Bunched-Beam Phase Rotation– Recent Optimizations

David Neuffer

Fermilab

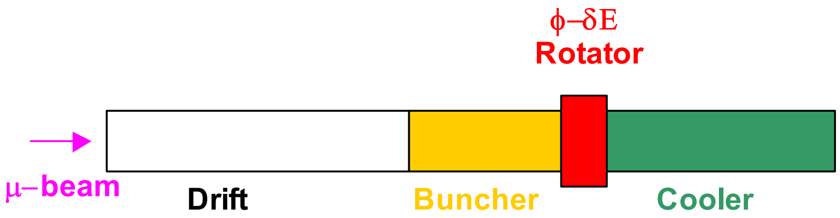
Outline

- Introduction
- "High-frequency" Buncher and ϕ–δE Rotation
  - Concept
  - 1-D simulations, 3-D simulations (ICOOL)
  - Matched cooling channel
- Study 2A scenario
  - Match to Palmer cooling section
  - Obtains up to ~0.25 μ/p
- Variations
  - Be absorber (or H_2, or …)
  - Shorter rotator (52m $\rightarrow$ 26m), fewer rf frequencies
  - Short bunch train (< ~20m)
  - Optimization ….

Adiabatic buncher + Vernier $\phi-\delta E$ Rotation

- **Drift** (90m)
  - $\pi \rightarrow \mu$ decay;
    beam develops $\phi-\delta E$ correlation

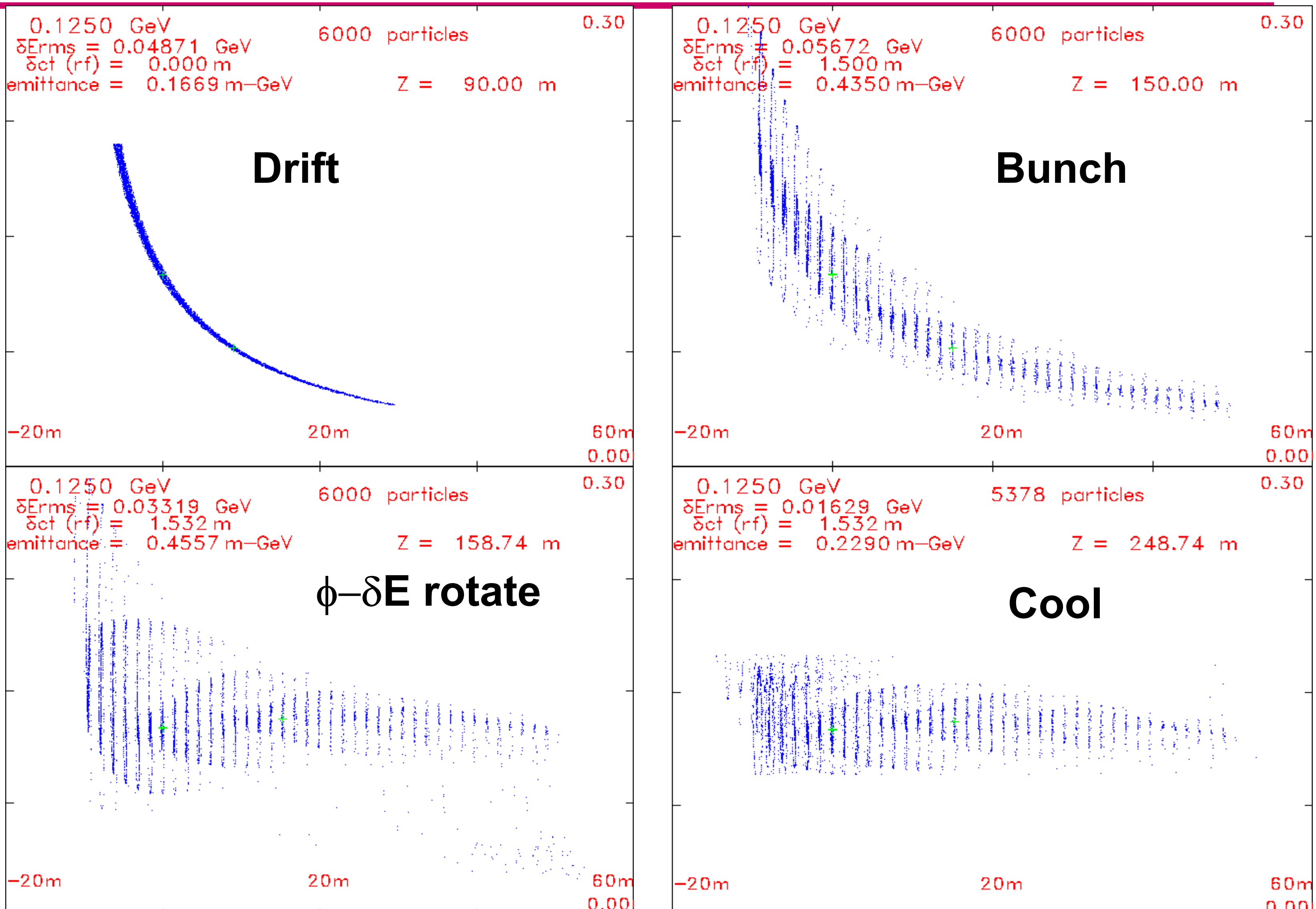
Overview of transport



- **Buncher** (60m) (~333→200MHz)
  - Forms beam into string of bunches
- **$\phi-\delta E$ Rotation**(~10m) (~200MHz)
  - Lines bunches into equal energies
- **Cooler**(~100m long) (~200 MHz)
  - fixed frequency transverse cooling system

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

Longitudinal Motion (1-D simulations)



System would capture both signs (μ^+, μ^-) !!

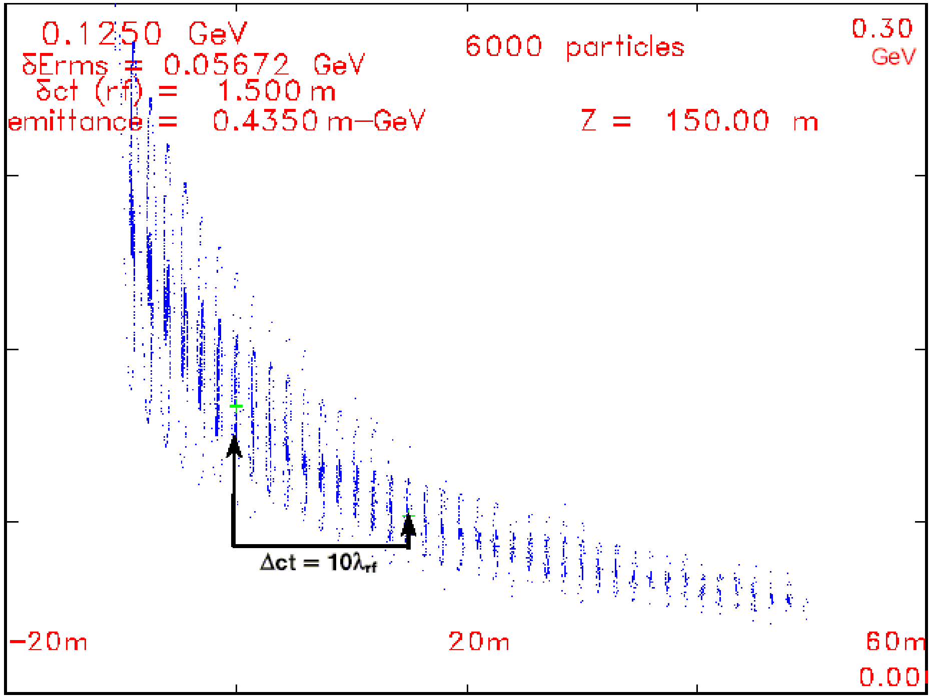
Adiabatic Buncher overview

- 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):

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



Example: λ_{rf} : 0.90→1.5m

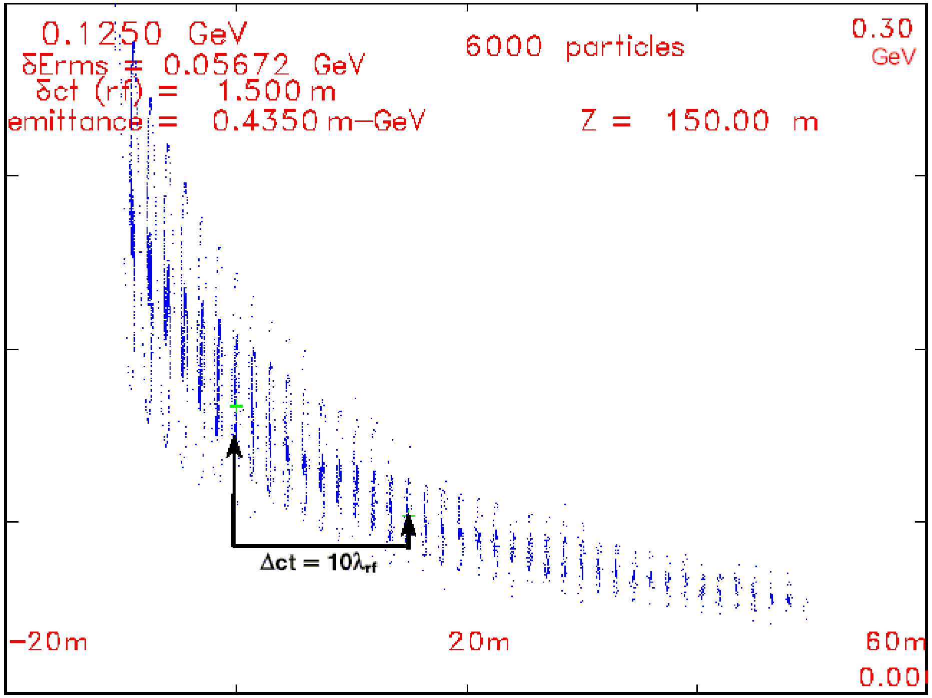
Adiabatic Buncher overview

- Adiabatic buncher
- Set T_0, $\delta(1/\beta)$:
  - 125 MeV/c, 0.01
- In buncher:

$$\lambda_{rf}(z) = z\,\delta(1/\beta)$$

- Match to λ_{rf}=1.5m at end:

$$L_{tot}\left(\frac{1}{\beta_1} - \frac{1}{\beta_0}\right) = L_{tot}\,\delta\left(\frac{1}{\beta}\right) = \lambda_{rf} = 1.5\text{m}$$



λ_{rf} : 0.90→1.5m

- zero-phase with $1/\beta$ at integer intervals of $\delta(1/\beta)$:

$$\frac{1}{\beta_n} = \frac{1}{\beta_0} + n\,\delta\left(\frac{1}{\beta}\right)$$

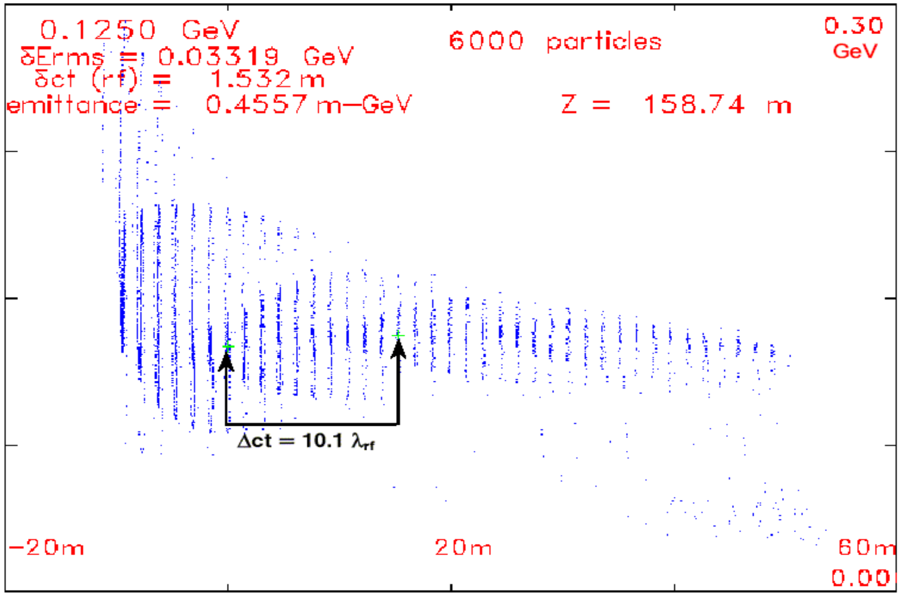
- Adiabatically increase rf gradient:

$$E_{rf}(z) = 4.8\frac{(z - z_D)^2}{(L_{tot} - z_D)^2} \quad \text{MV/m}$$

$\phi - \delta E$ Rotation

Muon Collaboration

- At end of buncher, change rf to decelerate high-energy bunches, accelerate low energy bunches
- Reference bunch at zero phase, set λ_{rf} less than bunch spacing (increase rf frequency)
- Places low/high energy bunches a accelerating/decelerating phases
- Can use fixed frequency (requires fast rotation)   or
- Change frequency along channel to maintain phasing   "Vernier" rotation –A. Van Ginneken

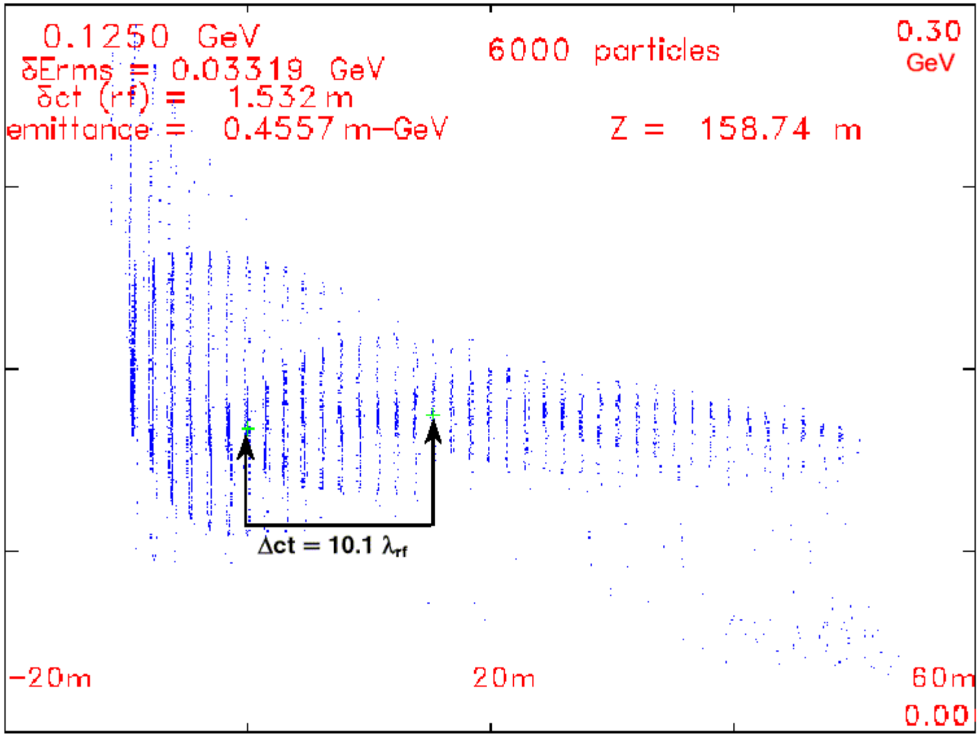


"Vernier" $\phi-\delta E$ Rotation

- At end of buncher, choose:
  - Fixed-energy particle T_0
  - Second reference bunch T_N
  - Vernier offset δ
- Example:
  - T_0 = 125 MeV
  - Choose N= 10, δ=0.1
    - T_{10} starts at 77.28 MeV
- Along rotator, keep reference particles at $(N + \delta)\ \lambda_{rf}$ spacing
  - ϕ_{10} = 36° at δ=0.1
  - Bunch centroids change:

$$T_{10}(z_R) = T_{10}(0) + e\,E_{rf}\sin(\phi_{10})\,z_R$$

- Use E_{rf} = 10MV/m; L_{Rt}=8.74m
  - High gradient not needed …
  - Bunches rotate to ~equal energies.



λ_{rf} : 1.485→1.517m in rotation;
λ_{rf} = Δct/10 at end

(λ_{rf} → 1.532m)

Nonlinearities cancel:
T(1/β) ; Sin(φ)

Key Parameters

- General
  - Muon capture momentum (200MeV/c?) 280MeV/c?
  - Baseline rf frequency (200MHz)
- Drift
  - Length L_D
- Buncher – Length (L_B)
  - Gradient, ramp V_B' (linear OK)
  - Final Rf frequency $(L_D + L_B)\,\delta(1/\beta) = \lambda_{RF}$
- Phase Rotator–Length ($L_{\phi R}$)
  - Vernier, offset : $N_{\phi R}$, δ_V
  - Rf gradient $V_{\phi R}'$
- COOLing Channel–Length (L_C)
  - Lattice, materials, V_C, etc.
- Match into cooling channel, Accelerator

Implementation in ICOOL

- Define Two reference particles: P_1, P_2
- ACCEL option 10
  - N –wavelengths between ref particles
  - $V(z) = A + Bz + Cz^2$
  - Long. Mode
  - Phase model 0 or 1
    - 0 at t_1 (REFP particle 1)
    - 1 at $(t_1 + t_2)/2$
- REFP –reference particle(s)
  - 3 –constant velocity
  - 4 –energy loss + reference energy gain in cavities

For **model = 10**
2 (not used)
3 (not used)
4 phase shift [deg] {0-360}.
5 number of wavelengths separating the two reference particles
6 reset parameter (see below)
7 Total length L of buncher [m]
8 g0 [MV/m]
9 g1 [MV/m]
10 g2 [MV/m]
11 longitudinal mode p {0,1}
For mode = 0 Rcav = 0.383 * λ
For mode = 1 Rcav = 2.405 / {(2 pi f)^2 - (pi/SLEN)^2 }^1/2
For pi mode, set SLEN = /2 => Rcav -->inf
12 phase model
  0: 0-crossing time set by t_{REFP}
  1: 0-crossing time set by ½ * (t_{REFP} + t_{REF2})

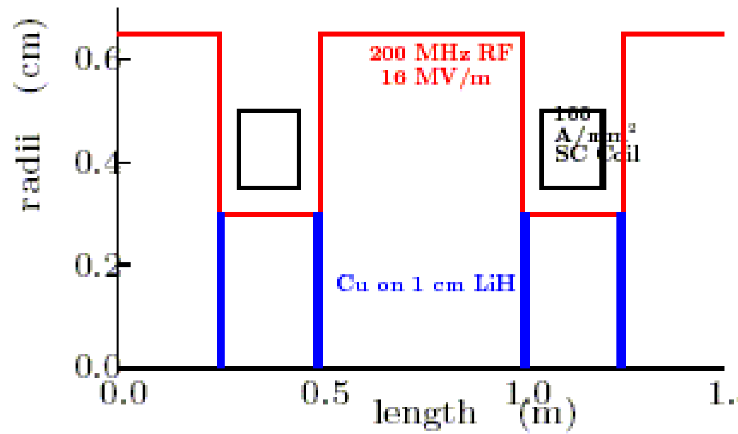
This model can only be used with phasemodel=3,4. The cavity frequency is set using the number of wavelengths (parameter 5) and the time difference between the two reference particles. When the reset parameter is 1, the starting location of the buncher is determined from the current position of the reference particle. Subsequent ACCEL commands should use parameter #6 set to 0 to sample later portions of the gradient waveform, which is given by
G = g0 + g1*(z/L) + g2*(z/L)^2
A new pulse shape can be started at any time by setting parameter #6 back to 1.

```
SREGION          !  RF
0.50  1    1e-2
1  0.   0.30
ACCEL
  10. 0. 0. 0. 5.05   1. 30. 15 0 0   0. 0. 0. 0. 0
VAC
NONE
    0. 0. 0. 0. 0.   0. 0. 0. 0. 0.
```

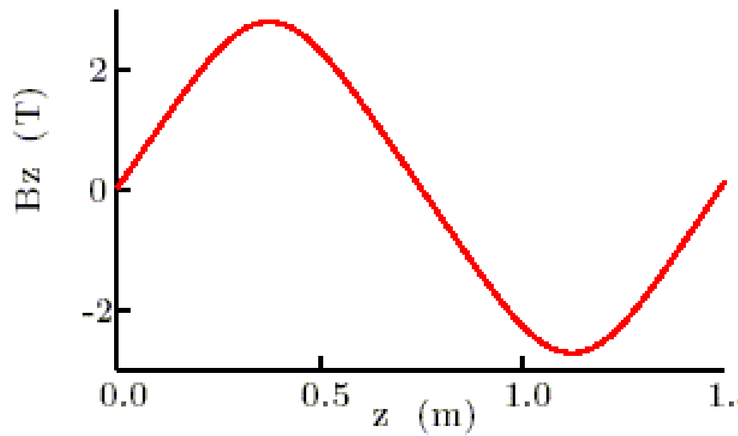
Caution: reference particles do not see actual rf fields

Study 2a Cooling Channel

- Need initial cooling channel
  - (Cool ε_T from 0.02m to 0.01m
  - Longitudinal cooling ?



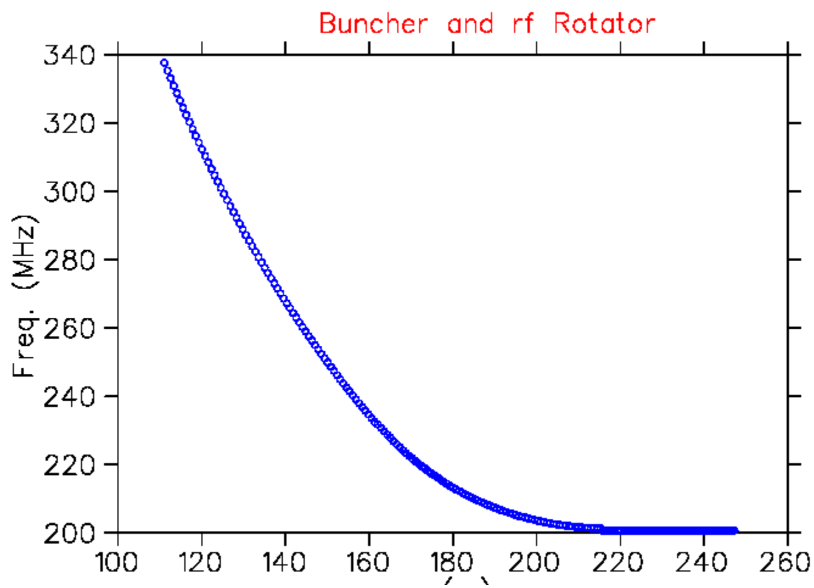
- Examples
  - Solenoidal precooler (Palmer)
  - "Quad-channel" precooler
  - 3-D precooler



- Match into precooler
  - First try was unmatched
  - Transverse match
    - B=Const. $\Rightarrow$ B sinusoidal
    - Gallardo, Fernow & Palmer

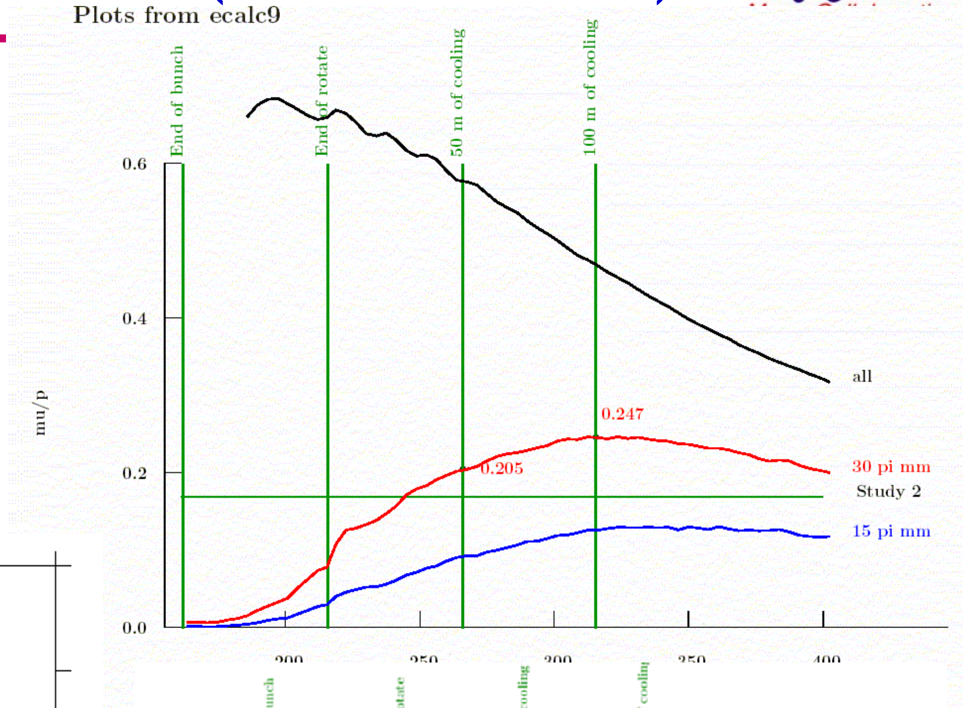
Palmer Dec. 2003 scenario

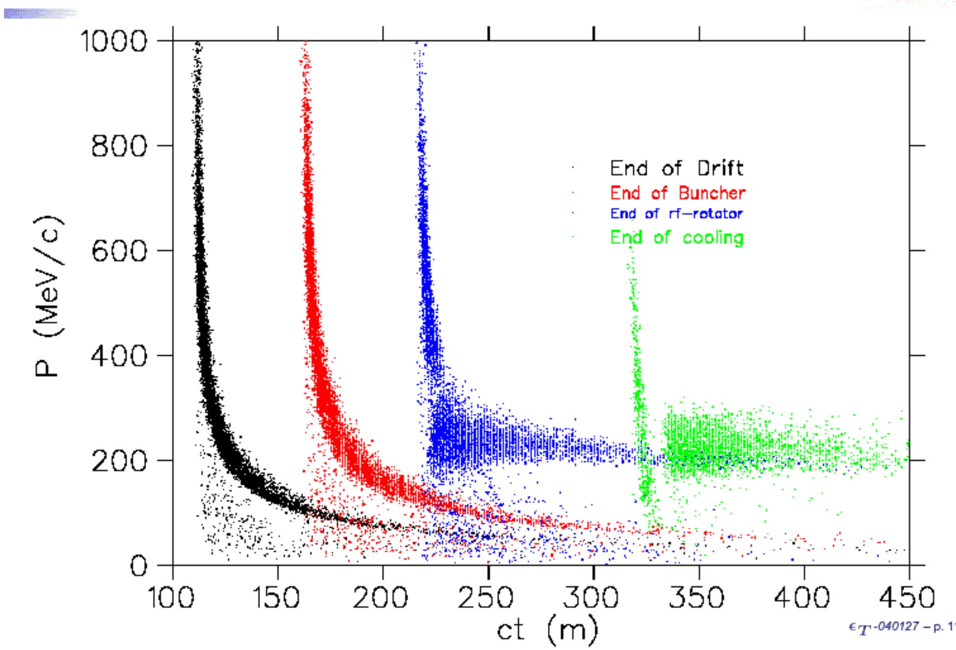
- Drift –110.7m
- Bunch –51m
  - $V' = 3(z/L_B) + 3\ (z/L_B)^2$ MV/m ($\times$ 2/3) (85MV total)
  - $\delta(1/\beta)$ =0.0079
- ϕ–E Rotate – 52m – (416MV total)
  - 12 MV/m ($\times$ 2/3)
  - P_1=280 , P_2=154 δV = 18.032
- Match and cool (100m)
  - V' = 15 MV/m ($\times$ 2/3)
  - P_0 =214 MeV/c
  - 0.75 m cells, 0.02m LiH

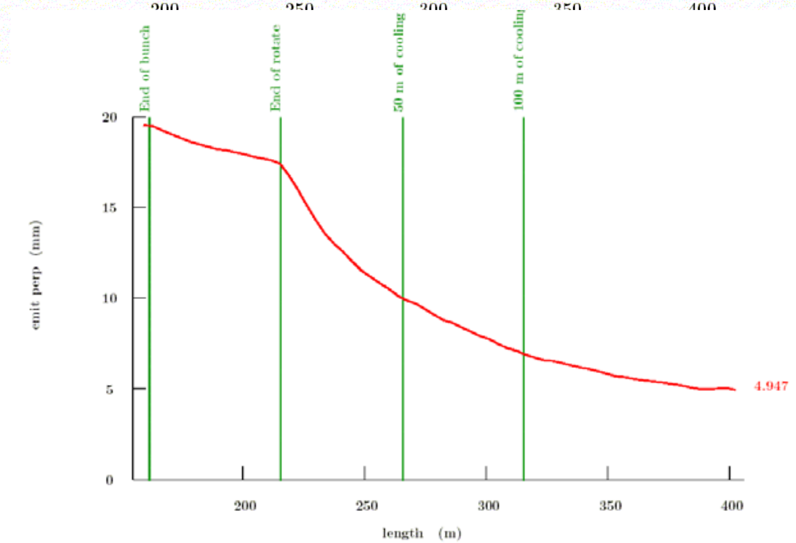


Simulation results (from Gallardo)

- (Palmer, Gallardo, Fernow,…
- 0.25 μ/p in 30π mm acceptance





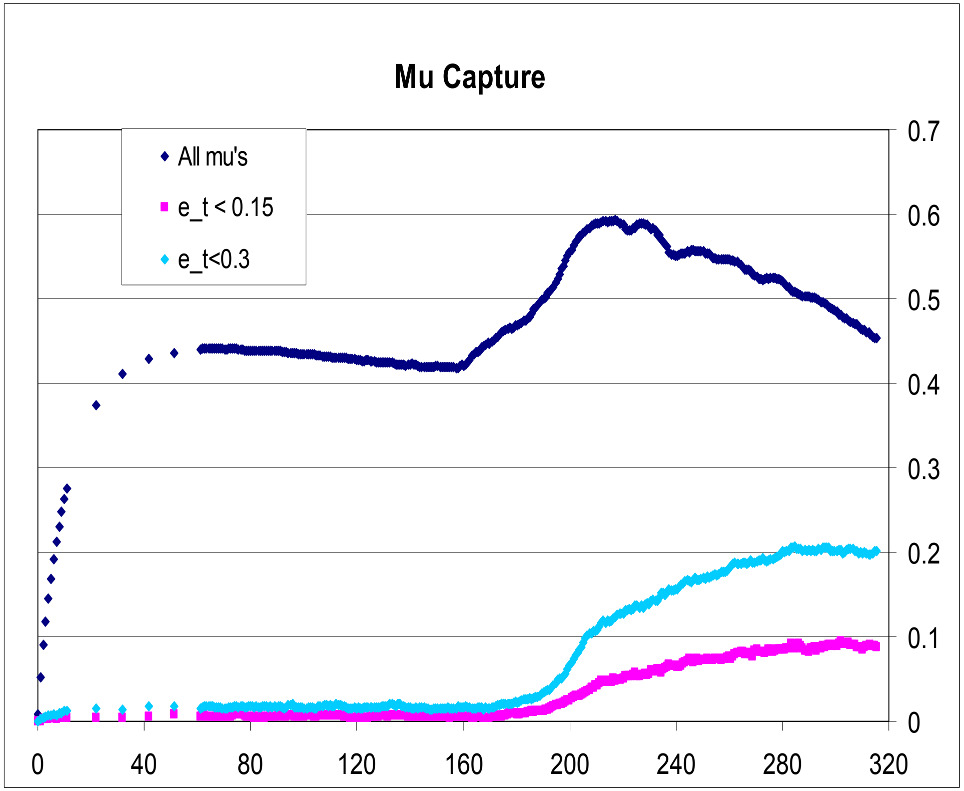


Variation –Be absorbers

- Simply replace LiH absorbers with Be absorbers
  - suggested by M. Zisman
  - (0.02m LiH⇒ 0.0124m Be)

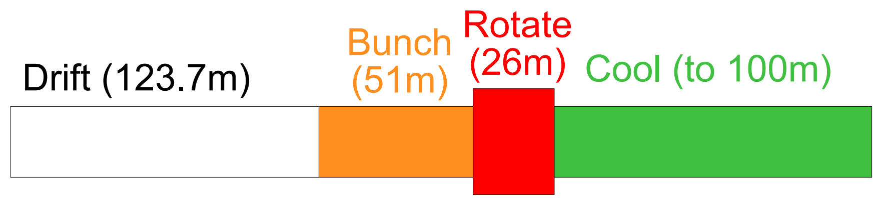
- Performance somewhat worse
  - Cooling less

  (ε_{tr} ~0.0093; LiH has 0.0073)
- Best is ~0.21μ/p within cuts after 80m cooling
  - (where LiH has ~0.25 at 100m)
- Be absorbers could be rf windows
- H_2 gas could also be used
  - Gas-filled cavities (?)

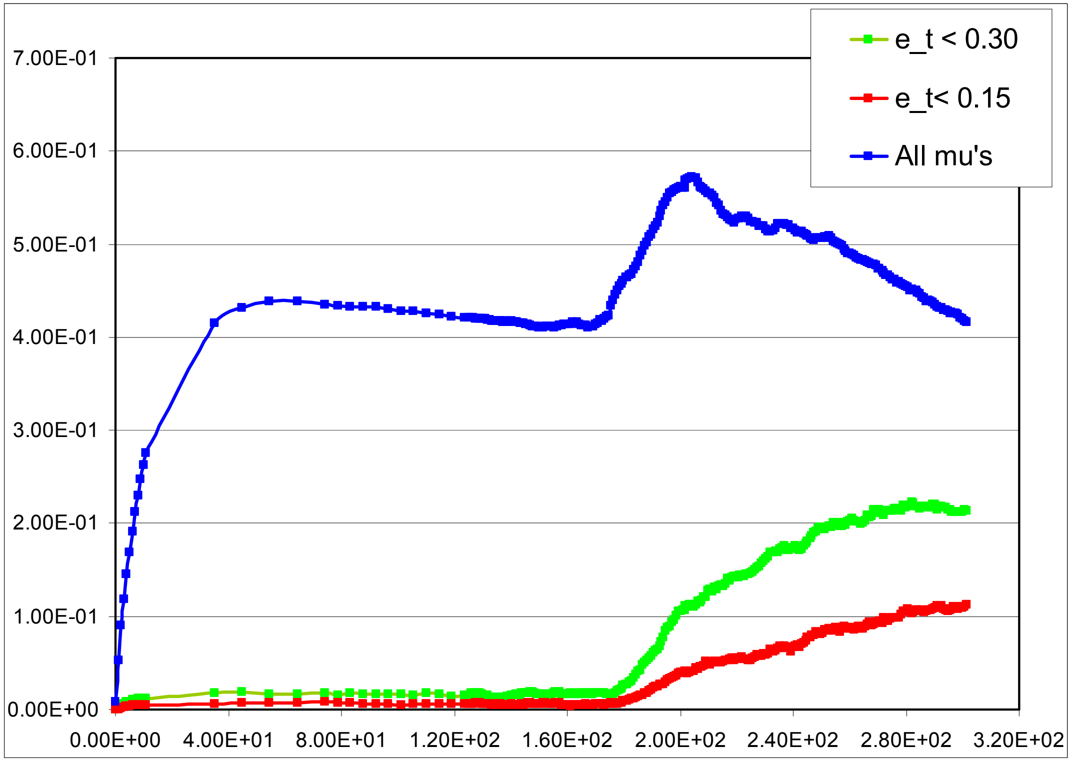


Shorter bunch Rotator

- Drift –123.7m (a bit longer)
- Bunch –51m
  - $V' = 3(z/L_B) + 3\,(z/L_B)^2$ MV/m
  - $\delta(1/\beta) = 0.0079$



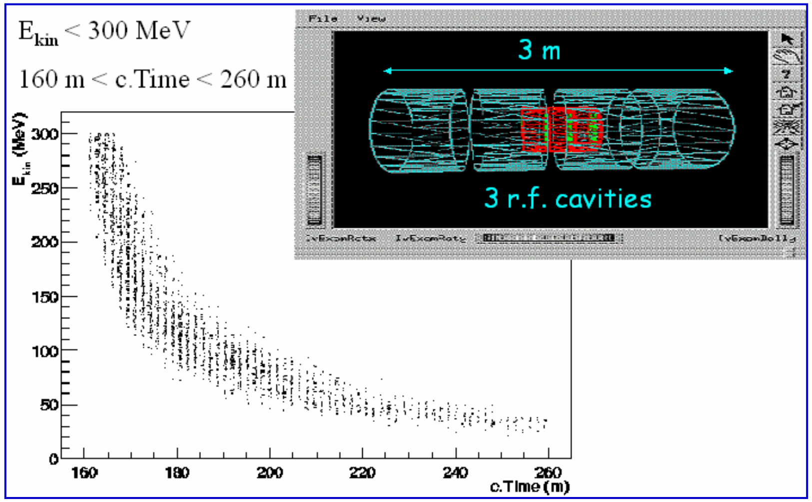
- φ–E Rotate – 26m –
  - 12 MV/m (× 2/3)
  - $P_1 = 280$, $P_2 = 154$ $\delta V = 18.1$
  - (Also $P_1 = 219$, $P_2 = 154$, $\delta V = 13.06$)
- Match and cool (100m)
  - $V' = 15$ MV/m (× 2/3)
  - $P_0 = 214$ MeV/c
  - 0.75 m cells, 0.02m LiH
- Obtain ~0.22 μ/p



How many rf frequencies?

- Example has new frequency every rf cavity
- Elvira and Keuss explored how many different rf cavities were needed, using Geant4
- 60 initially
  - 20 OK
  - 10 also OK, but slightly worse performance

- Need to go through this exercise for present scenario



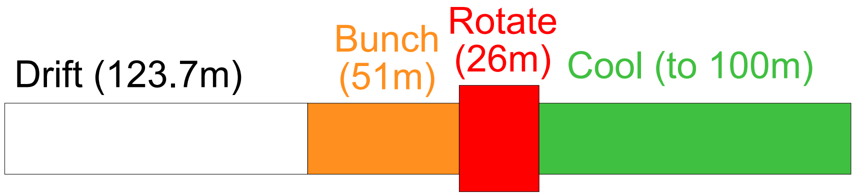
Only 20 frequencies and voltages.

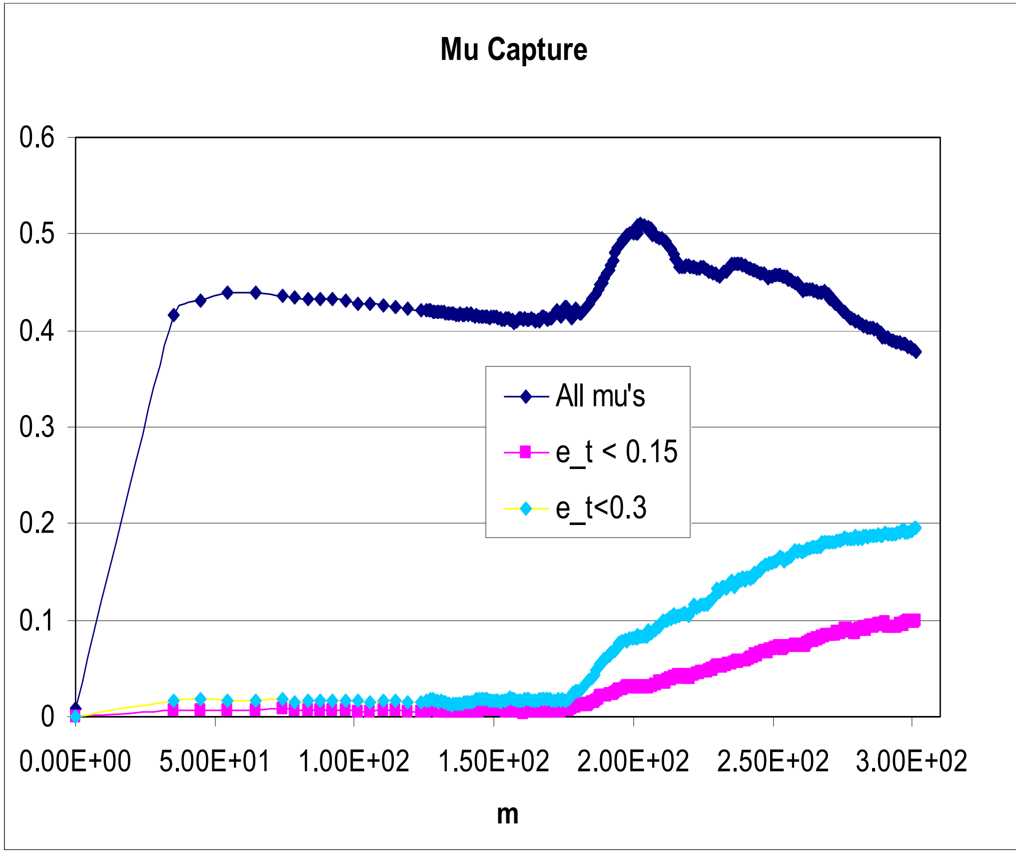
(20 equidistant linacs made of 3 cells)

Try with reduced number of frequencies

- Change frequency every 6 cells (4.5m)
- **Buncher (11 freqs.):**
  - 294.85, 283.12, 273.78, 265.04, 256.04, 249.13, 241.87, 235.02, 228.56, 222.43, 216.63 MHz
- **Rotator (6 freqs)**
  - 212.28, 208.28, 205.45, 203.52, 202.34, 201.76
- **Cooler** (200.76 MHz)

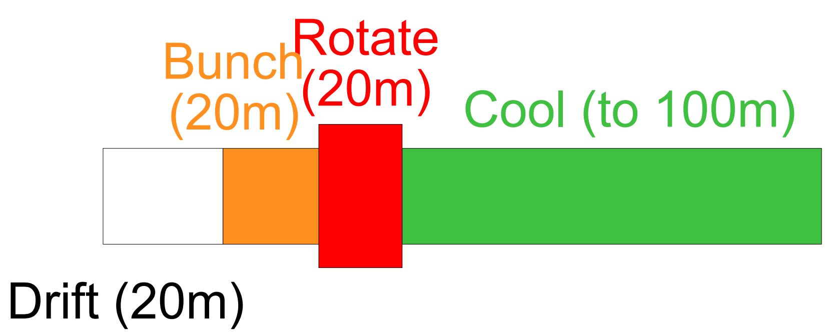
- **Obtains ~0.2 μ/p**
  - (~0.22 μ/p for similar continuous case - 105 frequencies)
- **Not** reoptimized ….
  - Phasing within blocks could be improved, match into cooling…

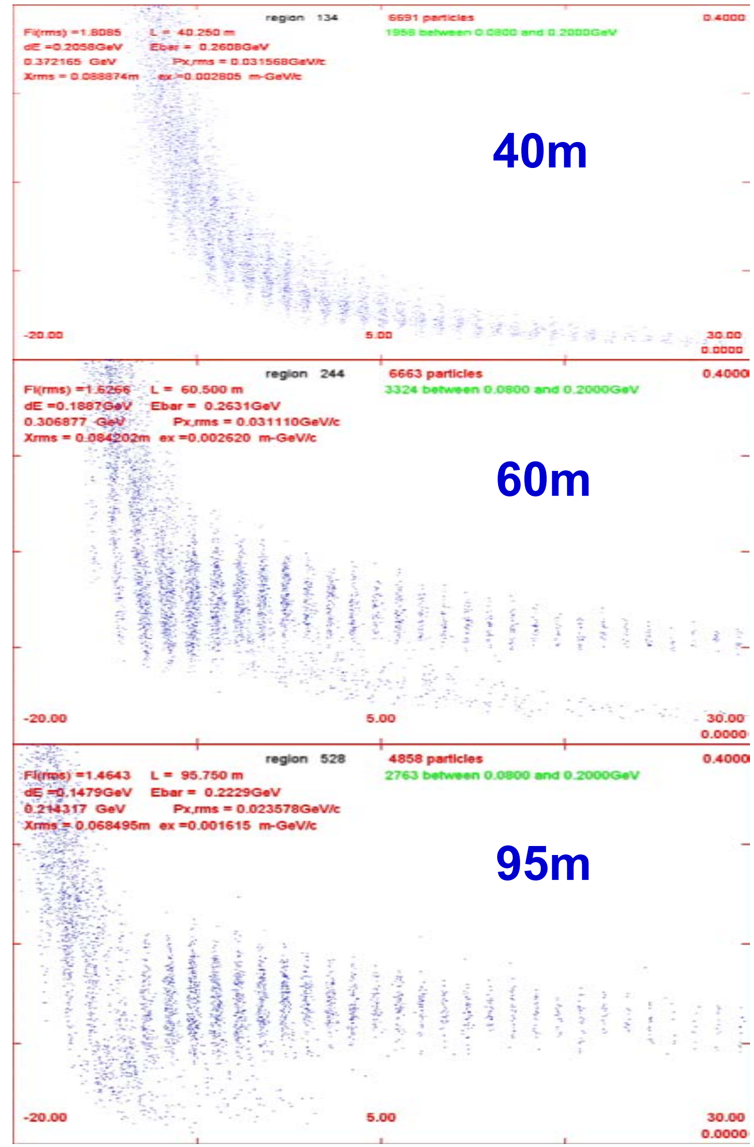




Short bunch train option

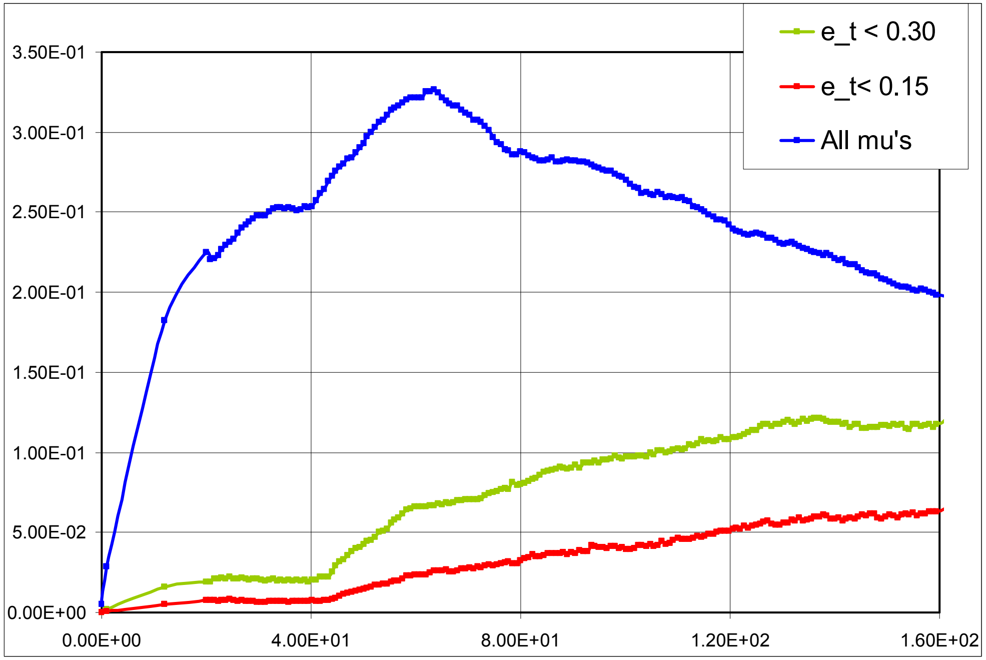
- Drift – 20m
- Bunch – 20m
  - Vrf = 0 to 15 MV/m (× 2/3)
  - P_1 at 205.037, P_2=130.94
  - δN = 5.0
- Rotate – 20m
  - δN = 5.05
  - Vrf = 15 MV/m (× 2/3)
- Palmer Cooler up to 100m
  - Match into ring cooler

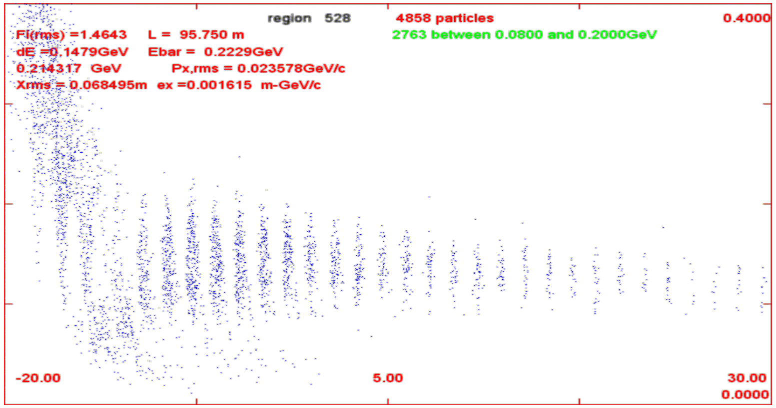


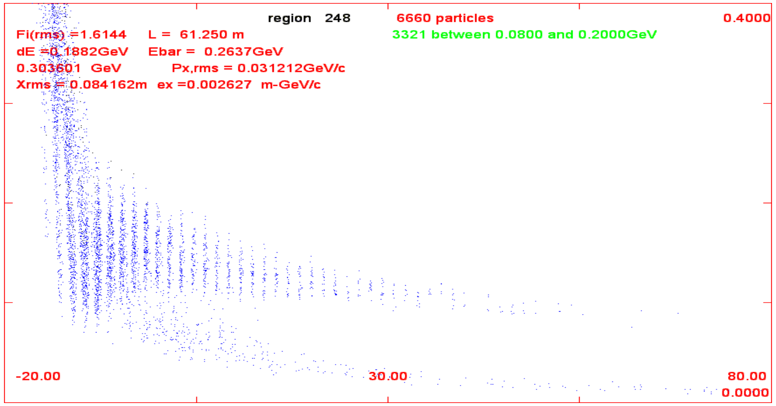


Simulation results

- ICOOL results
  - 0.12 μ/p within 0.3π cm acceptance
  - Bunch train ~12 bunches long (16m)
  - (but not 8 bunches …)
- Could match into ring cooler (C~40m)

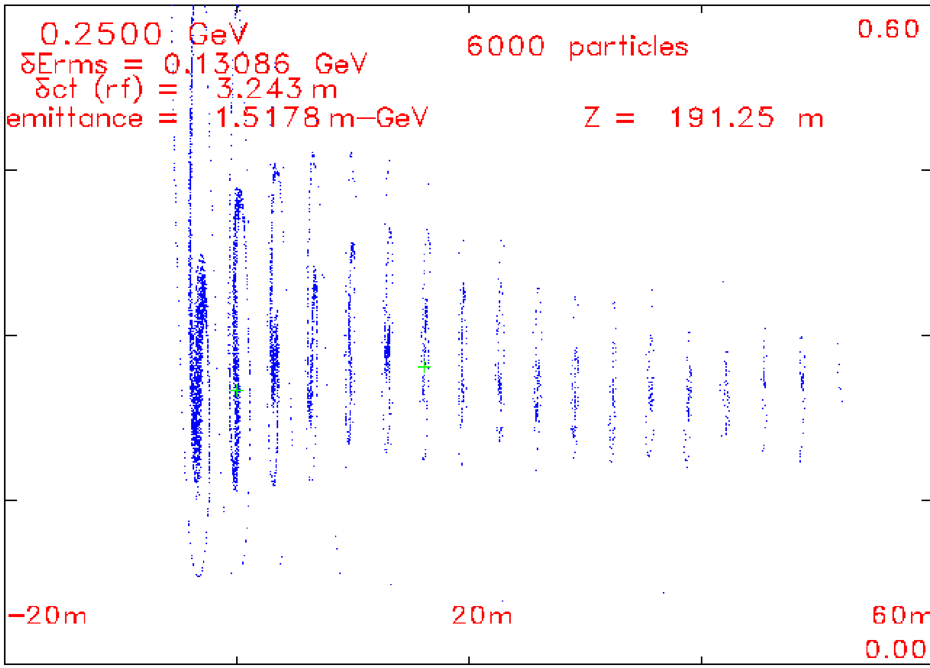




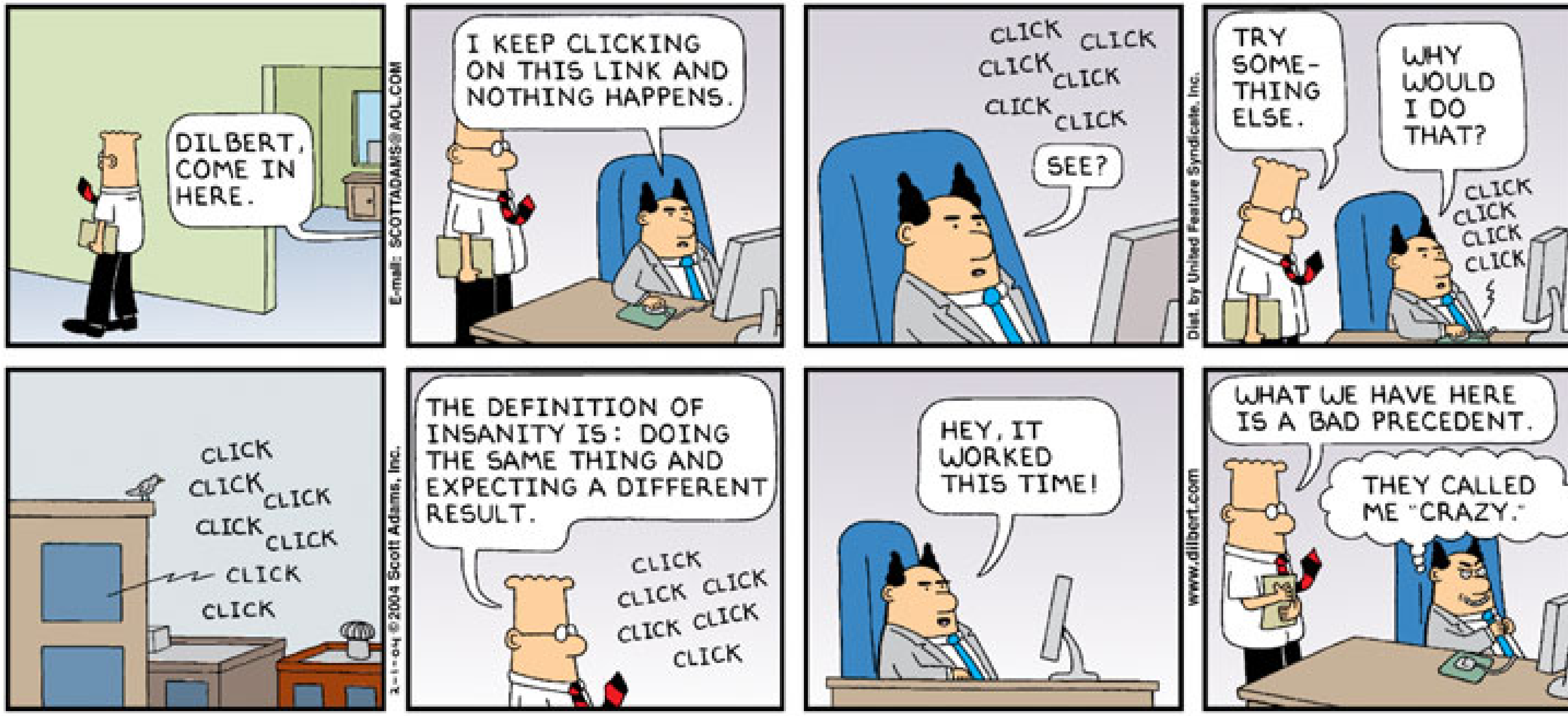


FFAG-influenced variation - 100MHz

- 100 MHz example
  - 90m drift; 60m buncher, 40m rf rotation
- Capture centered at 250 MeV
- Higher energy capture means shorter bunch train
- Beam at 250MeV ± 200MeV accepted into 100 MHz buncher
- Bunch widths < ±100 MeV
- Uses ~ 400MV of rf



Current Optimization procedures:



Optimization methods could be improved …

Summary

- High-frequency Buncher and $\phi - \delta E$ Rotator simpler and cheaper (?) than induction linac system
- Performance better (?) than study 2,

  And

- **System will capture both signs (μ^+, μ^-) !**

  (Twice as good ?)

- Method could be baseline capture and phase-energy rotation for **any** neutrino factory …

To do:

- Optimizations, Best Scenario, cost/performance …