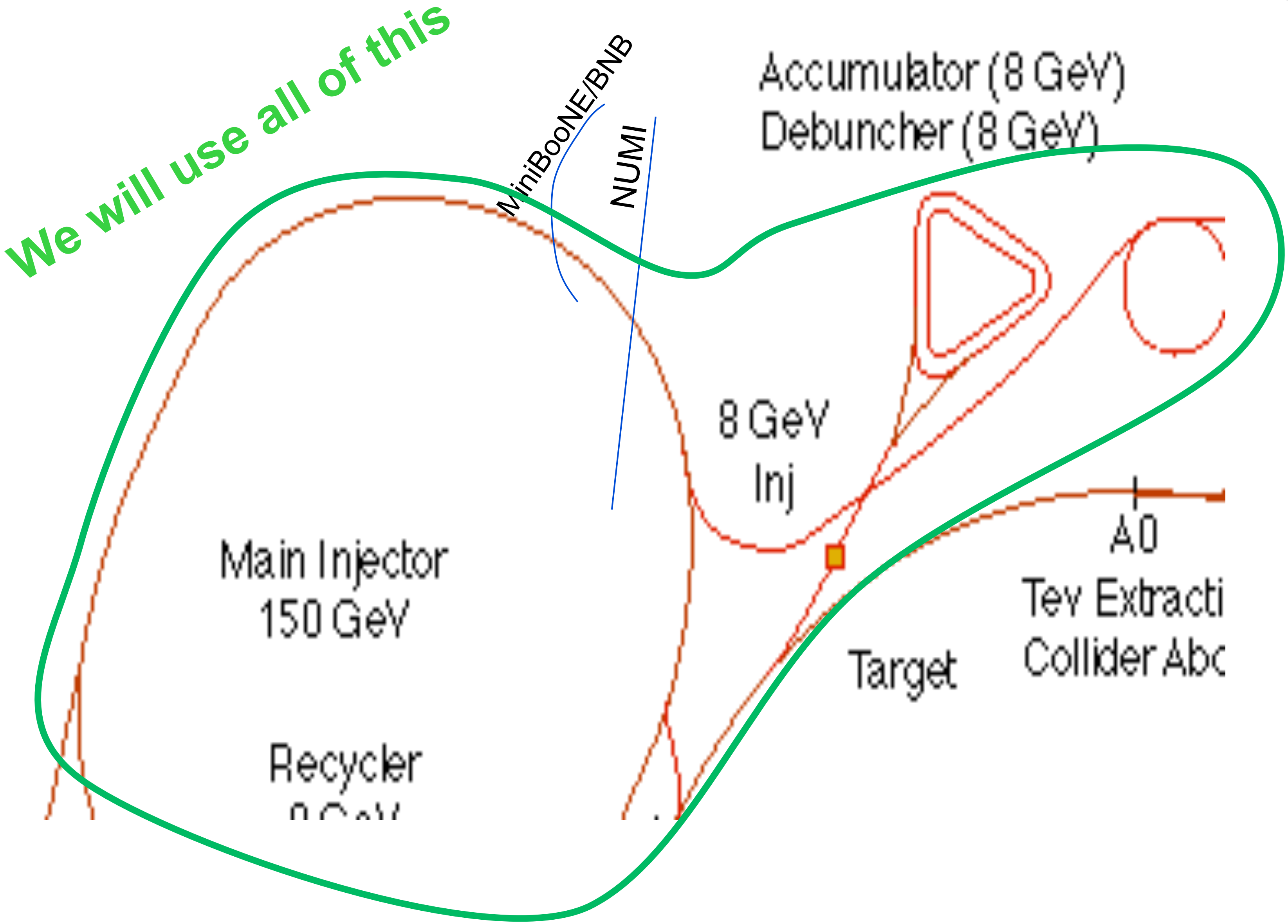
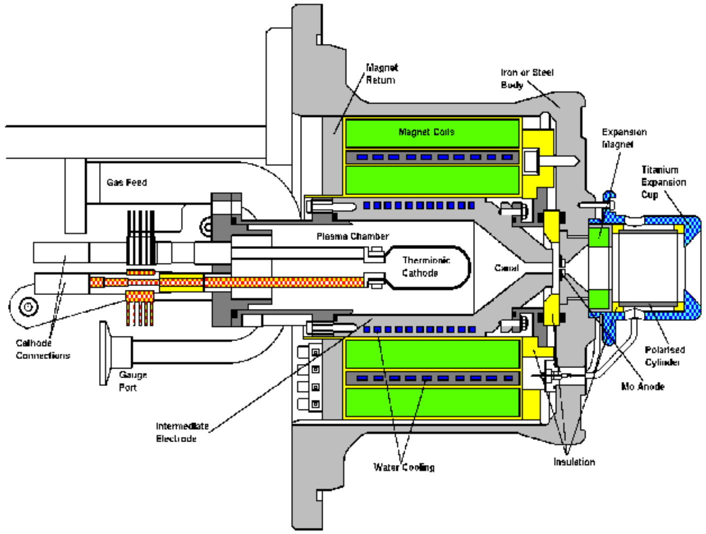
The Fermilab Accelerator Complex

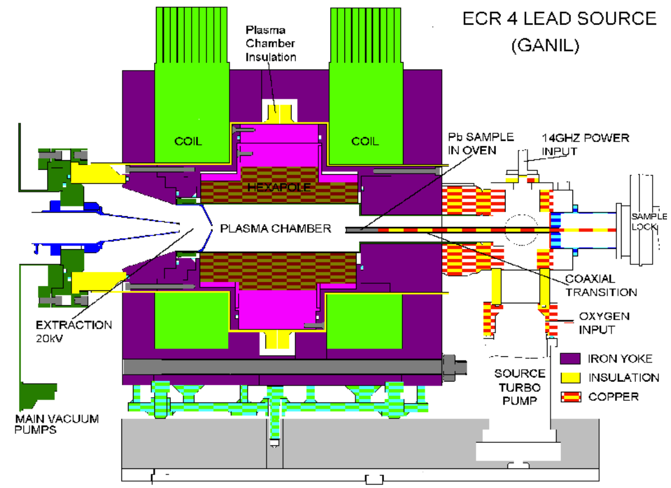


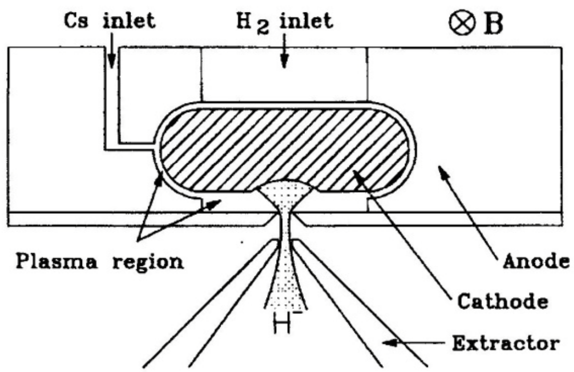
Getting started: Ion sources

CERN proton source



CERN Lead source



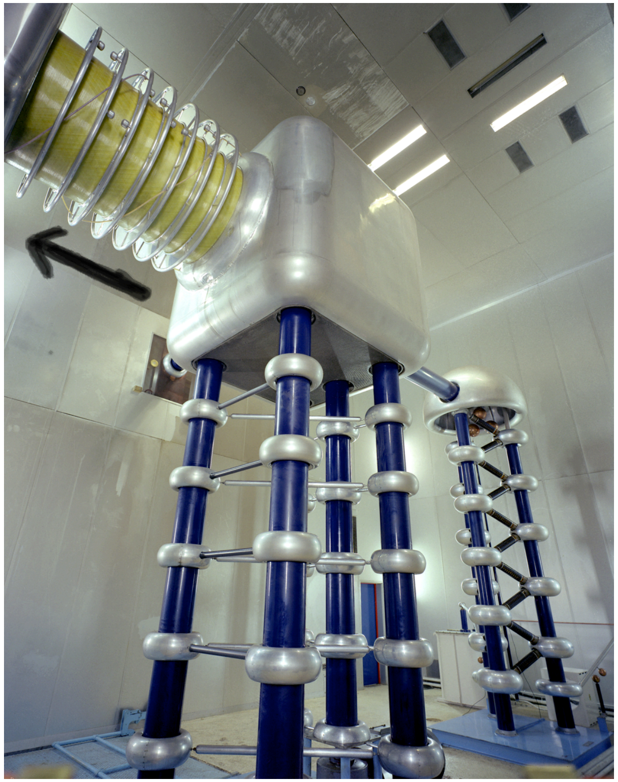


FNAL H- source. Mix Cesium with Hydrogen to add electron. (why? we'll get to that)

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!

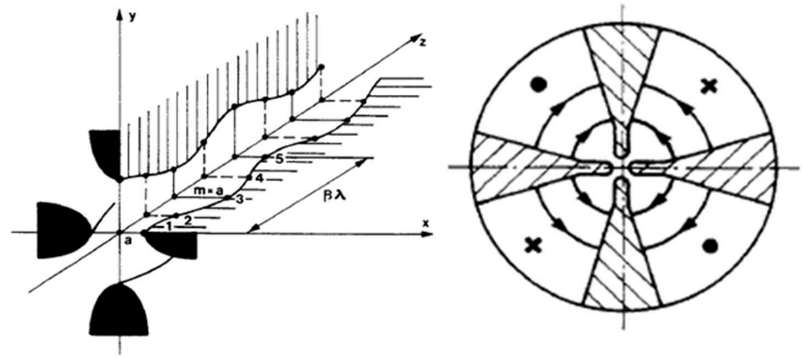
Initial acceleration

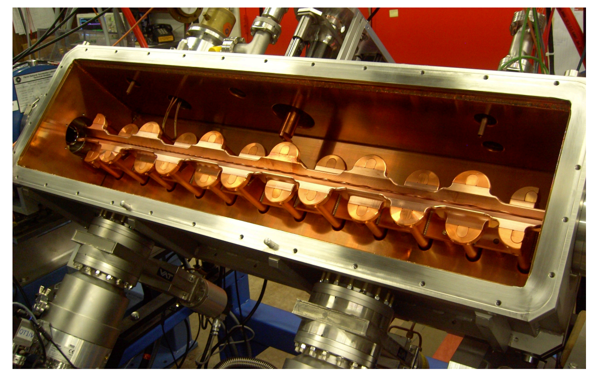
Old: Static



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

New: RF Quadrupole (RFQ)





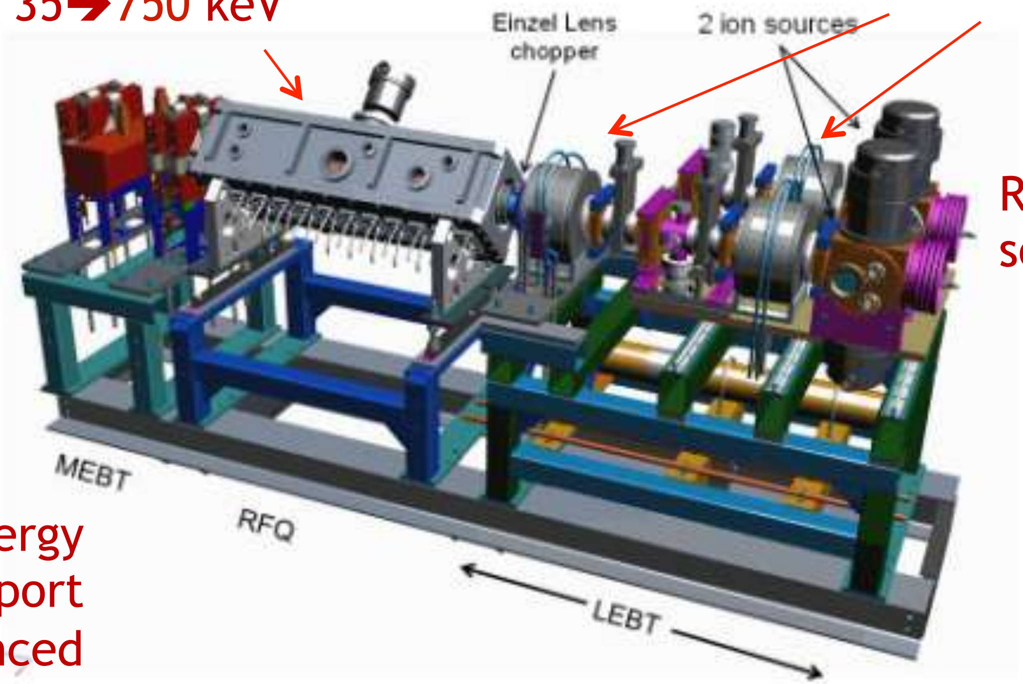
RF structure combines an electric focusing quadrupole with a longitudinal accelerating gradient.

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



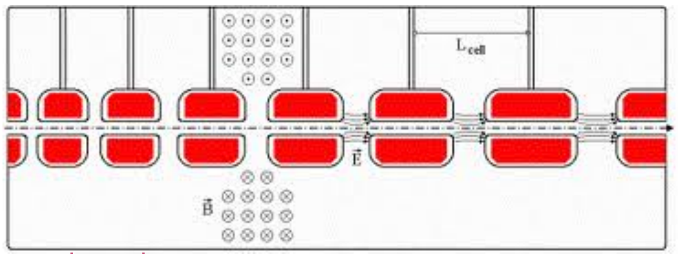
Redundant H^- sources: 0-35 keV

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

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

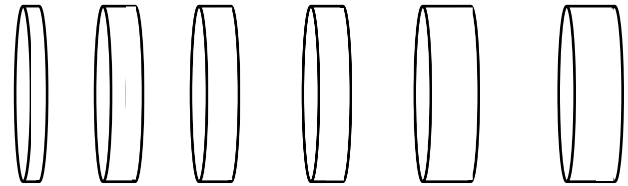
Drift Tube (Alvarez) Cavity

- 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*



$\approx$

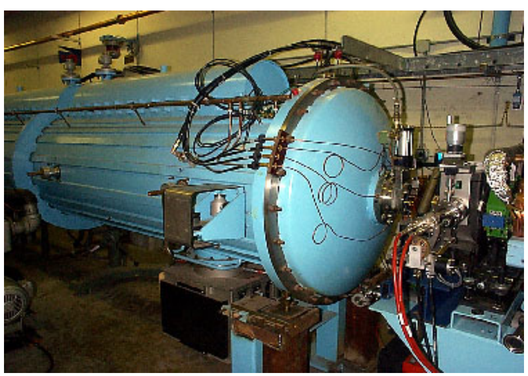
Bunch of pillboxes



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

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

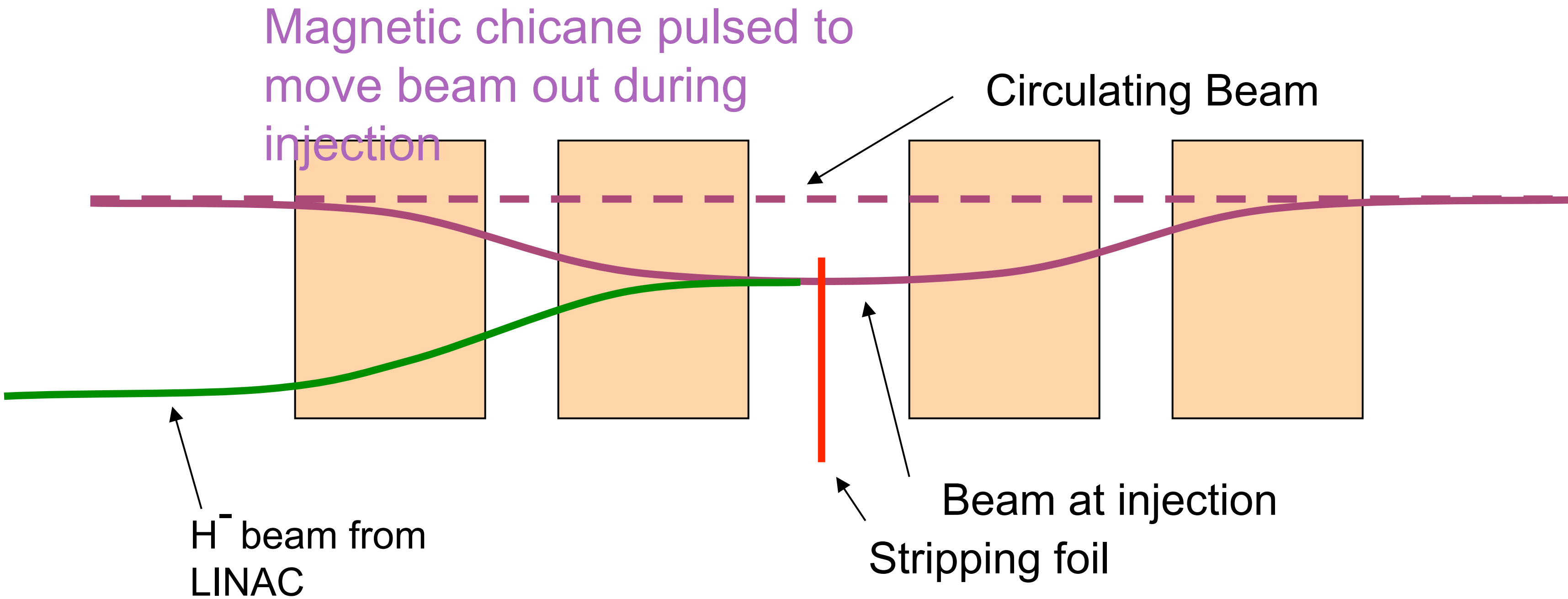
- In order to maximize the intensity in the synchrotron, we can
  - Increase the linac current as high as possible and inject over one revolution
    - There are limits to linac current
  - Inject over multiple (*N*) revolutions of the synchrotron
    - Preferred method
- Unfortunately, Liouville's Theorem 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

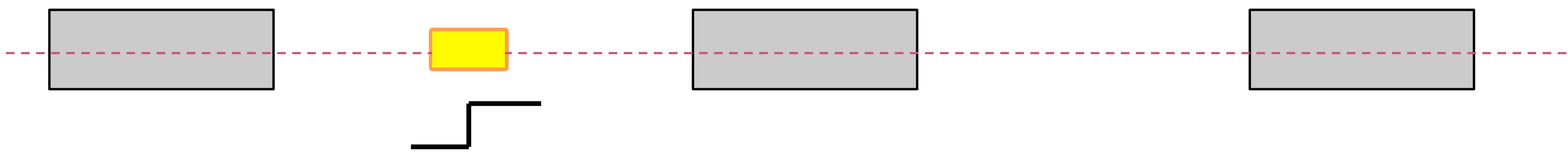
Ion (or charge exchange) injection



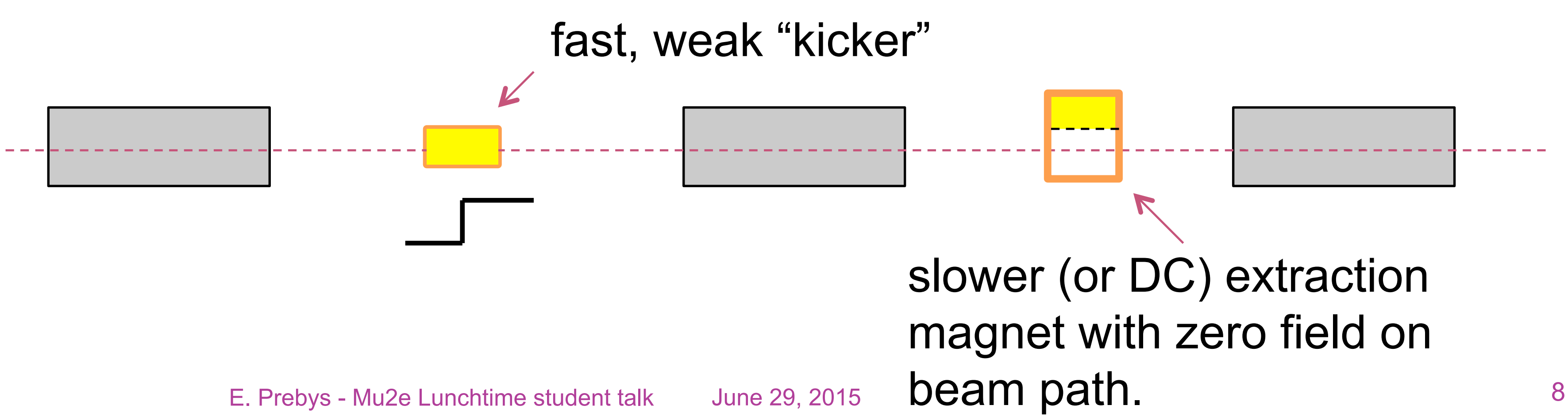
- Instead of ionizing Hydrogen, and electron is added to create H^-, which is accelerated in the linac
- A pulsed chicane moves the circulating beam out during injection
- An injected H^- beam is bent in the opposite direction so it lies on top of the circulating beam
- The combined beam passes through 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)



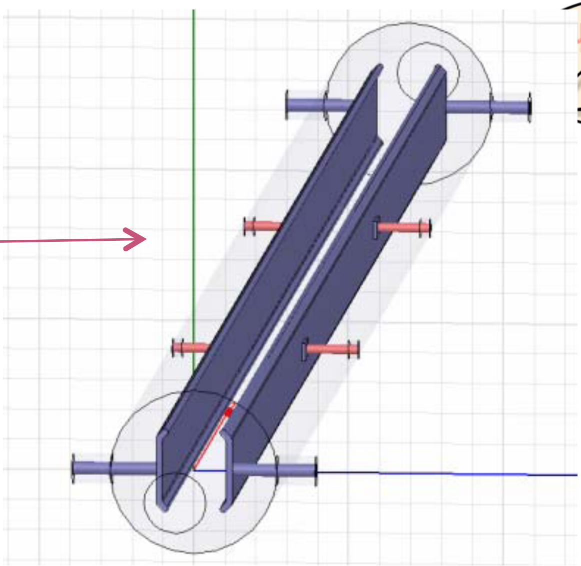
- Unfortunately, getting the required field in such a short time would result in prohibitively high inductive voltages, so we usually do it in two steps:



Extraction hardware

"Fast" kicker

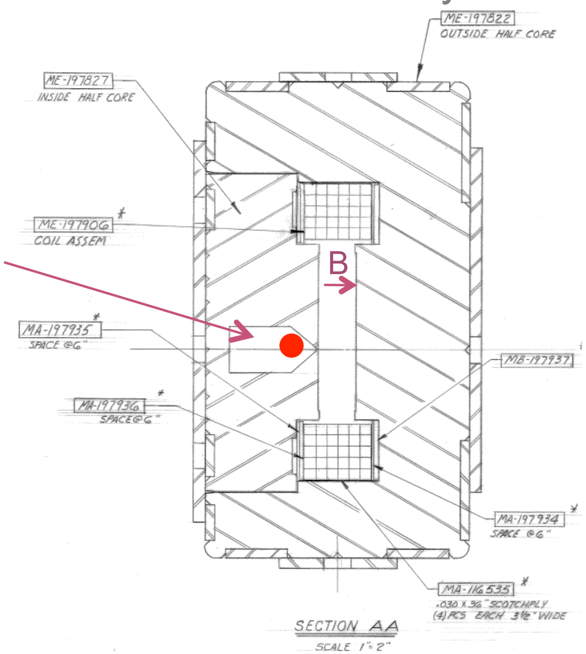
- usually an impedance matched strip line, with or without ferrites



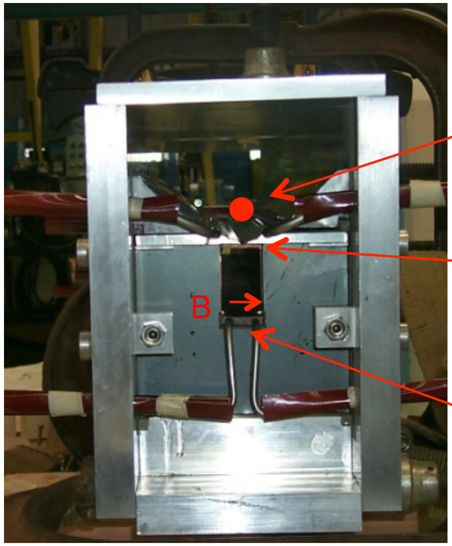
"Slow" extraction elements

"Lambertson": usually DC

circulating beam (B=0)



Septum: pulsed, but slower than the kicker



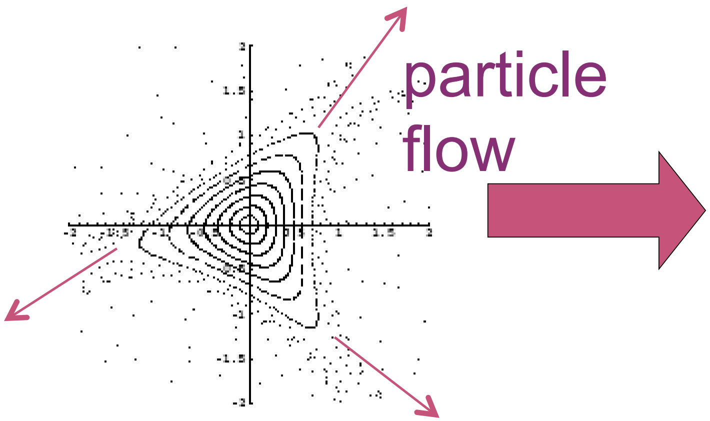
circulating beam (B=0)

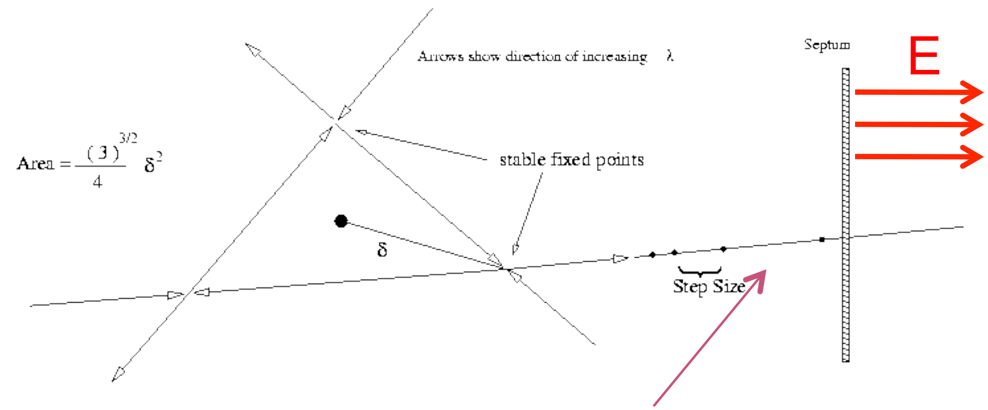
current "blade"

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



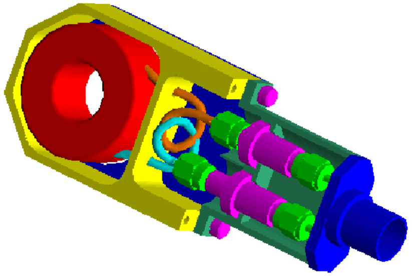


Particles will flow out of the stable region along lines in phase space into an electrostatic extraction field, which will deflect them into an extraction Lambertson

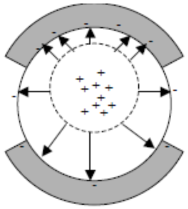
- Tune the instability so the escaping beam exactly fills the extraction gap between interceptions (3 times around for 3rd order)
  - Minimum inefficiency ~(septum thickness)/(gap size)
  - Use electrostatic septum made of a plane of wires. Typical parameters
    - Septum thickness: .1 mm
    - Gap: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

Standard beam instrumentation

- Bunch/beam intensity are measured using inductive toriods

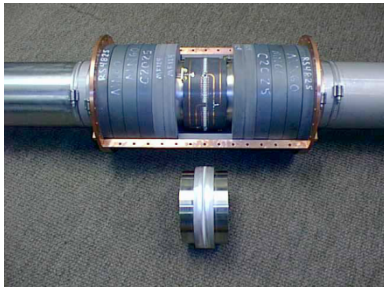


- Beam position is typically measured with beam position monitors (BPM's), which measure the induced signal on a opposing pickups



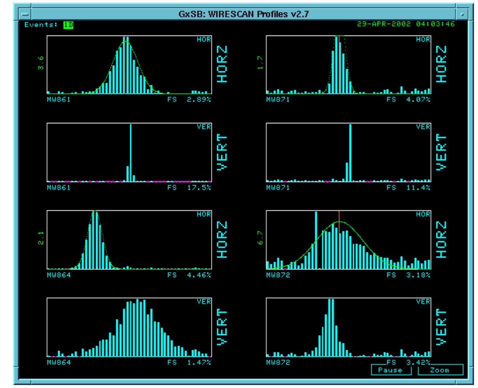
$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

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

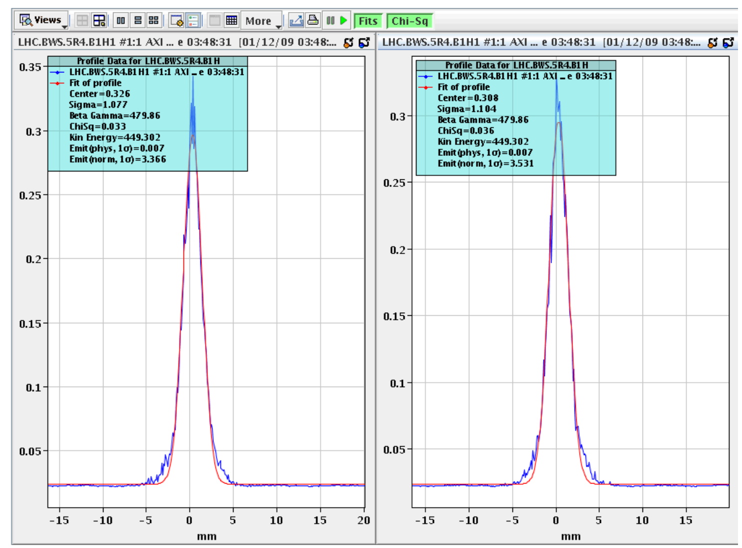


Beam instrumentation (cont'd)

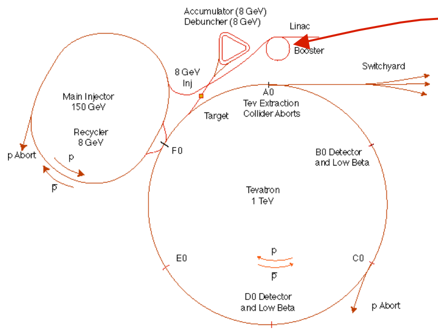
- Beam profiles in beam lines can be measured using secondary emission multiwires (MW's)
- Can measure beam profiles in a circulating beam with a "flying wire scanner", which quickly passes a wire through and measures signal vs time to get profile
- Non-destructive measurements include
  - Ionization 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

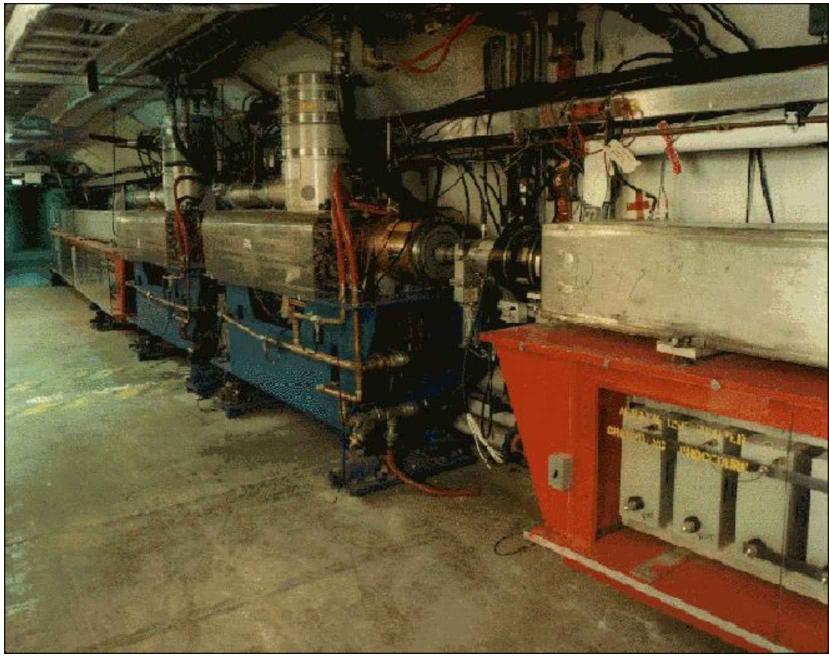


Flying wire signal in LHC



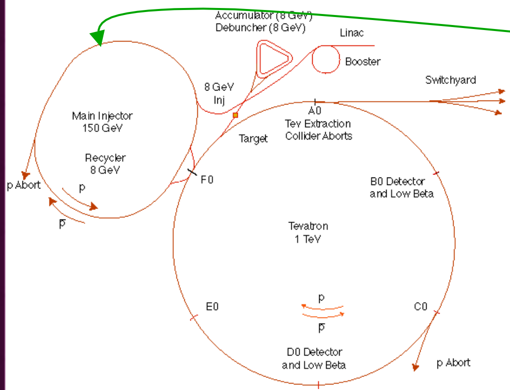
Booster

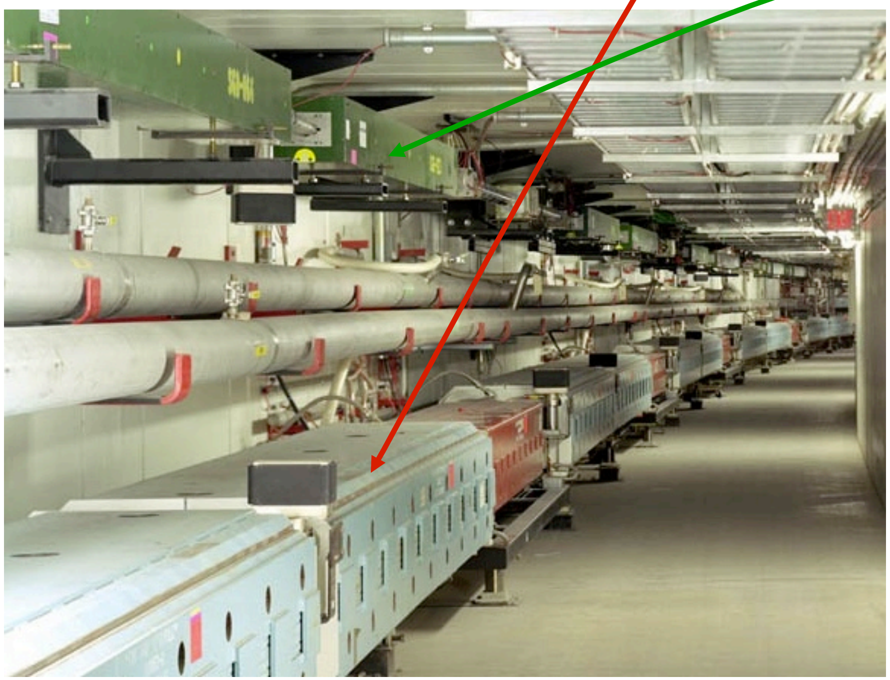
- Accelerates the 400 MeV beam from the Linac to 8 GeV
  - Operates in a 15 Hz offset resonant circuit
    - Cannot make required beam structure
    - That's why MECO wasn't proposed there
  - Sets fundamental clock of accelerator complex
- More or less original equipment
  - 40+ years old
- Supplying beam to neutrino program and Mu2e will require ~doubling output
  - Hardware limits ➔ Improve RF system
  - Radiation limits ➔ Improve acceleration efficiency



➔ "Proton Improvement Plan" (whole separate talk)

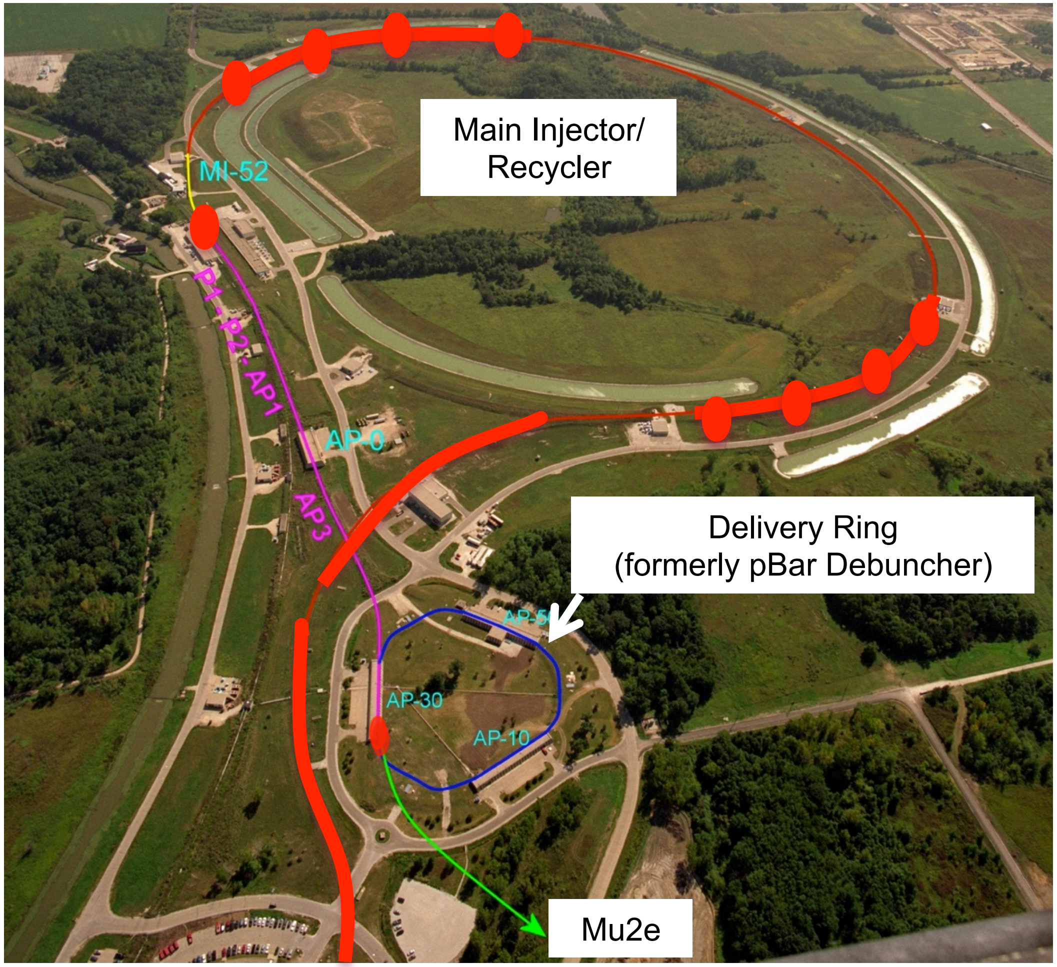
Main Injector/Recycler





- Main Injector
  - Accelerates protons (or pBars) from 8 GeV to 120 or 150 GeV
  - Can hold up to 12 Booster batches
- Recycler
  - Permanent magnet 8 GeV storage ring
  - During Tevatron program, used to store pBars
  - Currently being configured to pre-stack protons for loading into the Main Injector
  - In the future, it will be used to re-bunch protons for the g-2 and Mu2e experiments.

Mu2e Proton Delivery

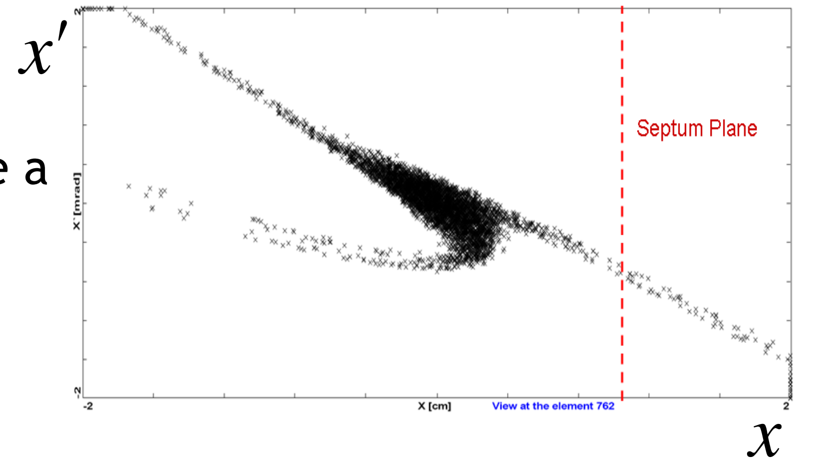


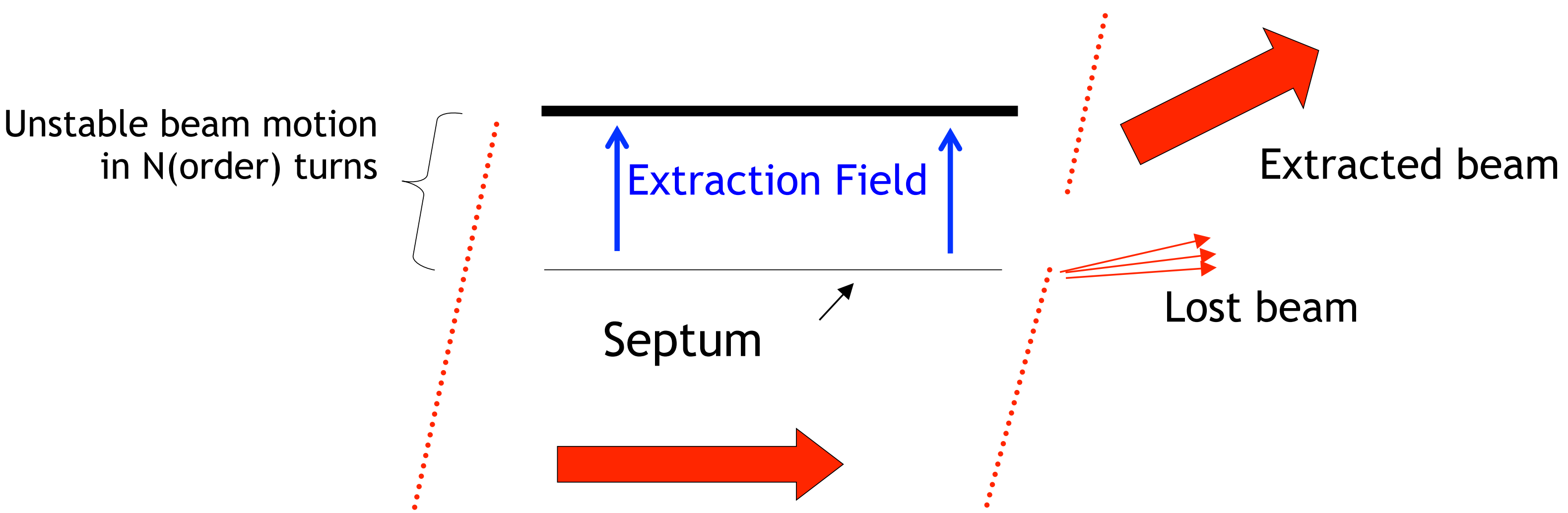
Booster

- One Booster "batch" is injected into the Recycler (8 GeV storage ring).
  - 4×10^{12} protons
  - 1.7 μsec long
- It is divided into 4 bunches of 10^{12} each
- These are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As a bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Bunches of ~3×10^7 protons each
  - Separated by 1.7 μsec

Resonant Extraction

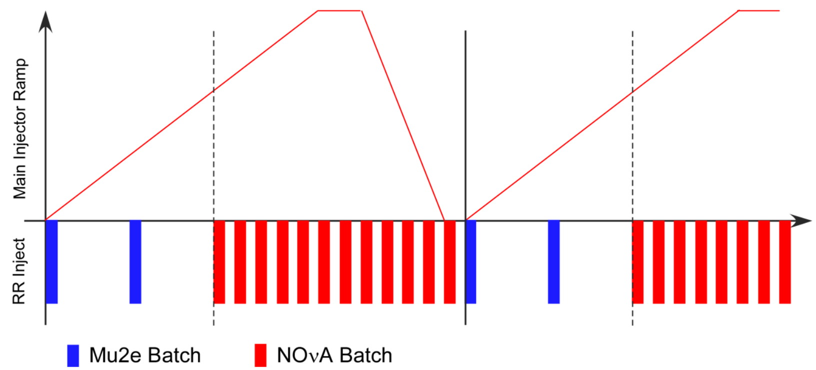
- Extracting all the beam at once is easy, but we want to extract it slowly over ~60 ms (~35,000 revolutions)
- Use nonlinear (sextupole) magnets to drive a harmonic instability
- Extract unstable beam as it propagates outward
  - Standard technique in accelerator physics



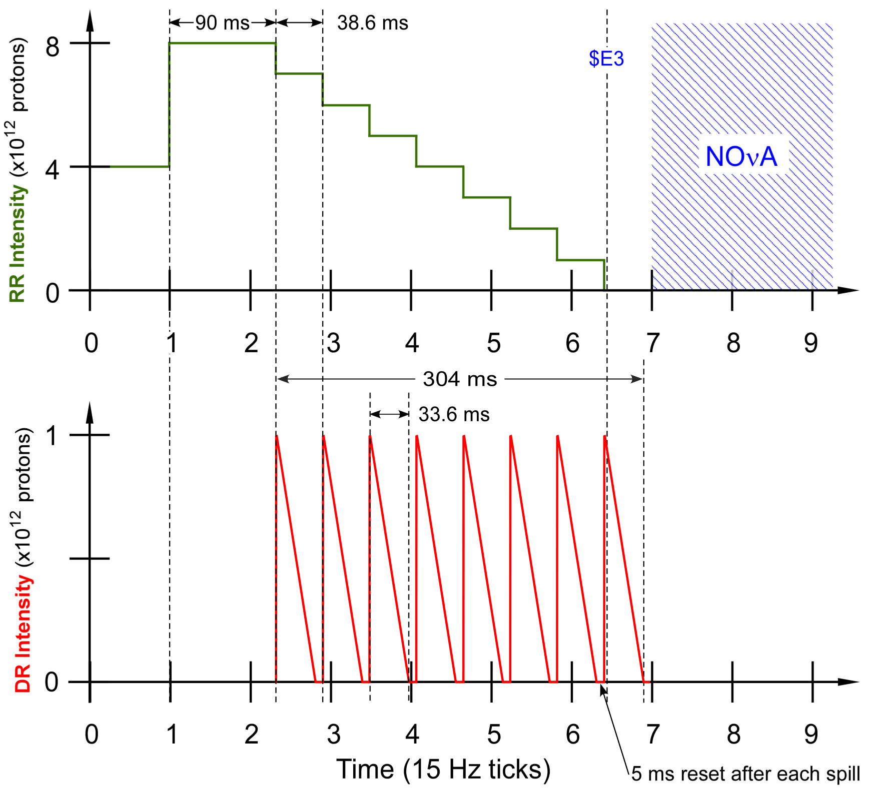


Mu2e Spill Structure

1.33 sec Main Injector cycle



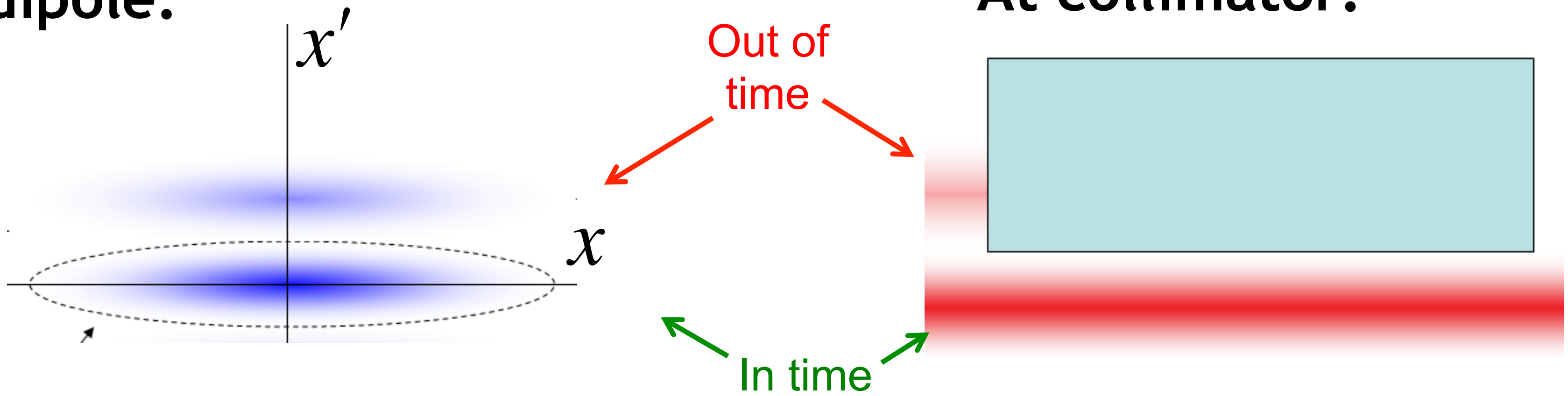
- **Detail:**
  - $3x10^7$ p/bunch
  - 1.7 μsec bunch spacing
  - ~30% duty factor
  - ~$1.2x10^{20}$ protons year



Beam line extinction

- A set of resonant dipoles in the beam deflects beam such that only in-time beam is transmitted through a system or collimators:
  - Think miniature golf!

At dipole: **At collimator:**

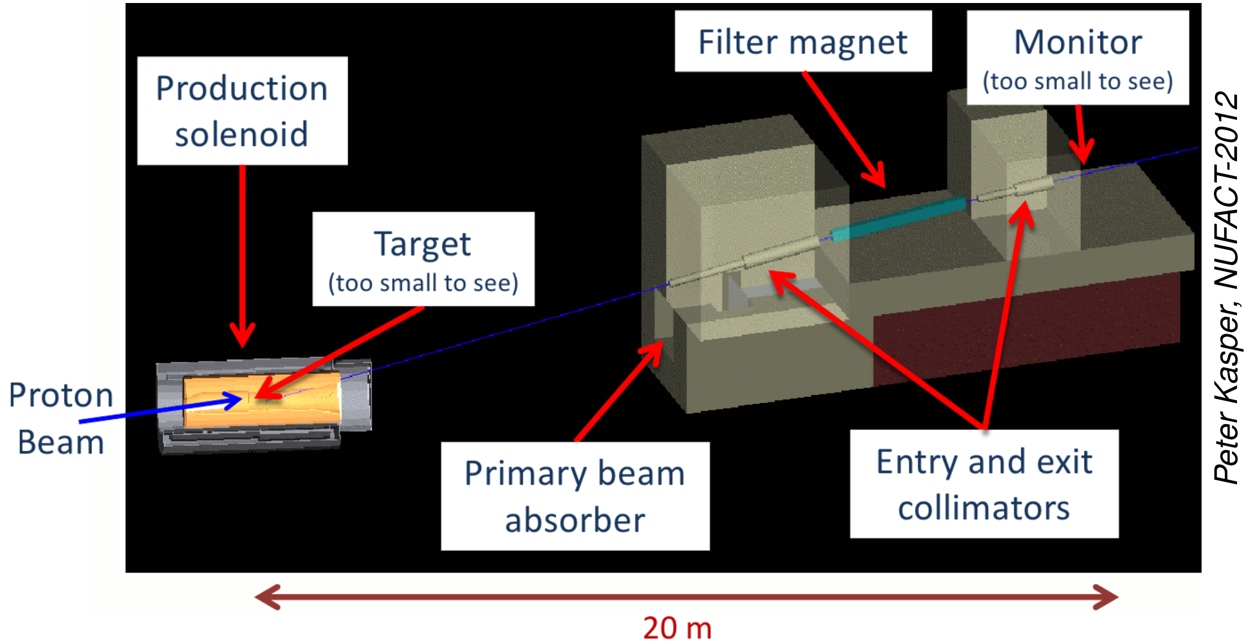


- Use resonant dipoles at two frequencies
  - ½ bunch frequency to sweep out of time beam into collimators
  - High harmonic to reduce motion during transmission window

Extinction Monitor

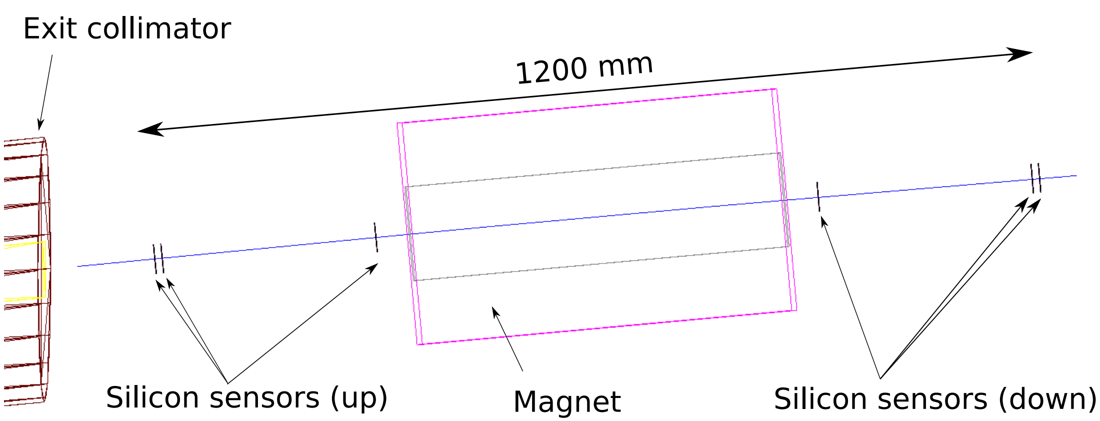
- Must measure extinction to 10^{-10} precision
  - Roughly 1 proton every 300 bunches!
- Monitor sensitive to single particles not feasible
  - Would have to be blind to the 3×10^{7} particles in the bunch.
- Focus on statistical technique
  - Design a monitor to detect a small fraction of scattered particles from target
    - 10-50 per in-time bunch
  - Good timing resolution
  - Statistically build up precision profile for in time and out of time beam.
- Goal
  - Measure extinction to 10^{-10} precision in one hour.

Extinction Monitor Design

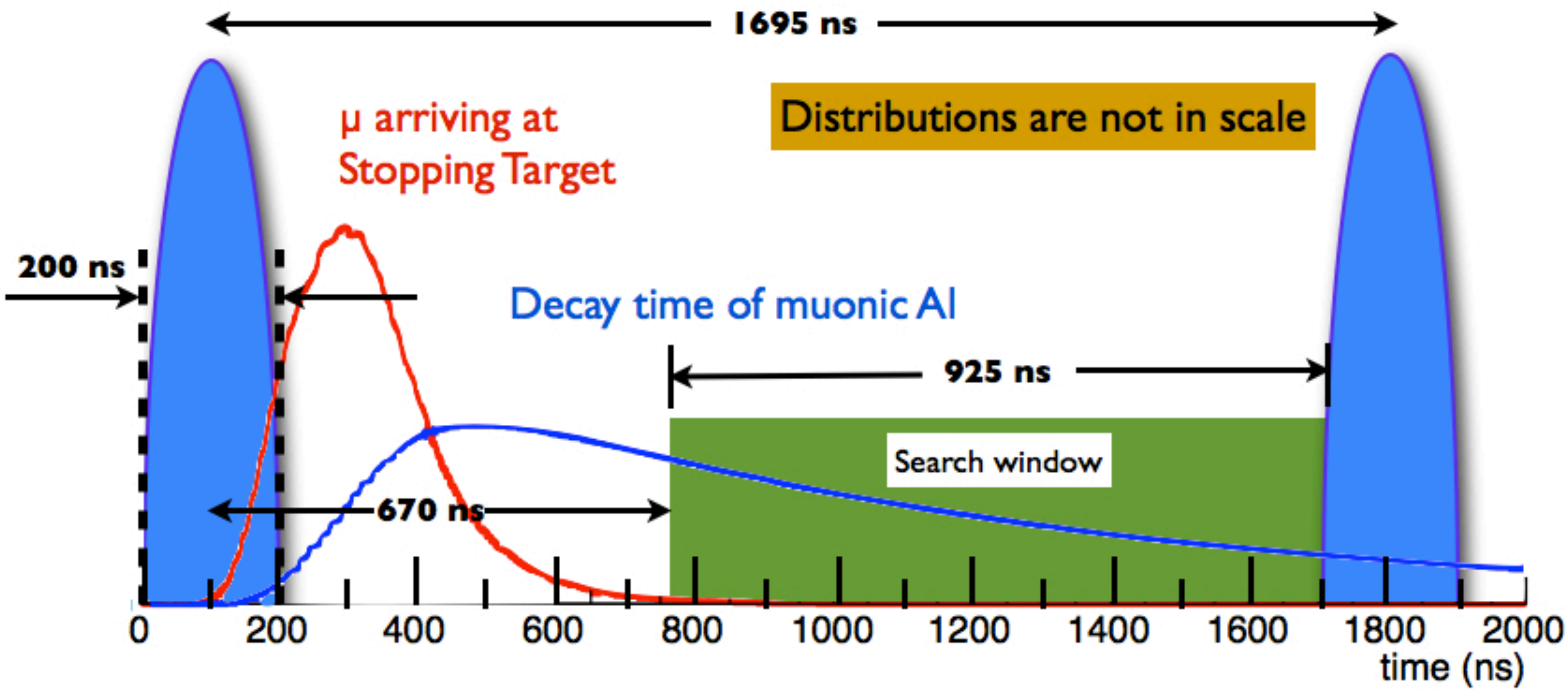


Selection channel built into target dump channel

- Spectrometer based on ATLAS pixels
- Optimized for few GeV/c particles



End Product



- μ^- are accompanied by e^-, π^-, …
- Extinction system makes prompt background ~equal to all other backgrounds
  - 1 out of time proton per 10^{10} in time protons.
- Lifetime of muonic Al: 864 ns.