Bunched-Beam Phase Rotation for a Neutrino Factory

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Fermilab

Outline

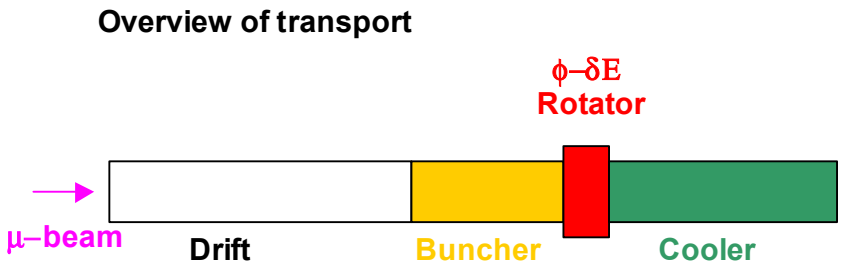
- Post MUTAC comments
- Scenario description
  - Drift
  - Buncher
  - Vernier Phase rotation
  - Match to ???
- “Vernier” rotation
  - Initial concept
  - Better than fixed frequency
- “Match” into cooling channel!!!!
  - Initial attempts
  - Compare with Study 2
  - Future plans

Post-MUTAC thoughts

- Previous discussion not quite accurate …
- Method works MUCH BETTER than described
- Method should be baseline capture and phase-energy rotation for any neutrino factory …
- "Vernier" ϕ–δE rotation is much better than single-frequency rotation …
- Need more study !!!
  - Many variations /optimizations possible, but variability will be greatly reduced after it is built

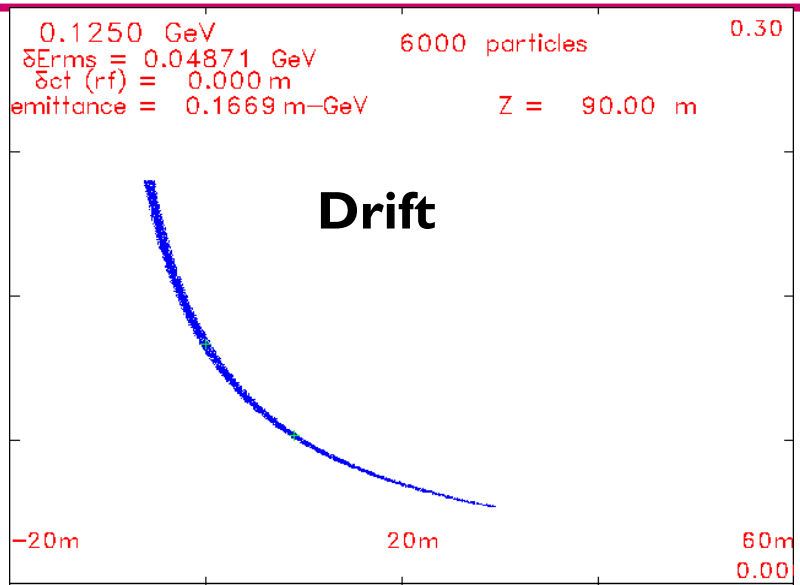
Adiabatic buncher + Vernier ϕ–δE Rotation

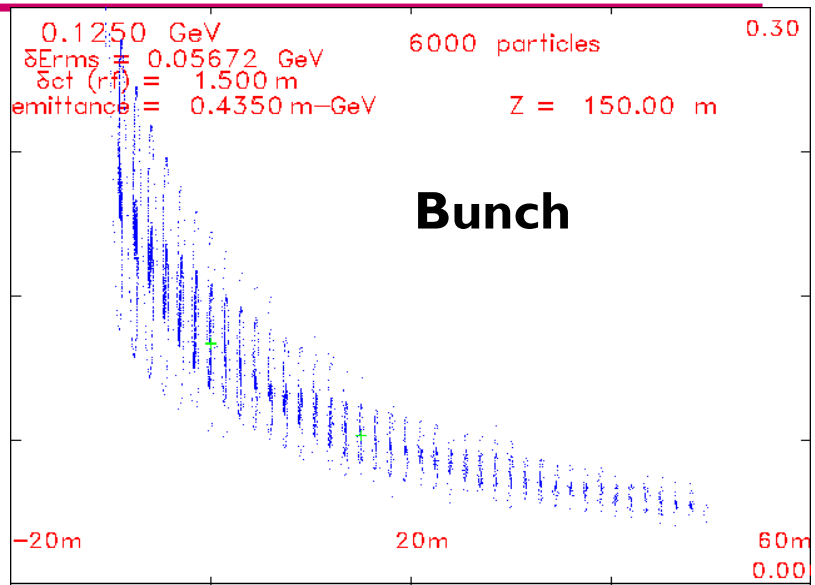
- **Drift (90m)**
  - **Allows $\pi \rightarrow \mu$ beam to decay; beam develops ϕ–δE correlation**
- **Buncher (60m) (~333→200MHz)**
  - **Bunching rf with E_0 = 125 MeV, $\delta(1/\beta) = 0.01$ { $L \times \delta(1/\beta)$ =1.5m at L_{tot} = 150m}**
  - **V_{rf} increases gradually from 0 to 4.8 MV/m**
- **ϕ–δE Rotation(~10m) (~200MHz)**
  - **Vernier rotation: E_0 = 125 MeV, E_1=77.281MeV, $10\lambda \rightarrow 10.1\lambda$ spacing**
  - **V_{rf} =10MV/m**
- **Cooler(~100m long) (~200 MHz)**
  - **fixed frequency transverse cooling system**

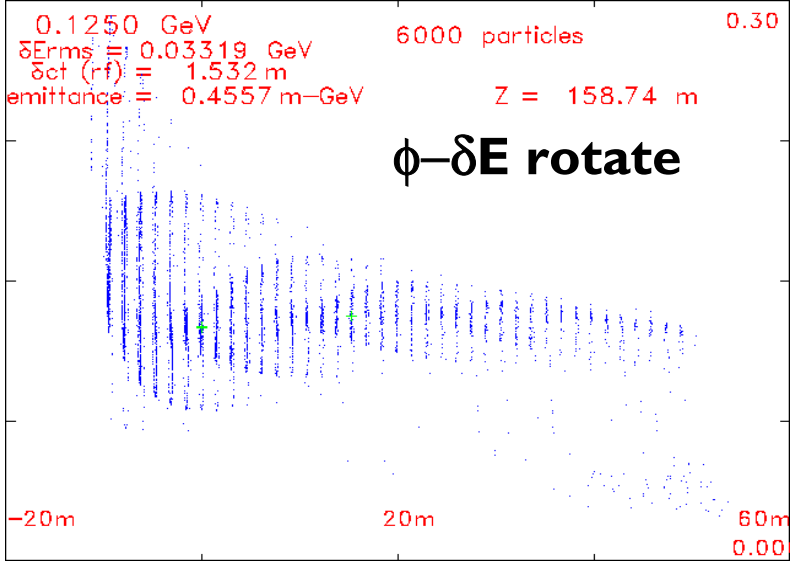


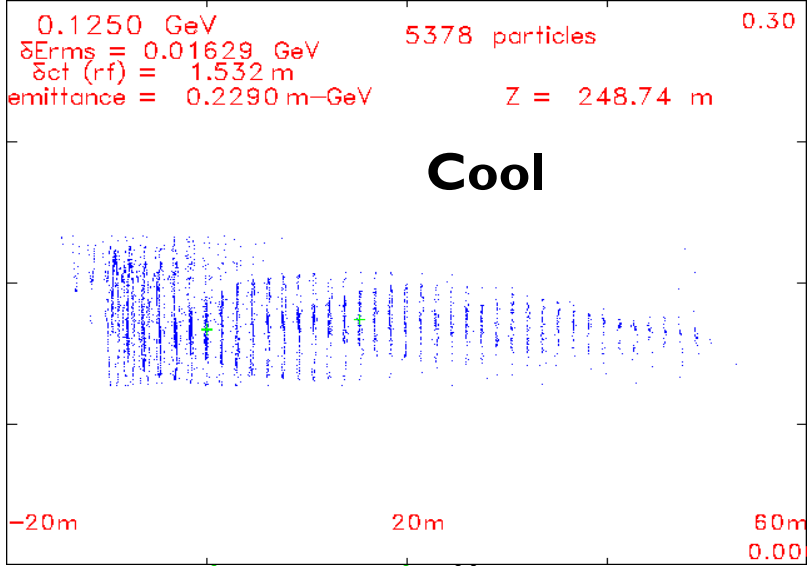
Replaces Induction Linacs with medium-frequency rf (~200MHz) !

Longitudinal Motion (updated) (1-D simulations)





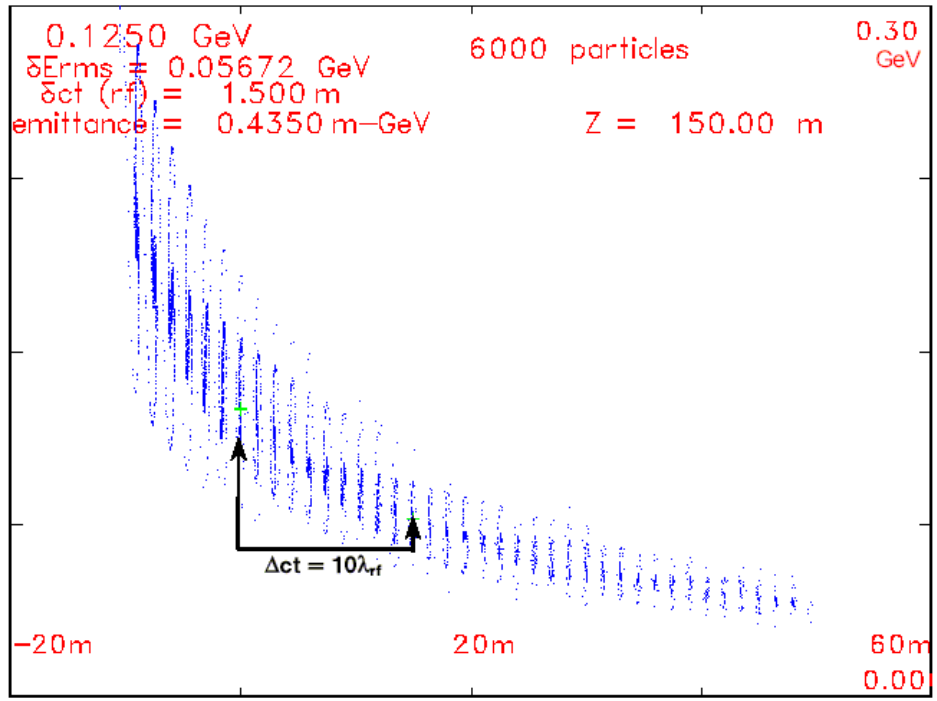




System would capture both signs (μ^+, μ^-) !!

Buncher overview

- Drift for z_D meters;
- Adiabatic bunch for $(L_{tot}-z_D)$ m
- Set reference energy 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 at energies with $1/\beta$ at integer $\delta(1/\beta)$ intervals:

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

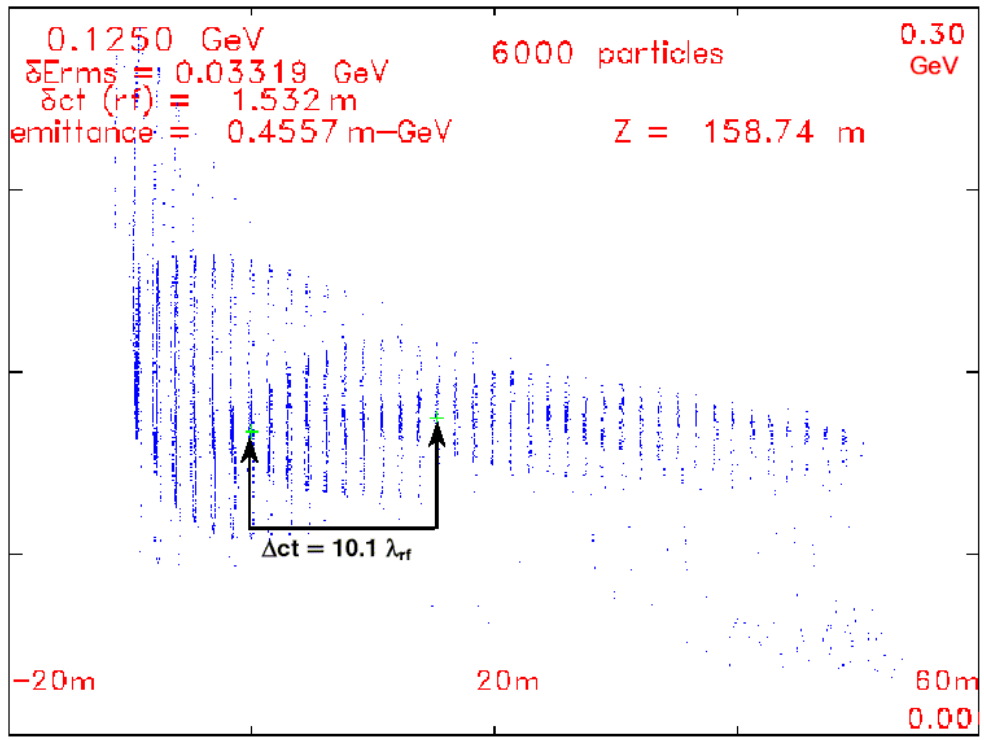
- Adiabatically increase gradient: $E_{rf}(z)=4.8\dfrac{(z-z_D)^2}{(L_{tot}-z_D)^2}\ \text{MV/m}$
- Then begin rotation:

"Vernier" ϕ–δE Rotation

- At end of bunch, choose:
  - Fixed-energy particle T_0
  - Second reference bunch T_N
  - Vernier offset δ
- Example:
  - T_0 = 125 MeV (P_0=205.37 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:

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

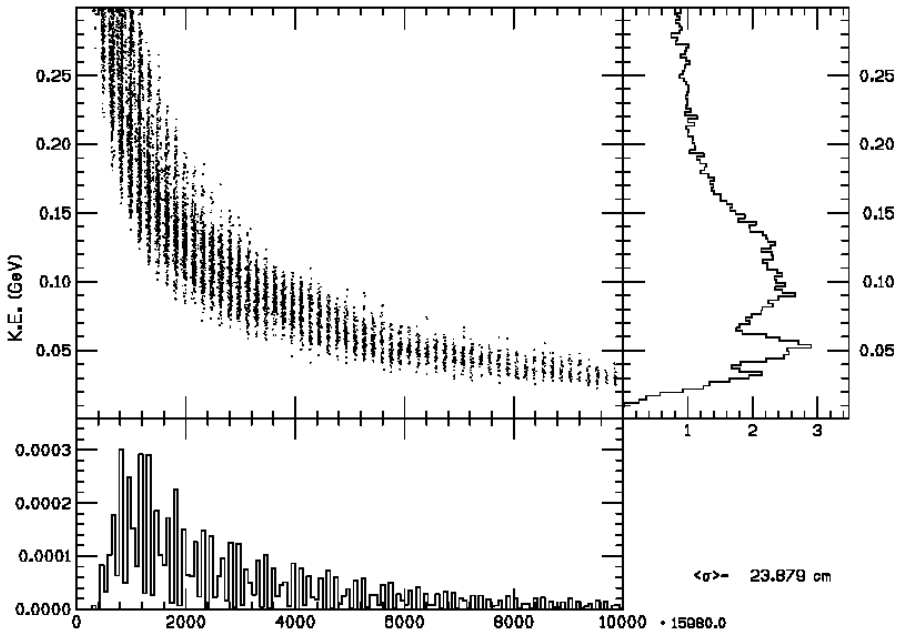
- Use E_{rf} = 10MV/m; L_{Rt}=8.74m
  - High gradient not needed …
  - Bunches rotate to ~equal energies.

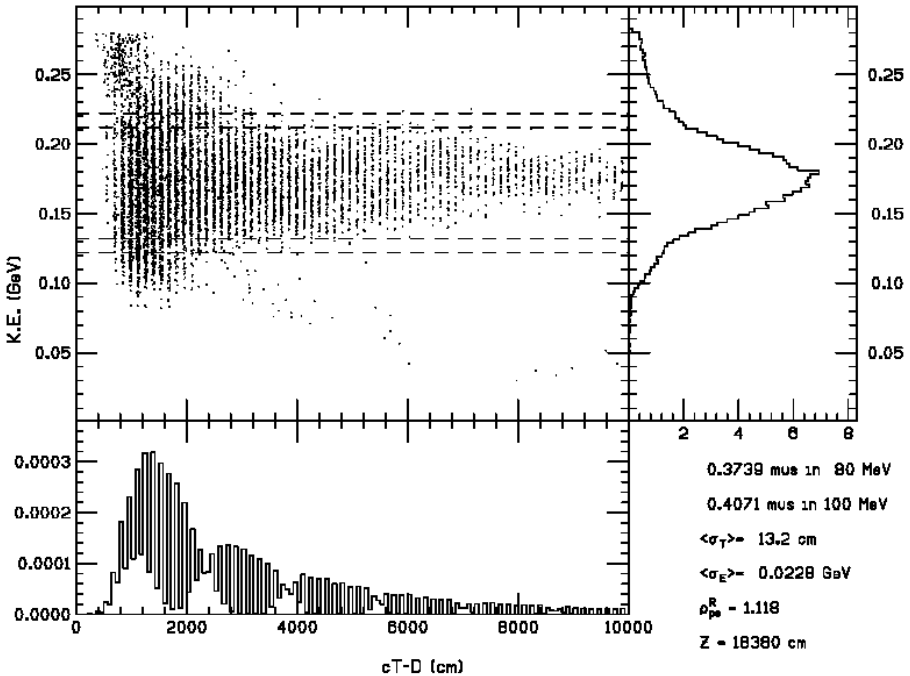


λ_{rf} : 1.485→1.517m in rotation;
Snap to $\lambda_{rf} = \Delta ct/10$ at end
($\lambda_{rf} \rightarrow$ 1.532m)

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

3-D simulation – SIMUCOOL and ICOOL





Beam after drift plus adiabatic buncher – Beam is formed into string of ~ 200MHz bunches

Beam after ~200MHz rf rotation; Beam is formed into string of equal-energy bunches; matched to cooling rf acceptance

Next step: match into cooling channel !

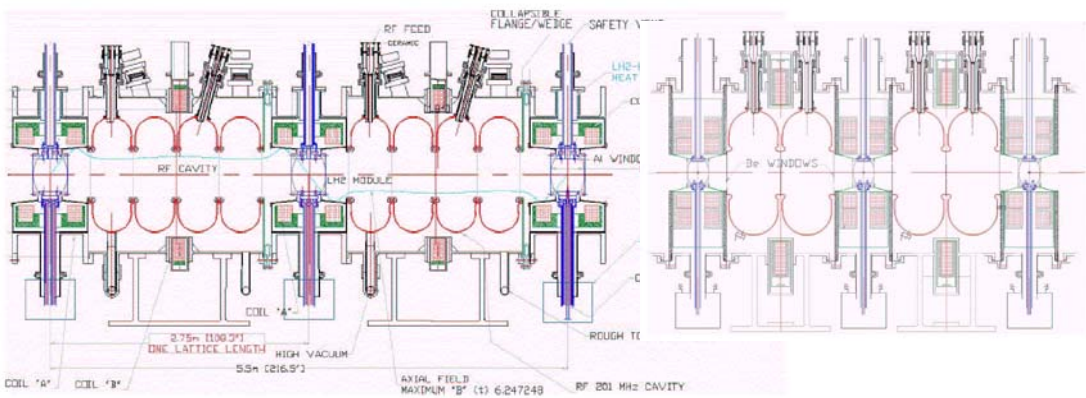
- Need to design a new cooling channel, matched to bunched/rotated beam
- Do not (yet) have redesigned/matched cooling channel

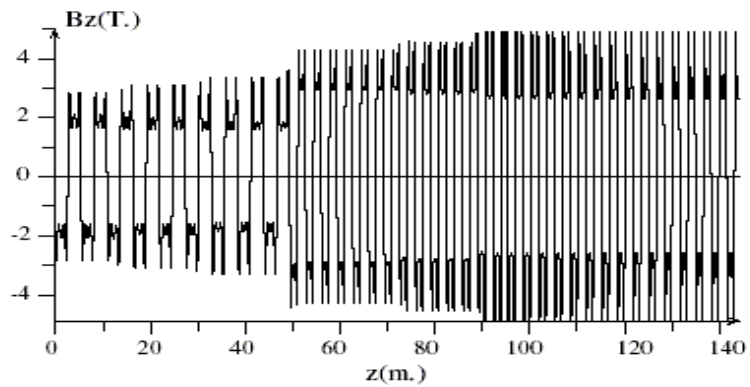
- **Use (for initial tries):**
  - ICOOL beam from end of AVG simulations
    - Beam has transverse emittance $\varepsilon_\perp \cong 0.02$
    - Better betatron match with B = 3T
  - Study II cooling channel
    - Cools (or collimates) from $\varepsilon_\perp \cong 0.012$m to $\varepsilon_\perp \cong 0.0022$m
  - Direct transfer of beam (no matching section)
    - Varied central energy; central rf phase

Caveats: Not properly matched

- This is **not** the way to design a neutrino factory
- Not properly matched in betatron and synchrotron phase space
- Cooling channel acceptance is much smaller than initial beam (no precooler)
- Correlation factors "wrong" – no field flip before cooler

- "Cooling" channel collimates as much as it cools …





Results (~ICOOL)

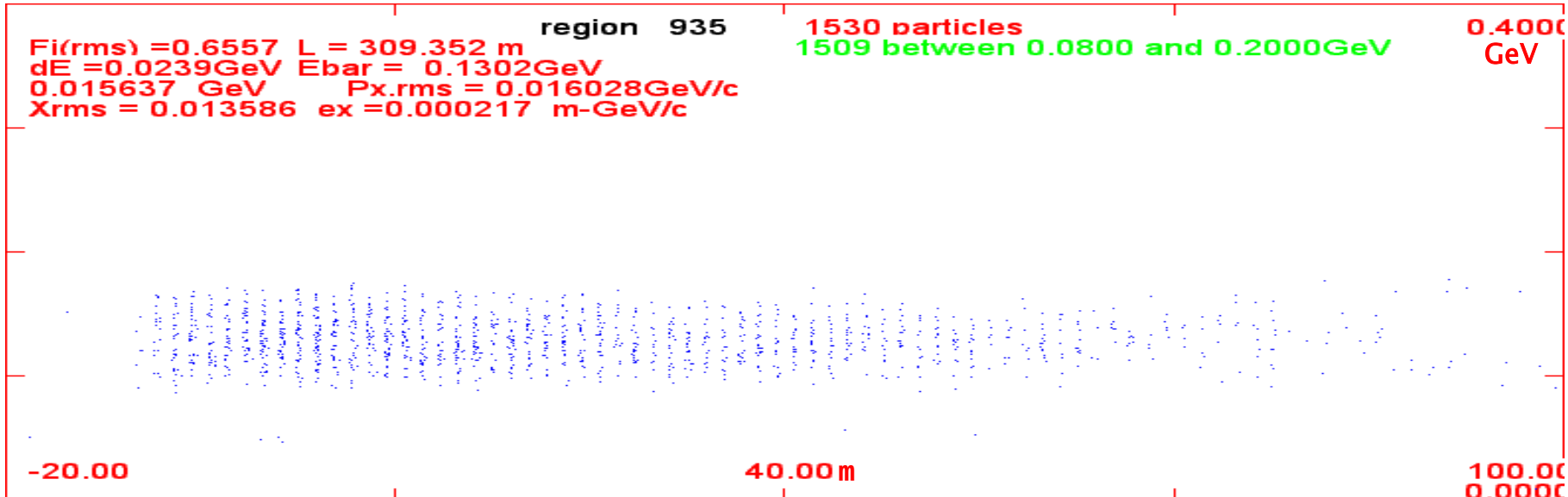
- In first ~10m, 40% of μ's from buncher are lost,

$\varepsilon_\perp \cong$ **0.020m** $\rightarrow \varepsilon_\perp \cong$ **0.012m**

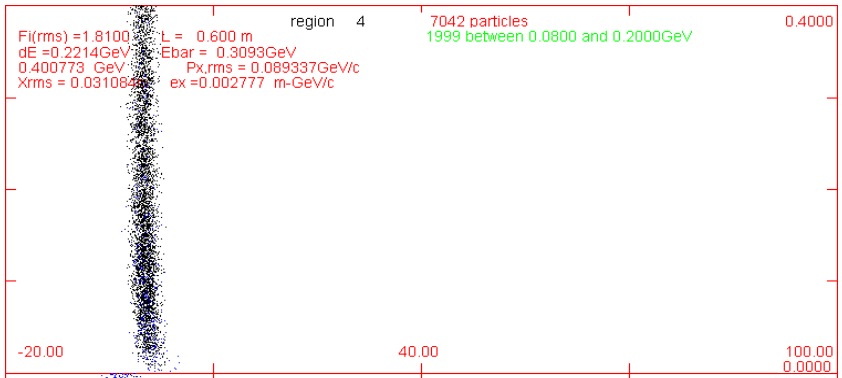
- Remaining μ's continue down channel and are cooled and scraped, $\varepsilon_\perp \rightarrow$ **~0.0022m,** similar to Study 2 simulation.

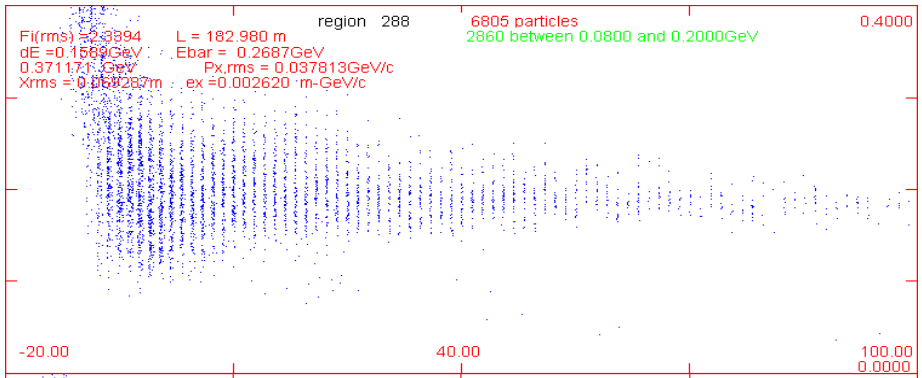
- **Best energy, phase gives ~0.22 μ's /24 GeV p**

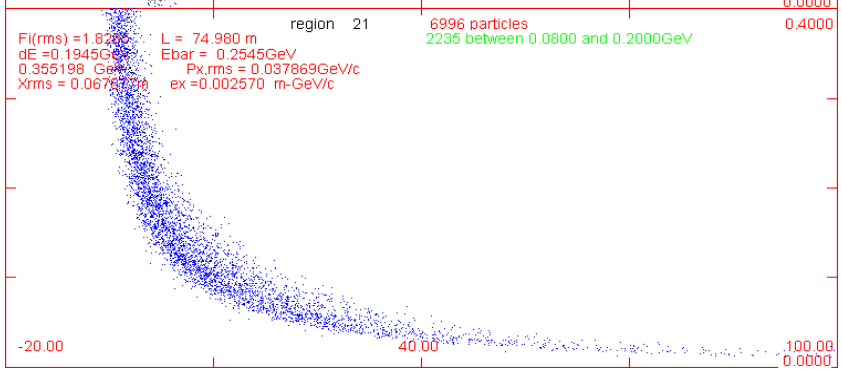
- Study II baseline ICOOL results is ~0.23 μ's/p

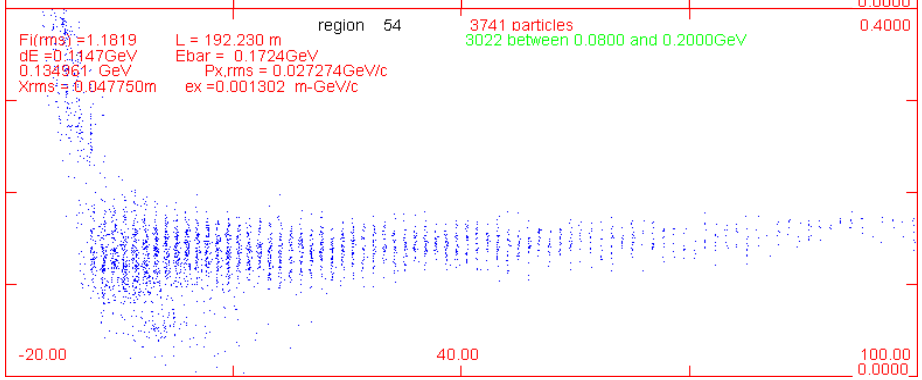


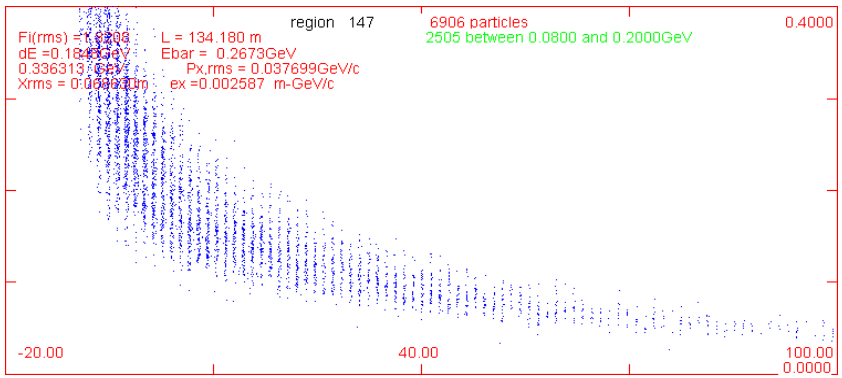
ICOOL simulation –Buncher, ϕ–δE, Cool

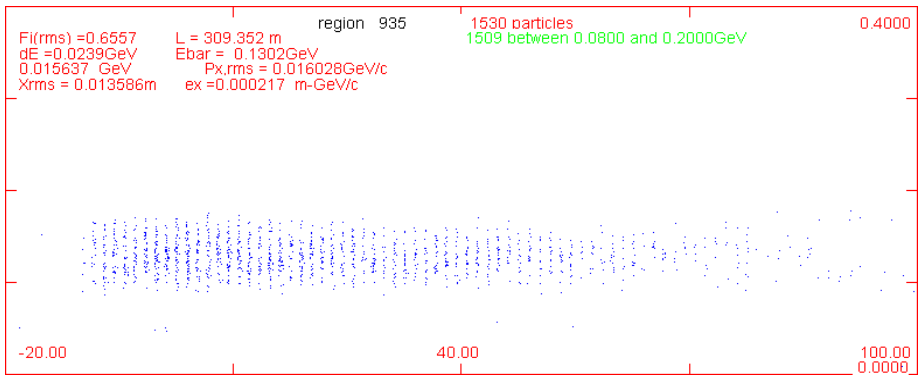






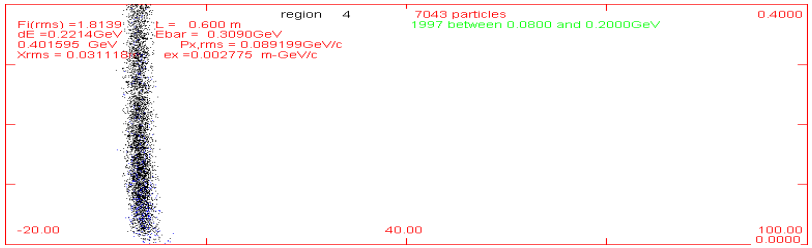


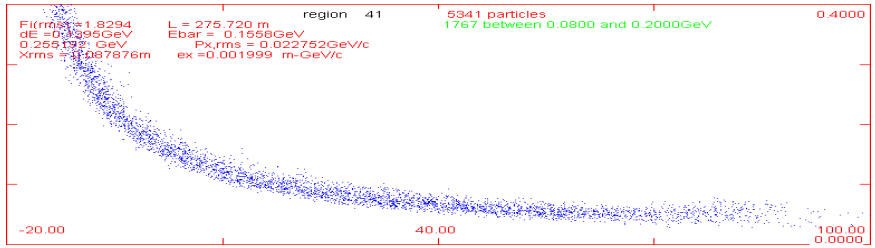


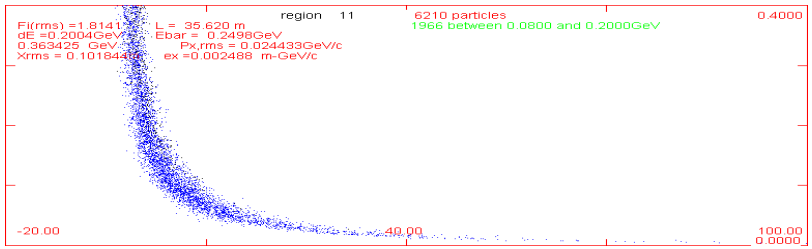


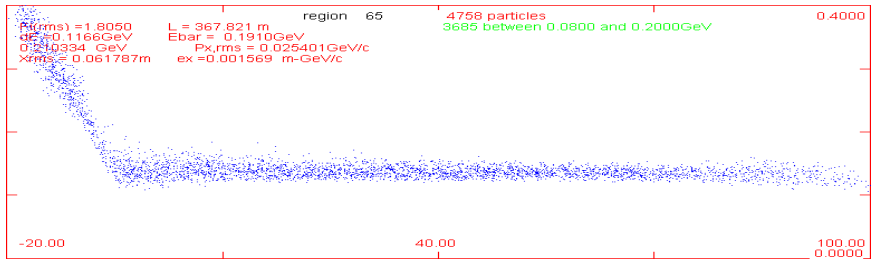
x: –20 to 100m; y: 0 to 400 MeV

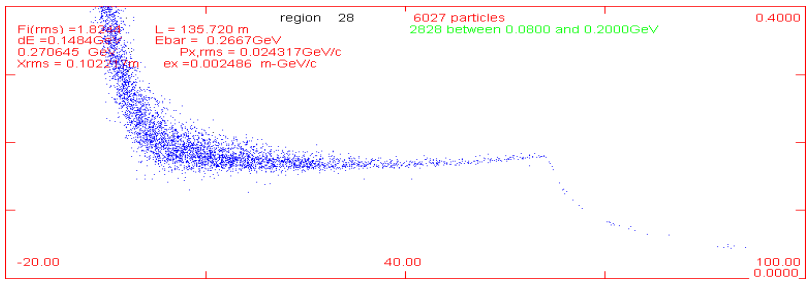
Compare with Study II (Capture + Cooling)

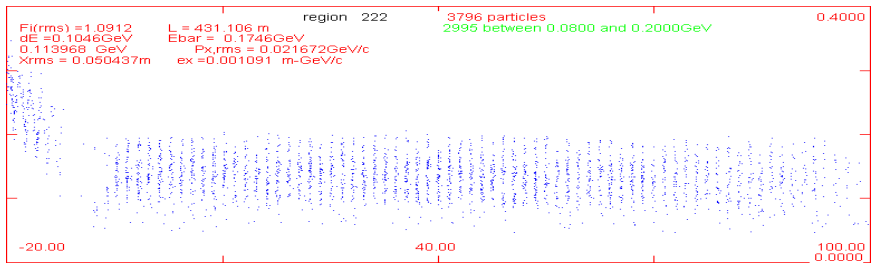


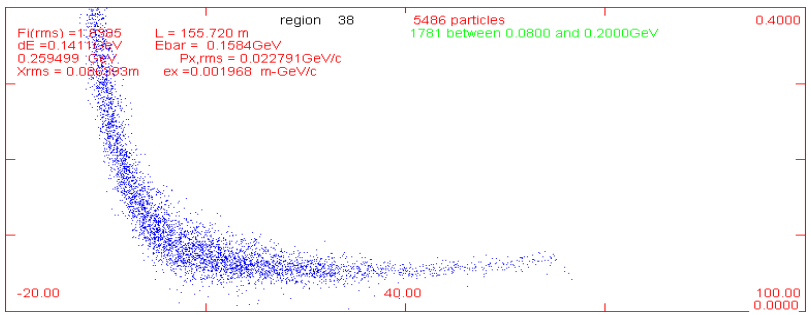


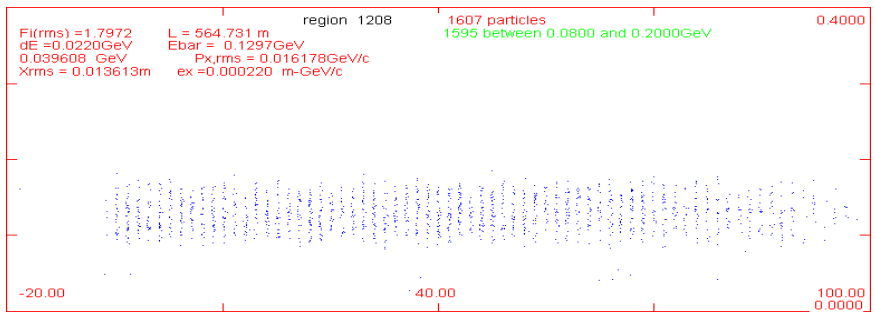












x: –20 to 100m; y: 0 to 400 MeV

Summary

- High-frequency Buncher and ϕ–δE Rotator simpler and cheaper than induction linac system
- Performance as good (or almost …) as study 2, (or better ?)

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

  (Twice as good ??)
- **To do:**
  - Complete simulations with **matched** cooling channel!
  - Optimizations, Scenario reoptimization
- **Other Variations:**
  - Shorter bunch trains (OK in 1D), quad focussing, lower rf frequency(OK in1-D) , collider parameters …

rf Buncher-Rotator Comments

- Not really “high-frequency”
  - Can work just fine for 50, 100, 200, 400 MHz …
- Not really “variable-frequency”
  - rf frequency changes along the transport; each cavity is fixed frequency
- “Adiabatic” ??
  - Buncher is quasi-adiabatic; ϕ–δE rotation is not …
- “Faster, Cheaper, Better”
  - probably

MuTAC results