Capture/Phase Rotation for The Neutrino Factory and μ^+-μ^- Collider

David Neuffer

Fermilab

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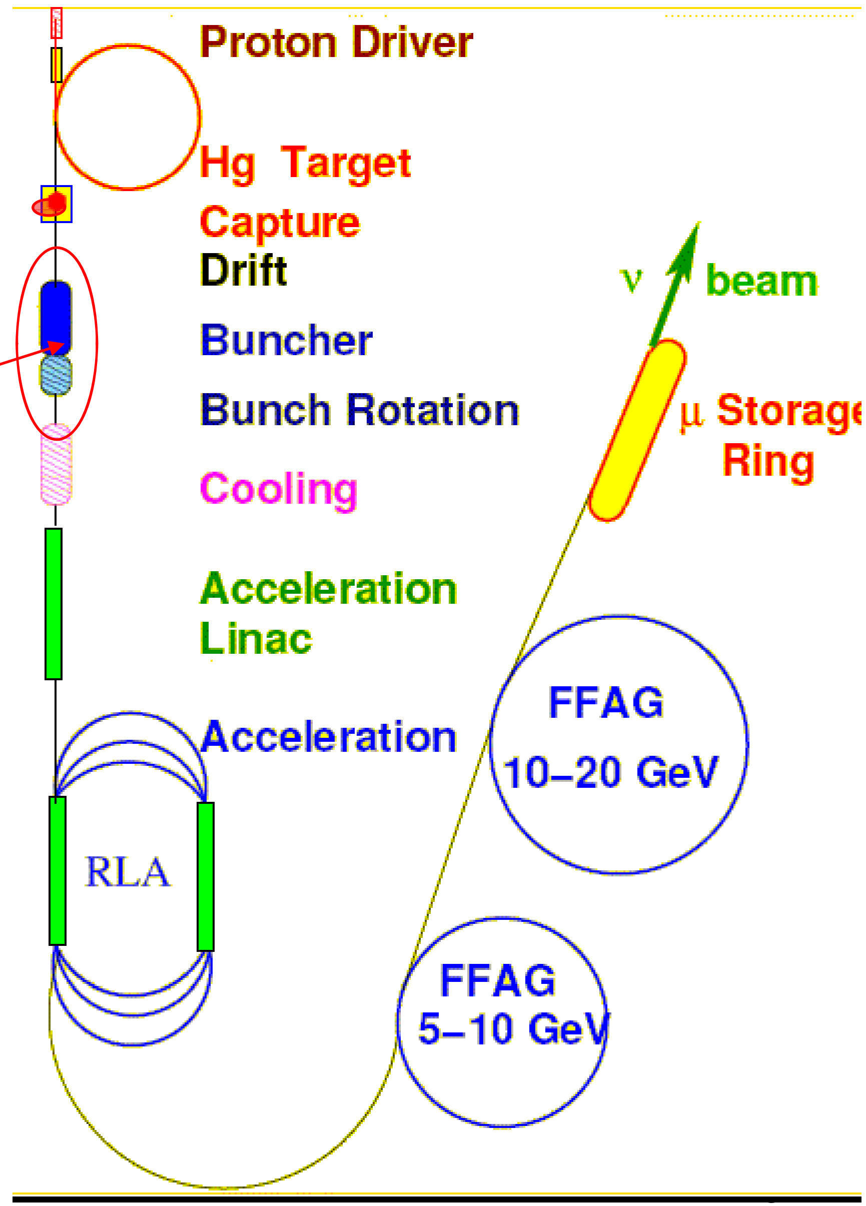
Outline

- Introduction
- Capture and Φ-E rotation options
  - Low-frequency Single bunch
  - Induction linac: Study 2 ν-Factory
  - High Frequency buncher/rotation
    - Study 2A and ISS ν-Factory
- μ^+-μ^- Collider
  - Adaptation and reoptimization
  - Front end variations for Collider and ν-Factory
- Discussion

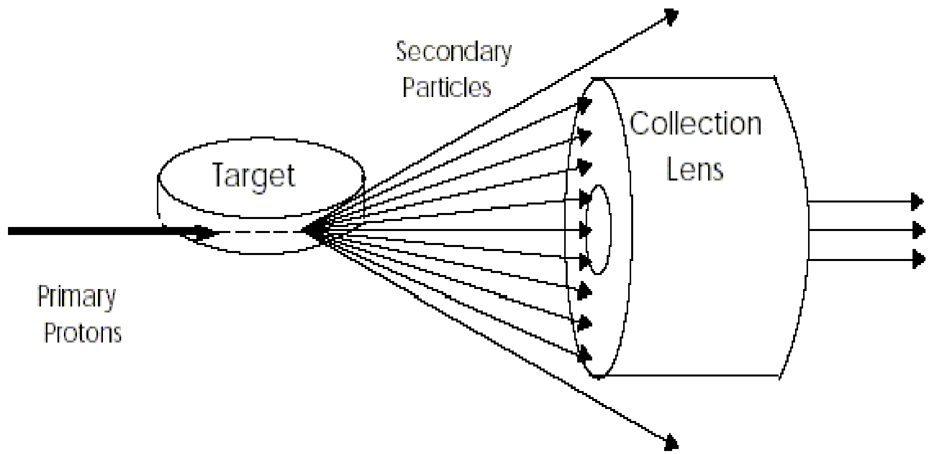
Neutrino Factory - Study 2A

- Proton driver
  - Produces proton bunches
  - ~10 GeV, ~10^{15}p/s, ~50bunches
- Target and drift
  - $\pi \rightarrow \mu$ (> 0.2 μ/p)
- Buncher, Φ-E rotation
  - Cool
- Accelerate μ to 20 GeV or more
  - Linac, RLA and FFAGs
- Store at 20 GeV (0.4ms)
  - $\mu \rightarrow e + \nu_\mu + \nu_e^*$
- Long baseline ν Detector
- >10^{20} ν/year

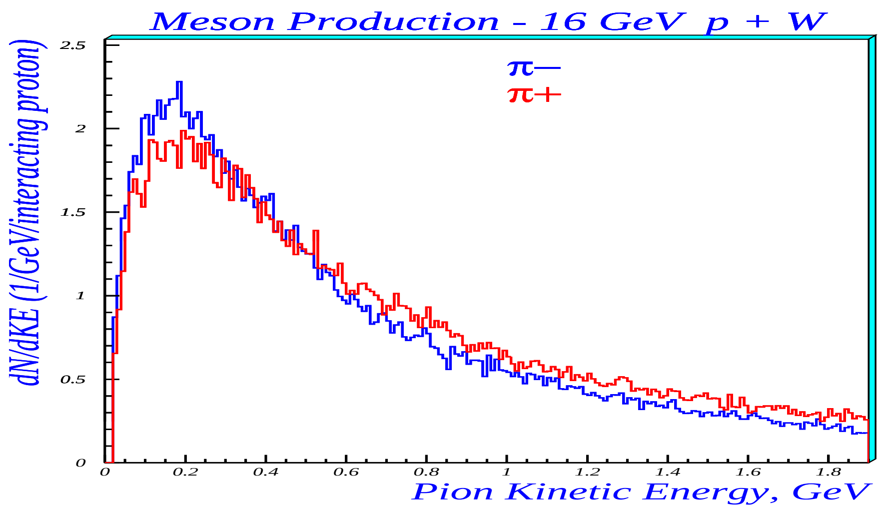


π capture from target

- **Protons on target produce large number of π's**
  - Broad energy range (0 to 10+GeV)
  - More at lower energies
  - Transverse momentum (up to ~0.3GeV/c)

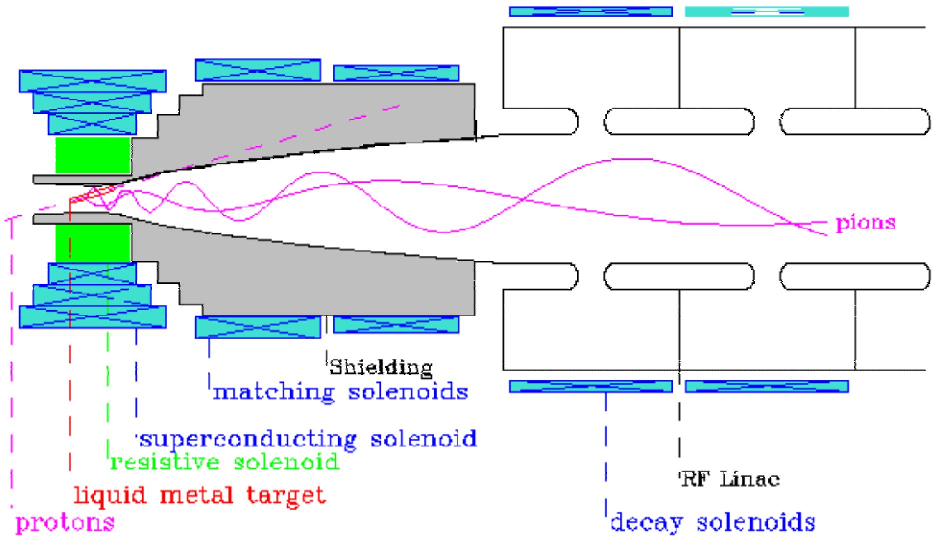


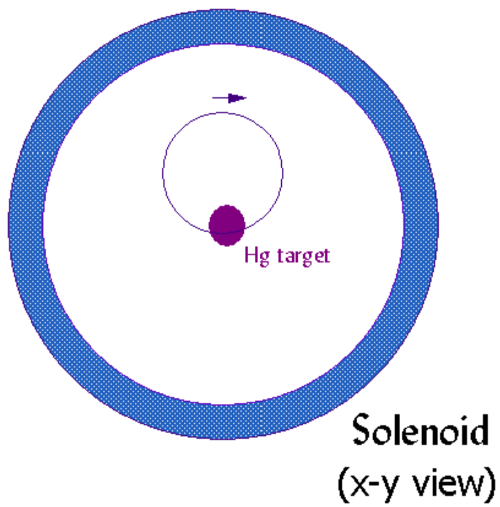
- **Capture beam from target**
- **Options:**
  - Li lens
  - Magnetic horn
  - **Magnetic Solenoid**



Solenoid lens capture

- Target is immersed in high field solenoid
- Particles are trapped in Larmor orbits
  - B= 20T -> ~2T
  - Spiral with radius $r = p_\perp/(0.3\ B_{sol}) = B\rho_\perp/B$
  - Particles with $p_\perp < 0.3\ B_{sol}R_{sol}/2$ are trapped
  - $\mathbf{p_{\perp,max} < 0.225}$ **GeV/c** for B=20T, R_{sol} = 0.075m
  - Focuses both + and - particles

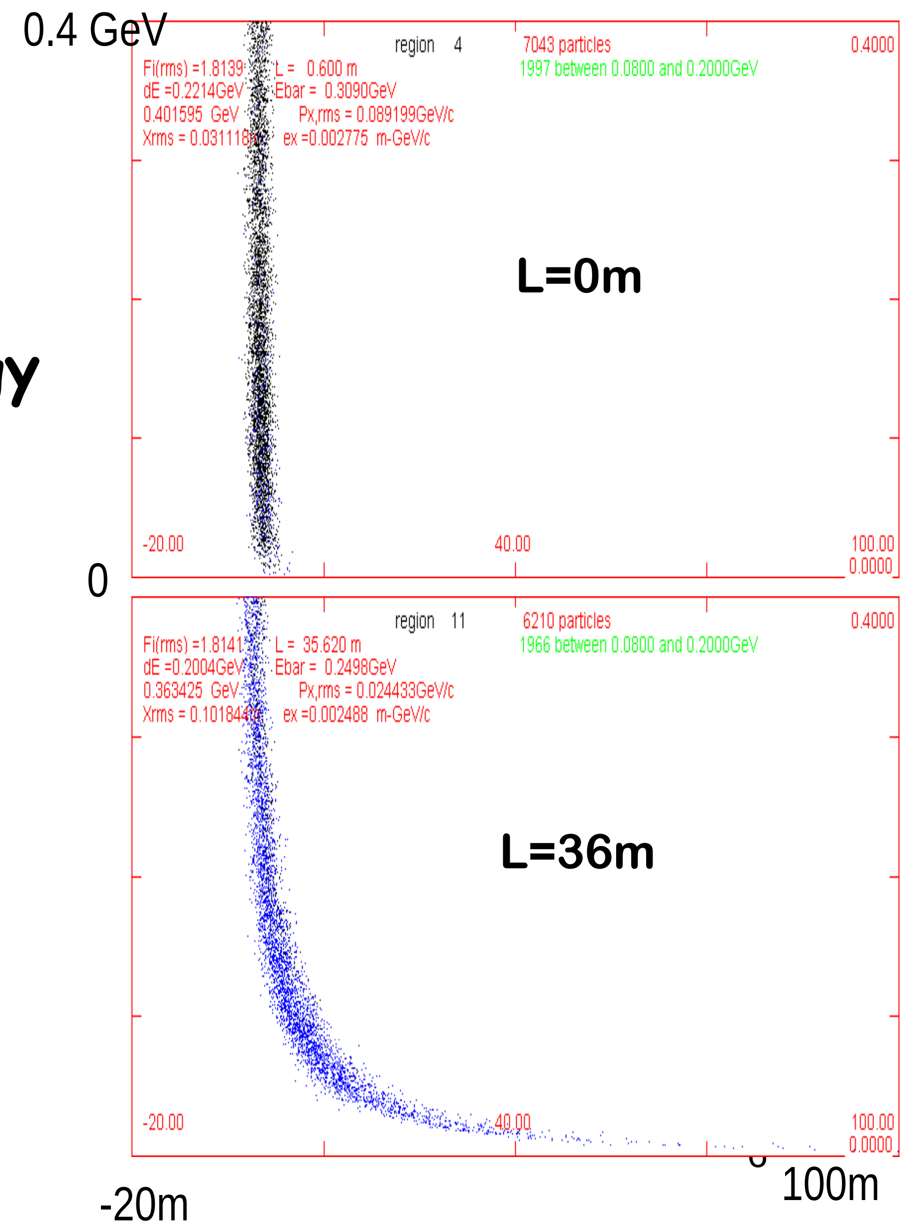




π→μν decay in transport

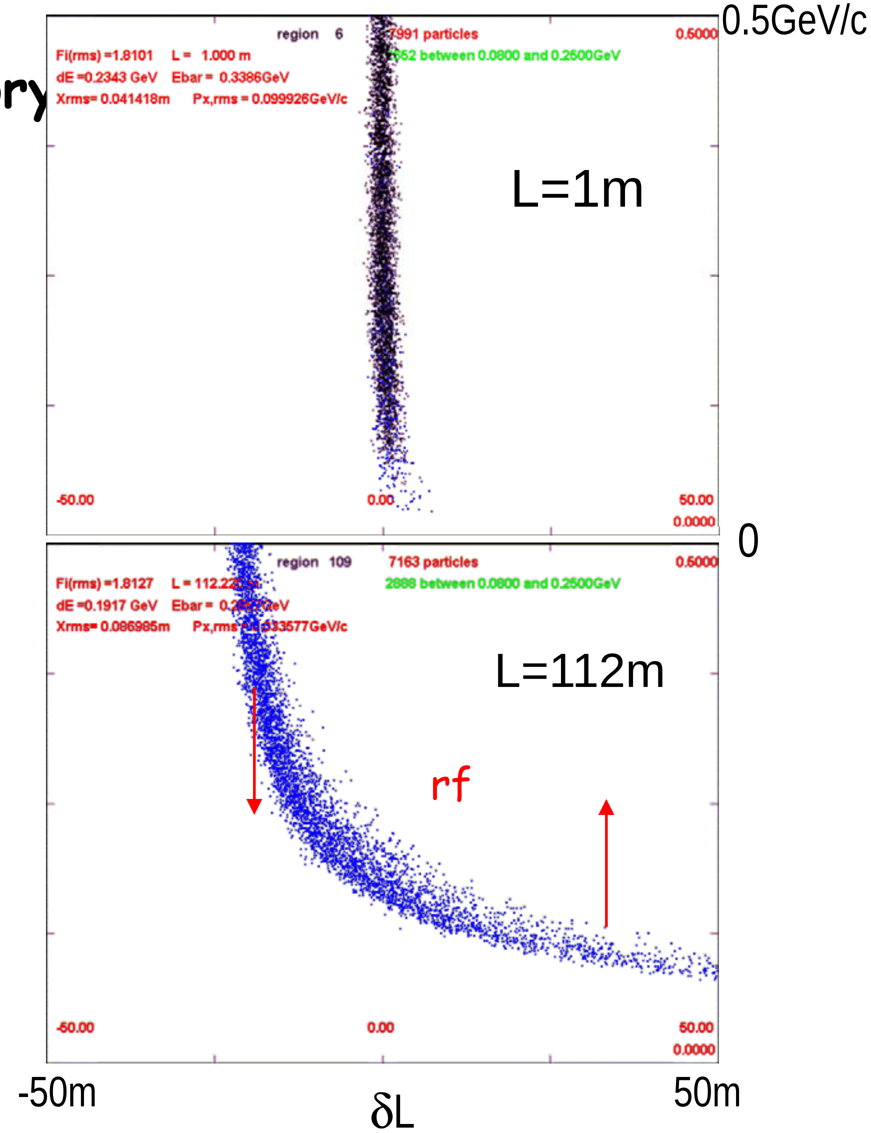
- π-lifetime is 2.60×10^{-8}γ s
  - L = 7.8 βγ m
- For π → μ+ν,
  - $\langle P_{T,rms}\rangle$ is 23.4 MeV/c, E_μ=0.6 to 1.0E_π
- Capture relatively low-energy π → μ
  - 100 – 300 MeV/c
- Beam is initially short in length
  - Bunch on target is 1 to **3 ns** rms length
- As Beam drifts down beam transport, energy-position (time) correlation develops:

$$c\tau_{arrival} = \frac{L}{\beta}$$



Phase-energy rotation

- **To maximize number of ~monoenergetic μ's, neutrino factory designs use phase-energy rotation**
- **Requires:**
  - "short" initial p-bunch ($\sigma \approx 3$ns)
  - Drift space
  - Acceleration (induction linac or rf)
    - at least ±100 MV
- **Goal:**
  - Accelerate "low-energy tail"
  - Decelerate "high-energy head:
  - Obtain long bunch
    - with smaller energy spread



$$\delta L = \delta \frac{L}{\beta(p_\mu)}$$

Phase Energy rotation options

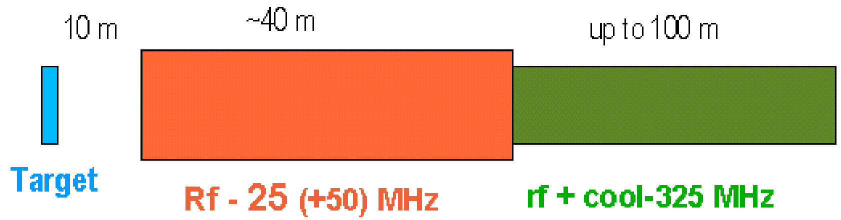
- **Single bunch capture**
  - Low-frequency rf (~30MHz)
  - Best for collider (?) (but ~ only μ^+ or μ^-)

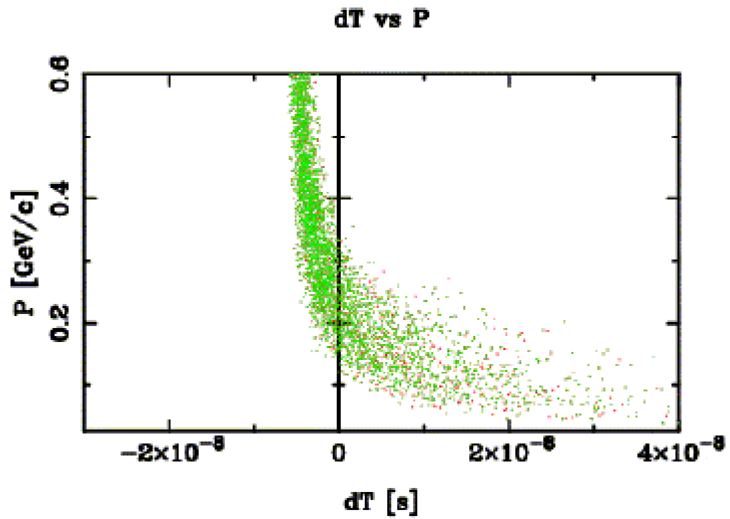
- **Induction Linac**
  - Nondistortion capture possible
  - Very expensive technology, low gradient
  - Captures only μ^+ or μ^-

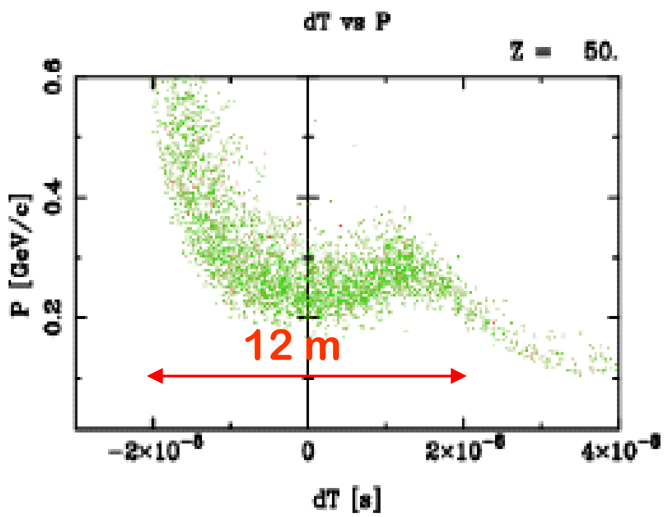
- **"High Frequency" buncher and phase rotation**
  - Captures into string of bunches (~200MHz)
  - **Captures both μ^+ and μ^-**

Phase/energy rotation

- **Low-frequency rf; capture into single long bunch**
  - 25MHz - 3MV/m
  - +25% 50MHz
  - 10m from target to 50m
- **But:**
  - Low-frequency rf is very expensive





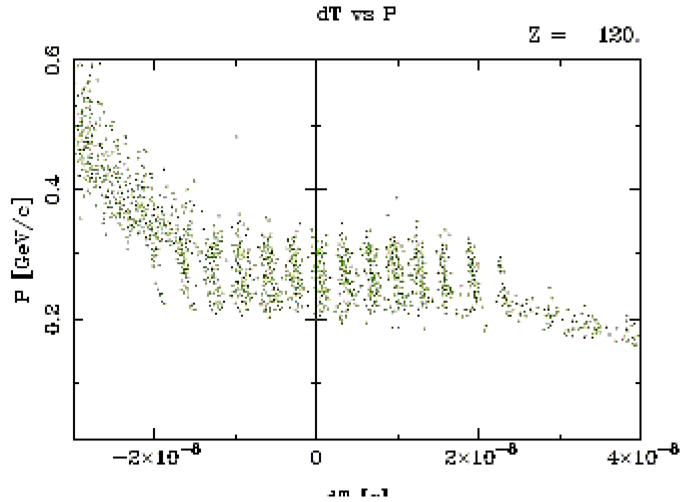


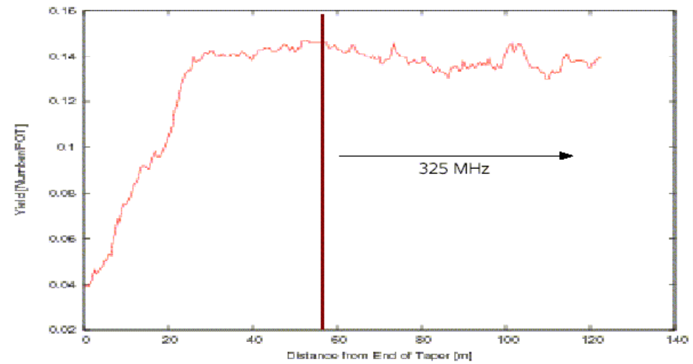
Capture into high-frequency bunches

- Cooling requires high-gradient rf !
  - (>!10MV/m)
- ⇒ > ~200MHz rf frequency

- Capture into string of rf bunches
  - i. e., ~ 12 325 MHz bunches
    - K. Paul MuCool Note 518
  - > ~0.1 μ/p (~10 GeV p)
  - C. Yoshikawa continuing study

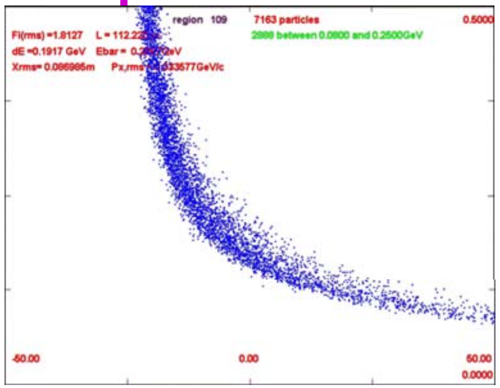
- For collider, cool and recombine to minimum number of bunches
  - Only captures one sign …

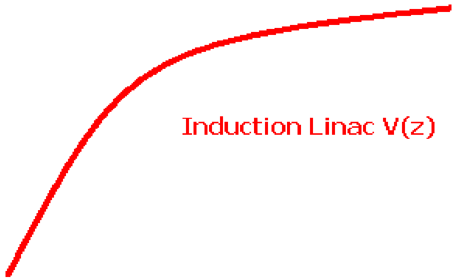


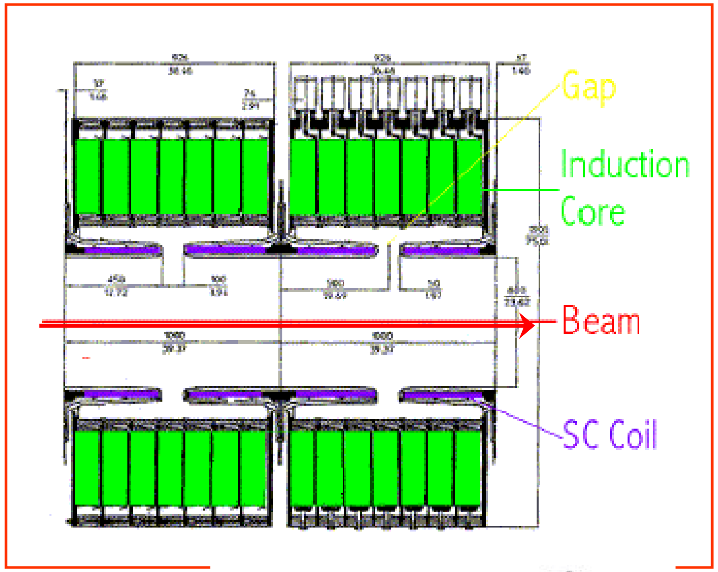


Induction Linac for φ-E Rotation

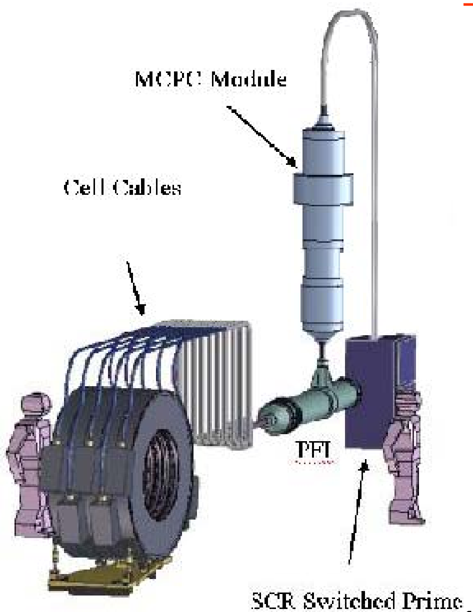
- Induction Linac can provide long pulse for φ-E rotation
- Arbitrary voltage waveform possible





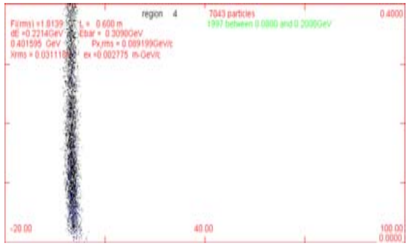


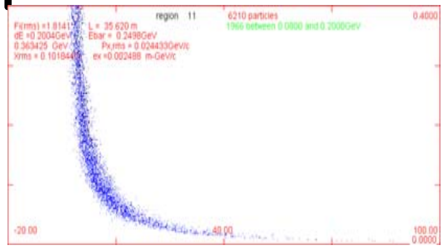
- Limited to < ~1MV/m
  - need > ~200MV, > 200m
- Very expensive, large power requirements
- Only captures one sign



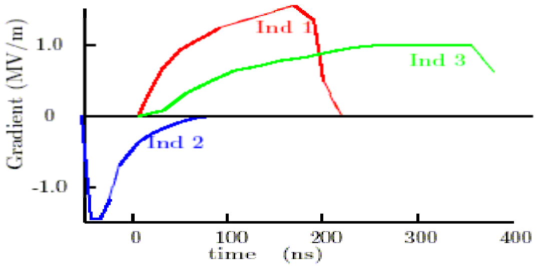
Study 2 system

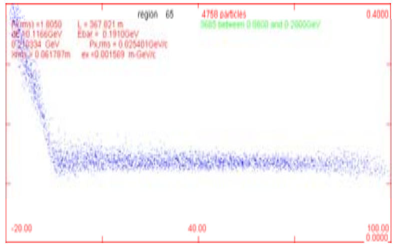
- Drift to develop Energy- phase correlation



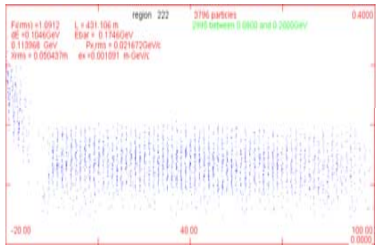


- Accelerate tail; decelerate head of beam, non-distortion (280m induction linacs (!))

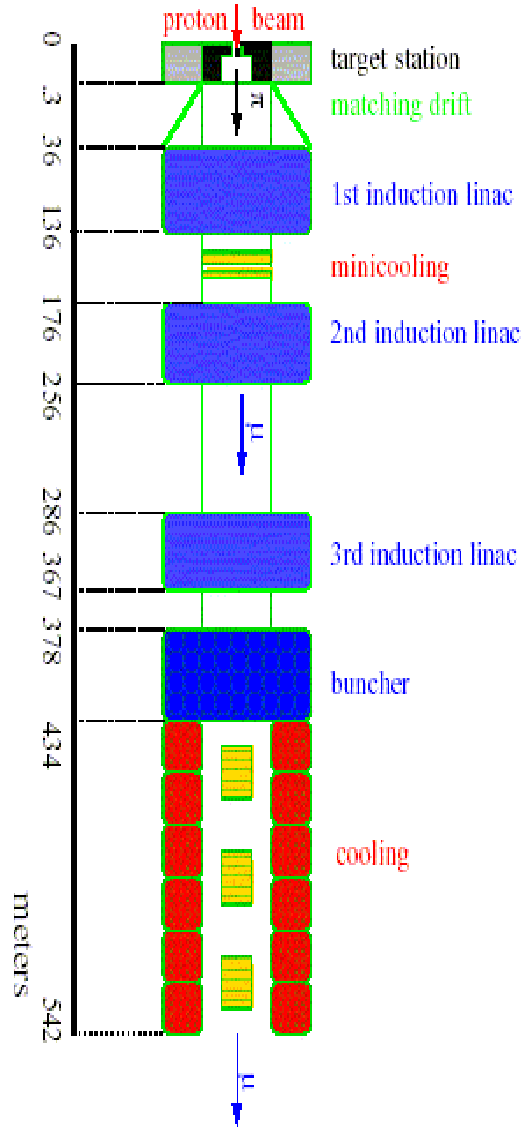




- Bunch at 200 MHz
  - ~0.2 μ/p (24 GeV p)
  - Only μ^+ or μ^-

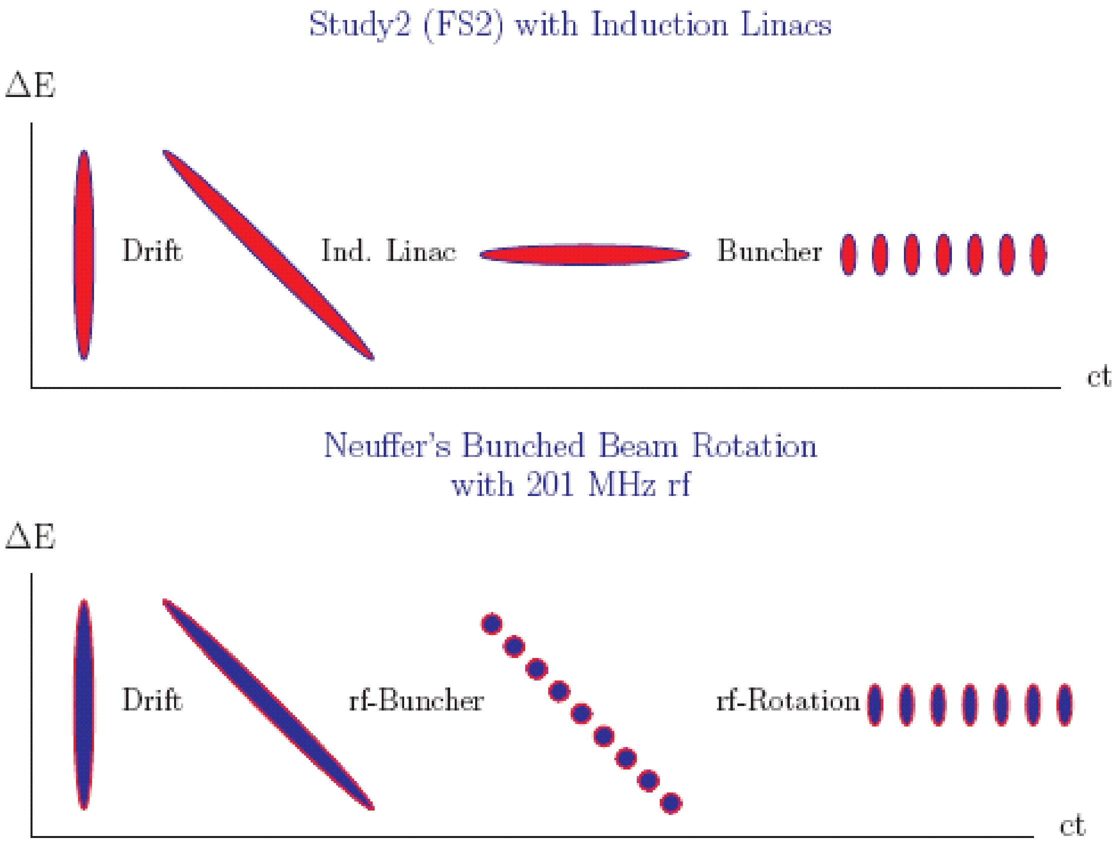


- Inject into 200 MHz cooling system



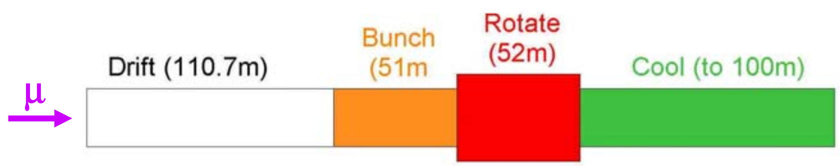
High-frequency buncher and φ-E Rotator

- Form bunches first
- Φ-E rotate bunches



High-frequency Buncher + ϕ–δE Rotation

- Drift (110m)
  - **Allows $\pi \rightarrow \mu$ beam to decay; beam develops ϕ–δE correlation**
- Buncher (~333→230MHz)
  - P_{ref} = 150 to 280 MeV/c
  - V_{rf} increases gradually from 0 to ~6 MV/m



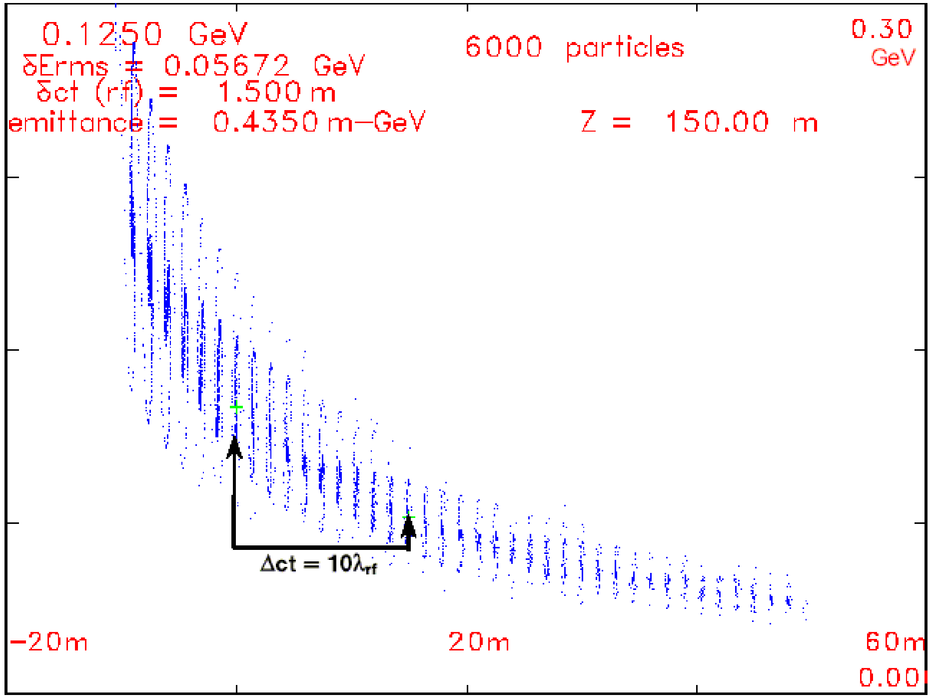
- ϕ–δE Rotation (~233→200MHz)
  - **Adiabatic rotation**
  - **V_{rf} =~10 MV/m**
- Cooler(~100m long) (~200 MHz)
  - fixed frequency transverse cooling system

Replaces Induction Linacs with medium-frequency rf (~200MHz)

Captures both μ^+ and μ^- !!

Adiabatic Buncher overview

- **Want** rf phase to be zero **for reference energies as beam travels down buncher**
- **Spacing must be N λ_{rf} $\Rightarrow\lambda_{rf}$ increases (rf frequency decreases)**
- Match to λ_{rf}= ~1.5m **at end:**
- Gradually increase rf gradient **(linear or quadratic ramp):**



Example: λ_{rf} : 0.90→1.5m
For 90 → 150m drift

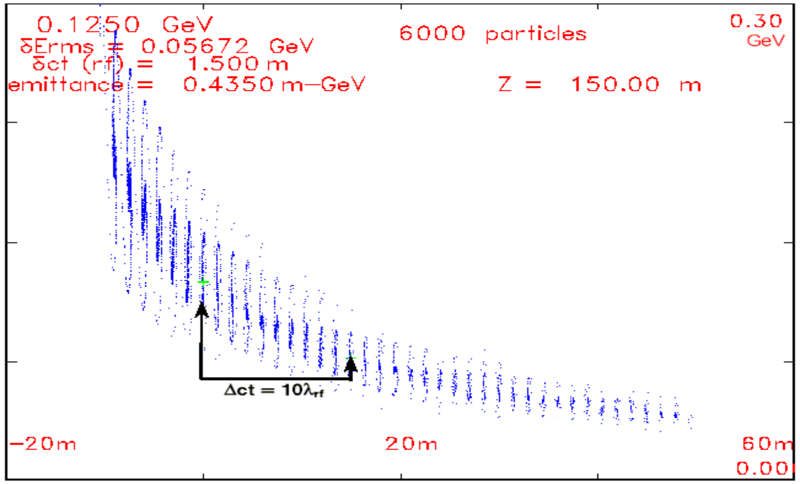
$$E_{rf}(z) = B\frac{(z - z_D)}{L_B} + C\frac{(z - z_D)^2}{L_B^{\;2}}$$

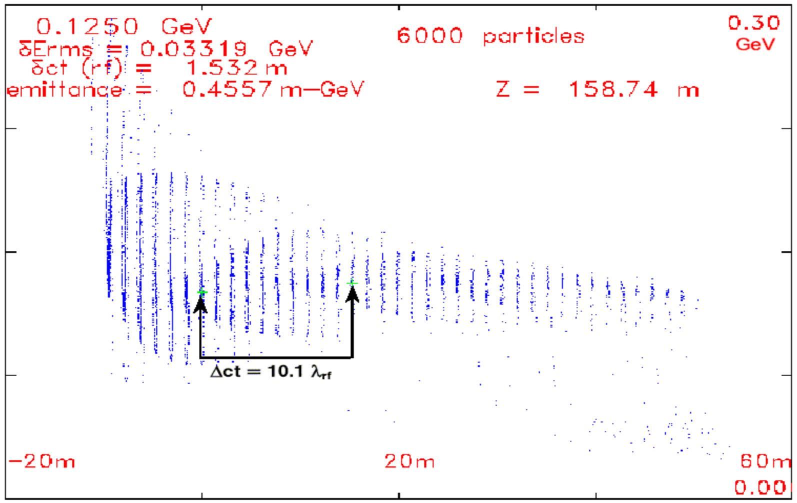
Bunches are equally spaced in 1/β(p)

φ–δE Rotation

- At end of buncher, change rf to decelerate high-energy bunches, accelerate low energy bunches
- **Central bunch at zero phase, set λ_{rf}** less than bunch spacing

  (increase rf frequency)
- Place low/high energy bunches at accelerating/decelerating phases





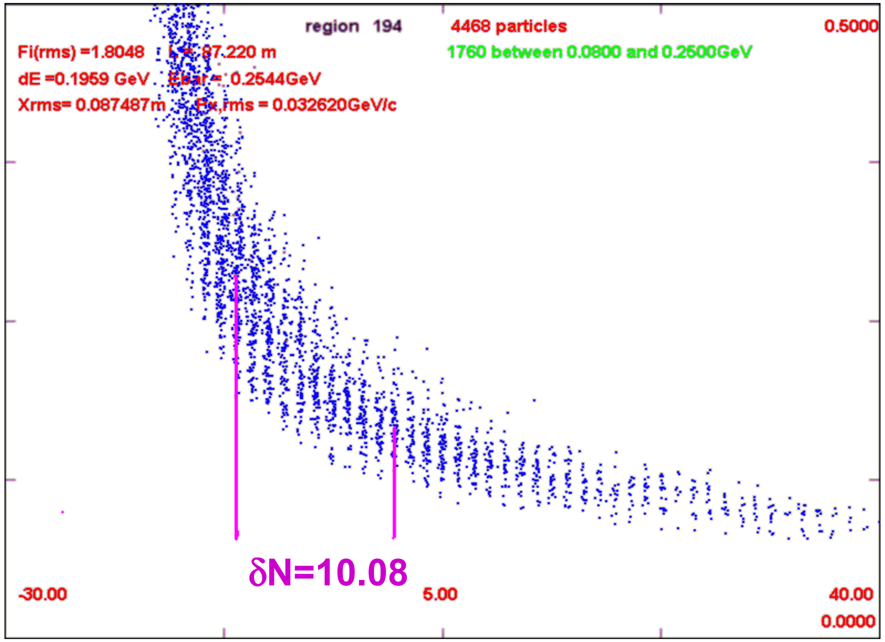
- **Can use** fixed frequency **(fast rotation)**

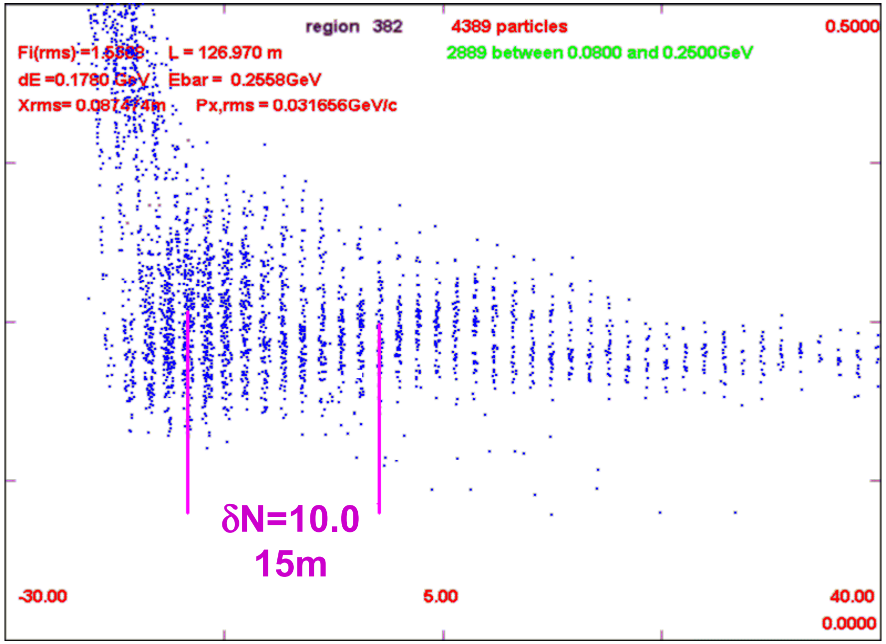
  or
- **Change frequency along channel to maintain bunching**
  - High-energy bunch decelerated
  - Low-energy accelerated

Adiabatic ϕ–δE Rotation

- At end of buncher, choose:
  - reference particles $P_{0,}$ P_N
  - N wavelengths apart, offset δ
- Example:
  - P_0 = 280, P_{10} =154 MeV/c
  - Choose N= 10, δ=0.08
- In ICOOL
  - $T_0 = T_0 + E_0' z$…; $T_N = T_N + E_N' z$
  - Rotate until $P_0 \cong P_N$
- Along rotator, keep reference particles at $(N + \delta)\ \lambda_{rf}$ spacing
  - $E_N' \cong eV' \sin(2\pi\delta)$
- **λ_{rf} ~1.4 to 1.5 m over buncher**

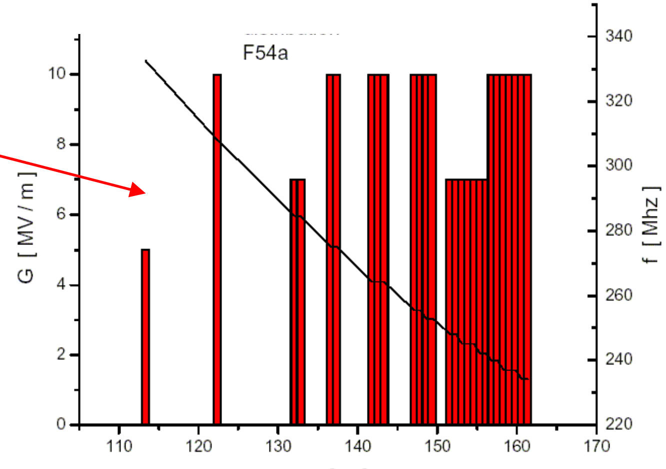
- ~Adiabatic
- Particles remain in bunches as bunch centroids align
- Match into 201.25 MHz Cooling

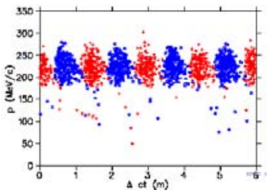


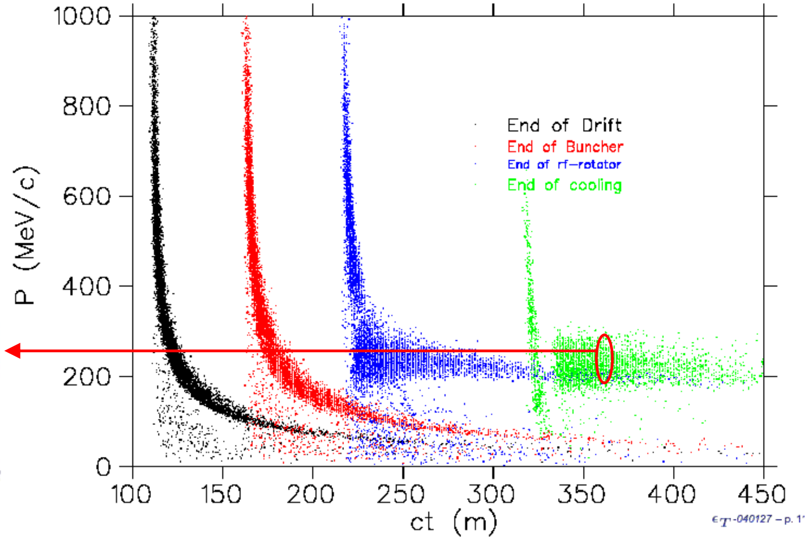


Study2A June 2004 scenario

- Drift –110.7m
- Bunch -51m
  - $\delta(1/\beta)$ =0.008
  - 12 rf freq., 110MV
  - 330 MHz → 230MHz
- ϕ-E Rotate – 54m – (416MV total)
  - 15 rf freq. 230→ 202 MHz
  - P_1=280 , P_2=154 δN_V = 18.032
- Match and cool (80m)
  - 0.75 m cells, 0.02m LiH
- Captures both μ^+ and μ^-
  - ~0.2 μ/(24 GeV p)

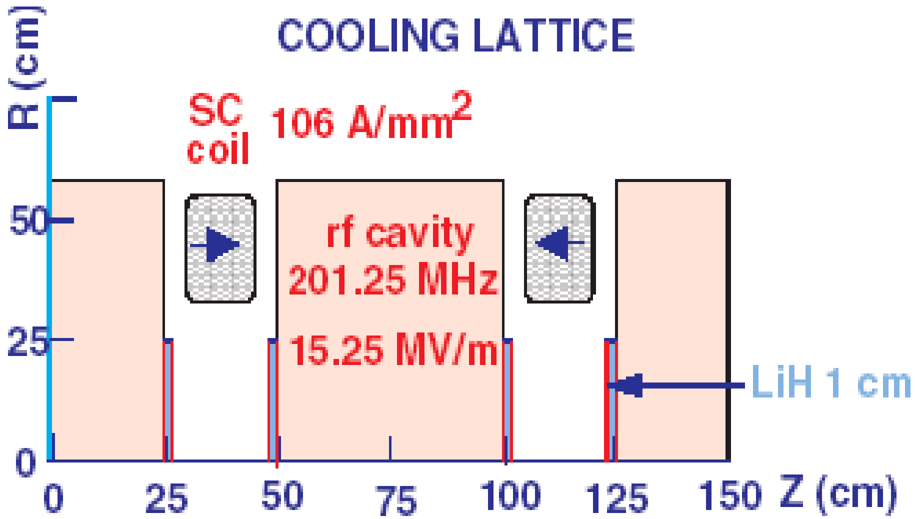




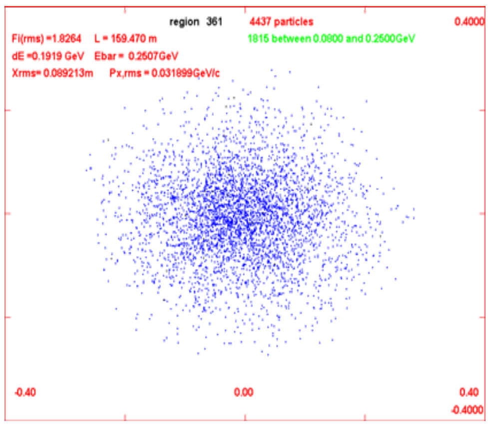


ν-Factory Study 2A cooling channel

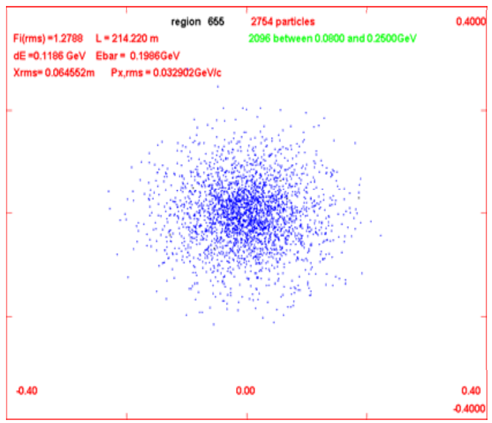
- **Lattice is weak-focusing**
  - B_{max} = 2.5T, solenoidal
  - $\beta_\perp \cong 0.8$m
- **Cools transversely**
  - $\varepsilon_\perp$ from ~0.018 to ~0.007m
  - in ~80m
- **Should be improved for Collider**



Before



After cooling

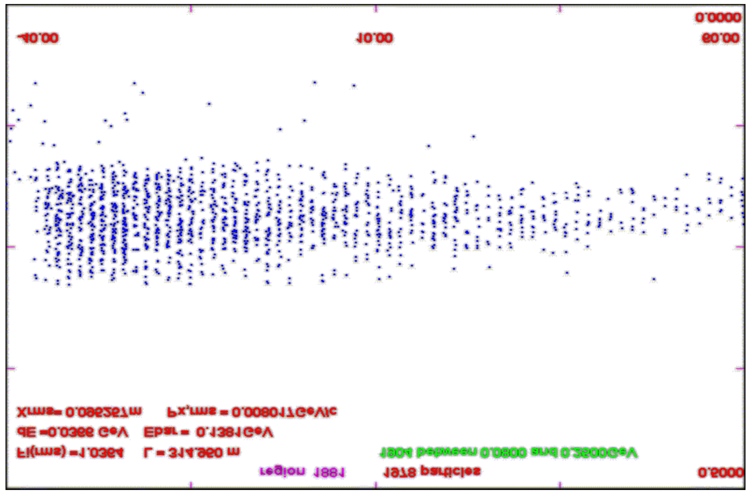


-0.4m +0.4m

Features/Flaws of Study 2A Front End

- Fairly long system ~300m long (217 in B/R)
- Produces long trains of ~200 MHz bunches
  - ~80m long (~50 bunches)
  - Transverse cooling is ~2½ in x and y, no longitudinal cooling
  - Initial Cooling is relatively weak ? -
- Requires rf within magnetic fields
  - in current lattice, rf design; 12 MV/m at B = 1.75T
  - Marginal for pillbox cavities; OK for open-cell cavities ??
  - Gas-filled cavities?

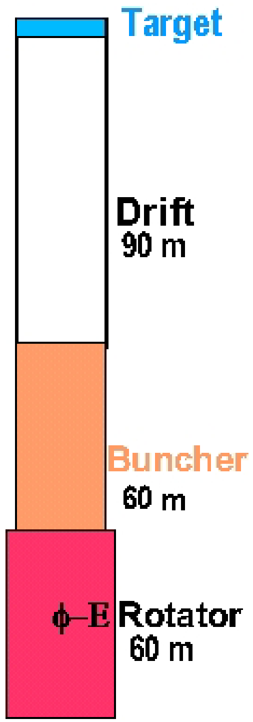
500 MeV/c

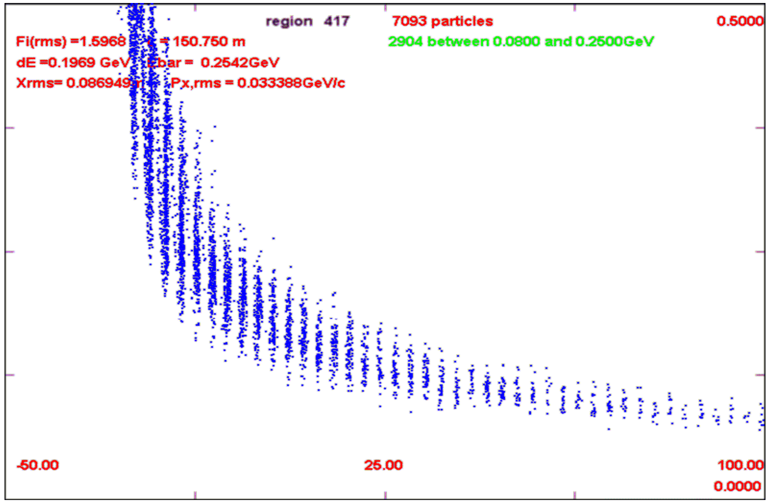


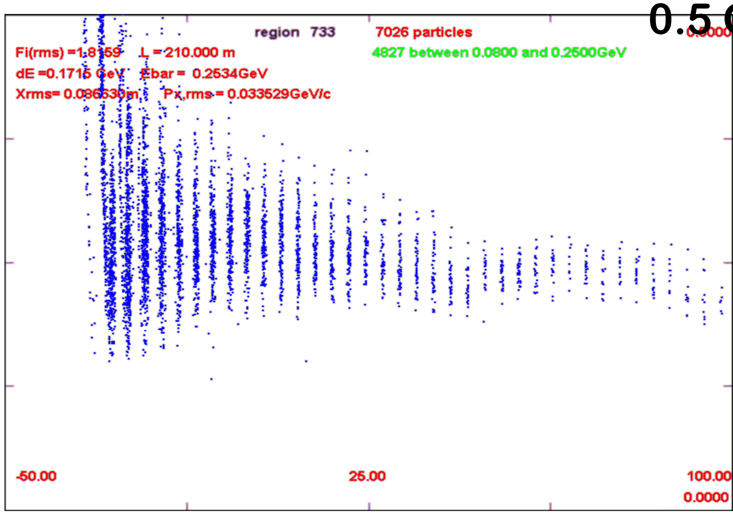
-40 60m

Another example: ~88 MHz

- Drift – 90m
- Buncher-60m
  - Rf gradient 0 to 4 MV/m (6MV/m in cavities)
  - Rf frequency: 166→100 MHz
  - Total rf voltage 120MV
- Rotator-60m
  - Rf gradient 7 MV/m – 100→87 MHz (10.5 × ⅔)
  - 420MV total
- Acceptance ~ study 2A (but no cooling yet)
  - Less adiabatic





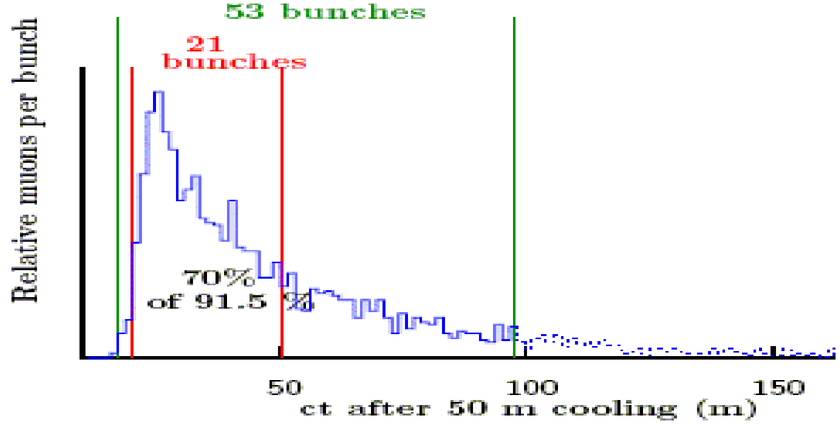


0.5 GeV/c

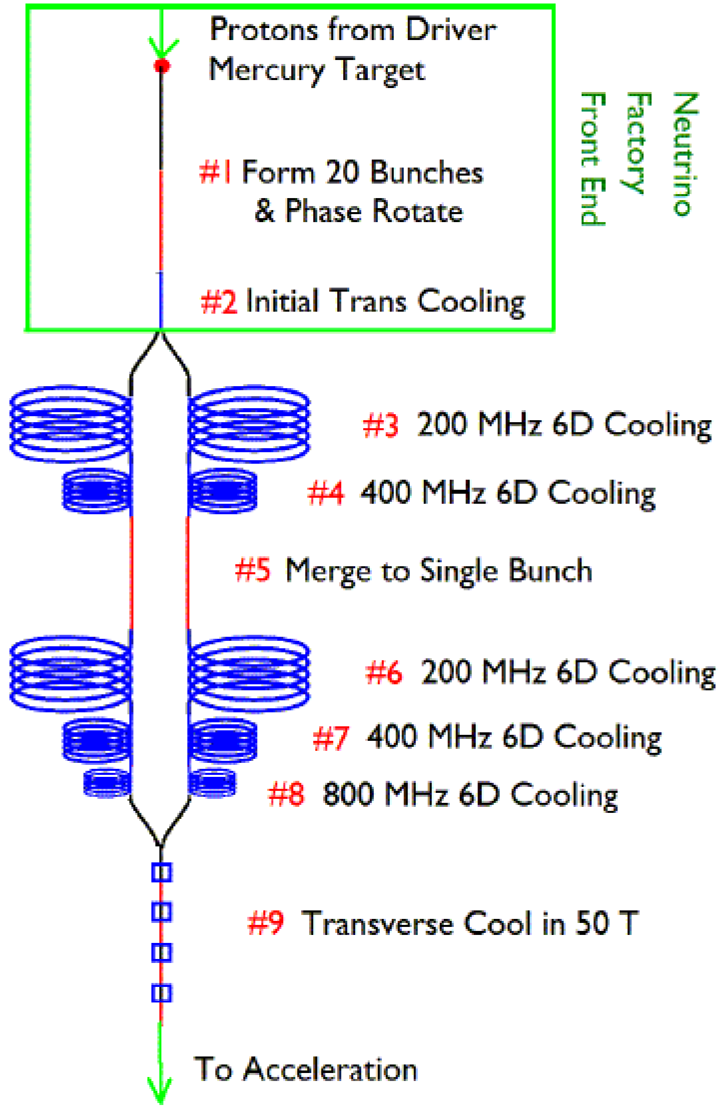
0 GeV/c

Study 2A to $\mu^+\mu^-$ Collider

- Use front end as start of cooling channel R. Palmer et al.
  - Have both signs ($\mu^+ + \mu^-$)
  - Natural upgrade of facility
- Use only first ~21 bunches (70% of μ's)

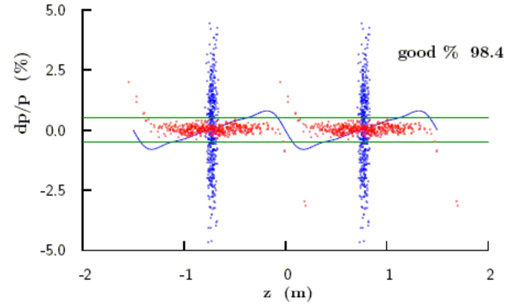


- After initial 6-D cooling; recombine bunches

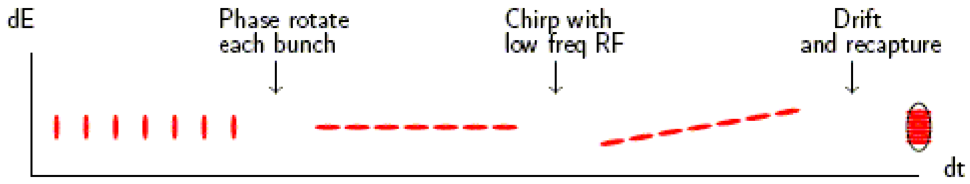


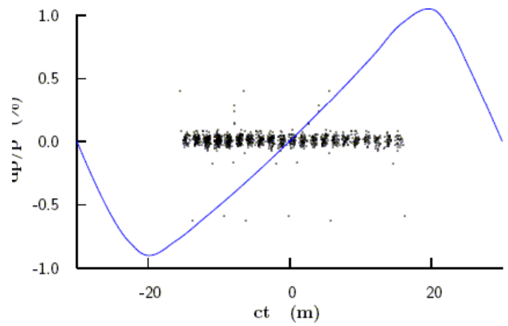
Adapt to Collider (R Palmer)

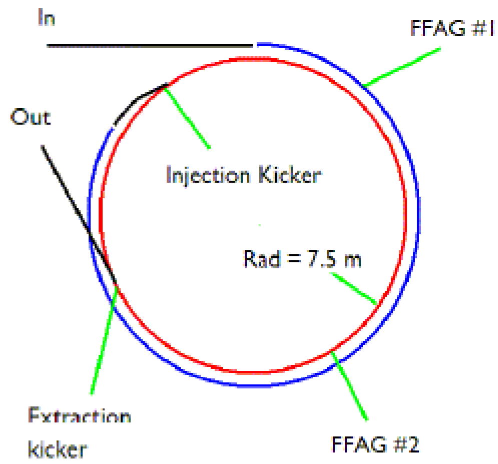
- Recombine cooled bunches
  - Buncher "wiggler" (k=-3 FFAGs)
  - 21 ⇒ 1 bunch (after ~200m) + 2 rf systems
  - ~50% losses in rebunching …



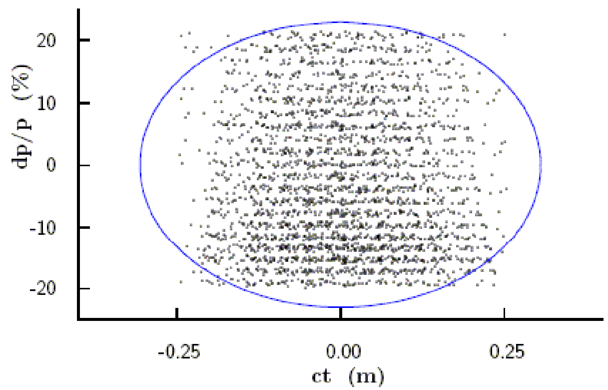
Bunch Merging







not decayed (%) 97.09896 87.72808
in accept (%) 94.57606 eff (%) 80.56277
long acceptance (pi mm) 134.0572
long beta (m) 1.330435 emitlong (mm) 23.18362

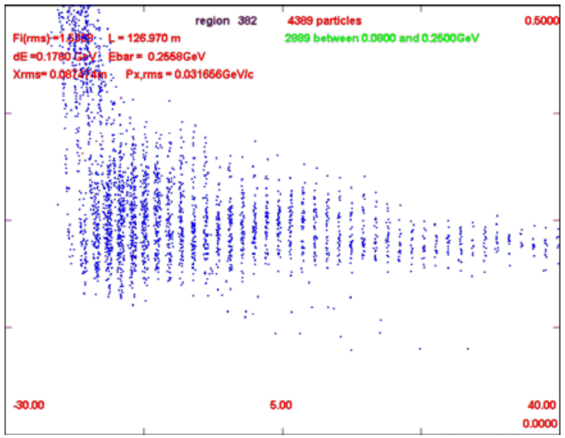


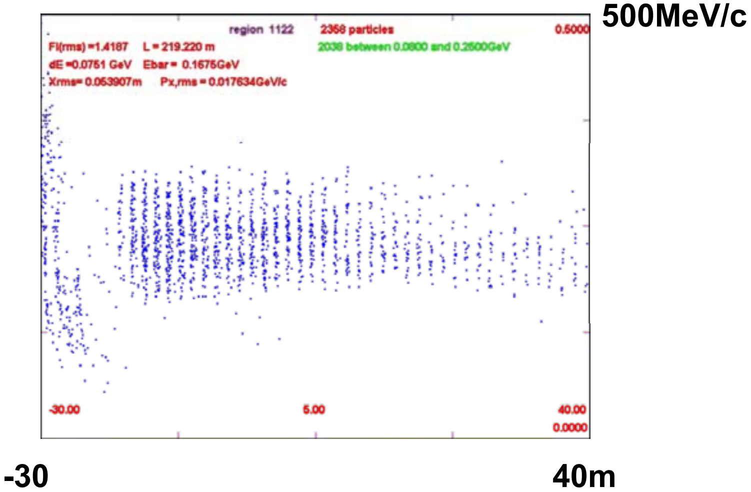
Difficulties

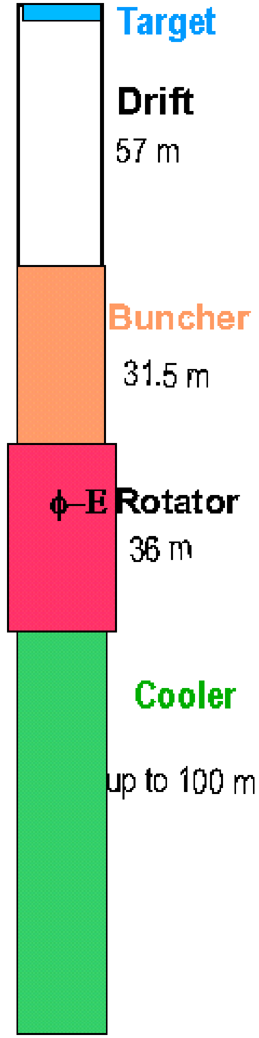
- >21 200MHz bunches -> 1 is awkward
  - Bunch train is too long (21 bunches =31.5m)
  - Loses a lot of useful μ's
    - (decay plus using "only" 21 bunches)
- Buncher/Rotator is too long (~215m)
  - Shorter system will produce shorter bunch train
  - More adiabatic than needed …

Shorter Bunch train example (~2/3)

- **Reduce drift, buncher, rotator to get shorter bunch train:**
  - 217m ⇒ **125m**
  - **57m drift, 31m buncher, 36m rotator**
  - **Rf voltages up to 15MV/m (×2/3)**
- Obtains **~0.27 μ/p** in ref. acceptance
  - **Slightly better ?**
    - **~0.25 μ/p for Study 2A baseline**
- 80+ m bunchtrain reduced to < 50m
  - **Δn: 18 -> 10**

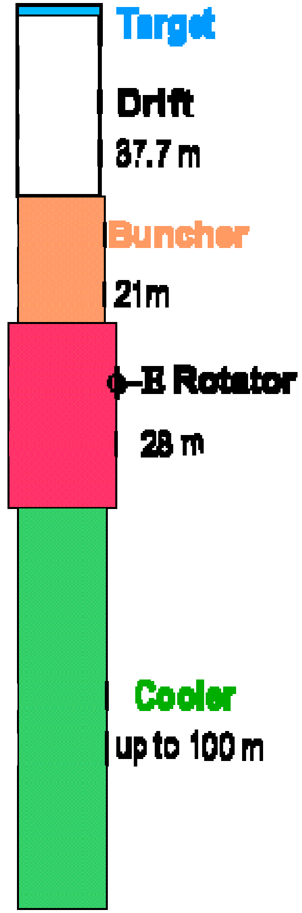


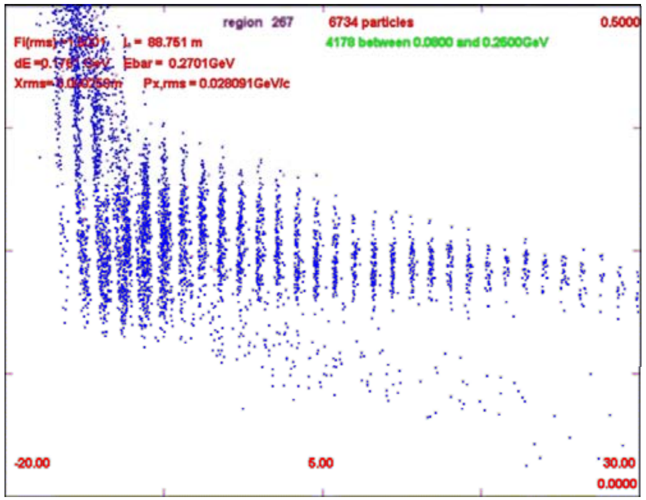


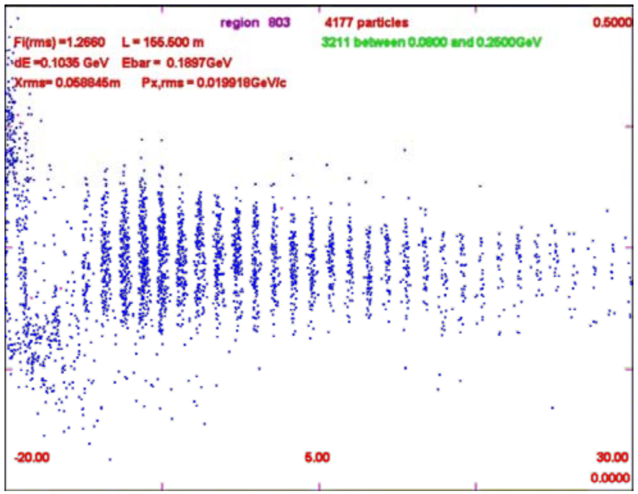


Even Shorter Bunch train ~$(2/3)^2$

- Reduce drift, buncher, rotator to get shorter bunch train:
  - 217m ⇒ 86m
  - 38m drift, 21m buncher, 27m rotator
  - Rf voltages 0-15MV/m, 15MV/m (×2/3)
- Obtains ~0.23 μ/p in ref. acceptance
  - 201.25 MHz cooling
  - Slightly worse than previous ?
- 80+ m bunchtrain reduced to < 30m
  - 18 bunch spacing dropped to 7







500MeV/c

-20

30m

Details of ICOOL model

- **Drift– 37.7m**
  - B=2T
- **Bunch- 21m**
  - $P_{ref,1}$=280MeV/c, $P_{ref,2}$ =154 MeV/c, δn_{rf} = 7
  - V_{rf} 0 to 15MV/m (0.5m rf, 0.25m drift) cells
  - 350 MHz → 230MHz
- **φ-E Rotate – 27m –**
  - V_{rf} = 15MV/m (0.5m rf, 0.25m drift) cells
  - **δN_V = 7.1 (230 -> 204 MHz)**
- **Match and cool (80m)**
  - Old ICOOL transverse match to ASOL (should redo)
  - P_{ref}= 220MeV/c, f_{rf} = 201.25 MHz
  - 0.75 m cells, 0.02m LiH, 0.5m rf, 15.25MV/m, φ_{rf} =30°

Discussion

- **Guess: Optimum is ~ 8—10 bunches**
  - (for collider) (~12 better for ν-factory)
  - Looks similar to ~30 MHz large-bunch Φ-E rotate, rebunched at ~300 Mhz
- **Optimum is ~1/2 × Study2A / ISS example**
  - 215m -> 90—120m

- **Much shorter buncher/rotator will not be as good ~**
  - Need ~100MV rf for buncher; 200 for rotator
    - ~10MV/m real estate gradient
  - > 80m needed ?
- **Shorter buncher/rotator is cheaper**
  - cost × ~2/3 ….