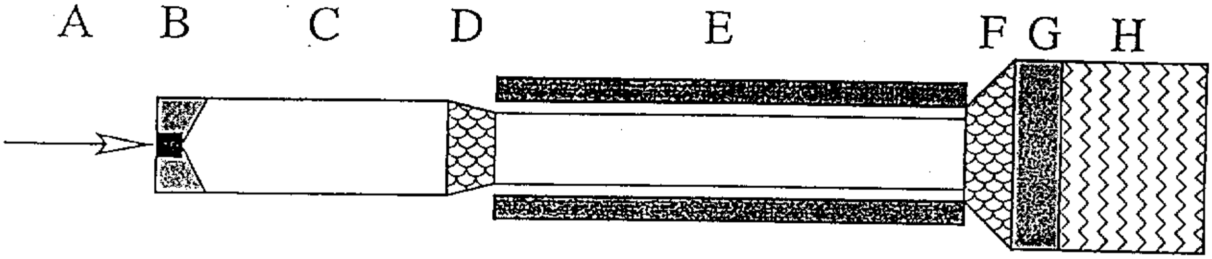
Precooling Stage of Muon Storage Ring

V. Balbekov, Fermilab, Febr. 15, 2000

OUTLINE



A - Protons 16 GeV, 4 pulses with interval about 600 ns.
B - Target station with carbon target (Mokhov's file).
C - Drift-decay channel: L = 47 m, B = 1.25 Tesla, R = 30 cm.
D - Matching section: L = 3 m, B = 1.25 - 3 T, R = 30 - 20 cm.
E - Induction linac: L = 100 m, B = 3 T, R = 20 cm,
V' = (-0.5) - (1.5) MV/m.
F - Matching section: L = 2 m, B = 3 - 5 T, R = 20 - 70 cm.
G - Minicooling LH2: L = 2.45 m, B = 5 T, R = 70 cm.
H - Buncher: L = 15 m, B = 5 T, R = 70 cm, V = 3 x 15 MV.

Yield: 0.17 μ/p at $160 < E_{tot} < 260$ MeV;
0.13 μ/p in the bucket.

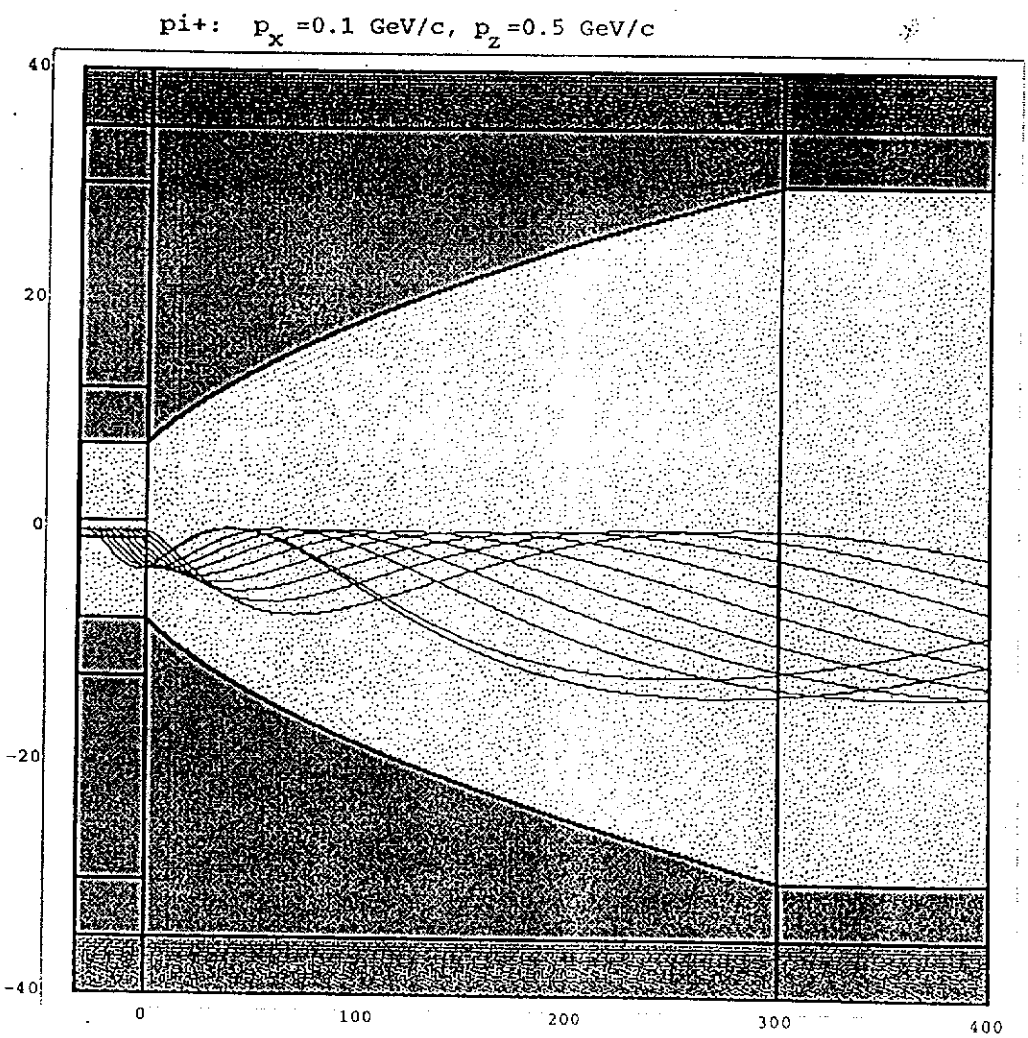
Emittance: ε_x = 11.2 mm with excluded x-p_y correlation
$\sigma_x \sigma_{px}$ = 12.2 mm inside of solenoid
$\sigma_x \sigma_{px}$ = 15.0 mm outside of solenoid

TARGET STATION (N. Mokhov, R. Weggel)

- Carbon target L = 80 cm or Mercury L = 45 cm
  B = 20 T, R = 7.5 cm

- 3 m matching section.
  B decays linearly from 20 T to 1.25 T. BR = const

- 1 m solenoid B = 1.25 T, R = 30 cm



DRIFT-DECAY CHANNEL

Uniform solenoid: L = 47 m, R = 30 cm, B = 1.25 T

Yield at $E_{tot} < 500$ MeV: $\pi^+/p = 0.009$, $\mu^+/p = 0.216$; $(\pi^+ + \mu^+)/p = 0.225$;

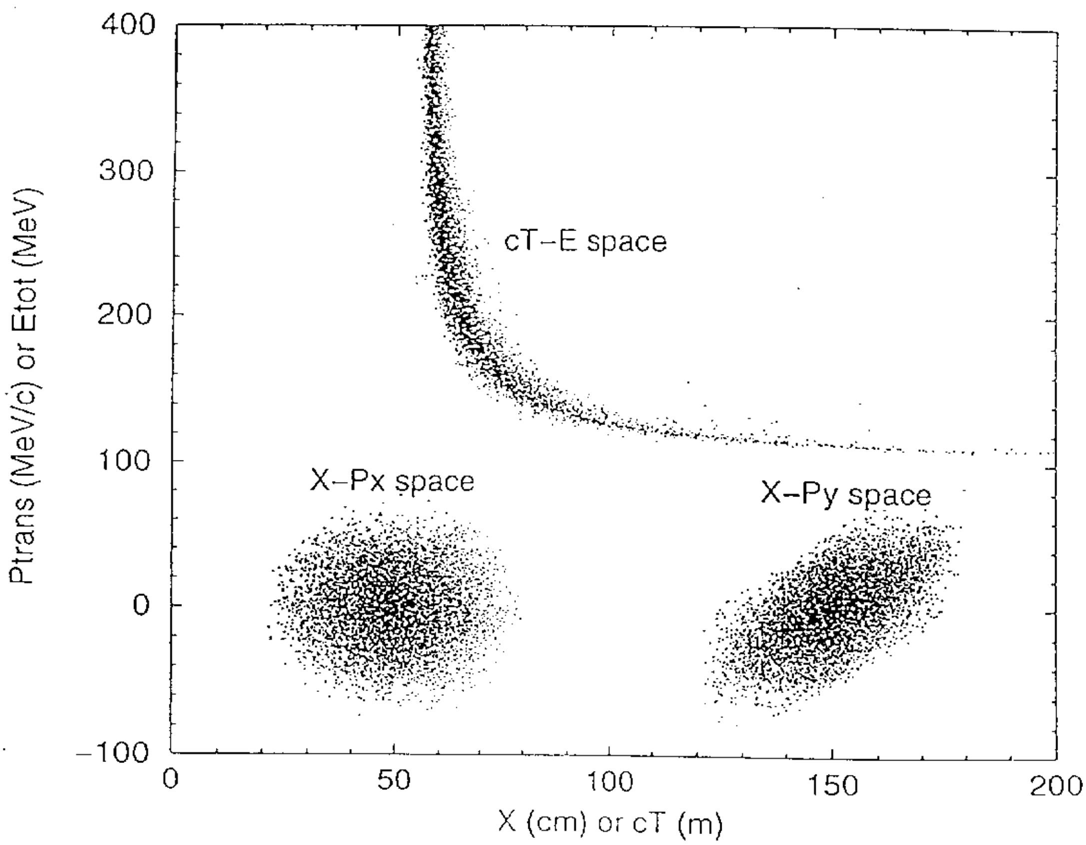
Normalized transverse emittance

$\sigma_x \sigma_{px}$ = 19.7 mm inside of solenoid,

$\sigma_x \sigma_{px}$ = 16.4 mm outside of solenoid,

ε_x = 15.8 mm without no x-p_y correlation;

Phase space



1^{st} MATCHING SECTION

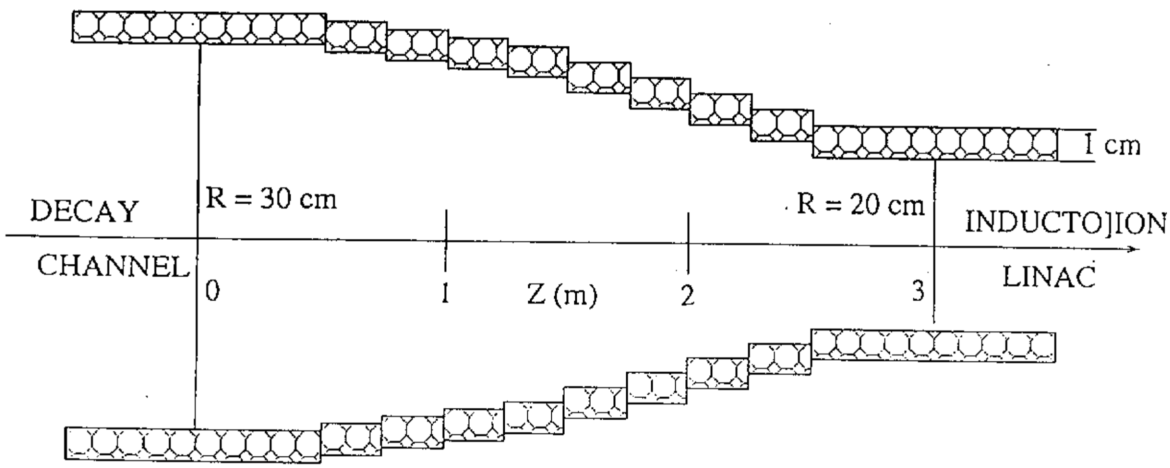
Adiabatic increase of the magnetic field from 1.25 T to 3 T and decrease of the solenoid radius from 30 cm to 20 cm

$$j(A/mm^2) \approx 86.8/[1-0.255Z(m)]$$

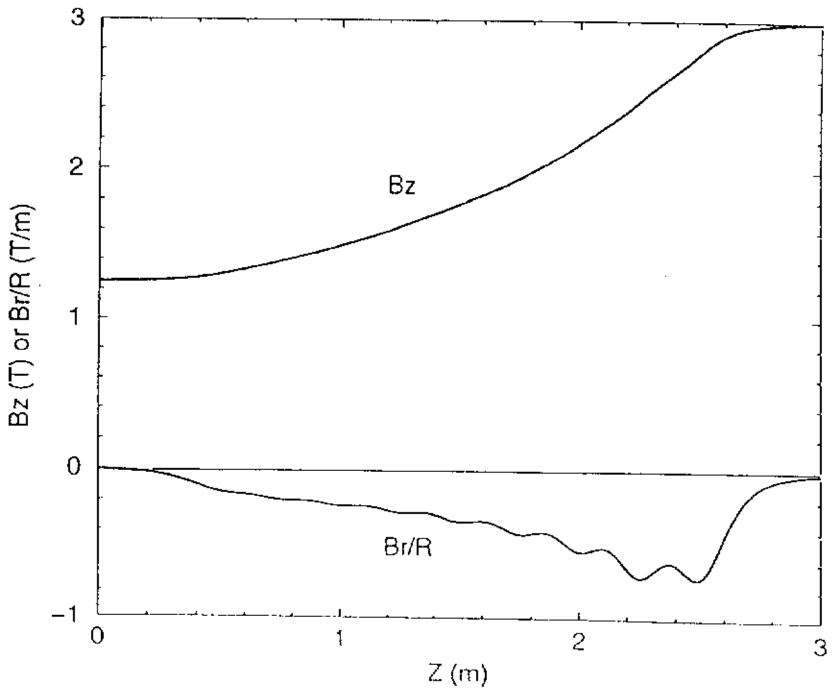
$$R(cm) \approx 32.1[1-0.255Z(m)]^{1/2}$$

Transmission 99.6% with decay.

COILS OF MATCHING SECTION (not in scale)



Axial and radial magnetic field on the axes



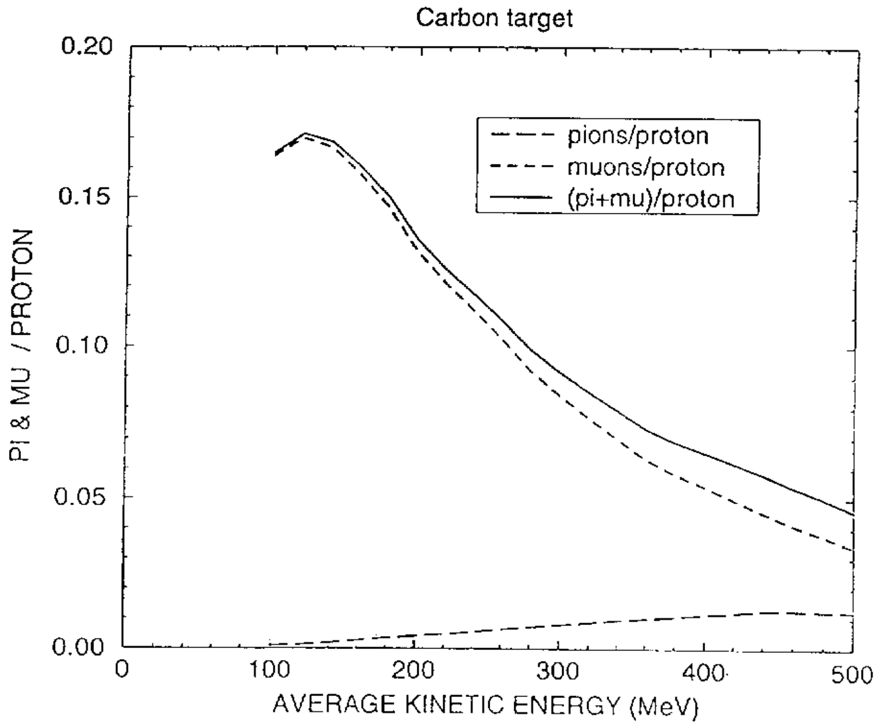
OPTIMIZATION OF ENERGY

100 m induction linac with accelerating gradient

$-0.5 \text{ MV/m} < V' < 1.5 \text{ MV/m}$

can accept energy interval $\Delta E = 200$ MeV

Number of pions and muons in interval 200 MeV



Maximal number of pions and muons in the interval at

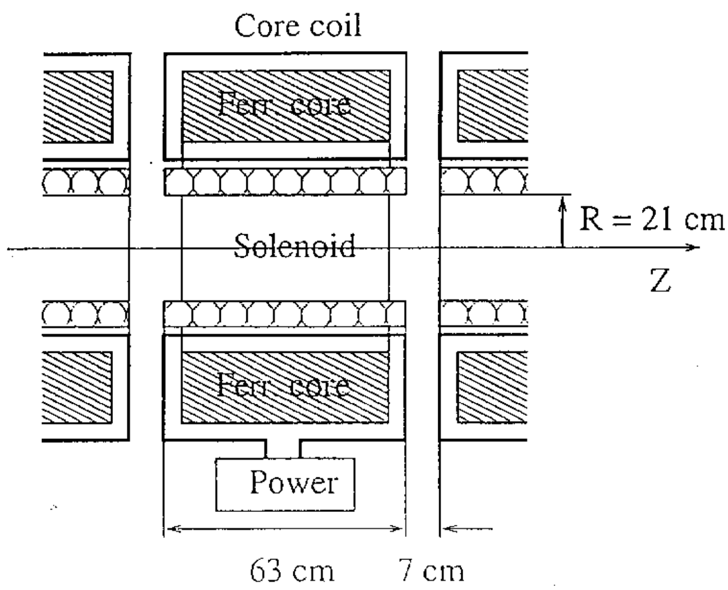
$125 \text{ MeV} < E_{tot} < 225 \text{ MeV}$

$(\pi+\mu) / p = 0.17$

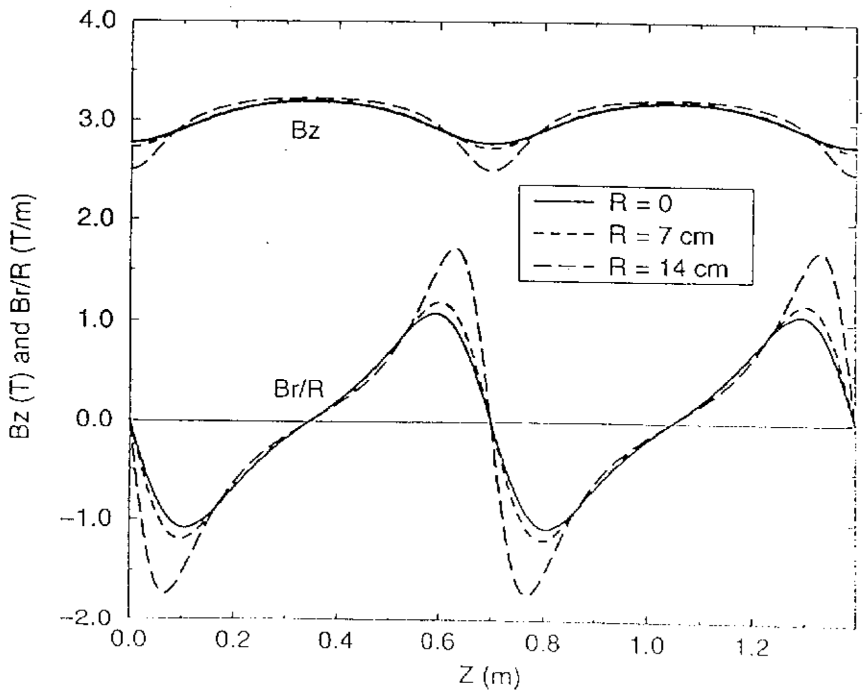
INDUCTION LINAC: LATTICE AND MAGNETIC FIELD

Full length 100.1 m (143 cells)

LATTICE OF THE INDUCTION LINAC



Magnetic field at the induction linac



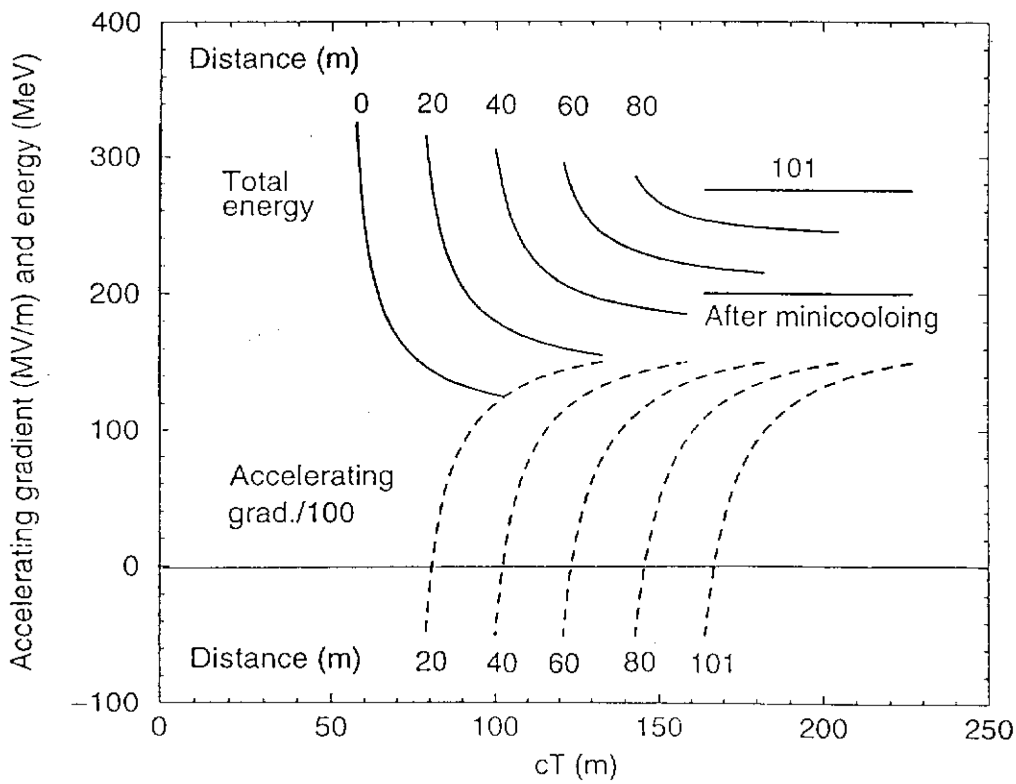
INDUCTION LINAC: VOLTAGE

- Pilot beam: muons born at $t = 0$ in the target center at

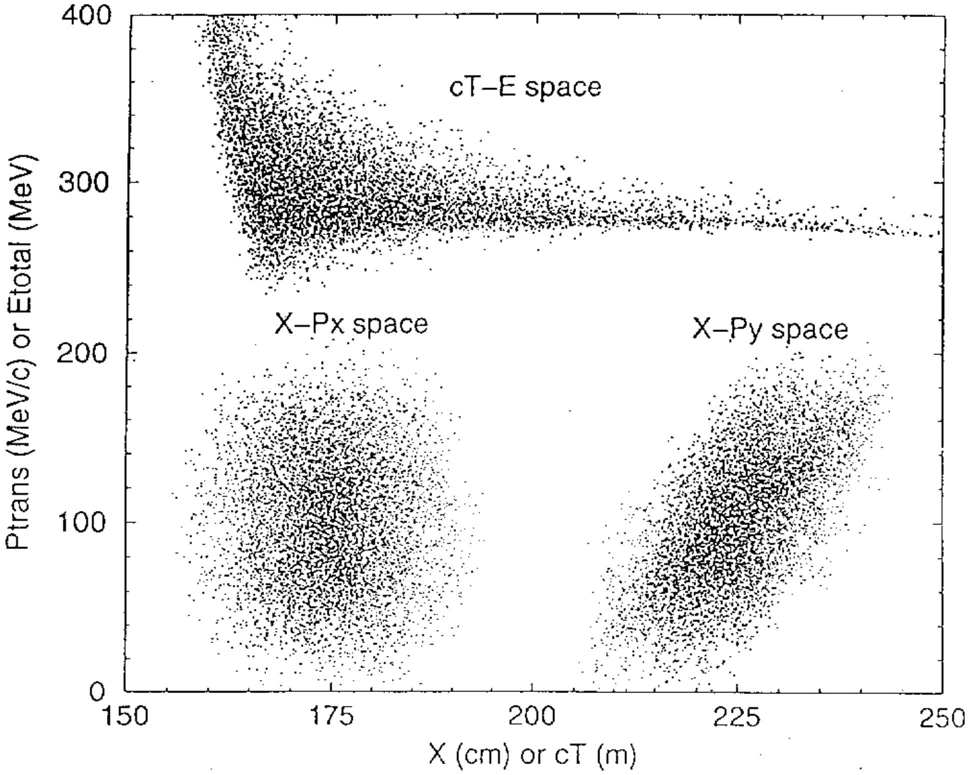
$E_{min} < E < E_{max}$, (E_{min}=125 MeV, E_{max}=325 MeV, ΔE=200 MeV);

- Drift to 1st accelerating gap generates dependence E(t);
- Voltage calculated as $V(t)$ (MV) = 0.007x[275 MeV-E(t)]/ΔE;
- The same for 2nd gap with new ΔE, etc.

Voltage on the gaps and phase space of the pilot beam



Phase space of muons after the linac



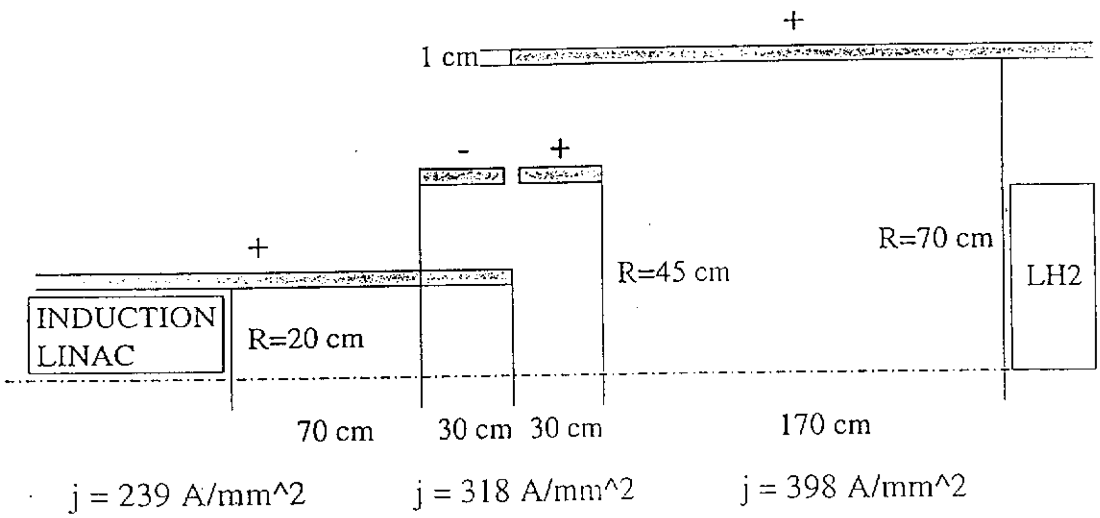
Yield at $E_{tot} < 375$ MeV: $\mu^+/p = 0.194$

Transverse emittance: $\sigma_x\sigma_{px} = 19.1$ mm inside of solenoid,
$\sigma_x\sigma_{px} = 16.2$ mm outside of solenoid,
$\varepsilon_x = 15.6$ mm without x-p_y correlation;

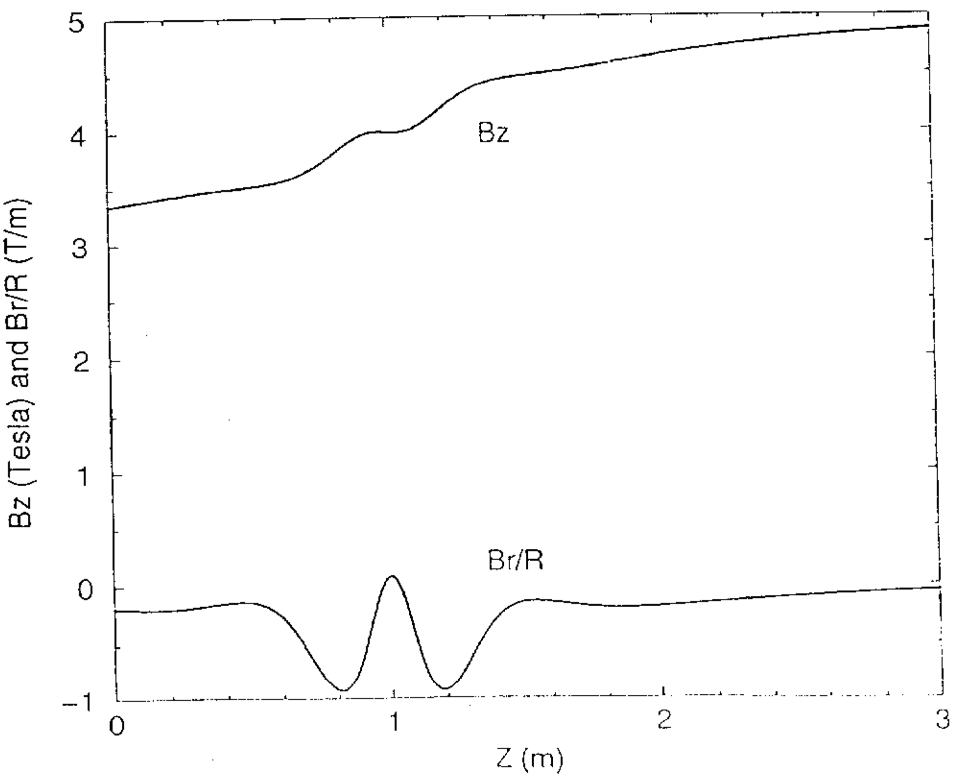
2^{nd} MATCHING SECTION

Adiabatic increase of the magnetic field from 3 T to 5 T and increase of the solenoid radius from 20 cm to 70 cm
Transmission 99.9% with decay.

COILS IN THE MATCHING SECTION



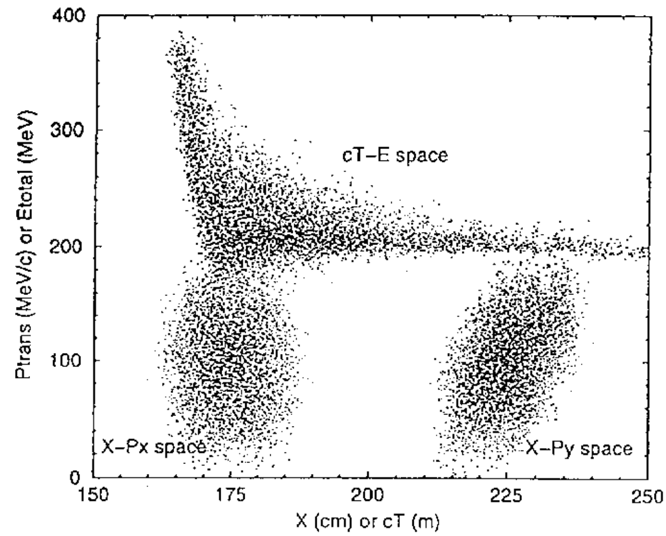
Magnetic field on the axes



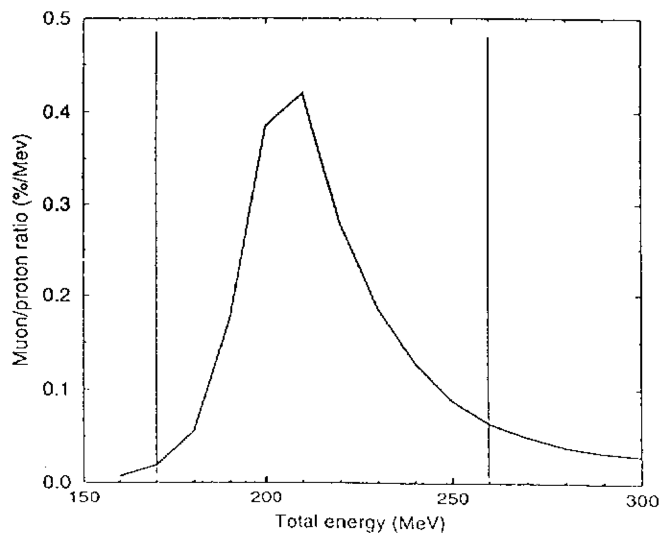
MINICOOLING

245 cm of LH_2 in solenoid B = 5 T
Yield at $E_{tot} < 300$ MeV: $\mu^+/p = 0.193$
Transverse emittance $\sigma_x \sigma_{px} = 12.4$ mm inside of solenoid,
$\sigma_x \sigma_{px} = 14.9$ mm outside of solenoid,
$\varepsilon_x = 11.3$ mm without x-p_y correlation;

Phase space of muons after minicooling

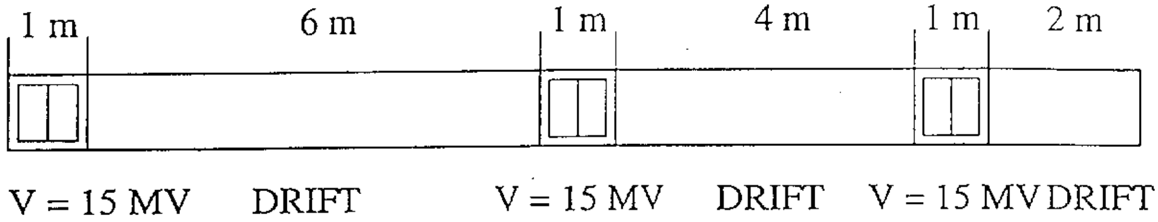


Distribution of muons on energy after minicooling

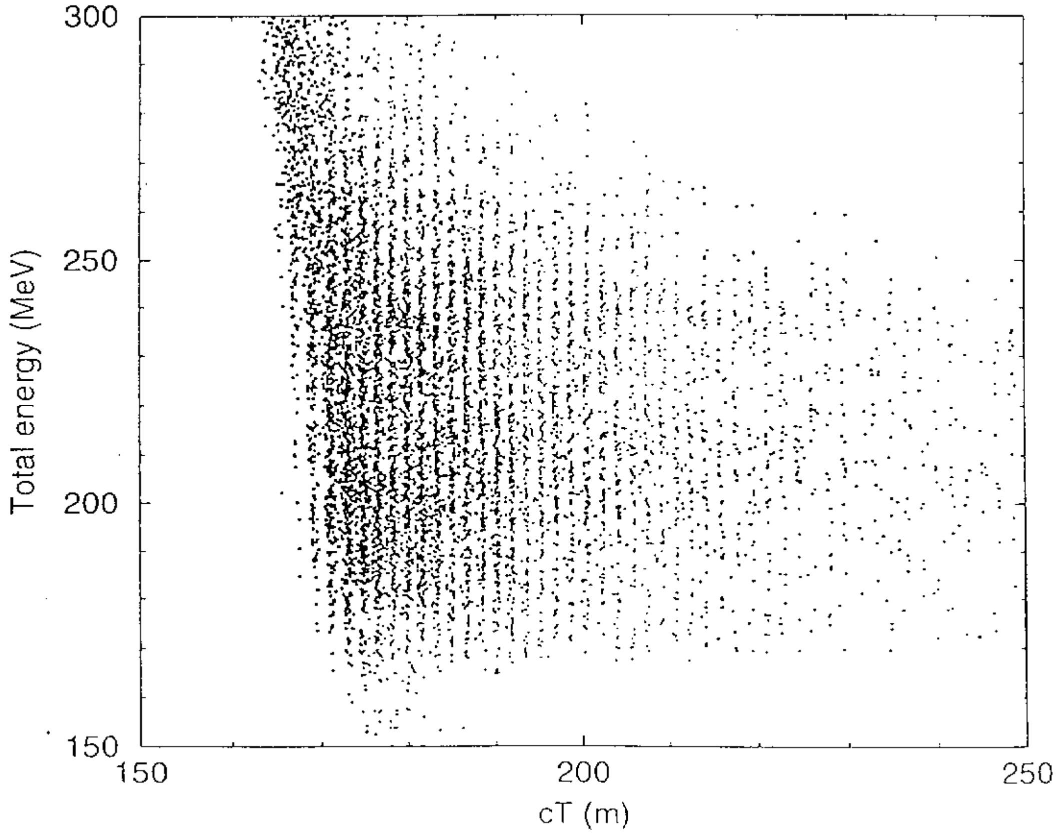


BUNCHING

Solenoid: B = 5 T, R = 70 cm;
Acceleration: f =175 MHz, V'=15 MV/m, E_{ref}=200 MeV;



Longitudinal phase space after the bunching



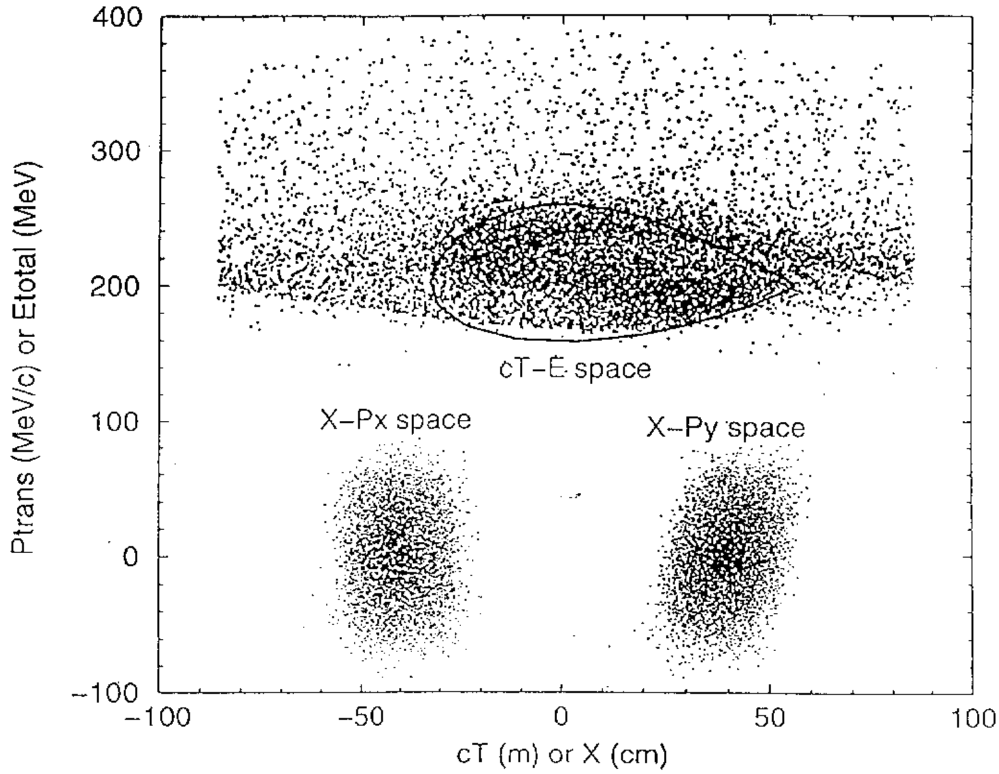
Yield at $E_{tot} < 300$ MeV: $\mu^+/p = 0.190$. in the bucket;

Transverse emittance $\sigma_x\sigma_{px} = 12.2$ mm inside of solenoid,

$\sigma_x\sigma_{px} = 14.8$ mm outside of solenoid,

$\varepsilon_x = 11.2$ mm without x-p_y correlation;

Phase space after the bunching



In the bucket ($V' = 15$ MeV/m, $\varphi_s = 30^{\circ}$, $\Delta E' = 7.5$ MeV/c)

$\mu^+/p = 0.132$

Transverse emittance $\sigma_x\sigma_{px} = 12.2$ mm inside of solenoid

$\sigma_x\sigma_{px} = 15.0$ mm outside of solenoid

$\varepsilon_x = 11.3$ mm without x-p_y correlation;

Muon Budget

Number of muons with cut on energy

Step	Energy Cut (MeV)	π/p	μ/p
Target Station	< 500	0.182	0.086
Drift	< 500	0.009	0.216
Induction linac	< 335	0	0.179
Minicooling	< 260	0	0.178
Bunching	< 260	0	0.170

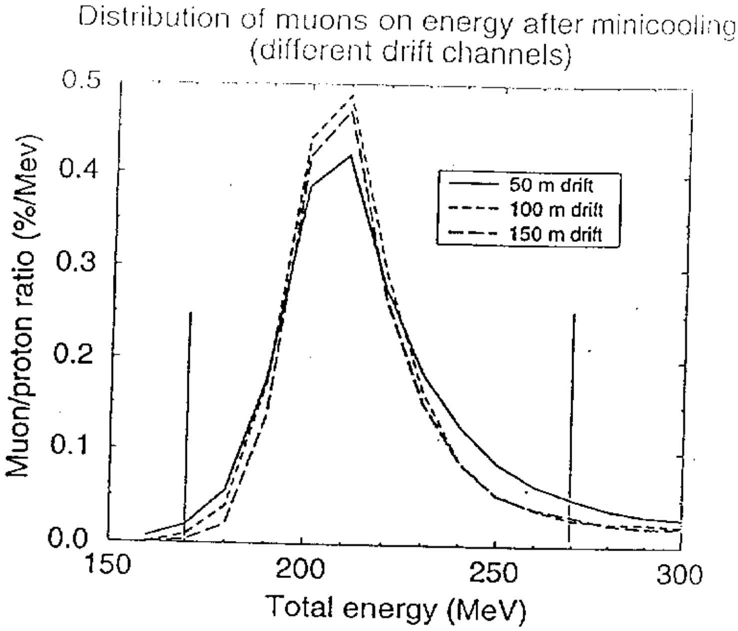
Number of muons suitable for a cooling (efficiency of subsystems)

Step	μ/p
Target Station*	0.041
Drift	0.036
Induction linac **	0.089
Minicooling	0.088
Bunching	0.132

* With 50 m decay channel and RF: 175 MHz, 15 MeV/m.

** At E_{ref} = 275 MeV instead of 200 MeV

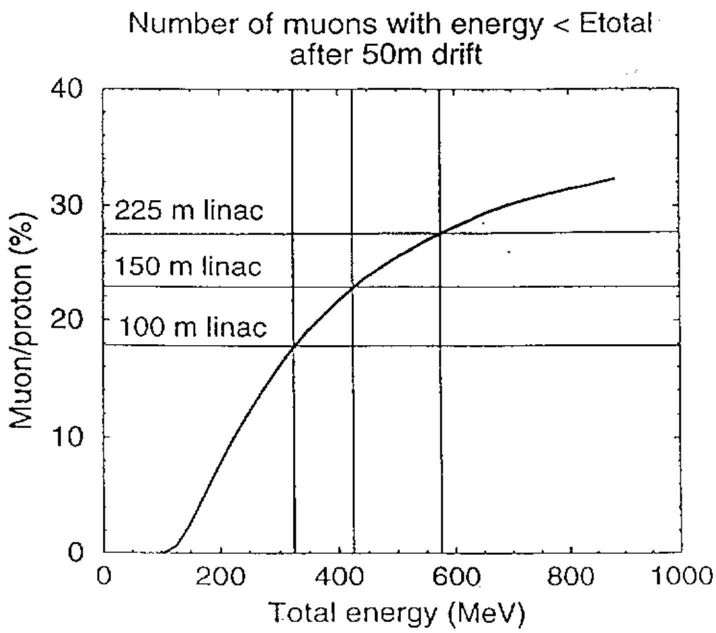
CONCLUSION: How can one improve the system?



1. Longer drift channel.

As follows from left plot, longer drift channel provides more narrow energy distribution, but not enough to use the adiabatic capture. If the drift is longer 100 m, muon decay is considerable. Therefore compression of the energy distribution is ineffective . *The channel length should be chosen to provide an optimal operation of the induction linac (duration of the pulse).*

2. Double phase rotation. The previous point concerns double phase rotation, too. At constant total acceleration voltage it can provide only compression of the energy spread what is not enough to increase the yield. For unpolarized muon beam, the choice between a low frequency RF accelerating system and an induction linac is mainly technical and economical problems.



3. **Longer induction linac.**

Left plot shows number of muons/proton after 50 m drift vs maximal muon energy (total). Considered option corresponds to E_{max} = 325 MeV and provides about 0.18 μ/p. 150 m linac with the same accelerating gradient can give 27% more. At least 225 m linac is required to provide an increase by factor 1.5.

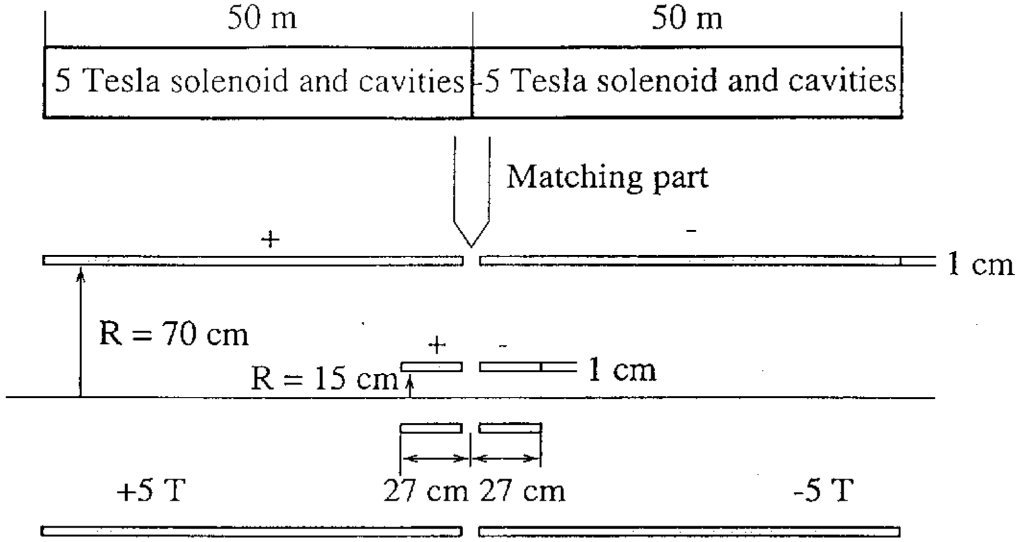
Muon cooler with long solenoids

V. Balbekov, Fermilab, Febr. 15, 2000

OUTLINE

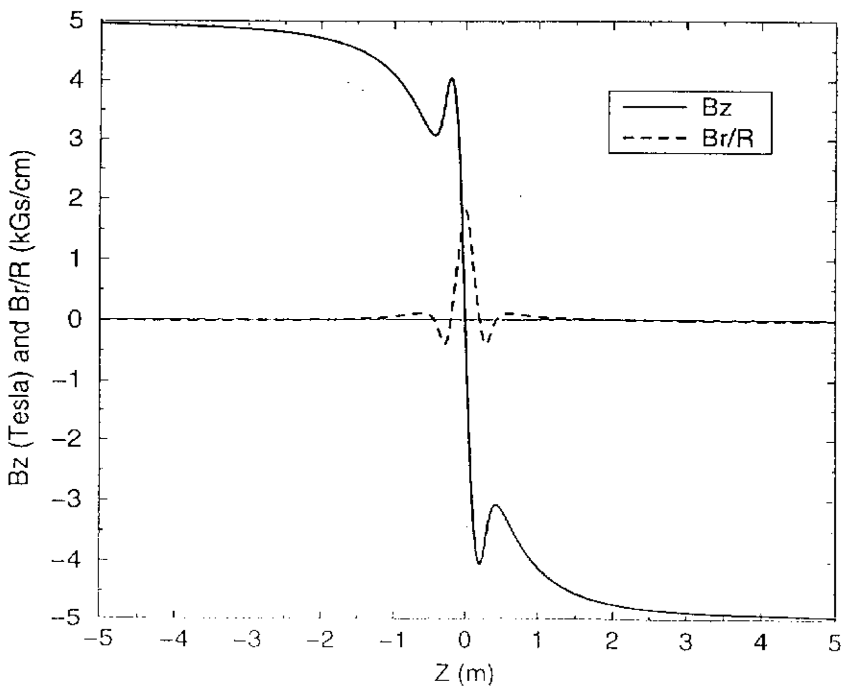
- Muon cooling inside long (2 x 50 m) 5 Tesla solenoids is considered.
- The only reverse of the field from B = 5 T to B =-5 T is used.
- Special short matching section providing fast reverse of the magnetic field is described.
- As a result, magnetic field on the solenoid coils does not exceed 5 T.
- Liquid hydrogen absorbers providing average energy loss 6 MeV/m are used for the cooling.
- Accelerating gradient is 15 MeV/m at f = 175 MHz and synchronous phase 30° (E' = 7.5 MeV/m).
- Slow acceleration (1.5 MeV/m) is used to prevent particle loss because of growth of longitudinal emittance
- Realistic incident muon beam obtained by consideration of precooling part of the system is used for simulation.
- The following results are obtained: number of cooled muons is 0.096 per proton, r.m.s. transverse emittance 3.2 mm, no (X-P_y) and (Y-P_x) correlations.
- Excitation of synchrotron oscillations at the field reverse is the main cause of the particle loss (dependence of flying time on transverse momentum which changes at the reverse).

THE COOLER LATTICE



Current density in the coils is 398 A/mm^2.
The main goal of the matching is to get as fast field reverse as possible (a system with $|B_z|$= const provides a perfect focusing).

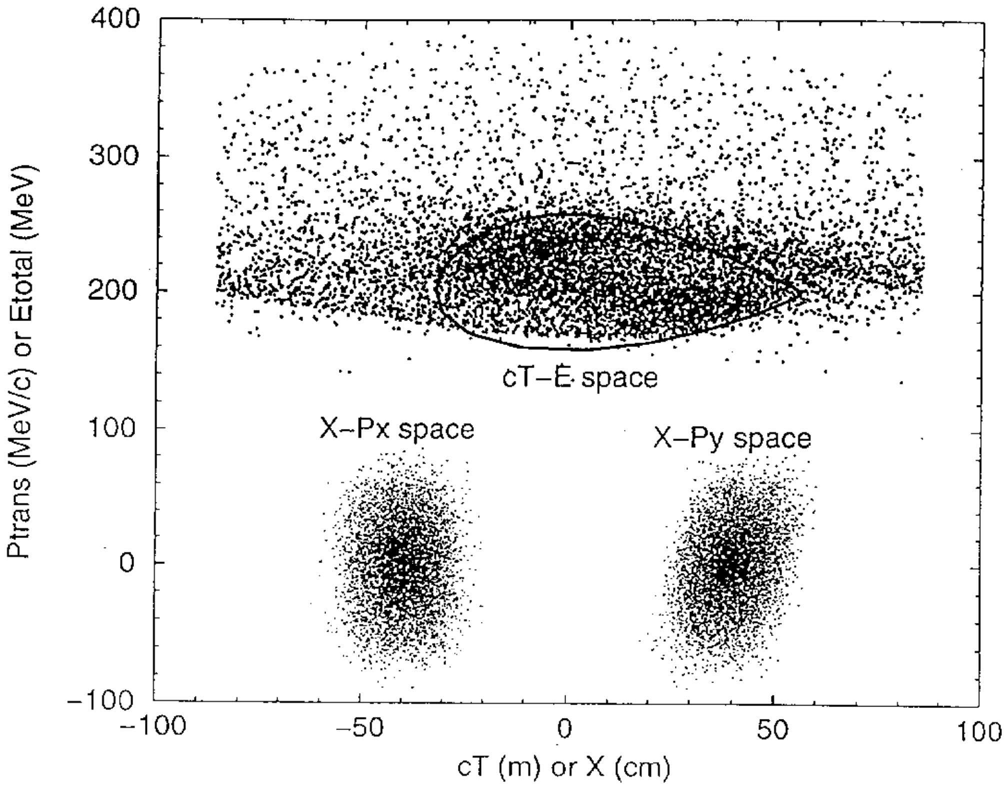
Field on the axes of matching section



INCIDENT MUON BEAM

Foregoing stages: drift - induction linac - minicooling - bunching.

Phase space after the bunching



At $E_{tot} < 300$ MeV: $\mu^+/p = 0.190$

$\sigma_x\sigma_{px} = 12.2$ mm inside of solenoid

$\sigma_x\sigma_{px} = 14.8$ mm outside of solenoid

$\varepsilon_x \quad = 11.2$ mm (excluded x-p_y correlation);

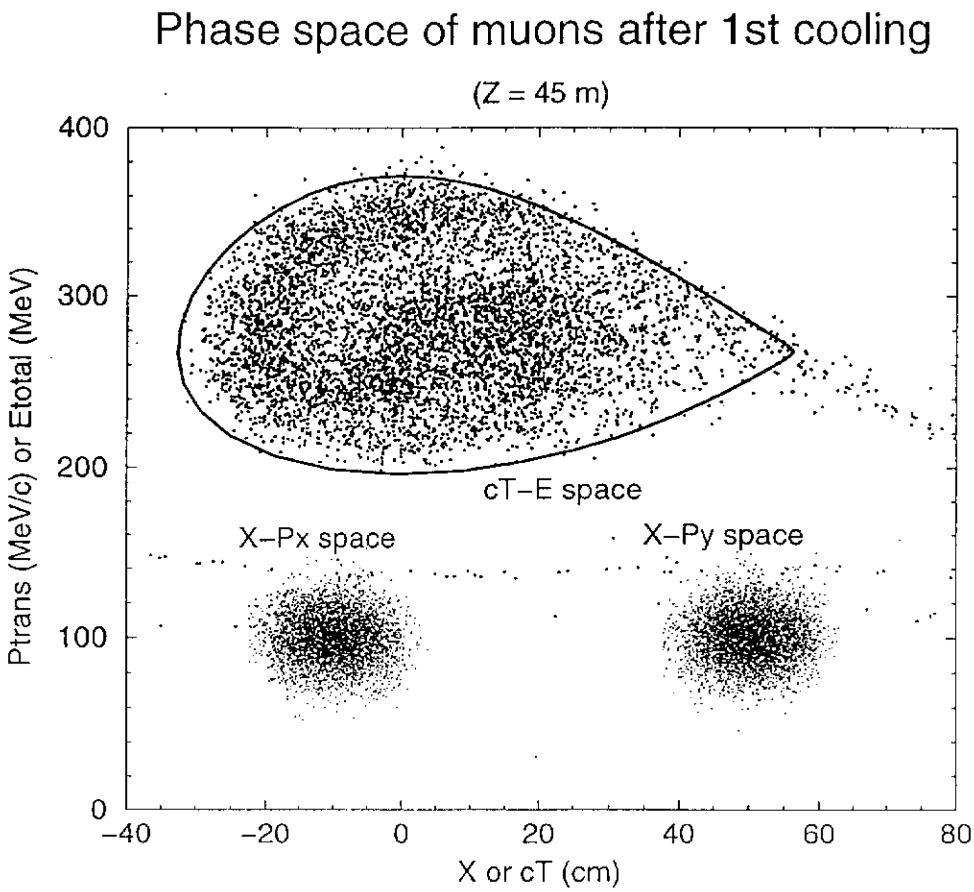
In the bucket: $\mu^+/p \;= 0.132$

$\sigma_x\sigma_{px} = 12.2$ mm inside of solenoid

$\sigma_x\sigma_{px} = 15.0$ mm outside of solenoid

$\varepsilon_x \quad = 11.3$ mm (excluded x-p_y correlation);

MUON BEAM AFTER 1st COOLING (Z = 45 m)



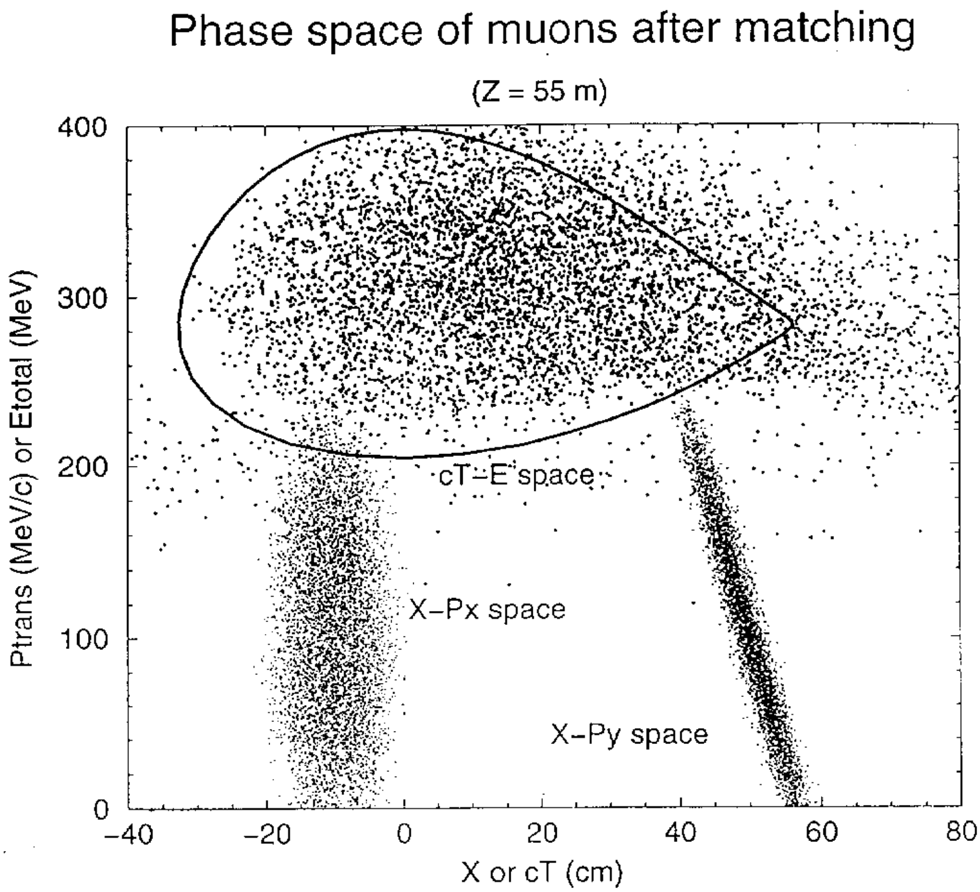
$\mu^+/p = 0.137$

$\sigma_x\sigma_{px} = 4.90$ mm inside of solenoid

$\sigma_x\sigma_{px} = 13.4$ mm outside of solenoid

$\varepsilon_x = 4.82$ mm (excluded x-p_y correlation);

MUON BEAM AFTER MATCHING SECTION (Z=55 m)



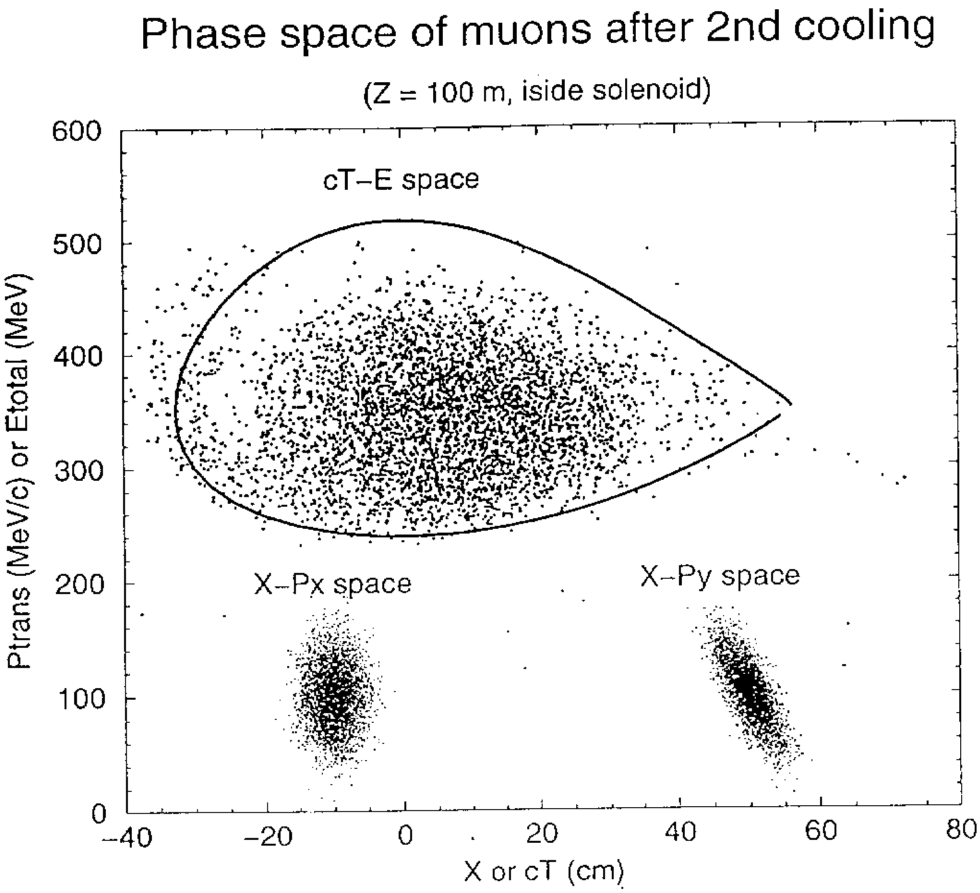
$\mu^+/p = 0.132$

$\sigma_x\sigma_{px} = 19.7$ mm inside of solenoid

$\sigma_x\sigma_{px} = 10.2$ mm outside of solenoid

$\varepsilon_x = 5.06$ mm (excluded x-p_y correlation);

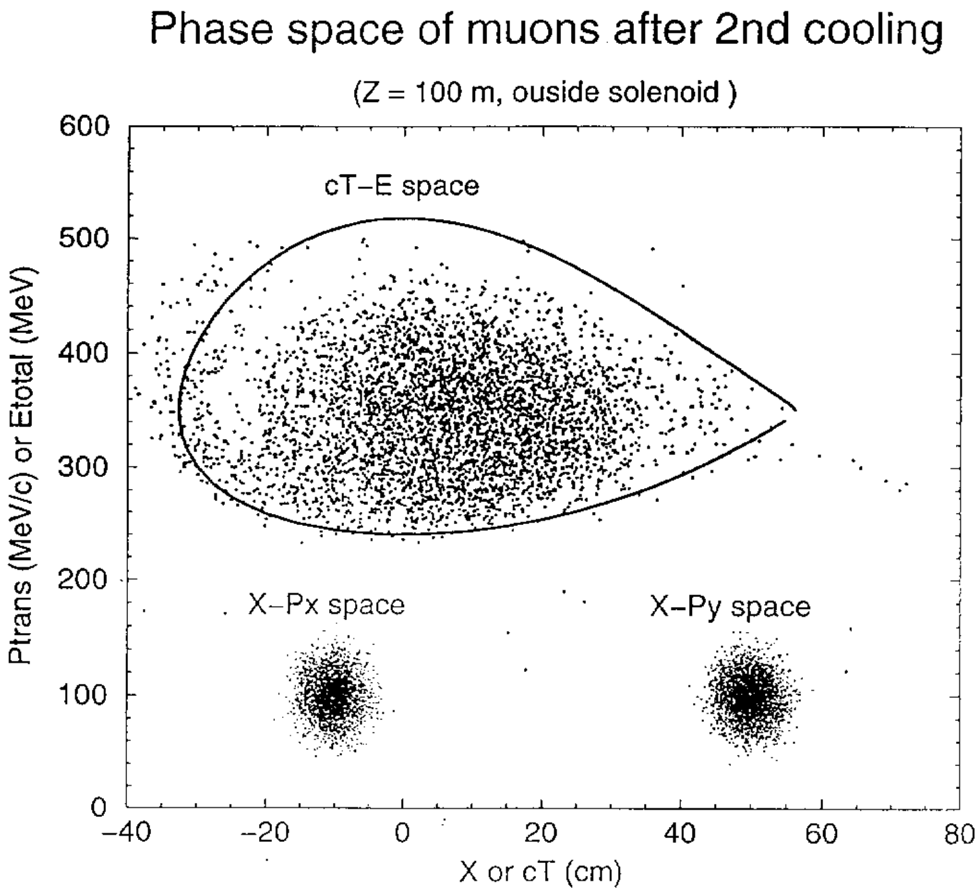
MUON BEAM AFTER 2nd COOLING (Z=100 m, inside sol.)



$\mu^+/p = 0.096$

$\sigma_x\sigma_{px} = 4.63$ mm

MUON BEAM AFTER 2nd COOLING (Z=100 m, outside sol.)



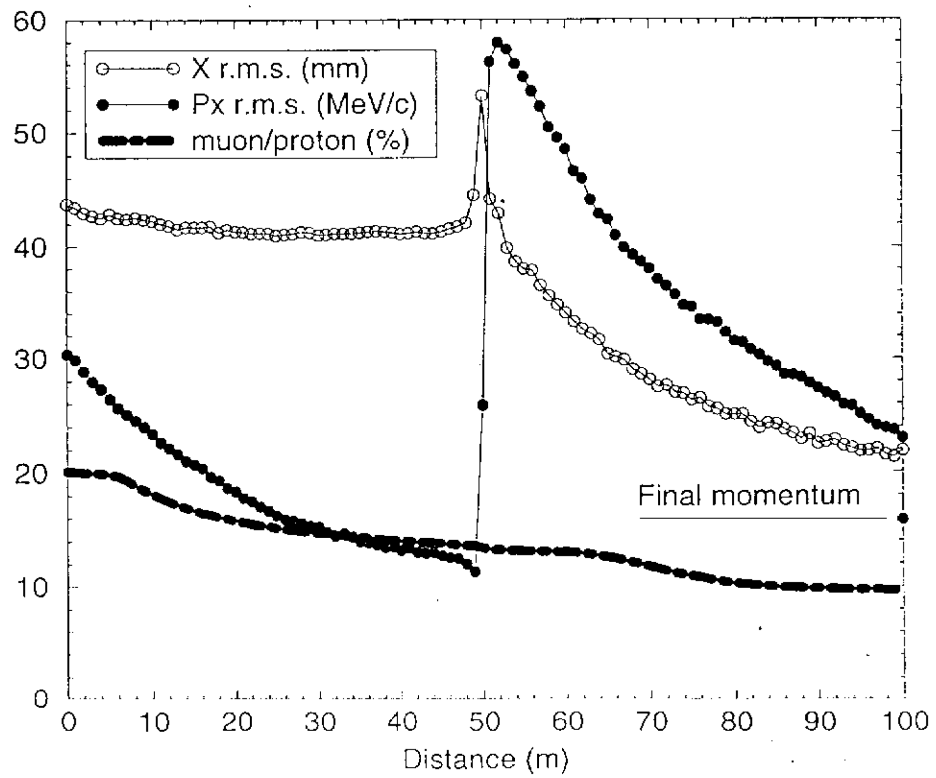
$\mu^+/p = 0.096$

$\sigma_x \sigma_{px} = 3.21$ mm

BEAM RADIUS AND TRANSVERSE MOMENTUM

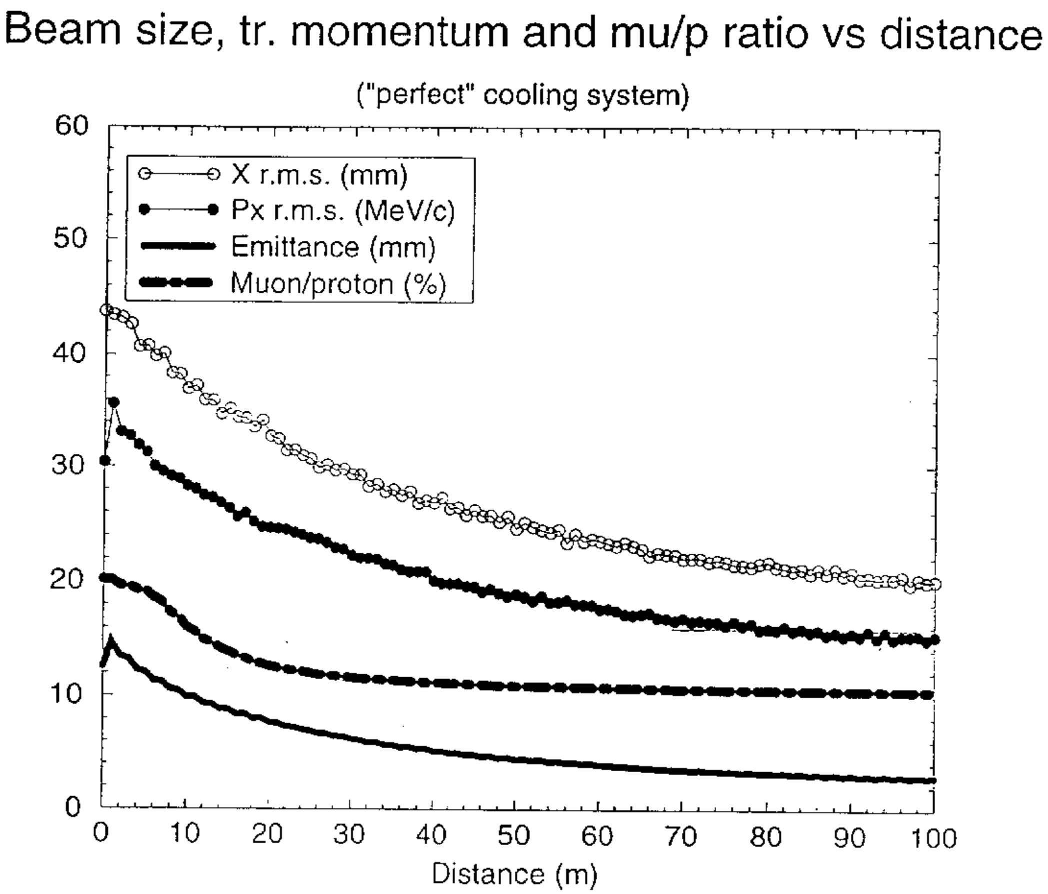
1. Beam radius almost does not change at the 1st solenoid. There is a small growth at Z>40 m because of diffusion of Larmor centers). Reversible peak at Z=50 m explained by decrease of magnetic field near this point. After that there is a decay of the size which ends at Z≈100 m (again diffusion of Larmor centers).
2. Transverse momentum decreases in both solenoids but there is a strong growth between them because of the kick by radial field which excites angular momentum. The kick at the end of 2nd solenoid suppressed residual angular momentum and decreases r.m.s transverse momentum.
3. Number of muons essentially decreases at Z≈ 10 m and 70 m. 1st decrease is a loss of muons which are not captured on the bucket at the bunching. The jump of transverse momentum at Z = 50 m changes the longitudinal velocity. It excites synchrotron oscillations and 2nd decrease of the intensity.

Beam size, tr. momentum and mu/p ratio vs distance



COOLING BY "PERFECT" SYSTEM

- 100 m cooling channel;
- |B| = 5 Testa anywhere;
- Sign B changes each 1 meter.



MAGNETIC FIELD IN TNE MATCHING SECTION

- Outer solenoid:
  R coil = 70-71 cm, gap between ± coils 20 cm;
- Inner solenoid:
  R coil = 15-16 cm, gap between ± coils 2 cm; length of each coil 27 cm;
- Current density 398 A/mm^2.