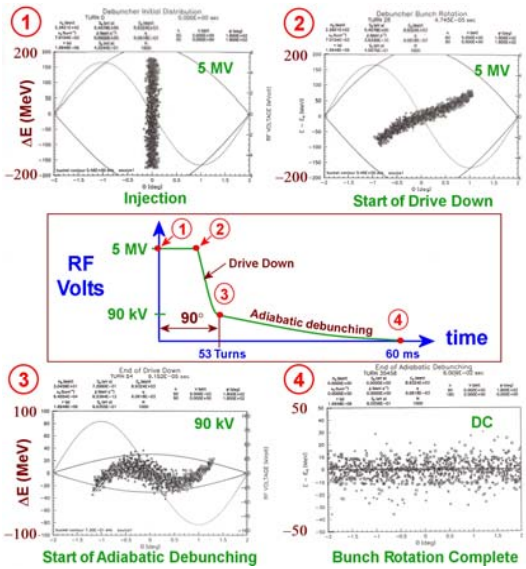
Pbars arriving at the RF Cavity

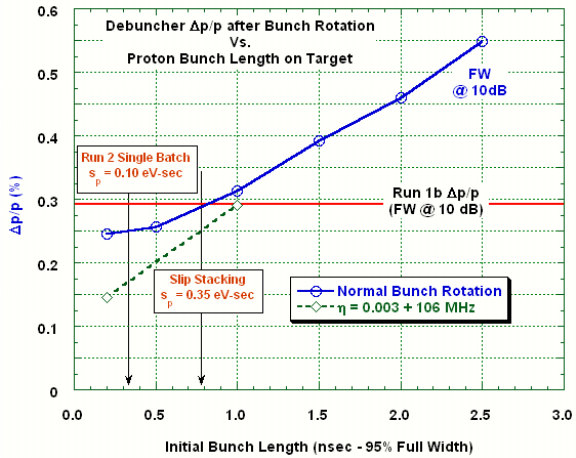


Pbars after many turns

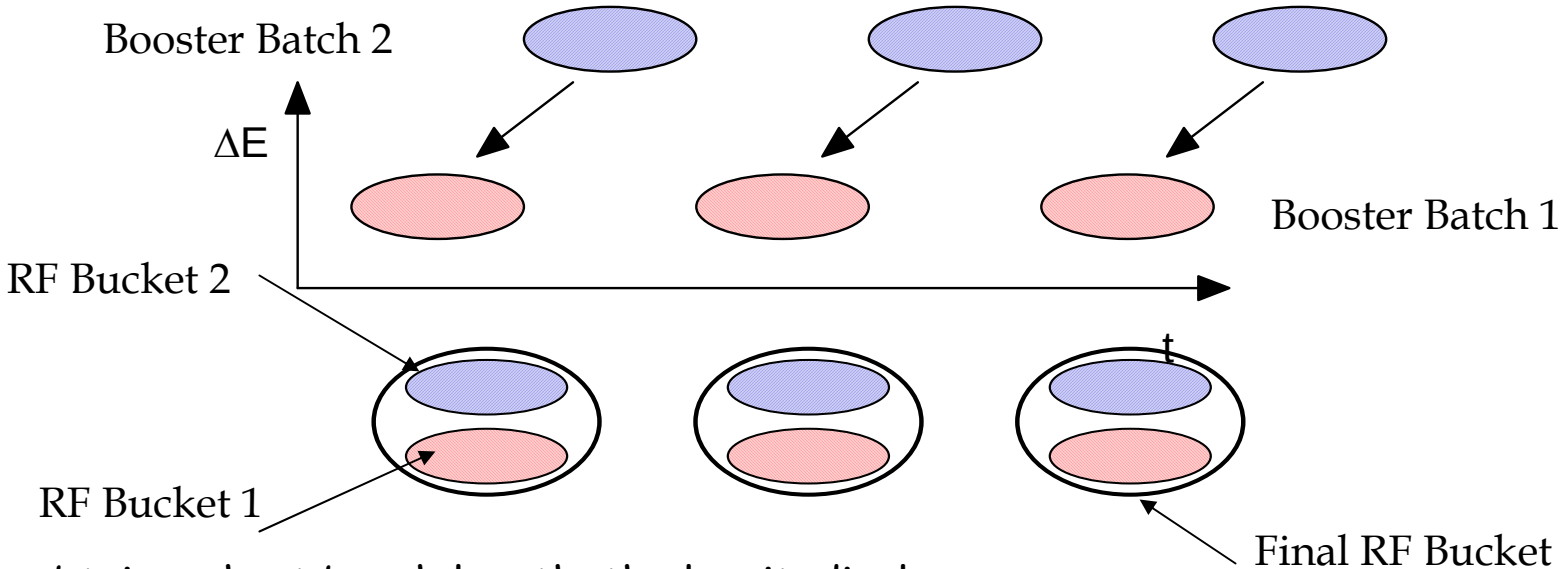


Pbars at the end of Debunching

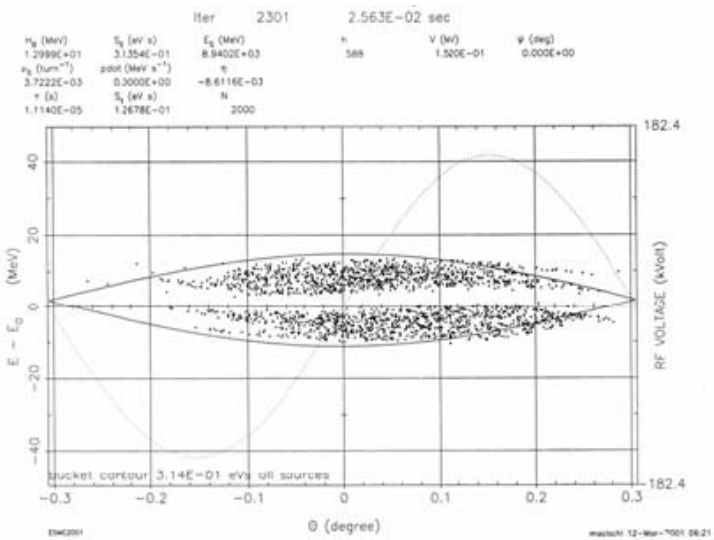




Longitudinal Emittance and Slip Stacking

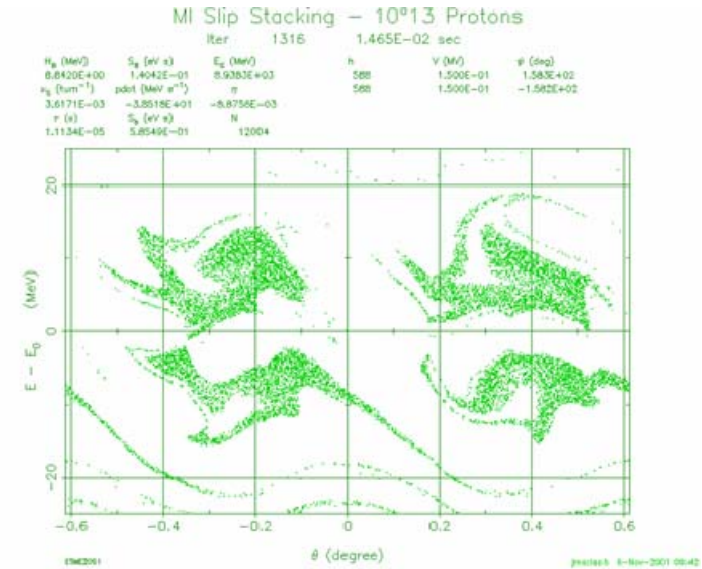


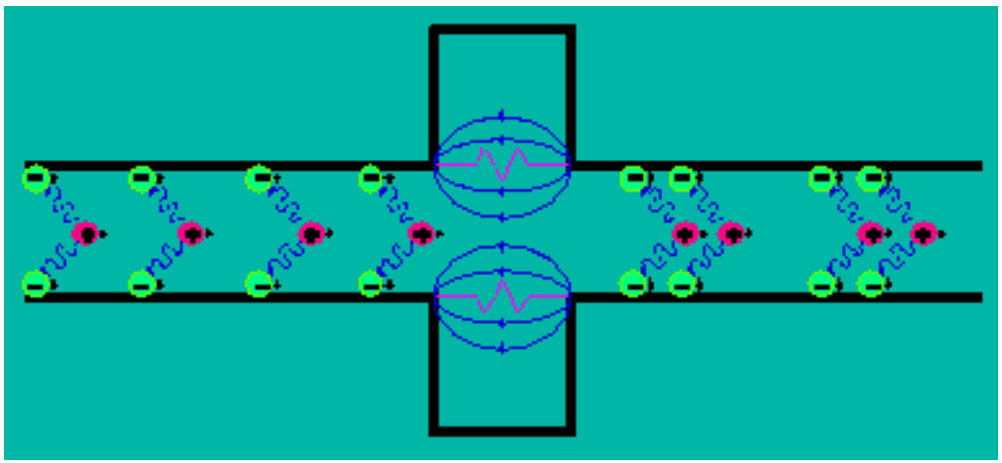
- To obtain a short bunch length, the longitudinal emittance of the proton bunches should be small as possible.
- A small longitudinal emittance requires that energy separation between the A & B batches be as small as possible during the final capture.
- The small energy separation requires that the RF buckets of the A & B batches not overlap
- The bucket heights which is proportional to the RF voltage must be very small.

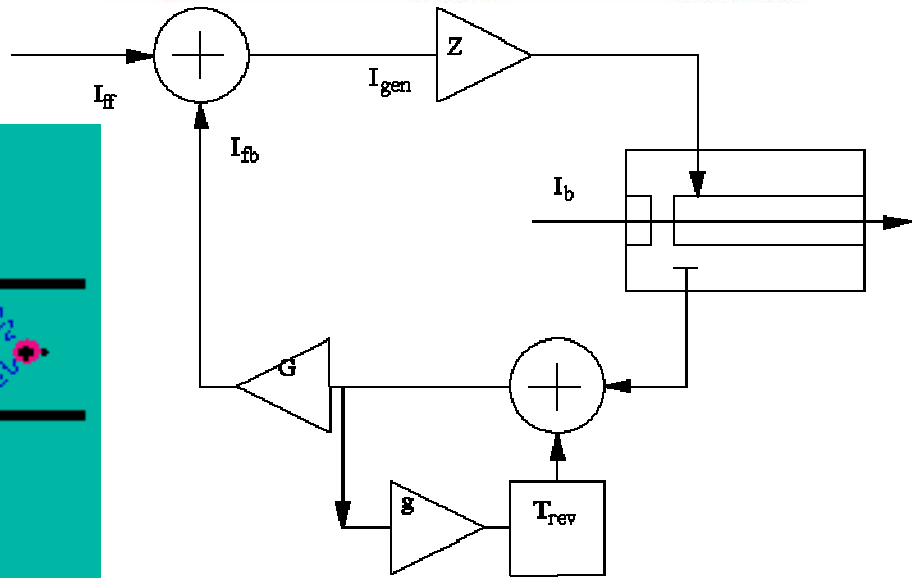


Beam Loading

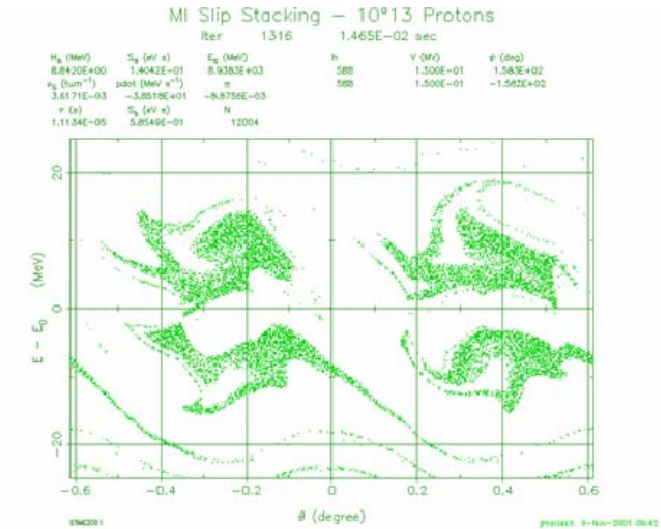
- Low Frequency (< 100 MHz) RF power sources, such as tetrodes, are typically current sources.
- The particle beam is accelerated with an electric field or a "voltage" gradient.
- An RF cavity can be thought of as a narrow band transformer that converts current to voltage.
  - The larger the cavity impedance, the more voltage that can be obtained for the same RF power.
- The particle beam travelling through the RF cavity is also a "current" source (especially at these energies).



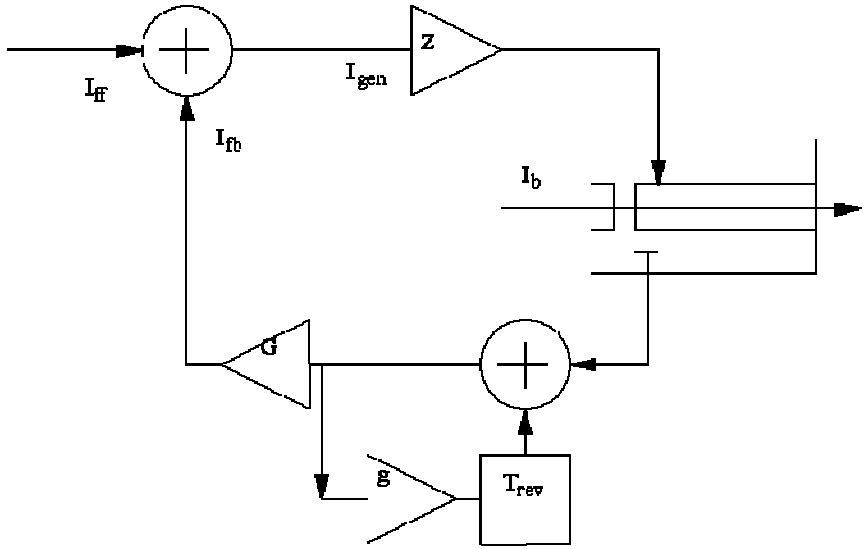




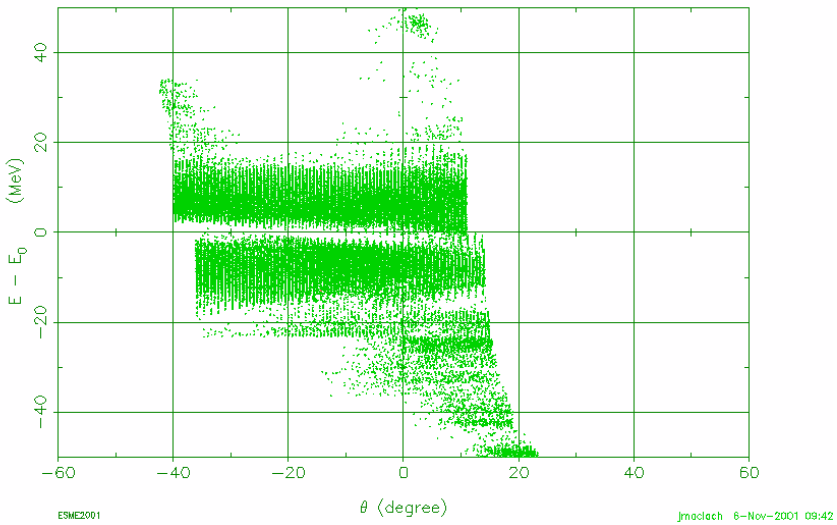
Beam Loading Compensation

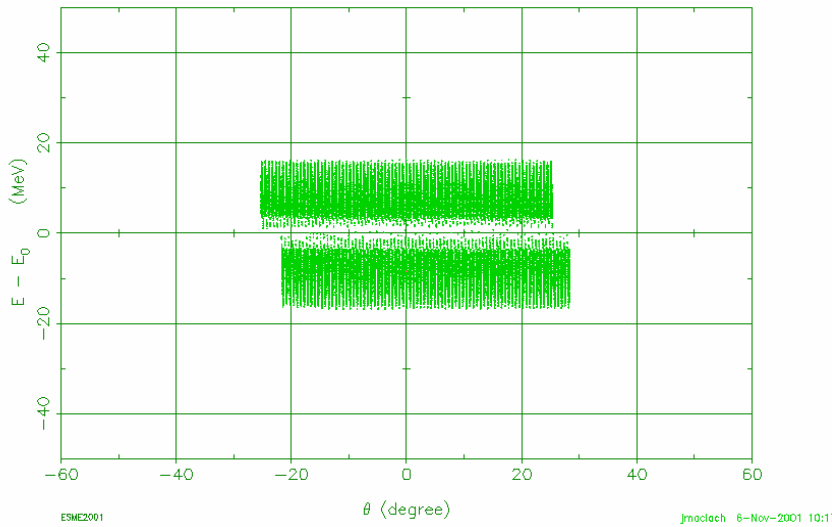


Batch phase space without compensation

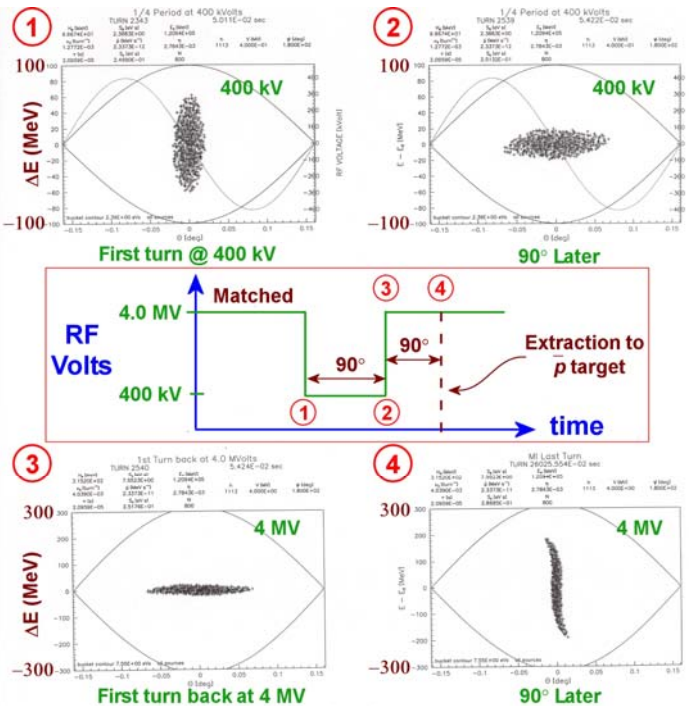


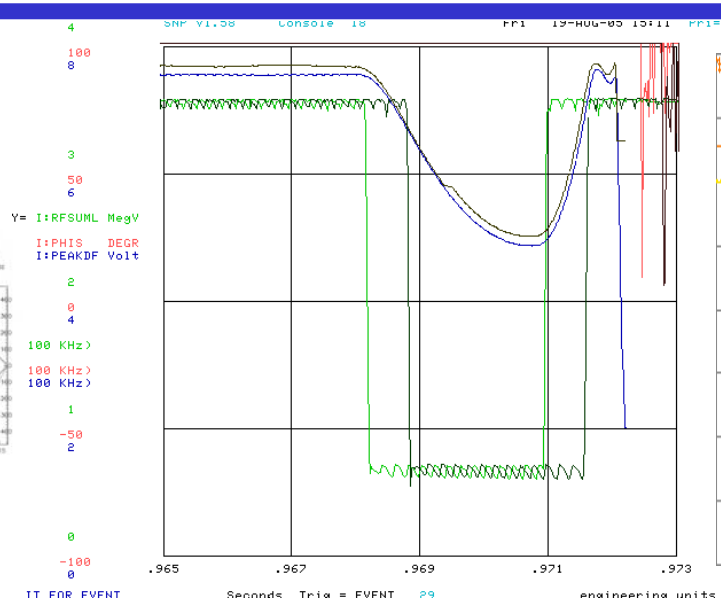
Batch phase space with compensation

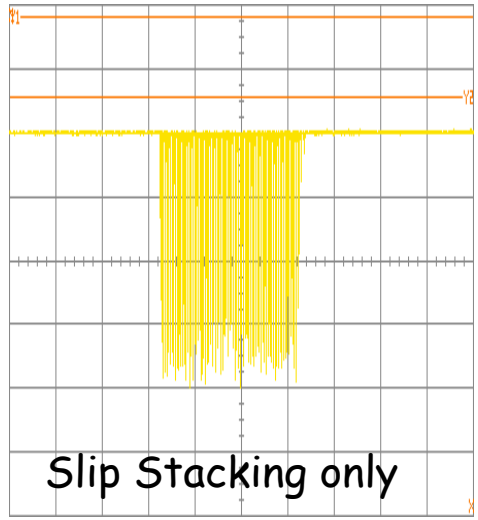


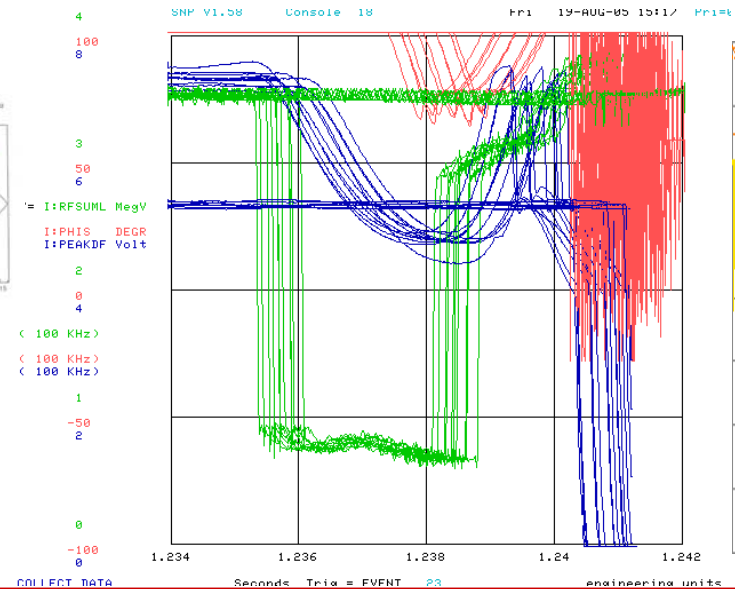


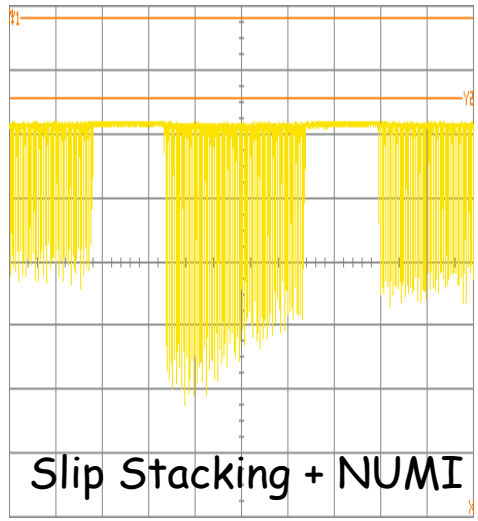
Main Injector 120 GeV Bunch Rotation



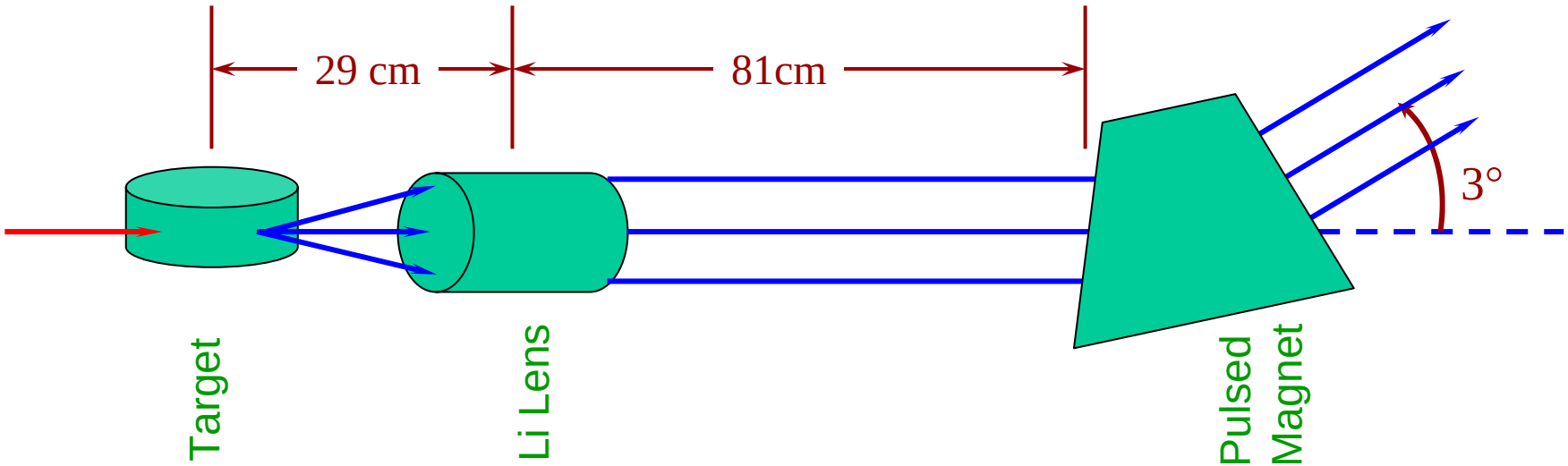


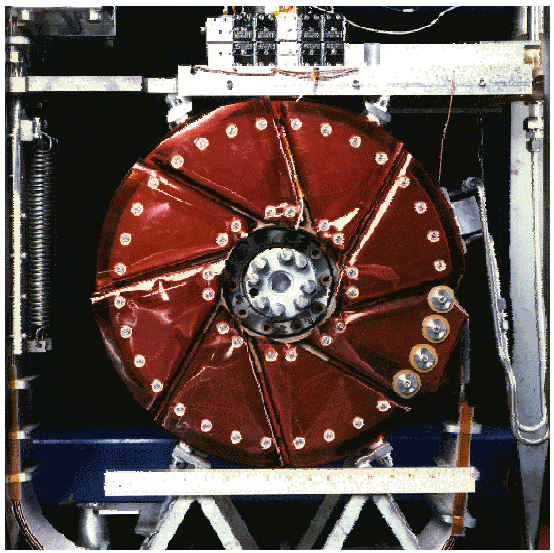


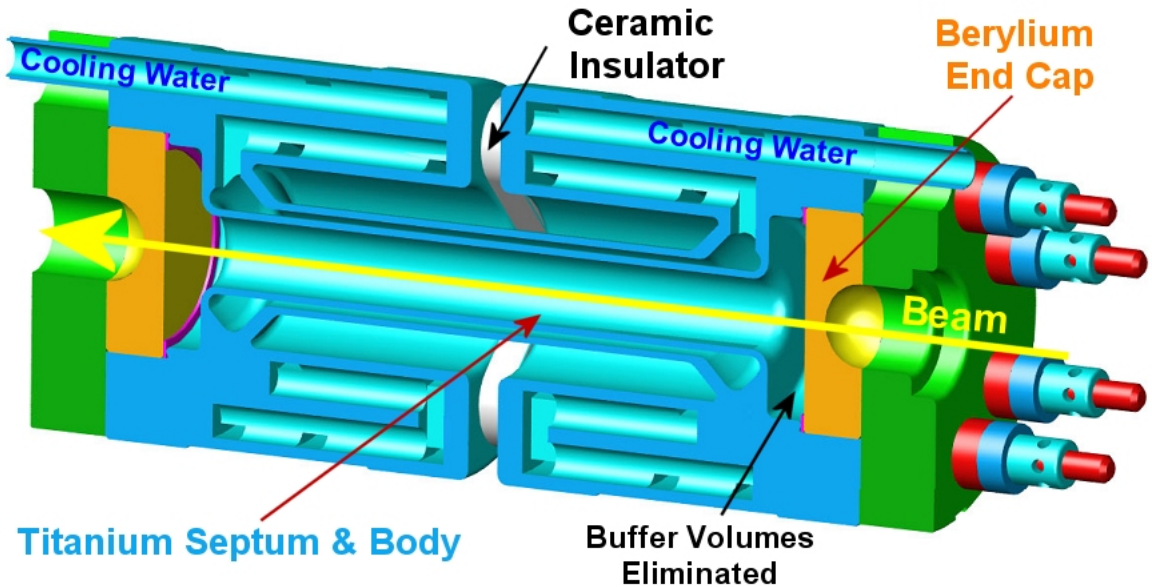




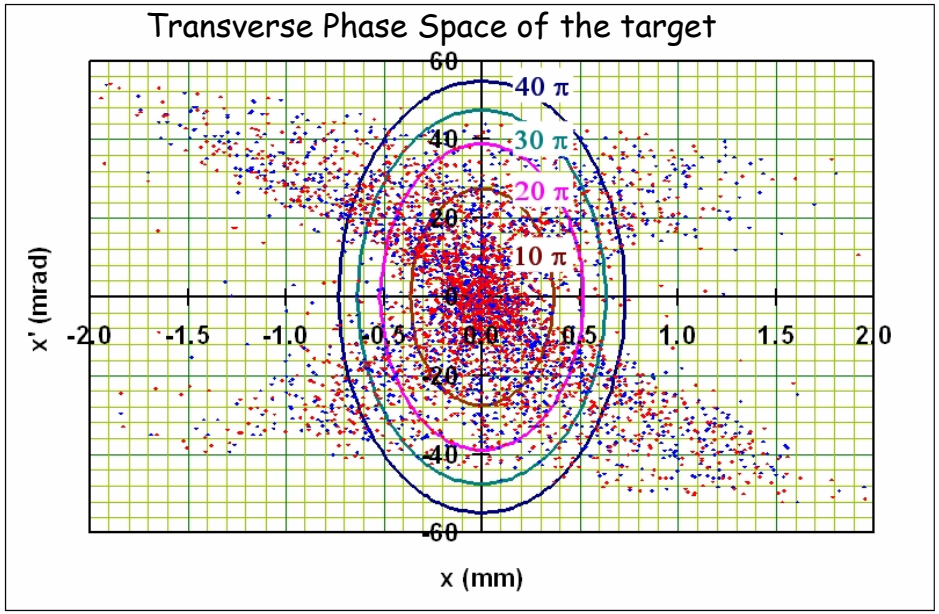
Antiproton Production

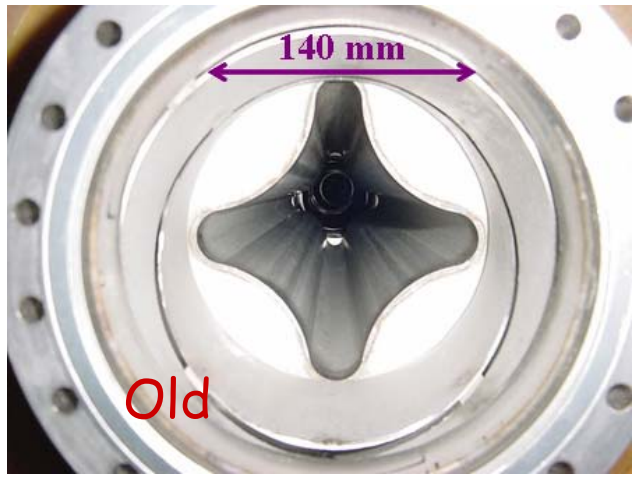






Antiproton Aperture





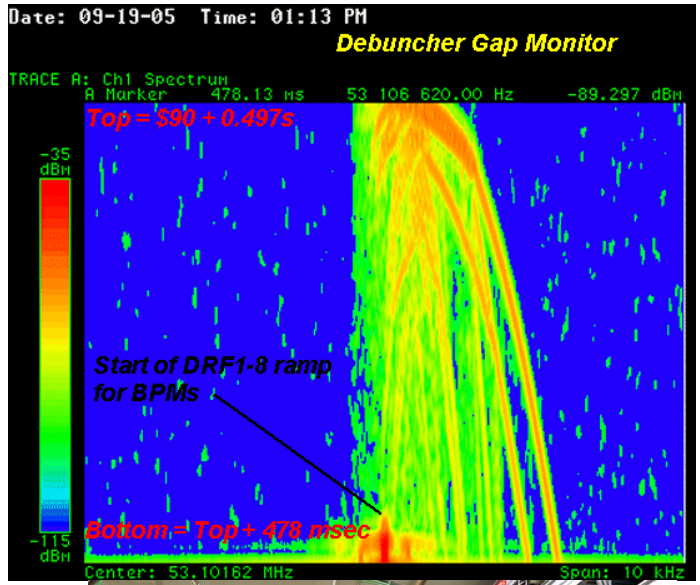
- The measured aperture of the initial stages of the antiproton production chain is about 65% of the available physical aperture.
- An aggressive beam-based alignment program is under development to bring the measured aperture to the physical aperture.
  - Would increase the stacking rate by over a factor of 2
  - The final design goal is to achieve 77% of the physical aperture which will increase in stacking rate by 40%
- The goal for this year is to increase the aperture for each plane from 65% to 72% of the available physical aperture which would result in a 20% increase in antiproton production rate

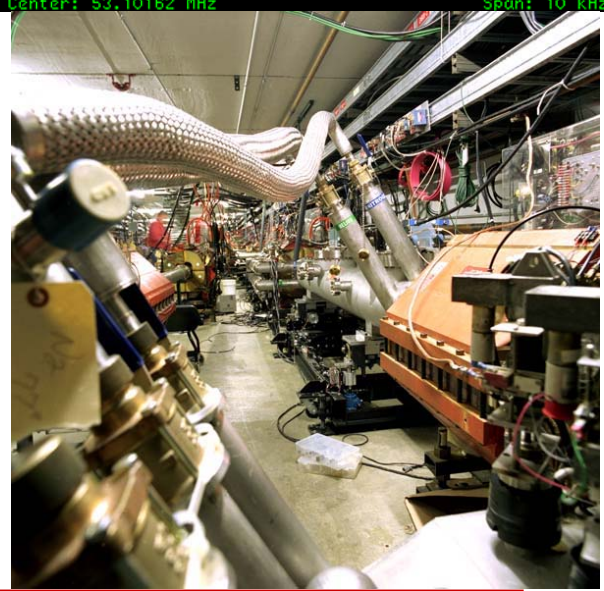
Beam Based Alignment

- For maximum aperture, we would like the beam to go through the center of the quadrupoles
- You cannot trust the absolute position of beam position monitors.
- If the beam goes off center through a quadrupole, it gets a kick. The kick is proportional to
  - strength of the quad
  - the offset of the transverse beam position with respect to the center of the quad.
- To measure how far off center the beam is in the quad
  - Measure the beam trajectory downstream of the quad with BPMs
  - Change the Quad current (strength)
  - Measure the difference in beam position
    - If the beam goes though the center of the quad, the trajectories will be the same
  - Change the position of the beam through the quad with an upstream trim magnet until the quad does not steer the beam.

Beam Based Alignment

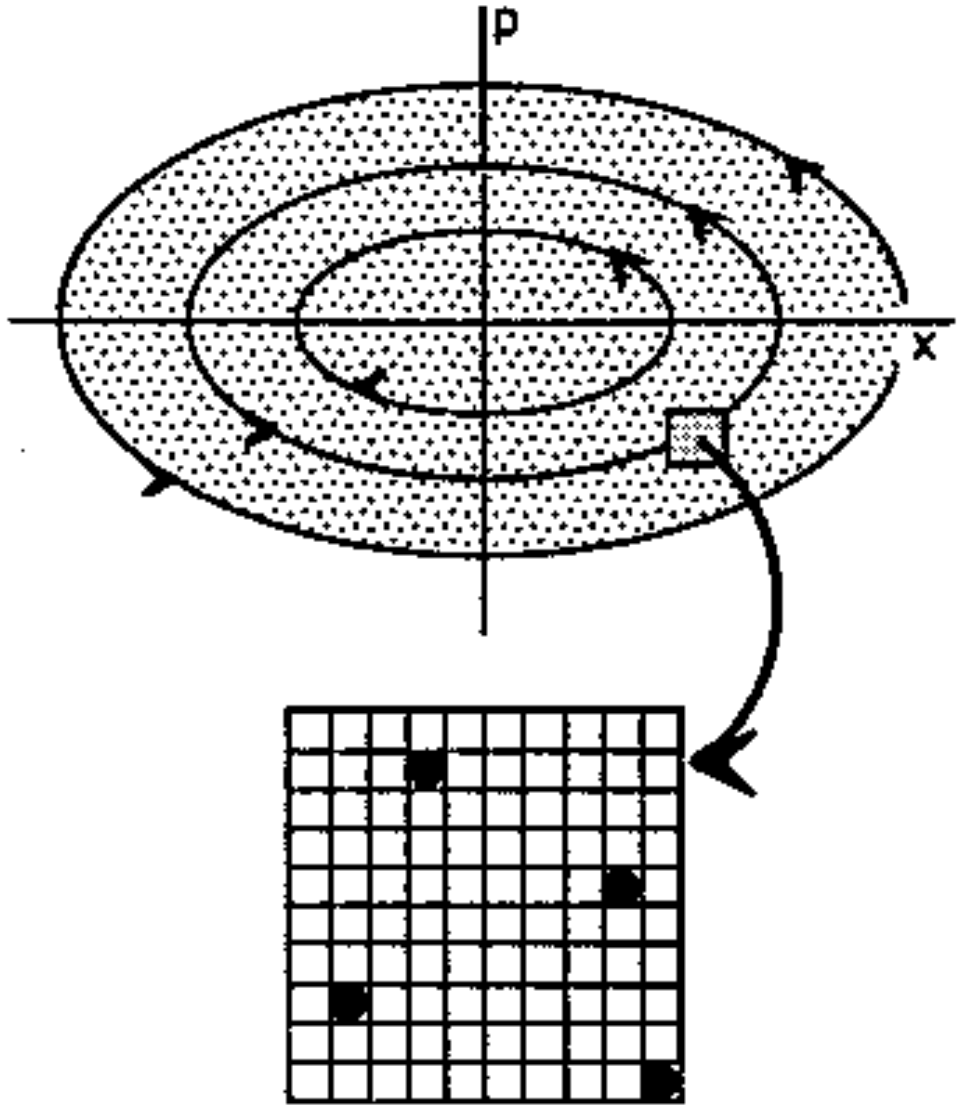
- Necessary components
  - Beam position system
  - Individual control of quad strength
  - Trim magnets to control the orbit
- Problems in the Debuncher
  - Beam position system
    - Pbar current extremely low
    - Secondary spray
    - Reverse proton beam loading
  - Quad strength
    - Quads are on busses – had to add lots of shunts
  - Trim magnets
    - There is no space in the Debuncher to add trim magnets
    - Orbit correction is done by placing quads on remote control stands
  - Overall
    - Align with reverse protons
      - Large setup overhead
    - Stack with forward pars
    - Just isn't the same!





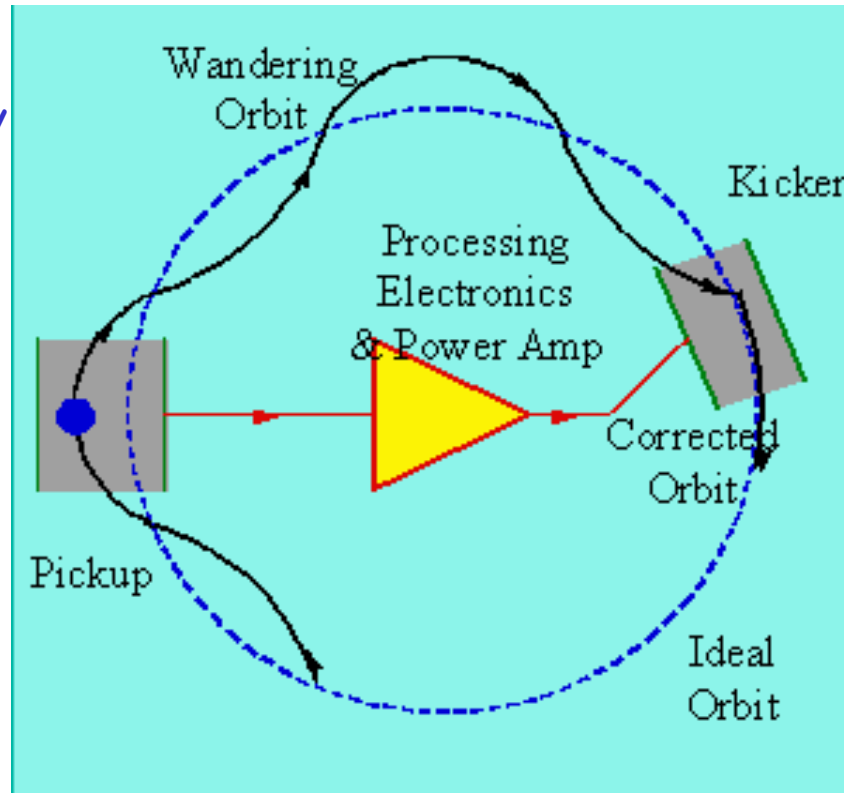
Stochastic Cooling

- Electron Cooling works well for narrow, intense beams
- Stochastic Cooling works well for wide, diffuse beams
- Stochastic cooling re-arranges phase space by placing particles into the "empty holes" in phase space.



Stochastic Cooling

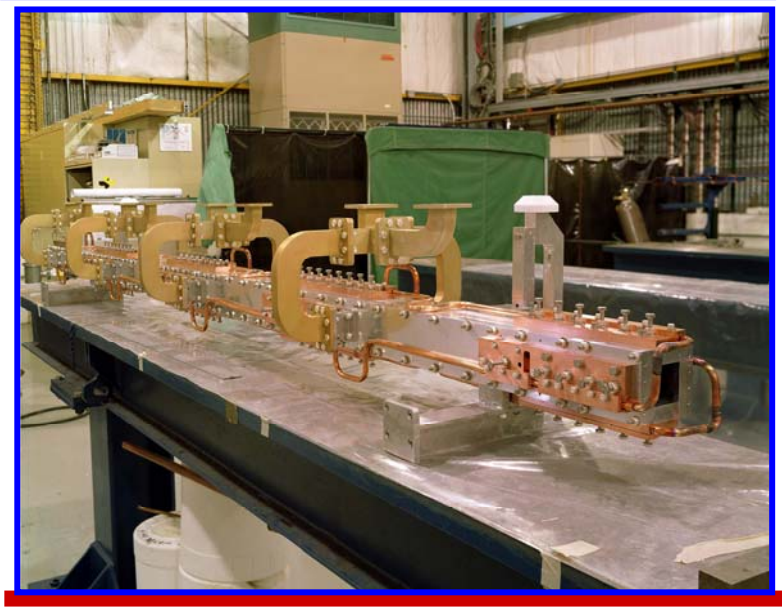
- Stochastic cooling uses feedback
- A pickup electrode measures an "error" signal for a given pbar.
  - This error signal could be the pbar's position or energy
  - The pickup signal can be extremely small, on the order of 1 pW
  - The Debuncher pickups are cooled to 4 Kelvin to reduce the effect of thermal noise and 300 Kelvin "shine"
- This signal is processed and amplified
  - The gain of the Debuncher systems is about 150 dB (a factor of 10^{15})
- The opposite of the error signal is applied to the pbar at the kicker
  - The kicker signal can be as large as 2 kW

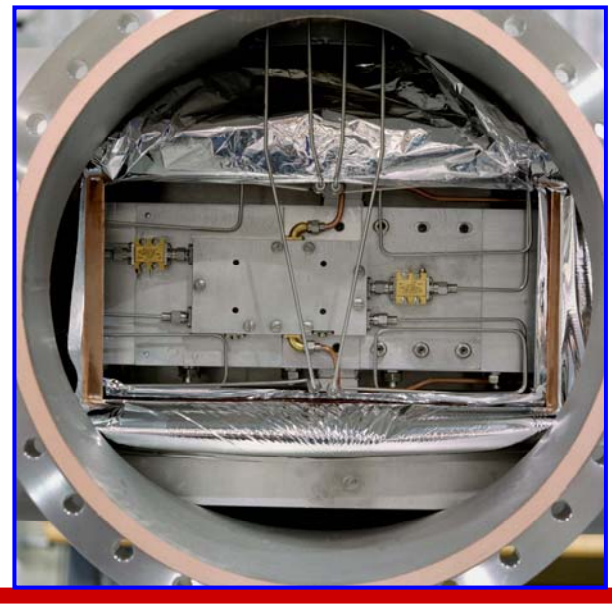


Stochastic Cooling Bandwidth

- The ability of a pickup to resolve a single pbar is proportional to the bandwidth of the pickup
- To resolve a single pbar in the Accumulator, the pickup bandwidth would have to be greater than 6×10^{17} Hertz
- The maximum bandwidth of the cooling systems we have built so far is 4 GHz (f_{max} =8 GHz), so on average there are 2×10^{8} pbars underneath a pickup in the Accumulator at any given time
- But these other pbars are sources of noise for a given pbar that needs to be cooled…

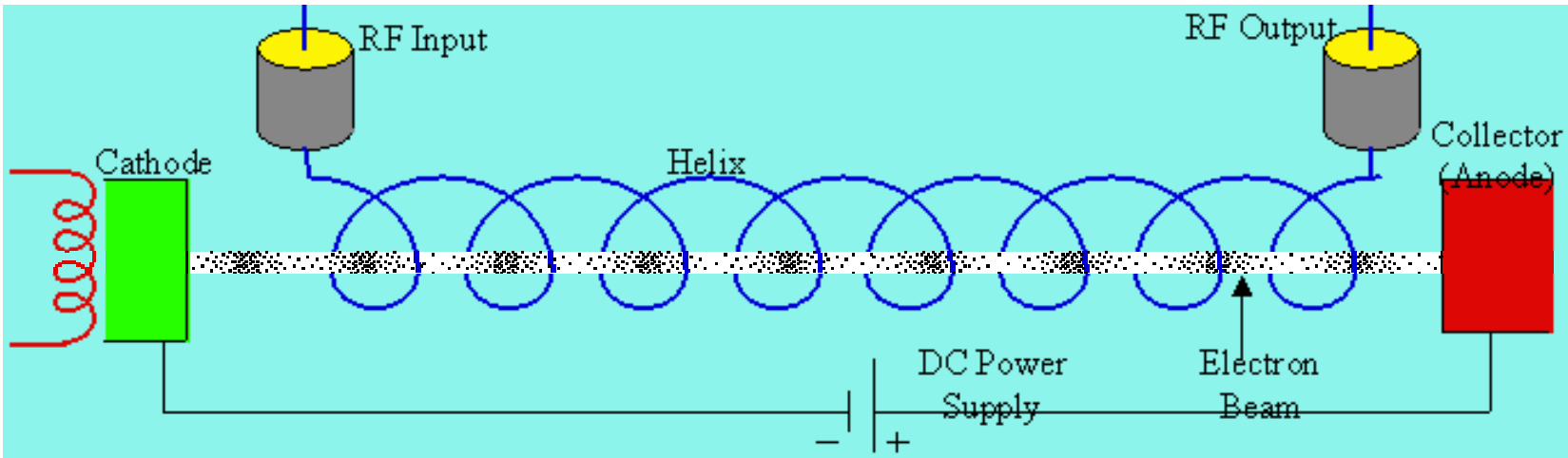
Stochastic Cooling Pickups



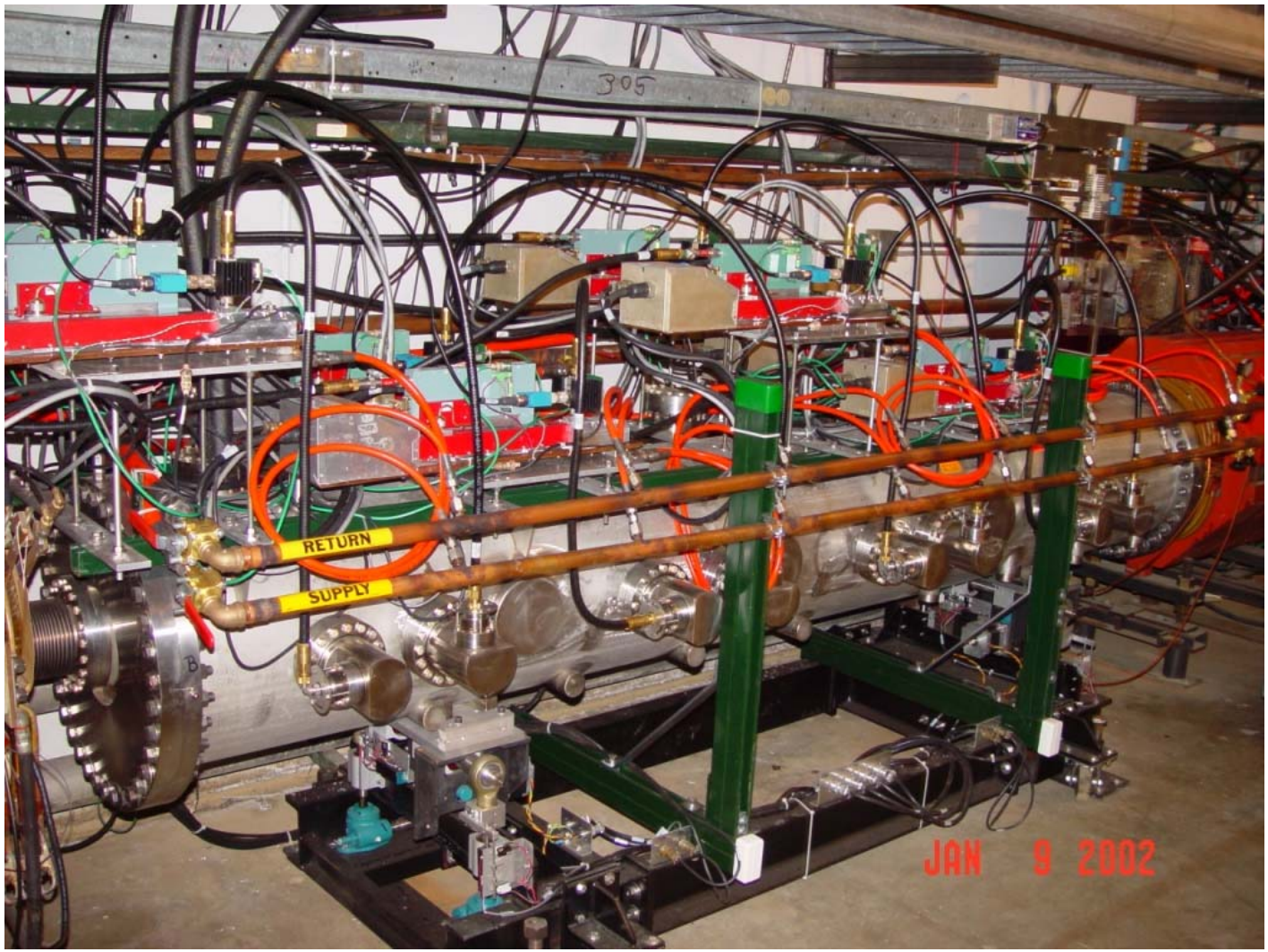


Traveling Wave Tubes

- The power amplifier for stochastic cooling must have a large bandwidth
- Traveling wave tubes (TWTs) can have bandwidths as large as an octave ($f_{max} = 2 \times f_{min}$)
- TWTs have a helix which wraps around an electron beam
  - The helix is a slow wave electromagnetic structure.
  - The phase velocity of the slow wave matches the velocity of the electron beam
- At the input, the RF modulates the electron beam.
- The beam in turn strengthens the RF
- Since the velocities are matched, this process happens all along the TWT resulting in a large amplification at the output (40dB = 10000 x)

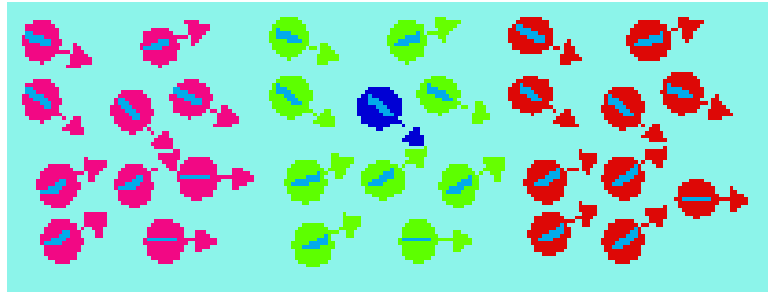


Stochastic Cooling Kicker

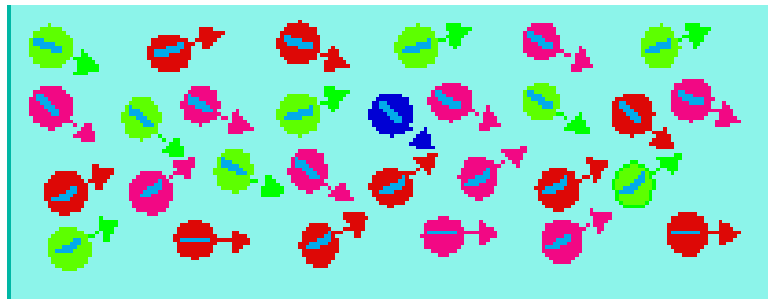


Stochastic Cooling Mixing

- Since each pbar has a slightly different energy than any other pbar, every pbar will take a different time to travel around the accelerator
- This causes the pbars to continually mix up so that the noise contribution of the other pbars underneath the pickup averages to zero in the long run.
- This effect is caused Mixing. The mixing factor is given as how many turns around the accelerator does it take for the beam to randomize its sample underneath the pickup
  - Proportional to momentum spread
  - Proportional to the maximum frequency of the cooling system



Before Mixing

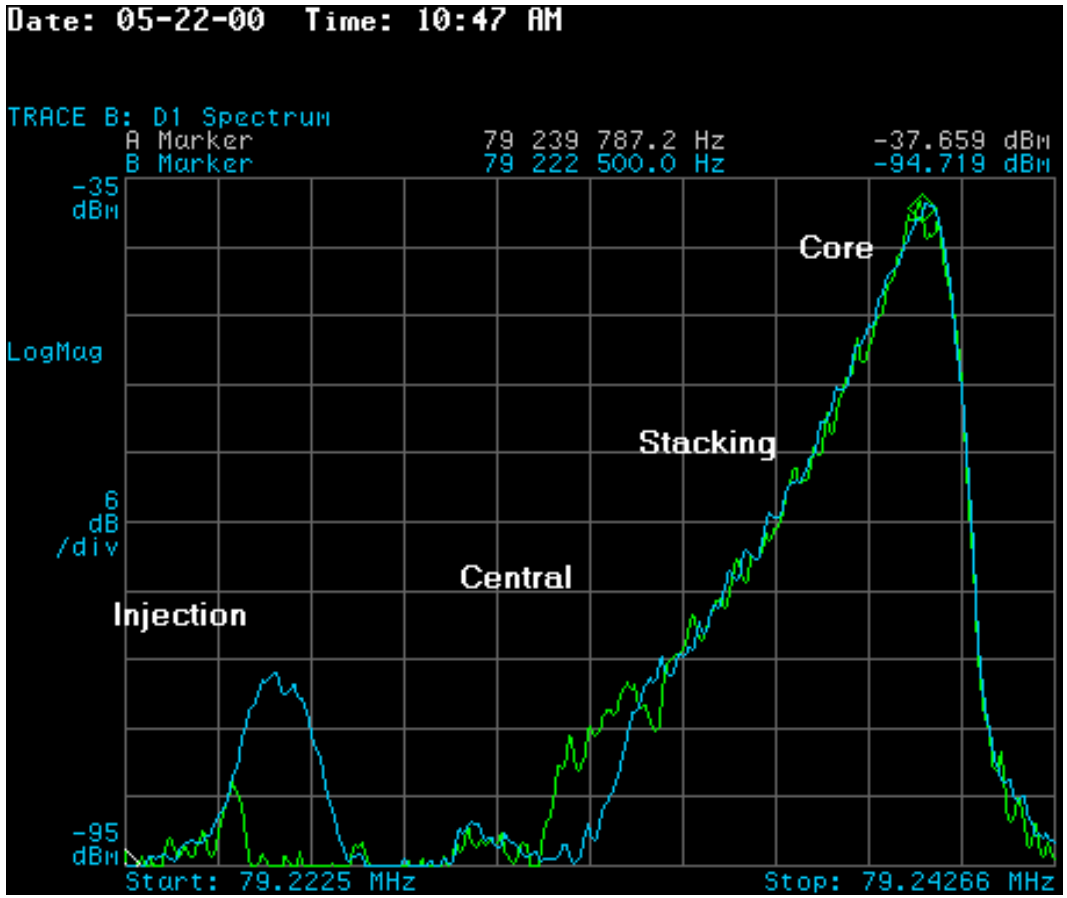


After Mixing

$$\frac{1}{\tau_{cool}} = \frac{W}{N_p M}$$

Antiproton Stacking – Stacktail System

- Beam is injected onto the Injection Orbit
- Beam is
  - Bunched with RF
  - Moved with RF to the Stacking Orbit
  - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core



Antiproton Stacking – Stacktail System

- The time evolution of the antiproton phase space during cooling is best described by the Fokker-Plank Equation

$$\frac{\partial\psi}{\partial t} = -\frac{\partial\phi}{\partial E}$$

$$\phi_c = \frac{\Delta E_c}{T_o}\psi = eV_o f_o \psi \sum_n \mathrm{Re}\{G_n(E)\}$$

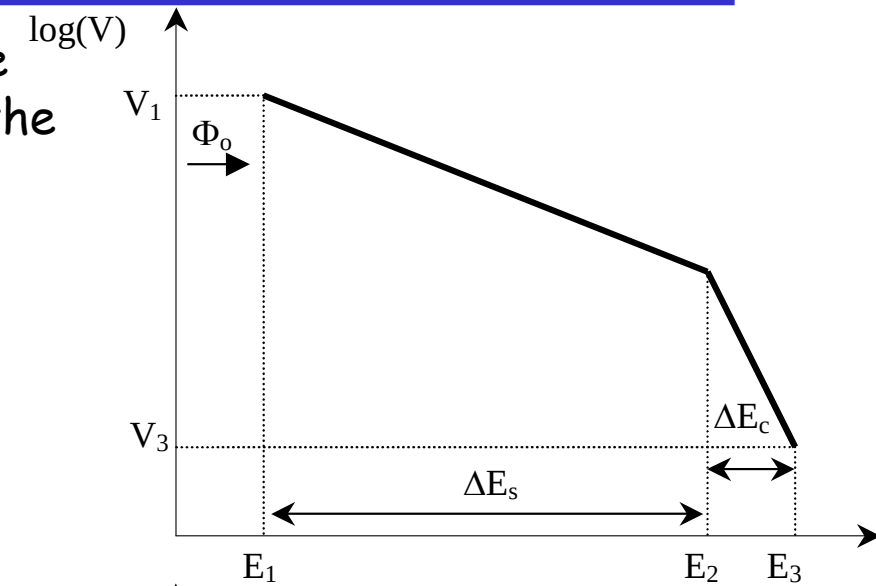
$$\phi_h = \frac{1}{2}\frac{\Delta E_h{}^2}{T_o}\frac{\partial\psi}{\partial E} = \frac{1}{4}(eV_o f_o)^2 \frac{E_o}{\eta f_o}\psi\frac{\partial\psi}{\partial E}\sum_n |G_n(E)|^2$$

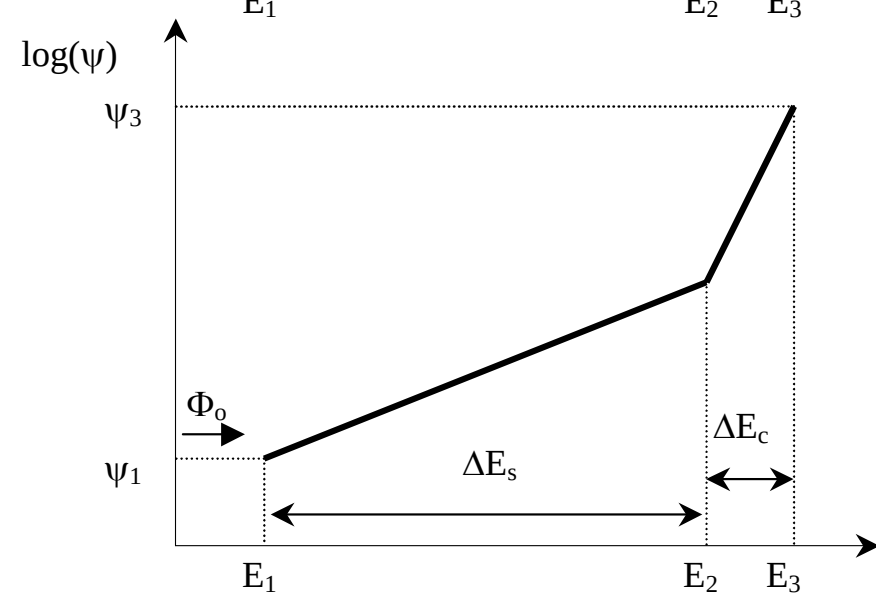
- Optimum profile that maximizes dψ/dE is exponential

$$\psi(E) = \psi_o e^{E/E_d}$$

$$G_n(E) = g_o e^{-E/E_d}$$

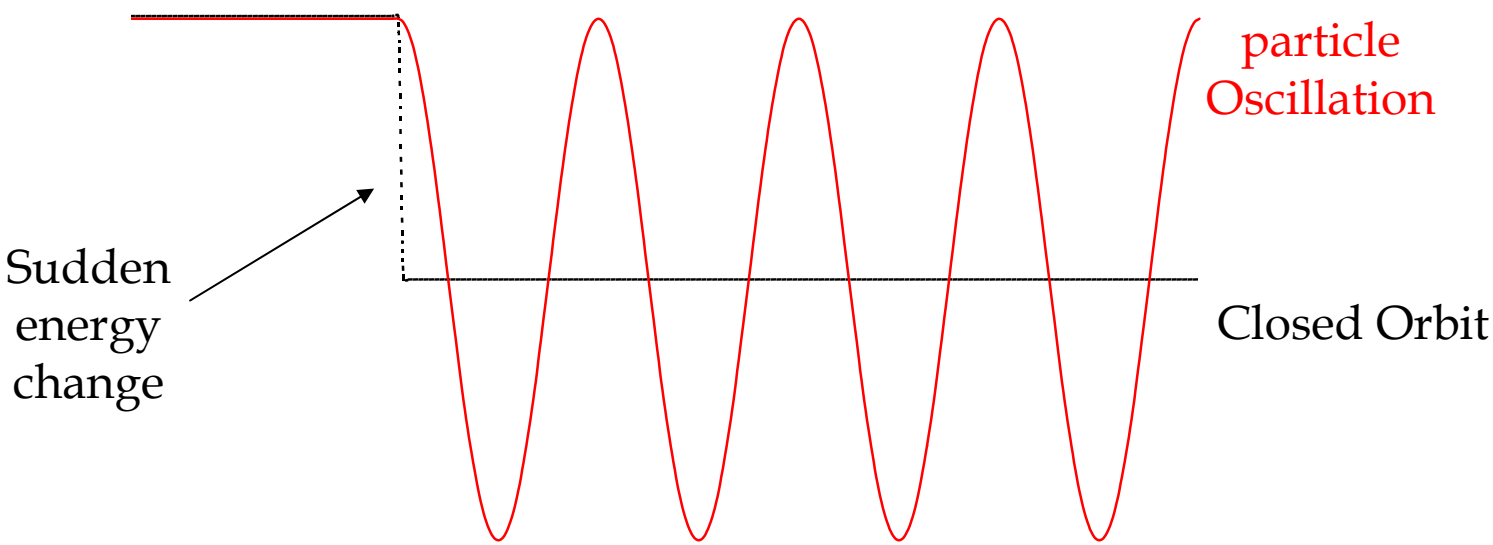
$$\phi_m = \eta f_o \frac{E_d}{E_o}\frac{\left(W/f_o\right)^2}{\ln\left(f_{max}/f_{min}\right)}$$



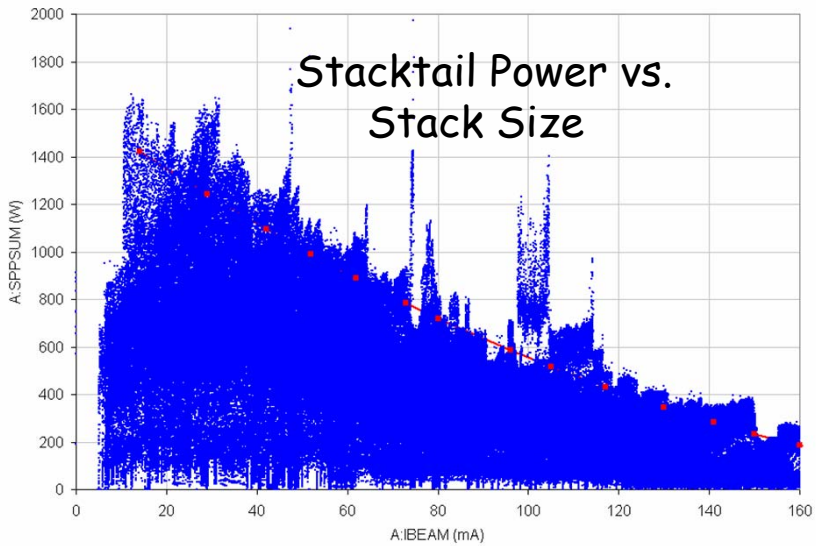


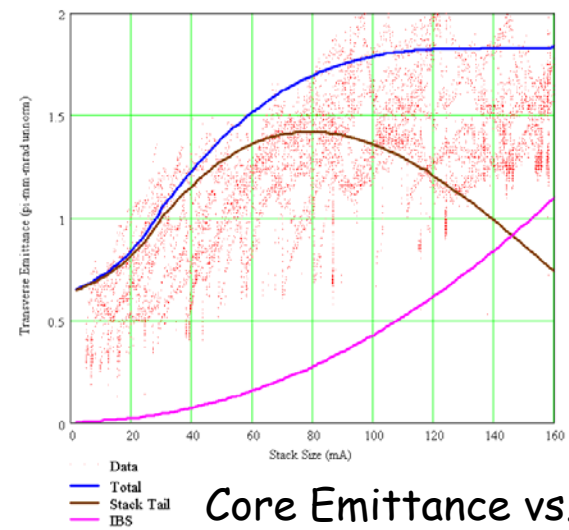
Stacktail Heating

- To push fast cycle times the gain of the Stacktail is increased
- More power in the Stacktail can transversely heat the core beam
  - Longitudinal tanks transversely misaligned give transverse kicks
  - Residual dispersion gives transverse kick
    - Dispersion is defined as the transverse position as a function of energy
    - Longitudinal kick in dispersion changes local reference orbit which results in a betatron oscillation

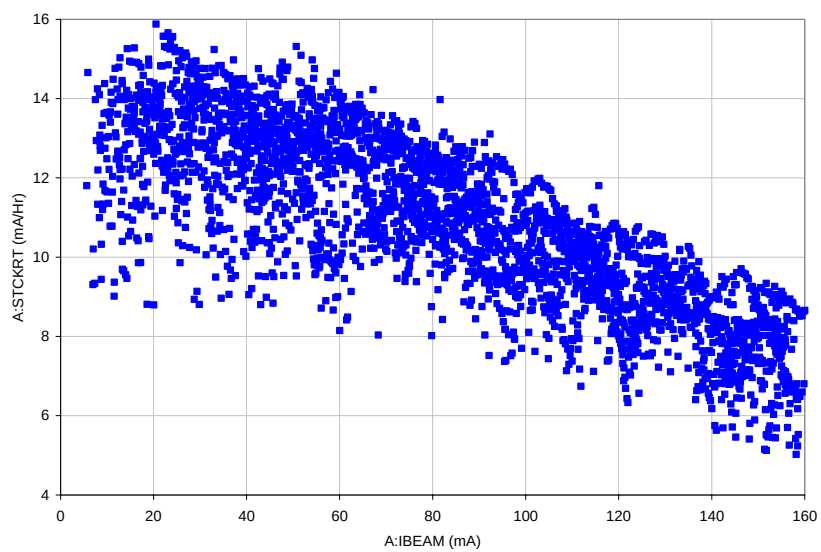


StackTail Heating





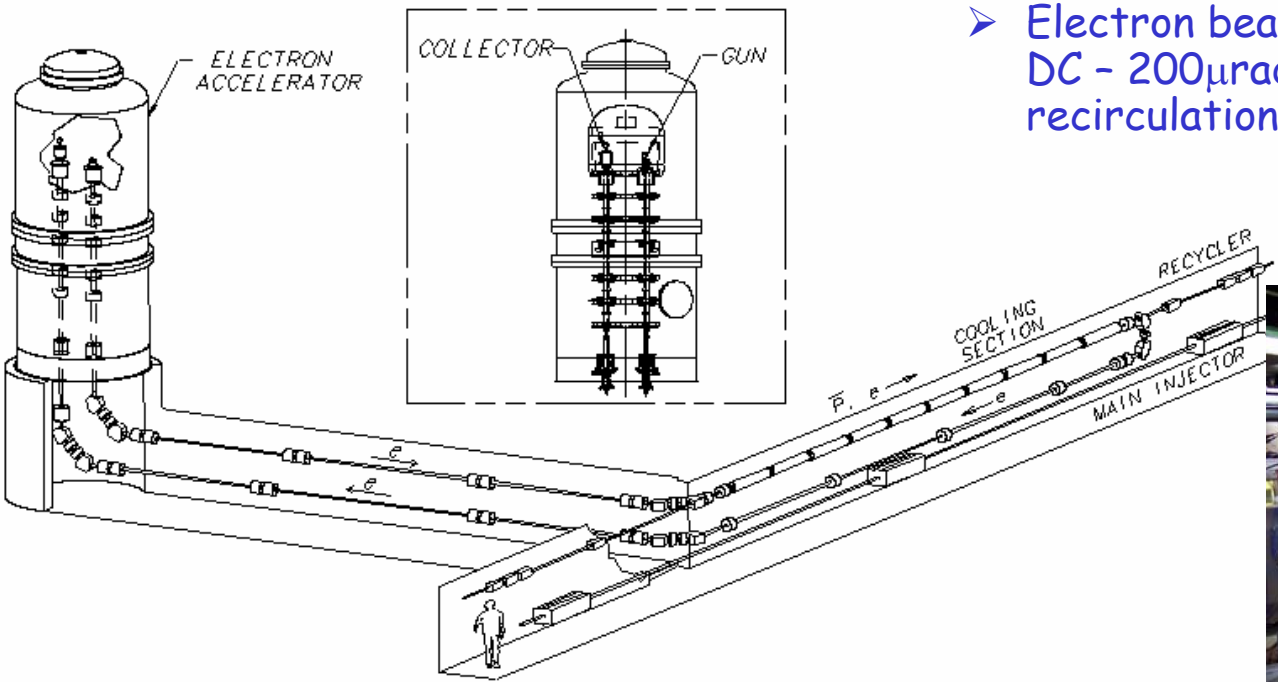
Core Emittance vs. Stack Size

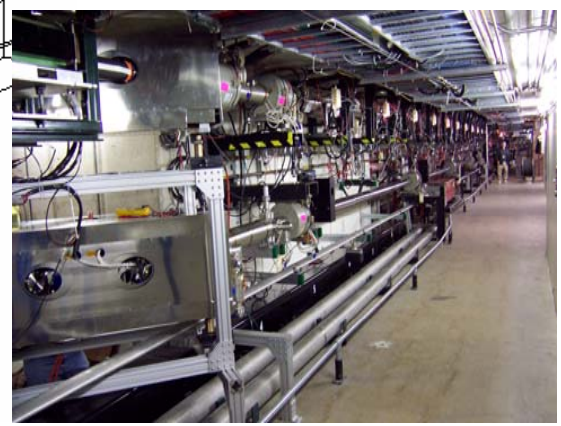


Stack Rate vs Stack Size

Recycler Electron Cooling

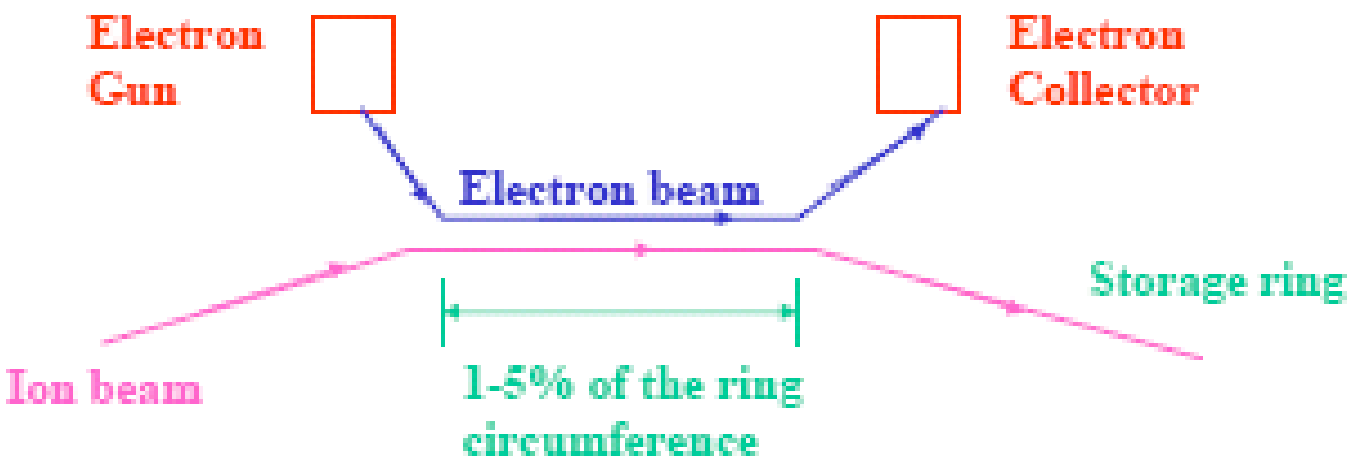
- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency





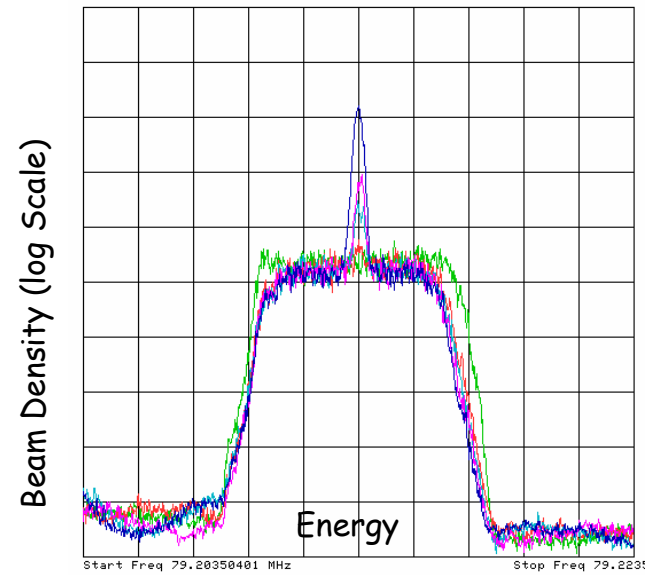
Electron Cooling

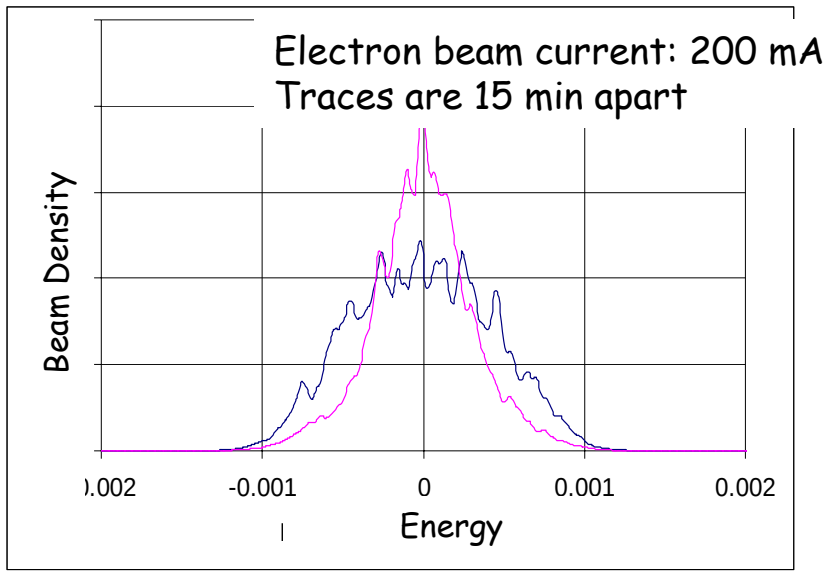
- The velocity of the electrons is made equal to the average velocity of the antiprotons.
- The antiprotons undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the antiprotons to the co-streaming electrons until some thermal equilibrium is attained.
- The cooling rate is:
  - Proportional to the electron current
  - Inversely proportional to the electron temperature (emittance)
  - Independent of the number of antiprotons
- Electron Cooling works well for narrow, intense beams



Recycler Electron Cooling

- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 (two months ahead of schedule).
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling goals
  - Can presently support final design goal of rapid transfers (30eV-Sec/2hrs)
  - Can presently reliably support stacks of 250×10^{10} (FY06 design goal)
  - Have achieved 500 mA of electron beam which is the final design goal.

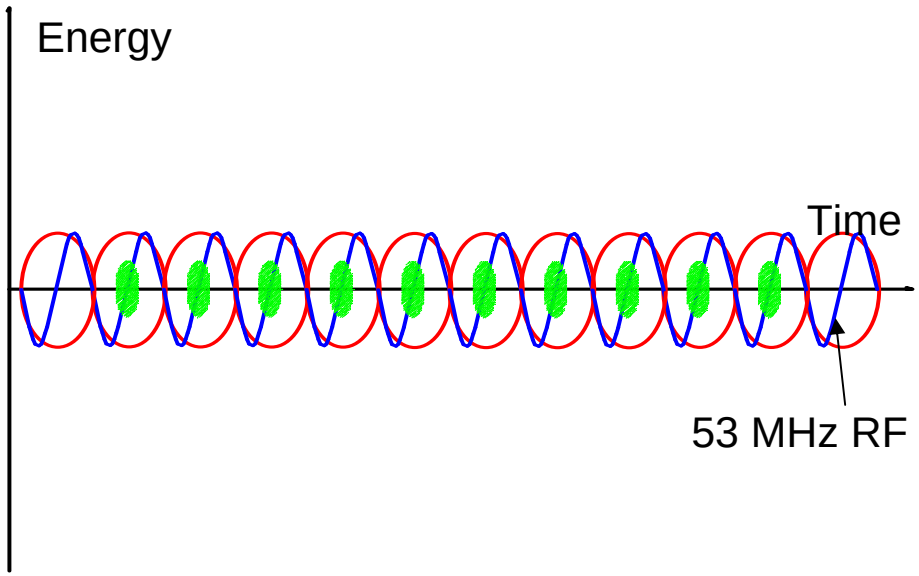




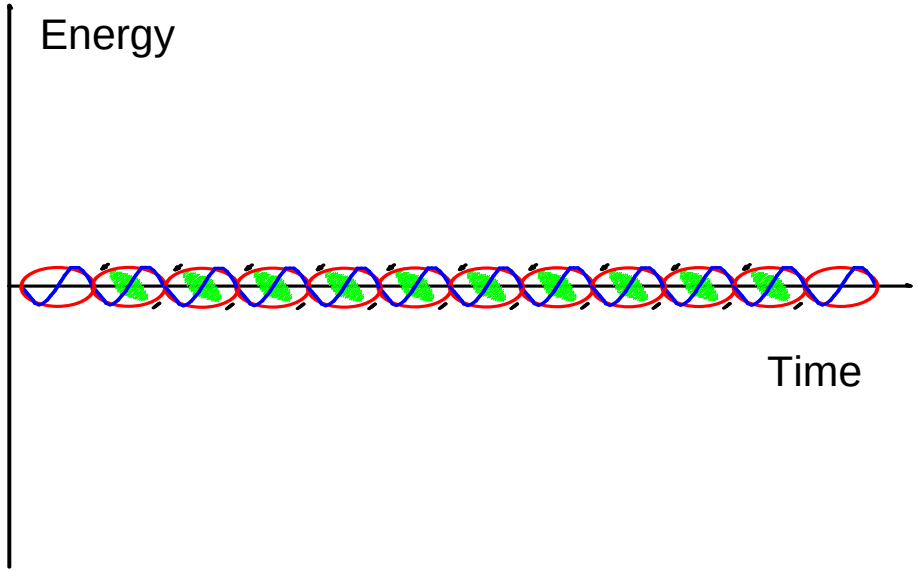
Coalescing

- In most cases, it is better to have the beam spread out uniformly throughout the accelerator
  - Momentum aperture
  - Instabilities
  - Stochastic cooling
- Collider detectors want the beam contained in a short bunch
- Coalescing is a method of combining many (~11) low intensity short bunches into a single high intensity short bunch.

Coalescing

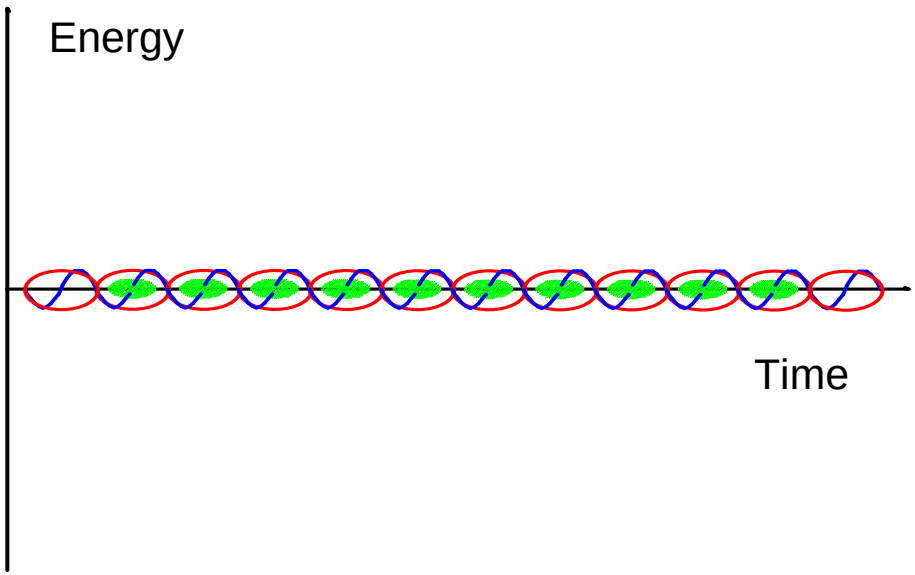


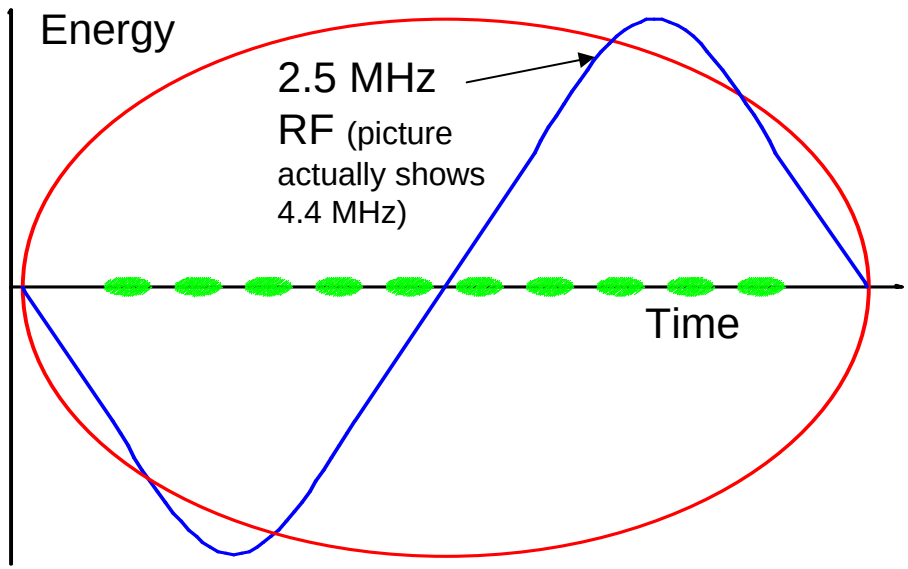
Step 1. Accelerate about 10 -11 bunches to 150 GeV in 53 MHz Buckets



Step 2. Abruptly reduce the 53 MHz RF voltage. This will cause each bunch to rotate in its own RF bucket.

Coalescing

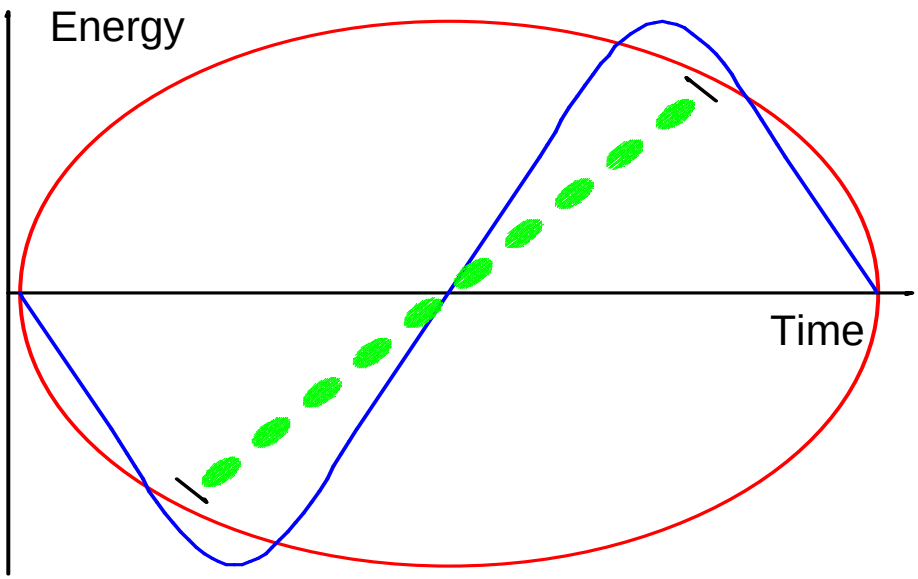




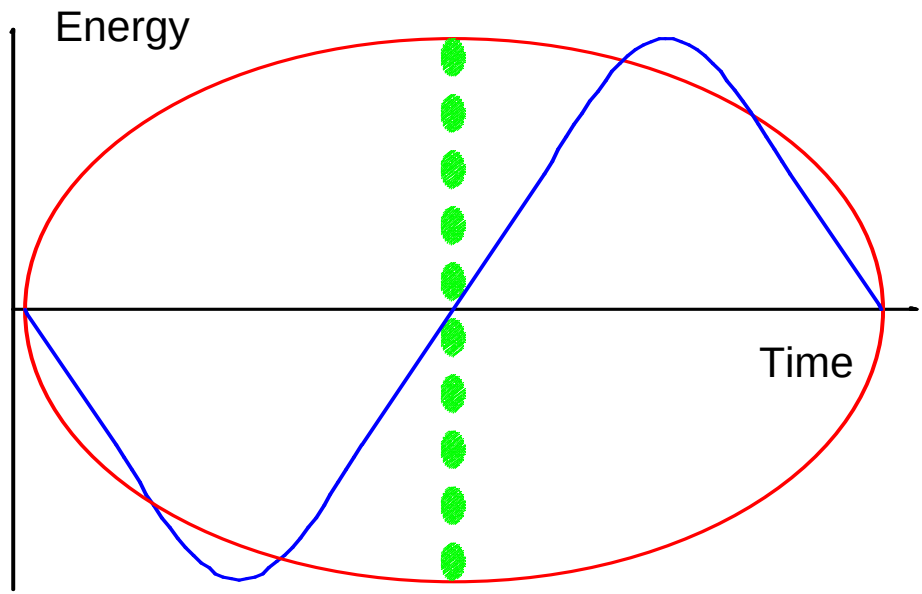
Step 3. Wait until the bunches have rotated 90 degrees. The bunches will have a small energy spread but a long time spread.

Step 4. Turn off 53 MHz RF and abruptly turn on the 2.5 MHz RF.

Coalescing

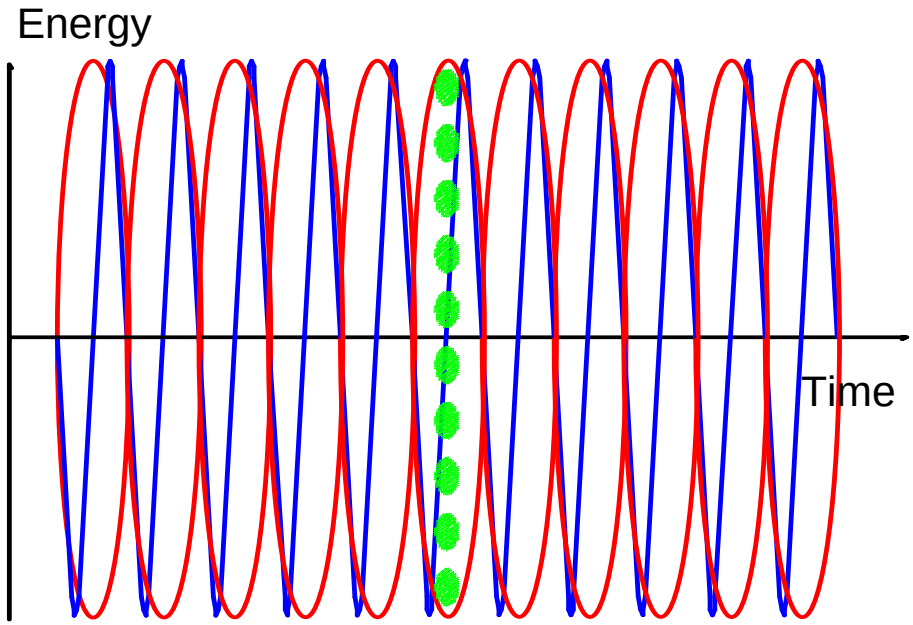


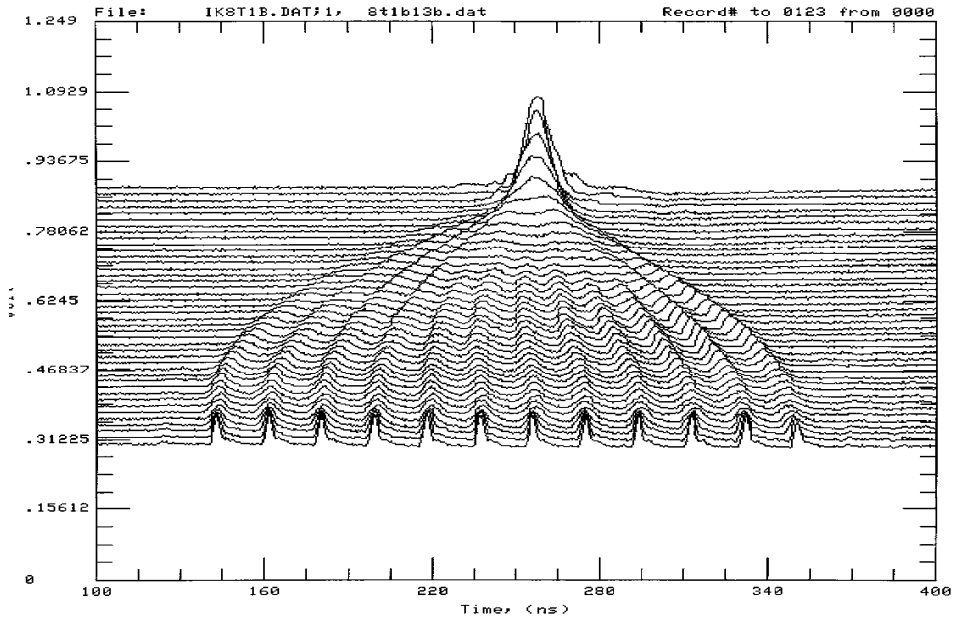
Step 5. The entire collection of bunches will rotate around the 2.5 MHz bucket.



Step 6. Wait until the collection of bunches have rotated 90 degrees and are all aligned in time.

Coalescing





Step 7. Snap on the 53 MHz RF and turn off the 2.5 MHz RF. All the bunches are now contained in a single 53 MHz RF Bucket

Summary

- A key feature to the success of a high energy collider is the beam brightness or luminosity.
- The beam brightness is determined by particle motion or evolution though the accelerator chain.
- To first order, the motion of particles in an accelerator can be described by simple harmonic motion around an ideal trajectory or energy.
- This motion can be portrayed using the concept of phase space.
- There are many more accelerator phenomena that are clearly described with simple phase space concepts
  - Transition crossing
  - Intra-beam scattering
  - Beam-beam tuneshift
  - Etc..