Views of Cooling Front Ends

NuFact'00,
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Outline

1. **Overview**
   - *Design approach (FNAL study)*
   - *Constraints*
2. **Front End**
   - *Performance*
   - *Limitations*
3. **Summary/Outlook**

FNAL Neutrino Source Design Study

The charge (part 1)

⇒ Design concept for a muon storage ring and associated suport facilities that could, **with reasonable assurance**, meet performance goals required to support a compelling neutrino based research program.

Approach: conventional solutions where possible.

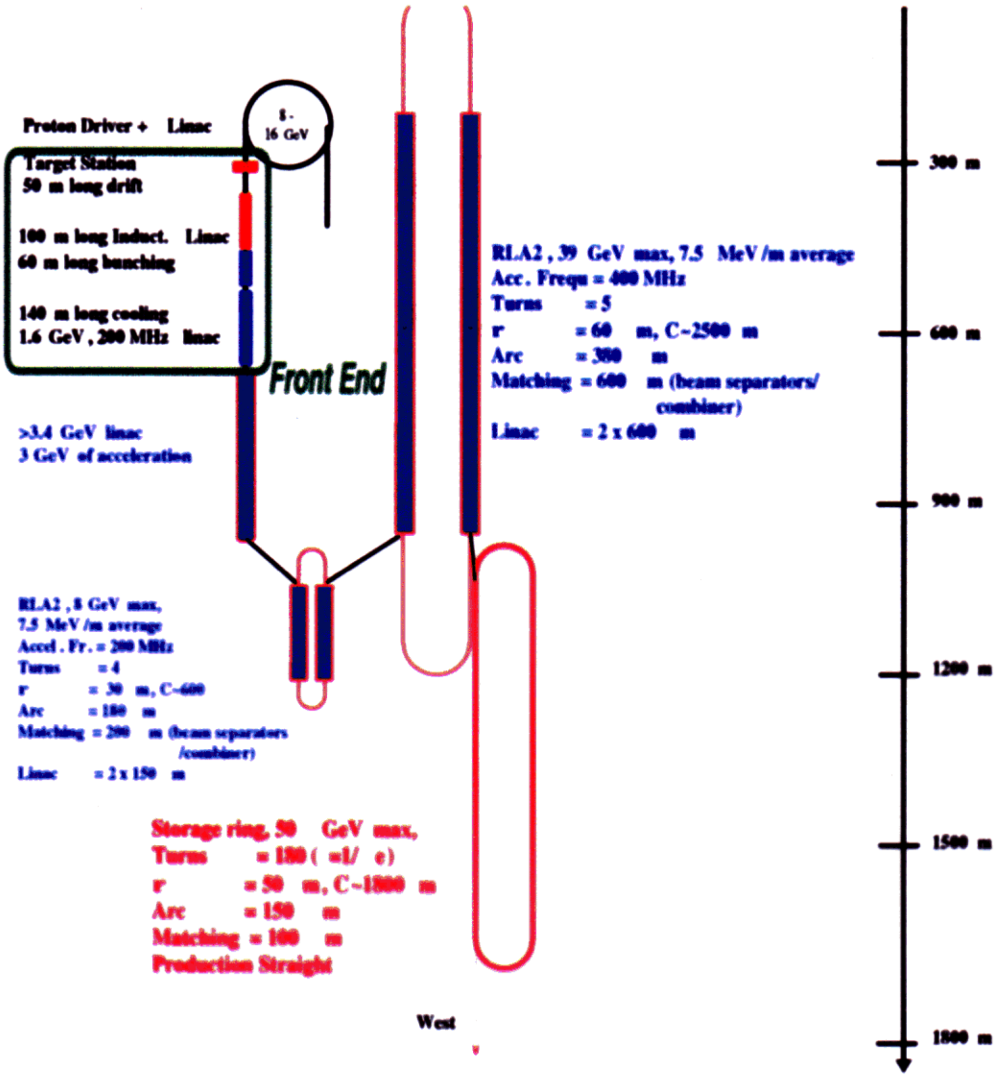
→ longer bunch (1ns → 3ns) in the proton driver

→ Solid carbon target

→ Avoid very low frequency RF, use induction linac.

→ Realistic engineering constraints on Front-End designs (phase-rotation, bunching, cooling) and acceleration.

Design goals: $2 \times 10^{20}\nu/\text{year}$, 50GeV energy, no polarization, both μ^+ and μ^-.

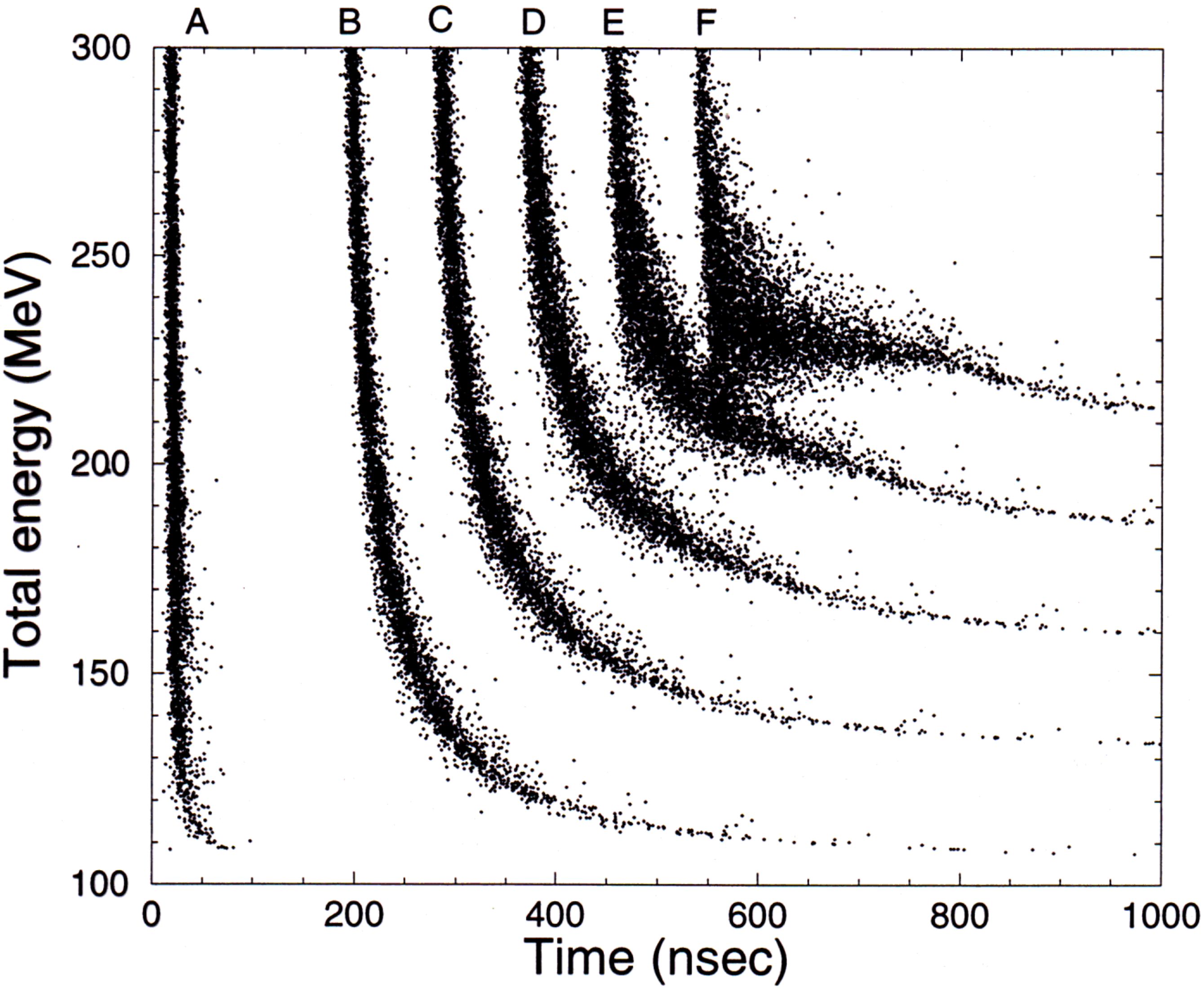


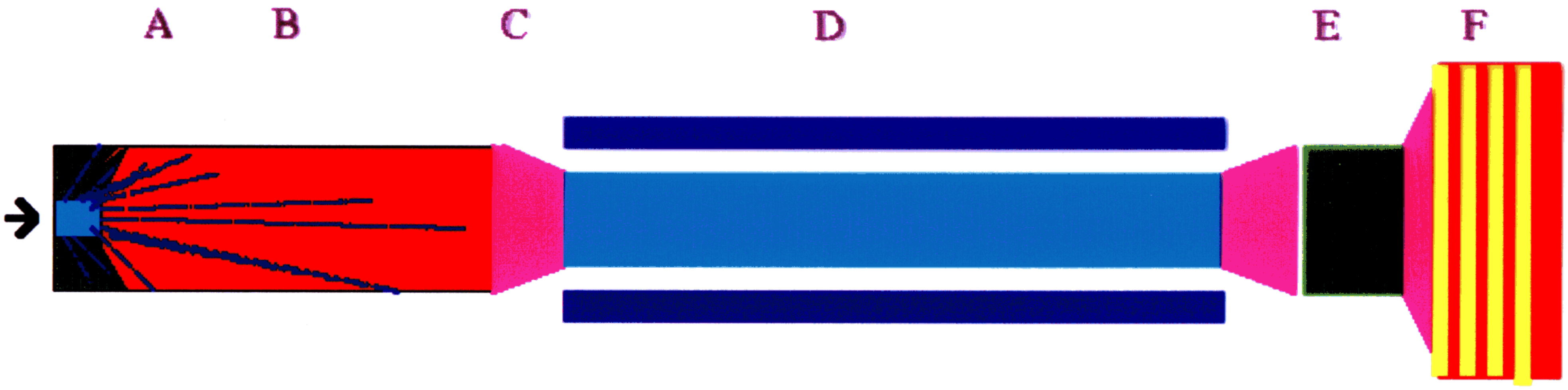
Basic Calculation: with 1/3 of μ's decay in the straight, 2×10^7 sec/year, and 2×10^{13} POT per pulse at 15Hz

⇒ **need** $2 \times 10^{12}\mu$ per pulse to be delievered to the acceleration ($0.1\mu/p$), to acheive the 10^{20} ν's per year objective.

Beam Properties Along the Capture and Bunching Section

Region	Position	$\pi + \mu$ / proton	E-window	$\epsilon_{t,N}$ (mm)	σ_x (m)
A. After Target	0	0.242	$< 500 MeV$	15.1	0.09
B. Decay Channel	47m	0.226	$< 500 MeV$	15.9	0.092
C. Matching	50m	0.222	$< 500 MeV$	16.5	0.057
D. Induction Linac	150m	0.191	$< 500 MeV$	16.3	0.060
E. Minicooling	153.45m	0.191	$< 450 MeV$	12.6	0.055
F. Buncher (all μ's)	170.9m	0.188	$< 375 MeV$	12.4	0.046
Buncher (in bucket)	170.9m	0.123	$< 375 MeV$	12.0	0.046





(Lengths of Sections are Not to Scale)

Schematic Overview: π -> μ production, capture, and bunching

A. Proton Beam (16 GeV, 4 bunches)

Target Station (Carbon target)

B. Drift: π -> μ decay region (L = 47 m, B = 1.25 T)

C. Matching Section (L = 1 m)

D. Induction Linac (L = 100 m, B = 3 T, -0.5 < V' < 1.5 MV/m)

Matching Section (L = 1m)

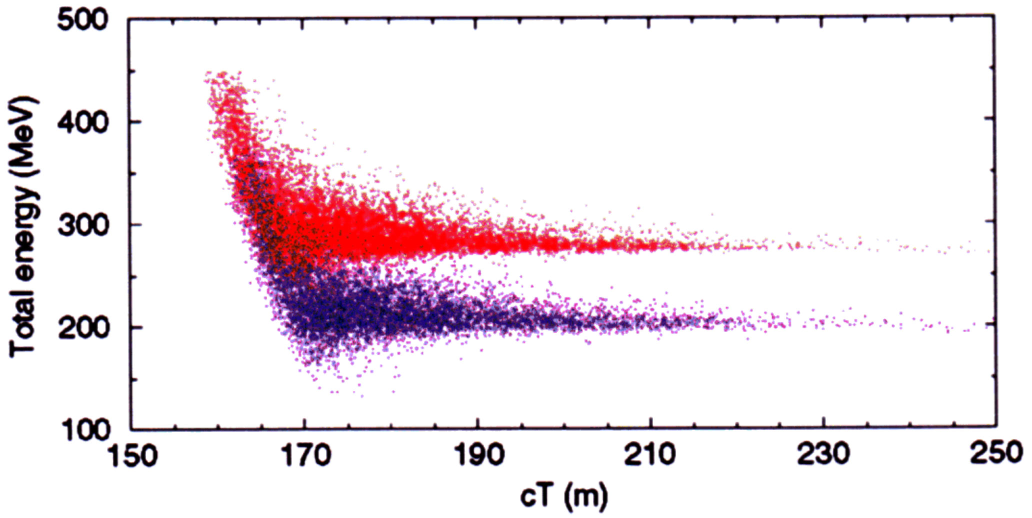
E. Minicooling (Liquid Hydrogen, L = 2.45 m, B = 5 T)

Matching Section (L = 1m)

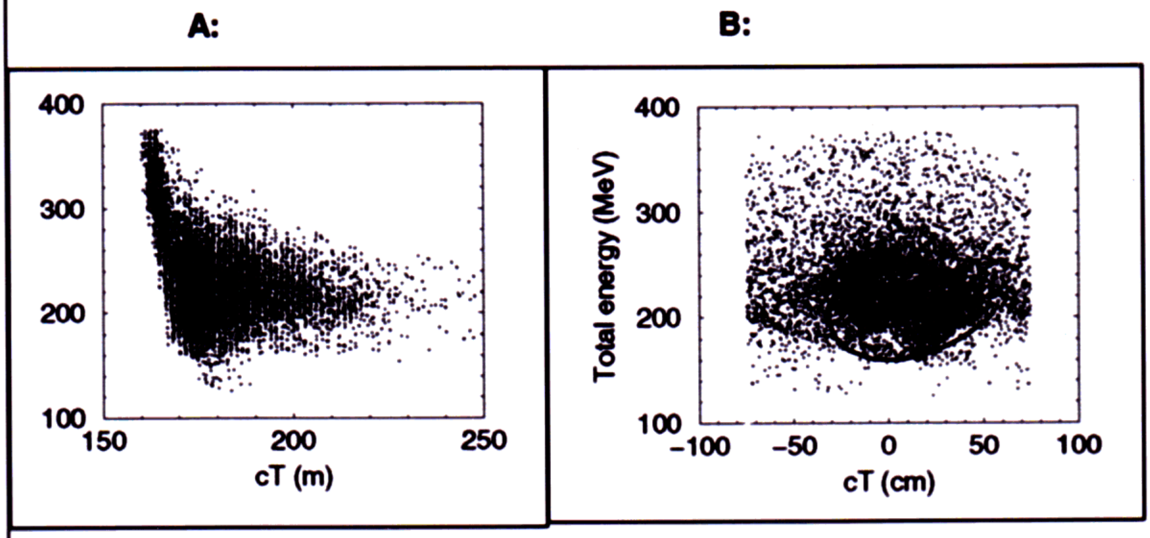
F. Buncher (L = 16.432 m, B = 5 T, includes 3x2m RF accelerating cells)

Bunching and Capture

- ΔE/E after phase rotation
- bunching into string of 35 bunches or so



Longitudinal phase space distributions of the μ=beam before (above, red) and after (below, violet) the minicool energy loss insert.



Beam distributions in energy –distance coordinates. A shows the full beam length; B shows the distribution folded over the 201.25 MHz periodicity, with an RF bucket for 200 MeV, 200 MHz cooling.

Cooling Channel Summary
(LAST MILLENIUM !!!)

SFoFo: 20 m long, $B_{max} = 6.6T$, p0 = 190 MeV; uncorrelated beam
in: $\sigma_{xy} = 1cm$, $\sigma_z = 1.5cm$, $\sigma_{pT} = 0.015$, $\sigma_{pz} = 6MeV$

Variable	Unit	Initial	Final	R = Final/Initial
Particles Tracked + cut	-	1000	994	0.994
Transverse Emittance(x)	$\pi\, mm - mrad$	1411	946.2	0.67
6-D Emittance	$(\pi\, mm)^3$	2.219	1.838	0.82

FoFo: 50 μ Al windows 130 m long, $B_{max} = 3.4T$, p0=186 MeV
in: $\sigma_{xy} = 4cm$, $\underline{\sigma_z = 8.1cm}$, $\sigma_{pT} = 0.023$, $\underline{\sigma_{pz} = 10MeV}$; correlated beam

Variable	*unit*	*Initial*	*Final*	$R = Final/Initial$
Particles Tracked		1000	895(≈600)	0.895(0.55)
Transverse Emittance(x)	$\pi mm - mrad$	8050	1940(2900)	0.2410.36)
6-D Emittance(x10^{-10})	(πmm^3)	841	100	0.119

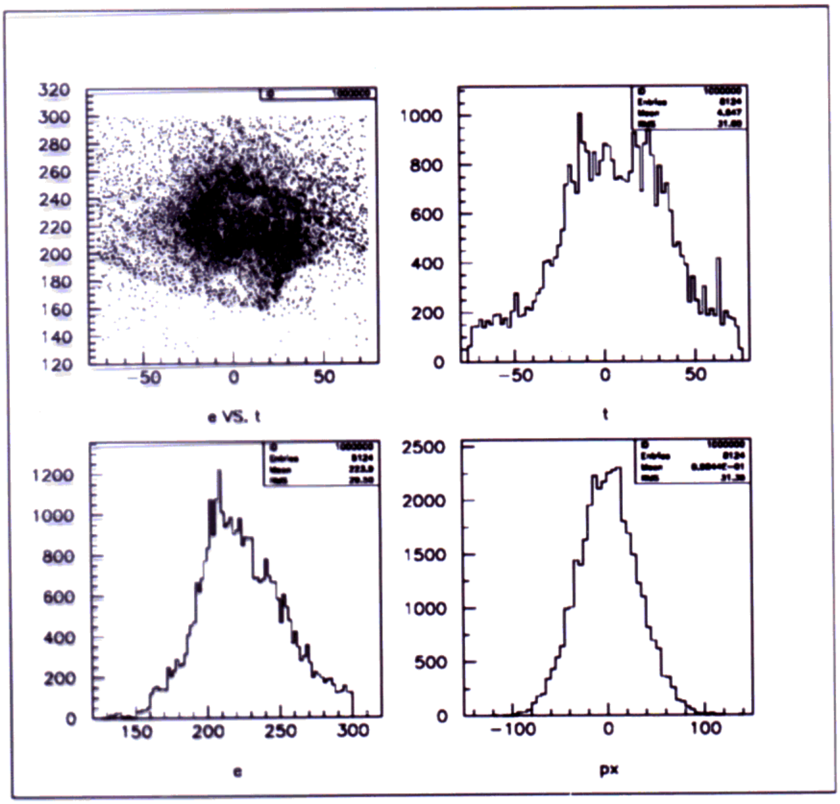
Alternating Solenoid: 20 m long, $B_{max} = 15T$, p0=186 MeV
in: $\sigma_{xy} = 4cm$, $\sigma_z = 1.12cm$, $\sigma_{pT} = 0.018$, $\sigma_{pz} = 6MeV$; correlated beam

Variable	*unit*	*Initial*	*Final*	$R = Final/Initial$
Particles Tracked	-	1000	980	0.98
Transverse Emittance(x)	$\pi mm - mrad$	1500	750	0.5
6-D Emittance(x10^{-10})	(πmm^3)	1.665	0.8	0.48

In Progress:

- Adiabatic SoSo (FNAL)
- Long Solenoid (LBL, FNAL)
  trans: 50 percent; ϵ_T: 10,000 → $1500 \pi mm - mrad$
- 2+ FoFo channels, with matching (LBL)
  trans: 35 percent; ϵ_T: 15,000 → $2{,}000\ \pi mm - mrad$

FNAL Integrated Front End Simulation: Cooling Channel Input Beam



Typical Beam Into Cooling:

x (rms) = 4.5 cm

px (rms) = 32 MeV (16%)

E(rms) = 40 MeV (18 %)

z(rms) = 30 cm (1 ns.)

- non-gaussian distributions
- mean momentum = 200 MeV
- Energy Cut: $E \leq 300$ MeV

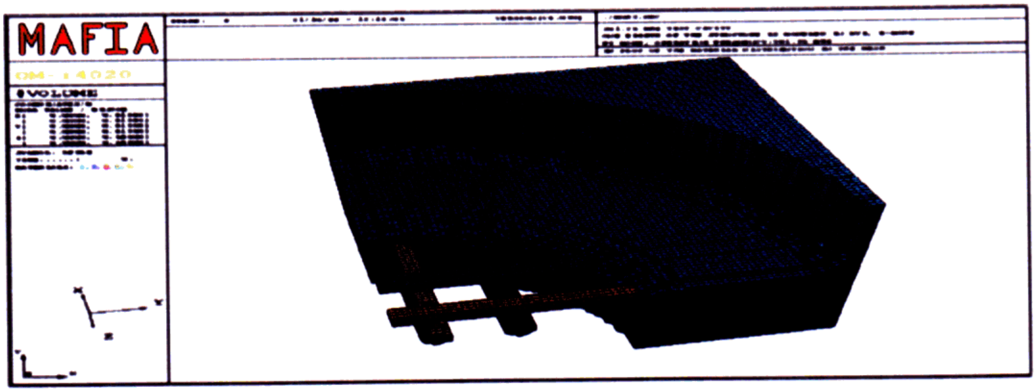
Cooling Simulations

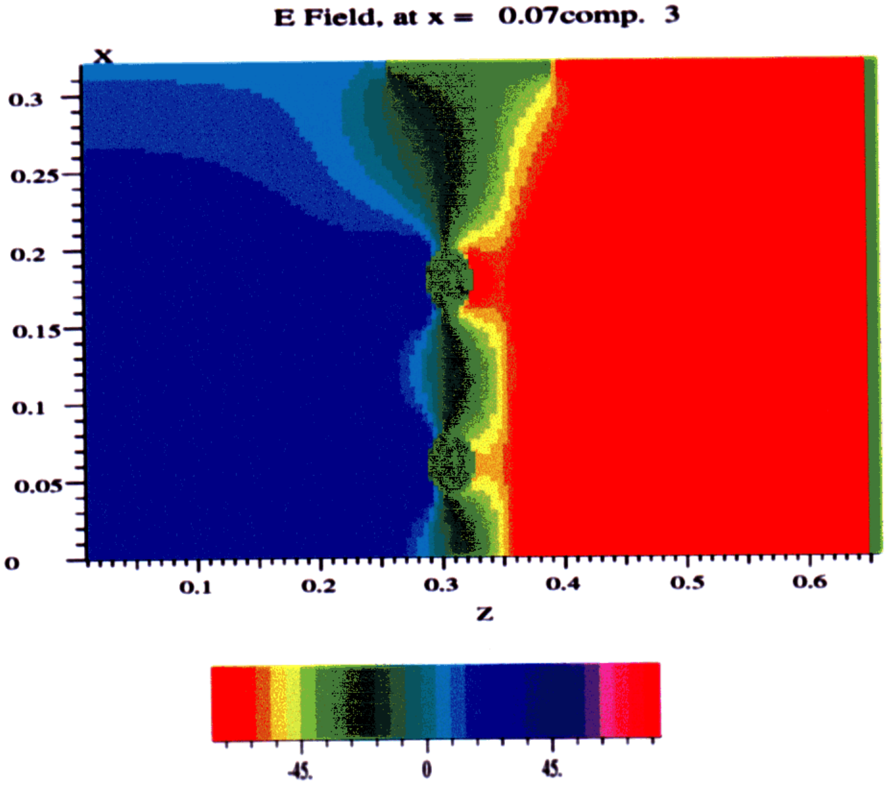
- 2 cooling channels for NuFactory: solenoid focusing **FoFo** and "larmor cooling" **single-flip**.
  - ▷ Design with **engineering constraints**, realistic **beam**; optimize for **accelerator acceptance** → "integrated optimization"

    also, DPGeant and Icool x-checked, same figure of merit calculation & definition.
- Design procedure: "simple tracking" used to **narrow parameter space, verify design idea**; DPGeant or Icool and Minuit optimizer to find optimal solution with realistic geometry and component implementation
  - ⇒ Statement of detailed tracking "checking" "simple-tracking" results is misleading → really prove design idea and find optimal realistic solution

paradigm worked for Alt.Sol, lilens channel, single-flip

DPGeant "3D" Implementations: gridded 201MHz rf cavity



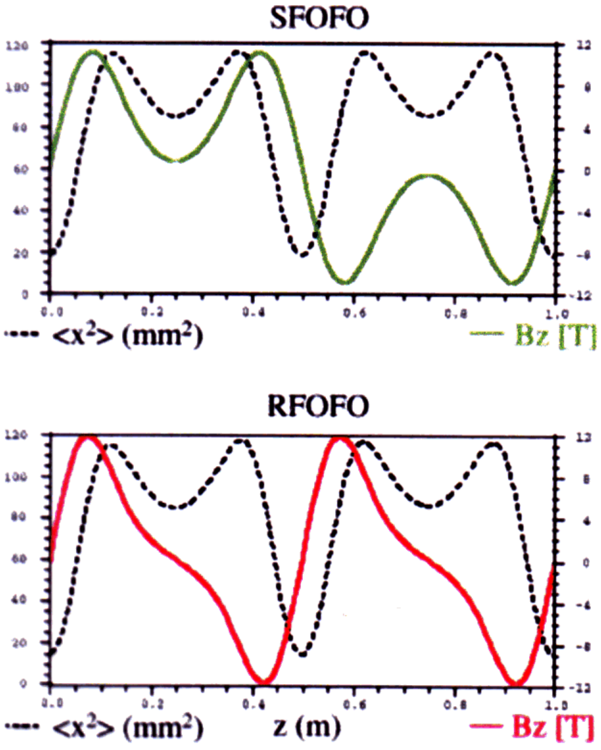


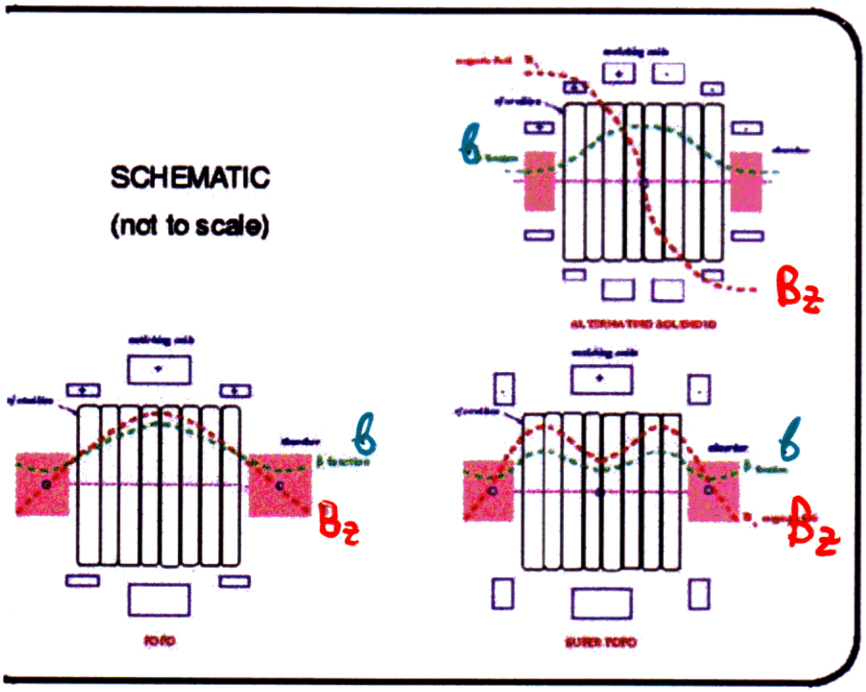
Simulation Effort at LBNL

- “From the Target through the Cooling”
  - Different Lattice types
  - Cell length ~ Coil diameter ⇒ non efficient use of H_{crit}
  - Field 3.5-7 T or more ⇒ $NiSn_3$ with this kind of diameter
  - Analytical description ⇒ G. Penn, LBL / K. Kim ANL+Univ. Chicago/ Y. Derbenev, Michigan State/FERMI

→ need to reverse field to cancel angular momentum

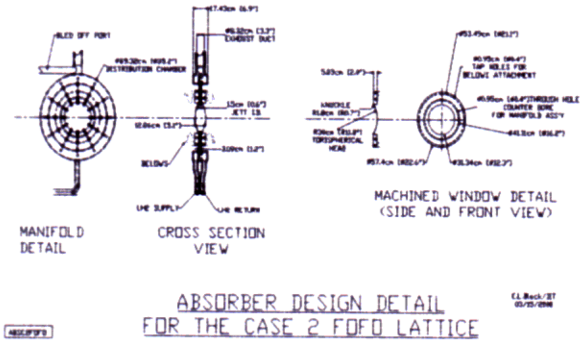
Fields and beta functions: two examples
(note $\langle x^2\rangle \propto \beta$)

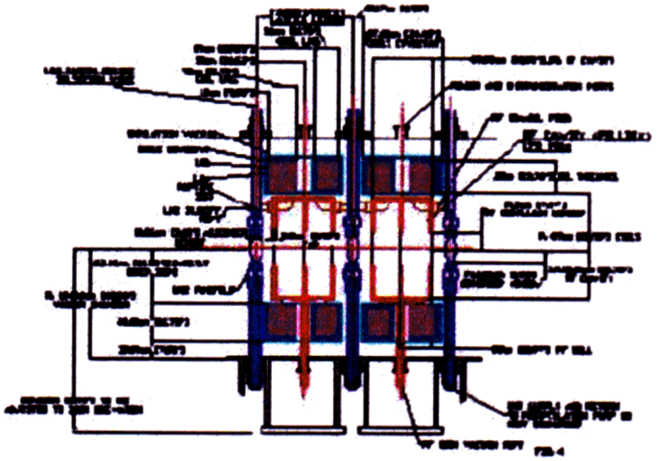




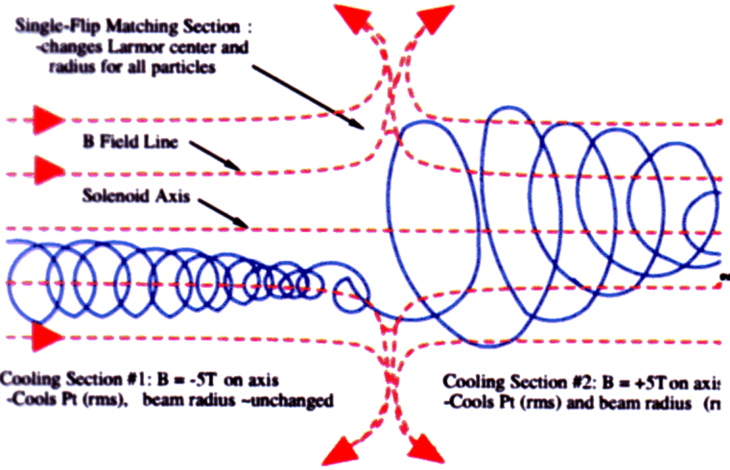
Other Cooling Channels

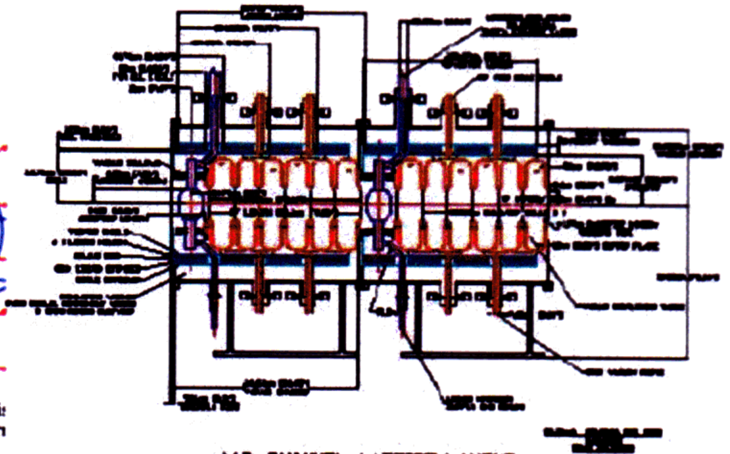
- Baseline: FOFO





- Single Flip

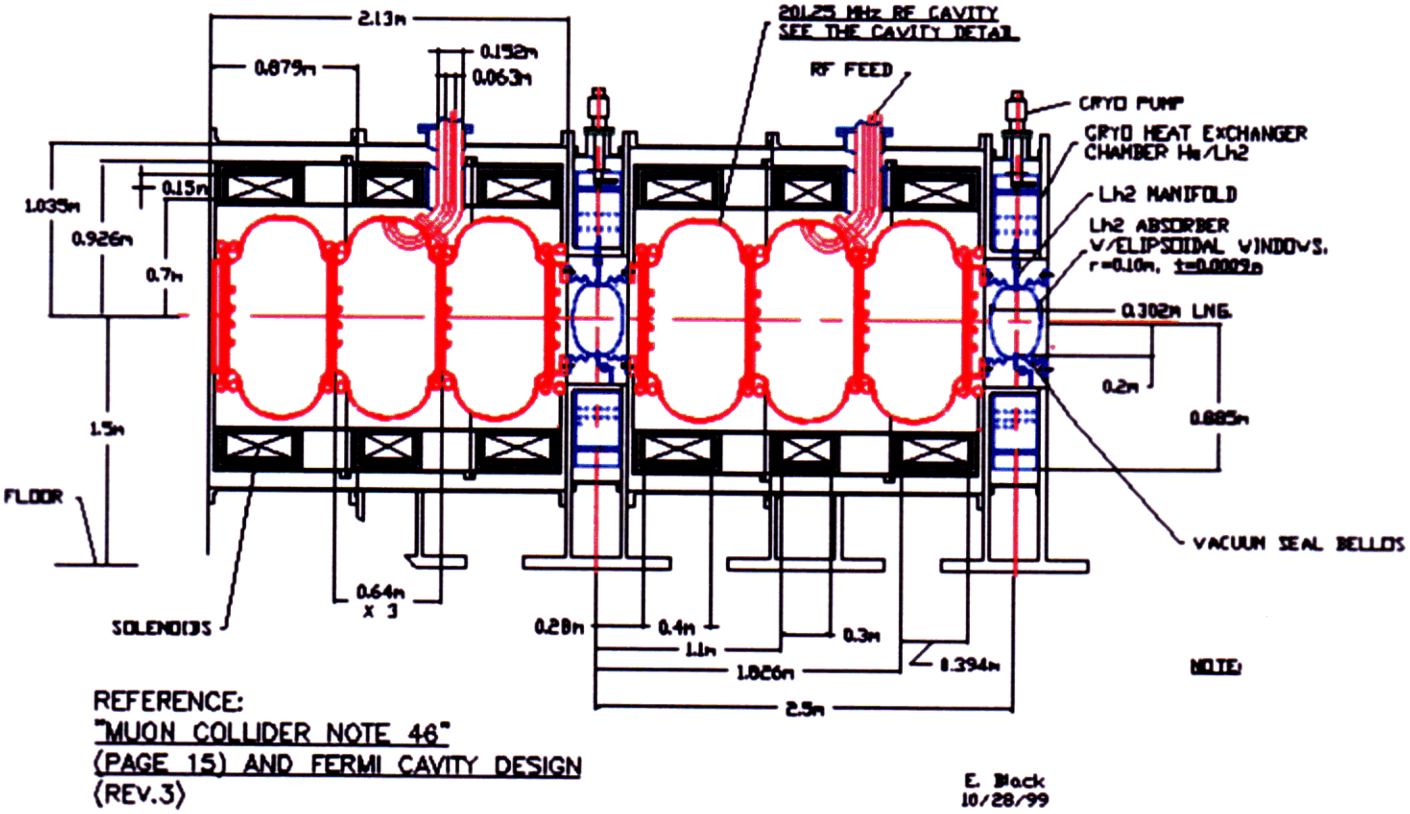




V.B. CHANNEL LATTICE LAYOUT

The Heart of the Cooling Channel for a Neutrino Factory

- **IIT, BNL, LBNL, FNAL:** go through an engineering design faster
- Goal: Do all the cooling with one set of hardware



B_z ~ 3.5 T max

E_{acc} ~ 15 MV/m @ 200 MHz

Figure of Merit # 1

Technical Feasibility:

RF Cavities

- Power Feeds → gaps between solenoids > 20 cm
- R = 60 cm → solenoid radii > 65 cm

Absorbers

- Windows:
  SF Absorbers have L = 35 cm, R = 20 cm
  → ellipsoidal shape, thickness $\geq 280\mu m$

Solenoids

- Hoop Stress
- Quench Protection

⇒ Limits Achievable Field on Axis,
Current Density, Coil Thickness, Coil Separation,
SC Material, Support Structure ...

Golden Rule:

$$B \; J \; R \; \leq \; 350 \; MPa$$

Figure of Merit # 2

Acceleration Acceptance Cuts:

- Longitudinal Acceptance

$$accepted\ \epsilon_L \;=\; (2.5\,\sigma)^2 \times \sigma_z\,\frac{\Delta p}{p}\,\beta\,\gamma$$

FNAL Design Study	Single Flip
$\sigma z \;=\; 12\ cm,\ \frac{\Delta p}{p} = 0.11$	p = 280 MeV
p = 200 MeV, $\Rightarrow \Delta p = 22$ MeV	$\Delta p = 22$ MeV $\Rightarrow \frac{\Delta p}{p} = 0.08$
$accepted\ \epsilon_L \;=\; 150\ mm$	$accepted\ \epsilon_L \;=\; 150\ mm$

- Transverse Acceptance

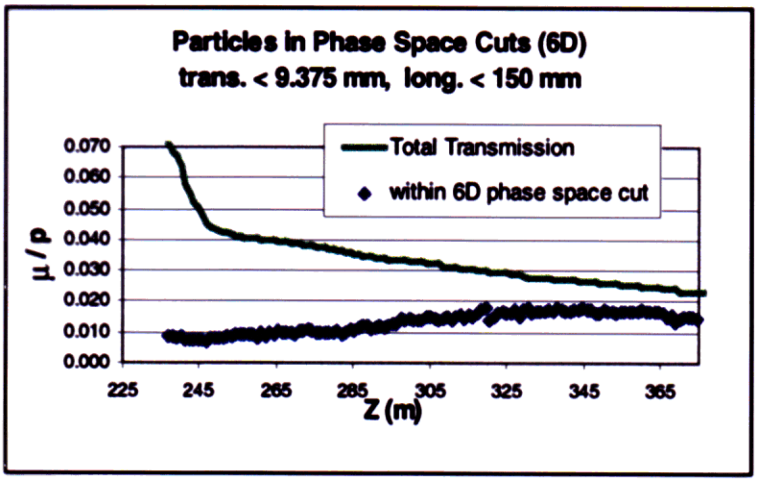
$$accepted\ \epsilon_T \;=\; (2.5\,\sigma)^2 \times\ \epsilon_T$$

FNAL Design Study	Single Flip
$\epsilon_T \;=\; 1.5\ mm$	$\epsilon_T \;=\; 3.0\ mm$
$accepted\ \epsilon_T \;=\; 9.375\ mm$	$accepted\ \epsilon_T \;=\; 18.75\ mm$

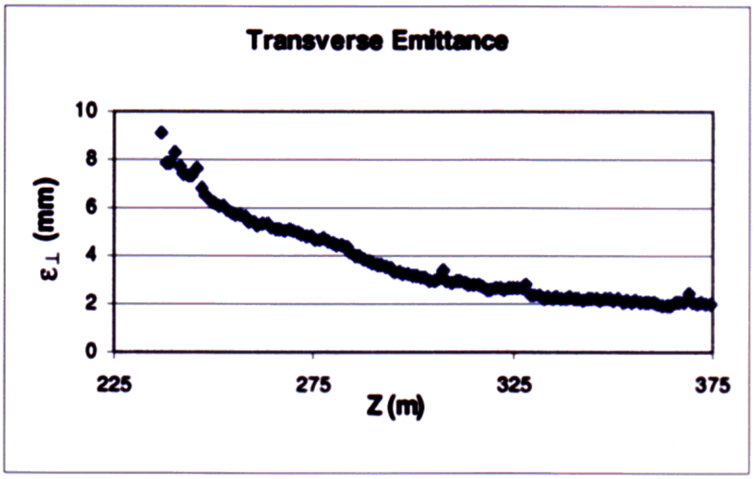
Larger Tranverse Acceptance Feasible? YES!

Do We Achieve Our Goal?

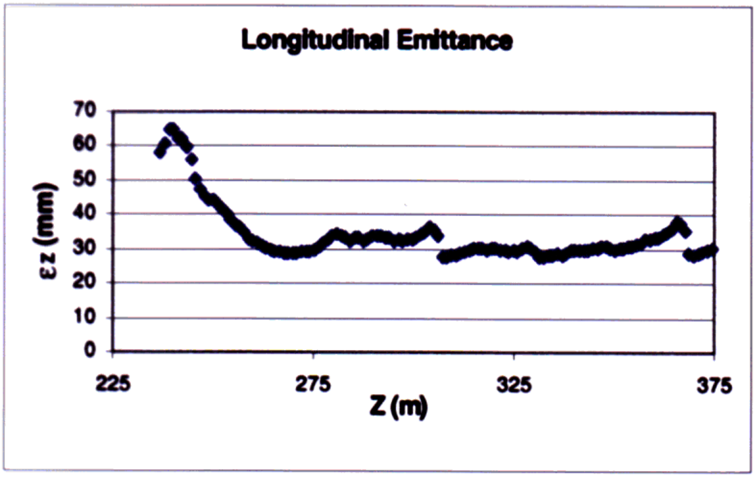
- Nasty question:
  - partially: 2×10^{19} is ok probably 4×10^{19}
  - potential for better channels: -> Derbenev: single flip!!!



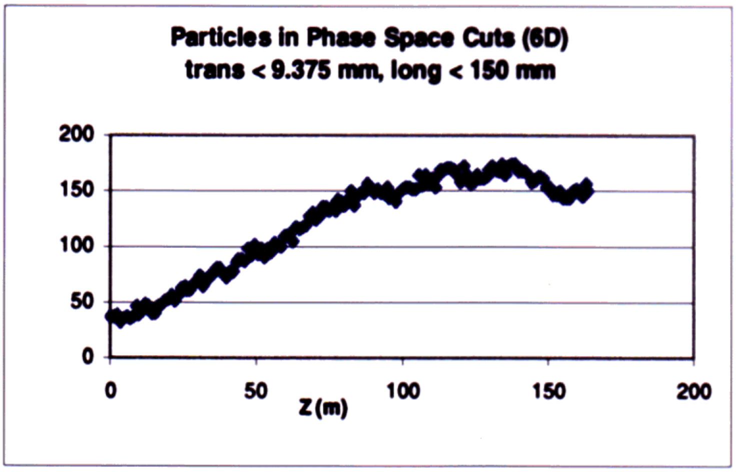
The transmission and the muon yield within the acceptance of the accelerator.



The transverse emittance versus z in the FoFo cooling channel.



The longitudinal emittance.



Relative yield increase within the acceptance of the accelerator.

⊛ main problem: ε_L too large!

Performance could improve with better matched input beam.

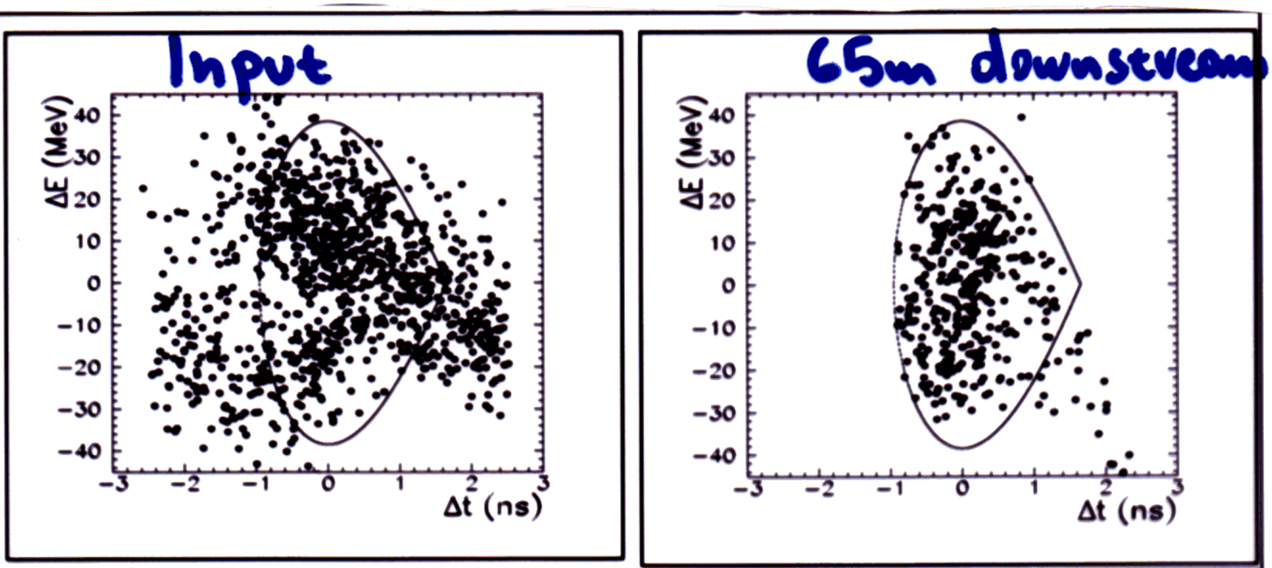


Figure 9: The longitudinal phase space of the bunch entering the FOFO cooling channel (left) and 65m further downstream (right). Muons from the integrated simulation are shown together with an approximate representation of the separatrix.

Neutrino Factory Feasibility Study - 6-10 - April 15th, 2000

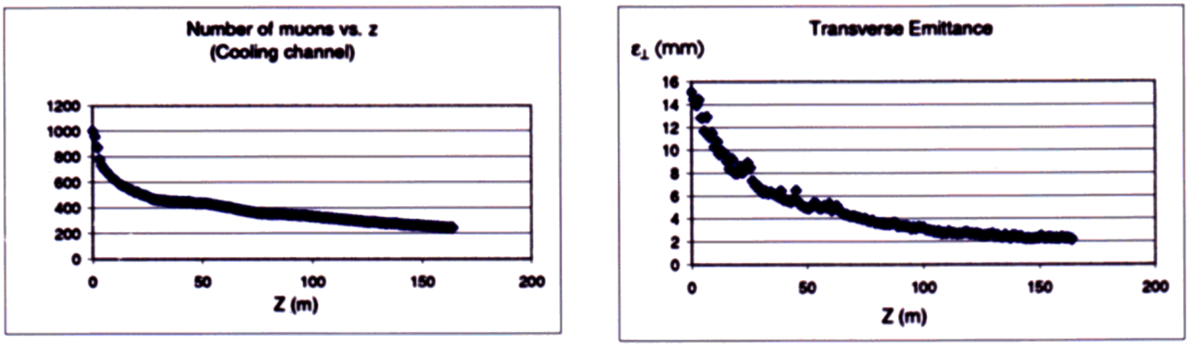


Figure 7a: Transmission in the FOFO channel vs. distance using the idealized beam described in the text.

Figure 7b: Transverse emittance vs. distance for the idealized beam.

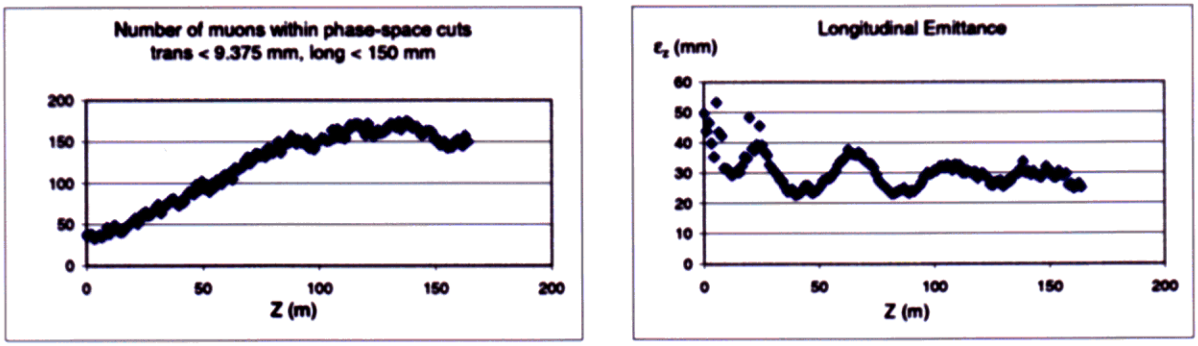


Figure 7c: Relative yield increase within the acceptance of the accelerator (9.375π mm.rad transverse, 150π mm longitudinal) using the idealized beam.

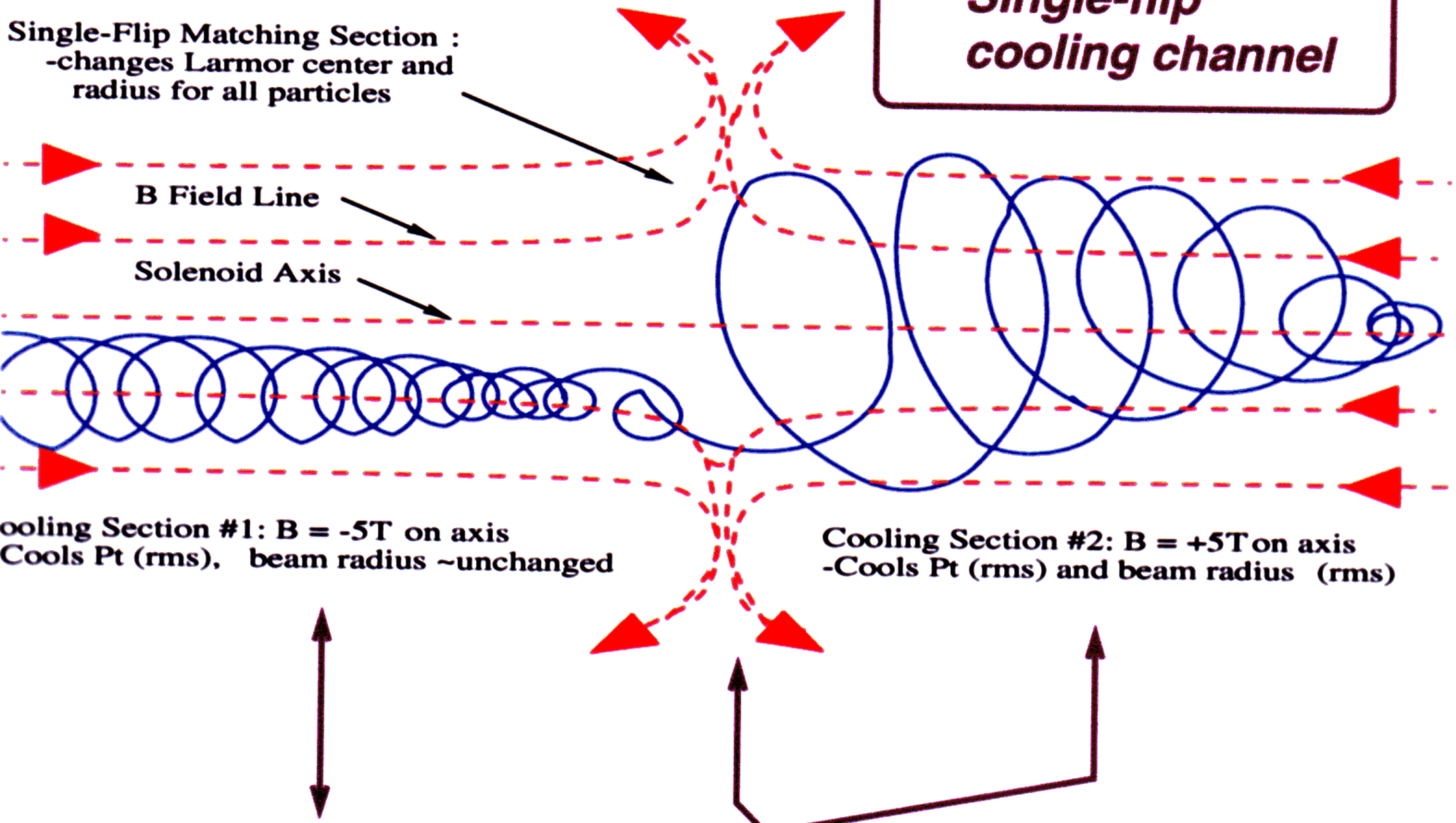
Figure 7d: The longitudinal emittance of the idealized beam in the FOFO channel.

Figure 7: Summary of cooling performance of the channel with an idealized beam.

Example of increase of cooling performance using an optimal imput beam. The above case corresponds to the beam for which the channel was designed and optimized

⇨ **Need for integrated optimization**

Single-flip cooling channel



Single-Flip Matching Section :
-changes Larmor center and
radius for all particles

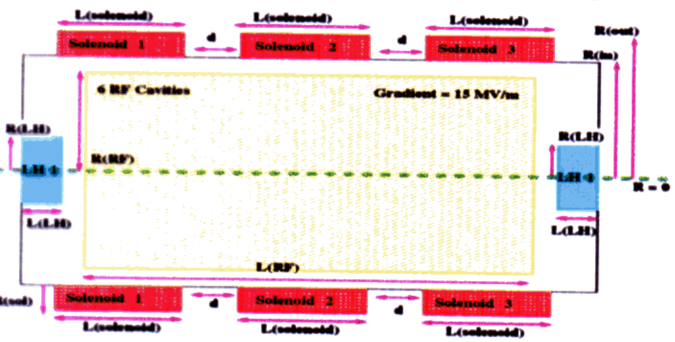
B Field Line

Solenoid Axis

ooling Section #1: B = -5T on axis
Cools Pt (rms), beam radius ~unchanged

Cooling Section #2: B = +5T on axis
-Cools Pt (rms) and beam radius (rms)

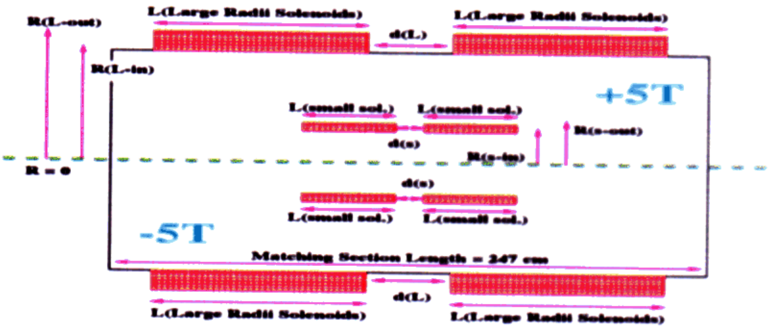
Single Flip Cooling Channel Cell Geometry



Cooling Channel Dimensions:

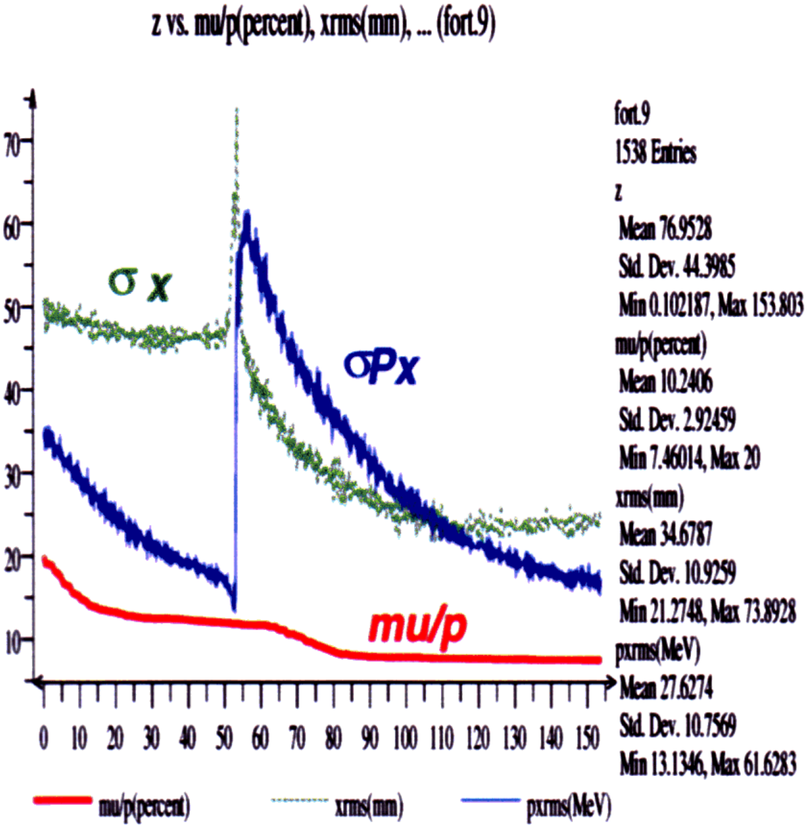
Magnets:	Absorber:	RF:
L(solenoid) = 58.6 cm	L(LH) = 16 cm	L(RF) = 197 cm
R(sol) = 12 cm , d = 24 cm	R(LH) = 20 cm	R(RF) = 60 cm
Current Density = 89 A/mm^2	Al windows: 0.03 cm	Be windows: 0.0125 cm
R(in) = 70 cm, R(out) = 82 cm		
Field on axis: +/- 5T		
Field at R = 70 cm: 6T		

BJR = 373.8 MPa
(at max. B)



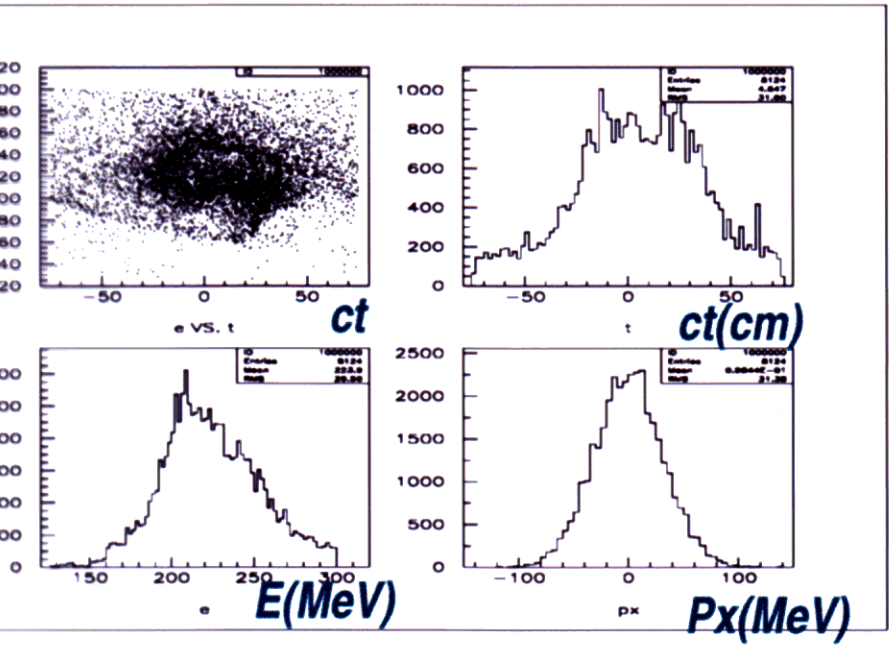
Matching Section Solenoid Dimensions:

Large Radii Solenoids:	Small Radii Solenoids:
L(Large Radii Solenoids) = 75 cm	L(small sol.) = 50 cm
R(L-out) = 82 cm , R(L-in) = 70 cm	R(s-out) = 26 cm, R(s-in) = 20 cm
thickness = 12 cm	thickness = 6 cm
Current Density = 50 A/mm^2	Current Density = 58.3 A/mm^2
Separation d(L) = 30 cm	Separation d(s) = 10 cm
Field on axis: 4 to 0T	Field on axis: 0T
Max. Field at R = 70 cm: 4.8 T	Max. Field at R = 20 cm: 3.2 T
BJR = 168 MPa (at max B)	BJR = 37.3 MPa (at max B)



mm ε_L	mmrad ε_T	μ/p
all transmit		0.08
150	9.375	0.032
150	18.75	0.050*
for 150m of channel		

*for this acceptance, same mu/p for 100m long channel



Typical Beam Into Cooling:

x (rms) = 4.5 cm

px (rms) = 32 MeV (16%)

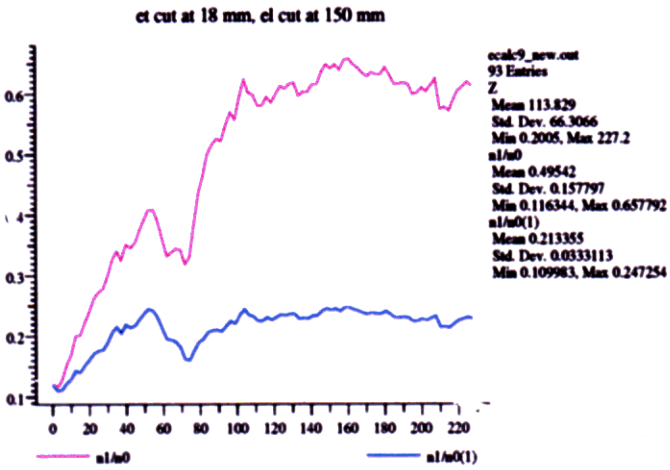
E(rms) = 40 MeV (18 %)

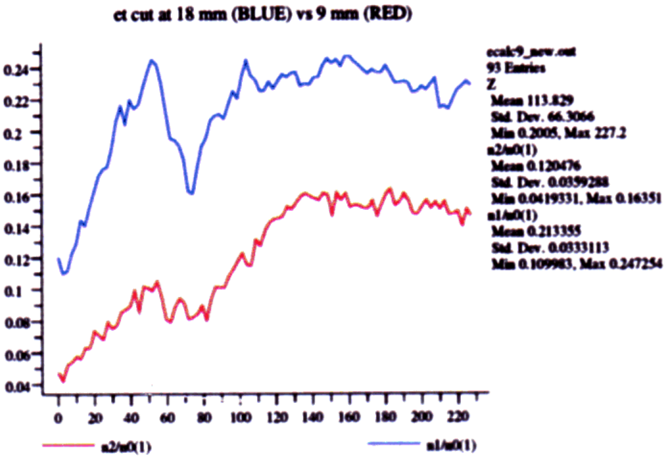
z(rms) = 30 cm (1 ns.)

Single Flip: Transmission into SF Acceleration Acceptance

Single Flip Acceptance Cuts:

$$n1/n0 = \frac{N_{in}(z)}{N_{tot}(z)} \qquad n1/n0(1) = \frac{N_{in}(z)}{N_{tot}(z=0)}$$

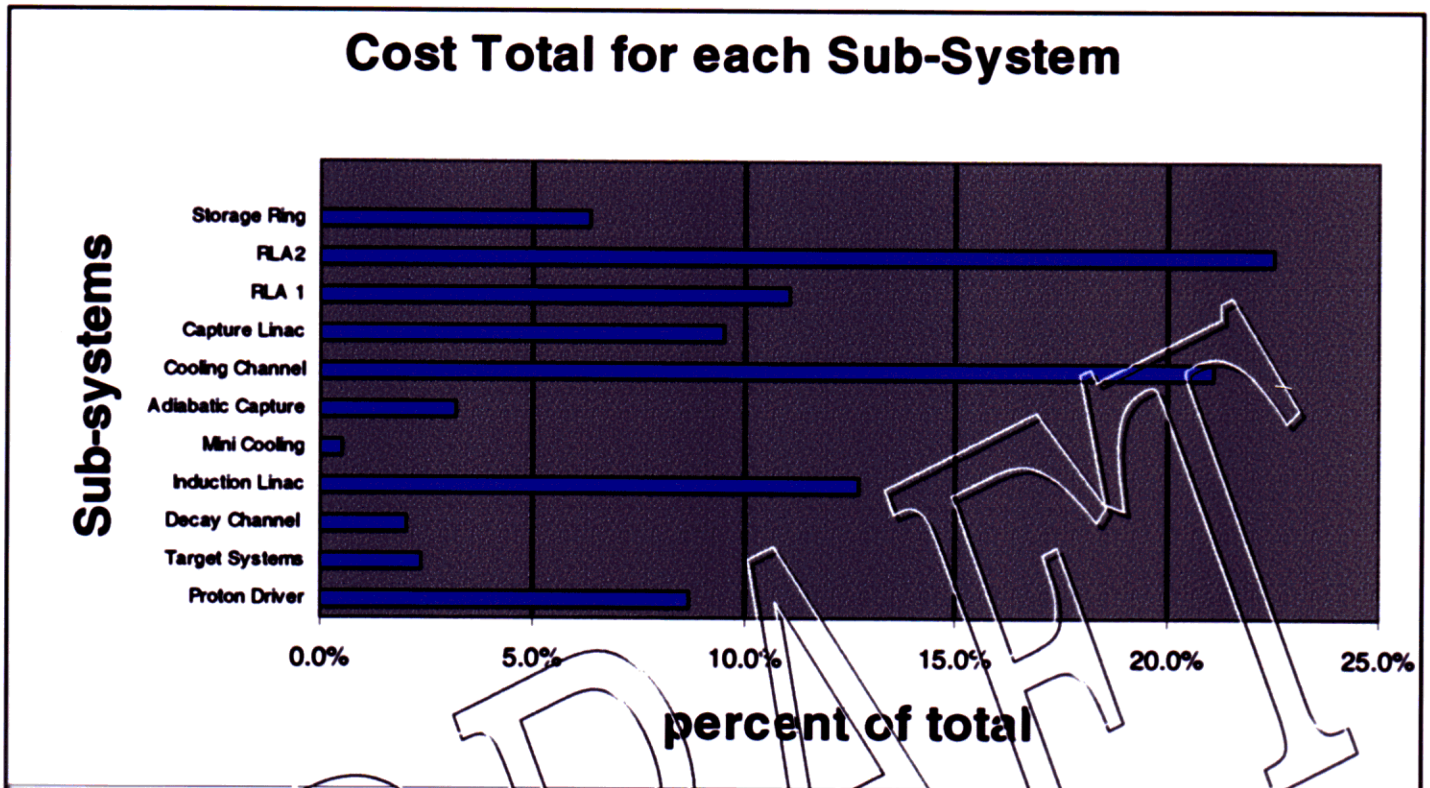


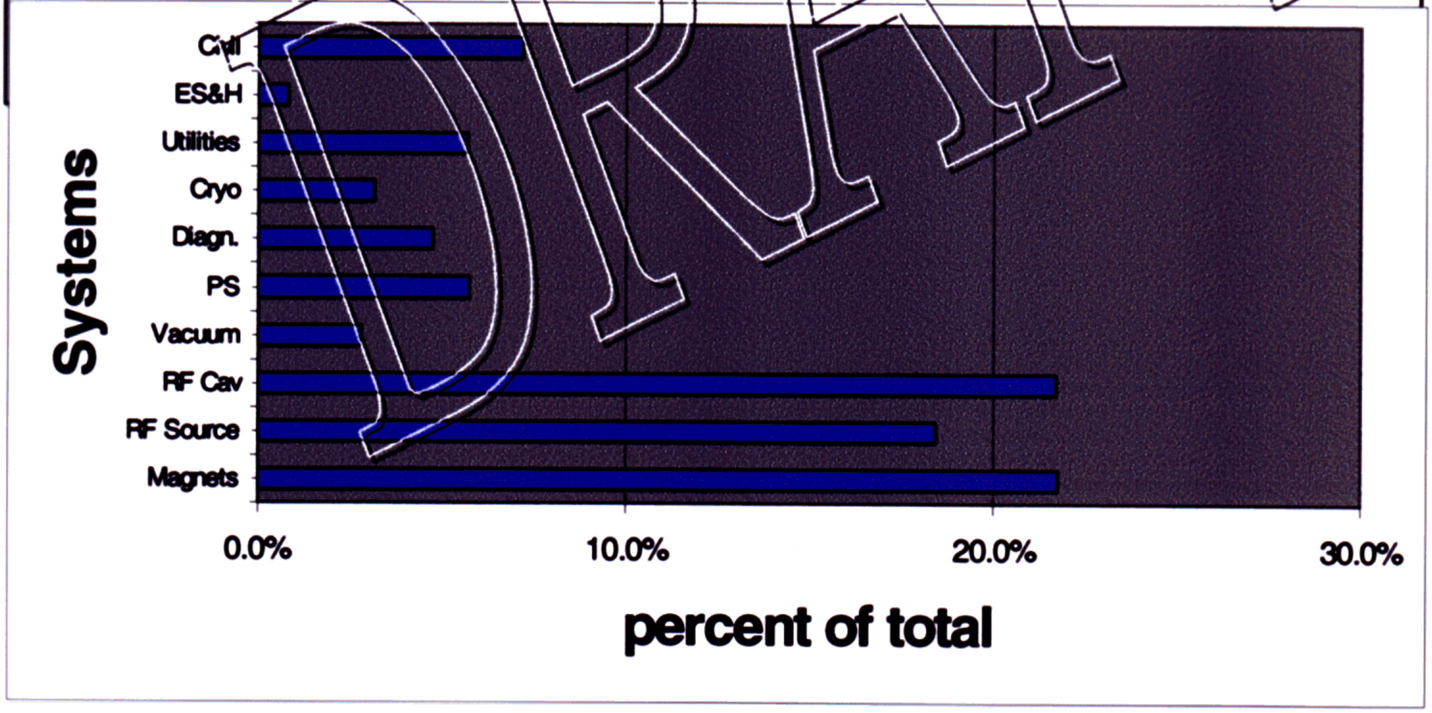


ϵ_T mm-Rad.	ϵ_L mm.	n1/n0(1), z = 100 m.	n1/n0(1), z = 150 m.
9.375	150	12% (0.024 μ/p)	16.4% (0.032 μ/p)
18.75	150	25% (0.05 μ/p)	25% (0.05 μ/p)
no cut	150	32% (0.064 μ/p)	30% (0.06 μ/p)
18.75	no cut	29% (0.058 μ/p)	32% (0.064 μ/p)

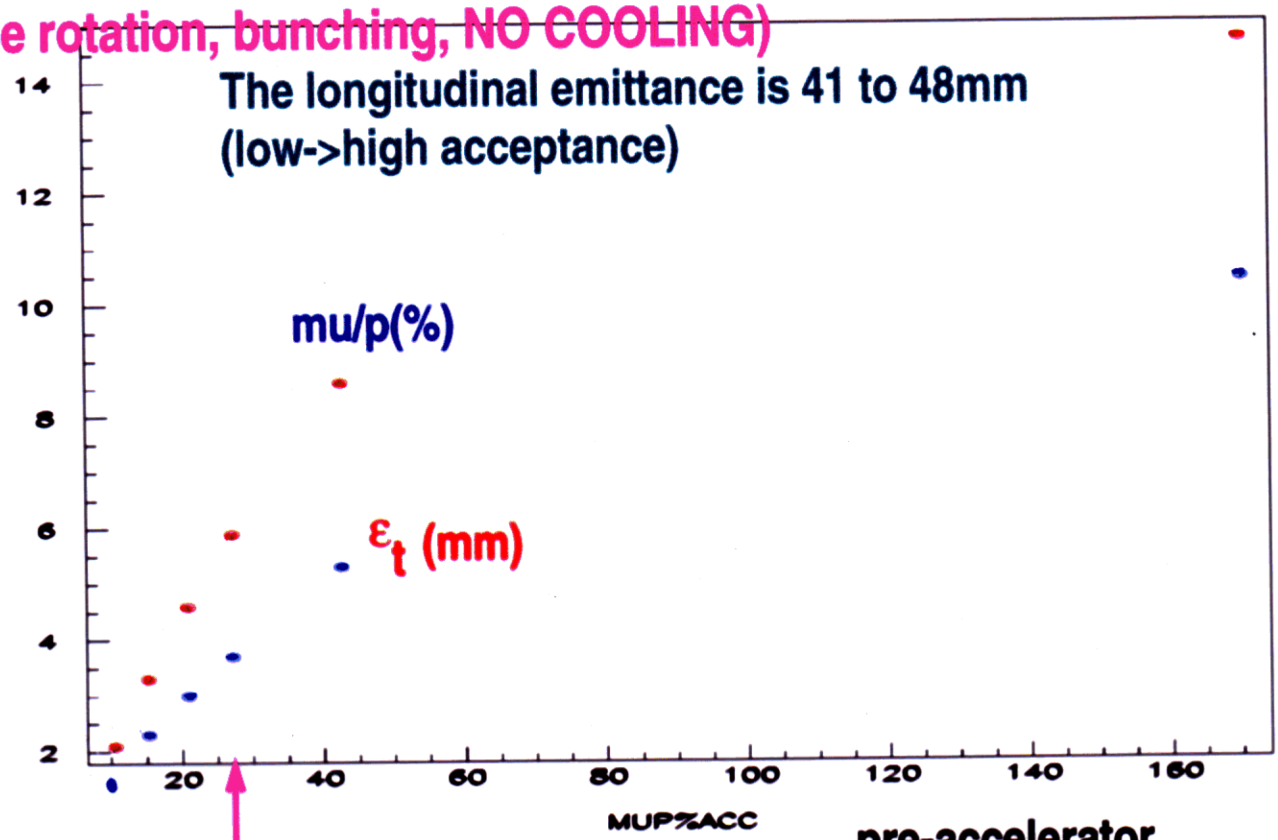
Cost

- Hot Topic: Proposal for Presentation.





Beam parameters vs transverse acceptance of the pre-accelerator (p-source, C target, decay channel, phase rotation, bunching, NO COOLING)



The longitudinal emittance is 41 to 48mm (low->high acceptance)

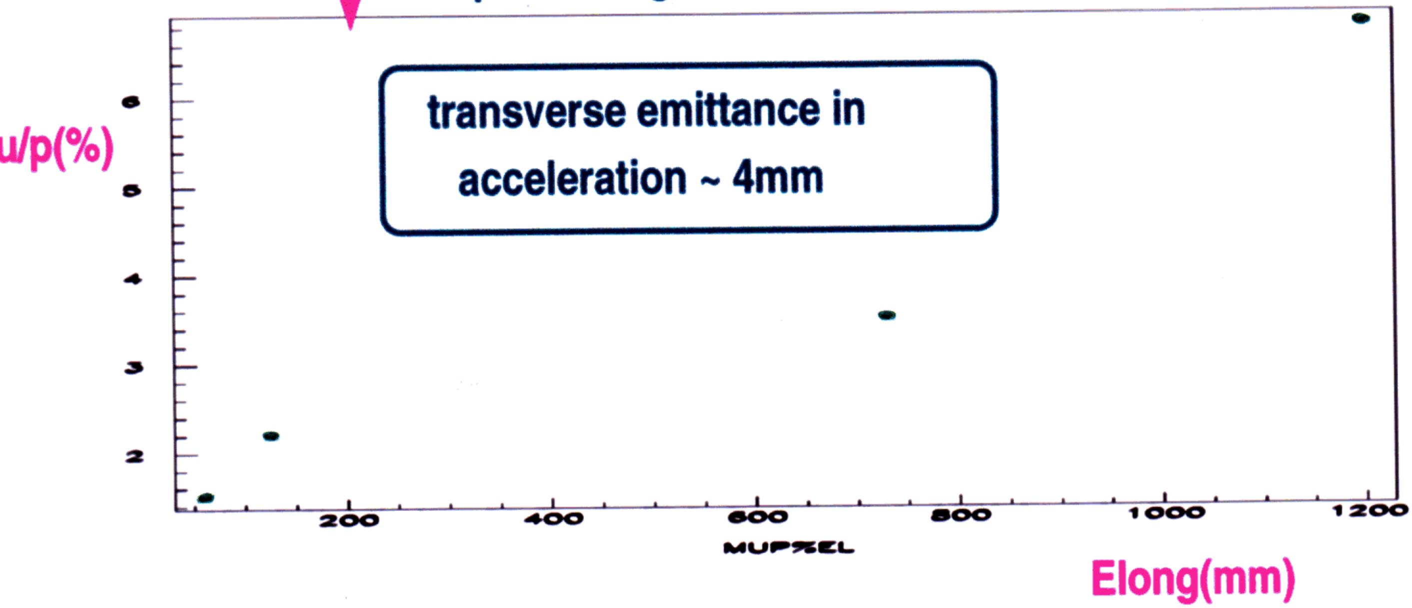
mu/p(%)

ε_t (mm)

pre-accelerator acceptance(mm)

For pre-accelerator acceptance of 27.2mm

mu/p vs Elong of the accleration



transverse emittance in acceleration ~ 4mm

Summary

- Integrated Front End design with
  - engineering constrains
  - "as conventional as possible" hardware components
- Performance x4 "shy" of design goal. This factor could go down ≈ to the amount of realism one is willing to lose
- Very successful effort considering the level of detail...

Summary, cont.

- Impressive progress despite missing factor of ~4

- Machine can be staged ($)

- Integrated design optimization could improve results

⇒ Longitudinal cooling should make the biggest difference

– OR –

much smaller ε_L from Ph rotation and buncher