High-Frequency "Adiabatic" Buncher

David Neuffer
A. Van Ginneken
Fermilab

Outline

- High-Frequency Buncher
  - Capture beam in high-frequency buckets
  - Reduce energy spread with high-frequency ϕ–δE rotation
  - Inject into fixed-frequency cooling system
- High-Frequency Buncher Simulations & Development
  - Icool simulations
  - Simucool simulations –
  - Comparisons with baseline scenario
- Discussion – future development and improvement

High Frequency ϕ-δE Rotation

- **Induction Linac ϕ-δE Rotation is long and expensive; requires new technology**

- **Would like to use shorter system, which uses existing rf technology (~200 MHz…)**

$\Rightarrow$ Alternative Scenario:

- allow beam to decay + drift

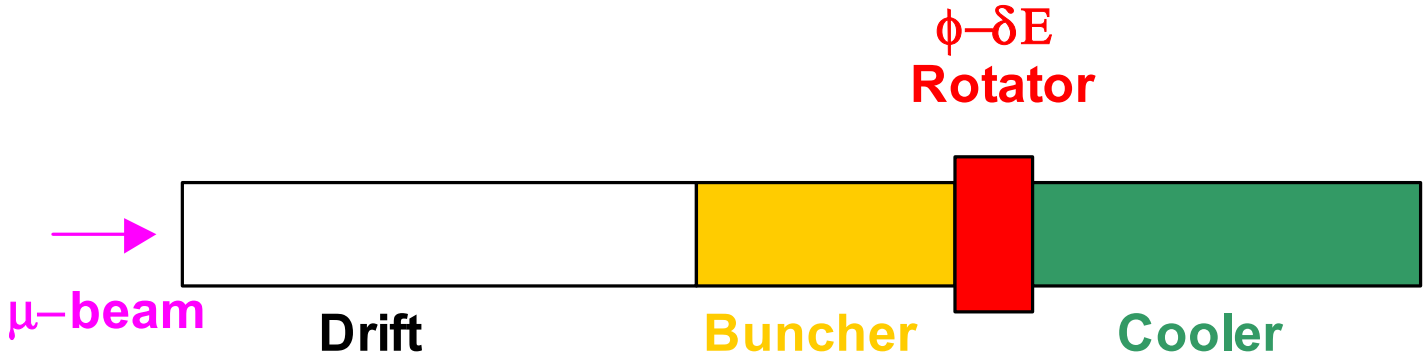
- impose varying-frequency rf to trap beam into string of ~200 MHz bunches

- rotate string of bunches to obtain same mean energy of bunch using (?) fixed-frequency rf

-capture beam into cooling rf

System Components

Overview of transport

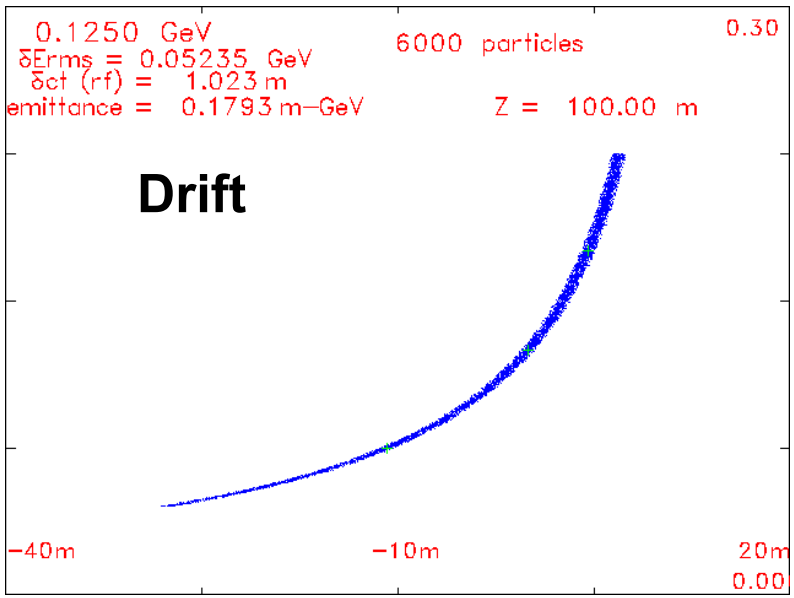


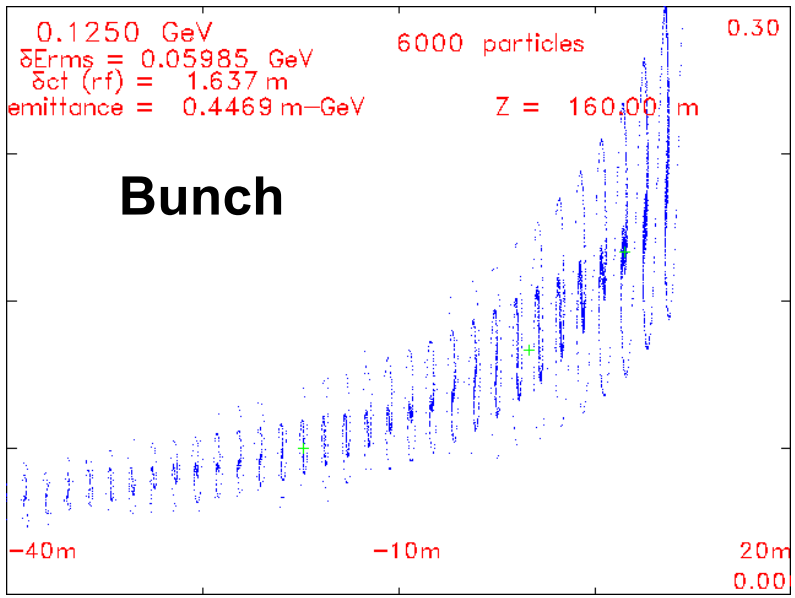
- **Drift (100m)**
- **Buncher (60m) 300→187MHz, V′ → 4.8 (z/L)² MV/m**
- **ϕ–δE Rotator(8.4m) 187MHz, V′ = 10 MV/m**
- **Cooler (100m) 183MHz**

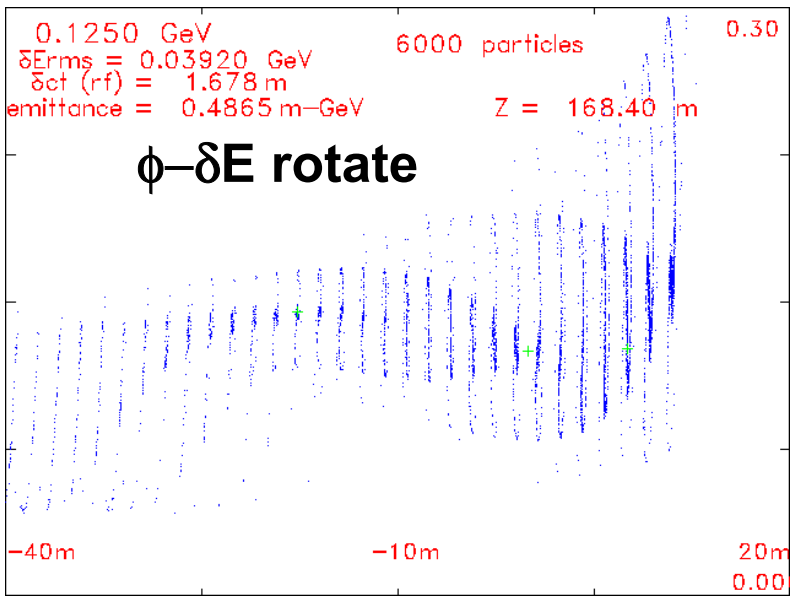
Component Parameters

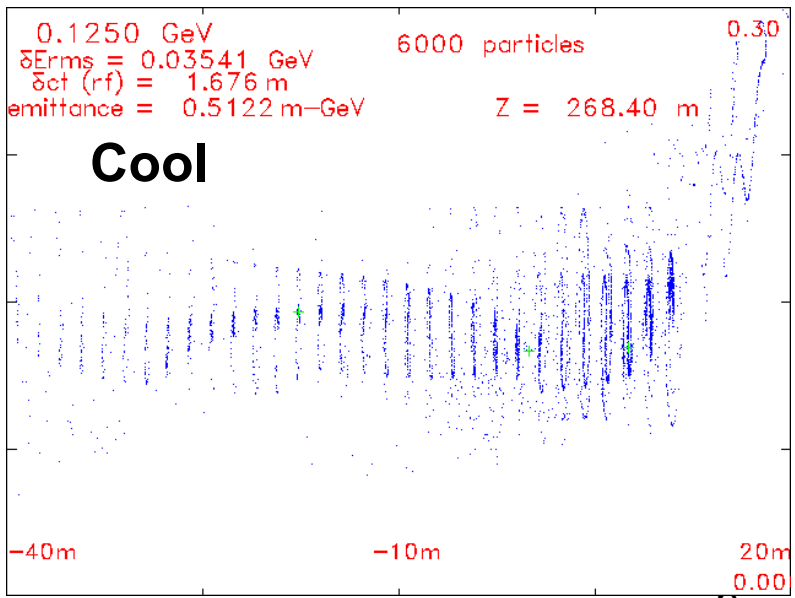
- **Drift (100m)**
  - **Allows $\pi \rightarrow \mu$ beam to decay;**
    lengthens to develop ϕ–δE correlation
- **Buncher (60m (?))**
  - **Bunching rf with E_0 = 125±50 MeV set at 15 λ separation**
    - **V_{rf} increases gradually from 0 to 4.8 MV/m**
- **ϕ–δE Rotation**
  - **Fixed frequency; V_{rf} set at a maximum value (10MV/m)**
    - **Beam rotates by ~1/4 synchrotron oscillations**
      to reduce δE
- **Cooler**
  - **fixed frequency transverse cooling system (~100m long)**

Longitudinal Motion Through System









Longitudinal motion (ΔE–ϕ space)

$$\frac{d\Delta E}{ds} = eV'(\cos(\phi+\phi_s)-\cos\phi_s) \cong -eV'\sin\phi_s\,\phi$$

$$\frac{d\phi}{ds} \cong \frac{1}{\beta^3\gamma}\left(\frac{1}{\gamma^2}-\frac{1}{\gamma_t^2}\right)\frac{2\pi}{\lambda_0}\frac{\Delta E}{mc^2} = \frac{1}{\beta^3\gamma}\alpha_p\frac{2\pi}{\lambda_0}\frac{\Delta E}{mc^2}$$

Where $M_{56}' = 1/\gamma_t^2 = \eta/R$ indicates a (possibly) nonisochronous transport

Equilibrium trajectories follow:

$$eV'\sin\phi_s\;\phi^2 + \frac{1}{\beta^3\gamma}\frac{2\pi}{\lambda_0}\frac{\alpha_p}{mc^2}\Delta E^2 = \text{constant}$$

which implies:

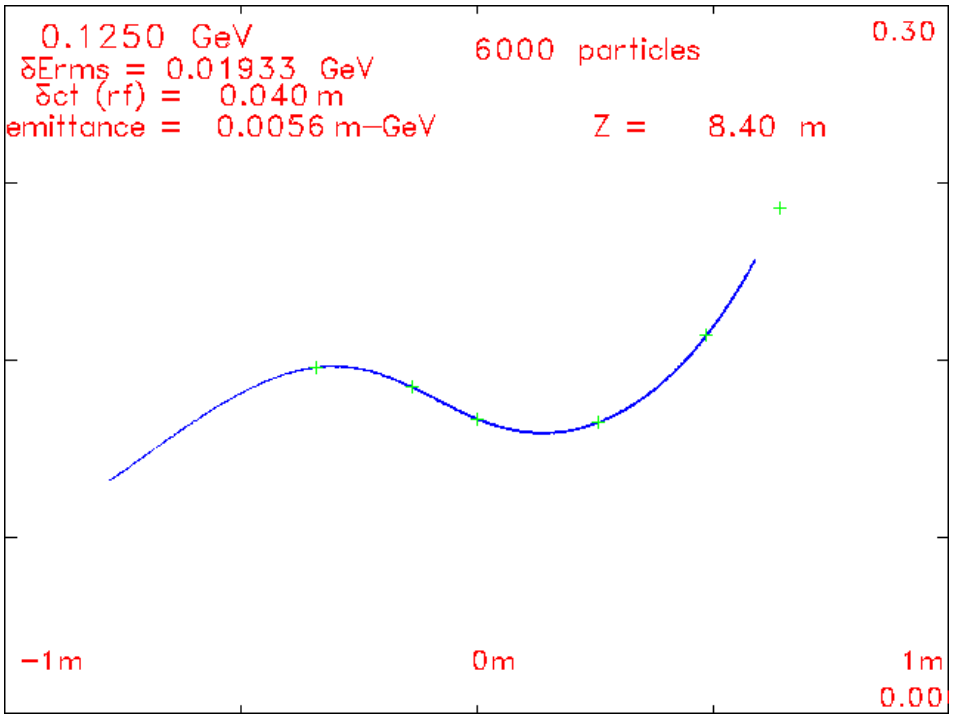
$$\frac{\langle\phi^2\rangle}{\langle\Delta E^2\rangle} = \frac{1}{\beta^3\gamma\, eV'\sin\phi_s}\frac{2\pi}{\lambda_0}\frac{\alpha_p}{mc^2} \equiv \beta_\phi^{\,2}$$

, where β_ϕ is a "longitudinal betatron function"

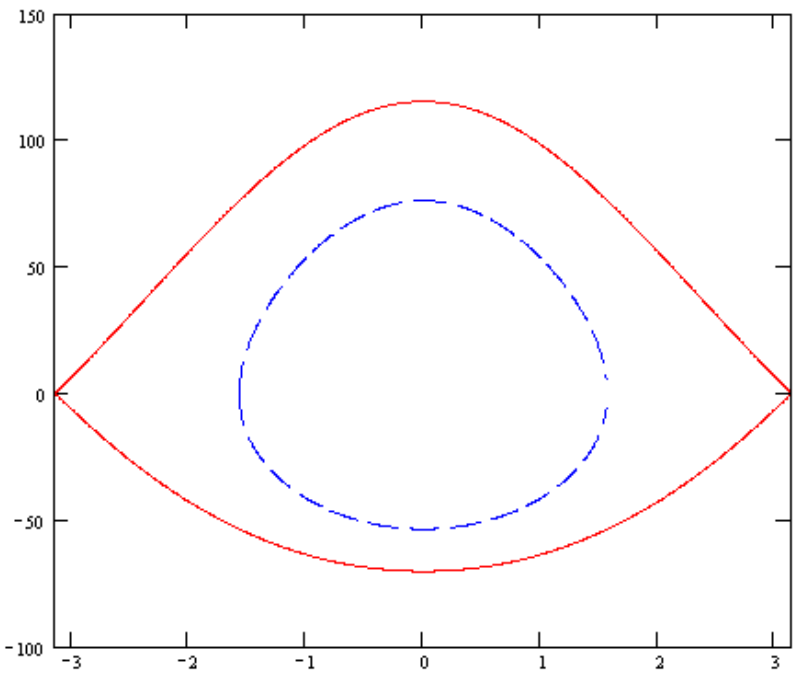
Note: longitudinal cooling requires reducing $\lambda_0\,\beta_\phi$; (by smaller α_p, λ_0; larger V')

187MHz φ–δE-Rotation & rf Bucket

- φ–δE **Rotation over many bunches is similar to rotation in single bunch**



Small phase-spread beam after 8.4m

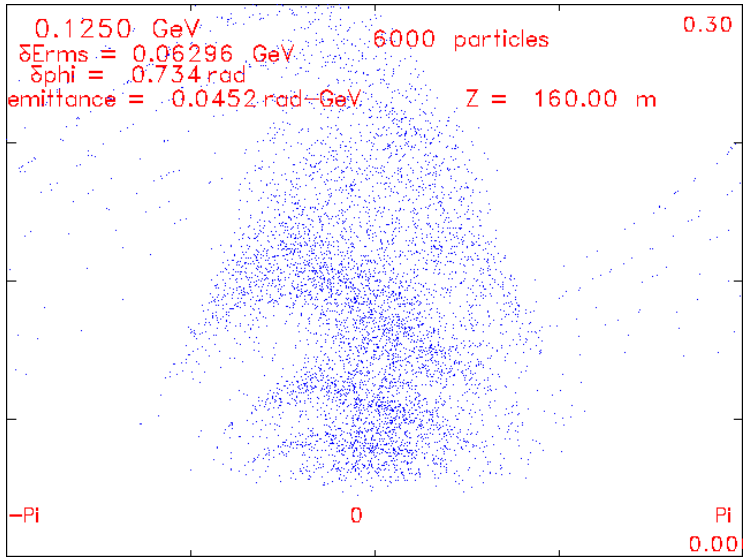


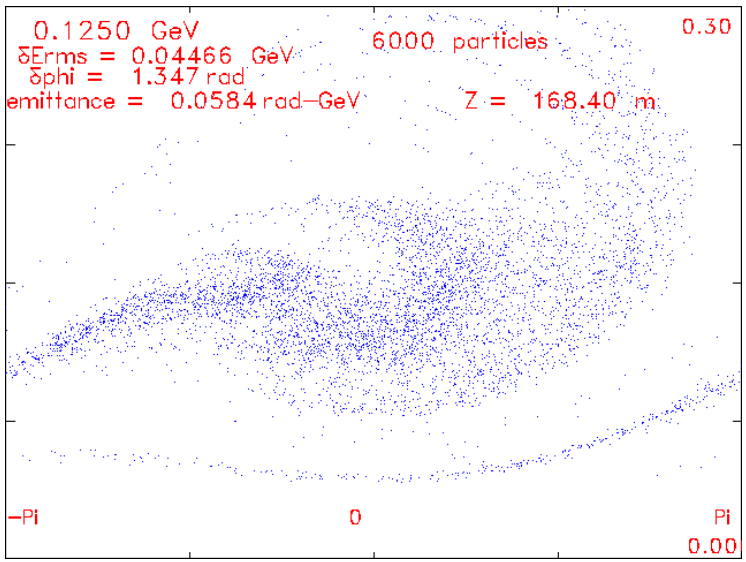
187MHz, 10 MV/m rf bucket

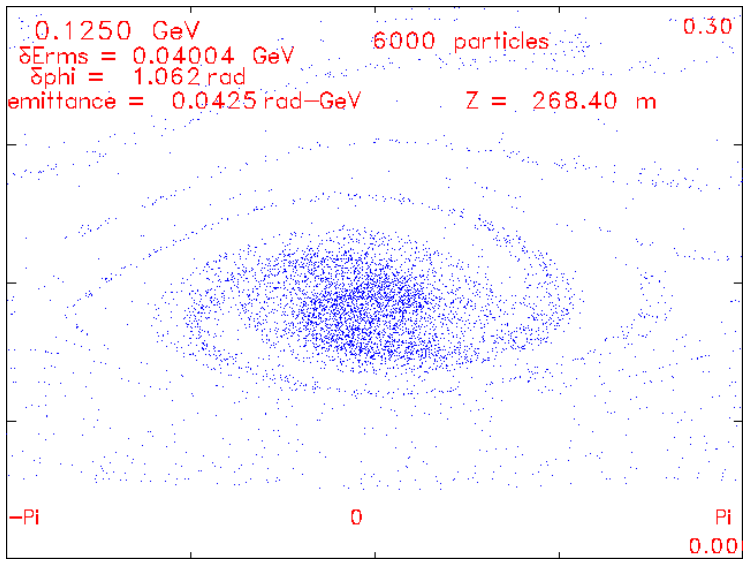
Phase-E Distributions (–π, +π)

Aliased view
- Particle phases as located within local rf wave

$$\phi = 2\pi\left(\frac{(z - z_0)}{\lambda_{rf}} - \text{round}\left[\frac{(z - z_0)}{\lambda_{rf}}\right]\right)$$





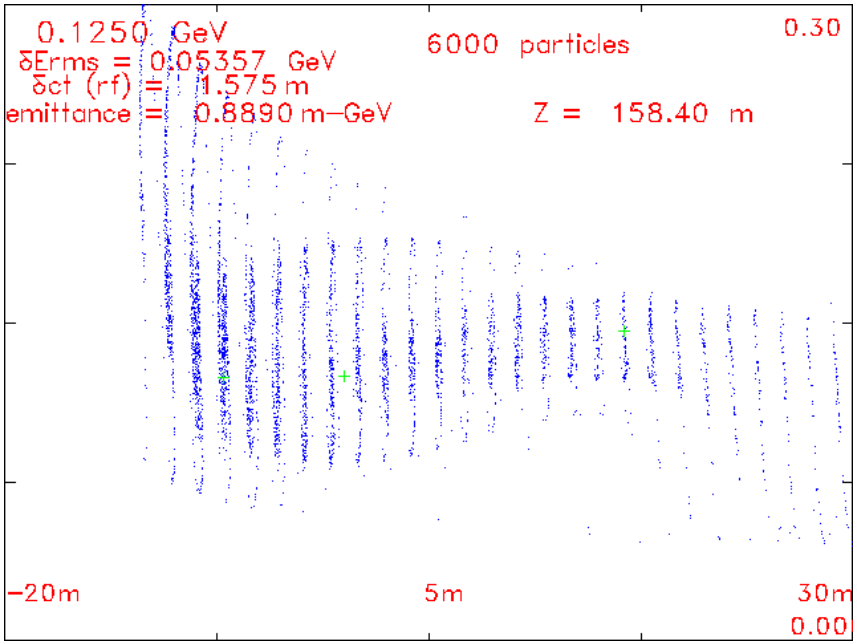


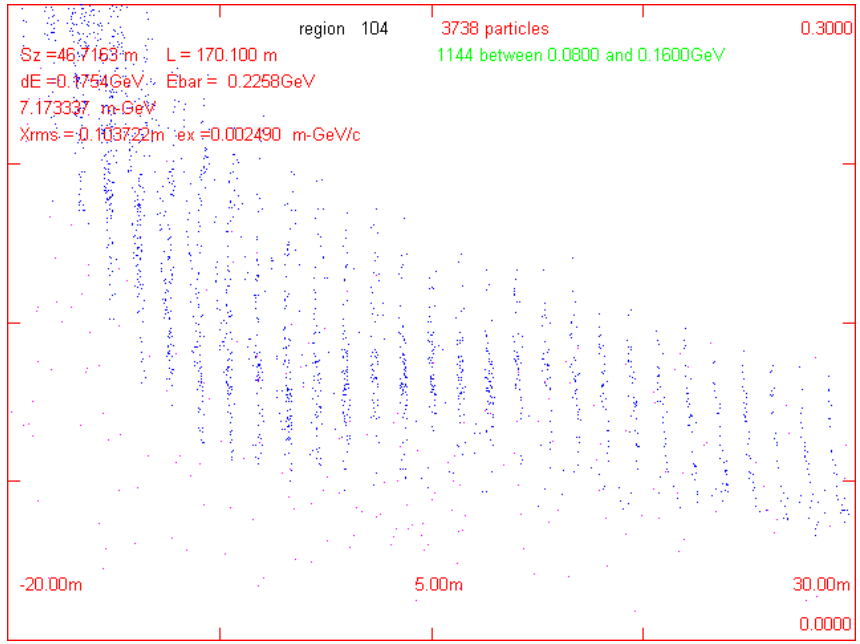
ICOOL Simulations

- **ICOOL Simulations**
  - **Include Transverse motion + realistic initial distributions**
- **Initial beam - Palmer target production**
- **Transverse focusing -**
  - **20 T(Target) $\rightarrow$ 1.25T solenoid**
  - **1.25 T focusing throughout (σ_x = 10cm)**
- **Buncher + $\phi \rightarrow \delta E$ rotation**
  - **Use parameters approximating 1-D simulation;**
  - **NOT reoptimized**

- **Buncher + $\phi \rightarrow \delta E$ rotation ~ works**

First ICOOL simulations





1-D Simulation
- beam at end of buncher
+ ϕ-E rotation

Initial beam: idealized μ-production

3-D ICOOL Simulation
- beam at end of buncher
+ ϕ-E rotation

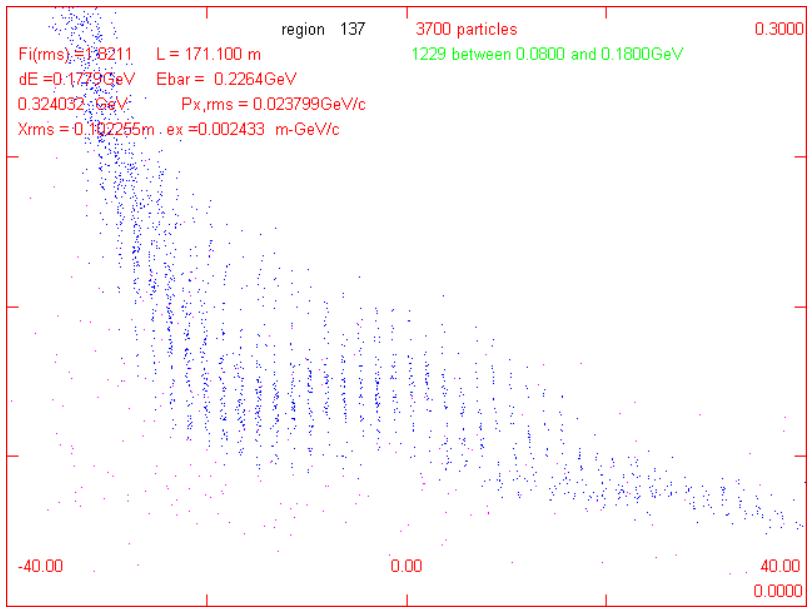
Initial beam: Target π-production

Icool Simulations

- R. Fernow has added "adiabatic buncher" to ICOOL elements
- Adds new acceleration element with
  - Ramped rf
  - Length, amplitude and shape of ramped rf can be varied.
  - Variable frequency with fixed # of λ's between reference energies
- Initially; matches to fixed frequency rf at end of adiabatic buncher

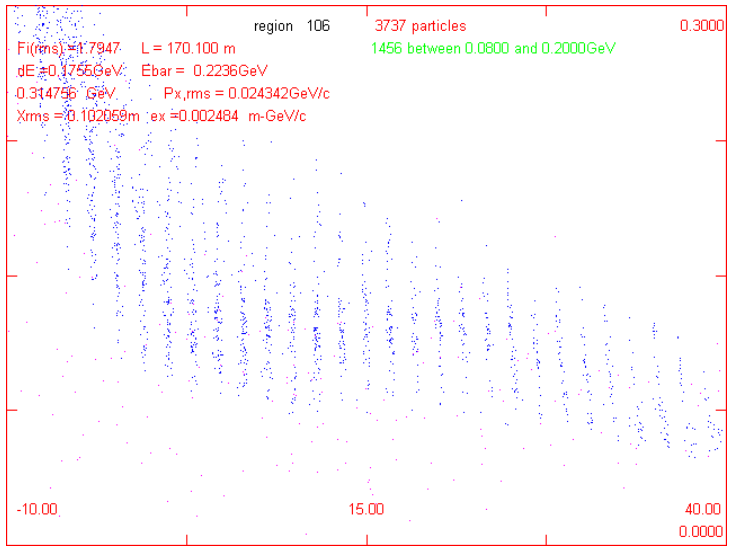
Agrees qualitatively with 1-D simulations

First try :



Icool simulations: early tests

- Re-optimize phases of rf

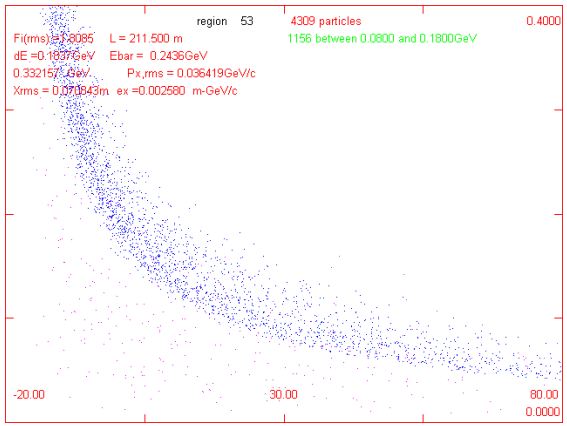


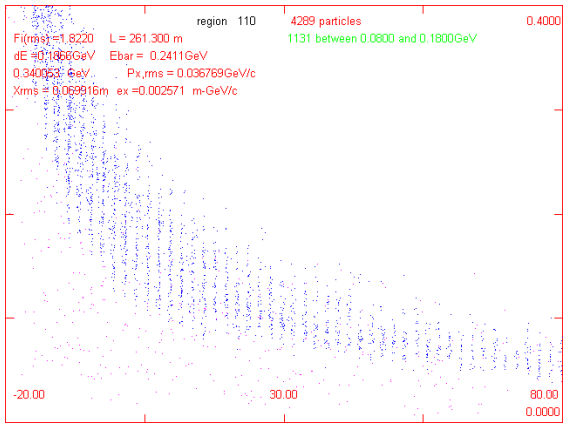
- Change focusing from 1.25T to 3T
  - Slightly better capture but bigger beam
- Change drift from 100 m to 200m

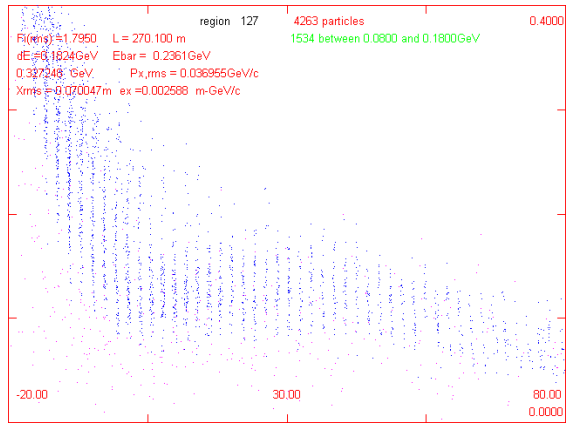
200m drift simulations

Muon Collaboration

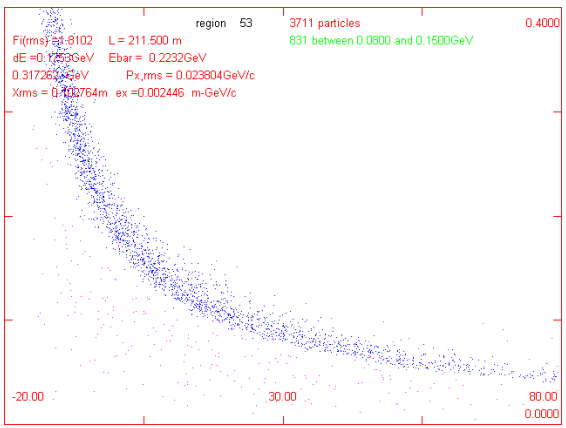
B=3 T - drift (200m) **bunch(60m)** **rotate (10m)**

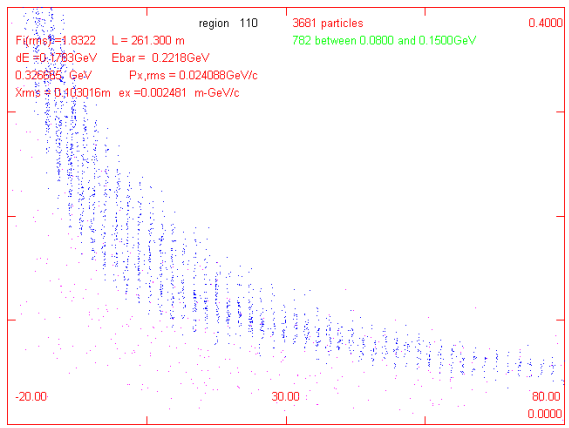


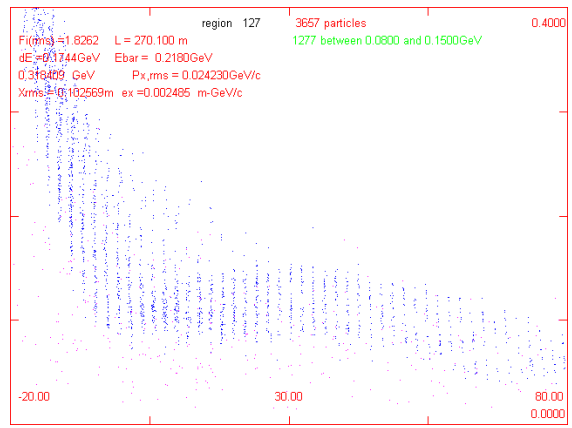




B=1.25T







Simucool optimizations (AvG)

- Large statistics tracking code (**SIMUCOOL**) can be used to reoptimize Buncher + ϕ–δE Rotation

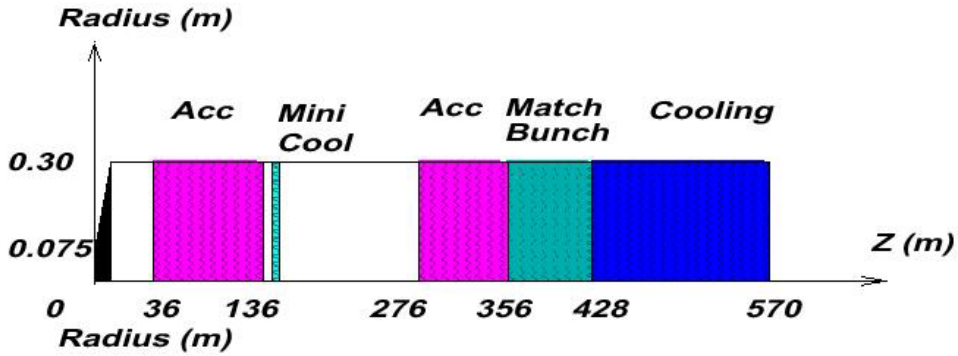
- **Reoptimize** baseline adiabatic buncher and fixed frequency ϕ–δE **rotation** (track rms bunches in each band)
  - – Obtains ~0.3 μ/p (up from 0.25)

- **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**

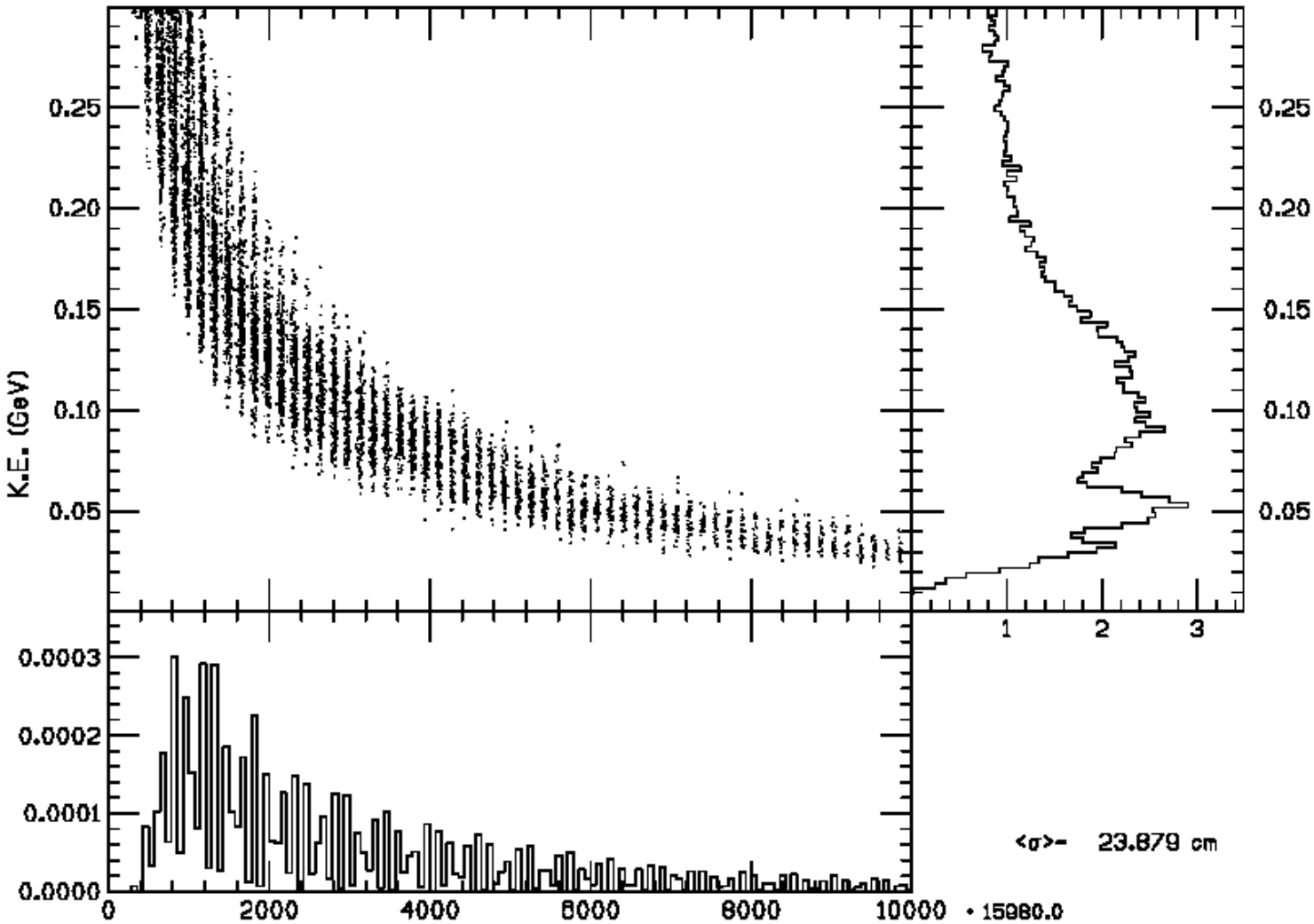
- **Retrack with ICOOL – similar results are obtained**

Baseline BNL Induction Linacs + rf buncher

- Obtains ~0.375 μ/p at end of buncher
- Nondistortion

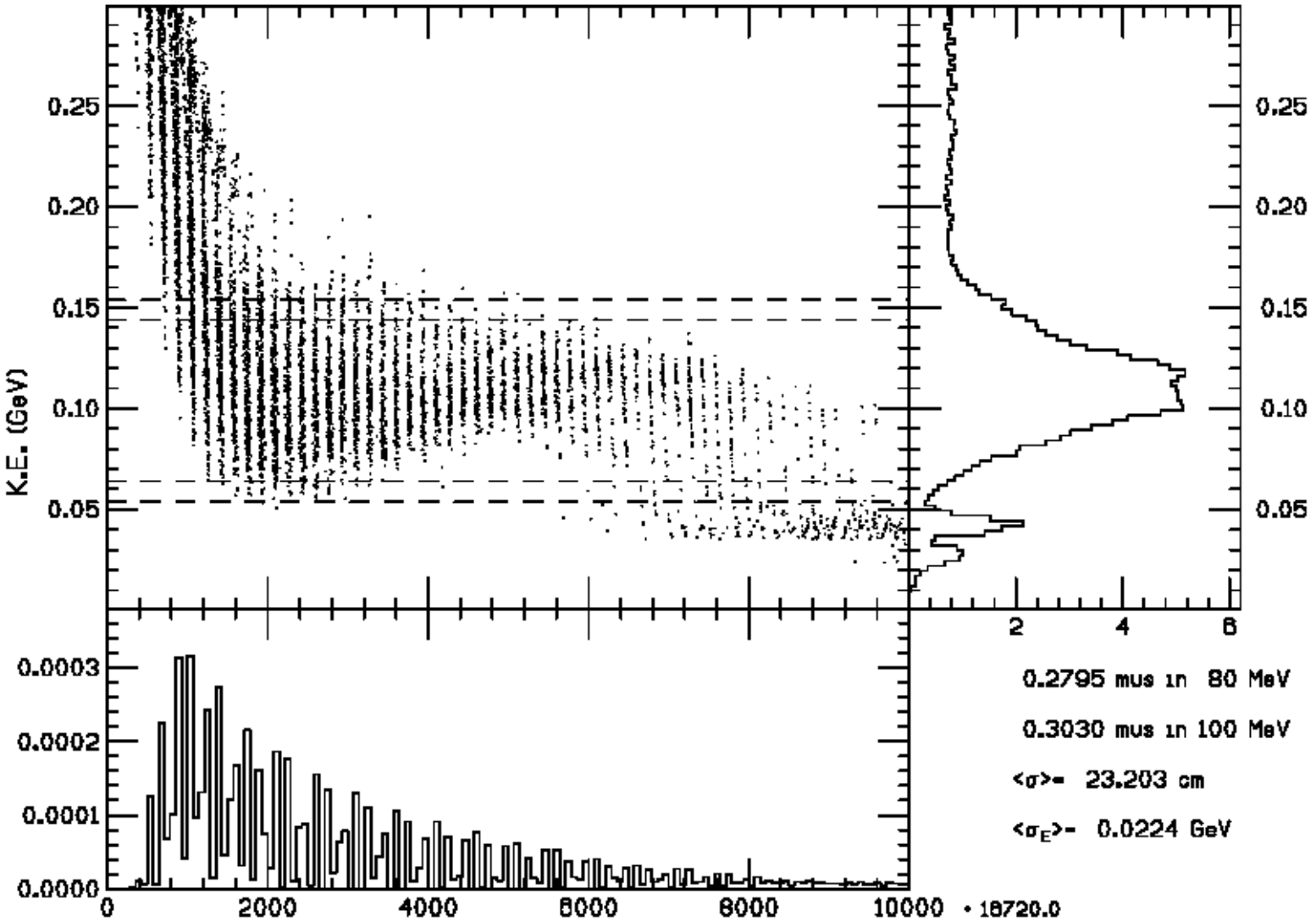


SIMUCOOL Beam at end of buncher



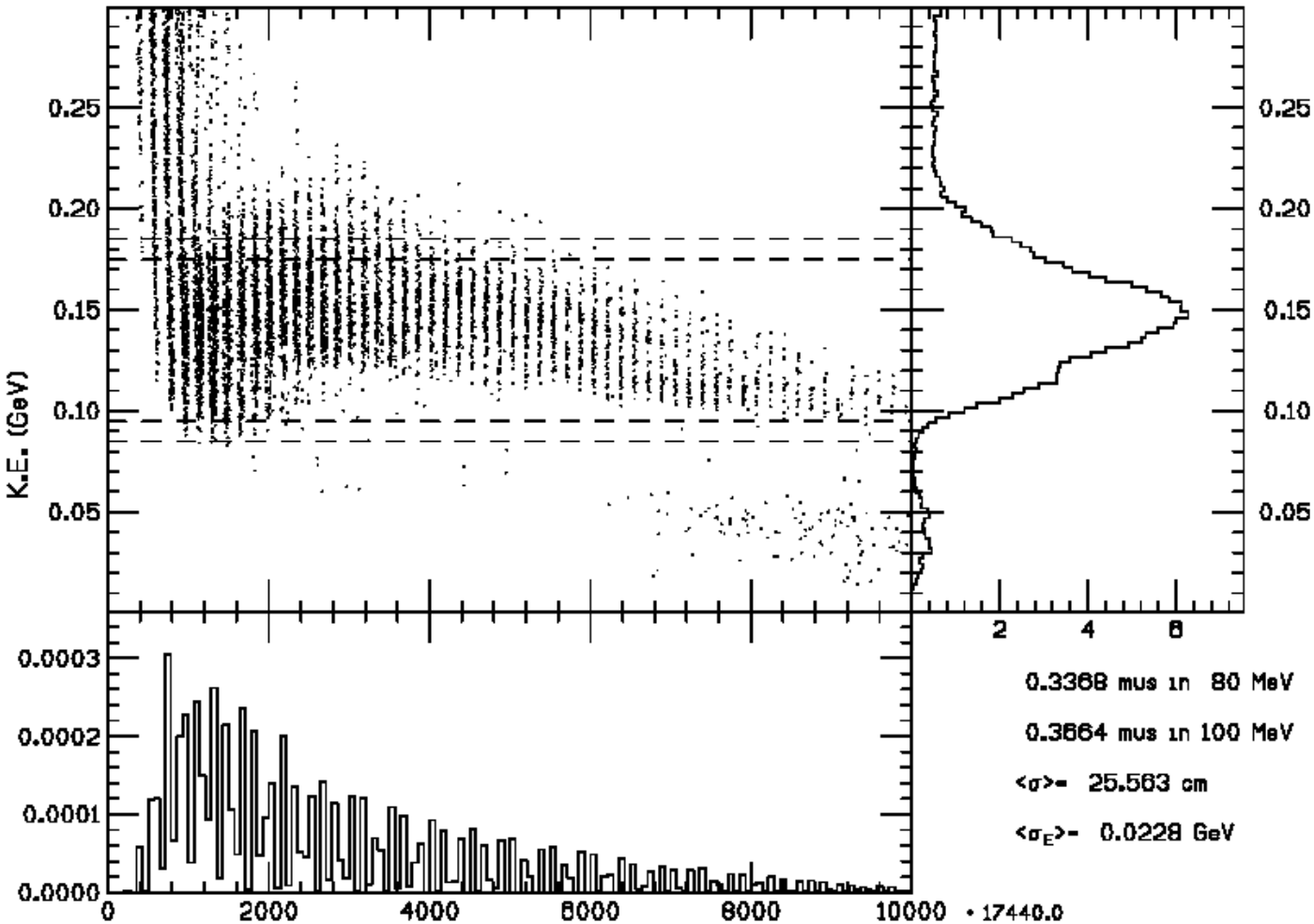
Simucool-reoptimized buncher and fixed frequency ϕ–δE rotation

- Obtains ~0.28 μ/p at end of buncher



"Vernier"-optimized ϕ–δE rotation

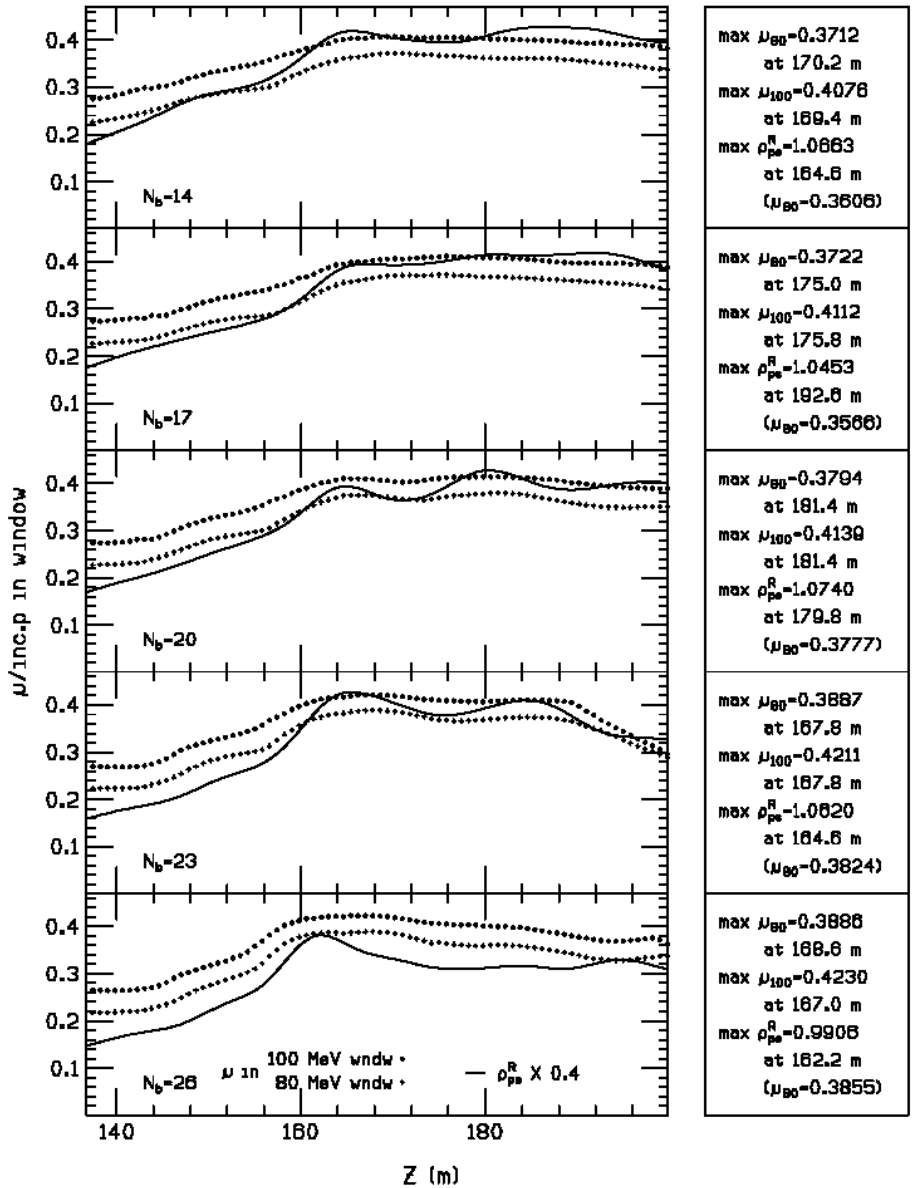
- Obtains ~0.34 μ/p at end of buncher



Latest Optimizations

- A van Ginneken has completed a new set of optimizations; changes some parameters
- Drift – reduced to ~76m (B=1.25T)
- Buncher parameters changed:
  - Reference kinetic 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 (~20m)

Increase in acceptance along channel



AvG Table of simulations

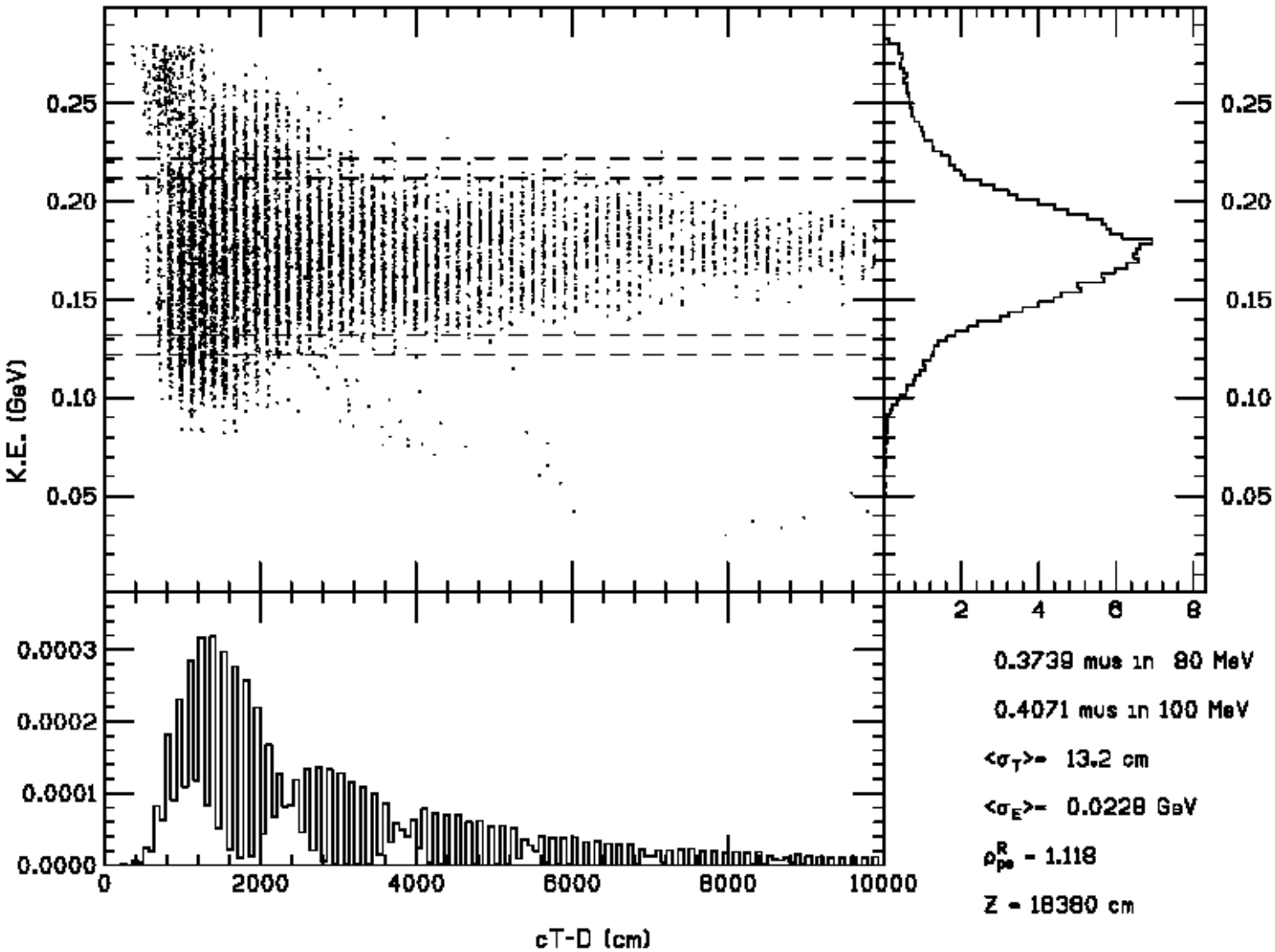
- Andy varied a number of parameters in a search for an “optimum”
- Table on right displays a search varying the parameters:
  - N – Number of rf bunches
  - δ – phase shift of rotator
- Other parameters varied included length of rotator, voltage, buncher voltage and program

d		$N_b = 14$	$N_b = 17$	$N_b = 20$	$N_b = 23$	$N_b = 26$
0.06	$\hat{\mu}$	$\geq$ 0.3567	$\geq$ 0.3497	$\geq$ 0.3789	$\geq$ 0.3606	$\geq$ 0.3206
	max ρ_{ps}	$\geq$ 0.5866	$\geq$ 0.6083	0.8351	$\geq$ 0.8813	$\geq$ 0.7791
	max ρ^R_{ps}	$\geq$ 0.8721	$\geq$ 0.7994	0.9300	$\geq$ 0.8890	$\geq$ 0.6919
	Z,m	$\geq$ 200.6	$\geq$ 200.6	195.8	$\geq$ 200.6	$\geq$ 200.6
	μ(Z)	$\geq$ 0.3567	$\geq$ 0.3497	0.3703	$\geq$ 0.3606	$\geq$ 0.3206
0.09	$\hat{\mu}$	0.3805	0.3764	0.3738	0.3748	0.3748
	max ρ_{ps}	0.6037	0.6828	0.8910	0.9804	1.0652
	max ρ^R_{ps}	0.9172	0.9223	1.0114	1.0031	0.9650
	Z,m	190.2	193.4	189.4	191.8	195.0
	μ(Z)	0.3654	0.3622	0.3728	0.3738	0.3702
0.12	$\hat{\mu}$	0.3835	0.3840	0.3918	0.3840	0.3808
	max ρ_{ps}	0.6627	0.7581	0.9112	1.0653	1.1180
	max ρ^R_{ps}	0.9494	0.9497	1.0362	1.0772	0.9415
	Z,m	168.6	173.4	187.0	184.6	168.6
	μ(Z)	0.3741	0.3733	0.3696	0.3796	0.3799
0.15	$\hat{\mu}$	0.3784	0.3781	0.3900	0.3902	0.3954
	max ρ_{ps}	0.7053	0.8149	1.0051	1.1105	1.1808
	max ρ^R_{ps}	1.0219	1.0236	1.0741	1.0485	0.9737
	Z,m	166.2	169.4	167.0	166.2	163.0
	μ(Z)	0.3697	0.3749	0.3873	0.3879	0.3931
0.18	$\hat{\mu}$	0.3711	0.3739	0.3822	0.3862	0.3923
	max ρ_{ps}	0.7072	0.8156	1.0183	1.0936	1.1688
	max ρ^R_{ps}	1.0313	1.0137	1.0767	1.0139	0.9570
	Z,m	163.8	164.6	162.2	161.4	160.6
	μ(Z)	0.3652	0.3701	0.3825	0.3862	0.3917
0.21	$\hat{\mu}$	0.3656	0.3720	0.3842	0.3884	0.3921
	max ρ_{ps}	0.6783	0.8017	0.9649	1.0278	1.1250
	max ρ^R_{ps}	0.9908	0.9868	1.0042	0.9437	0.9232
	Z,m	161.4	161.4	158.2	157.4	158.2
	μ(Z)	0.3651	0.3720	0.3841	0.3879	0.3909
0.24	$\hat{\mu}$	0.3691	0.3760	0.3899	0.3951	0.3911
	max ρ_{ps}	0.6413	0.7625	0.9684	1.0517	1.1446
	max ρ^R_{ps}	0.9338	0.9339	0.9943	0.9582	0.9406
	Z,m	158.2	157.4	155.8	155.0	155.8
	μ(Z)	0.3675	0.3739	0.3869	0.3939	0.3911
0.27	$\hat{\mu}$	0.3738	0.3815	0.3923	0.3948	0.3881
	max ρ_{ps}	0.6254	0.7588	0.9741	1.0933	1.1677
	max ρ^R_{ps}	0.9002	0.9234	0.9897	0.9911	0.9629
	Z,m	156.6	155.8	153.4	153.4	154.2
	μ(Z)	0.3661	0.3758	0.3909	0.3938	0.3879
0.30	$\hat{\mu}$	0.3763	0.3841	0.3909	0.3909	0.3821
	max ρ_{ps}	0.6332	0.7569	0.9813	1.0963	1.1547
	max ρ^R_{ps}	0.8978	0.9128	0.9850	0.9886	0.9541
	Z,m	153.4	155.8	151.0	152.6	153.4
	μ(Z)	0.3763	0.3799	0.3909	0.3894	0.3790
0.33	$\hat{\mu}$	0.3754	0.3828	0.3866	0.3853	0.3740
	max ρ_{ps}	0.6401	0.7537	0.9511	1.0857	1.1297
	max ρ^R_{ps}	0.8904	0.8975	0.9509	0.9678	0.9275
	Z,m	151.0	151.8	150.2	151.0	151.8
	μ(Z)	0.3751	0.3907	0.3866	0.3843	0.3723
frequency range in MHz		155 to 269	187 to 327	222 to 384	255 to 442	288 to 500

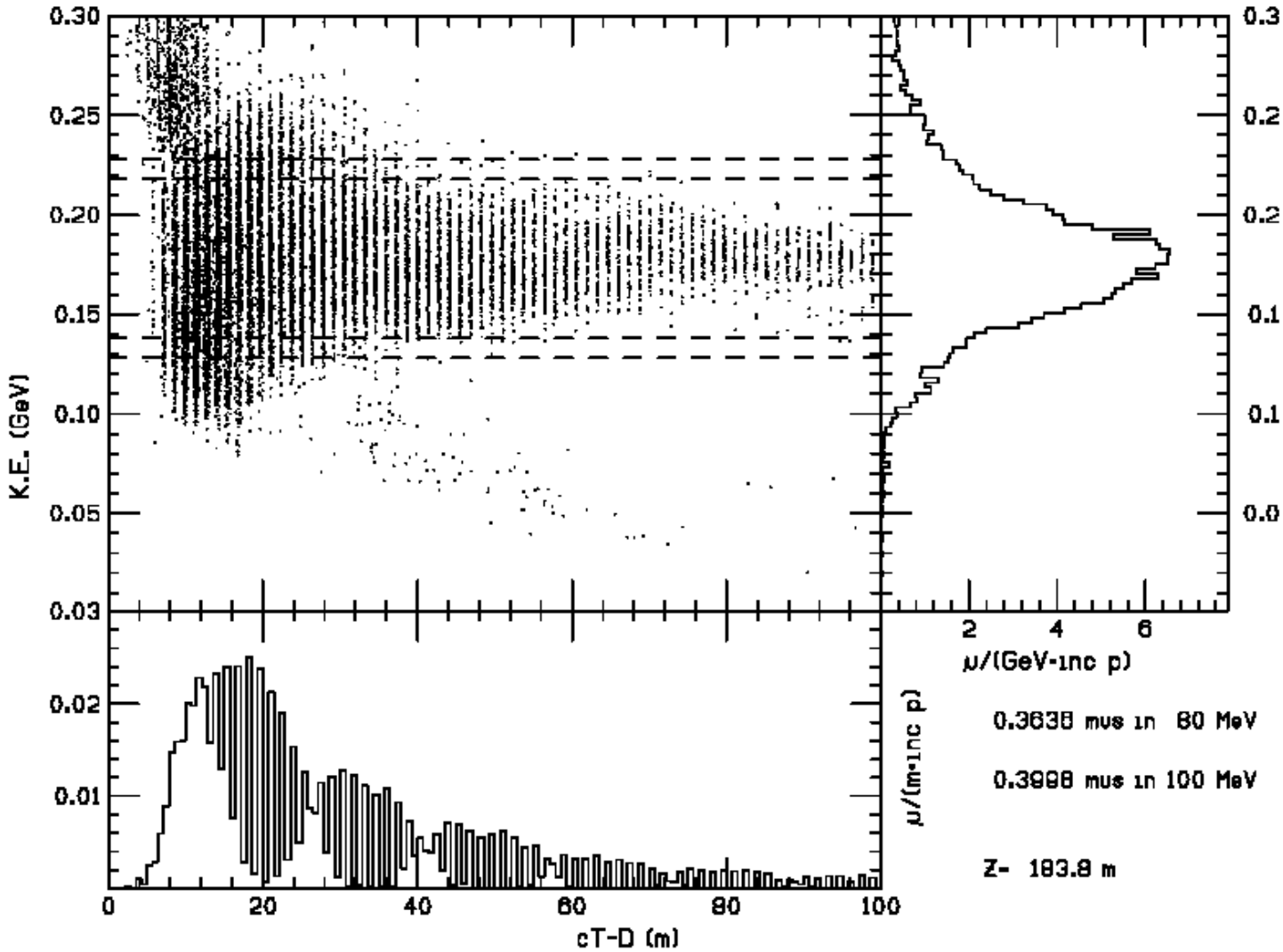
Latest Results

- Initial beam was (MARS) 24 GeV p on Hg target, captured in 20→1.25T
- Best examples obtain ~0.40 μ/initial proton
- Longitudinal density ~2X that of earlier simulations
- Compatible results obtained in SIMUCOOL and ICOOL runs

AvG Simulation of optimized buncher



ICOOL simulation of buncher



Summary

- High frequency buncher and rotation appears to work ...
- It requires:
  - Drift section (100m ?)
  - Buncher; for ~ adiabatic capture of beam into string of bunches
  - (~60m, up to ~6MV/m, 300 to 200 MHz rf)
  - Bunch rotator (~10—100m, 10MV/m, ~200MHz;)
  - matched optics, into cooling channel
  - transverse focusing throughout ...
- System obtains strings of both μ^+ and μ^- bunches

- Integration into complete ν–Factory scenario is still required (next: match into cooling channel)

Improved Version ...