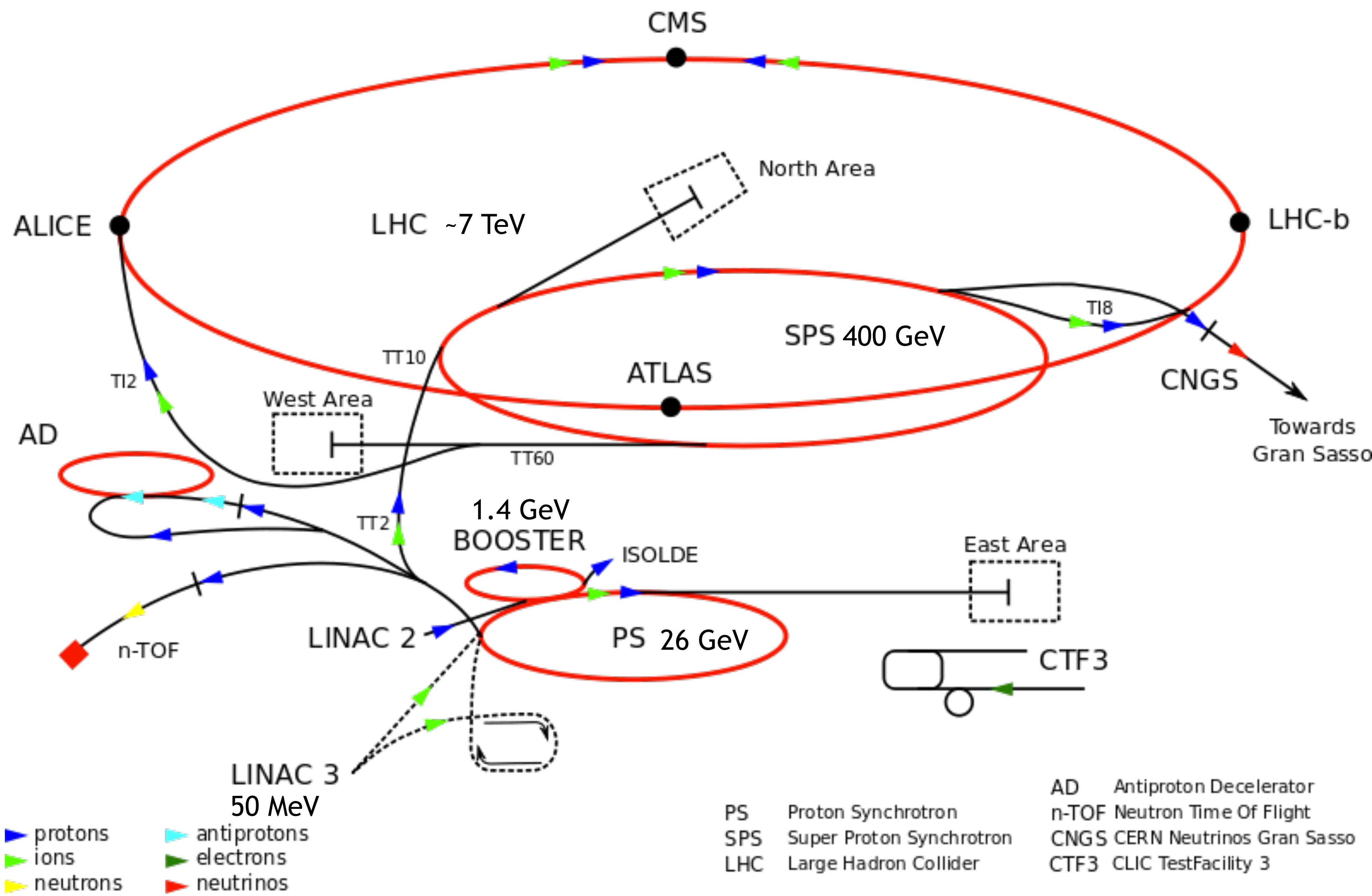
Tricks of the Trade (Stuff that really doesn't fit anywhere else)

Multi-stage Acceleration

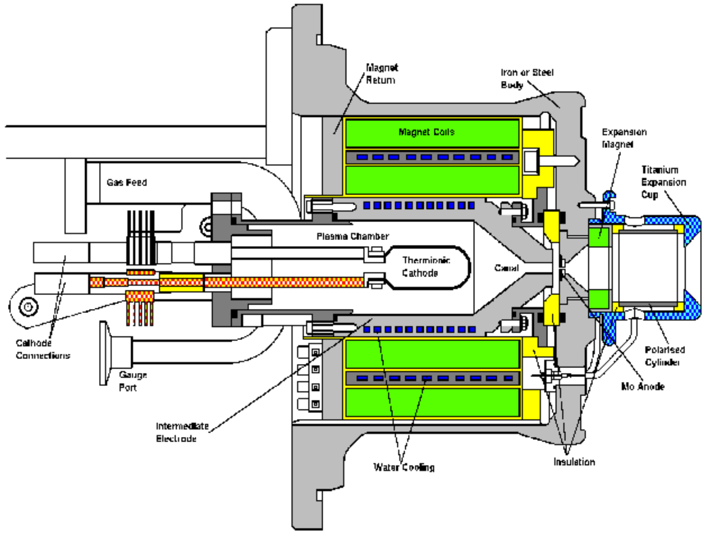
- Early synchrotrons had low energy injection and provided all the acceleration in a single stage.
- The energy range of a single synchrotron is limited by
  - An aperture large enough for the injected beam is unreasonably large at high field.
  - Hysteresis effects result in excessive nonlinear terms at low energy (very important for colliders)
- Typical range 10-20 for colliders, larger for fixed target
  - Fermilab Main Ring: 8-400 GeV (50x)
  - Fermilab Tevatron: 150-980 GeV (6.5x)
  - LHC: 400-7000 GeV (17x)
- The highest energy beams require multiple stages of acceleration, with high reliability at each stage
- How is this done?

Example: CERN Accelerator Complex

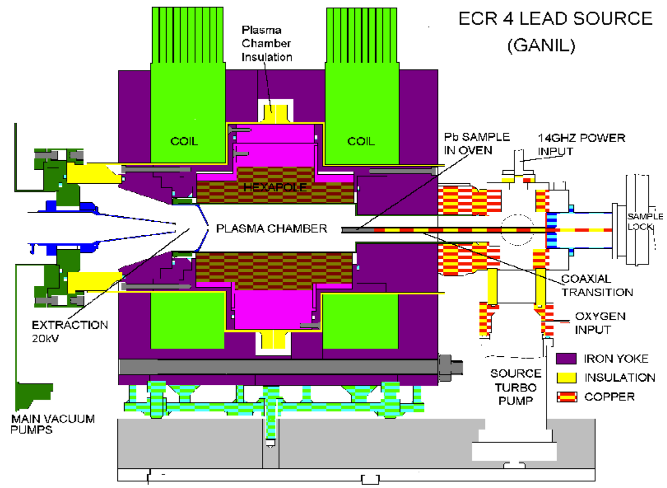


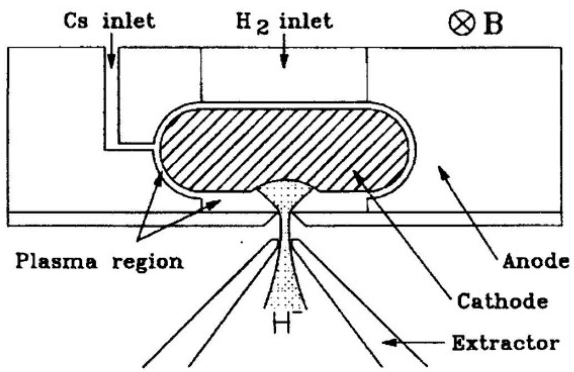
Getting Started: Ion Sources

CERN proton source



CERN Lead source



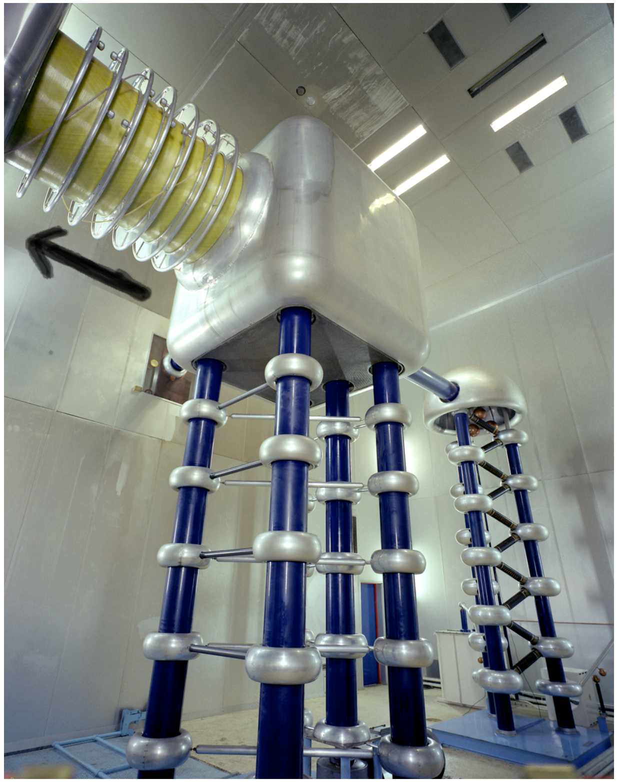


FNAL H- source. Mix Cesium with Hydrogen to add electron. (why? we'll get to that)

Typically 10s of keV and mAs to 10s of mA of current. Want to accelerate as fast as possible before space charge blows up the beam!

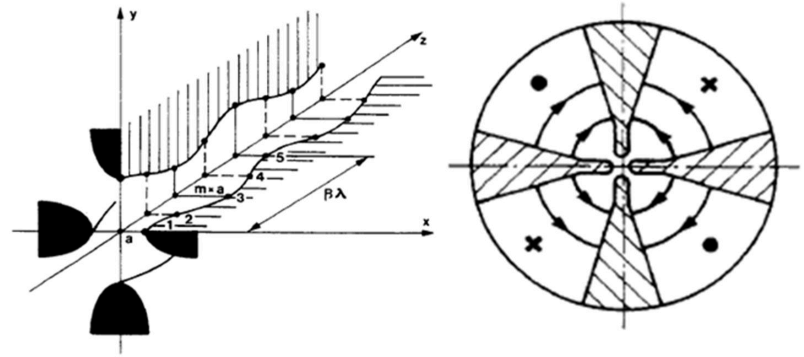
Initial Acceleration

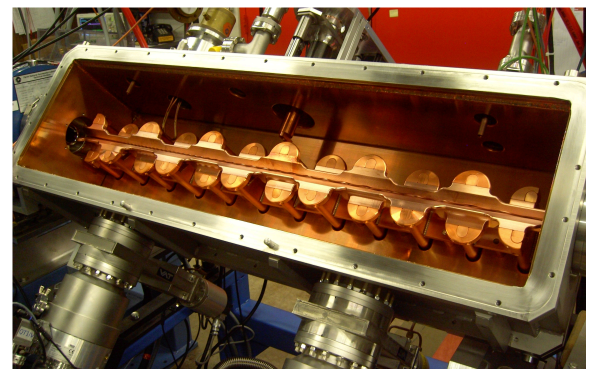
Old: Static



Static acceleration from Cockcroft-Walton.
FNAL = 750 keV
max ~1 MeV

New: RF Quadrupole (RFQ)





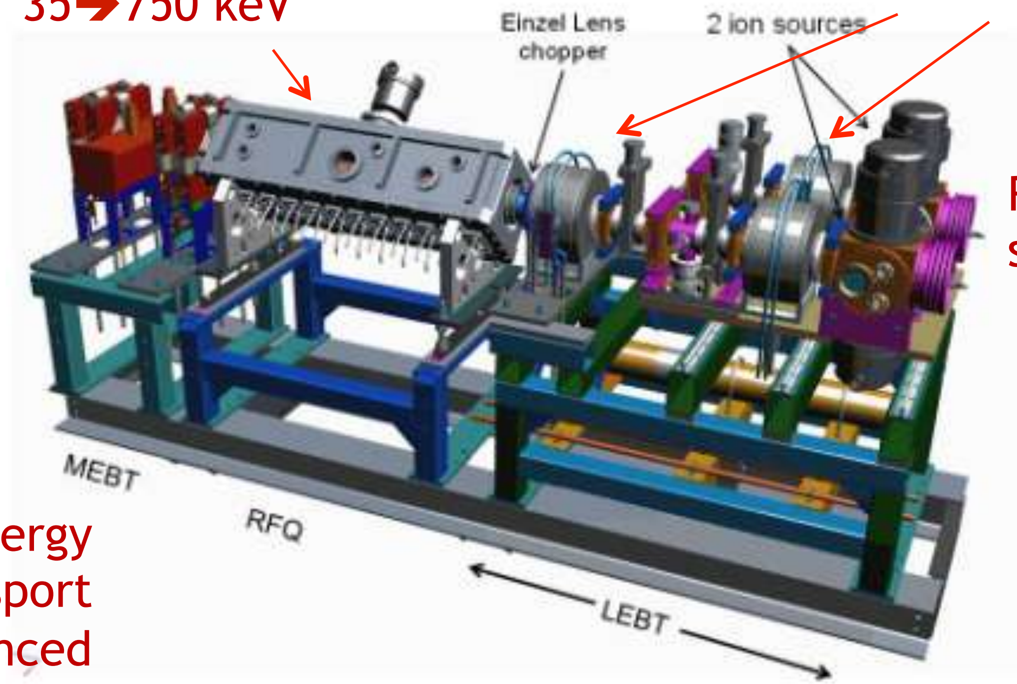
RF structure combines an electric focusing quadrupole with a longitudinal accelerating gradient.

Early Stages

- The front end of any modern hadron accelerator looks something like this (Fermilab front end)

200 MHz RFQ:
35➔750 keV

Solenoidal focusing for low energy beam



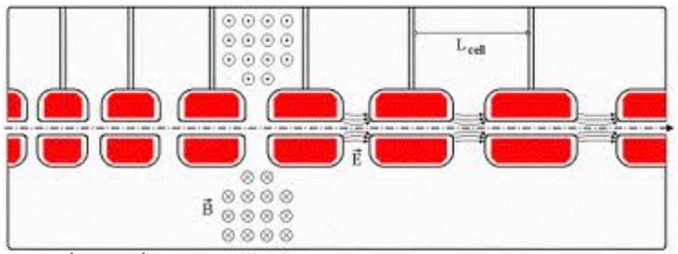
Redundant H$^-$ sources: 0-35 keV

Medium Energy Beam Transport (MEBT, pronounced “mebbit”): 750 kEV

Low Energy Beam Transport (LEBT, pronounced “lebbit”): 35 keV

Drift Tube (Alvarez) Cavity

- Because the velocity is changing quickly, the first linac is generally a Drift Tube Linac (DTL), which can be beta-matched to the accelerating beam.
- Put conducting tubes in a larger pillbox, such that inside the tubes *E=0*



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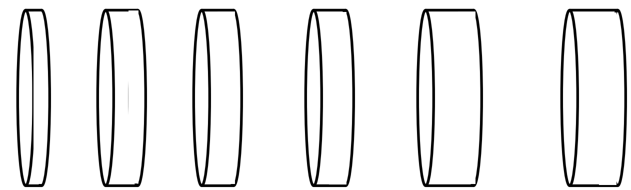
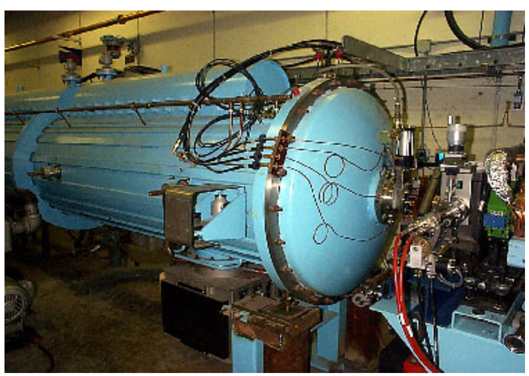
Bunch of pillboxes



$$d = \frac{v}{f}$$

Gap spacing changes as velocity increases

Drift tubes contain quadrupoles to keep beam focused



Fermilab low energy linac

Inside

- As energy gets higher, switch to "pi-cavities", which are more efficient

Linac -> Synchrotron Injection

- Eventually, the linear accelerator must inject into a synchrotron

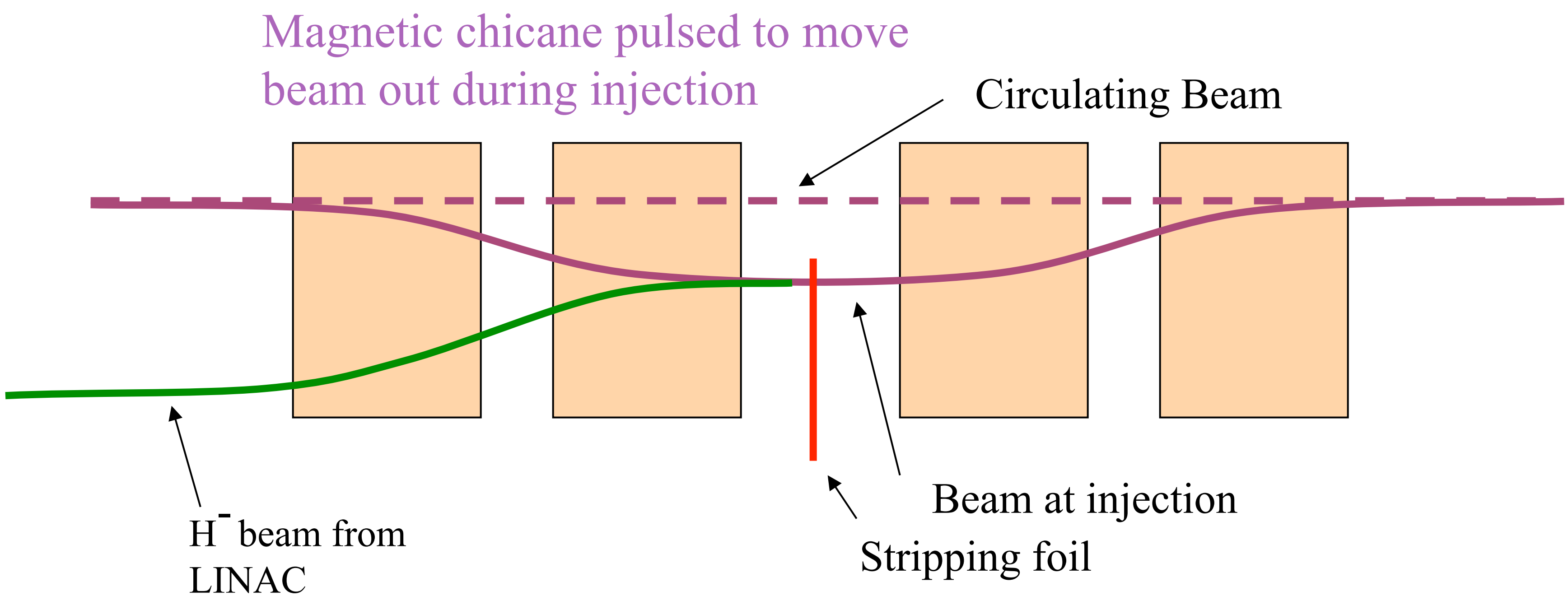
- In order to maximize the intensity in the synchrotron, we can
  - Increase the linac current as high as possible and inject over one revolution
    - There are limits to linac current
  - Inject over multiple (*N*) revolutions of the synchrotron
    - Preferred method
- Unfortunately, Liouville's Theorem says we can't inject one beam on top of another
  - Electrons can be injected off orbit and will "cool" down to the equilibrium orbit via synchrotron radiation.
  - Protons can be injected a small, changing angle to "paint" phase space, resulting in increased emittance

$$\epsilon_S \geq N\epsilon_{LINAC}$$

Linac emittance

Synchrotron emittance

Ion (or Charge Exchange) Injection

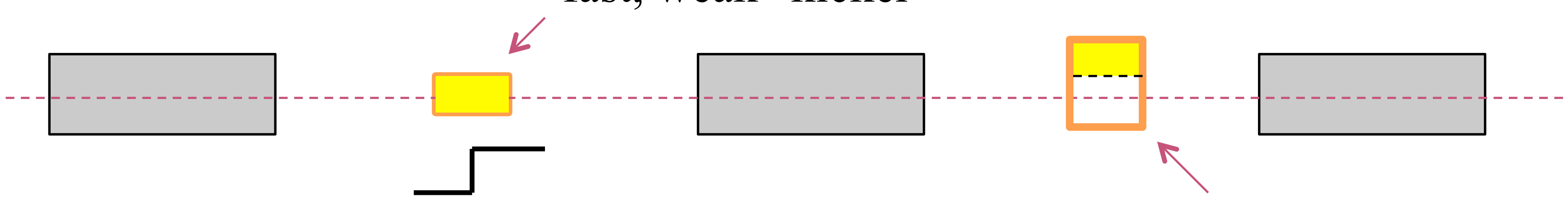


- Instead of ionizing Hydrogen, and electron is added to create H^-, which is accelerated in the linac
- A pulsed chicane moves the circulating beam out during injection
- An injected H^- beam is bent in the opposite direction so it lies on top of the circulating beam
- The combined beam passes through a foil, which strips the two electrons, leaving a single, more intense proton beam.
- Fermilab was converted from proton to H^- during the 70's
- CERN *still* uses proton injection, but is in the process of upgrading (LINAC4 upgrade)

Injection and Extraction

- We typically would like to extract (or inject) beam by switching a magnetic field on between two bunches (order ~10-100 ns)

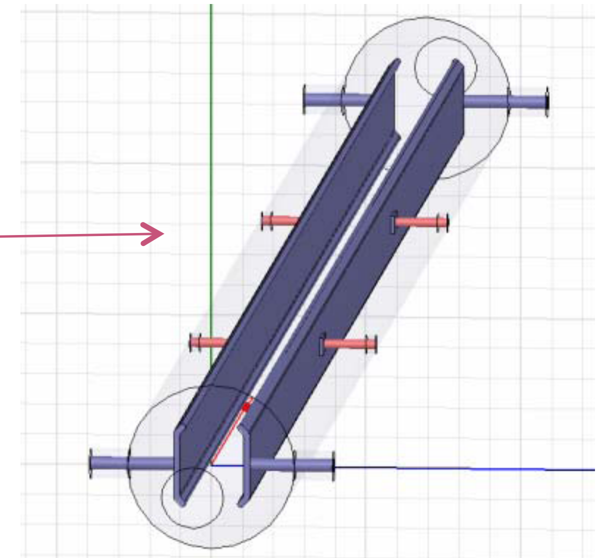
- Unfortunately, getting the required field in such a short time would result in prohibitively high inductive voltages, so we usually do it in two steps:



Extraction Hardware

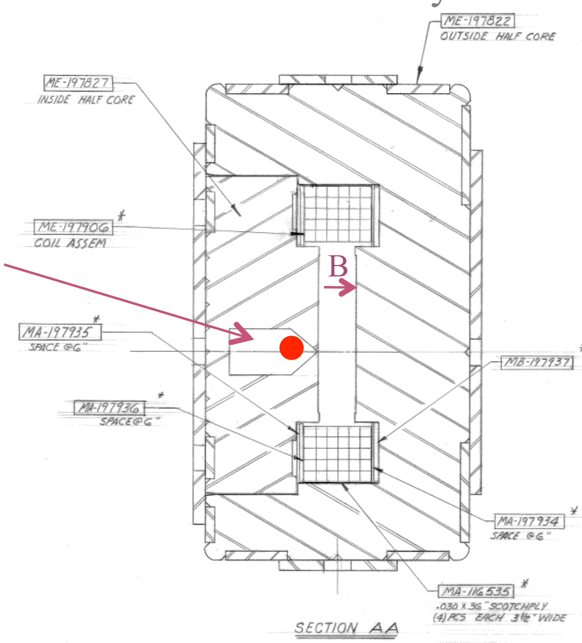
“Fast” kicker

- usually an impedance matched strip line, with or without ferrites



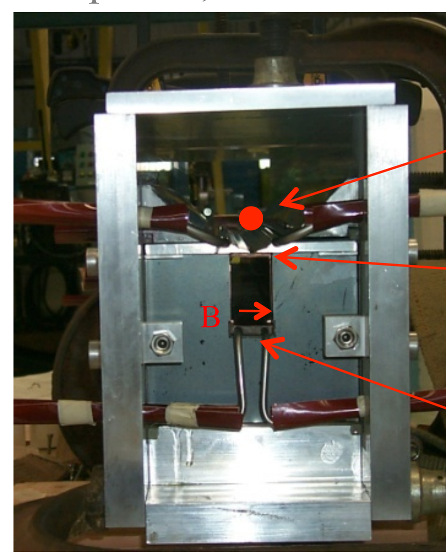
“Slow” extraction elements

“Lambertson”: usually DC



circulating beam (B=0)

Septum: pulsed, but slower than the kicker



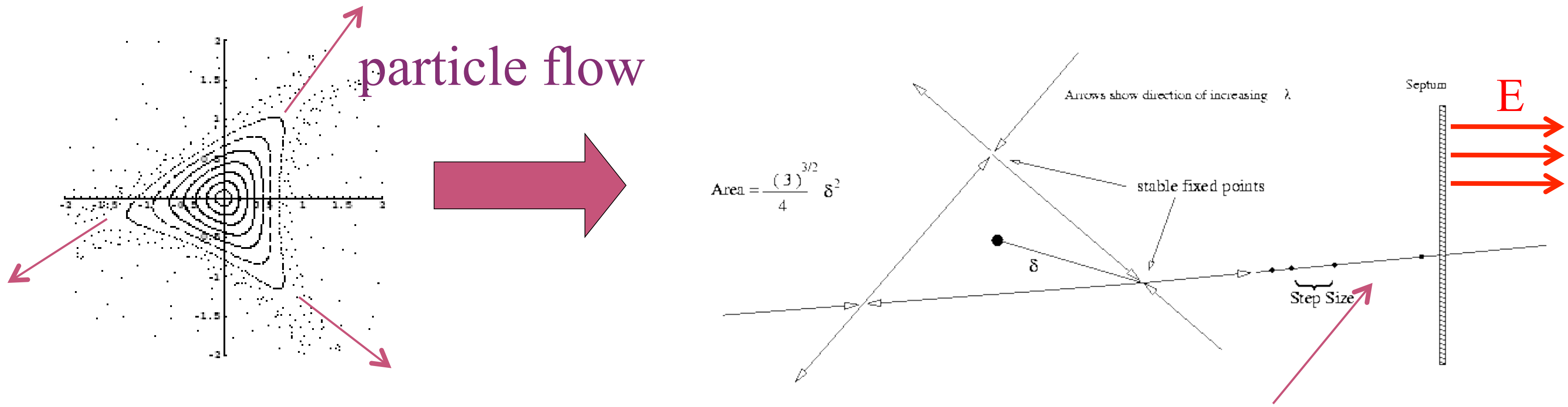
circulating beam (B=0)

current “blade”

return path

Slow Extraction (not important for colliders)

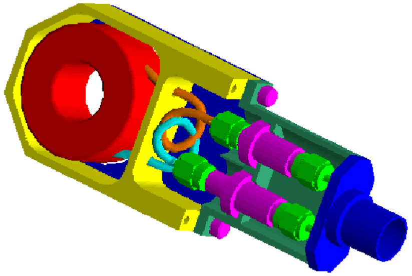
- Sometimes fixed target experiments want beam delivered *slowly* (difficult)
- To do this, we generate a harmonic resonance
  - Usually sextupoles are used to create a 3rd order resonant instability



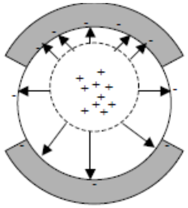
Particles will flow out of the stable region along lines in phase space into an electrostatic extraction field, which will deflect them into an extraction Lambertson

- Tune the instability so the escaping beam exactly fills the extraction gap between interceptions (3 times around for 3rd order)
  - Minimum inefficiency ~(septum thickness)/(gap size)
  - Use electrostatic septum made of a plane of wires. Typical parameters
    - Septum thickness: .1 mm
    - Gap: 10 mm
    - Field: 80 kV

Standard Beam Instrumentation



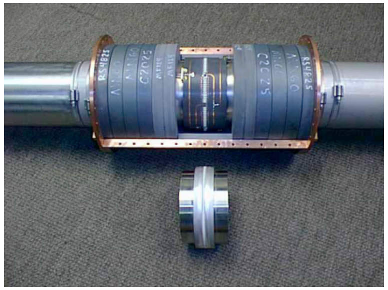
- Bunch/beam intensity are measured using inductive toriods



- Beam position is typically measured with beam position monitors (BPM's), which measure the induced signal on a opposing pickups

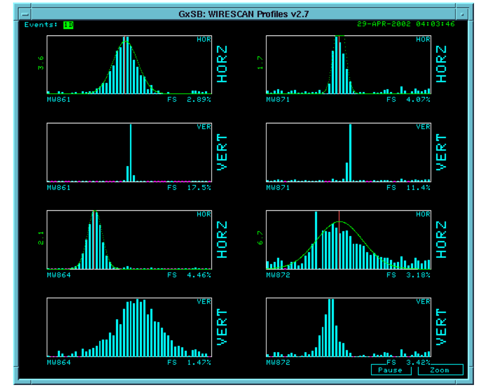
$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

- Longitudinal profiles can be measured by introducing a resistor to measure the induced image current on the beam pipe -> Resistive Wall Monitor (RWM)

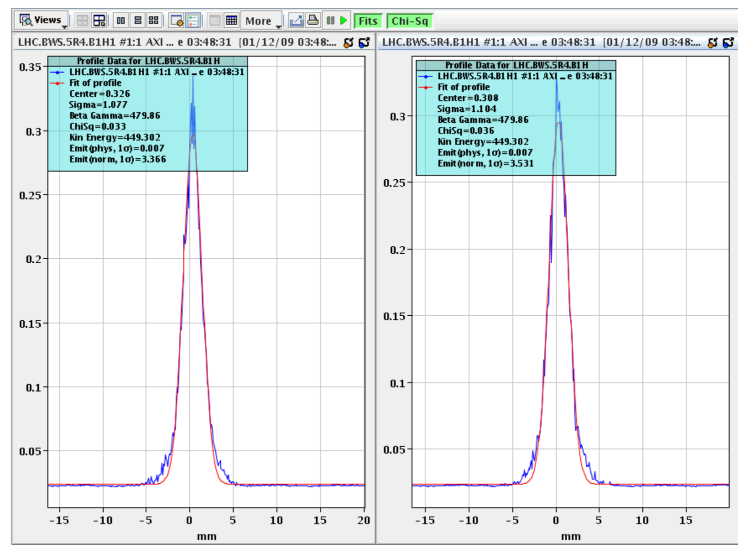


Beam Instrumentation (cont'd)

- Beam profiles in beam lines can be measured using secondary emission multiwires (MW's)
- Can measure beam profiles in a circulating beam with a "flying wire scanner", which quickly passes a wire through and measures signal vs time to get profile
- Non-destructive measurements include
  - Ionization profile monitor (IPM): drift electrons or ions generated by beam passing through residual gas
  - Synchrotron light
    - Standard in electron machines
    - Also works in LHC



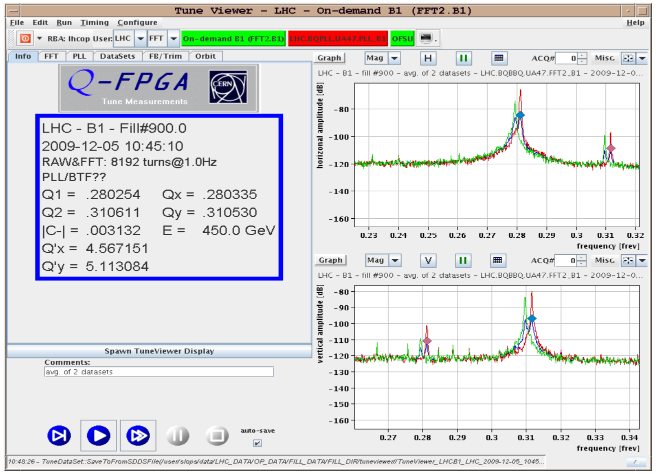
Beam profiles in MiniBooNE beam line



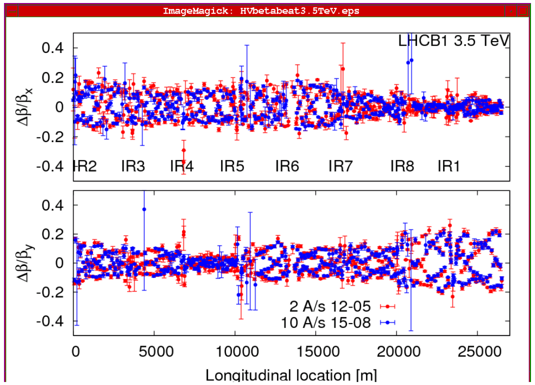
Flying wire signal in LHC

Measuring Lattice Parameters

- The fractional tune is measured by Fourier Transforming signals from the BPM's
  - Sometimes need to excite beam with a kicker

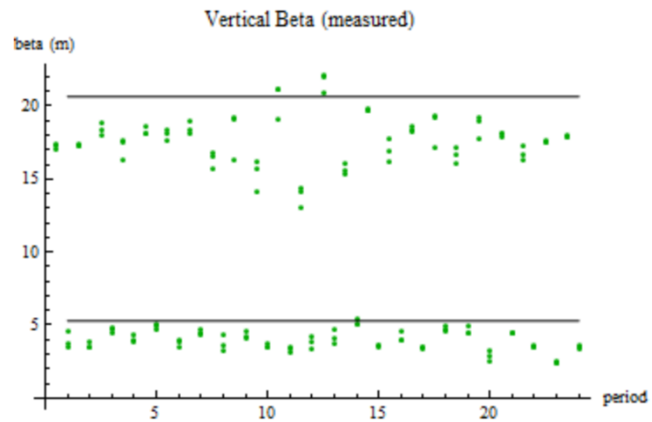


- Beta functions can be measured by exciting the beam and looking at distortions
  - Can use kicker or resonant ("AC") dipole



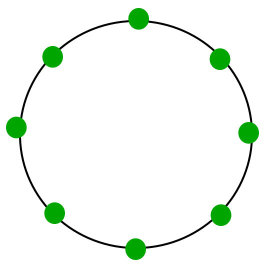
- Can also measure the by functions indirectly by varying a quad and measuring the tune shift

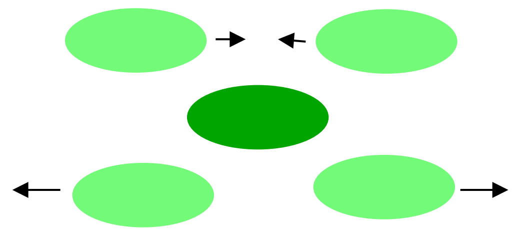
$$\Delta\nu = \frac{1}{4\pi}\frac{\beta}{f}$$



Colliding Beam Luminosity

Circulating beams typically "bunched"





(number of interactions)

$$= \left(\frac{N_1}{A}\right) N_2 \sigma$$

Cross-sectional area of beam

Total Luminosity:

$$L = \left(\frac{N_1 N_2}{A}\right) r_b = \left(\frac{N_1 N_2}{A}\right) n \frac{c}{C}$$

crossing rate

Number of bunches

Circumference of machine

Luminosity of Colliding Beams

- For equally intense Gaussian beams

Collision frequency

Particles in a bunch

Geometrical factor:
- crossing angle
- hourglass effect

$$L = f \frac{N_b^{\ 2}}{4\pi\sigma^2} R$$

Transverse size (RMS)

- Using $\sigma^2 = \frac{\beta^* \epsilon_N}{\beta\gamma} \approx \frac{\beta^* \epsilon_N}{\gamma}$ we have

prop. to energy

$$L = f_{rev} \frac{1}{4\pi} n_b N_b^2 \frac{\gamma}{\beta^* \epsilon_N} R$$

Normalized emittance

Revolution frequency

Number of bunches

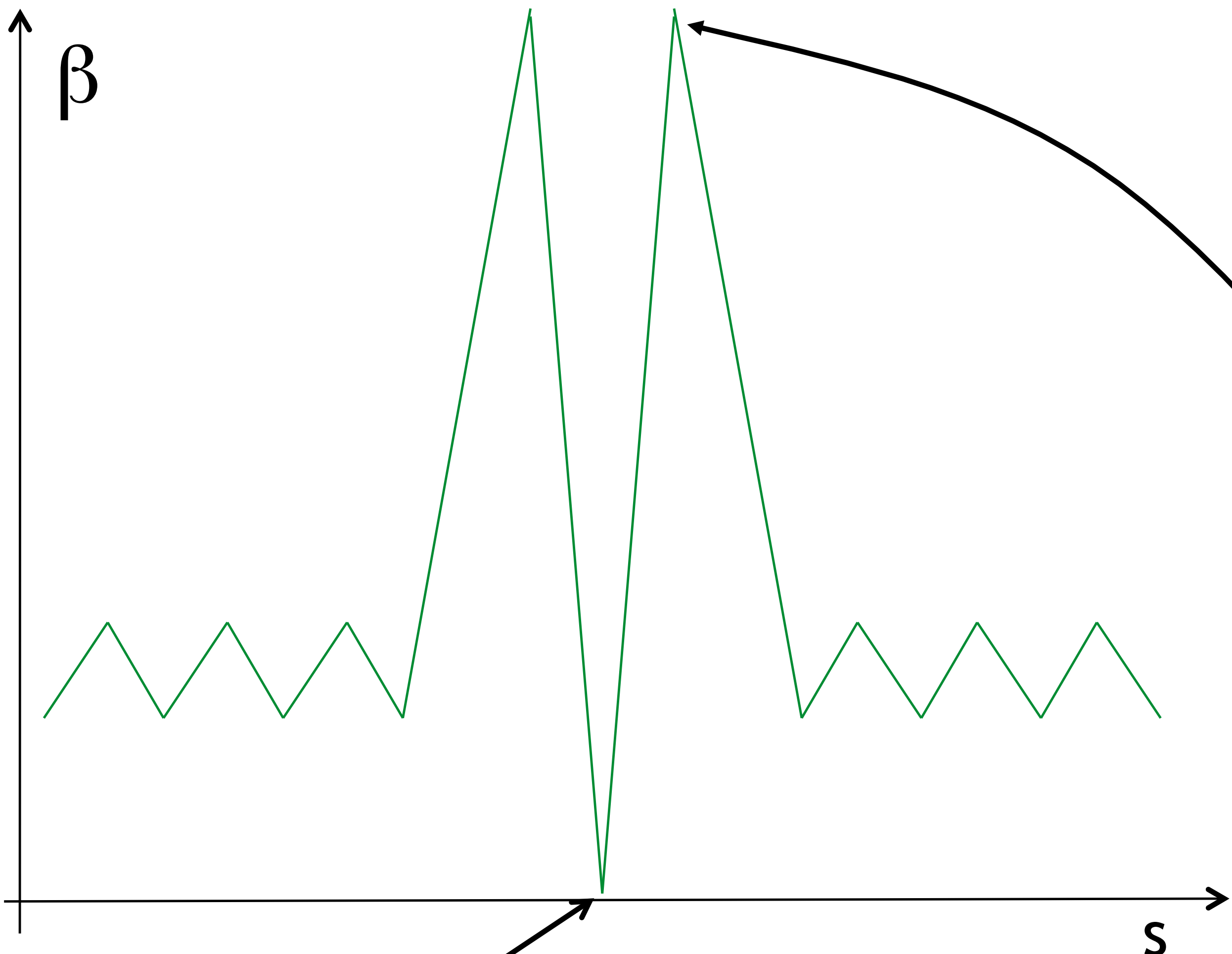
Betatron function at collision point ➔

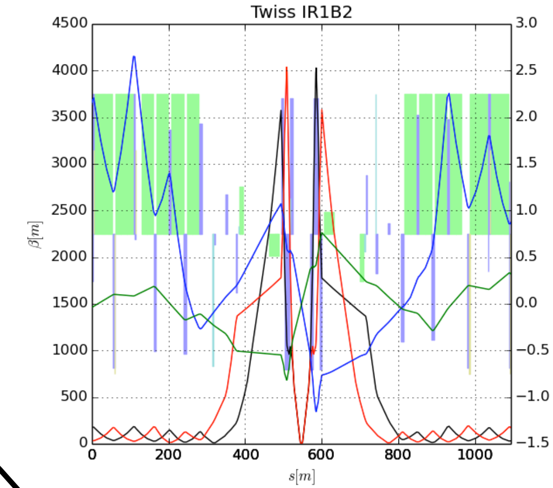
want a small β*!

Particles in bunch

Record e+e- Luminosity (KEK-B):	$2.11\text{x}10^{34}$ cm^{-2}s^{-1}
Record p-pBar Luminosity (Tevatron):	$4.06\text{x}10^{32}$ cm^{-2}s^{-1}
Record Hadronic Luminosity (LHC):	$7.0\text{x}10^{33}$ cm^{-2}s^{-1}
LHC Design Luminosity:	$1.00\text{x}10^{34}$ cm^{-2}s^{-1}

Limits to β*





$$\beta(\Delta s) = \beta^* + \frac{\Delta s^2}{\beta^*} \rightarrow \beta_{\max} \propto \frac{1}{\beta^*}$$

➔ small β* means large β (aperture) at focusing triplet

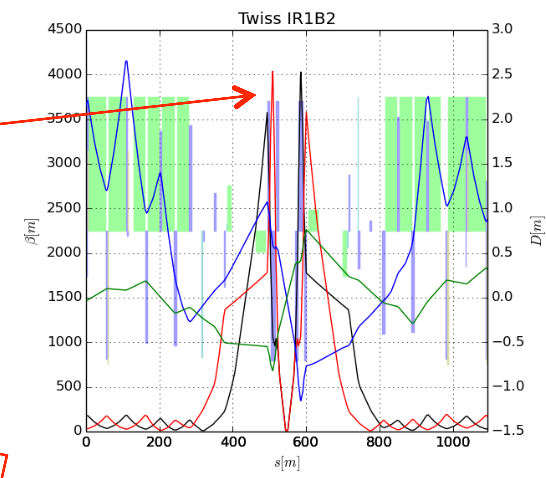
The "Squeeze"?

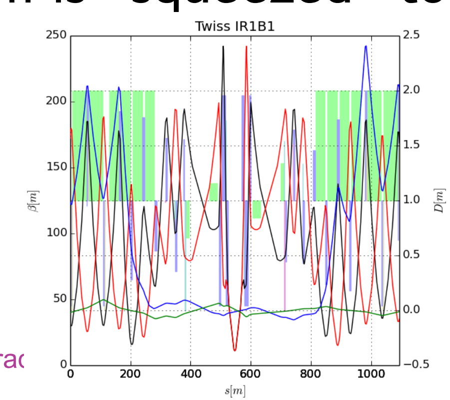
- In general, synchrotrons scale all magnetic fields with the momentum, so the optics remain constant – with one exception.
- Recall that because of adiabatic damping, beam gets smaller as it accelerates.

$$\sigma_x = \sqrt{\frac{\beta_x \epsilon}{\beta\gamma}} \propto \frac{1}{\sqrt{p}}$$

factor of ~4 for LHC

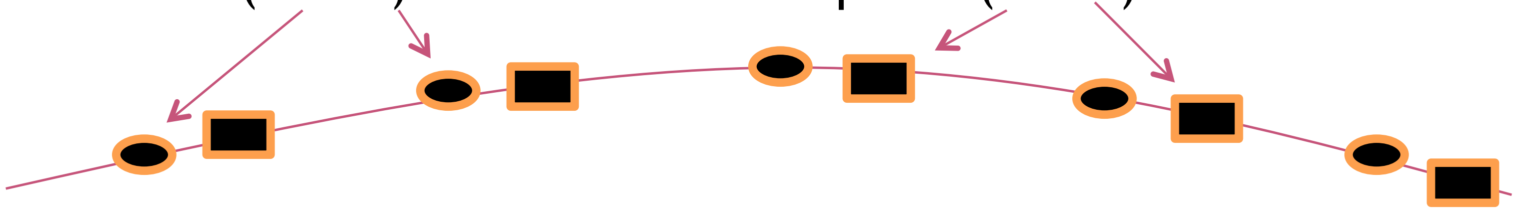
- This means all apertures must be large enough to accommodate the injected beam.
  - This a problem for the large β values in the final focus triplets
- For this reason, injection optics have a larger value of β*, and therefor a smaller value of β in the focusing triplets.
- After acceleration, beam is "squeezed" to a smaller β* for collision





Orbit correction

- Generally, beam lines or synchrotrons will have beam position monitors (BPM's) and correction dipoles (trims)



- We would like to use the trims to cancel out the effect of beamline imperfectins, ie

$$-\Delta x_i = \sum A_{ij}\theta_j$$

Cancel displacement at BPM *i* due to imperfections

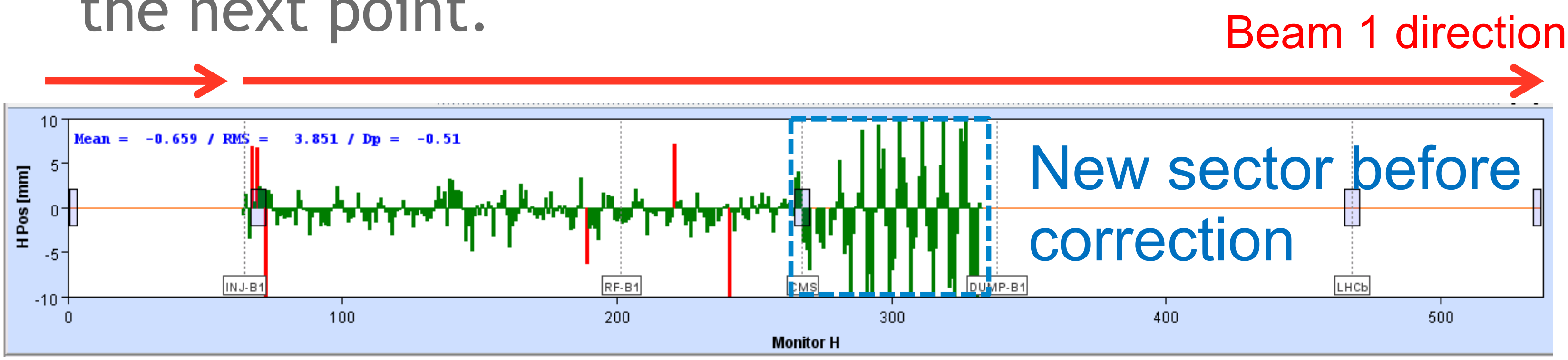
Setting of trim *j*

- Can express this as a matrix and invert to solve with standard techniques
  - If n=m, can just invert
  - If n>m, can minimize RMS

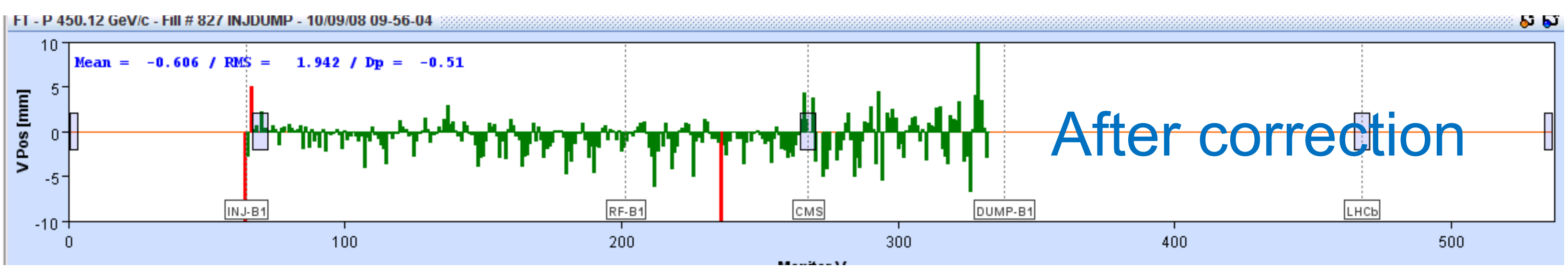
$$-\begin{pmatrix} \Delta x_0 \\ \Delta x_1 \\ \vdots \\ \Delta x_n \end{pmatrix} = \begin{pmatrix} A_{00} & A_{01} & \cdots & A_{0m} \\ A_{10} & A_{11} & \cdots & A_{1m} \\ \vdots & \vdots & \ddots & \\ A_{n0} & A_{n1} & & A_{nm} \end{pmatrix} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

Example: First Beam through LHC (Sept. 10, 2008)

- General procedure
  - Proceed one octant at a time, closing collimators at the next point.



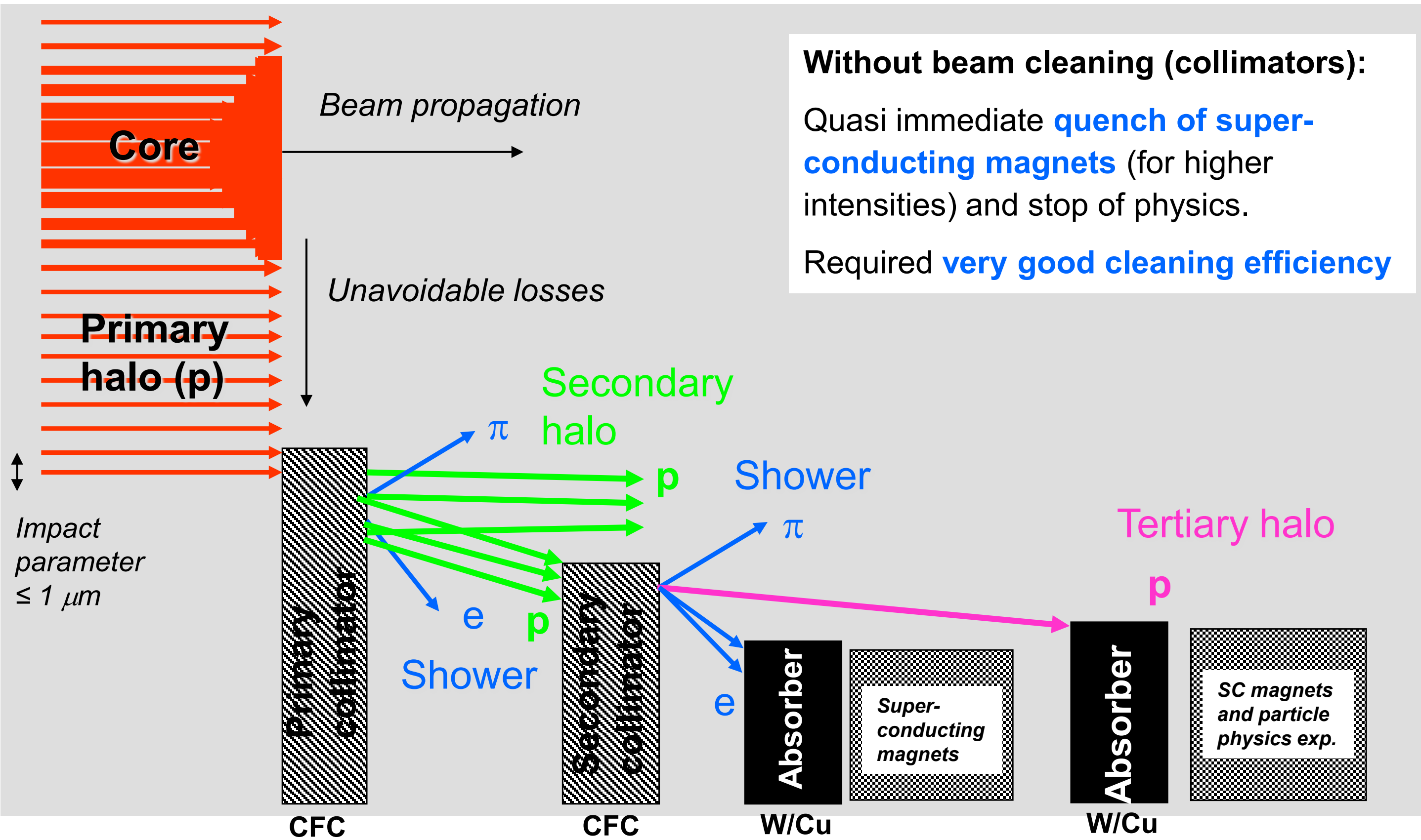
  - Measure the deviations from an ideal orbit, and calculate corrections



  - Might need to iterate a few times

Beam Collimation and Machine Protection

- As beams get more intense, machine protection becomes very important
  - Full LHC energy ~ 150 sticks of dynamite!
- Beam halo is generally cleaned up through multi-stage collimation



R. Assmann

Secondary Beams

- When a proton beam strikes a target, the energy of the beam goes into particle production. Charged particles include (in ~descending order of population)
  - $\pi^{\pm}$: Most of the energy
  - $K^{\pm}$: Charged particles containing a Strange quark
  - p: ordinary protons
  - $e^{\pm}$: These mostly come from neutral pions that immediately decay to two photons.
  - Antiprotons:
  - Other strange "hyperons"
- When and electron beam strikes a target, it makes mostly photons and $e^{\pm}$
  - Positron production targets can be very efficient.
- Generally, we design secondary beam lines to maximize acceptance of the species of beam we're looking for.

Special Case: Neutrino Beams

- Electron neutrinos are generally produces in nuclear reactors. High energy particle beams are used to produce primarily muon neutrinos in the reactions

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow (\nu_\mu e^- \bar{\nu}_e)\bar{\nu}_\mu$$

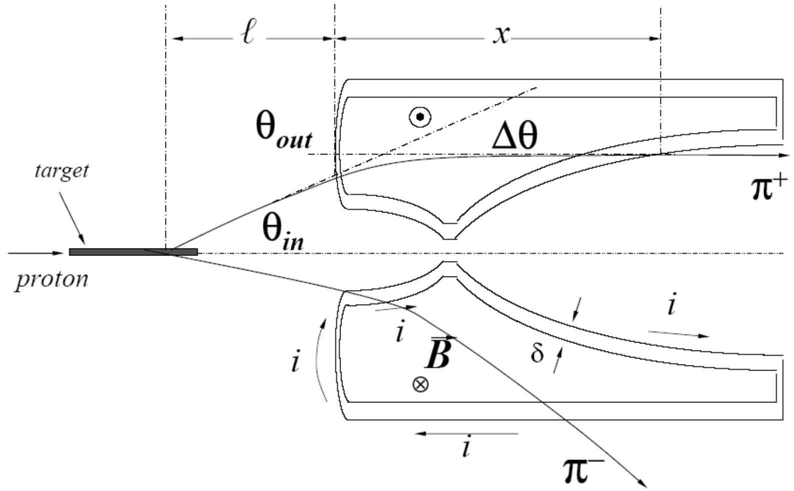
$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow (\bar{\nu}_\mu e^+ \nu_e)\nu_\mu$$

Leading particles

- Select correct neutrino species by focusing correct pion species

Neutrino Horns

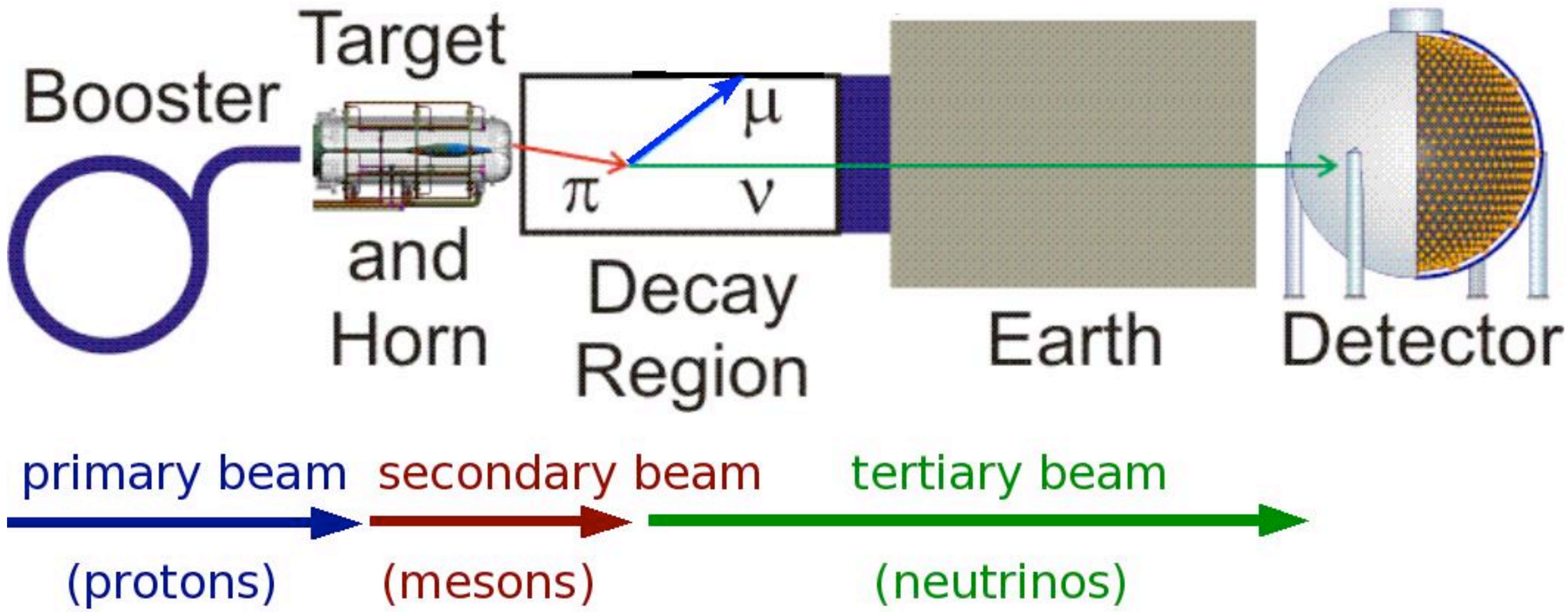
- Neutrino horns work by producing an coaxial current so the correct sign pions are focused in *both* planes.



- This is then followed by a decay region to allow the pions to decay

Example: MiniBooNE Neutrino Line

(not to scale!)



Practical Considerations

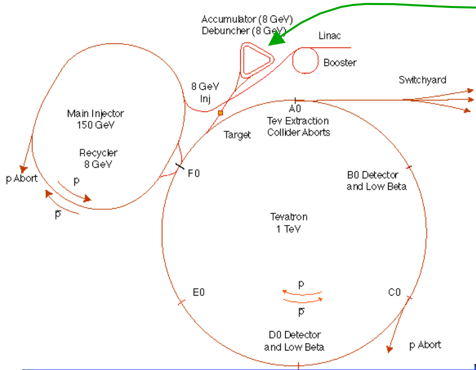
- Neutrino horns operate in fierce radiation environments, and are pulsed with currents of several hundred kA.
- They require water cooling and sophisticated mechanical analyses.

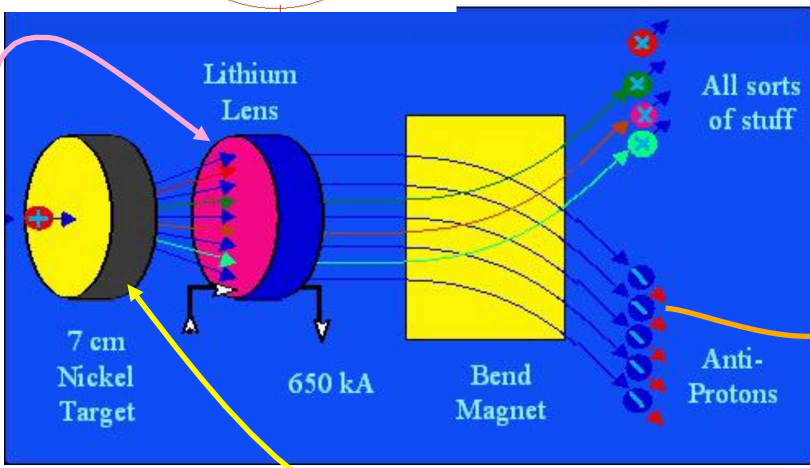
Neutrino Horn Assembly at J-Parc

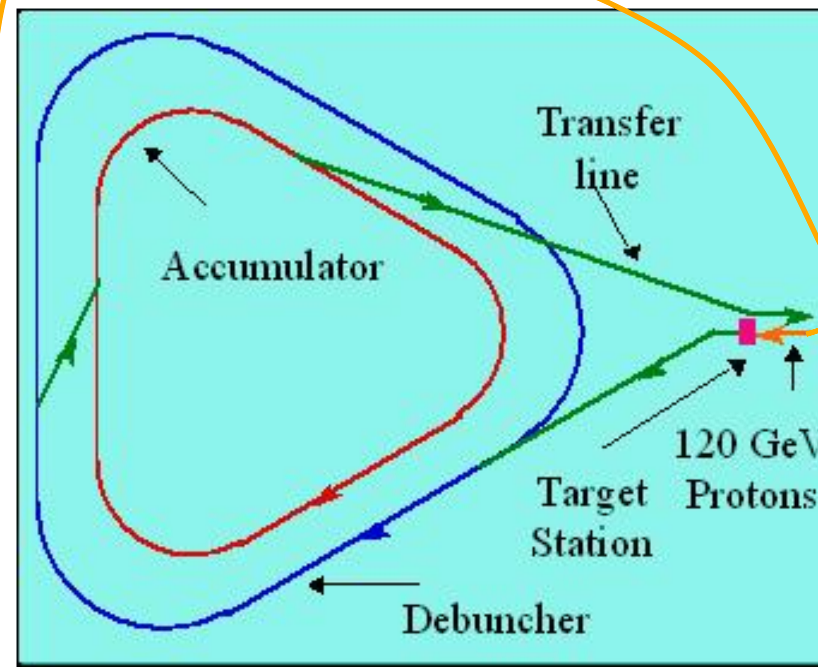
Antiproton Beams

- Antiprotons are produced in very small numbers in proton collisions.
- In order to be useful, these must be captured and "cooled" (i.e. have their area in phase space reduced).
- Although high energy proton-antiproton colliders are a thing of the past (homework problem), anti-protons are still of great interest at low energy:
  - CERN LEAR facility
  - FAIR Facility in Germany.

Highest Intensity Antiproton Source: Fermilab



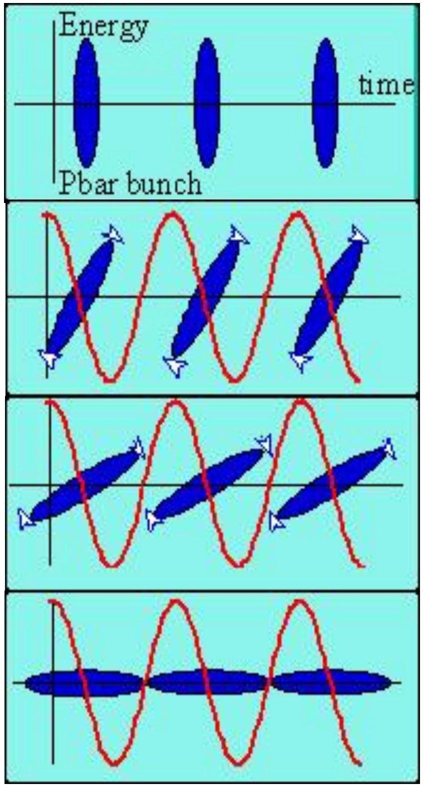




- 120 GeV protons strike a target, producing many things, including antiprotons.
- a Lithium lens focuses these particles (a bit)
- a bend magnet selects the negative particles around 8 GeV. Everything but antiprotons decays away.

- The antiproton ring consists of 2 parts
  - the Debuncher
  - the Accumulator.

Antiproton Source - debunching



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

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

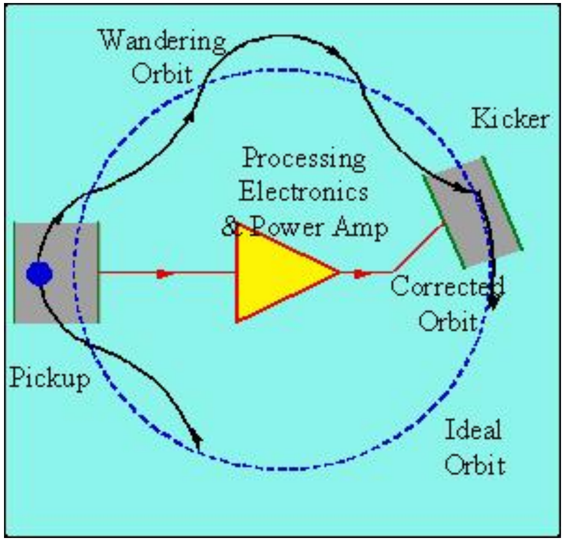
…and the RF is phased so they are decelerated (accelerated),

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

At this point, the pBars are transferred to the accumulator, where they are "stacked"

Stochastic cooling of antiprotons

- Positrons will naturally “cool” (approach a small equilibrium emittance) via synchrotron radiation.
- Antiprotons must rely on active cooling to be useful in colliders.
- Principle: consider a single particle which is off orbit. We can detect its deviation at one point, and correct it at another:

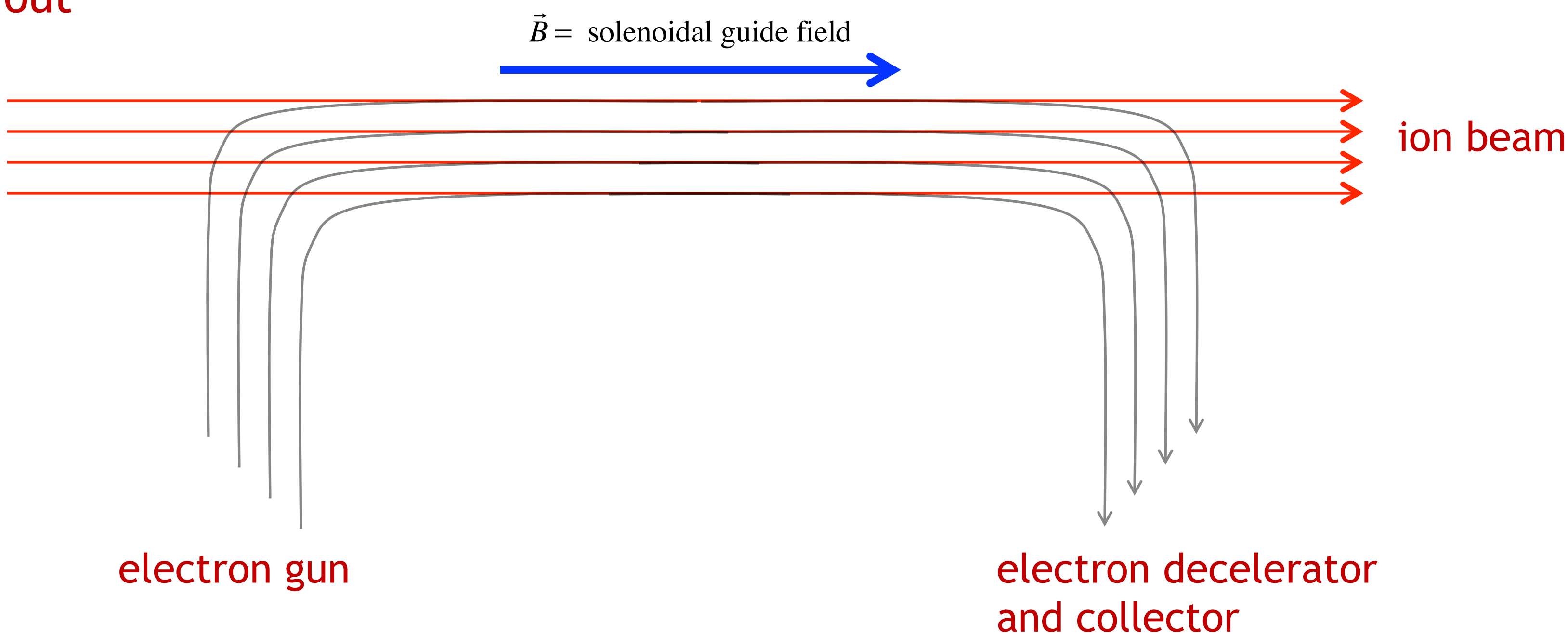


- But wait! If we apply this technique to an ensemble of particles, won’t it just act on the centroid of the distribution? Yes, but…
- Stochastic cooling relies on “mixing”, the fact that particles of different momenta will slip in time and the sampled combinations will change.
- *Statistically*, the mean displacement will be dominated by the high amplitude particles and over time the distribution will cool.
- Simon Van der Meer won the Nobel Prize for this.

Electron Cooling

Electron cooling works by injecting "cold electrons" into a beam of negative ions (antiprotons or other) and cooling them through momentum exchange.

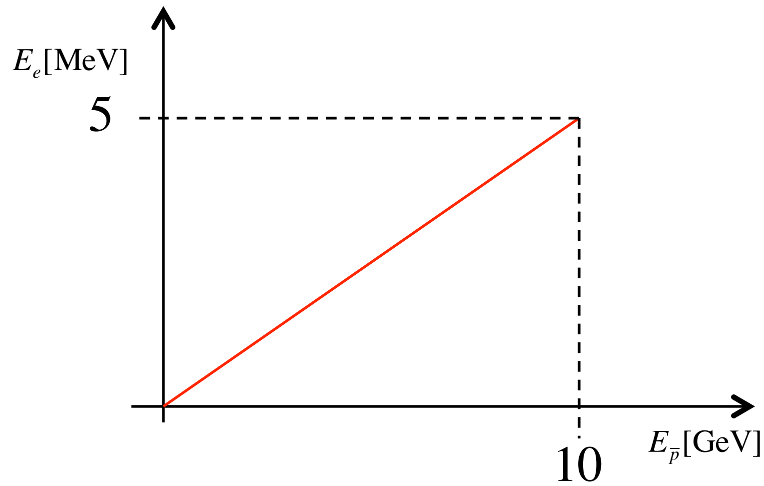
Layout



Want $$\beta_{electrons} = \beta_{ions} \rightarrow p_{electrons} \ll p_{ions}$$

$$\frac{p_e}{m_e c} = (\beta\gamma)_e = (\beta\gamma)_{ion} = \frac{p_{ion}}{m_{ion} c}$$

$$p_e = \frac{m_e}{m_{ion}} p_{ion}$$



The electrons act like a drag force on the ions. At low velocity, the ionization loss varies as

$$\frac{1}{\left(v^*\right)^2}$$

relative velocity

The velocity spread of the electrons is dominated by the energy distribution out of the cathode. In the rest frame, motion is non-relativistic

$$K = \frac{1}{2}\left(mc^2\right)\beta^{*2}$$

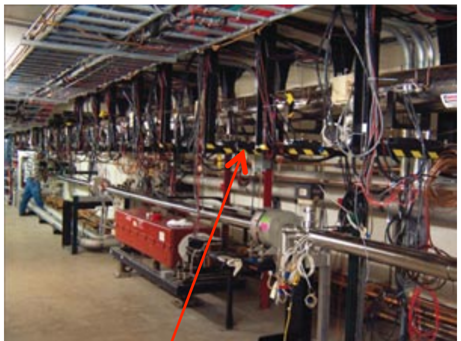
$$\Delta\beta^* = \sqrt{\frac{2\Delta K}{mc^2}}$$

Energy spread. Typically ~.5 eV

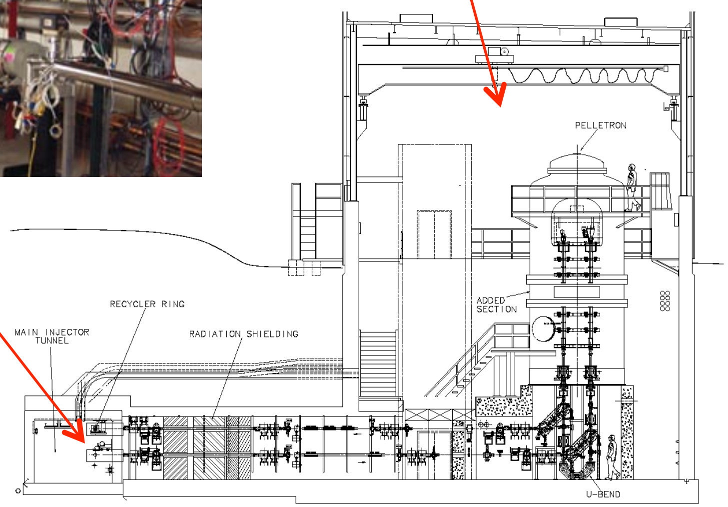
$$\sim 1.4 \times 10^{-3}$$

Electron Cooling in the Fermilab Recycler

One of the highest energy and most successful electron cooling systems was in the Fermilab "Recycler" – an 8 GeV permanent storage ring which was used to store anti-protons for use in the Tevatron collider.



pelletron



.5 A "u-beam"

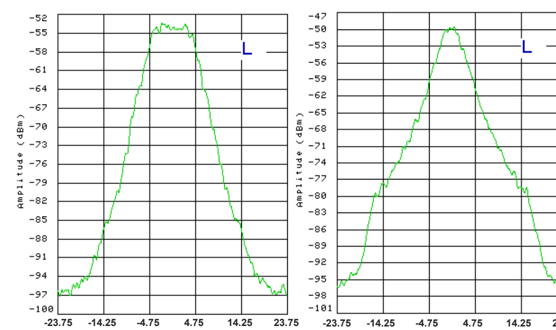


Figure 3: Antiproton longitudinal distributions measured with the 1.75 GHz Schottky detector. In both cases, the electron beam was on axis for ~2h at 100 mA. Bunch length = 6.1 μs. $N_p = 200\times10^{10}$ (left) and 280×10^{10} (right) particles.