# Cooling Channel Considerations and Performance

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Fermilab 2/15/00

# Cooling Channel Parameters

Bunched beam enters cooling channel at 0.2 GeV/c

- bunched with 175 MHz RF

  for historical reasons; use 200 MHz next iteration

- need 75 cm radius bore to fit RF cavities

Sinusoidal field with period 2.2 m

- need to flip sign of field to avoid build-up of angular momentum
- shorter cell sizes tend to give smaller beta functions because coils are at large radius, hard to flip field more often, requires large currents in high fields

# FOFO Lattice

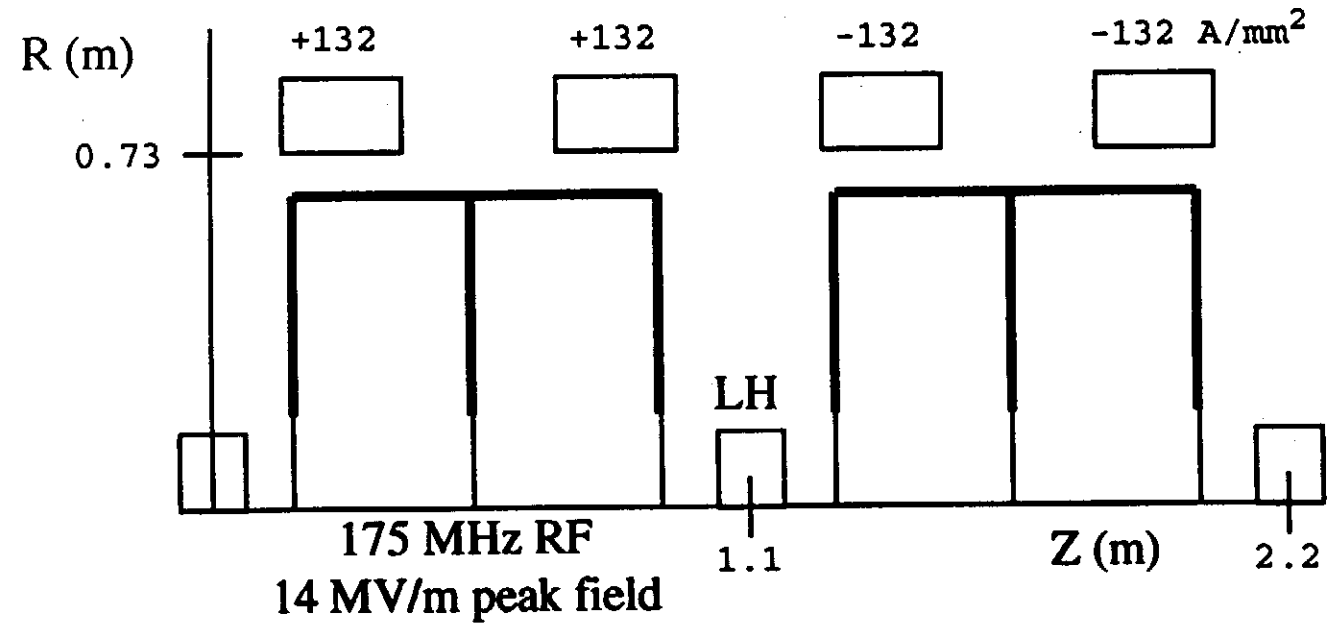
Symmetric field with $B_Z$ on axis roughly sinusoidal

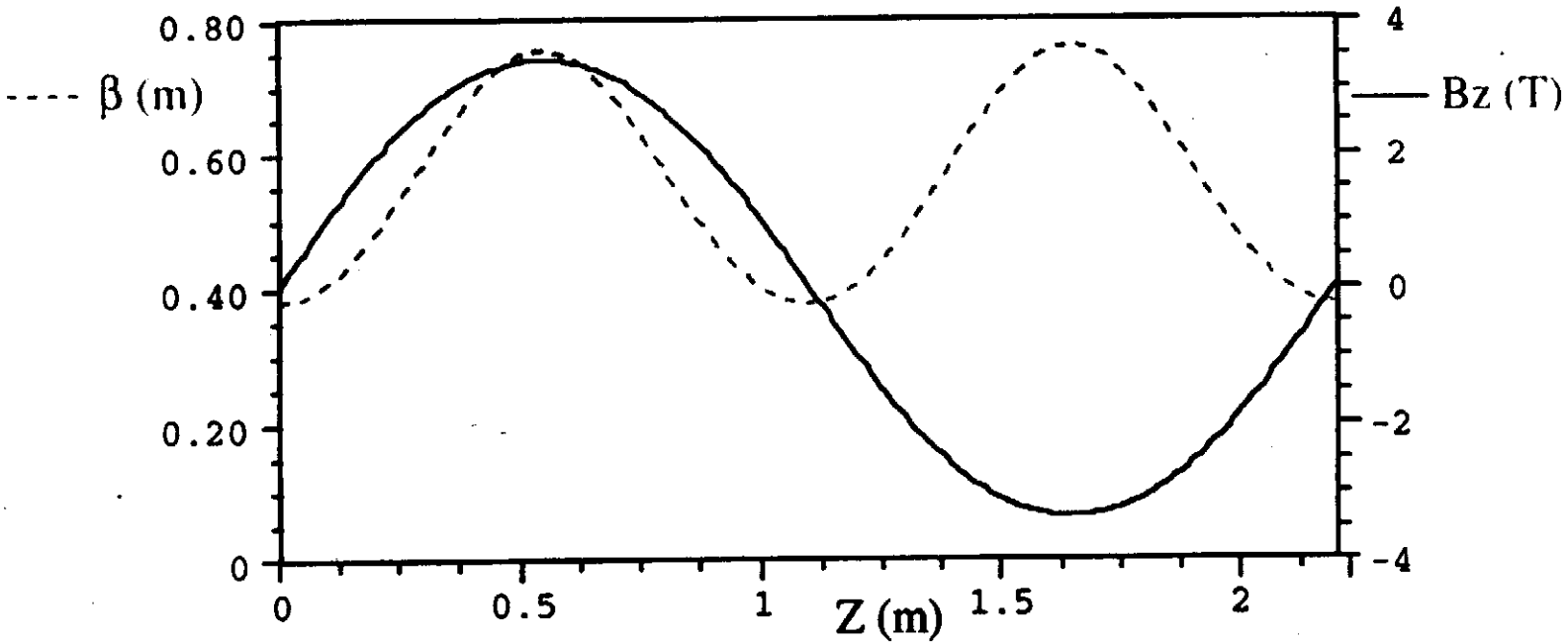
- rough guide, $B_{MAX}$ [T] $\approx$ 18 $P_Z$ [GeV/c] / L [m], where L is half cell length, $P_Z$ is beam momentum

Particles are not propagated for $P_Z$ sufficiently far below design momentum

- transverse particle losses at beginning roughly determined by maximum beta function
- final transverse emittance roughly determined by minimum beta function

# FOFO 1.1 m cell size



# Case 2 Design

Coils:

3.4 T peak field on axis

12 T peak field at coils

132 A/mm$^2$ current density

RF:

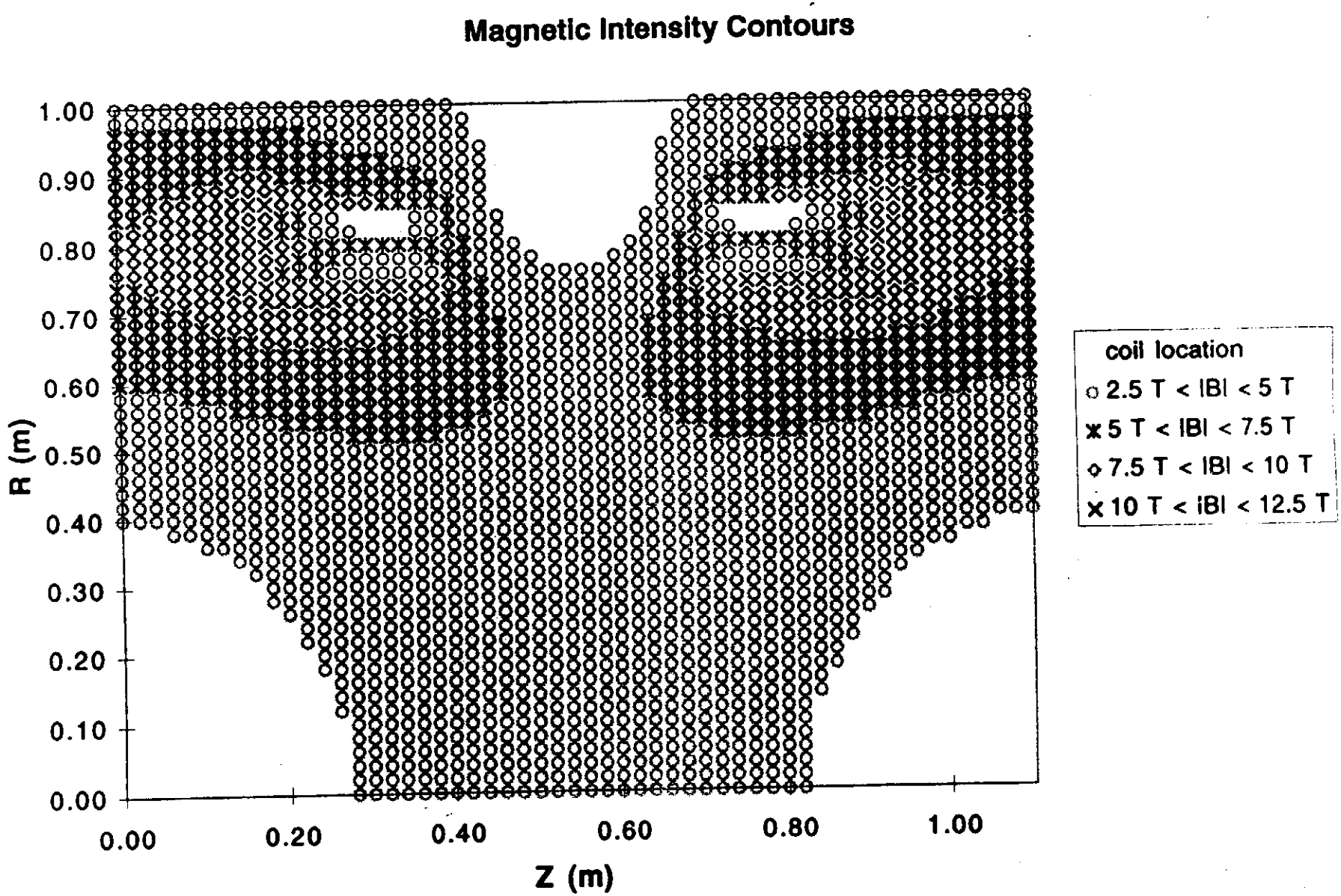
175 MHz with 14 MV/m peak field

absorbers, rescaled along lattice:

LH-filled cavity, radius 15 $\Rightarrow$ 8 cm

length 12.6 $\Rightarrow$ 13.2 cm

Al window, thickness 500 $\Rightarrow$ 200 $\mu$


Magnetic Intensity Contours
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
R (m)
0.00
0.20
0.40
0.60
0.80
1.00
Z (m)
coil location
2.5 T < IBI < 5 T
5 T < IBI < 7.5 T
7.5 T < IBI < 10 T
10 T < IBI < 12.5 T

# Radial Aperture in Channel

Radial cuts behave like hard emittance cuts

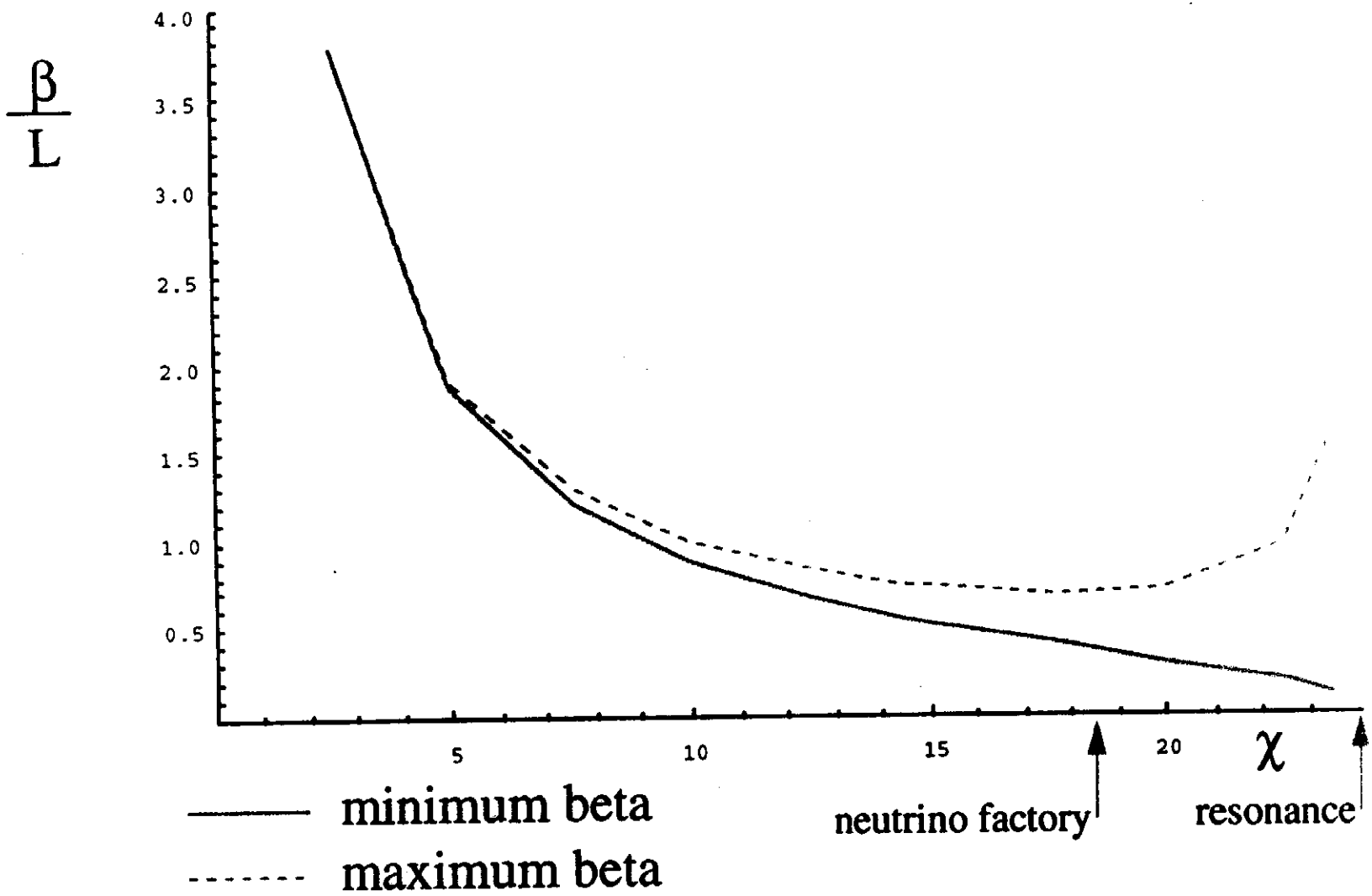
Most severe aperture restrictions:

- 19 cm Be windows, cuts in early stages of cooling
- last absorber type, 6 cm radius

Can equate with a corresponding amplitude cut:

| | Be window | LH cavity |
|---|---|---|
| radius (cm) | 19 | 6 |
| beta function (cm) | 75 | 38 |
| max amplitude (mm mrad) | 91000 | 18000 |
| beam emit (mm mrad) | 15000 | 2500 |
| expected survival | 81% | 87% |

# General FOFO scaling




$$\chi \equiv B_{MAX}\,[T]\; L\,[m] \,/\, P_Z\,[GeV/c]$$

# Hydrogen Absorber and Surrounding Walls

If walls of hydrogen absorber are made of Al, has radiation length 1/100 that of LH, so 100 X more multiple scatter.

Enhancement in energy loss is much weaker, so degrades cooling performance

- want long absorbers with thin walls
- to satisfy engineering constraints, use absorber with smallest radius possible
- size is reduced along lattice as beam is cooled and shrinks transversely
- length of absorber limited by geometry and need to re-accelerate

# Figure of Merit: Beam Emittance Cuts

Cooling characterized by $\varepsilon_N$, RMS beam emittance

can also consider # particles within given aperture

define transverse amplitude (corr to $\varepsilon_N$) as

$$A \equiv (P_Z/mc)\,\beta\,(r^2/\beta^2 + P_\perp{}^2/P_Z{}^2)$$

goal is final RMS emittance of 1500 mm mrad $\equiv \sigma_F$

look at particles having $A < 2\,\sigma_F$ ,

and $A < 4\,\sigma_F$.

# Beam Emittance and Spot Size

Can relate maximum amplitude of particles to the maximum required aperture

Consider 0.2 GeV/c beam with $\beta = 1$ m:

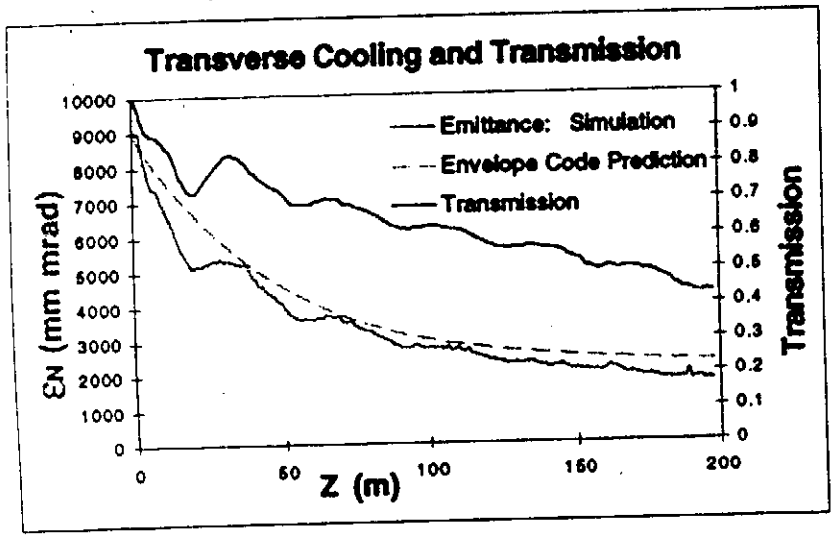
| max amplitude | radius (cm) | fraction w/in cut if $\varepsilon_N$ = 15000 | 1500 mm mrad |
|---|---|---|---|
| $\sigma_F$ | 2.8 | 0.0013 | 0.10 |
| $2\,\sigma_F$ | 4.0 | 0.0050 | 0.26 |
| $3\,\sigma_F$ | 4.9 | 0.011 | 0.44 |
| $4\,\sigma_F$ | 5.6 | 0.020 | 0.60 |

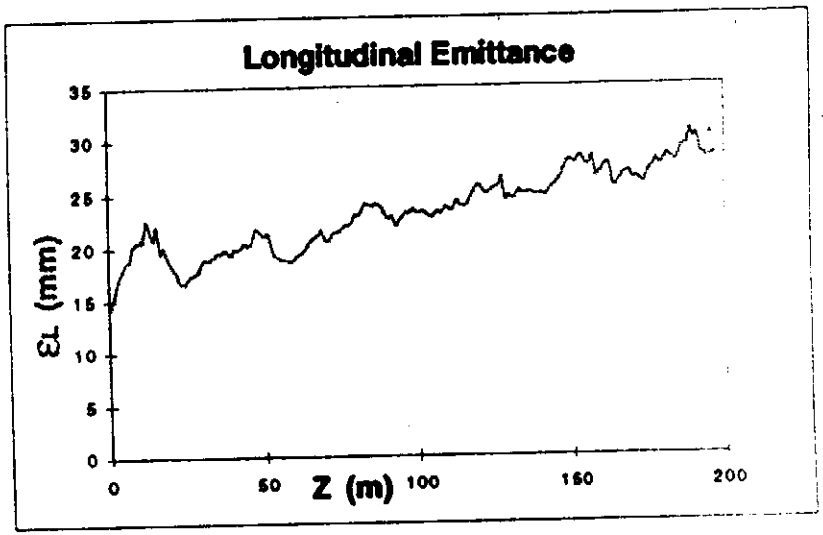
radius of beam scales as $(\beta / P_Z)^{1/2}$; $\sigma_F \equiv 1500$ mm mrad

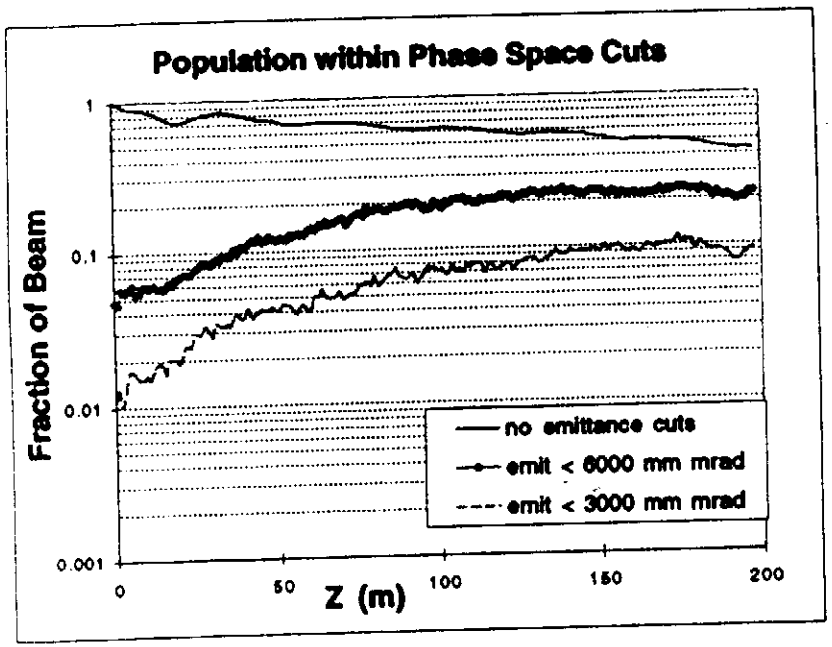
note: with $4\,\sigma_F$ cut, expect 30 X enhancement of number of particles within cut

# Case 2 Cooling Lattice

Gaussian Beam with Initial Design Emittance: $\varepsilon_\perp$ = 9000 mm mrad, $\varepsilon_L$ = 15 mm




Lattice Properties:

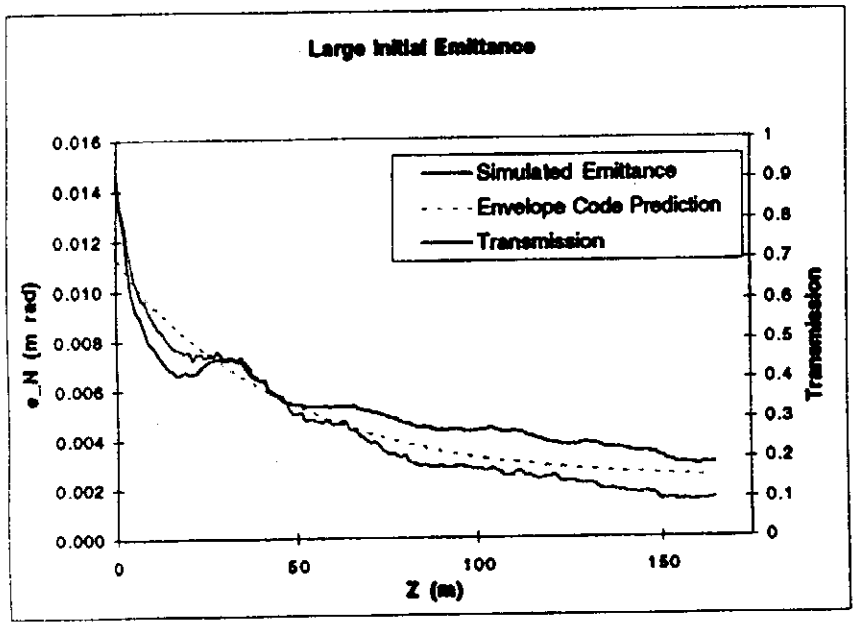
| | |
|---|---|
| Peak Field on Axis | 3.4 T |
| Peak Field at Coils | 12 T |
| Current Density | 132 A/mm2 |
| LH length | 12.6 cm --> 13.2 cm |
| LH radius | 15 cm --> 8 cm |
| Al wall thickness | 500 μ --> 200 μ |
| Be window thickness | 125 μ |
| Be window radius | 19 cm |
| RF | 175 MHz, 14 MV/m |

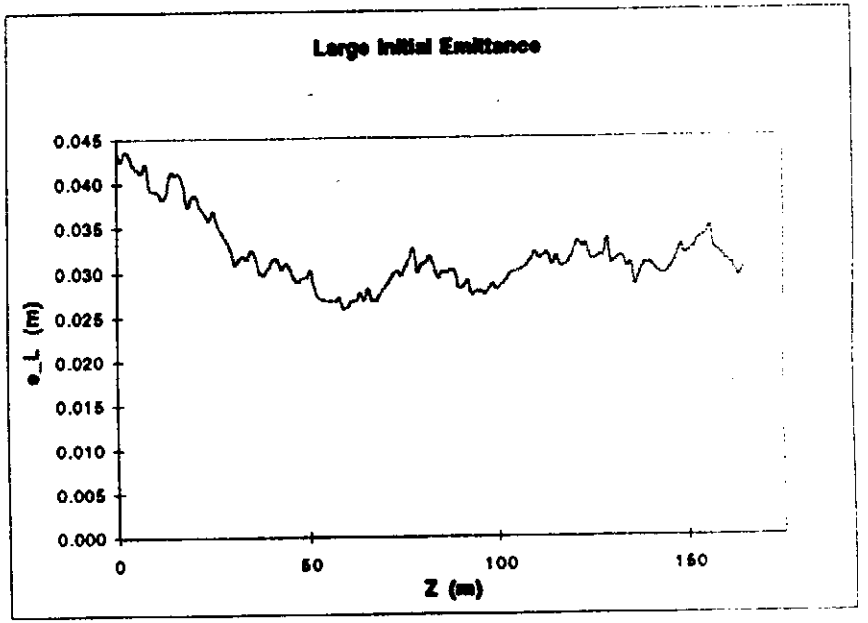
within 6000 mm mrad cut, # particles in phase space is enhanced by factor of 6

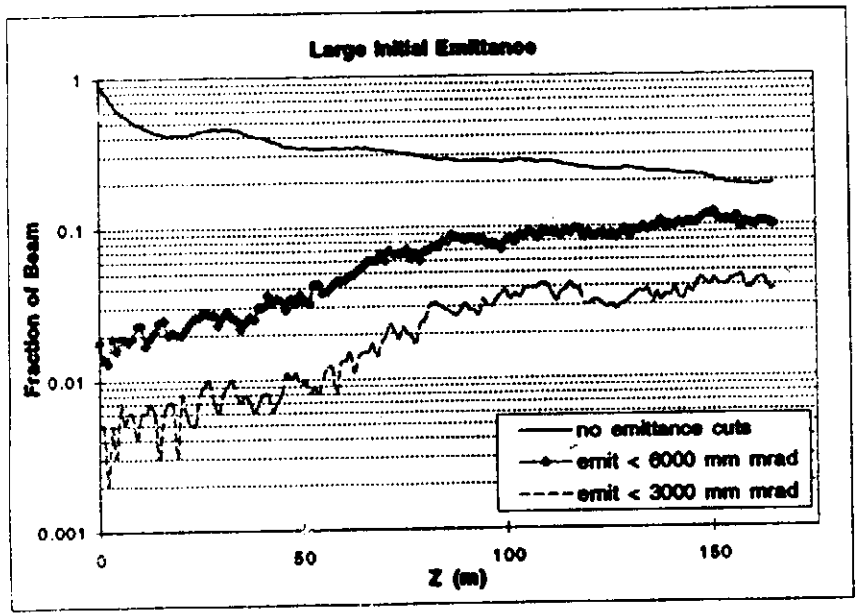
ideal case for cooling from 9000 to 1500 mm mrad is factor of 13

$0.15 < P_z < 0.25$ GeV/c "window"

# Trial Runs for Case 2 Cooling Lattice




w/in 6000 mm mrad,

6x enhancement after 150 m

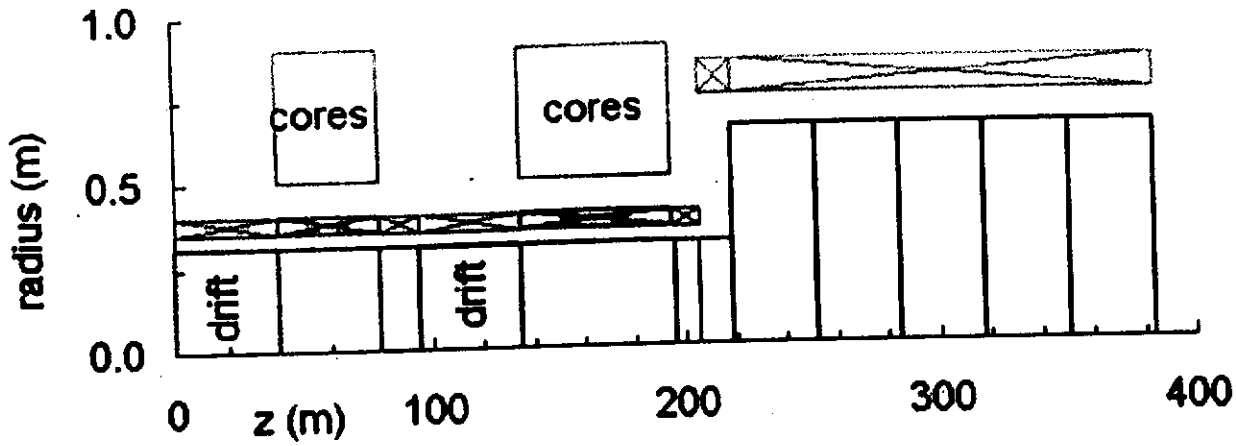
# Integrated Front-End Simulation

## Case 2

Charles Kim, LBL

Charles Kim, LBL

## CASE2 CONFIGURATION (NO POLARIZATION)




1st induction linac (40 m) field reversal & minicooling

2nd induction linac (60m)

matching & bunching

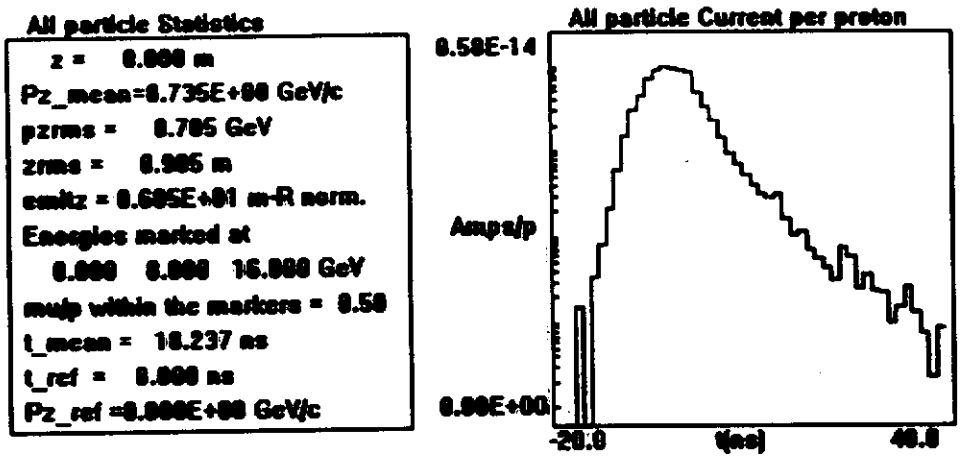
cooling section 1

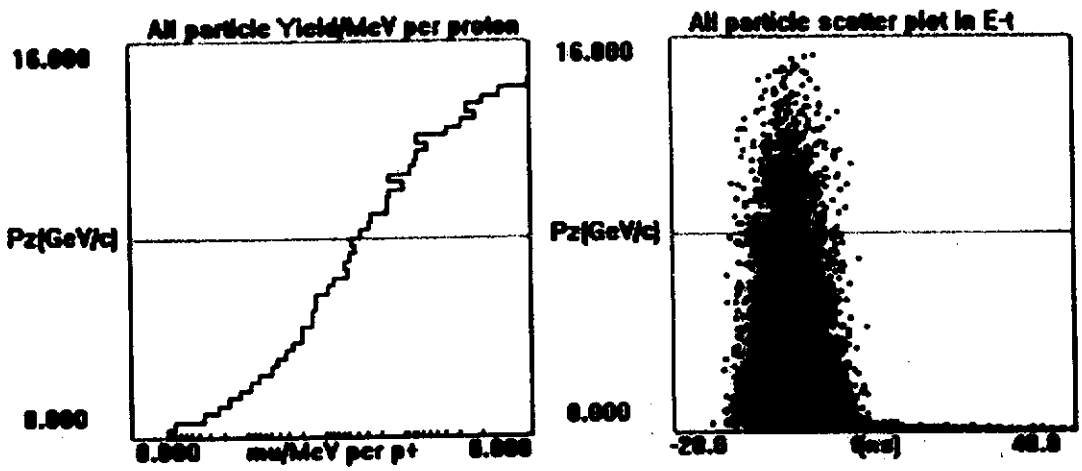
cooling section 6

| | dz meters | z start meters | z end meters |
|---|---|---|---|
| | | (Mokhov) | 4.00 |
| Carbon Target | | | |
| Drift | 6. | 4.00 | 40.00 |
| 1ST Induction Linac | 40. | 40.00 | 80.00 |
| Drift | 10. | 80.00 | 90.00 |
| Field Reversal | 3. | 90.00 | 93.00 |
| Minicool | 2. | 93.00 | 95.00 |
| Drift | 40. | 95.00 | 135.00 |
| 2ND Induction Linac | 60. | 135.00 | 195.00 |
| Drift | 1.0 | 195.00 | 196.00 |
| Matching | 9.9 | 196.00 | 205.90 |
| 1st Buncher | 2.2 | 205.90 | 208.10 |
| Drift | 4.4 | 208.10 | 212.50 |
| 2ND buncher | 3.3 | 212.50 | 215.80 |
| Drift | 3.3 | 215.80 | 219.10 |

# scatter plot of all particles at z=50 meters

## Longitudinal distribution




target = Carbon Target

length = two interaction length (LT=80 cm)long

radius = 0.75 cm tilted

angle = 50 m rad with respect to the solenoid axis at z=-LT/2

proton energy = 16 GeV

proton beam radius = 0.3 cm

rms bunch length = 3 ns

sigma z = 90 cm

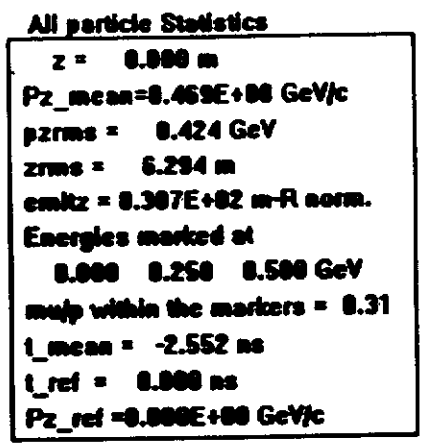
URL http://www-ap.fnal.gov/mokhov/mumu/target99/mars3.16ecy-c-50.dat

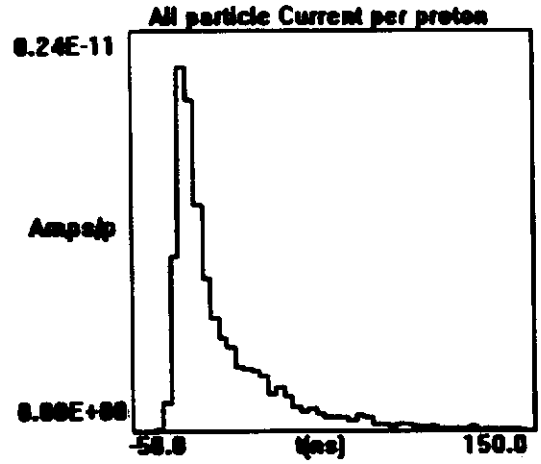


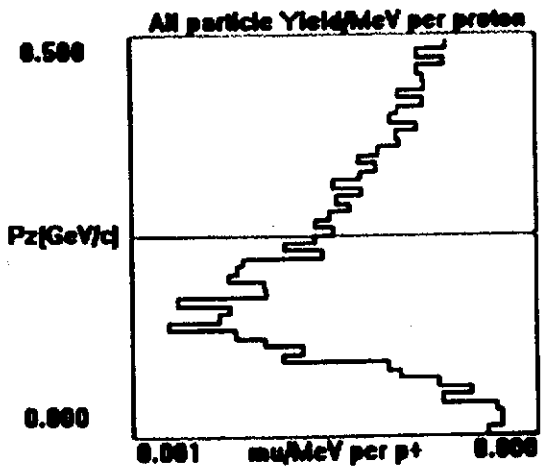
chkim@lbl.gov

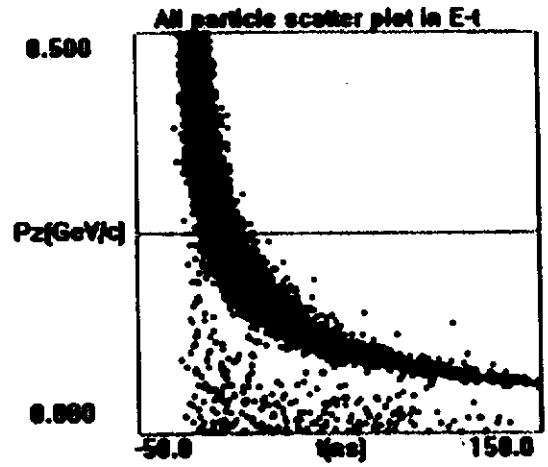
# scatter plot of all particles at z=50 meters

## Longitudinal distribution

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URL http://www-ap.fnal.gov/mokhov/mumu/target99/mars3.16gev-c-50.dat



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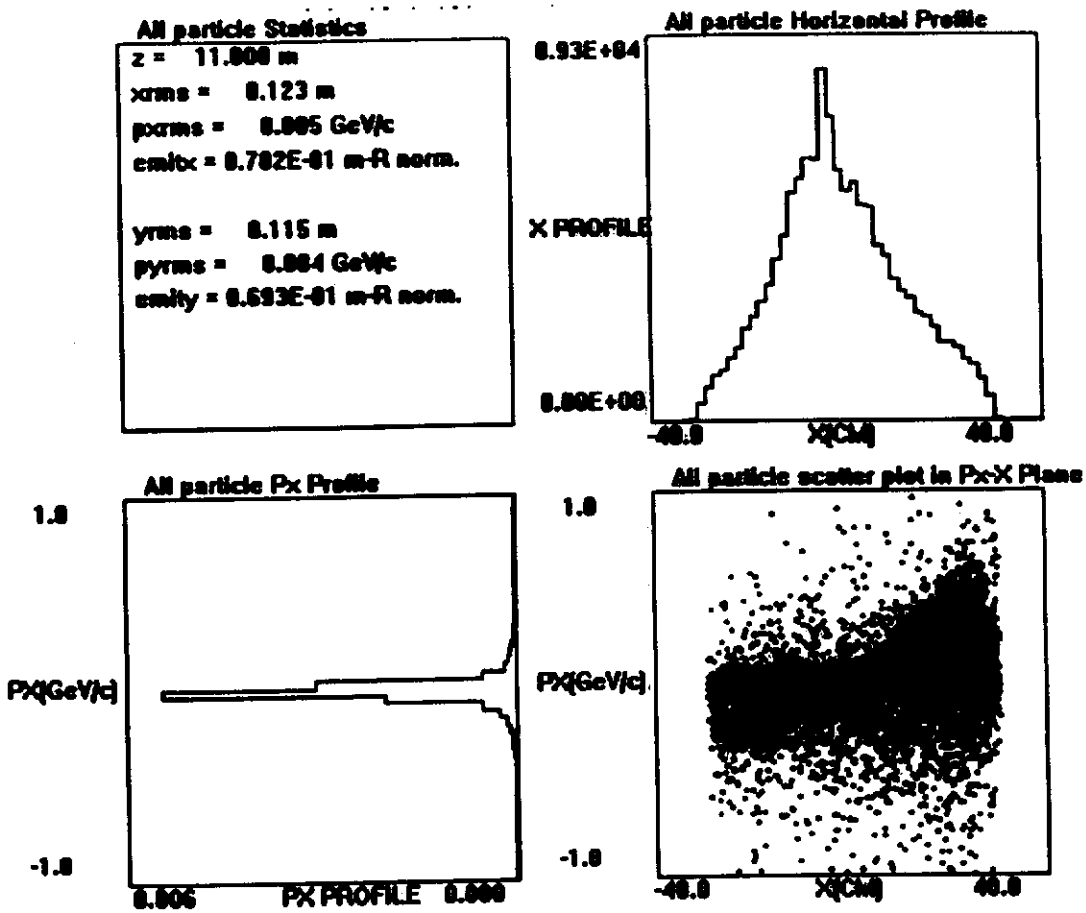
# scatter plot of all particles at z=50 meters

## Horizontal distribution



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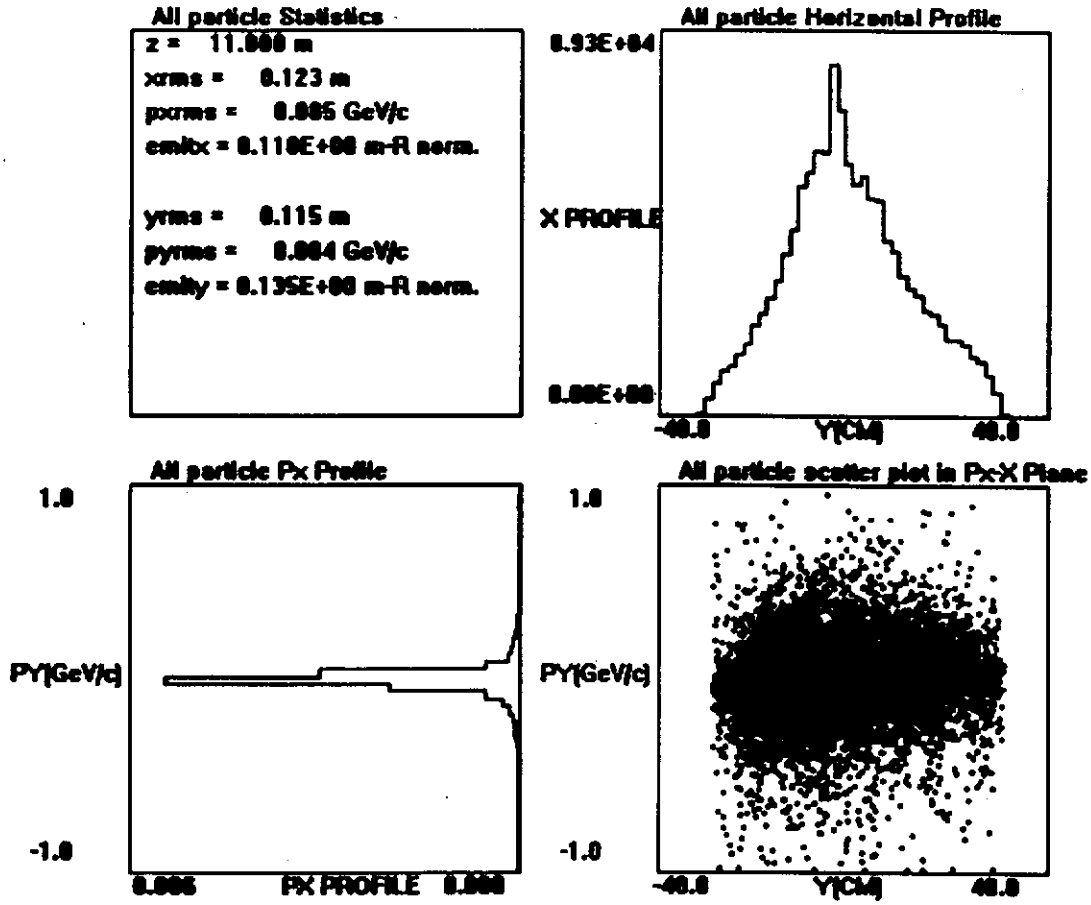
# scatter plot of all particles at z=50 meters

## Vertical distribution



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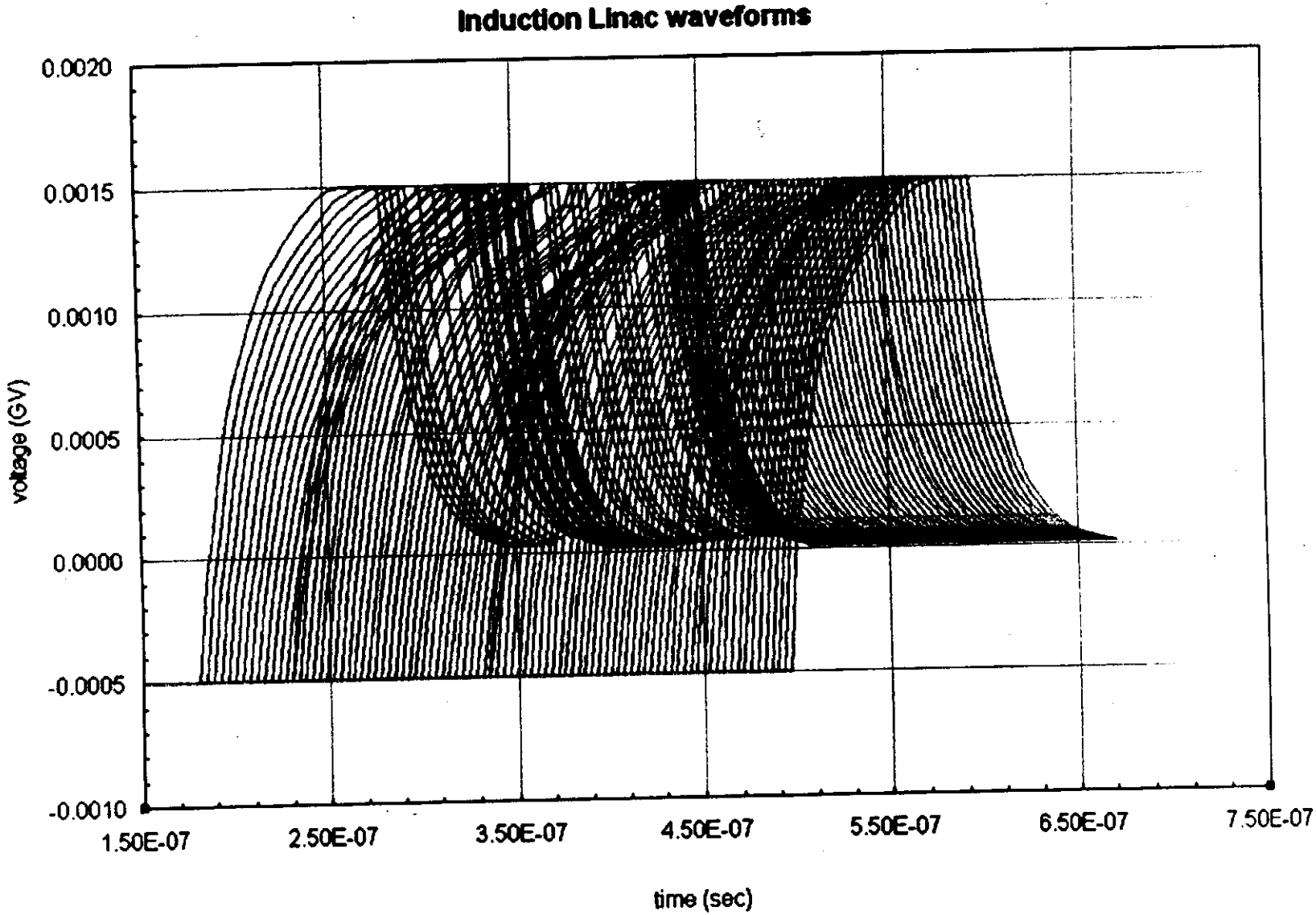
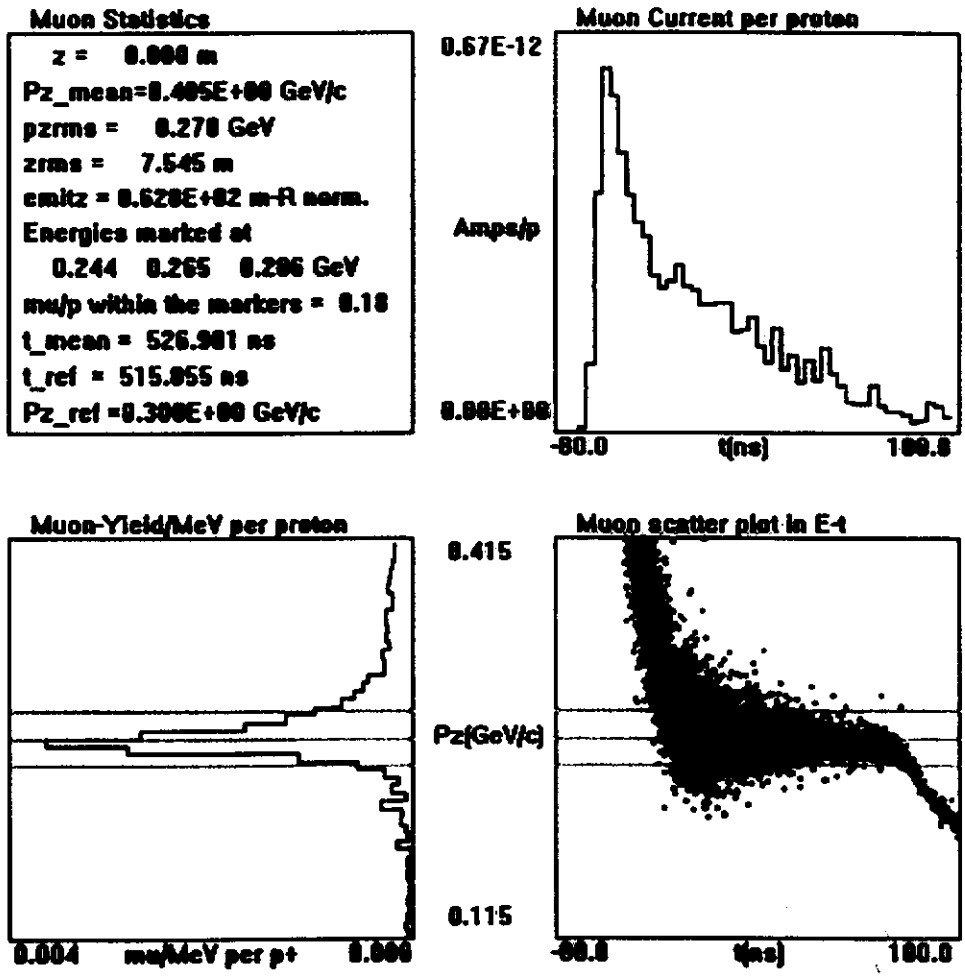

Induction Linac waveforms
0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
-0.0010
voltage (GV)
1.50E-07
2.50E-07
3.50E-07
4.50E-07
5.50E-07
6.50E-07
7.50E-07
time (sec)

# scatter plot of muons at z=140 meters

## Longitudinal distribution



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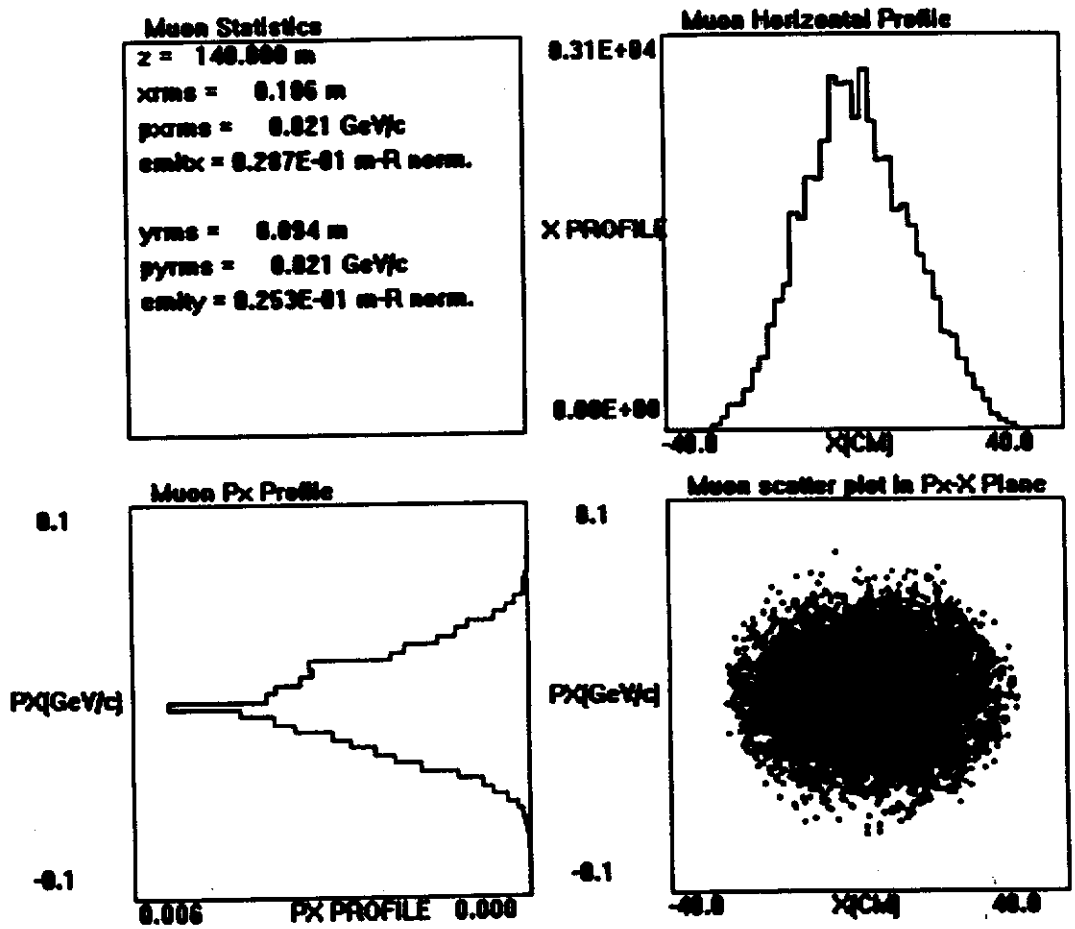
# scatter plot of muons at z=140 meters

## Horizontal distribution



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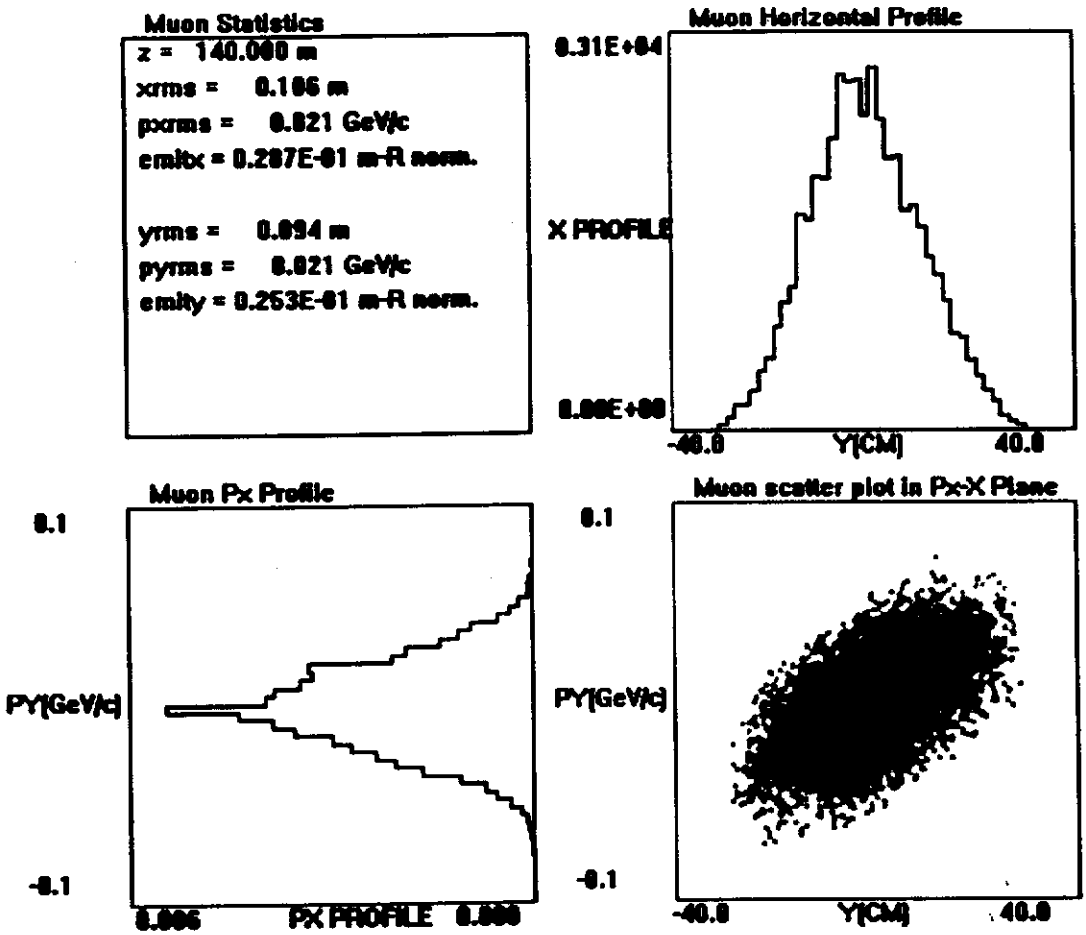
# scatter plot of muons at z=140 meters

## Vertical distribution



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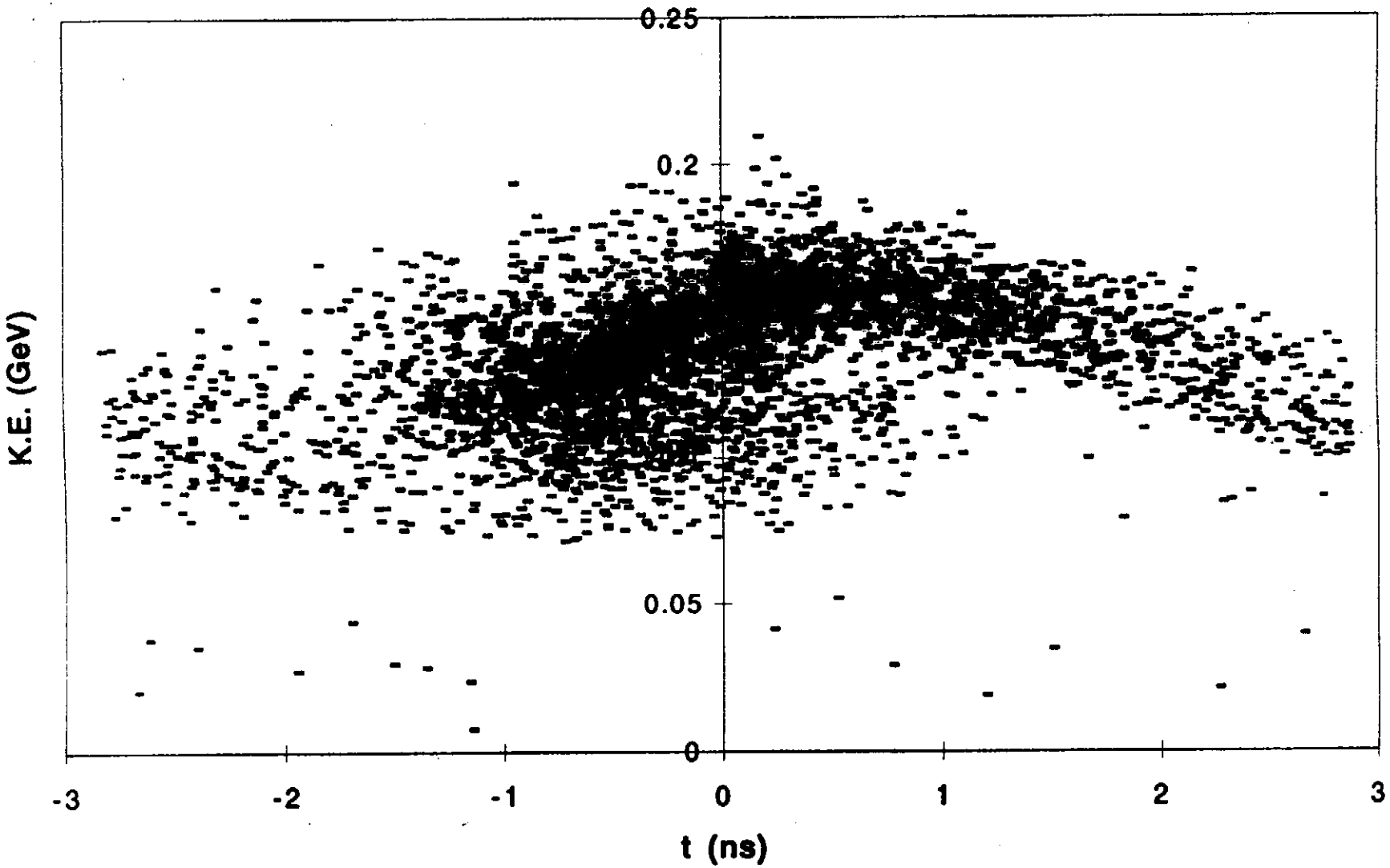
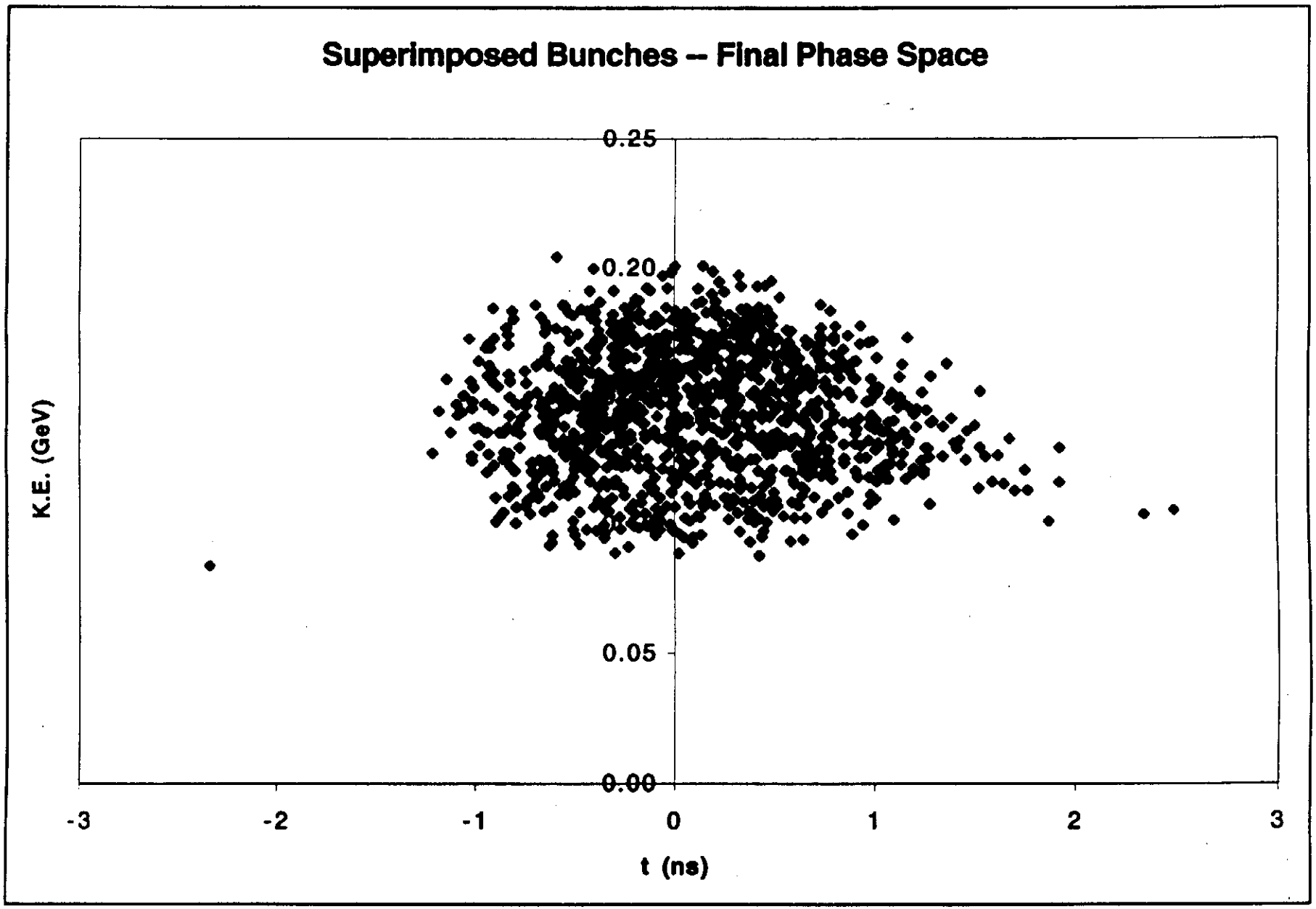
# CASE 2 ~~INITIAL~~ ~~ARTICLE DATA~~

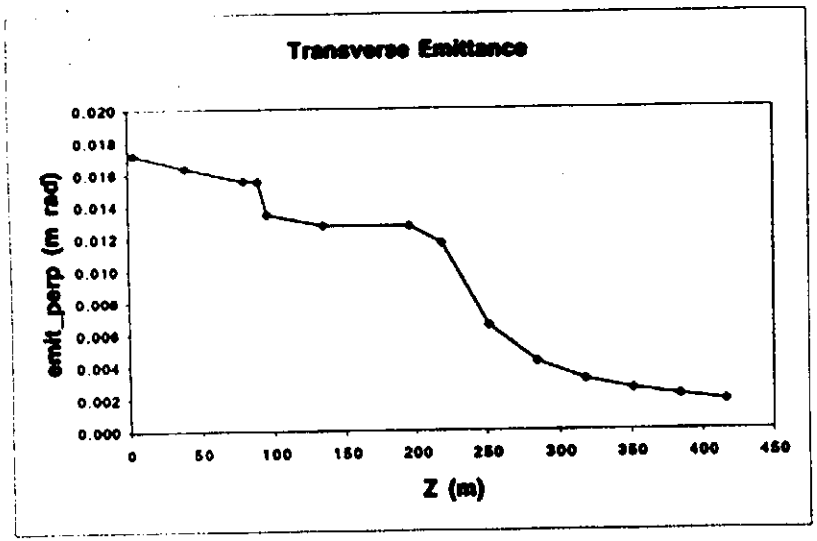
Beginning of Cooling Channel

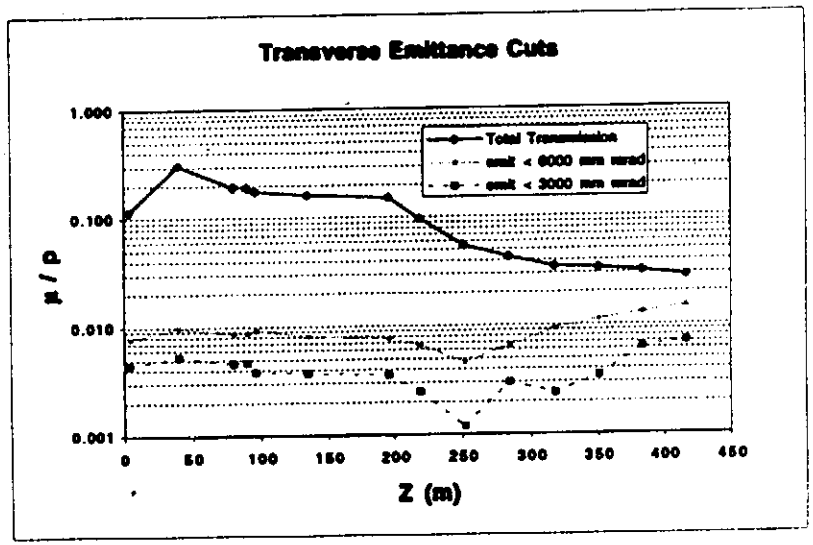
**Longitudinal Distribution, Superimposed**

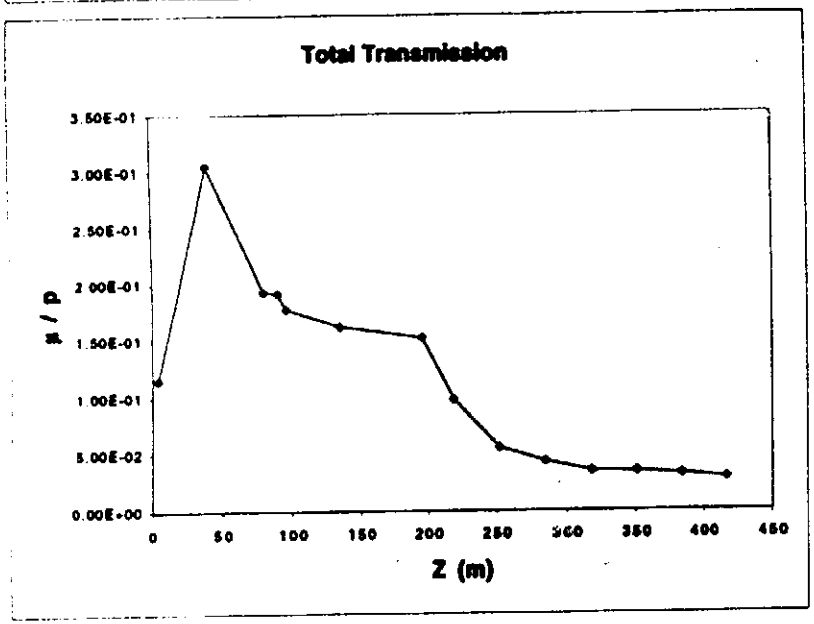



Superimposed Bunches -- Final Phase Space
0.25
0.20
0.05
0.00
K.E. (GeV)
-3
-2
-1
0
1
2
3
t (ns)

# Front End Simulation Summary
# (no energy cuts implemented)




Final mu/p : 0.028

Final emittance: 1800 mm mrad

Final mu/p within 4 sigma_f cut: 0.015

# Future Plans

induction linac:

- shorten bunch length
  allows shorter pulse
- evaluate 3T field

RF:

- switch to 200 MHz

bunching:

- improve bunching and capture efficiency
  implement D. Neuffer's scheme

cooling:

- evaluate single $\pi$-mode
  as substitute for double $\pi/2$-mode
- small adjustments to lower B of coils
  further from resonance (less current)
  lower $P_z$
  change X-section of coils
  reduce aperture (for 200 MHz RF)

figures of merit:

- full 6D phase space cuts

# General Remarks

- Likely that acceleration will be the most expensive part

**AIM**

Estimate size of capital intensive item

- RF Power
  - Size of klystrons
  - Pulse Length
  - Number of klystrons
  - AND ASSOCIATED HV, + MODULATORS
- Linac Length
  - Cavities, Cryomodules, ...
- Refrigerator
  - Cryogenic Heat Load
- AC POWER (Linac only)

Give Relative cost distributions in % (NOT $)

Guide : Neuffer
S. Berg

Figure 1: Overview of accelerator for a μ storage ring, showing a linac plus a sequence of two multiturn recirculating linacs.

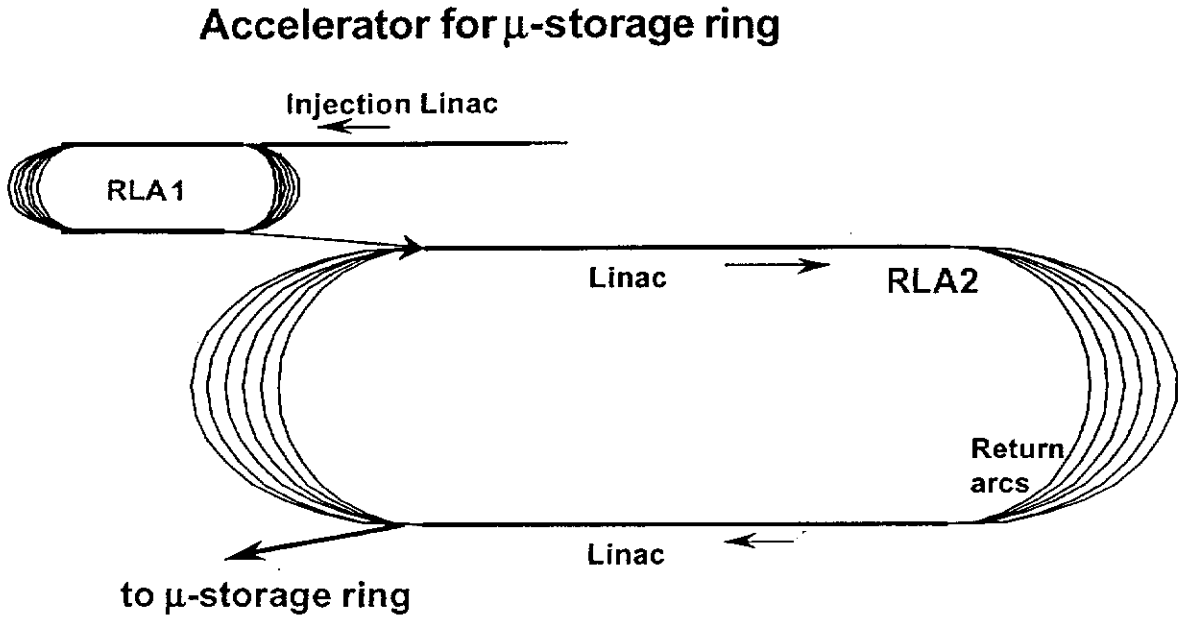



**Table 1: Accelerator Parameters**

| Parameter | Linac | RLA1 | RLA2 | |
|---|---|---|---|---|
| Initial Energy | 0.2 | 2.1 | 9.5 | GeV |
| Final Energy | 2.1 | 9.5 | 50 | GeV |
| Number of turns | 1 | 4 | 5 | |
| Rf Voltage/linac | 2.5 | 1.2 | 4.2 | GV |
| Acceleration phase | 70→0° | 40° | 30° | |
| $M_{56}$ per arc | --- | 0.6 | 0.2 | m |
| Rf frequency | 200 | 200 | 400 | MHz |
| Rms bunch length | 15 → 4.2 | → 2.5 | → 1.3 | cm |
| Rms energy spread | 20 → 80 | → 200 | → 250 | MeV |
| Linac length(10MV/m) | 250 | 120 | 420 | m |
| Arc length | --- | 120 | 400 | m |
| Decay survival | 0.92 | 0.93 | 0.953 | |

# Discuss Some Technical Aspects

Gradient

$Q_0$

Coupler Power

$Q_L$, Bandwidth

Number of cells

! Neglect Reserves

e.g. control margins for RF p

Refrigeration excess capacity