INITIAL PARAMETERS FOR STUDY 2

DESIGN A

DRAFT

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Abstract

The parameters are given for the front end of a neutrino factory (design A for Feasibility Study 2). No RF is employed near the target and little polarization is achieved, but the efficiency of producing muons is relatively high ($\approx 0.2\ \mu$/p with 24 GeV proton bunches with 3 ns rms length). The high efficiency is achieved by

1) using a liquid mercury target;

2) using two induction linacs to achieve non-distorting phase rotation to a long spread in time: the final muons are distributed over 300 ns with relatively uniform energy spread; and

3) tapering the focus strength in the cooling system so that the angular spread of the muons being cooled is maintained at a constant value until relatively near the end.

Contents

1 Introduction

This note gives starting specifications and some simulation results for a first (Design A) design of a Feasibility Study 2 neutrino factory. It is a design that does not use low frequency rf near the target, has relatively little polarization, and requires proton pulses only ≤ 3 ns. Although there are many details that need refining, the basic parameters will not change without an agreement among the editors.

This document can be found at:

http://pubweb.bnl.gov/people/palmer/nu/study2/paramsA.ps

and the tex files that made it at:

http://pubweb.bnl.gov/people/palmer/nu/study2/tex

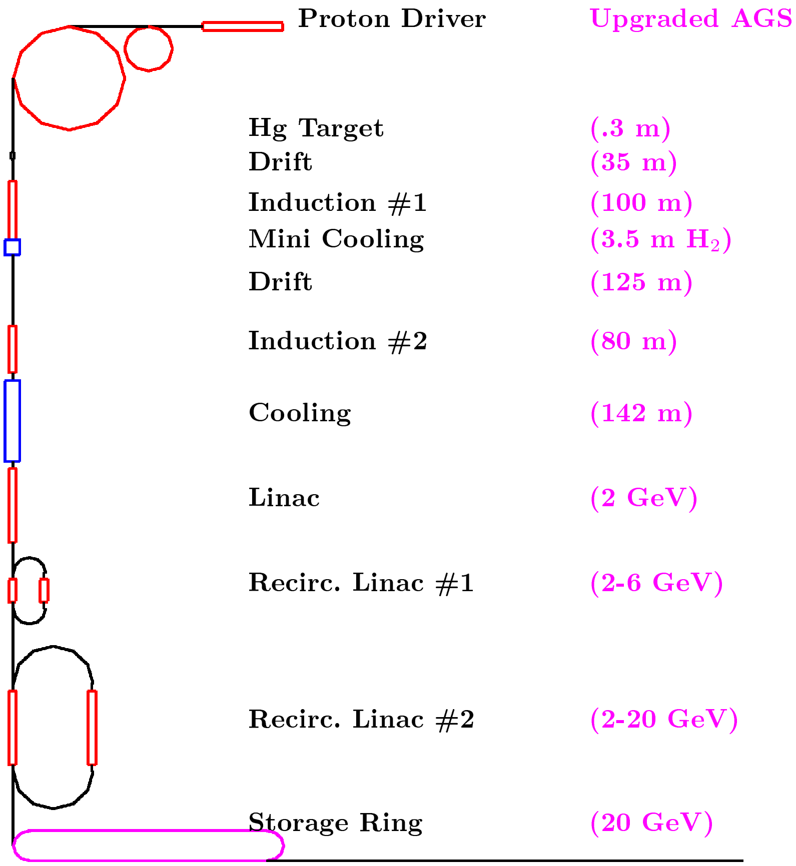
The ICOOL files to simulate this design can be found at:

http://pubweb.bnl.gov/people/palmer/nu/study2/icoolA/

Later, and distinct, designs could include:

- Design B: using low frequency RF to obtain polarization, but which will require shorter proton bunches.
- Design C: a design with an agreed lower muon rate, but with less induction linac, cooling etc. to reduce cost.

The scheme is illustrated in the following figure:



c: aaprog scheme nupict.td

The proton driver is an upgraded AGS.

The lengths of the components in the "Front End", up to the muon accelerators, are listed in the following table:

	length m	totals m
target	0.3	0.3
taper	17.6	17.9
drift	18	35.9
Induction 1	100	135.9
Drift	5	140.9
Mini-Cool	10	150.9
Drift	125	275.9
Induction 2	80	355.9
Match	17.5	373.4
Bunch	$20 \times 2.75 = 55$	428.4
cool part 1	$18 \times 2.75 = 49.5$	477.9
cool part 2	$56 \times 1.65 = 92.4$	570.3

The accelerators and storage ring will be specified later

2 Specifications

2.1 Proton driver

Energy	24	GeV
protons per bunch	$\approx 1.7\ \ 10^{13}$	
bunches per fill	6	
time between extracted bunches	≈ 20	ms
repetition rate	2.5	Hz
rms bunch length	≤ 3	ns
beam power	≥ 1	MW

Finite time between bunches is required for a nuber of reasons:

- To allow time to refil the RF cavities in the accelerating systems and avoid excessive beam loading;
- To avoid the need for multipulsing of the induction linacs; and
- to allow the liquid target to be re-established after its assumed dispersal by the previous bunch. It is this that sets the minimum spacing: The time required depends on the jet velocity and other parameters, and is not yet known for certain. The number of 20 ms is a reasonable starting assumption. An even separation of bunches at 15 Hz would also be even better, but would require an accumulator ring.

The possibility of an average power greater than 1 MW, up to 1.5 MW should also be considered. This would correspond to the average power assumed in Feasibility Study 1.

2.2 Target

material	mercury	
velocity	≈ 20	m/sec
length	30	cm
diameter	1	cm
angle to muon axis	100	mrad
displacement of front from axis	***	cm

It is expected that a single proton bunch will heat the liquid to a temperature above its boiling point and generate substantial shock pressures. It is not believed that these will have significant adverse consequences, but, if it did, liquid lead/tin eutectic could be used. A graphite target (as used in study 1) could also be considered as a backup, but would reduce the neutrino intensity by approximately a factor of 2.

2.3 Capture and matching Solenoids

The 20 T capture solenoid would be a hybrid copper (insert) and superconducting (outsert) magnet similar to that discussed in study 1. However, it is proposed here to use hollow copper conductor for the insert, rather than a Bitter style magnet in Study 1. The choice is aimed at achieving longer magnet life and avoiding any problems with highly irradiated water insulation. It is understood that the initial cost will be higher.

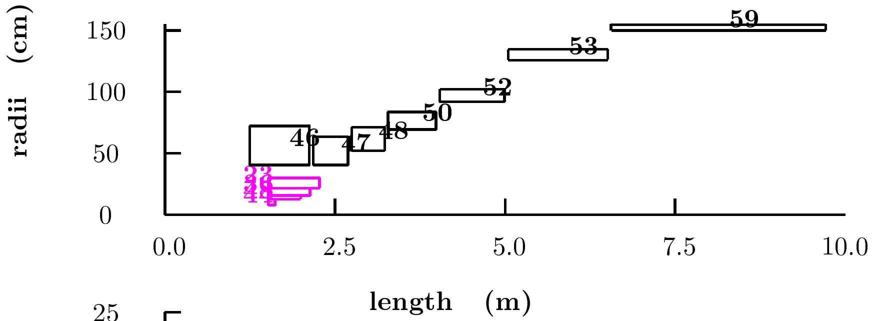
After the initial 20 T magnet, coils are designed to taper the axial field down slowly to 1.25 T at a distance of approximately 18 m. The form of the tapered field should be:

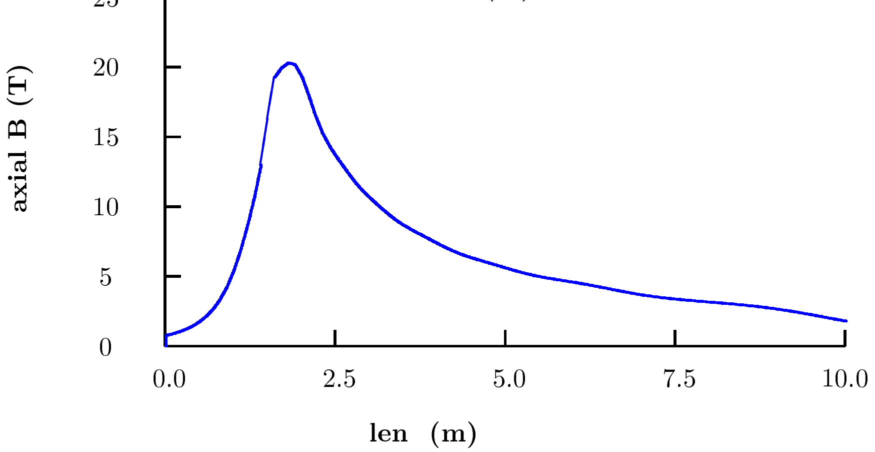
$$B(z) \approx \frac{20}{1 + k\ z}$$

Dimensions of coils that achieve this taper are given in the following table: The final design will have to include space for the beam dump and shielding.

len1 m	dl m	rad m	dr m		I/A A/mm^2
0.520	0.103	0.075	0.051	3	45.00
0.520	0.475	0.126	0.027	3	48.80
0.520	0.616	0.153	0.064	3	36.40
0.520	0.755	0.217	0.083	3	23.50
0.245	0.882	0.400	0.320	3	46.60
1.177	0.517	0.400	0.232	3	47.70
1.744	0.485	0.522	0.190	3	48.40
2.279	0.710	0.692	0.143	3	50.10
3.039	0.959	0.919	0.102	3	52.20
4.048	1.465	1.260	0.085	3	53.50
5.563	3.153	1.500	0.047	3	59.10
8.766	4.707	1.500	0.023	1	73.70
13.523	6.700	1.500	0.013	1	77.74
20.273	6.700	1.500	0.013	1	77.74

These coils, and thir axial field profile, are shown in the following figures:





To Be Done

- Design Beam dump.
- Modify coil designs for beam dump and shielding.

2.4 Drift 1

length	18	m
bore diameter	60	cm
axial field	1.25	T

The real drift would be formed of spaced solenoids, and would have some finite periodicity. Design and simulation of this is yet to be done.

To Be Done

- Design periodic focusing channel and simulate.

2.5 Induction Linac 1

length	100	m
inner radius	30	cm
Solenoid field	1.25	T
maximum gradient	140	MV/m
pulse length	125	nsec

The real field would be formed of spaced solenoids, and would have some finite periodicity (approx 1 m). Design and simulation of this is yet to be done.

The shape of the accelerating pulse is given in the following table:

time ns	Grad MV/m
0	-.06
10	.29
25	.66
45	.94
85	1.23
125	1.39

The total voltage gain is important, not the length or gradients used to achieve it.

To Be Done

- Design periodic focusing channel and simulate.
- Optimize induction length and gradient for minimum cost.
- Consider if there is an advantage in using differing pulse shapes along the unit.

2.6 Mini-cooling and Field reversal

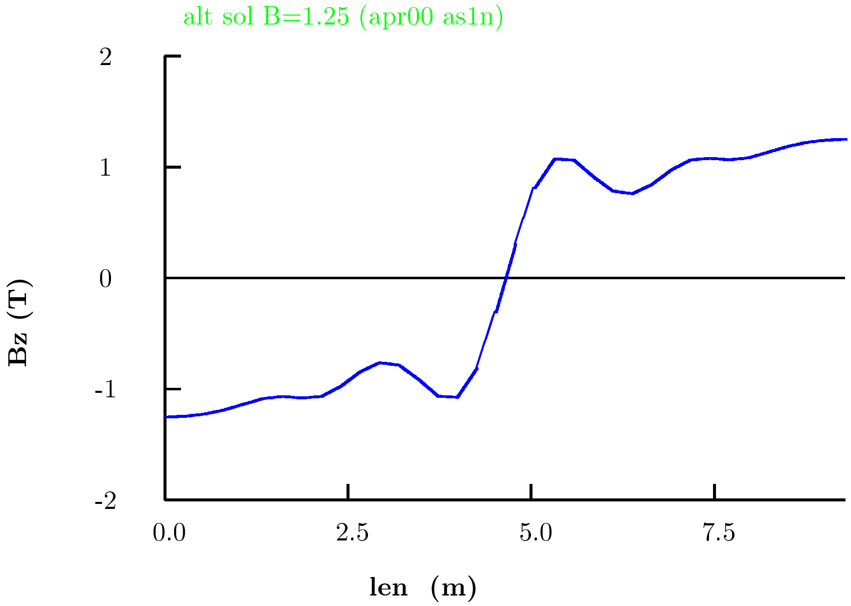
After a 3.25 m drift, there are two large hydrogen absorbers (1.75 m long each) with a 10 m chromatically matched field reversal between them.

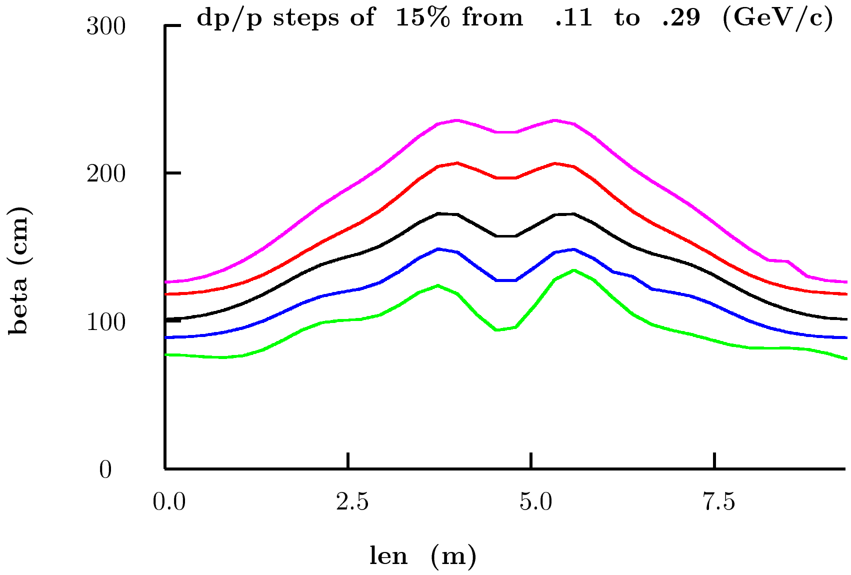
hydrogen length	2 × 1.75	m
hydrogen radius	30	cm
Solenoid fields	1.25	T

The field reversal was designed to match β's from start to end, over a momentum bite of 200 $+/-$ 90 MeV. The coils used in the optimization were larger than needed and had very low current densities. More reasonable coils will be relatively easy to design, but it has not yet been done. We thus specify the reversal by the required axial fields:

length m	Field T
.000	-1.25
.2655	-1.2446
.5309	-1.2242
.7963	-1.1874
1.0617	-1.1357
1.3271	-1.0852
1.5925	-1.0664
1.8579	-1.0801
2.1233	-1.0661
2.3887	-.97434
2.6541	-.84339
2.9195	-.76098
3.1849	-.78458
3.4503	-.9125
3.7157	-1.0631
3.9811	-1.0747
4.2465	-.81469
4.5119	-.30422
4.7773	.30242
5.0427	.81346
5.3081	1.0744
5.5735	1.0635
5.8389	.913
6.1043	.78483
6.3697	.76088
6.6351	.84302
6.9005	.97396
7.1659	1.0659
7.4313	1.0802
7.6967	1.0664
7.9621	1.0851
8.2275	1.1355
8.4929	1.1873
8.7583	1.2241
9.0237	1.2445
9.2891	1.251
10.0	1.25

These axial fields are plotted in the following figure, together with the β's obtained for a set of different momenta.


alt sol B=1.25 (apr00 as1n)
2
1
0
-1
-2
Bz (T)
0.0
2.5
5.0
7.5
len (m)


dp/p steps of 15% from .11 to .29 (GeV/c)
300
200
100
0
beta (cm)
0.0
2.5
5.0
7.5
len (m)

To Be Done

- Design realistic coils to generate the required field.
- Determine thickness of hydrogen windows and simulate their effects.
- Simulate the effect of shaped hydrogen windows

2.7 Drift 2

length	123.25	m
bore diameter	60	cm
axial field	1.25	T

The real drift would be formed of spaced solenoids, and would have some finite periodicity.

To Be Done

- Design periodic focusing channel and simulate.

2.8 Induction Linac 2

length	80	m
inner radius	30	cm
Solenoid field	1.25	T
maximum gradients	-110 to +103	MV/m
pulse length	350	nsec

The real field would be formed of spaced solenoids, and would have some finite periodicity (approx 1 m). Design and simulation of this is yet to be done.

The shape of the accelerating pulse is given in the following table:

time ns	Grad MV/m
0	-1.1
25	-0.48
50	0.00
90	0.43
150	0.78
250	1.03
350	0.93

As in the first induction linac, the total voltage gain is important, not the length or gradients used to achieve it.

If it is desired to lower the magnitude of the initial negative acceleration (-1.1 MeV/m), then all accelerations could be increased and a second mini-cooling introduced after this second induction unit.

To Be Done

- Design periodic focusing channel and simulate.
- Optimize induction length and gradient for minimum cost.
- Consider if there is an advantage in using differing pulse shapes along the unit.

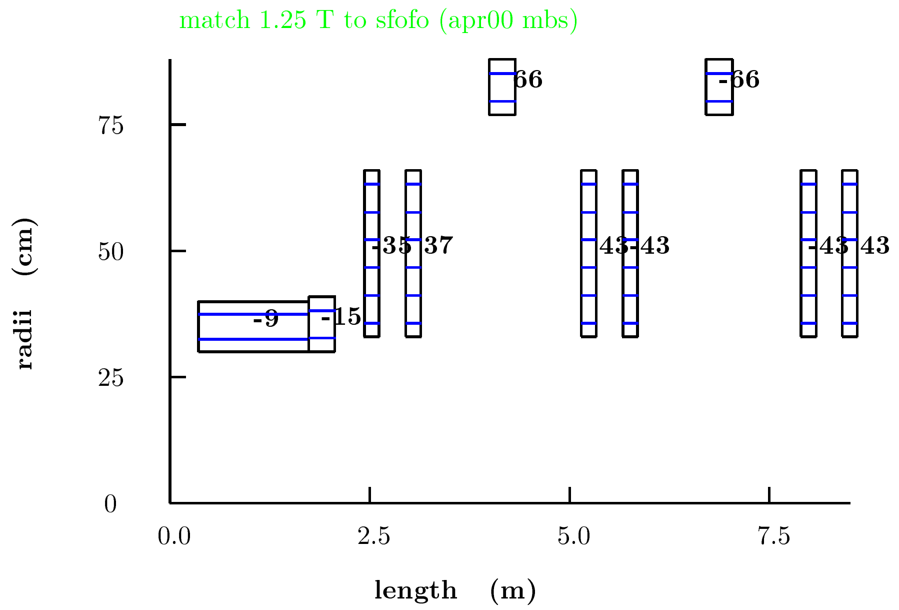
2.9 match form solenoid to super FOFO lattice

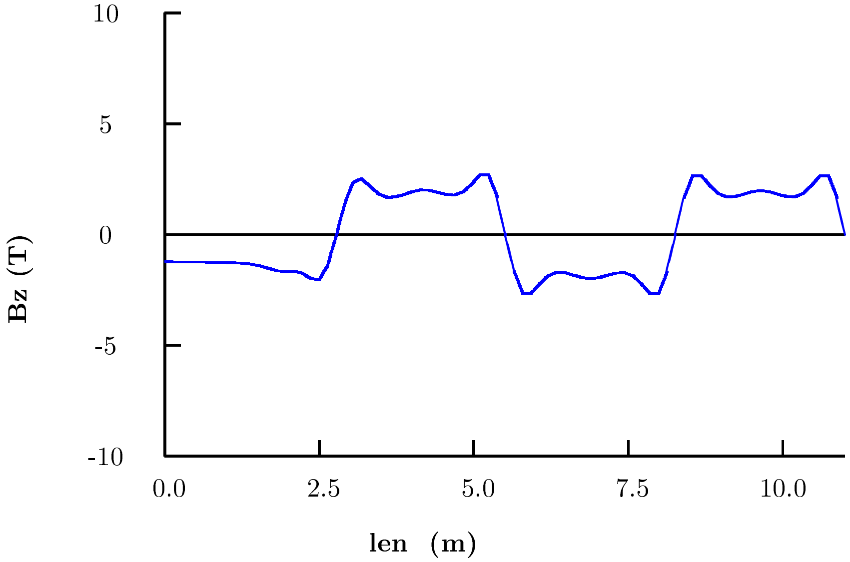
A match is required between the approximately uniform 1.25 T solenoid fields in the previous sections, and the super FOFO lattices used in the following. This match should be approximately chromatically matched, but since the momentum spread is relatively small (≈ 4 % rms), the chromatic correction is less critical than in the field reversal.

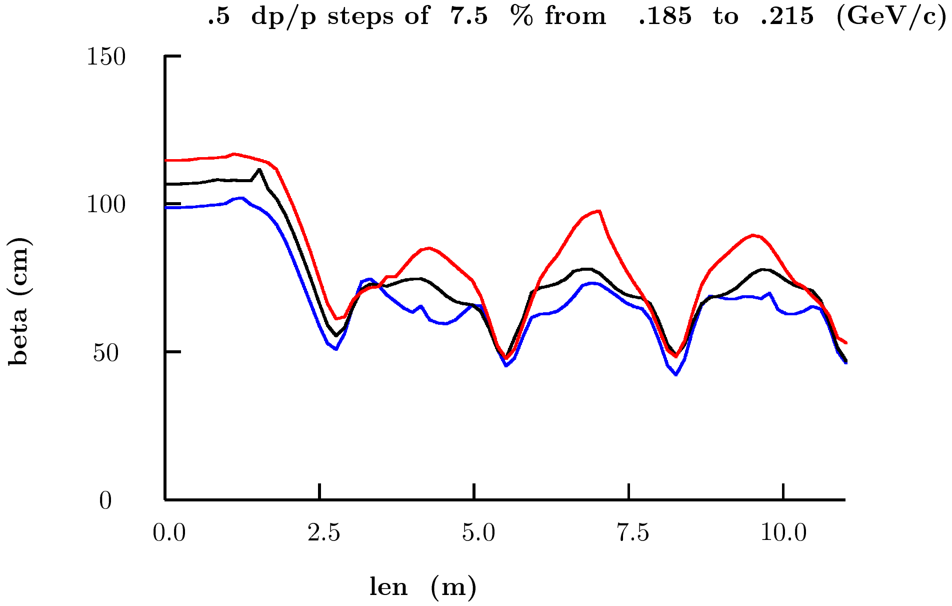
The following table gives coil dimensions and current densities for the match. The current densities are lower than used in the following lattice and should be increased here too, to minimize their cost.

len1 m	dl m	rad m	dr m		I/A A/mm^2
0.000	1.375	0.300	0.100	2	-9.99
1.375	1.375	0.300	0.100	2	-9.99
2.750	1.375	0.300	0.100	2	-9.99
4.125	1.375	0.300	0.100	2	-9.99
5.500	1.375	0.300	0.100	2	-9.99
6.875	1.375	0.300	0.100	2	-9.99
8.250	0.330	0.300	0.110	2	-15.59
8.949	0.187	0.330	0.330	6	-35.83
9.466	0.187	0.330	0.330	6	37.58
10.511	0.330	0.770	0.110	2	66.12
11.665	0.187	0.330	0.330	6	43.75
12.182	0.187	0.330	0.330	6	-43.75
13.227	0.330	0.770	0.110	2	-66.12
14.415	0.187	0.330	0.330	6	-43.75
14.932	0.187	0.330	0.330	6	43.75
15.977	0.330	0.770	0.110	2	66.12
17.165	0.187	0.330	0.330	6	43.75

The coils, their fields, and the β's for three different momenta are plotted in the following figure:







It is seen that the match is not very good, although there appear to be little adverse consequences.

Apertures ***

To Be Done

- Improve the match design
- Use the higher current densities (suggested by John Miller) as used in the cooling sections.
- Determine the optimum apertures.

2.10 Buncher

The bunching is done in the same lattice as used for the first cooling stage (1,1), which is described below.

*** $20 \times 2.75 = 55$ m

The buncher consists of three stages:

1. low field 200 MHz rf with 400 MHz harmonic, followed by a long drift (27.5 m)
2. medium field 200 MHz rf with 400 MHz harmonic, followed by a shorter drift (11 m)
3. higher field 200 MHz rf followed by a short drift (5.5 m)

	len m	freq MHz	grad Mv/m
harmonic rf	.186	402.5	6.4
space	.443		
rf	4 × .373	201.25	6.4
space	.443		
harmonic rf	.186	402.5	6.4
drift 1	10 × 2.75		
harmonic rf	.186	402.5	6
space	.443		
rf	4 × .373	201.25	6
space	.443		
harmonic rf	2 × .186	402.5	6
space	.443		
rf	4 × .373	201.25	6
space	.443		
harmonic rf	.186	402.5	6
drift 2	3 × 2.75		
space	.629		
rf	4 × .373	201.25	8
space	.629		
space	.629		
rf	4 × .373	201.25	8
space	.629		
drift 3	2 × 2.75		

rf window radii and thicknesses

	rad m	thickness μm
windows at ends of each 400 MHz cavity	.2	100
windows at end of each set of 4 200 MHz cavities	.21	125
windows between the 4 400 MHz cavities	.25	250

To Be Done

- Determine the required window thicknesses and simulate.
- Design the cavities and simulate.
- Find if there is sufficient space inside the smaller coils for the harmonic RF, and redesign the lattice with larger inside radii, if needed.

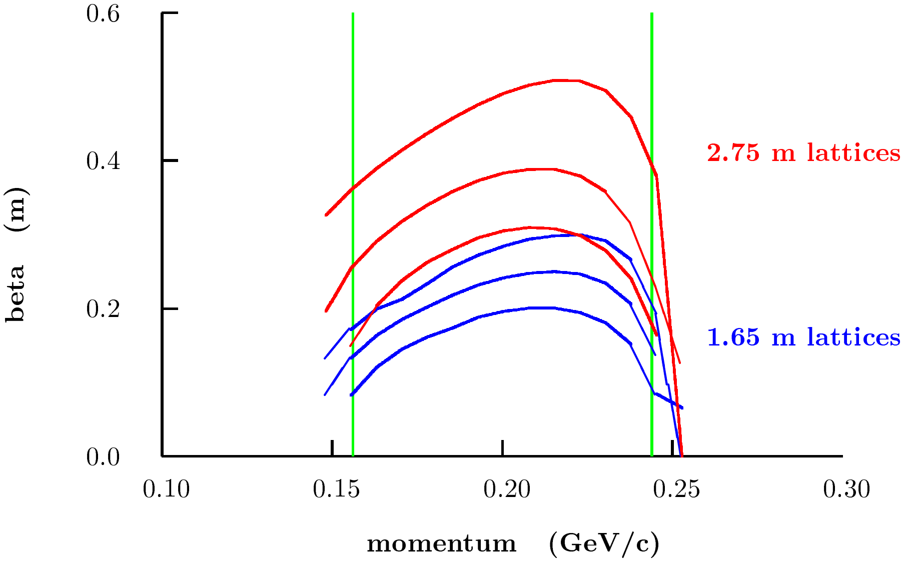
2.11 Cooling Latices

The cooling is done in six sections with steadily decreasing β's. The six sections are made from two different physical lattices [(1) and (2)], with three different current setting in each: 1,1 1,2 1,3 in the first lattice, and 2,1 2,2 2,3, in the second. The final cooling section (2,3) is further broken into 2 parts (2,3a) and (2,3b) that differ only in their window sizes and thicknesses.

The lengths of the sections are:

	length m	from target m
cool 1,1	$6 \times 2.75 = 16.5$	444.9
cool 1,2	$6 \times 2.75 = 16.5$	461.4
cool 1,3	$6 \times 2.75 = 16.5$	477.9
cool 2,1	$14 \times 1.65 = 23.1$	501
cool 2,2	$10 \times 1.65 = 16.5$	517.5
cool 2,3a	$16 \times 1.65 = 26.4$	543.9
cool 2,3b	$16 \times 1.65 = 26.4$	570.3

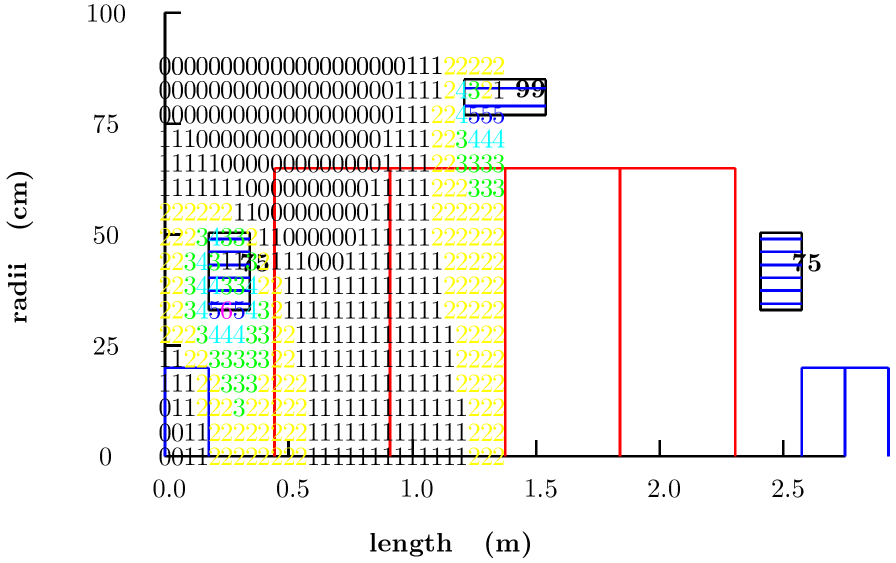
The following figure shows the beta's, as a function of momentum, for the six cases.

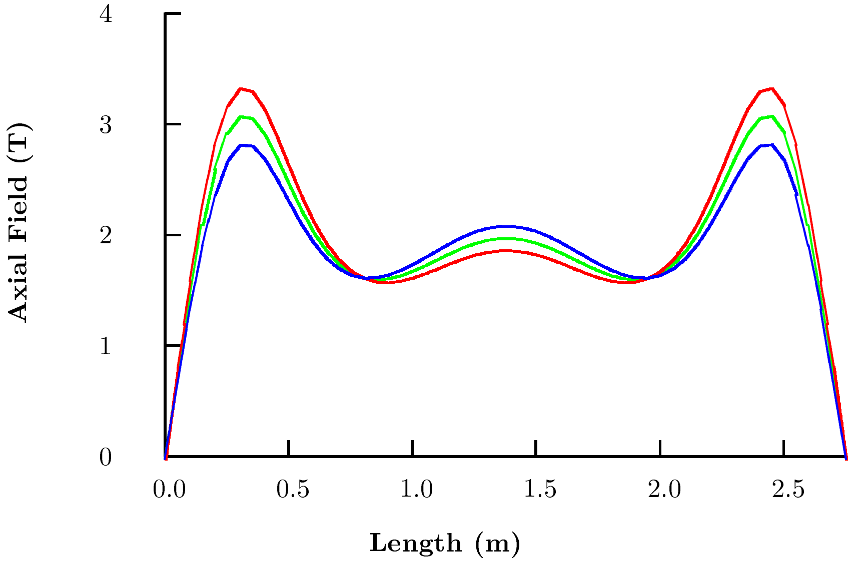


The physical coil dimensions and the three different current setting, for the first (2.75 m long) lattice, are:

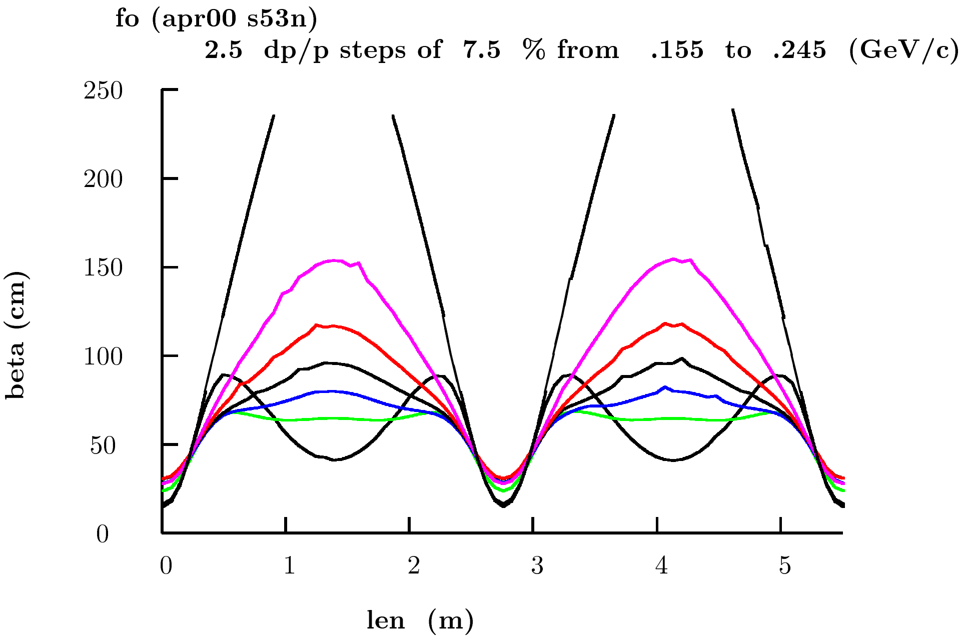
len1 m	dl m	rad m	dr m	j(1,1)	j(1,2) A/mm^2	j(1,3)
0.175	0.167	0.330	0.175	75.96	84.17	92.39
1.210	0.330	0.770	0.080	99.24	92.42	85.61
2.408	0.167	0.330	0.175	75.96	84.17	92.39

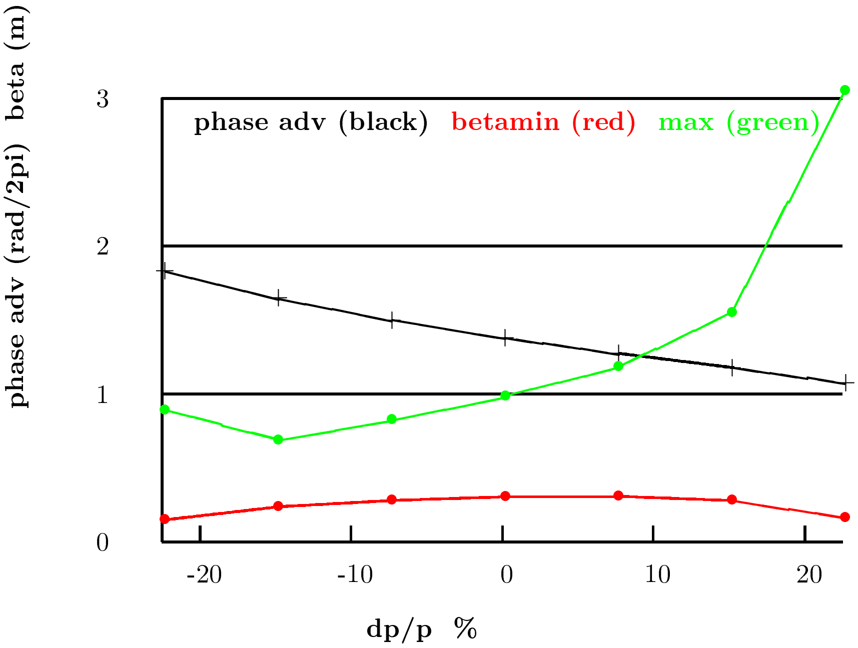
The coils and axial fields are shown below. The maximum field at the coils occurs in case 1,3, and is 7.4 T.





The beta functions in lattice (1,3), for a number of momenta, as a function of position along the cell are:

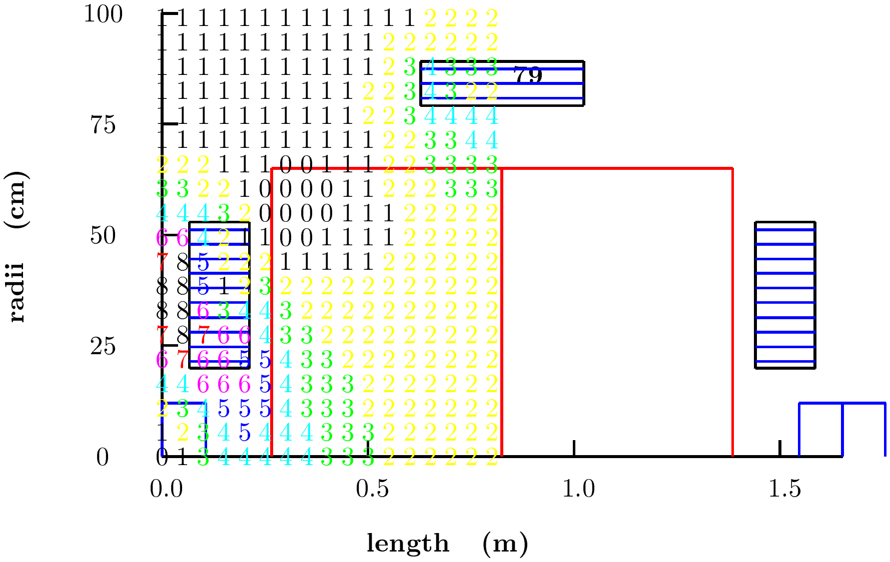

fo (apr00 s53n)
2.5 dp/p steps of 7.5 % from .155 to .245 (GeV/c)
beta (cm)
250
200
150
100
50
0
0
1
2
3
4
5
len (m)

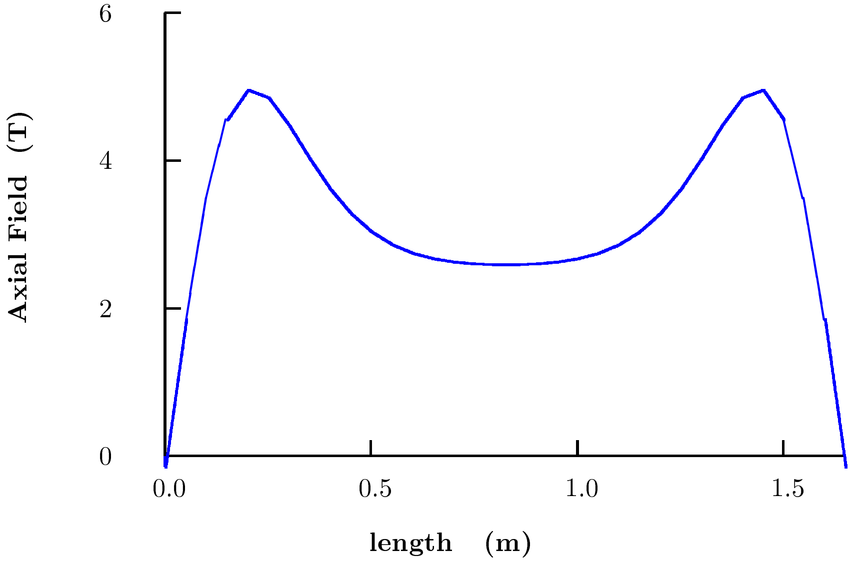

phase adv (rad/2pi) beta (m)
phase adv (black)
betamin (red)
max (green)
3
2
1
0
-20
-10
0
10
20
dp/p %

And for the second (1.65 m long) lattice, the coils are:

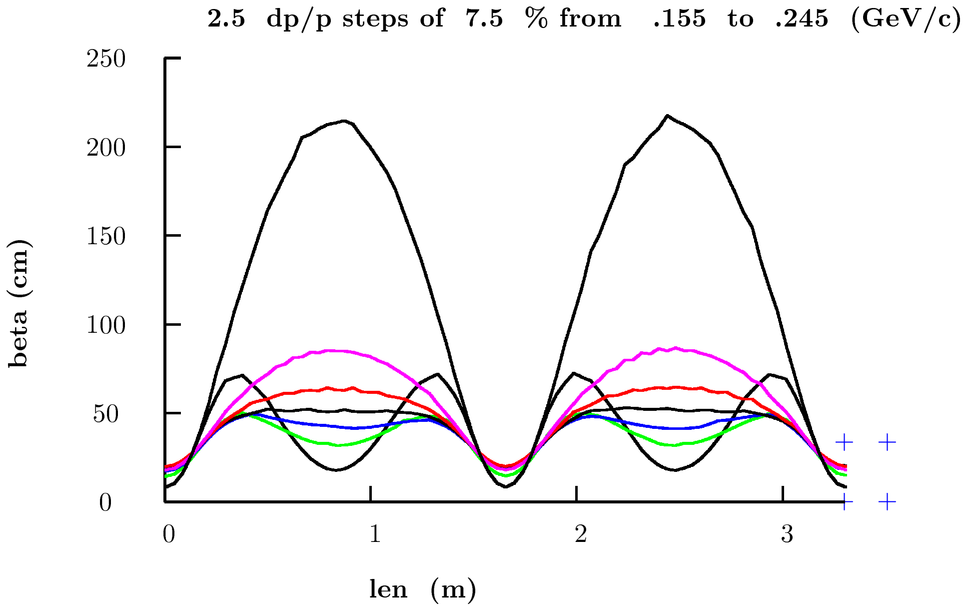
len1 m	dl m	rad m	dr m	j(2,1)	j(2,2) A/mm^2	j(2,3)
0.066	0.145	0.198	0.330	71.63	78.14	86.82
0.627	0.396	0.792	0.099	99.63	91.52	79.58
1.439	0.145	0.198	0.330	71.63	78.14	86.82

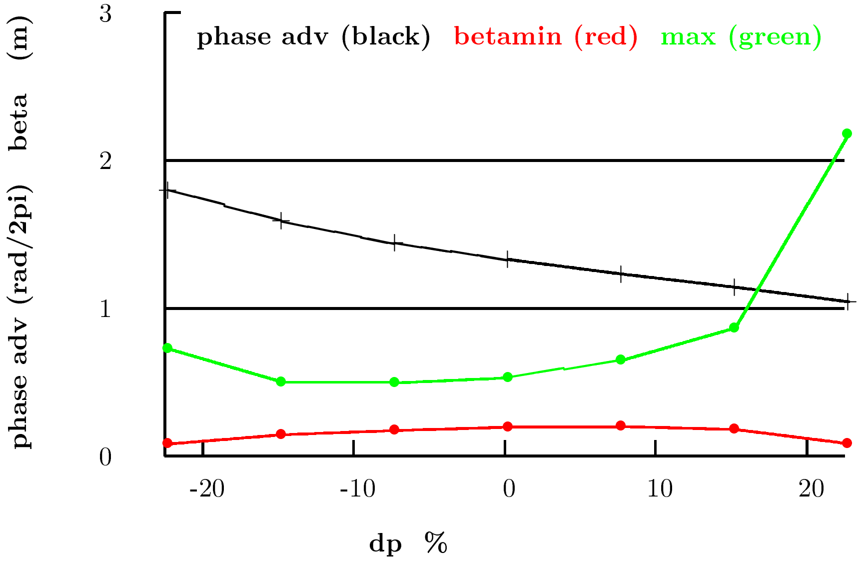
The coils and axial fields are shown below. The maximum field at the coils occurs in case 1,3, and is 8.5 T.





And the beta functions for (2,3):





To Be Done

- Try designing a third lattice with shorter cell, higher fields and yet lower beta, to further reduce the emittance. Determine the practicability of such a lattice and what cost savings in the following acceleration would be gained from the lower emittance achieved.

2.12 Cooling RF and absorbers

The hydrogen absorbers and rf within the three 2.75 m lattices are all the same except for their apertures which will be given in a separate table.

	dl cm	gradient MV/m
Hydrogen	35/2	
Space	26.7	
RF	4 × 46.6	16.29
Space	26.7	
Hydrogen	35/2	

The hydrogen absorber and rf within the 1.65 m lattices are:

	dl cm	gradient MV/m
Hydrogen	21/2	
Space	16	
RF	2 × 55.9	17.6
Space	16	
Hydrogen	21/2	

Hydrogen window sizes and thicknesses

Material: Aluminum

	rad m	thickness μm
1.1	.18	200
1.2	.15	250
1.3	.13	130
2.1	.11	110
2.2	.10	100
2.3a	.09	90
2.3b	.08	80

rf window sizes and thicknesses

Material: Beryllium

	ends		center	
	rad m	thickness μm	rad m	thickness μm
1.1	.25	250	.21	125
1.2	.25	250	.21	125
1.3	.25	250	.21	125
2.1	.21	125	.18	75
2.2	.18	75	.18	75
2.3a	.18	75	.15	75
2.3b	.15	50	.15	50

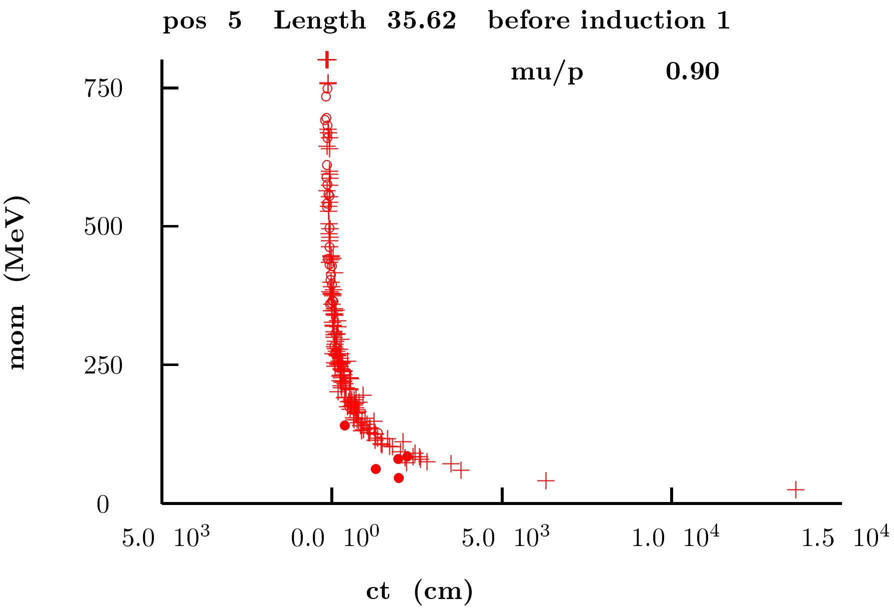
To Be Done

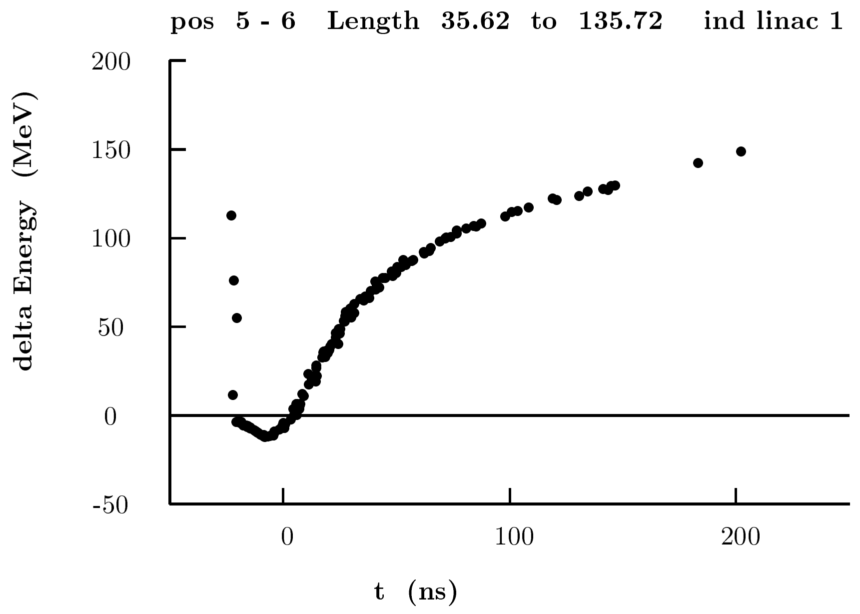
- Determine the required hydrogen and RF window thicknesses and re-simulate.
- Determine the hydrogen window thicknesses if they were made of AlBemet, and simulate.
- study the effects of windows with tapered thicknesses.
- Design rf cavities and simulate with the resulting fields.
- Study effects of random errors and set tolerances.
- Study effects of wake fields and space charge.
- Study the effects of differing theoretical assumptions about large angle scatters.

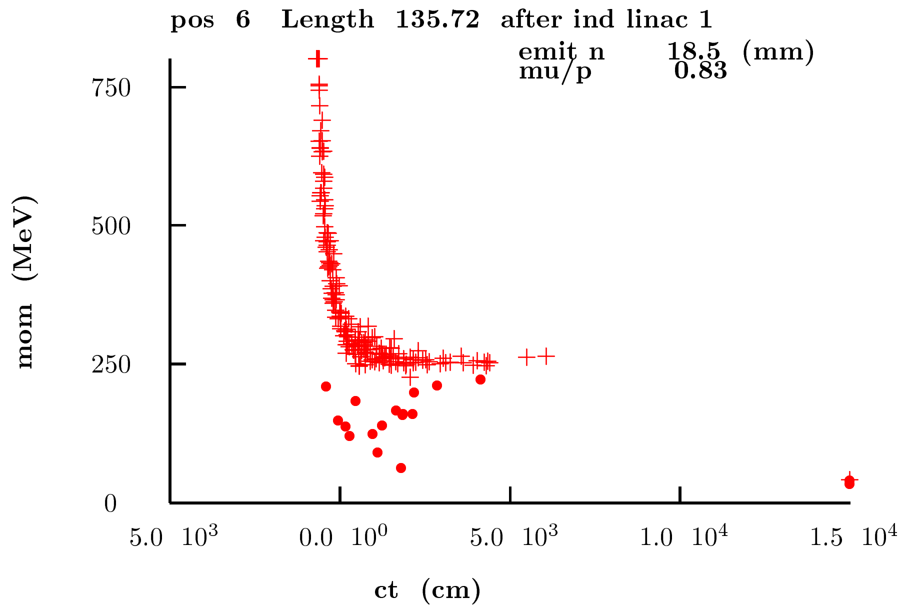
3 Simulated Performance

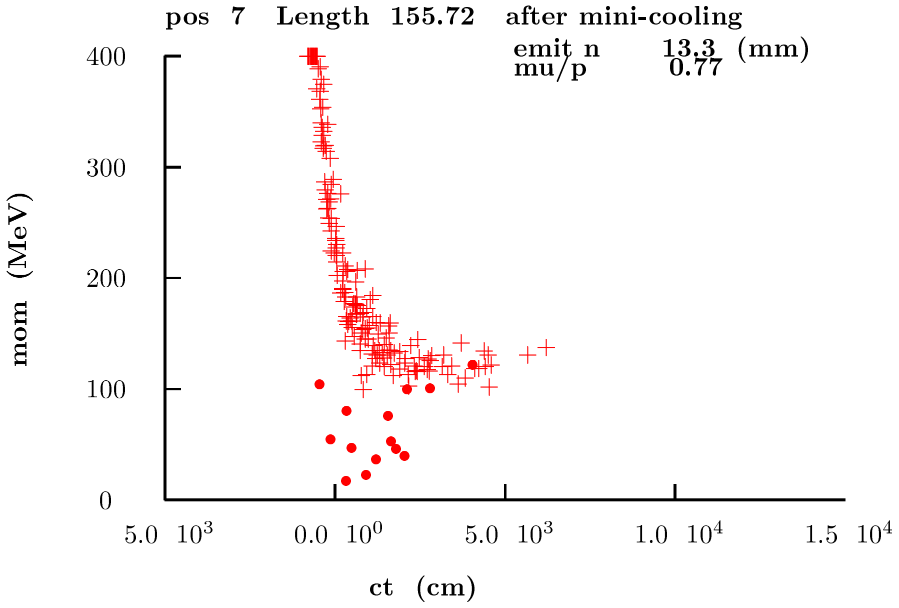
3.1 Introduction

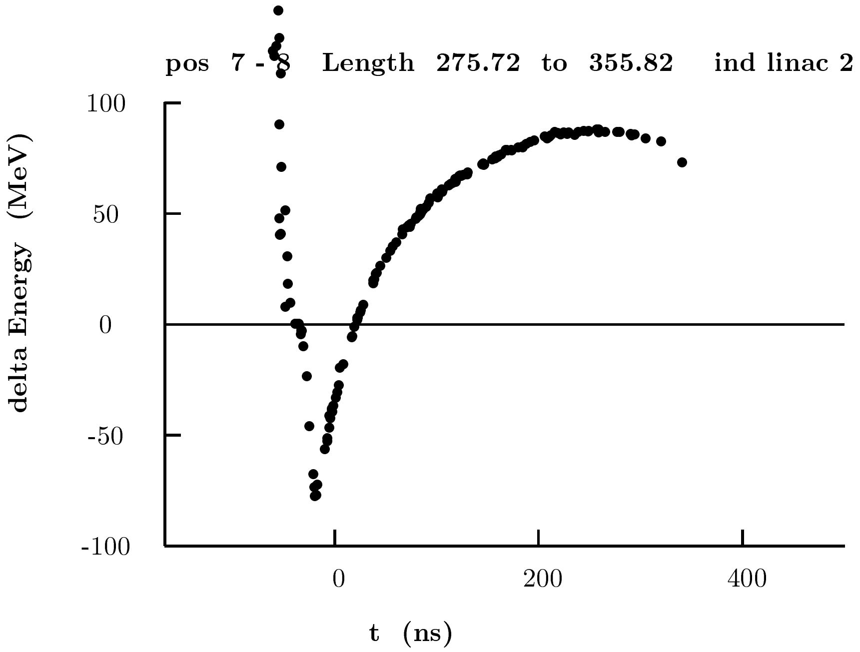
3.2 Phase Rotation

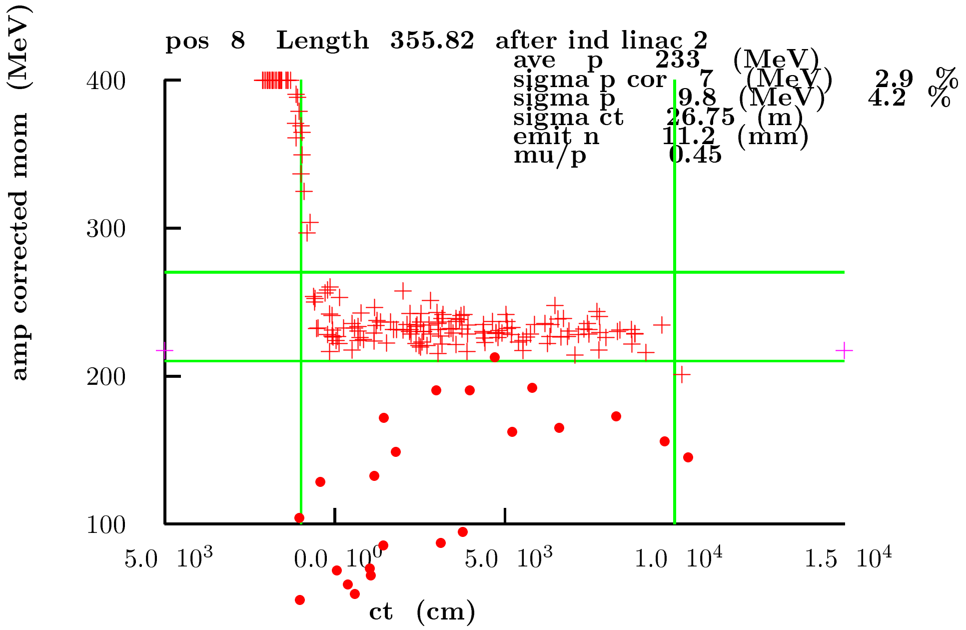



pos 5 - 6 Length 35.62 to 135.72 ind linac 1
delta Energy (MeV)
200
150
100
50
0
-50
0
100
200
t (ns)

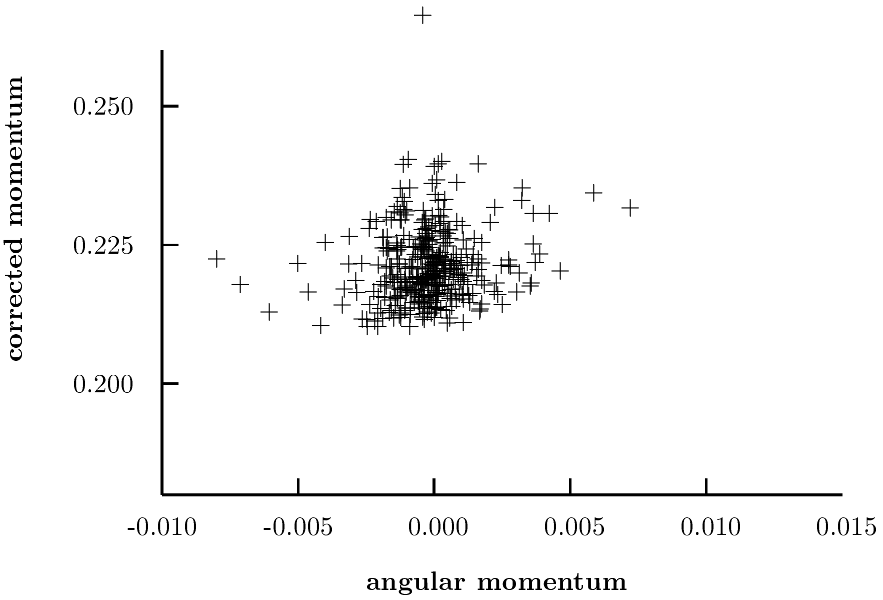

pos 6 Length 135.72 after ind linac 1
emit n 18.5 (mm)
mu/p 0.83
mom (MeV)
750
500
250
0
5.0 10^3
0.0 10^0
5.0 10^3
1.0 10^4
1.5 10^4
ct (cm)

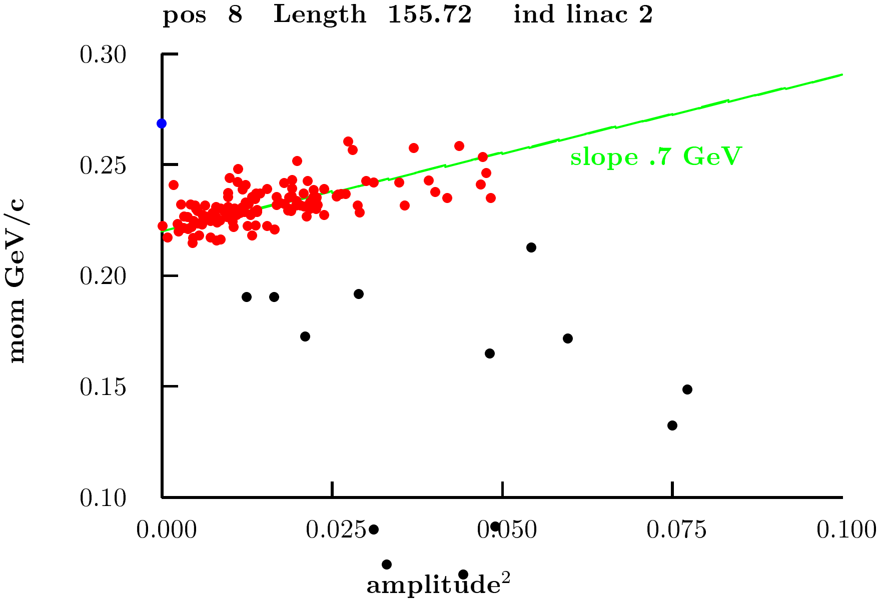

pos 7 Length 155.72 after mini-cooling
emit n 13.3 (mm)
mu/p 0.77
400
300
200
100
0
mom (MeV)
5.0 10^3
0.0 10^0
5.0 10^3
1.0 10^4
1.5 10^4
ct (cm)


pos 7 - 8 Length 275.72 to 355.82 ind linac 2
100
50
0
-50
-100
delta Energy (MeV)
0
200
400
t (ns)


pos 8 Length 355.82 after ind linac 2
ave p 233 (MeV)
sigma p cor 7 (MeV) 2.9 %
sigma p 9.8 (MeV) 4.2 %
sigma ct 26.75 (m)
emit n 11.2 (mm)
mu/p 0.45
amp corrected mom (MeV)
400
300
200
100
-5.0 10^3
0.0 10^0
5.0 10^3
1.0 10^4
1.5 10^4
ct (cm)

3.3 Correlations and Efficiency

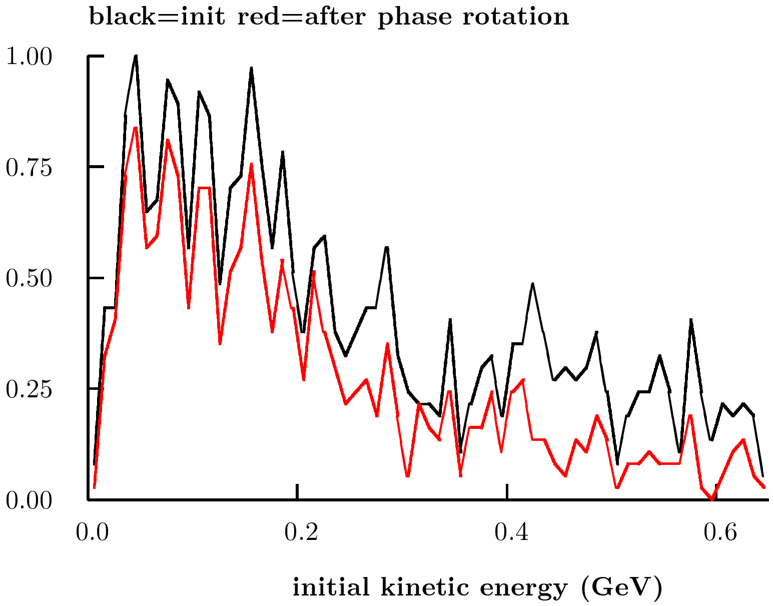




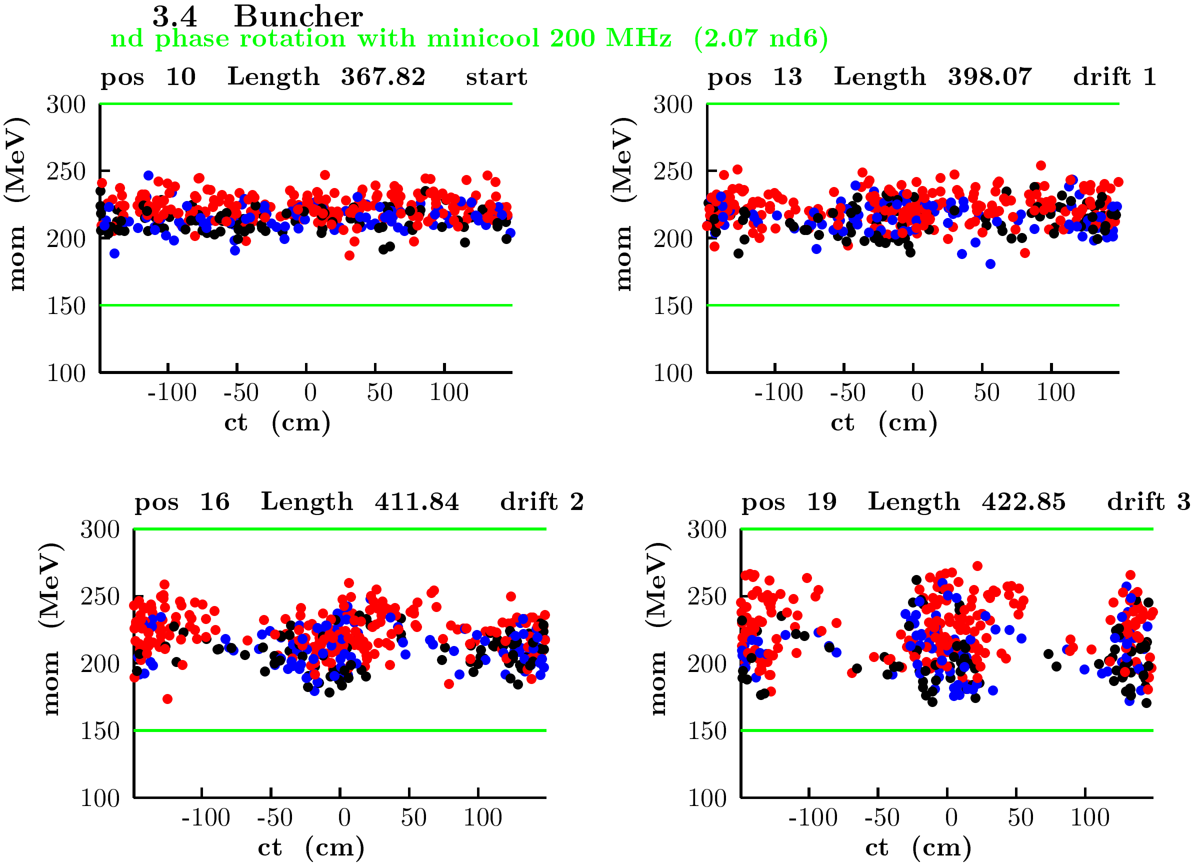
We see no momentum angular momentum correlation, so the field flip used in the mini cooling seems adequate.

The momentum-amplitude correlation is seen to be 0.7. A higher value than without the mini cool (.45). This is good, since it is closer to the required correlation in the cooling lattice (≈1.0).

Efficiency of use of initial pions:



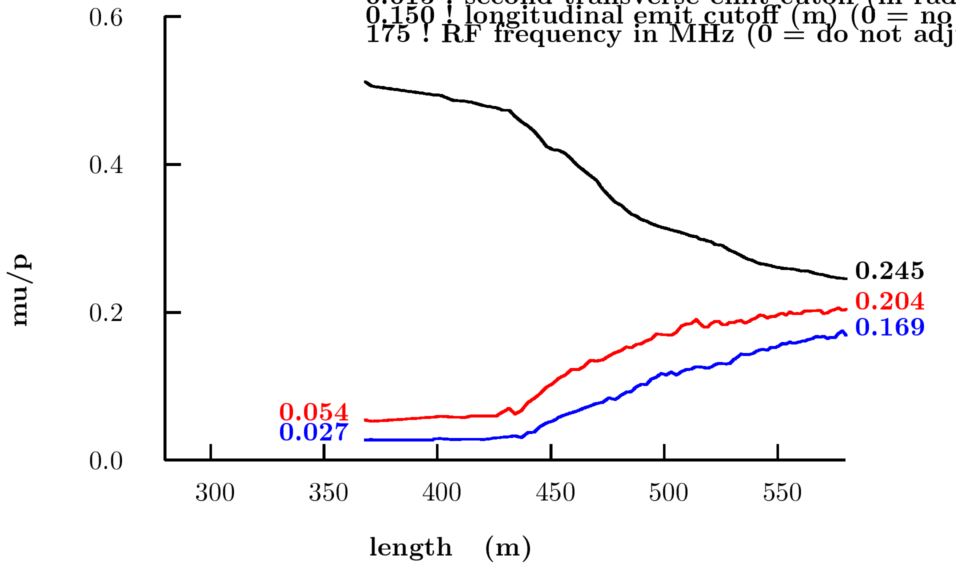
3.4 Buncher

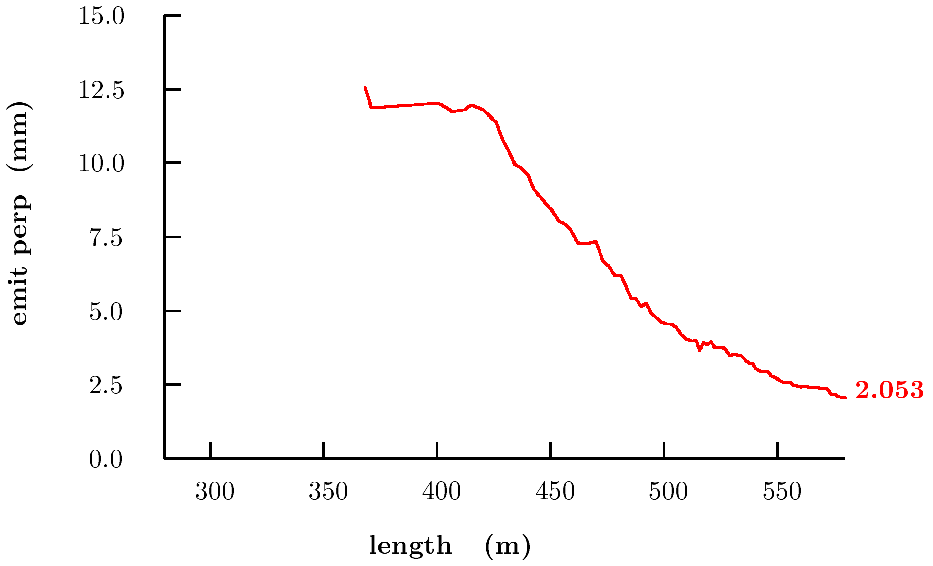


3.5 Cooling

Using Greg's program:

```
2   ! particle type (1=e 2=mu 3=pi 0=all)
.35  ! Pzmax  GeV/c (0 = no maximum)
0.1  ! Pzmin in GeV/c (0 = no minimum)
0.0095 ! first transverse emittance cutoff (m rad) (0 = no cutoff)
0.015 ! second transverse emit cutoff (m rad) (0 = no cutoff)
0.150 ! longitudinal emit cutoff (m) (0 = no cutoff)
175 ! RF frequency in MHz (0 = do not adjust times)
```





3.6 Performance Dependences

3.6.1 RF cavity aperture

maximum aperture	thickness	μ/p	μ/p
cm	μm	15 mm	9.75
30	500	0.21	.175
25	250	0.204	.168
21	125	0.189	.160

3.6.2 proton bunch length

rms bunch length	μ/p	μ/p
ns	15 mm	9.75
1	0.204	.168
3	0.20	.164
6	0.167	.138

3.6.3 target material & proton energy

rms bunch length	μ/p	μ/p	
ns	15 mm	9.75	
Mercury	24	0.204	.168
Carbon	16	***	***