Bunched-Beam Phase Rotation - Ring Coolers? - FFAGs?

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Fermilab

Outline

- Introduction
- Study 2 scenario
  - Induction linac phase rotation + 200 MHz buncher
- "High-frequency" Buncher and ϕ–δE Rotation
  - Concept
  - 1-D, 3-D simulations
  - Cost guesstimates …
- Continuing Studies …
  - Variations
  - Matching, Optimization $\Rightarrow$ Study 3
- For FFAG ν-Factory injection ??
  - Lower frequencies, larger energy spreads ??

Neutrino Factory Baseline Design

- Feasible, but expensive
- Find ways to reduce costs …

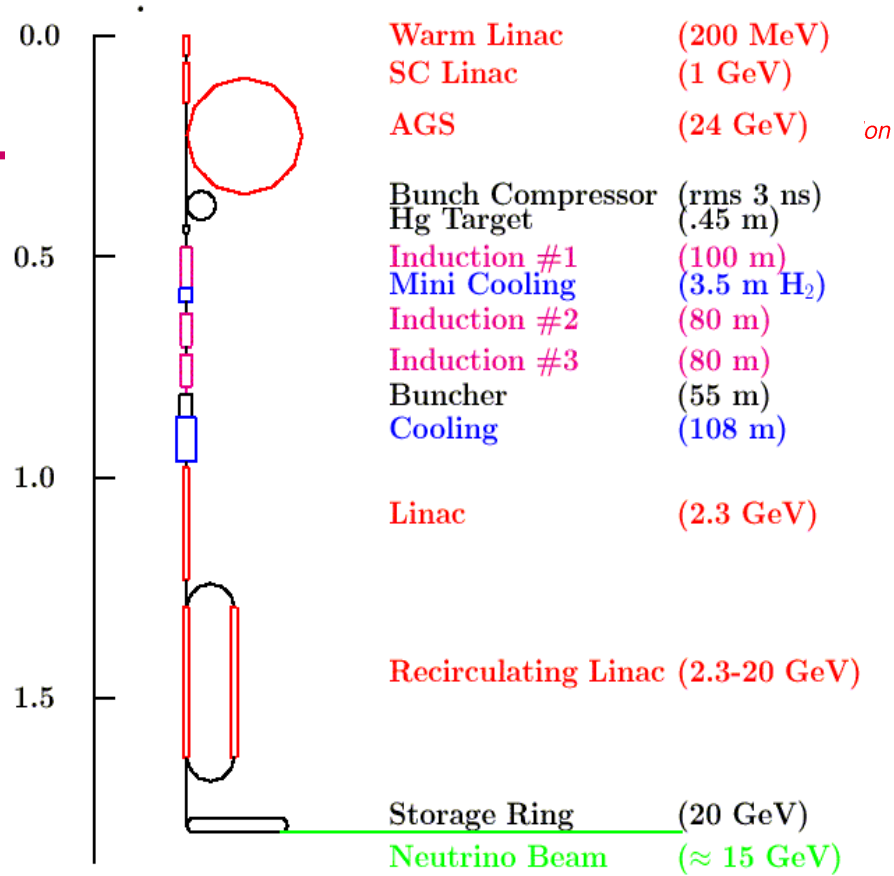
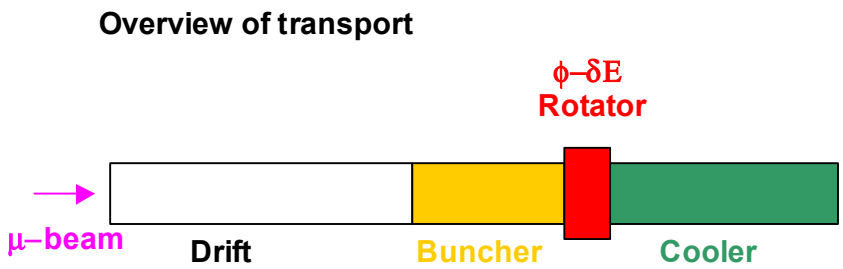


Table A.1: Construction Cost Rollup per Components for Study-II Neutrino Factory. All costs are in FY01 dollars.

System	Magnets ($M)	RF power ($M)	RF cav. ($M)	Vac. ($M)	PS ($M)	Diagn. ($M)	Cryo ($M)	Util. ($M)	Conv. Facil. ($M)	Sum ($M)
Proton Driver	5.5	7.0	66.1	9.8	26.6	2.2	28.5		21.9	167.6
Target Systems	30.3			0.8	3.5	8.0	18.8		30.2	91.6
Decay Channel	3.1			0.2	0.1	1.0	0.2			4.6
Induction Linacs	35.0		90.3	4.4	163.3	3.0	3.6		19.5	319.1
Bunching	48.8	6.5	3.2	2.7	2.1	5.0	0.3			68.6
Cooling Channel	127.6	105.6	17.7	4.3	4.8	28.0	9.5		19.5	317.0
Pre-accel. linac	46.3	68.4	44.1	7.5	3.0	6.0	13.6			188.9
RLA	129.0	89.2	63.4	16.4	5.6	4.0	28.9		19.0	355.5
Storage Ring	38.5			4.8	2.2	29.0	4.8		28.1	107.4
Site Utilities								126.9		126.9
Totals	464.1	276.7	284.8	50.9	211.2	86.2	108.2	126.9	138.2	1,747.2

Adiabatic buncher + Vernier ϕ–δE Rotation

- **Drift** (90m)
  - $\pi \rightarrow \mu$ decay;
    beam develops ϕ–δE correlation



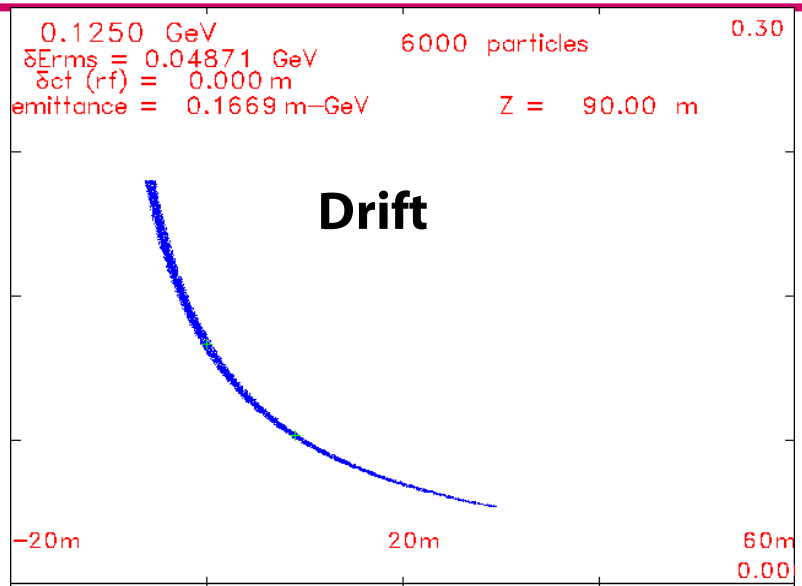
- **Buncher** (60m) (~333→200MHz)
  - Forms beam into string of bunches

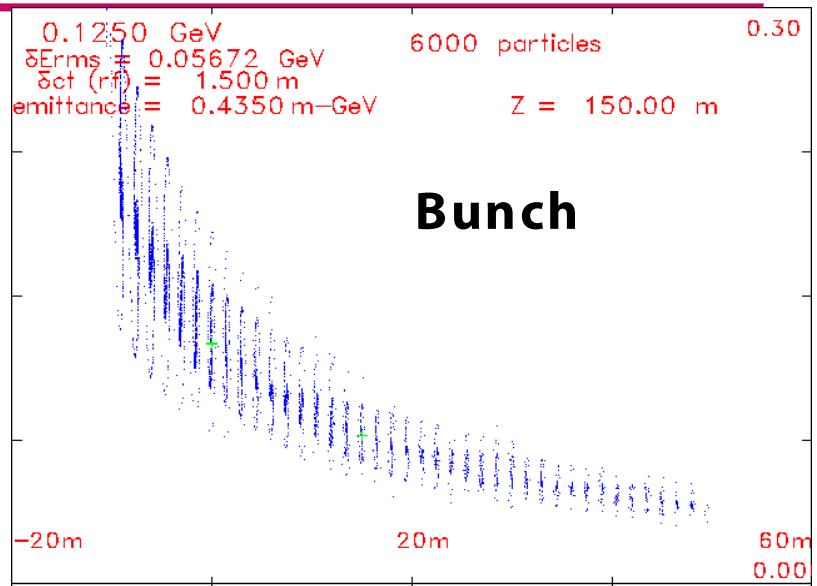
- ϕ–δE **Rotation**(~10m) (~200MHz)
  - Lines bunches into equal energies

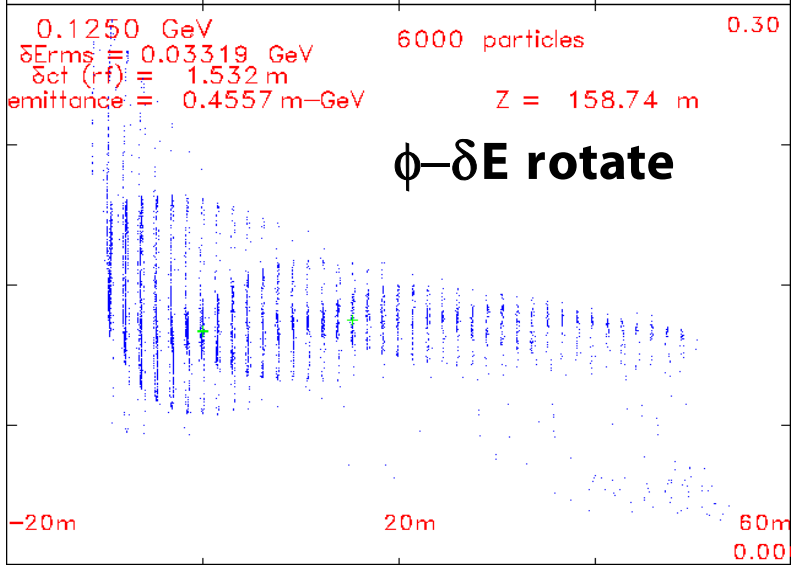
- **Cooler**(~100m long) (~200 MHz)
  - fixed frequency transverse cooling system

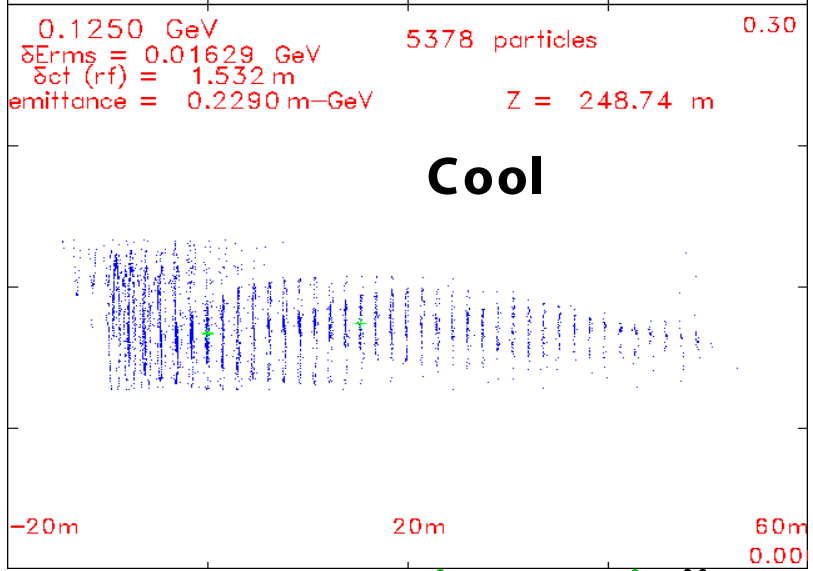
Replaces Induction Linacs with medium-frequency rf (~200MHz) !

Longitudinal Motion (1-D simulations)









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

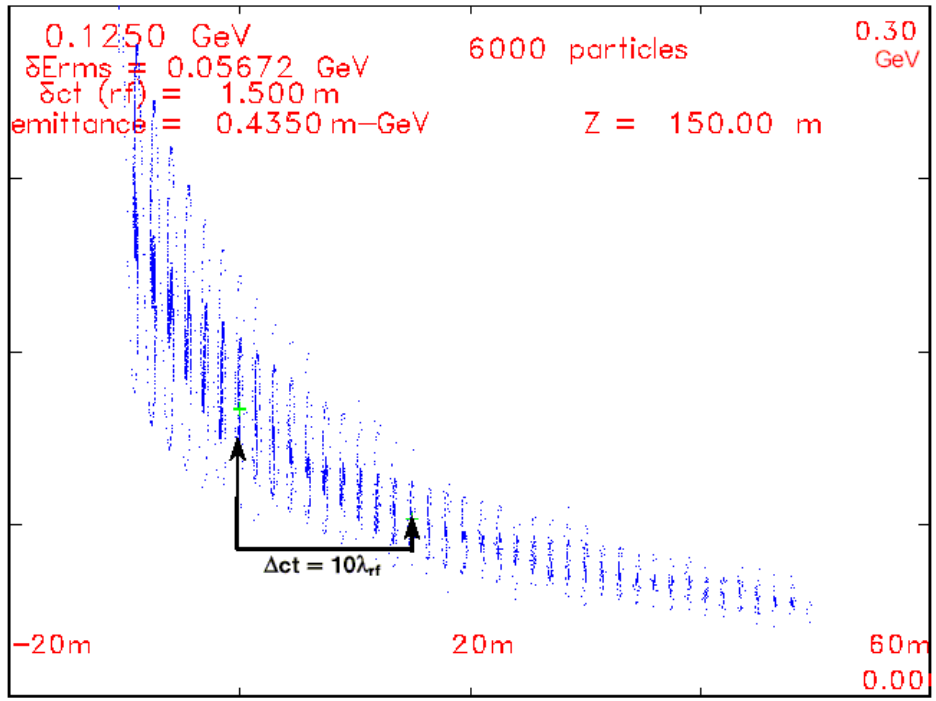
Buncher overview

- 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:

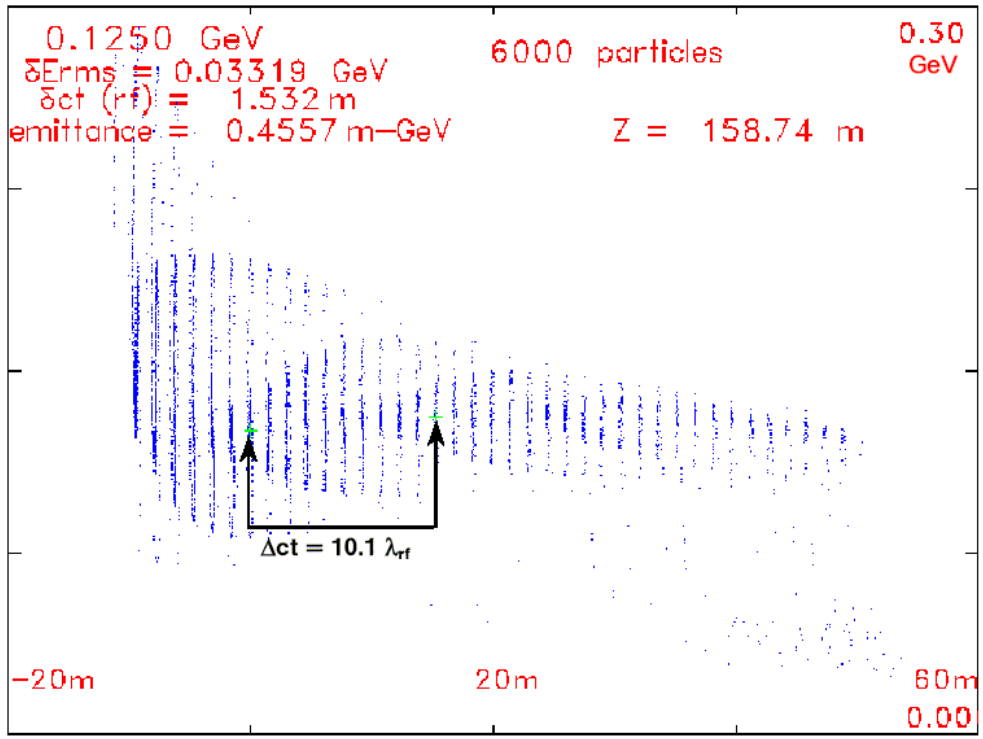
$$E_{rf}(z) = 4.8\frac{(z-z_D)^2}{(L_{tot}-z_D)^2} \quad \text{MV/m}$$

"Vernier" ϕ–δE 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;
$\lambda_{rf} = \Delta ct/10$ at end

($\lambda_{rf} \rightarrow$ 1.532m)

Nonlinearities cancel:
$T(1/\beta)$; $\sin(\phi)$

Key Parameters

- General
  - Muon capture momentum (200MeV/c?) 400MeV/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_B)
  - Vernier offset : N_B, δ_V
  - Rf gradient V_R'
- Cooling channel / Accelerator ???

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
  - **Study 2 cooling channel**
  - Direct transfer of beam (no matching section)

Results (~ICOOL)

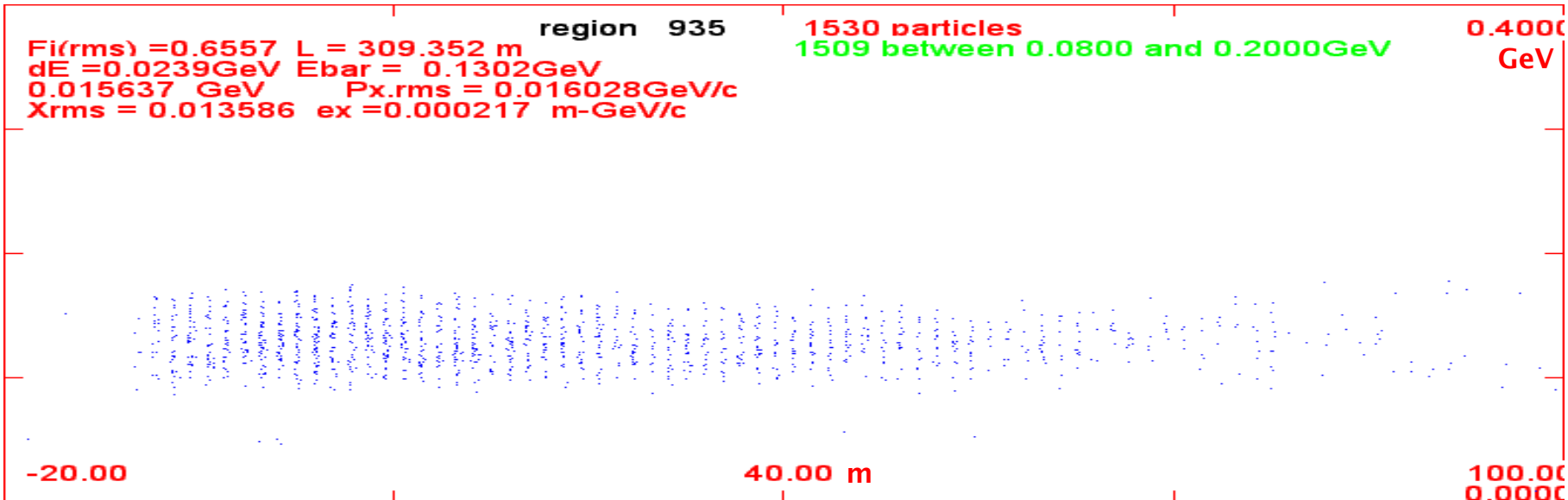
- In first ~10m, 40% of μ's from buncher are lost,

$\varepsilon_\perp \cong$ **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.

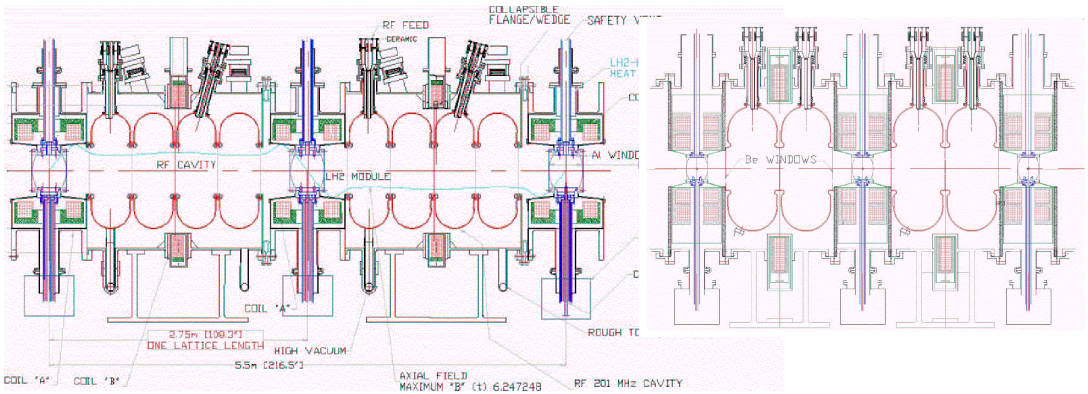
- **Best energy, phase gives ~0.22 μ's /24 GeV p**

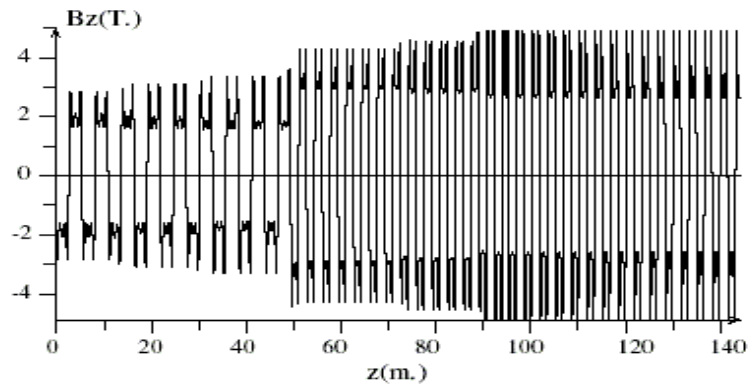
- Study 2 baseline ICOOL results is ~0.23 μ's/p



Caveats: Not properly matched

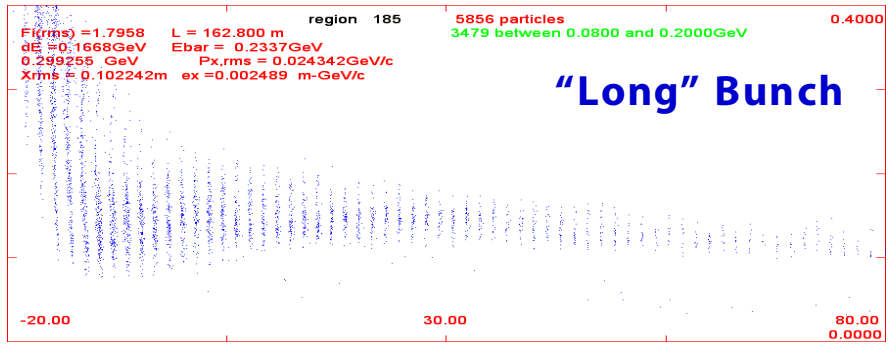
- This is **not** the way to design a neutrino factory
- Not properly matched in phase space
- Cooling channel acceptance is too small (add precooler ?)
- Correlation factors "wrong"
- "Cooling" channel collimates as much as it cools …

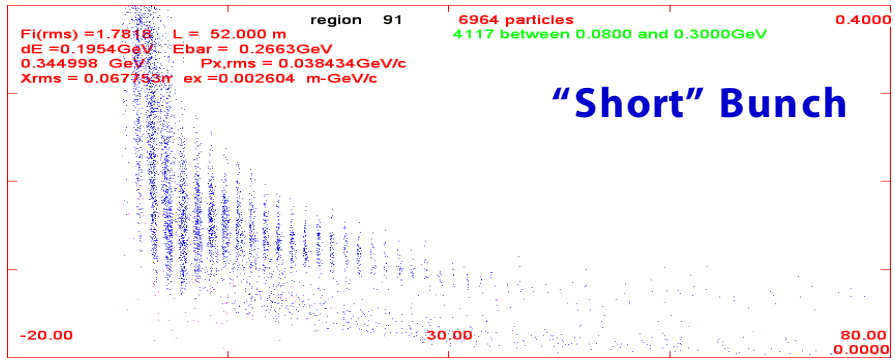


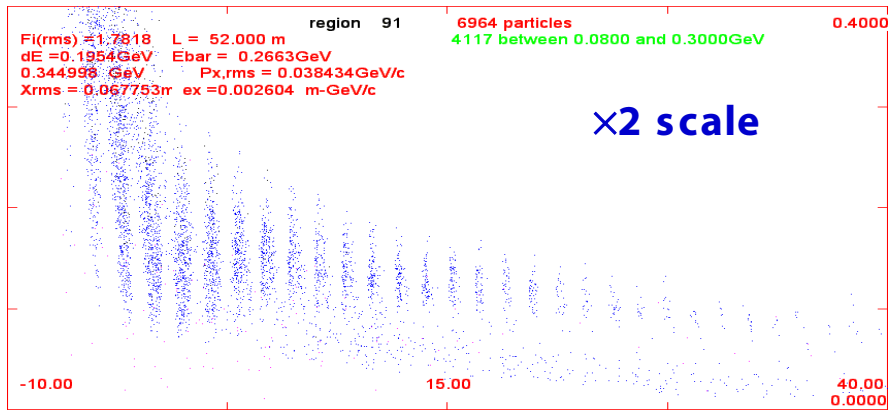


Shorter bunch train (for Ring Cooler ?)

- Ring Cooler requires shorter bunch train for single-turn injection – ~30m?
- 200MHz example
  - –reduce drift to 20m (from 90)
  - –reduce buncher to 20m
  - Rotator is ~12m
- ~85% within <~30m
- Total rf voltage required is about the same (~200MV)
- RFOFO cooler wants 12m bunch train !!!

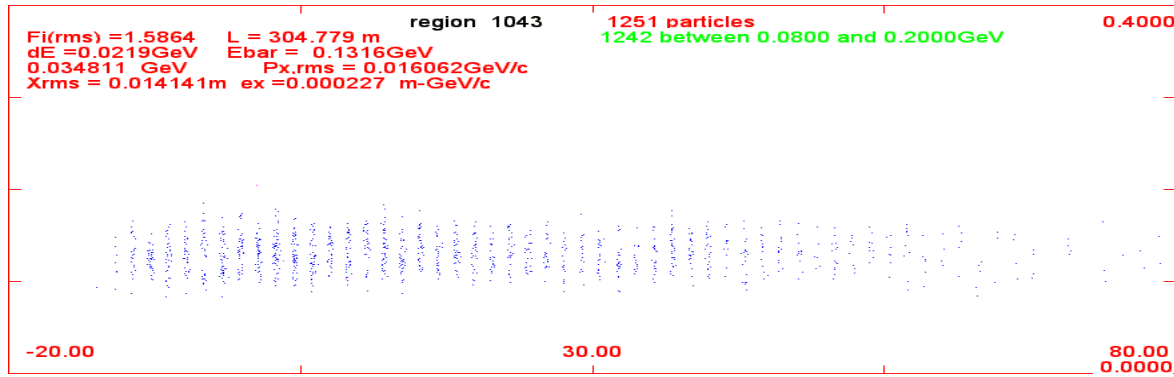


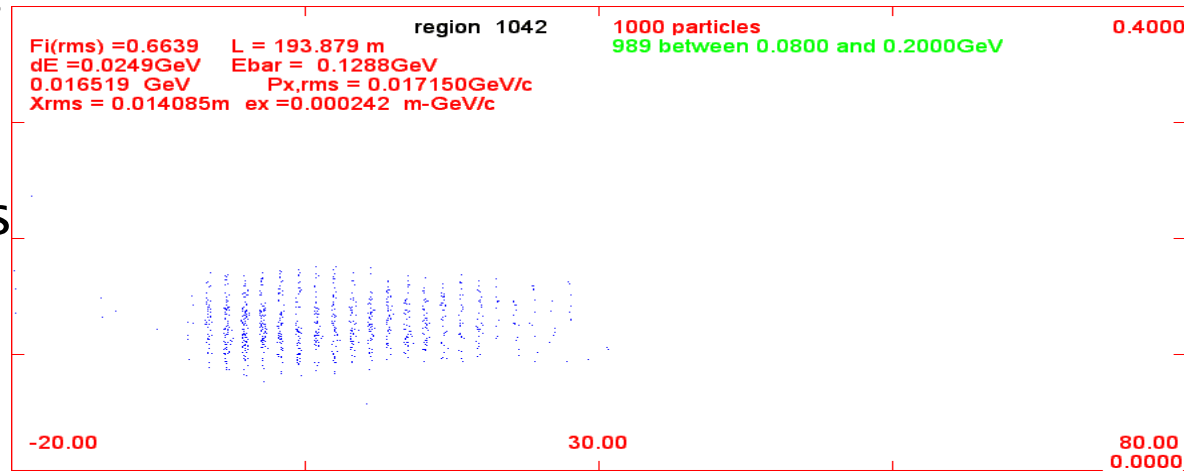




“Match” into “cooling channel”

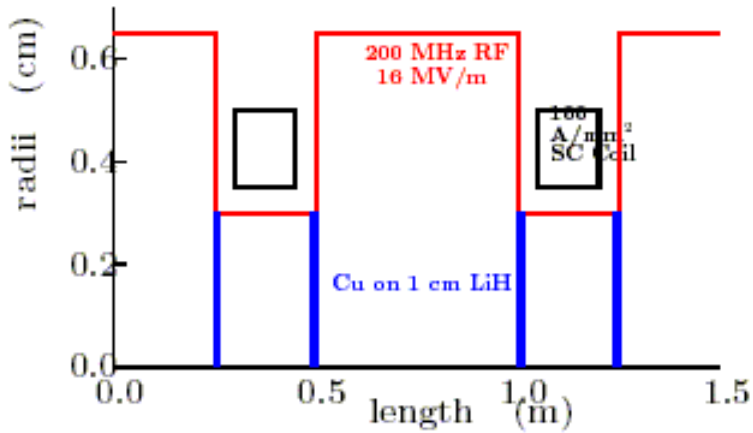
- Place beam output into Study 2 cooling channel
- No “matching”
- Long bunch case accepts ~0.20 μ/p
- Short bunch case accepts ~0.145 μ/p
- (Study 2 example is 0.23 μ/p in these units)

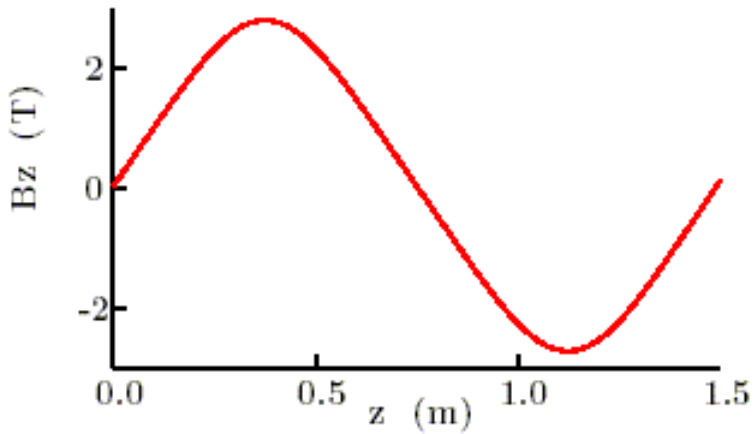




New Cooling Channel needed

- 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 unmatched

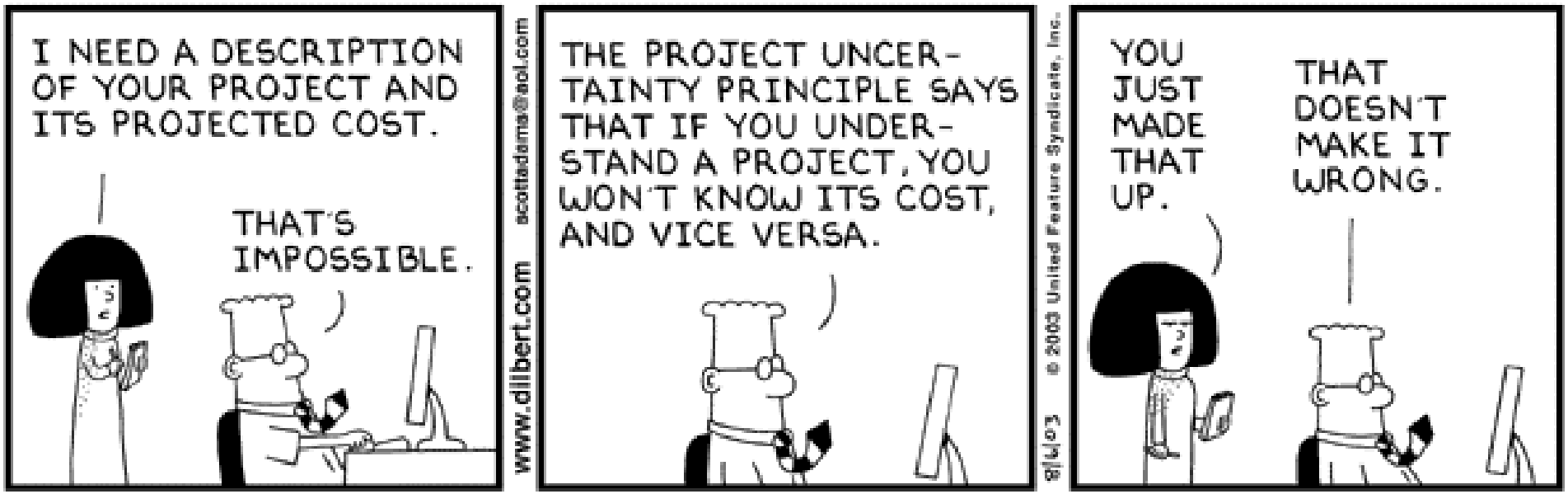




To do

- **Move to more realistic models**
- Continuous changes in rf frequencies to stepped changes …
- 3-D fields (not solenoid + sinusoidal rf)
- **Match** into realistic cooling channels …
- Estimate/Optimize **Cost** /performance

Comment on costs

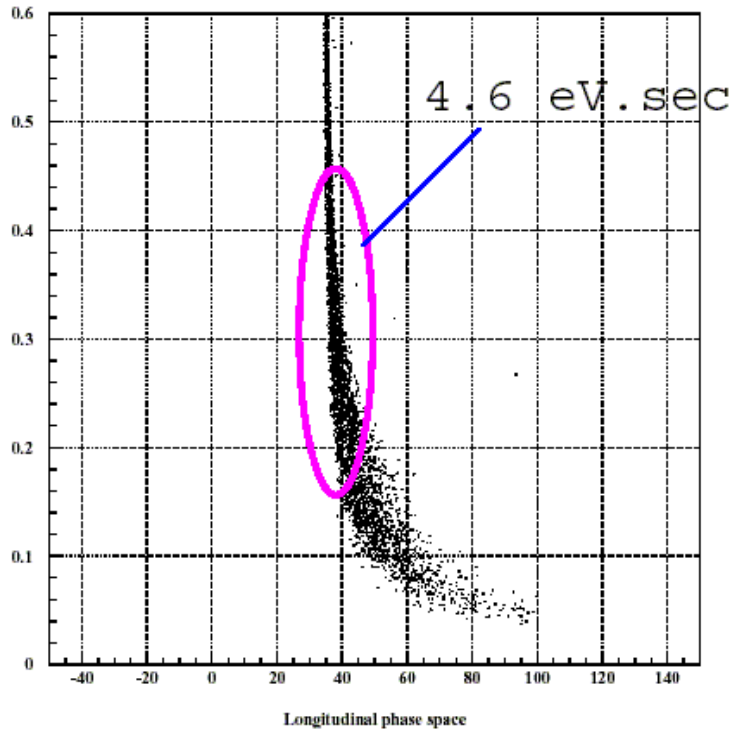


Variations/ Optimizations …

- **Many possible variations and optimizations**
  - But possible variations will be reduced after design/construction
- **Shorter bunch trains ??**
  - **For ring Coolers ?**
- **Other frequencies ??**
  - 200 MHz(FNAL) $\rightarrow$ 88 MHz ?? (CERN) $\rightarrow$??? ~44MHz
- **Cost/performance optima** for neutrino factory (Study 3?)
- **Collider ?? both signs (μ^+, μ^-) !**
- **Graduate students (MSU) (Alexiy Poklonskiy, Pavel Snopok) will study these variations; optimizations; etc…**

FFAG ν-Factory injection

- Baseline scenario is single bunch injection without ϕ-E rotation or bunch formation
- Capture is not matched to beam phase-space
- Capture is centered at higher energy than Study 2
- Requires very low-frequency bucket (~25 MHz or less)
- Rf Gradient is ~1 MV/m (or less)
- Can injection use buncher-rotator methods to improve acceptance, increase rf gradient ?



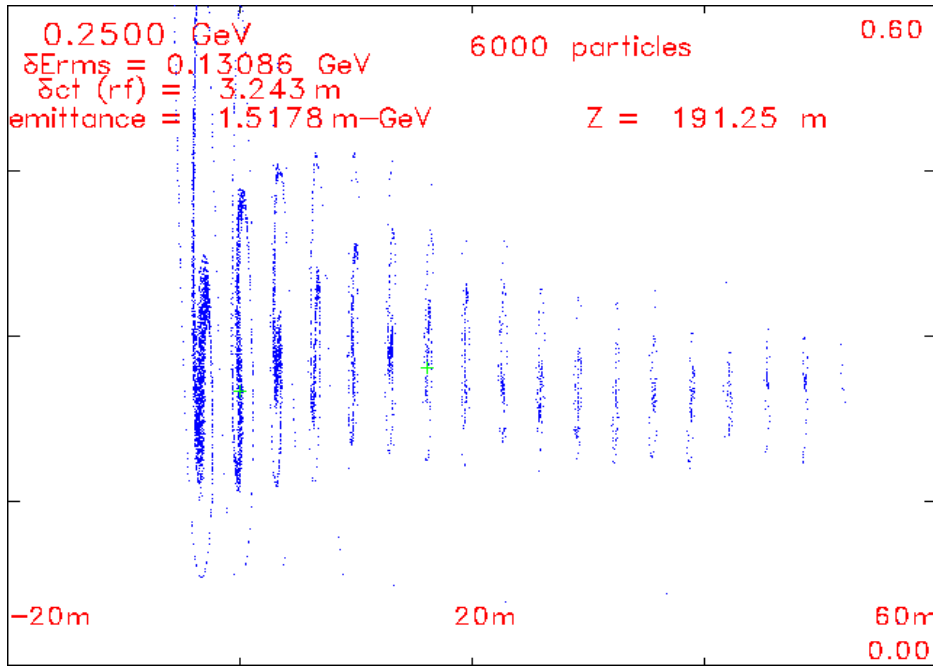
Capture is ± 150MeV, ± 12 ns

Bunch sizes for various rf scenarios

Case	Rf frequency	ΔE (MeV) ($\pm$)	Δz (m) ($\pm$)	$\pi \Delta E \Delta z / c$ (eV–s)
JNF (~300MeV)	5 MHz ??	150	3.00	4.7 (~1.0m ε_{rms})
~Study 2 (~125MeV)	200MHz	40	0.40	0.18 (~0.04m)
250 MeV	200MHz	80	0.4	0.36 (~0.08m)
125 MeV	100MHz	40	0.8	0.36 (~0.08m)
250 MeV	100MHz	80	0.8	0.72 (~0.16m)
125 MeV	50MHz	40	1.6	0.72 (~0.16m)
250 MeV	50MHz	80	1.6	1.5 (~0.32m)

FFAG-influenced variation – 100MHz

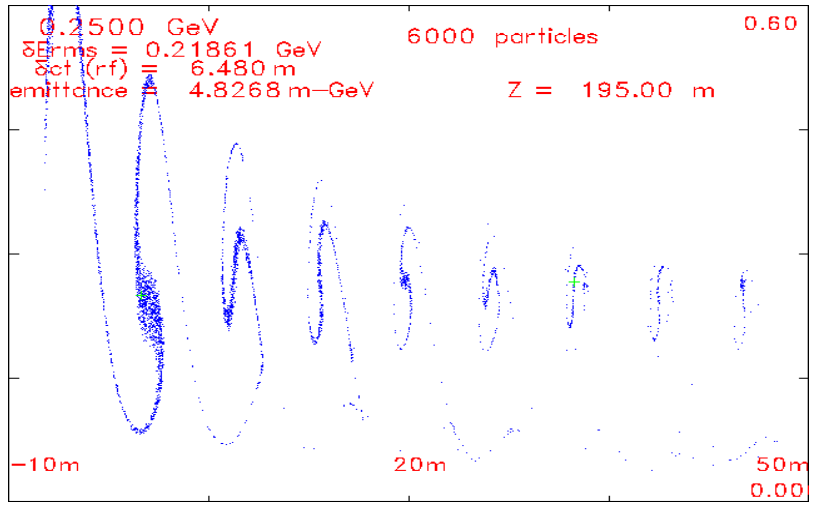
- 100 MHz example
  - 90m drift; 60m buncher, 40m rf rotation
- Capture centered at **250 MeV**
- **Higher energy capture means shorter bunch train**
- Beam at 250MeV ± 200MeV accepted into 100 MHz buncher
- Bunch widths < ±100 MeV
- Uses ~ 400MV of rf



~50 MHz variations

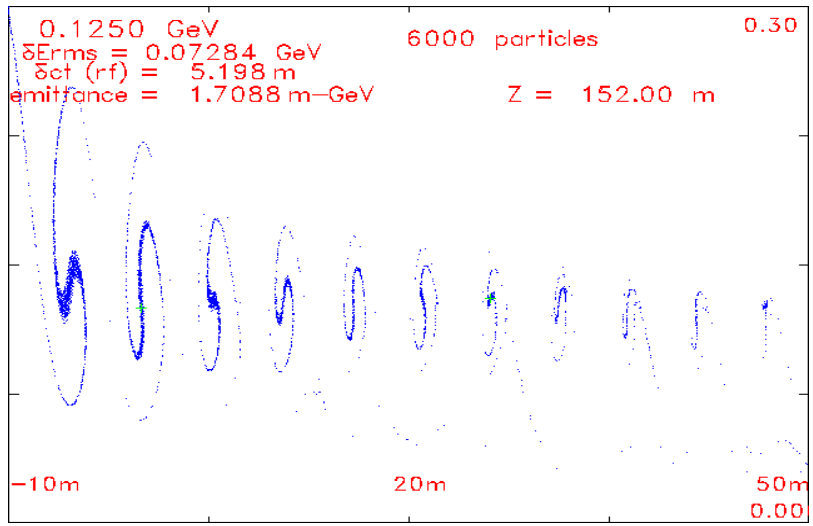
Example I (250 MeV)

- Uses ~90m drift + 100m 100→50 MHz rf (<4MV/m) ~300MV total
- Captures 250±200 MeV μ's into 250 MeV bunches with ±80 MeV widths



Example II (125 MeV)

- Uses ~60m drift + 90m 100→50 MHz rf (<3MV/m) ~180MV total
- Captures 125±100 MeV μ's into 125 MeV bunches with ±40 MeV widths



Summary

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

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

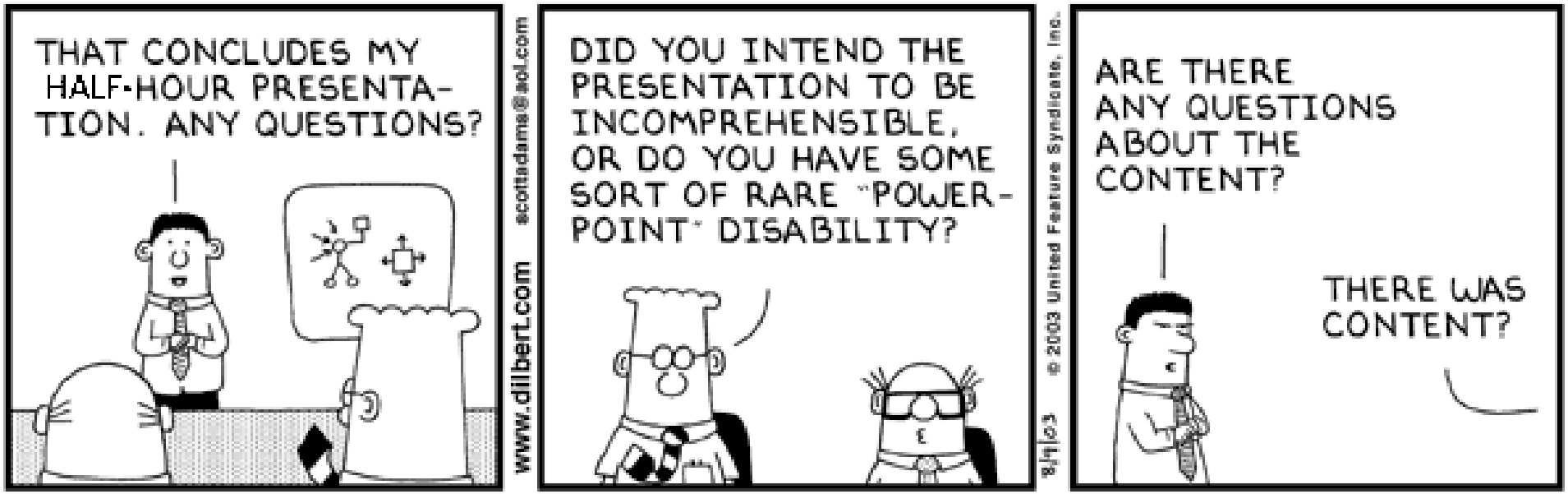
  (Twice as good ??)

- Method could (?) be baseline capture and phase-energy rotation for any neutrino factory … (FFAG)

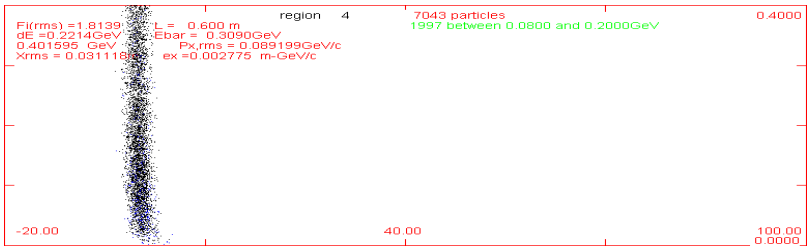
To do:

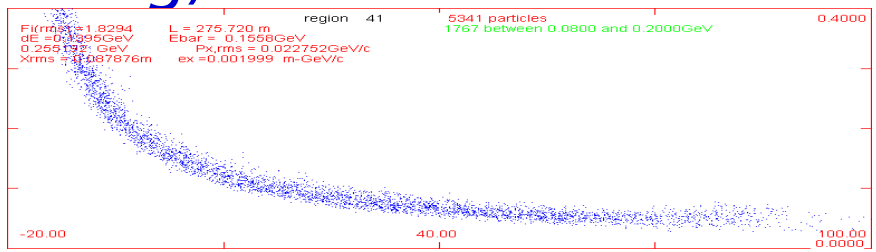
- Complete simulations with **matched** cooling channel!
- Optimizations, Best FFAG Scenario, …

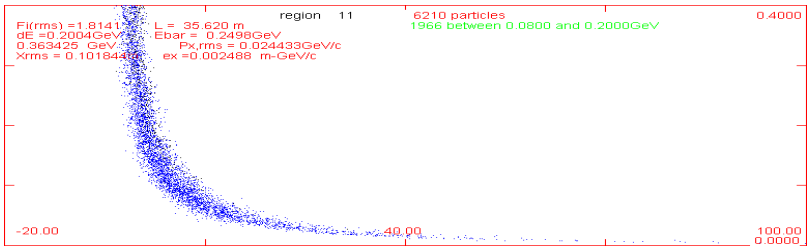
Last slide

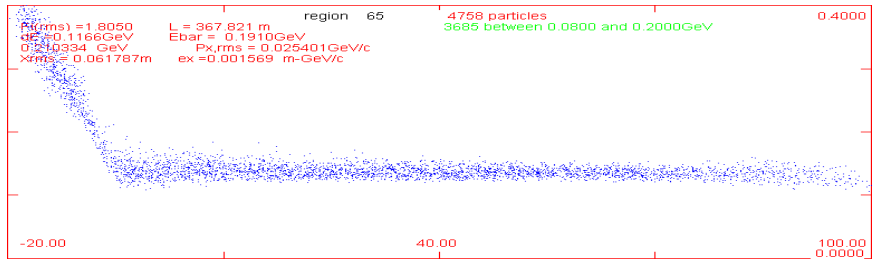


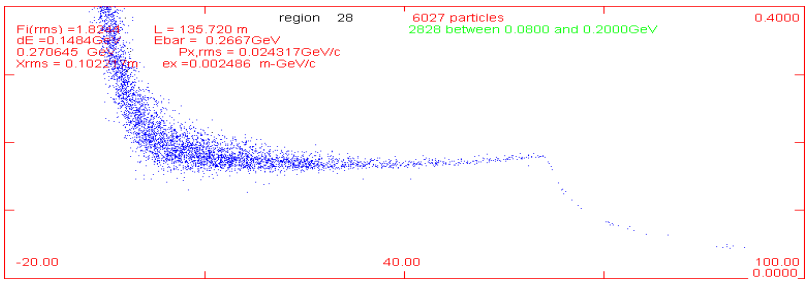
Compare with Study II (Capture + Cooling)

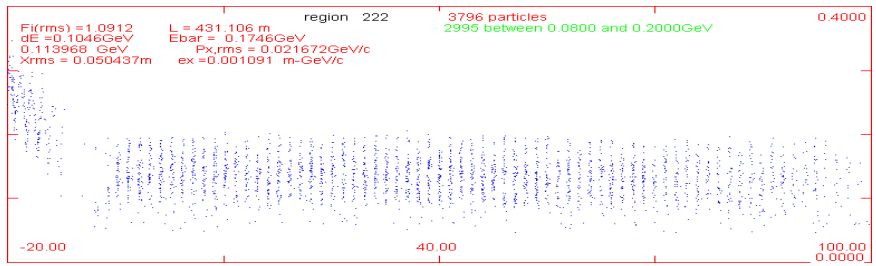


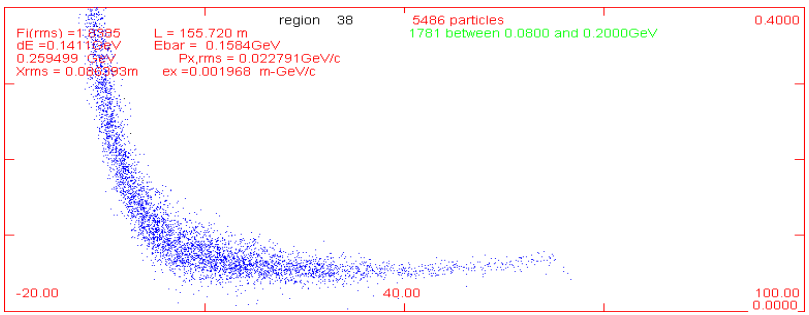


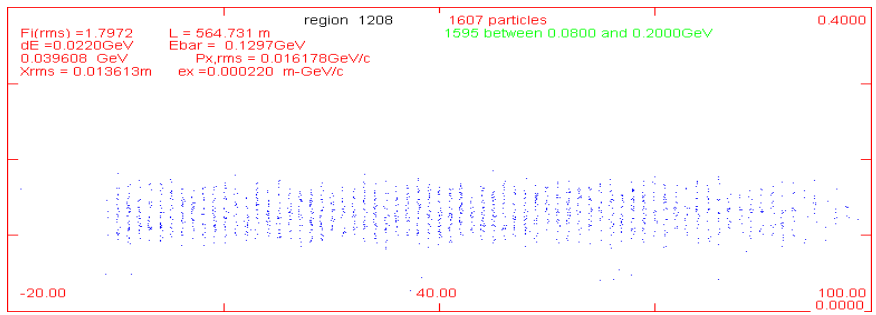






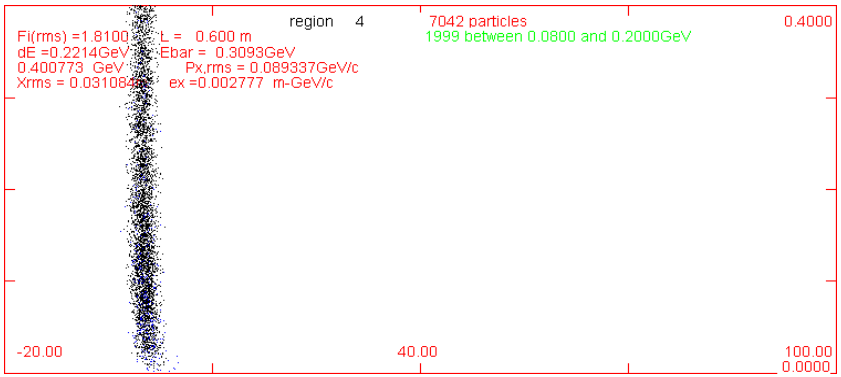


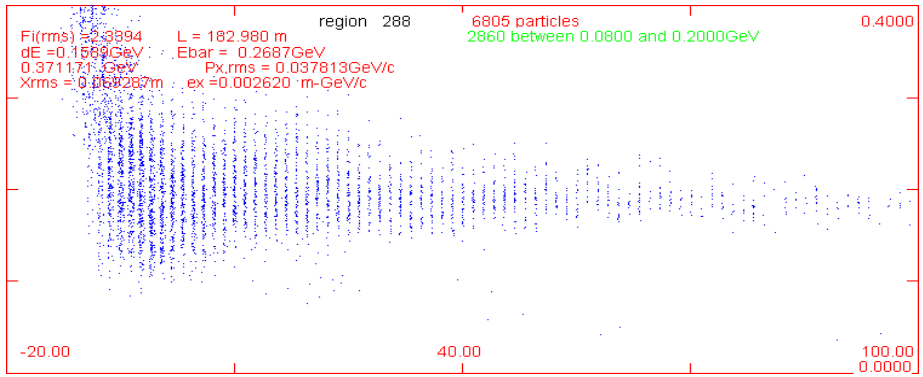


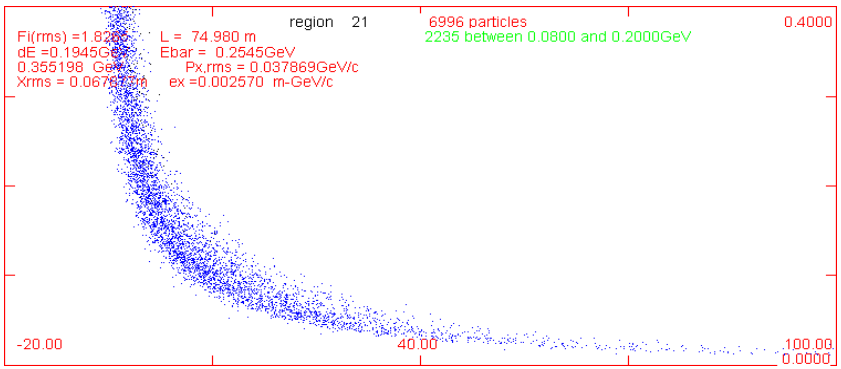


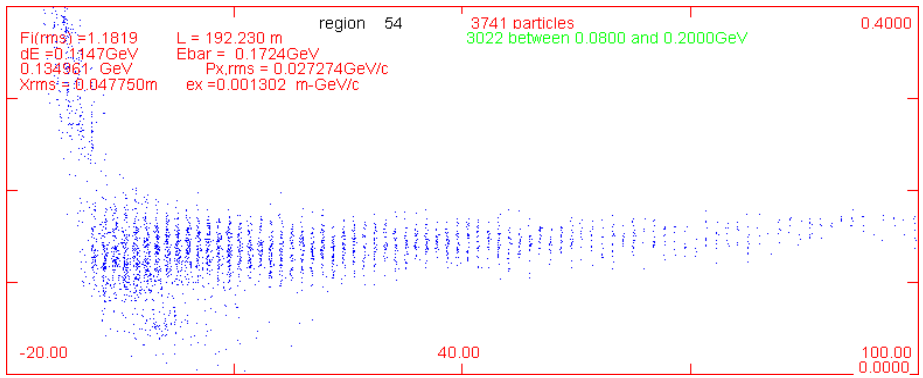
x: –20 to 100m; y: 0 to 400 MeV

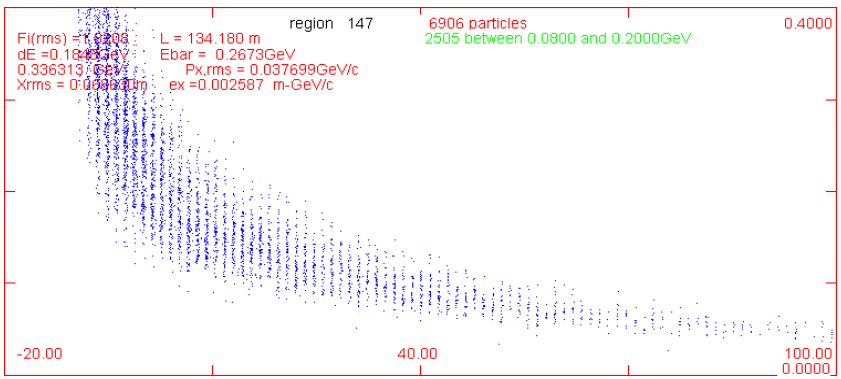
ICOOL simulation –Buncher, ϕ–δE, Cool

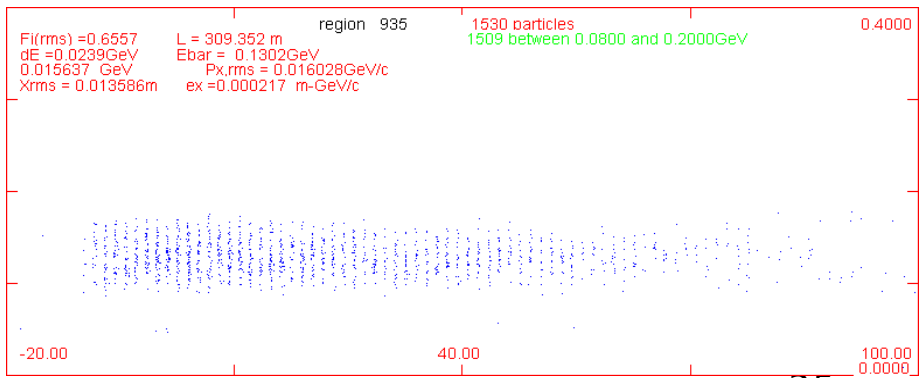






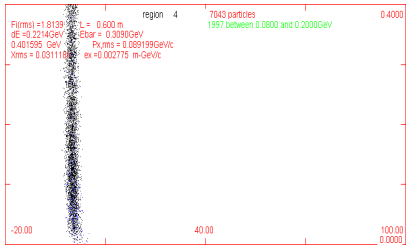


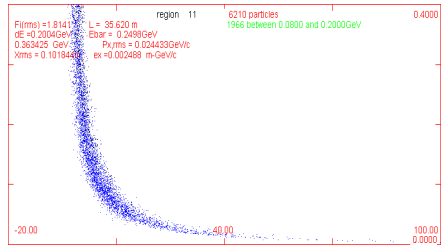




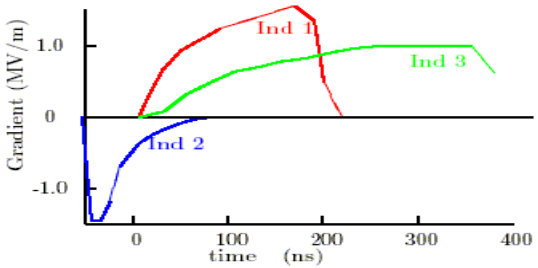
Study 2 system

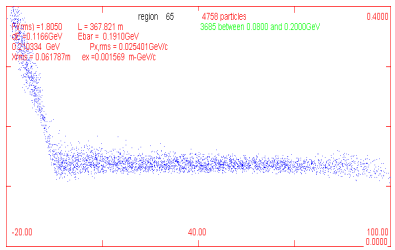
- **Drift** to develop Energy– phase correlation



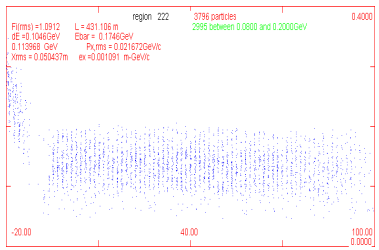


- Accelerate tail; decelerate head of beam (280m induction linacs (!))





- **Bunch** at 200 MHz



- Inject into 200 MHz cooling system