Bunched-Beam Phase Rotation for a Neutrino Factory

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Fermilab

Outline

- Study I – II ν-Factory – feasible but too expensive

- **Remove Induction Linac**
- Replace with **High-Frequency** Buncher and phase-energy rotation:
  - Capture beam in high-frequency buckets
  - Reduce energy spread with **high-frequency $\phi-\delta E$ rotation**
  - Inject into fixed-frequency cooling

- Simulation and Optimization
  - Simucool – adds transverse motion + some optimization
  - GEANT4 – fully realistic simulation; match into realistic cooling
- Discussion
  - Cost estimates ???
  - Future development

Study 2 Costs ....

- “Cost” reduced by ~25% from Study I

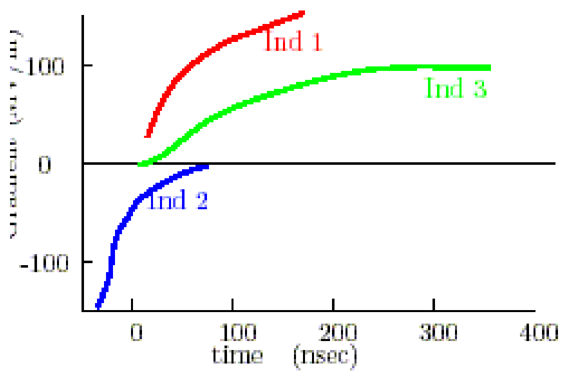
Table A.1: Construction Cost Rollup per Components for Study-II Neutrino Factory. All costs are in FY01 dollars.

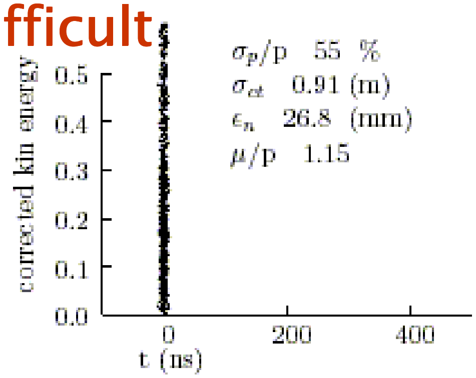
System	Magnets ($M)	RF power ($M)	RF cav. ($M)	Vac. ($M)	PS ($M)	Diagn. ($M)	Cryo ($M)	Util. ($M)	Conv. Facil. ($M)	Sum ($M)
Proton Driver	5.5	7.0	66.1	9.8	26.6	2.2	28.5		21.9	167.6
Target Systems	30.3			0.8	3.5	8.0	18.8		30.2	91.6
Decay Channel	3.1			0.2	0.1	1.0	0.2			4.6
Induction Linacs	35.0		90.3	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

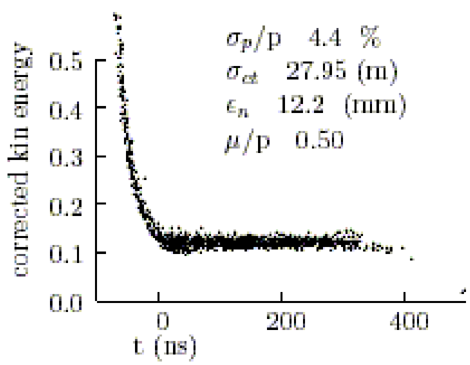
Induction Linac Technology

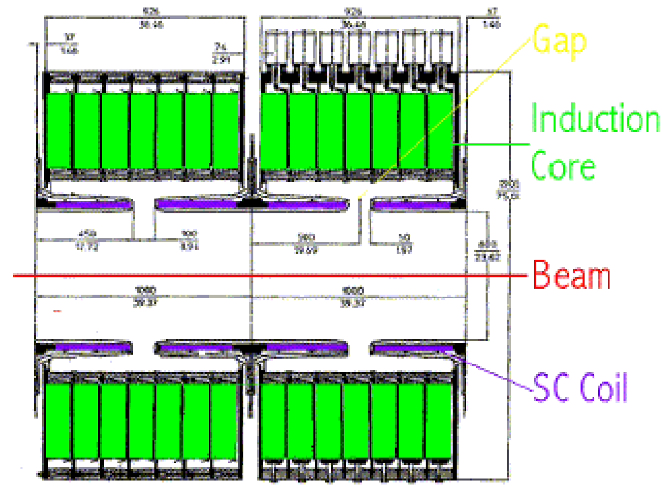
- Study II scenario uses ~ 250m long induction linac to capture muons.
- Cost is prohibitive
- Technology is difficult

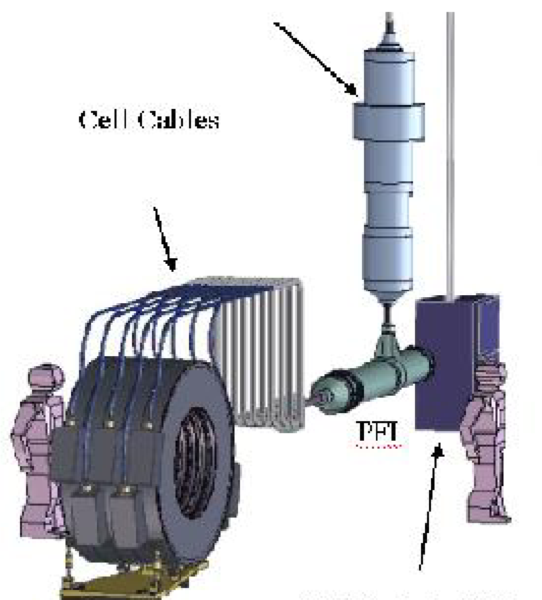
Hg Target	(.45 m)
Induction #1	(100 m)
Mini Cooling	(3.5 m H_2)
Induction #2	(80 m)
Induction #3	(80 m)





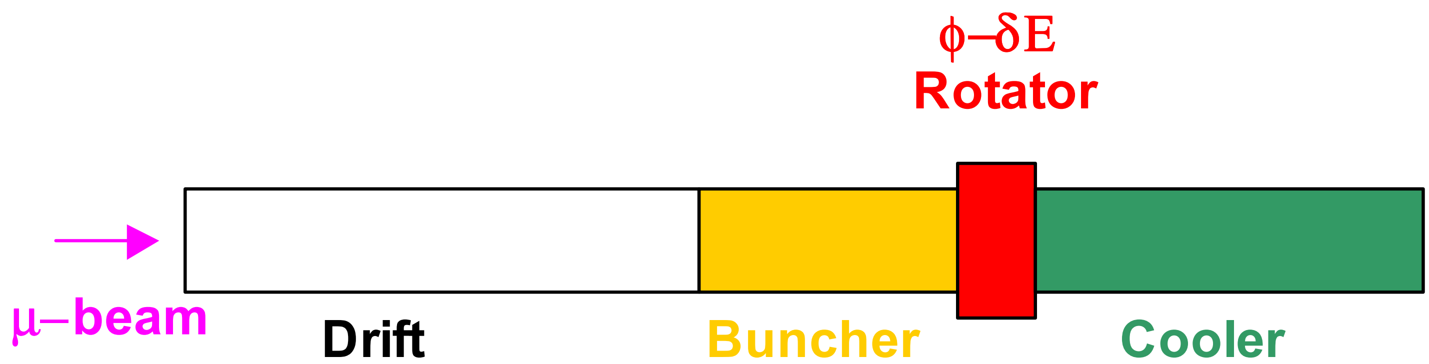






System Overview

Overview of transport



- **Drift (100m) – decay and drift**
- **Buncher (60m) 300 →187MHz, V' → 4.8 $(z/L)^2$ MV**
    - **Trap beam into string of ~200 MHz bunches**
- **φ–δE Rotator(8.4m) 187MHz, V' = 10 MV/m**
    - **rotate string of bunches to ~ equal energies**
- **Cooler (100m) 183MHz – ionization cooling**

Longitudinal Motion Through System

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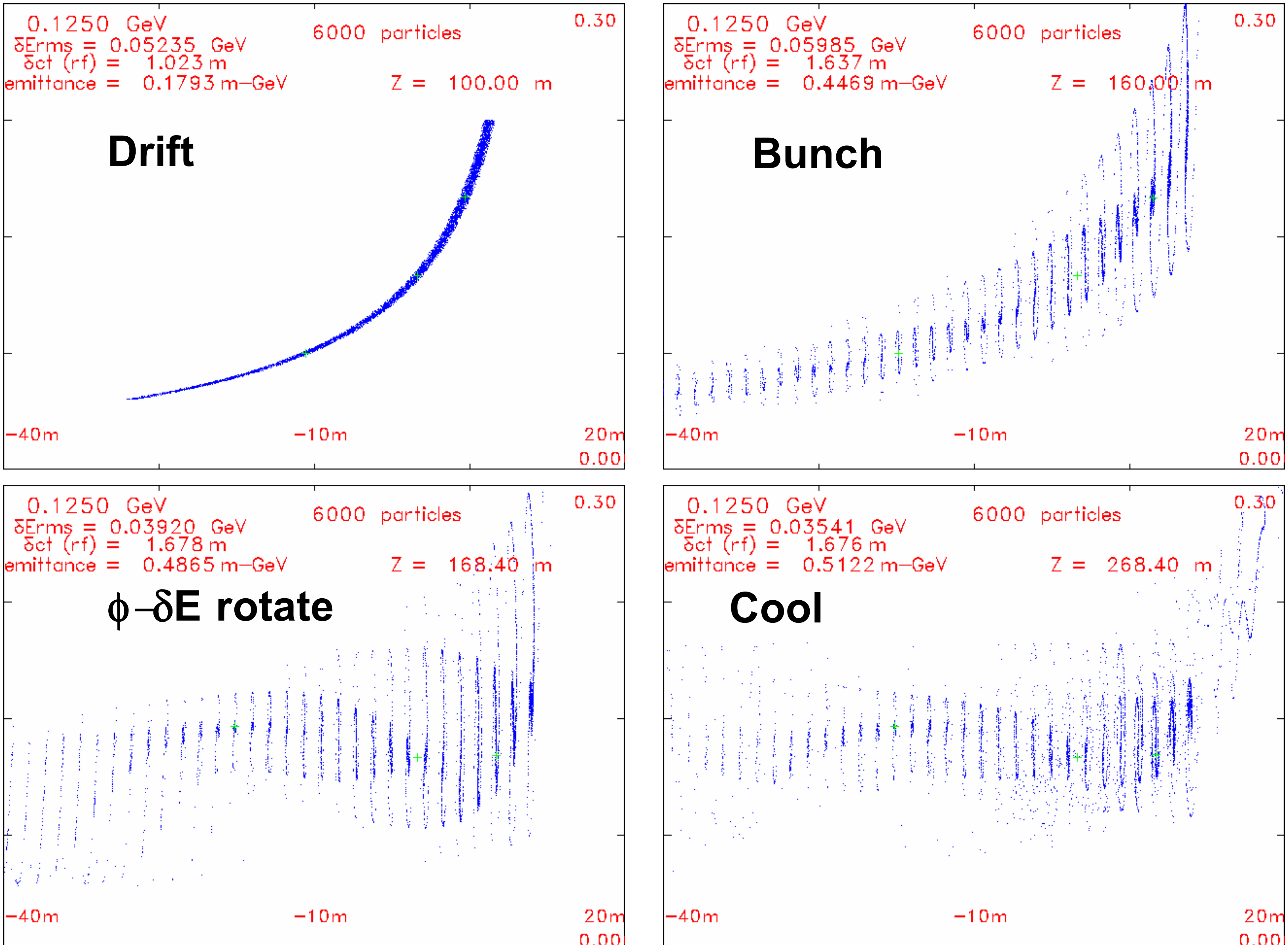
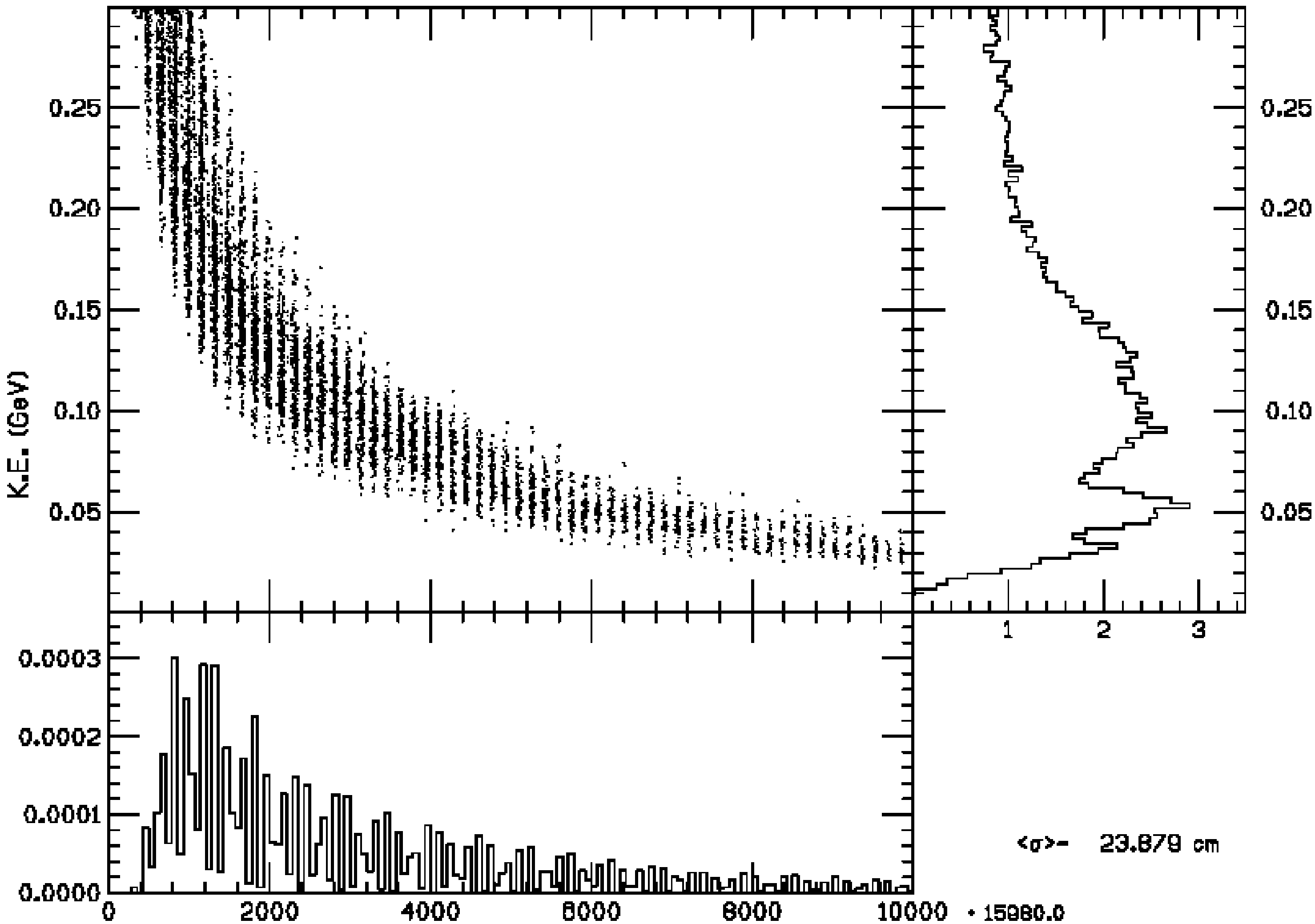
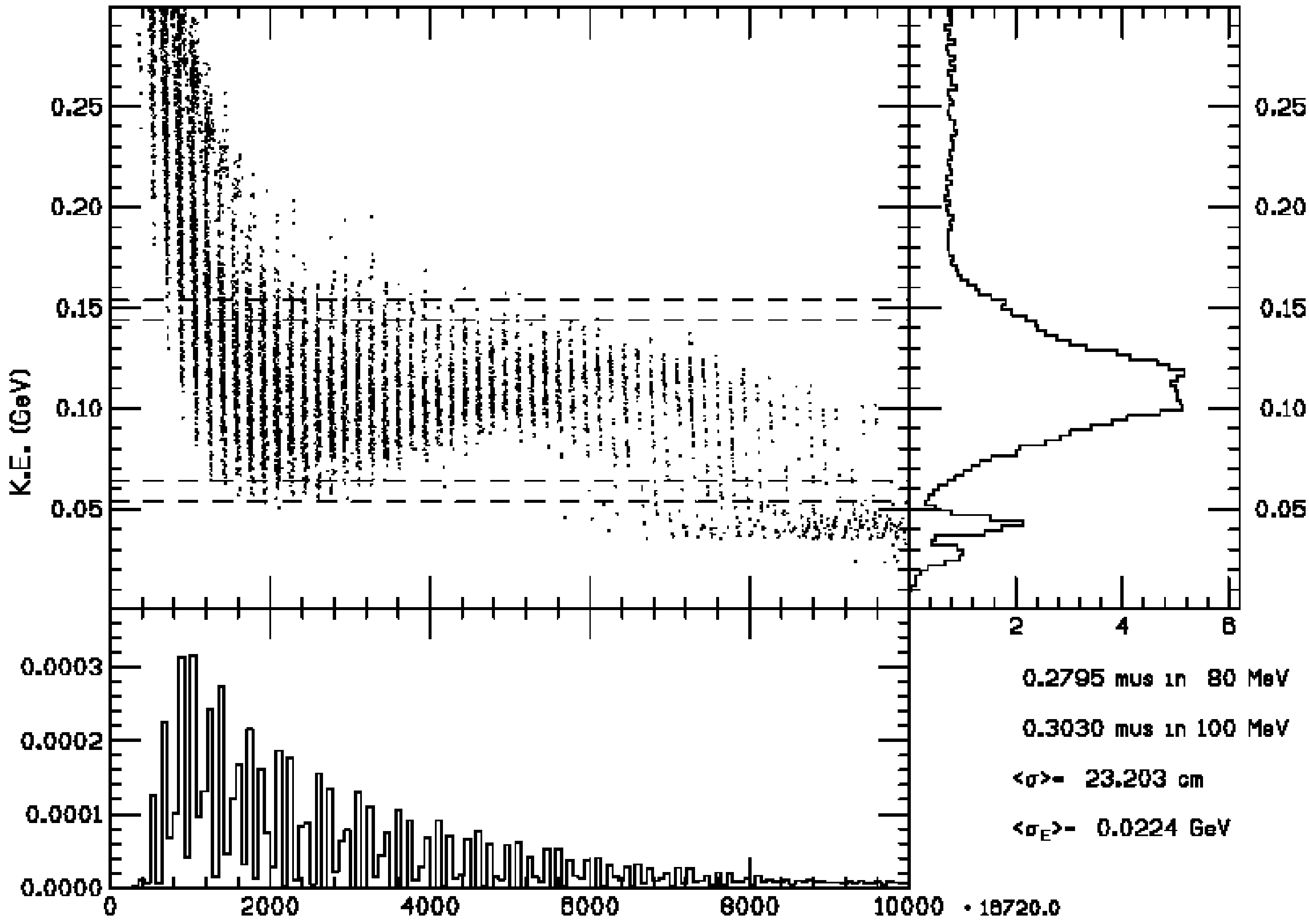


SIMUCOOL Beam at end of buncher



Simucool-optimized buncher and fixed frequency ϕ–δE rotation

- Obtains ~0.28 μ/p at end of buncher

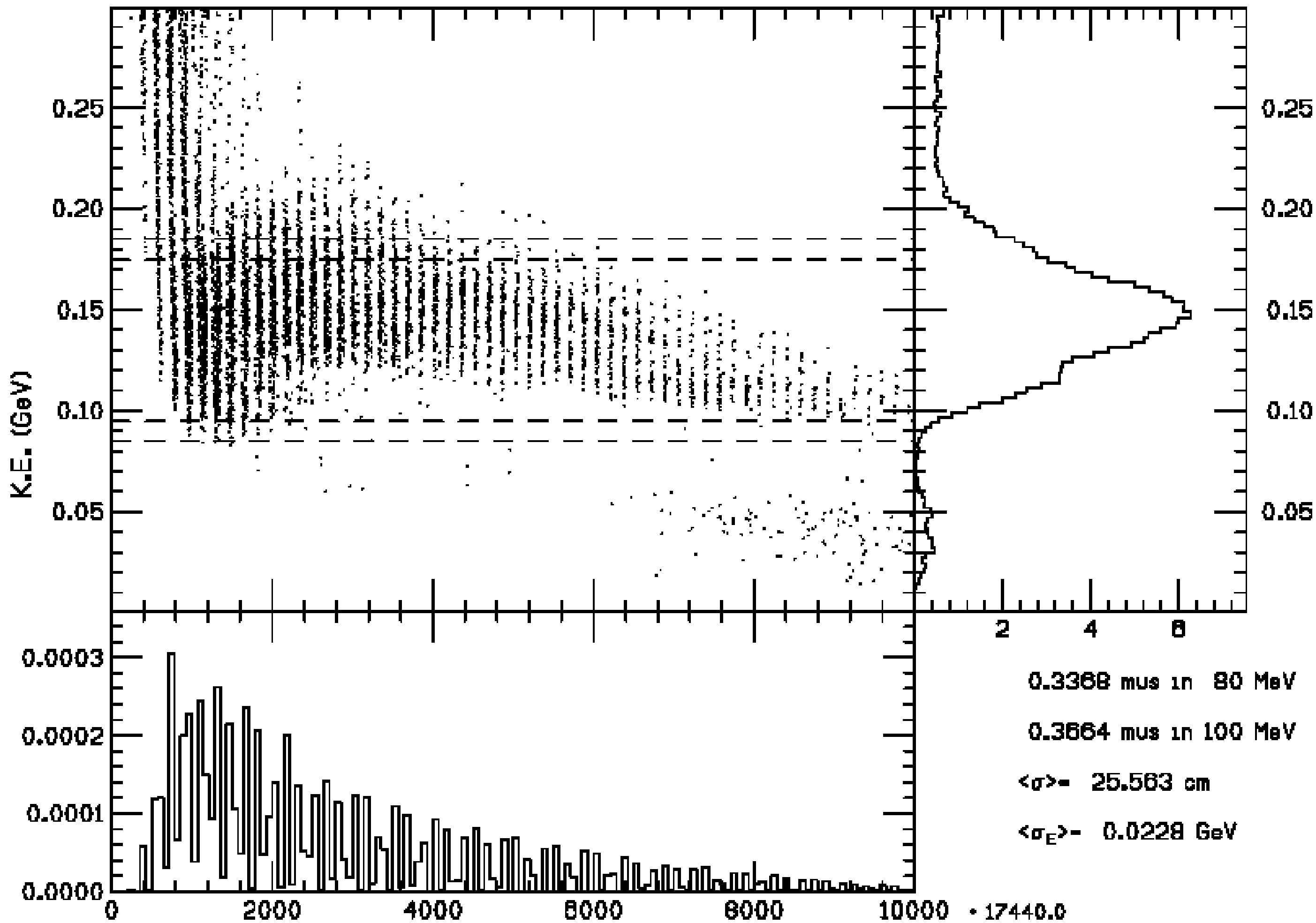


Simucool optimizations (AvG)

- Large statistics tracking code (**SIMUCOOL**) can be used to reoptimize Buncher + ϕ–δE Rotation
- **Reoptimize** baseline adiabatic buncher and fixed frequency **ϕ–δE rotation** (track rms bunches in each band)
  - – Obtains ~0.3 μ/p (up from 0.25)
- Change fixed-frequency **to "vernier"**; sets phase to N-1/2 wavelengths from first to last ref. bunch; maximizes ϕ–δE rotation – **obtains ~0.35 μ/p**
- Retrack with ICOOL – similar results are obtained

“Vernier”-optimized ϕ–δE rotation

- Obtains ~0.34 μ/p at end of buncher



AvG Optimizations

- A van Ginneken has completed a new set of optimizations; changes some parameters
- Drift – reduced to ~76m
- Buncher parameters changed:
  - Reference energies: 64 MeV; 186MeV
  - 20 bunches between reference energies 384 → 233 MHz
  - Linear ramp in voltage 0 to 6.5MV/m
  - Still 60m long
- Rotator changed
  - "vernier" frequency (20 + δ) wavelengths between reference bunches (234 → 220 MHz), 10MV/m
  - Optimize on longitudinal bunch densities
  - Best case has $\delta \cong 0.16$
  - Longer Rotator (~30m)

System Components (new version)

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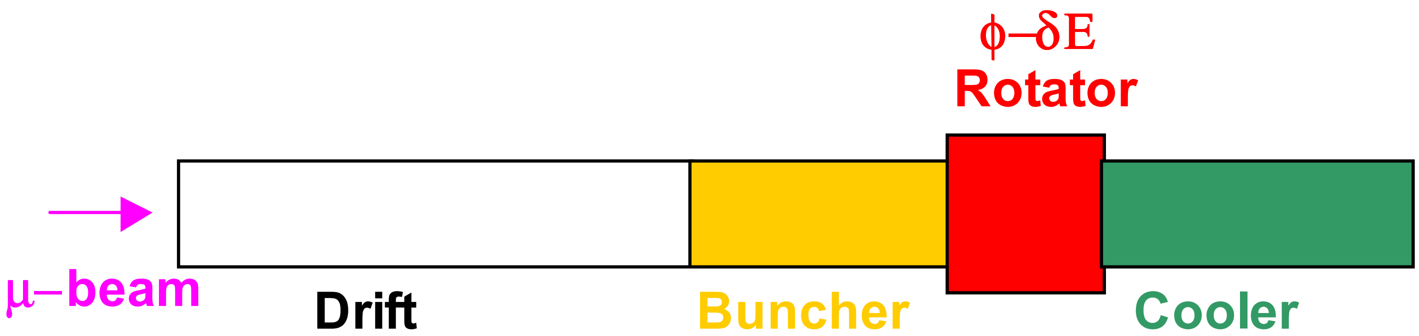
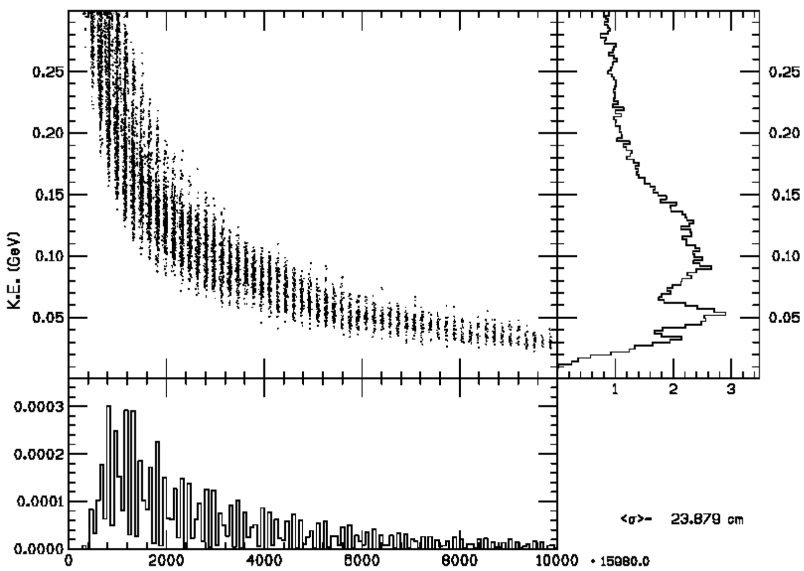
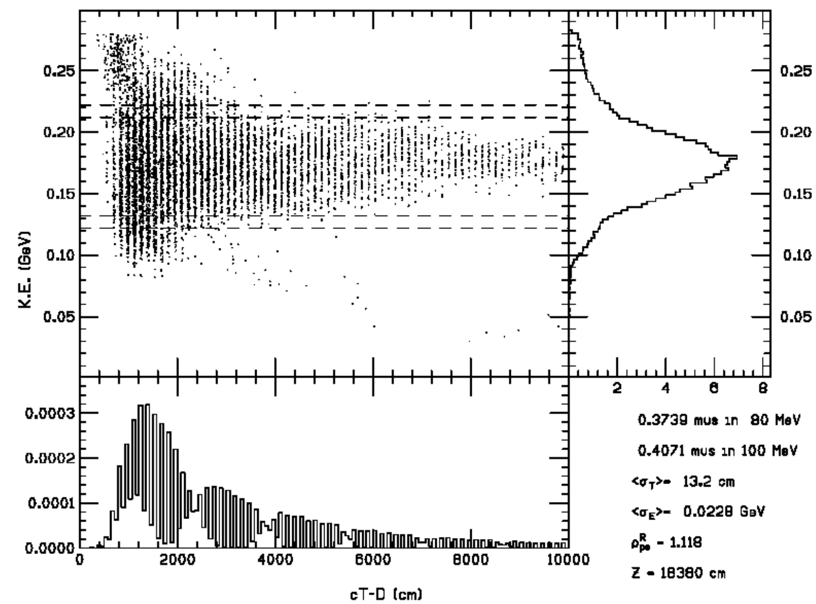
Overview of capture transport



- **Drift (80m)**
- **Buncher (60m) 380 →230 MHz, V′ → 6.5 (z/L) MV/m**
- **φ−δE Rotator(30m) 230 →220 MHz, V′ = 10 MV/m**
- **Cooler (100m) ~220 MHz**

Bunching and φ–δE Rotation





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

GEANT4 simulations (D. Elvira)

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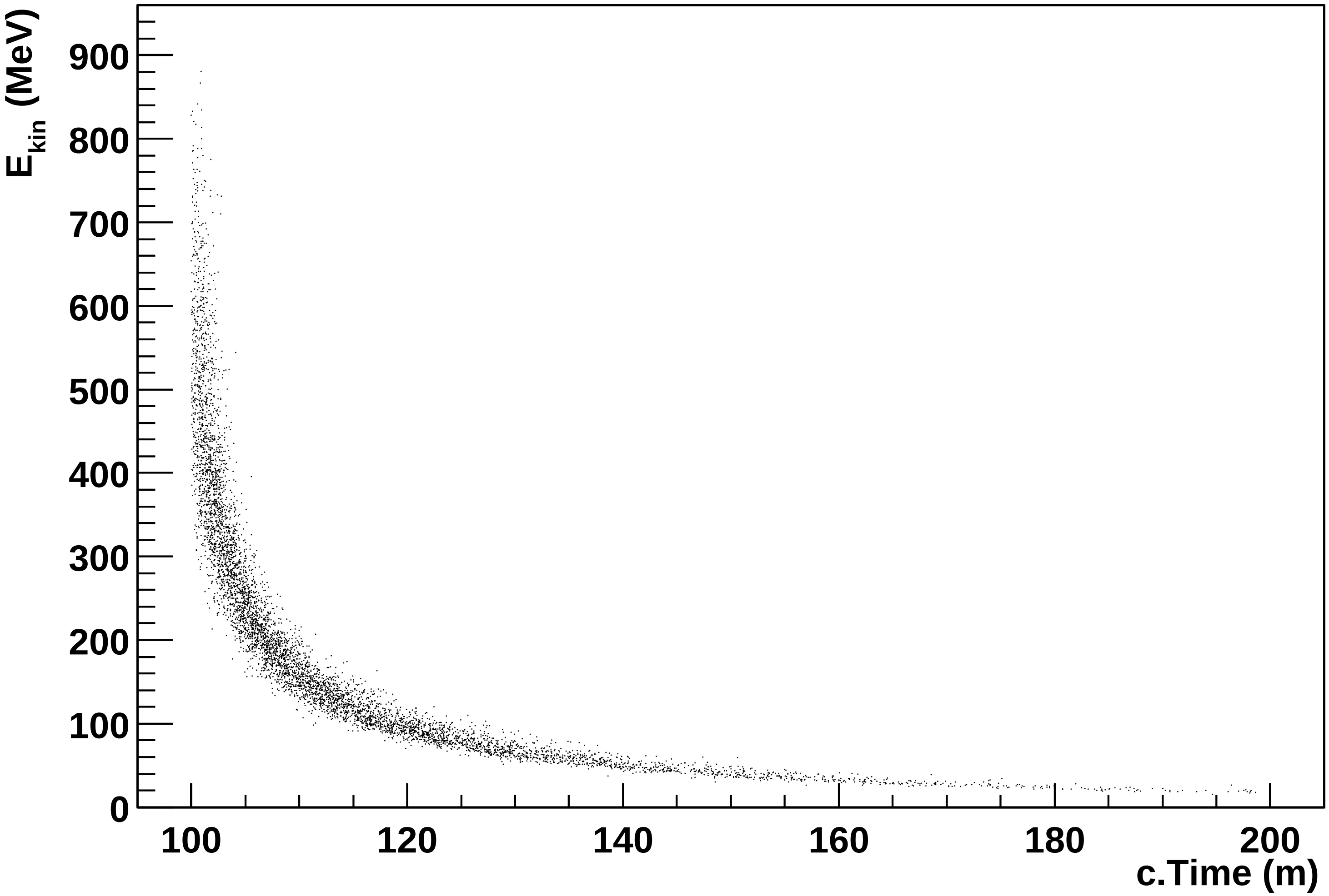
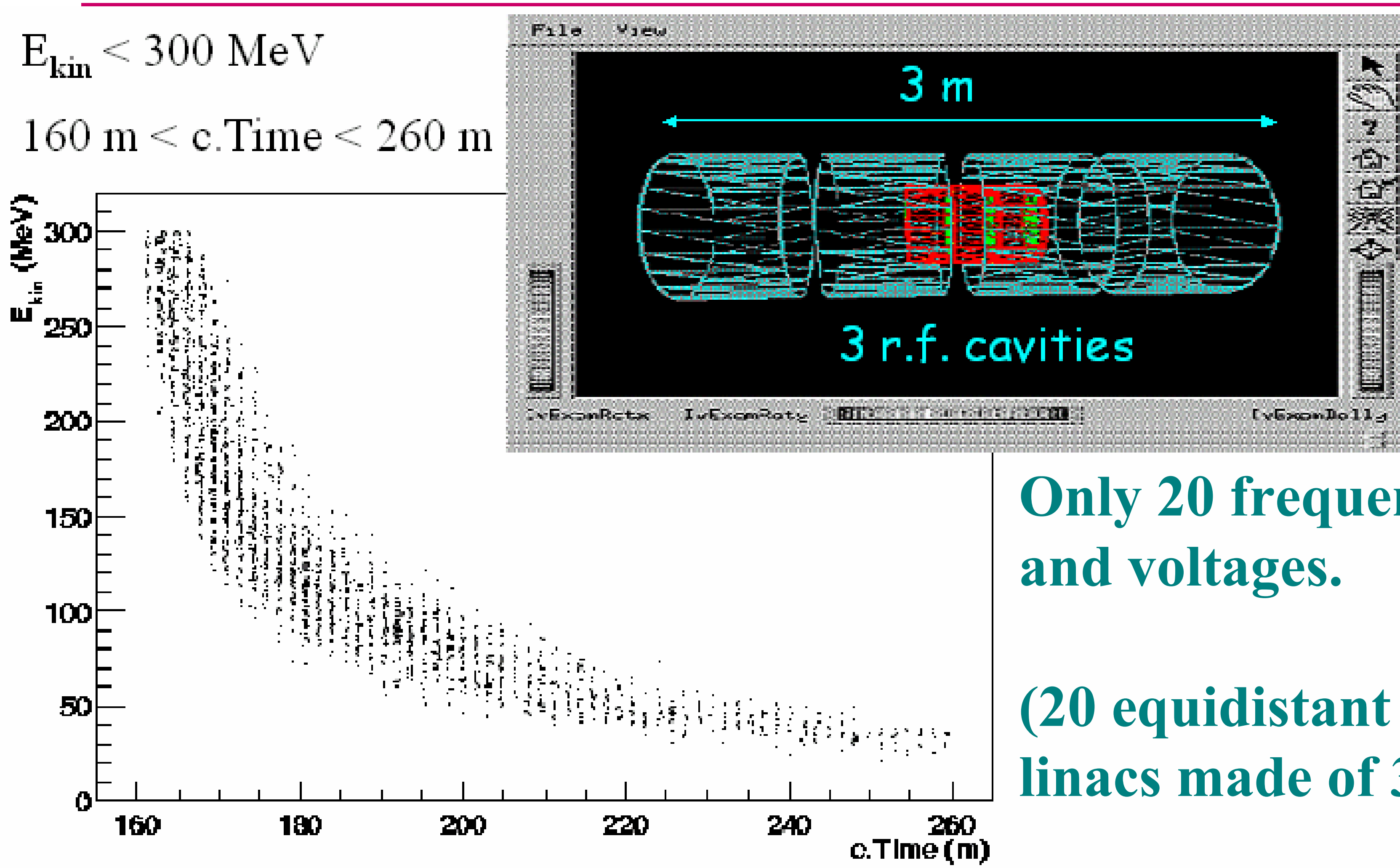
- Fully "realistic" transverse and longitudinal fields
  - Magnetic fields formed by current coils
  - Rf fields from pillbox cavities (within solenoidal coils
- Studied varying number of different rf cavities in Buncher
  - (60 (1/m) to 20 to 10) … 20 was "better", 10 only a bit worse
- Simulations of ϕ–E rotation
- Will (?) extend simulations + optimization through cooling channel

Beam at end of drift



20-frequency Buncher



Only 20 frequencies and voltages.

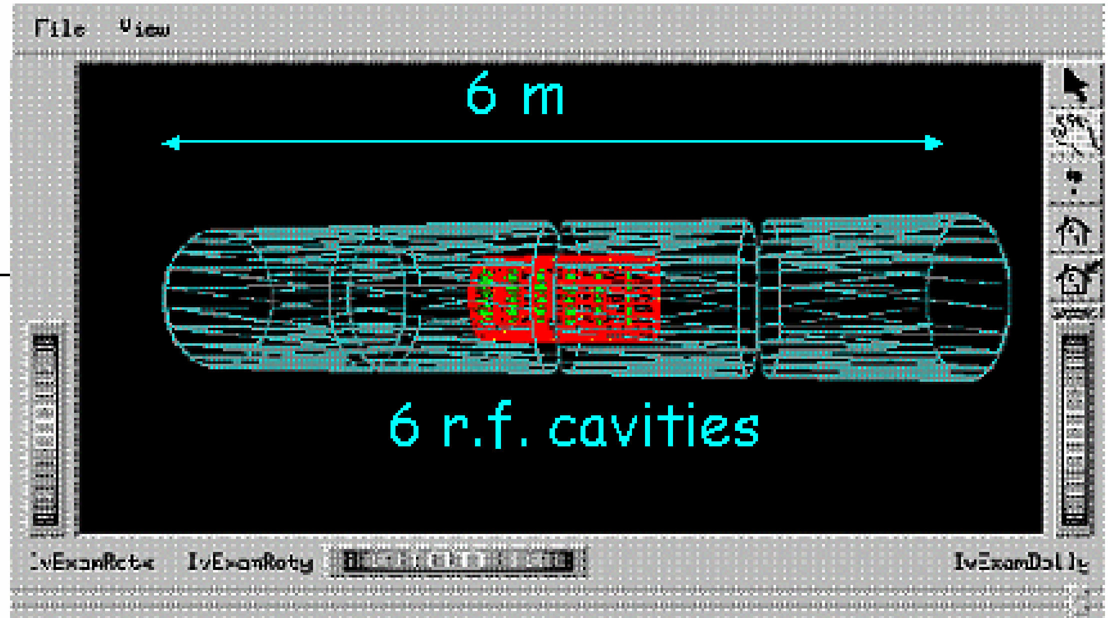
(20 equidistant linacs made of 3 cells)

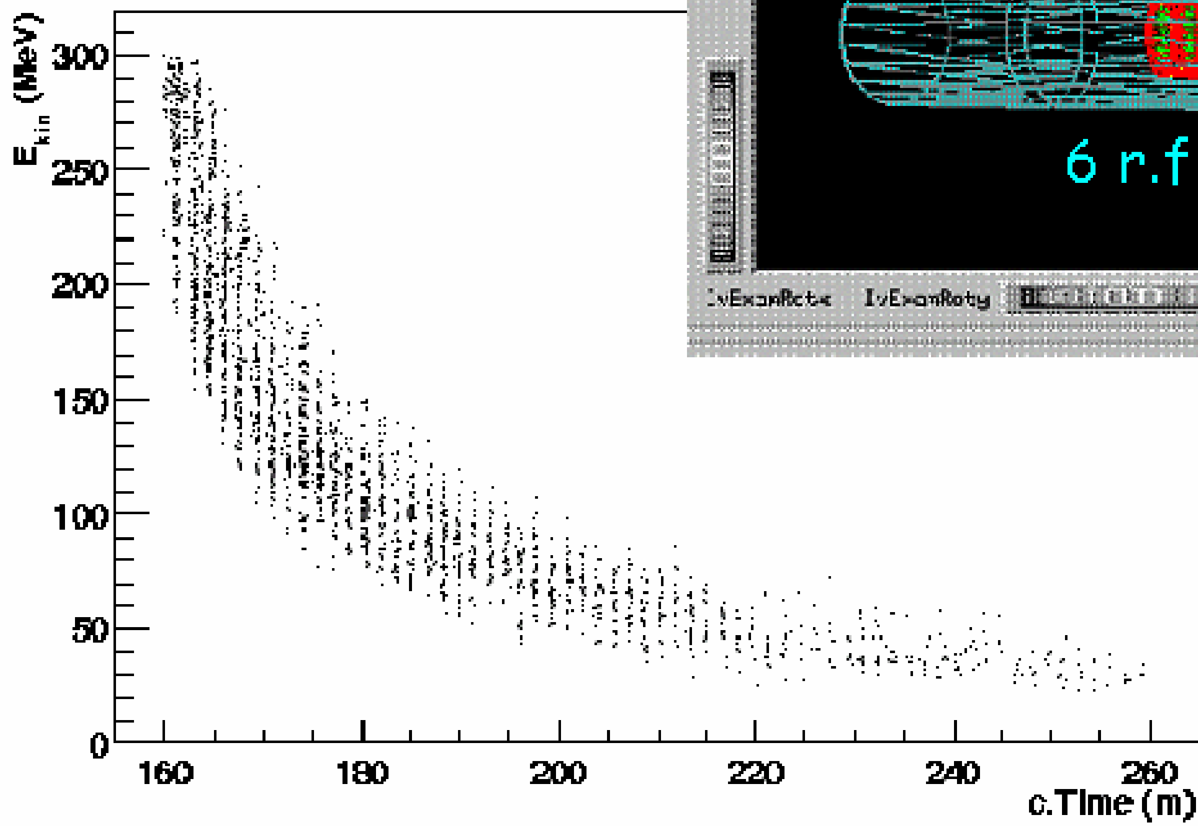
64.9% of the particles survive at the end of the buncher.

10-frequency Buncher

E_{kin} < 300 MeV

160 m < c.Time < 260 m





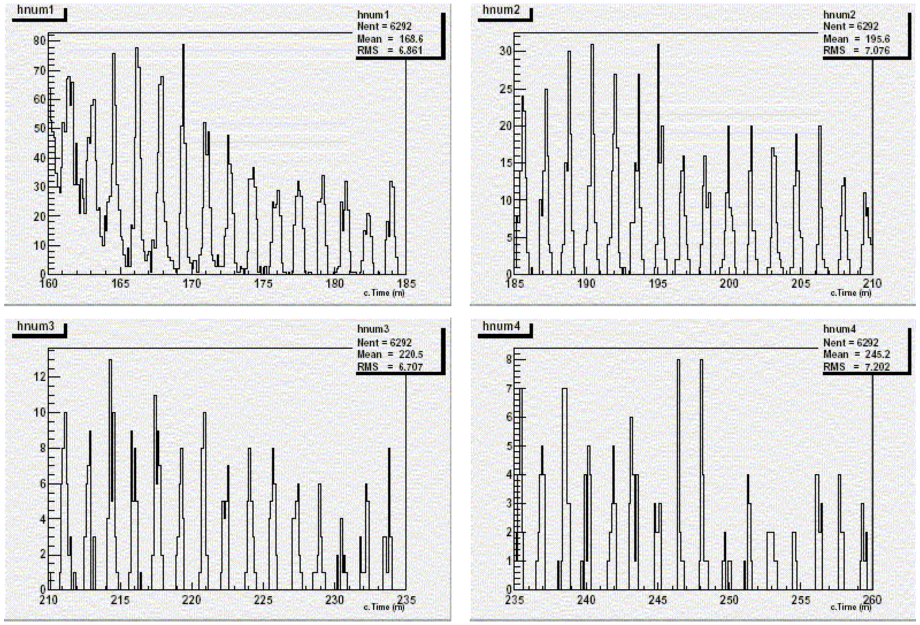
Only 10 frequencies and voltages.

(10 equidistant linacs made of 6 cells)

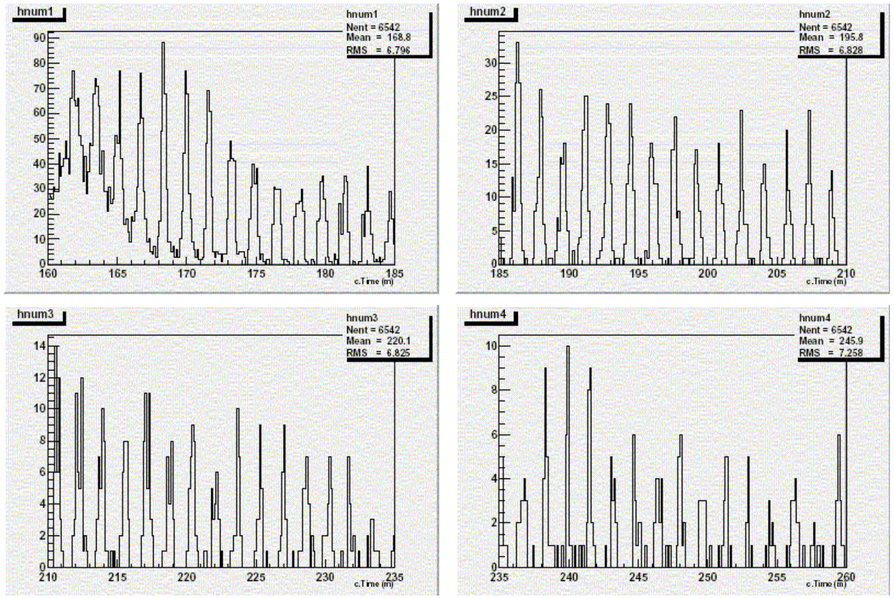
62.2% of the particles survive at the end of the buncher.

- Bunch formation in GEANT4 simulations

- 20 rf frequencies

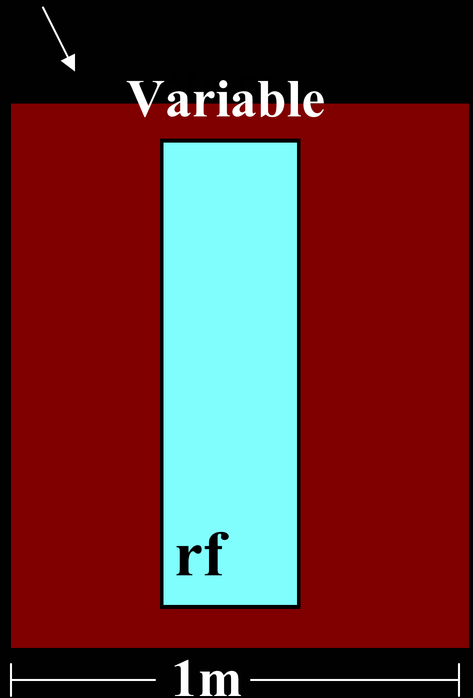


- 10 rf frequencies



Phase Rotator, Same Lattice Structure

Unit Cell, Buncher

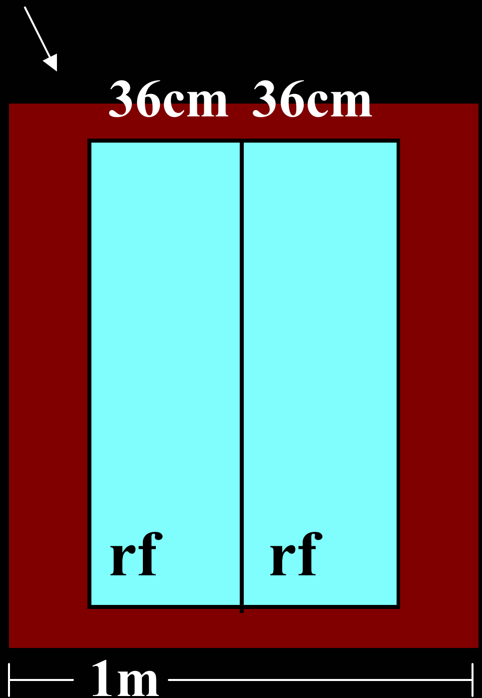


Variable Frequency: 290-180 MHz

$$\nu_{r.f.} = 15 \frac{c}{d\left(\frac{1}{\beta_{75}} - \frac{1}{\beta_{175}}\right)}$$

Gradient of electrostatic potential = 4.8 MV/m

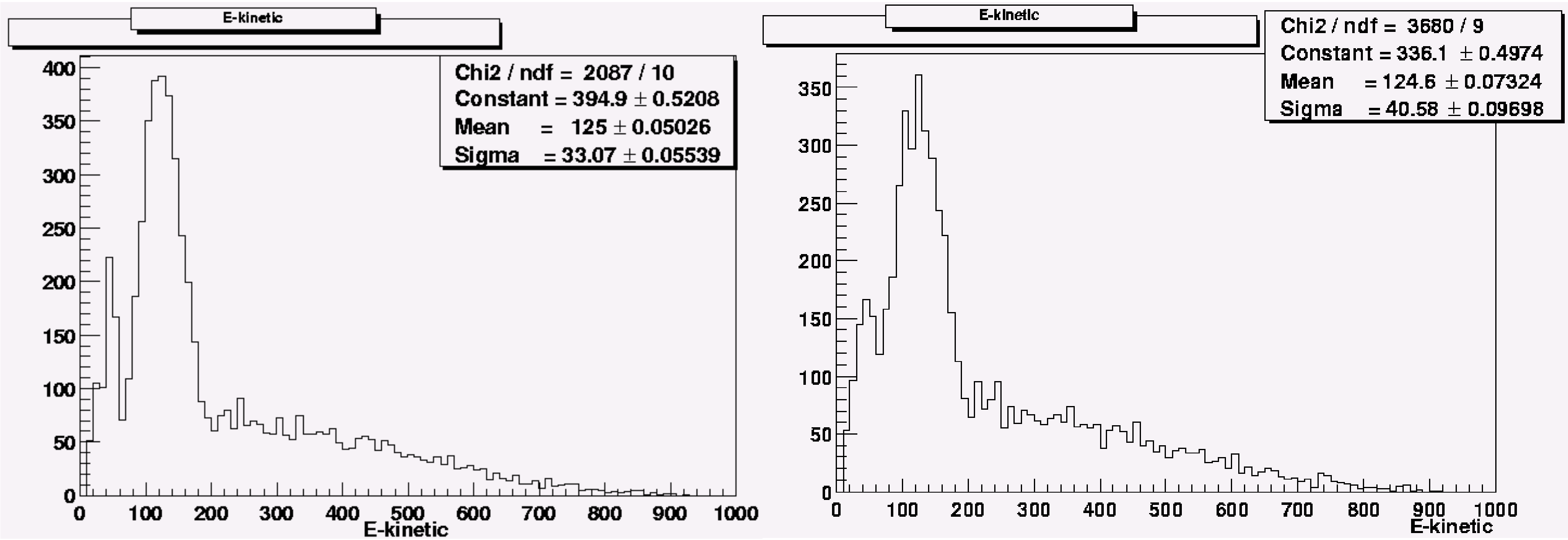
Unit Cell, Phase Rotator



Fixed Frequency: 183 MHz

Gradient of electrostatic potential = 10 MV/m

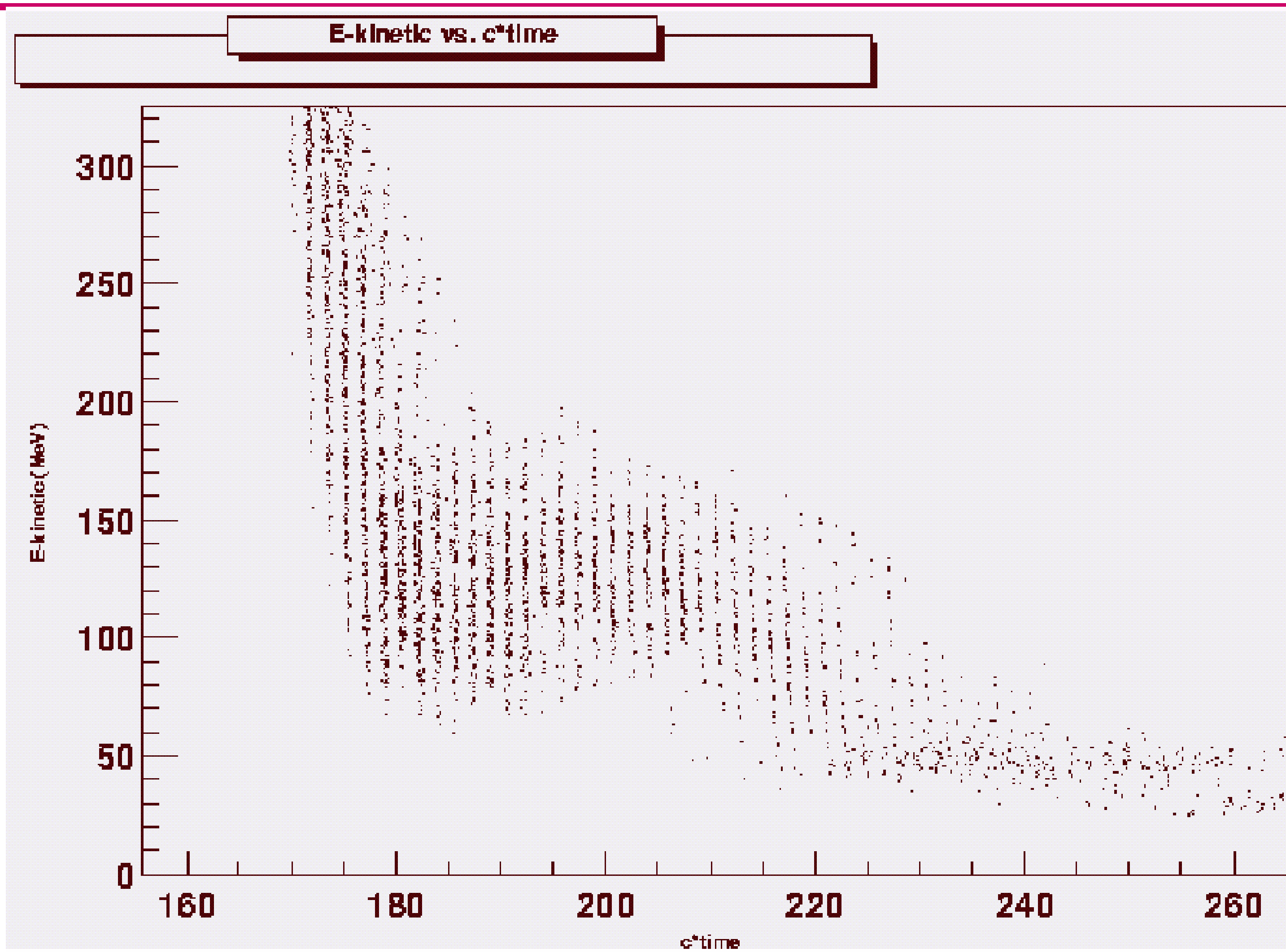
Energy projections (Elvira/Keuss)



20 rf frequency case
~0.38 μ/p within ±50 MeV of peak

10 rf frequency case
~0.35 μ/p within ±50 MeV of peak

GEANT4 results – rf rotation



- rf rotation with DPGeant

Conclusions

MuCOOL-254

At the end of the phase rotator, we see:

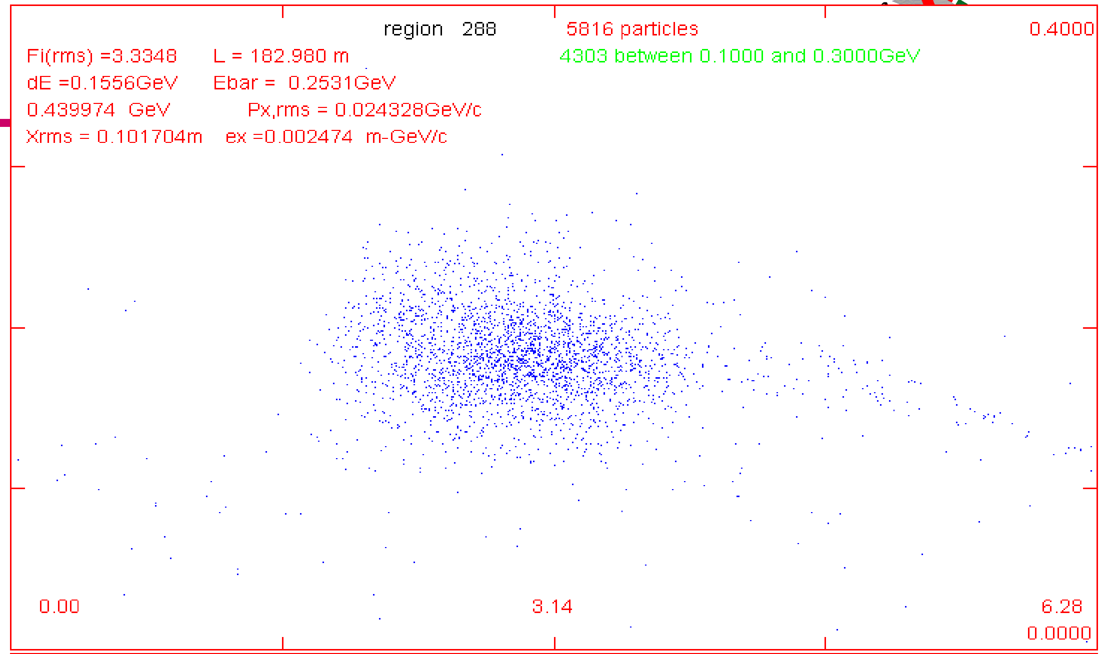
- Good quantitative agreement between GEANT4 realistic simulation and ideal 60 frequencies result from D.Neuffer & A. Van Ginneken.

- The simpler 20 and 10 frequencies bunchers show good performance as well.

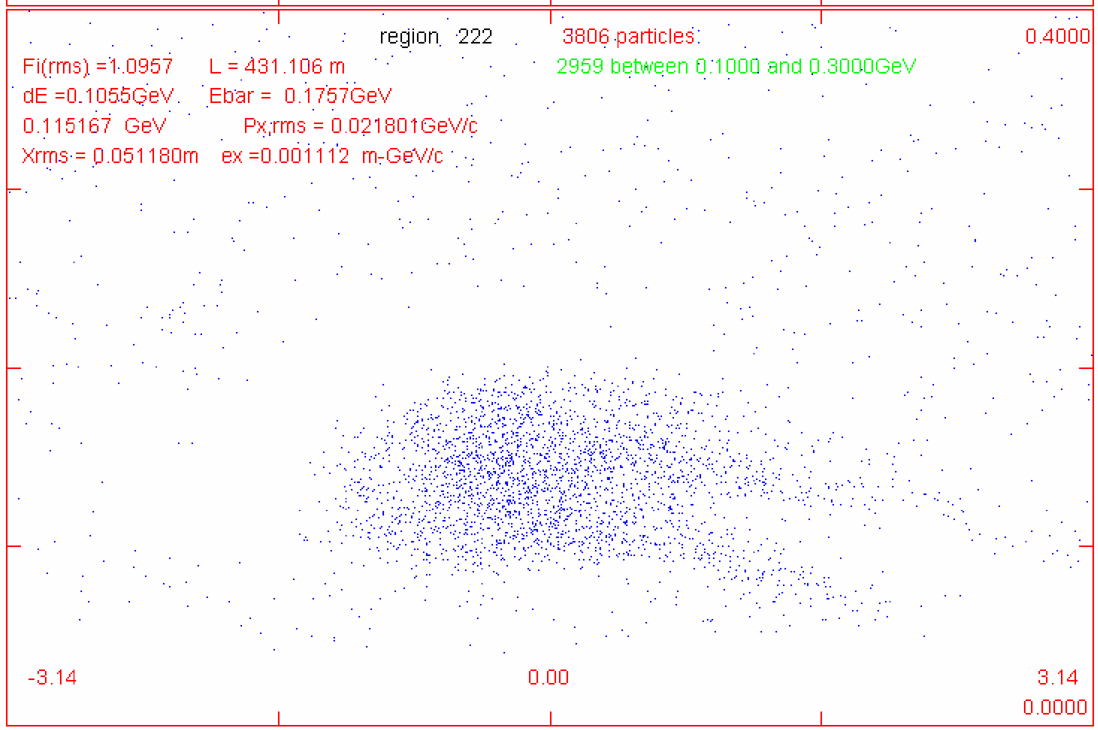
Future:

The buncher and phase rotator parameters should be optimized for whatever cooling channel follows them. A matching section should handle the transition, to achieve maximum acceptance of the beam by the cooling channel. The whole system should be re-optimized for maximum transmission and cooling.

- Beam after phase rotation and buncher (z= 183m) in AvG optimized case; measured at rf frequency; bunches are overlapped, mod f_{rf}



- Beam in Study 2 after phase rotation, buncher and initial cooling (z = 430m);
- phase space density is similar



Look at Individual bunchlets

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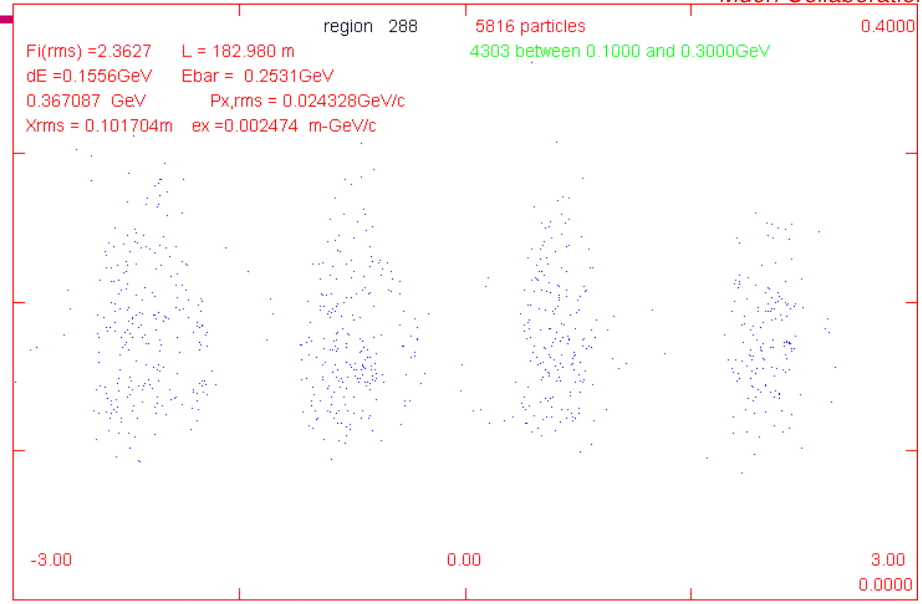
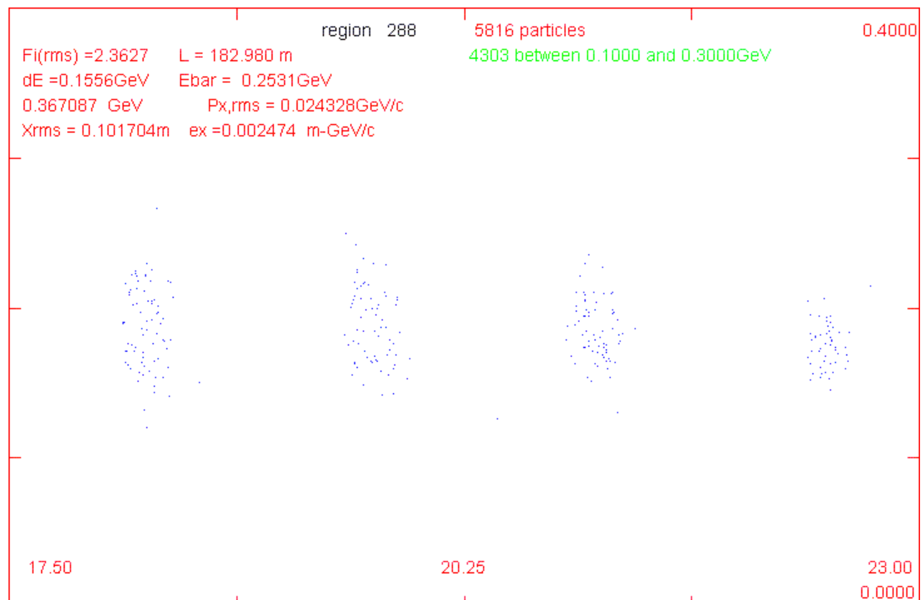
- After buncher + phase rotation; bunches are aligned and energy, with beam collected at 0 phase.
- Individual bunchlets are confined in center of rf bucket suitable for cooling and acceleration





Hardware For Adiabatic Buncher

- Transverse focussing (currently)
  - B=1.25T solenoidal focusing
  - R=0.30m transport for beam

Rf requirements:

- Buncher: ~300 →~210 MHz; 0.1 →4.8MV/m (60m)

  (initially 1 cavity every 1m; reduces frequency in 2-4MHZ steps; 1-D and GEANT4 simulations indicate ~10 frequencies are sufficient (~10MHz intervals)
- $\phi-\delta E$ Rotator: 210 →200 MHz; 10MV/m (~10m)

Rf Cost Estimate (Moretti)

Frequency	Cavity length	Cavity Cost	Rf Power	Total
300MHz	0.5 m	225 k$	225 k$	450k$
290	1	450	350	800
280	2	900	700	1600
270	2	900	1000	1900
260	2	900	1000	1900
250	2	900	1000	1900
240	2	900	1000	1900
230	3	1200	1500	2700
220	4	1400	1500	2900
210	5	1800	2000	3800
200	10	3800	4200	8000
	33.5m	13375	14475	27850k$

Transport requirements

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- Baseline example has 1.25 T solenoid for entire transport (drift + buncher + rf rotation) (~170m)
- Uncooled μ−beam requires 30cm radius transport (100m drift with 30cm IR – 1.25T)
- In simulations, solenoid coils are wrapped outside rf cavities.
  ⇒(~70m 1.25T magnet with 65cm IR)
- FODO (quad) transport could also be used …

Cost of magnets (M. Green)

- 100m drift: 11.9 M$ (based on study 2)

- Buncher and phase rotation: 26 M$ (study 2)
- Cryosystem: 1.5M$; Power supplies 0.5M$

- Total Magnet System : 40M$

- (D. Summers says he can do Al solenoids for ~10 M$)
- Would quad-focusing be cheaper ?

$$ Cost Savings ??

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- High Frequency $\phi-\delta E$ Rotation replaces Study 2:
  - Decay length (20m, 5M$)
  - Induction Linacs + minicool (350m, 320M$)
  - Buncher (50m, 70M$)
- Replaces with:
  - Drift (100m)
  - Buncher (60m)
  - Rf Rotator (10m)
  - Rf cost =30M$; magnet cost =40M$ Conv. Fac. 10M$ Misc. 10M$ ……
- Back of the envelope:

  (400M$ → ?? 100M$)

Summary

- High-frequency Buncher and ϕ–δE Rotation simpler and cheaper than induction linac system
- Performance probably not as good as study 2,

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

- To do:
  - Complete simulations with match into cooling channel!
  - Optimizations
  - Scenario reoptimization

Dilbert Comment