Possible 200 MHz Cooling Experiment Design

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With matching (Version 5)

11/9/01

Abstract

I will repeat those parts of version 4 that still apply, but I now include a specification of a complete experiment including matching into 60 (rather than 50) cm diameter measurement solenoids.

I had trouble obtaining a chromatically corrected match, but realized that since the selected input distributions must anyway be massaged to give the required correllations, it is a negligible complication to give the input distributions some small 'chromaticity' to cancell that introduced in the matches. This done, everything seems ok.

1 Specification of measurement Solenoid

1.1 Highest momentum track to be measured

Mean momentum in SFOFO lattice = momentum in center of absorber = 214 MeV/c

Momentum loss in one absorber = 12 MeV/c

Mean momentum to be measured before first absorber:

$$p_{\text{mean}} = 214 + 12/2 = 220\text{MeV/c}$$

Momentum acceptance = +/− 22 % = 48 MeV/c

Maximum momentum to be measured

$$p_{\text{max}} = 220 + 48 = 268\text{MeV/c}$$

1.2 Maximum required muon energy from beam

Maximum energy in measurement solenoid = 183 MeV (268 MeV/c)

Loss in lead scatterer ≈ 40 MeV

Maximum required KE before lead = 183 + 40 =**223 MeV**

1.3 Detector Solenoid length and field

Field for same beta as Janot's study in which the mean muon momenta were assumed to be 300 MeV/c:

$$B_{220} \;=\; B_{300}\,\frac{p_{220}}{p_{300}} \;=\; \frac{220}{300}\,5 \;\approx\; 3.6\mathrm{T}$$

Longest cyclotron wavelength (for maximum momentum=268 MeV/c)) is:

$$\lambda_{\mathrm{cyclotron}} \;=\; \frac{p\;2\;\pi}{c\;B} \;=\; \frac{.268\;2\pi}{0.3\;3.6} \;=\; 1.56\mathrm{m}$$

Minimum good field region required=2/3 $\lambda\ \approx 1$ m

Thus the specified good field region of 1.2 m allows the addition of one or more redundant planes prior to the minimum required measurement planes. The specified good field radius is 15 cm. The specified field uniformity within this length is $+/-$ 1 %

2 Solenoid design

The solenoid bore has been increased from 50 to 60 cm diameter. The dimensions and currents are given below in the section complete experiment.

3 New lattice

This lattice has the focus coils brought in to a smaller radius, on the assumption that the absorber boddy will be incorporated in the coil assembly, but keeping the ability to change the windows. The maximum field, maximum current density, stored energy and cost are all reduced and, surprisingly, the performance improved: the loss for cooling in 12 stages was reduced from 13 to 8 %.

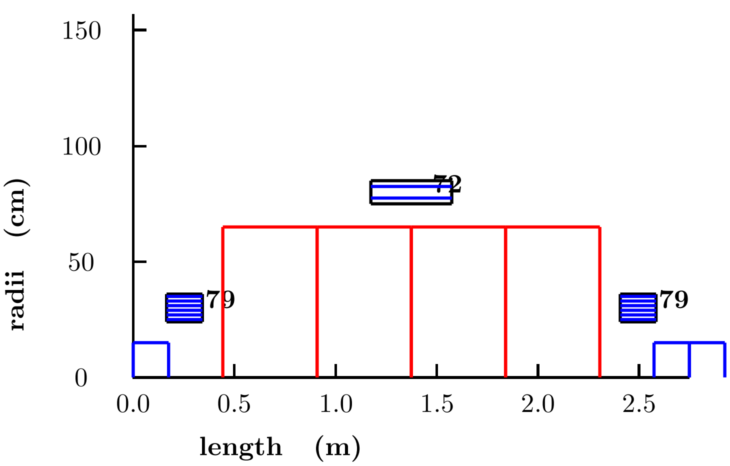
len1	dl	rad	dr		I/A
m	m	m	m		A/mm^2
0.165	0.177	0.240	0.120	6	79.10
1.175	0.400	0.750	0.100	2	73.00
2.408	0.177	0.240	0.120	6	79.10

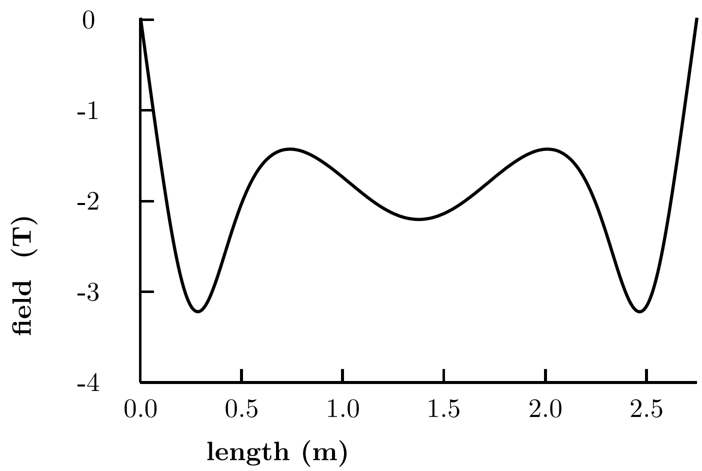
amp turns 6.28 (MA)
amp turns length 21.01096 (MA m)
cell length 2.750001 (m)
Stored Energy 465.933
maximum B (t) 5.578113
For comparison, the study 2 lattice was:

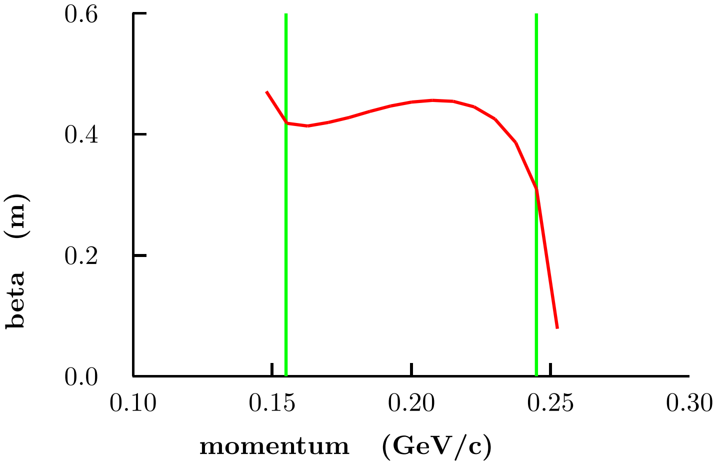
len1	dl	rad	dr		I/A
m	m	m	m		A/mm^2
0.175	0.167	0.355	0.125	12	105.20
1.294	0.162	0.729	0.162	16	99.07
2.408	0.167	0.355	0.125	12	105.20

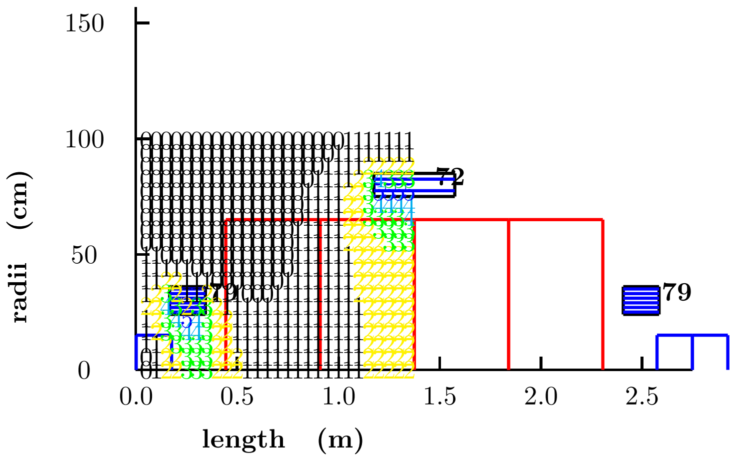
amp turns 6.992 (MA)
amp turns length 24.75359 (MA m)
cell length 2.750001 (m)
Stored Energy 549.9368
maximum B (t) 6.307168

Figures follow

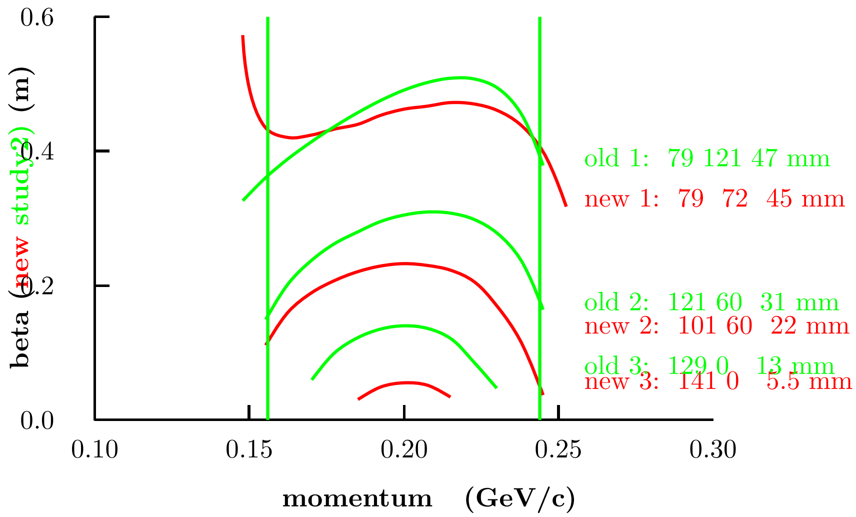








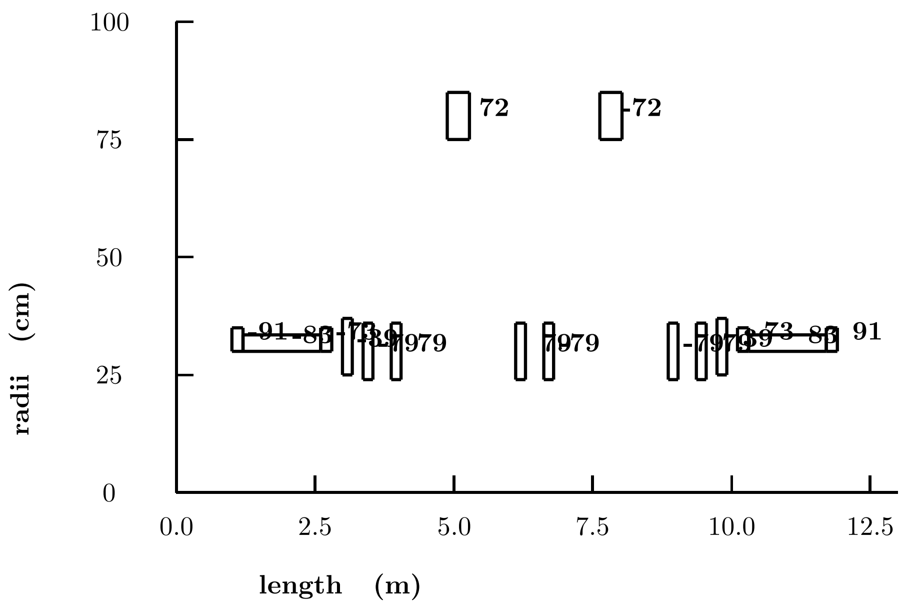
of particular interest for the future is the lattices ability to be tuned to smaller betas. The following figure shows the betas vs. momentum for the study 2 lattice (green) and the new lattice (red). First it may be noted that the highest (baseline) beta curves are flatter for the new lattice. The next lower curves give those for the lowest betas consistent with the full +/− 22 % acceptance. The new betas with this requirement are lower. Finally, it is noted that the lowest possible betas, ignoring momentum acceptance, are more than a factor of 2 lower for the new lattice.

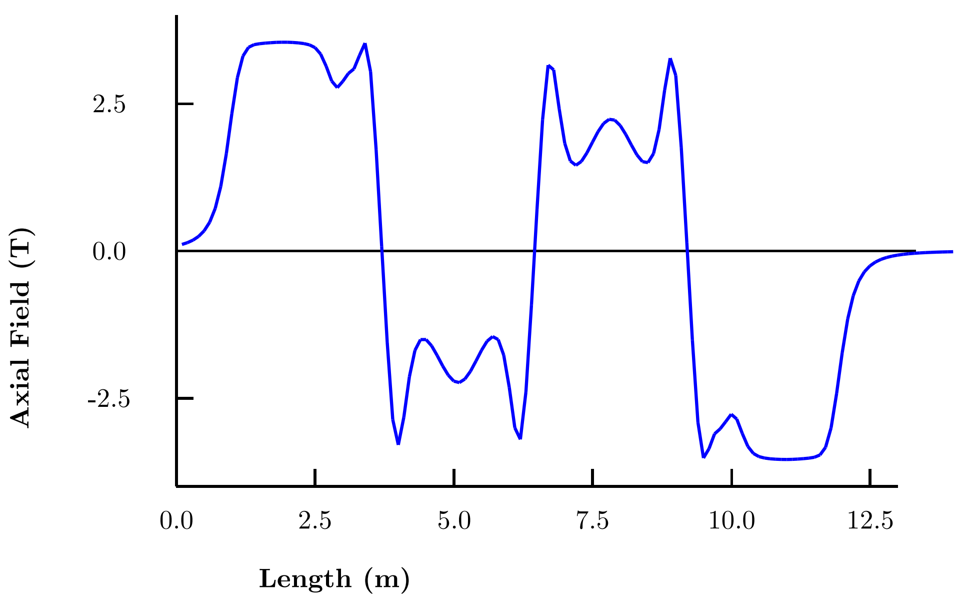


4 Complete Experiment

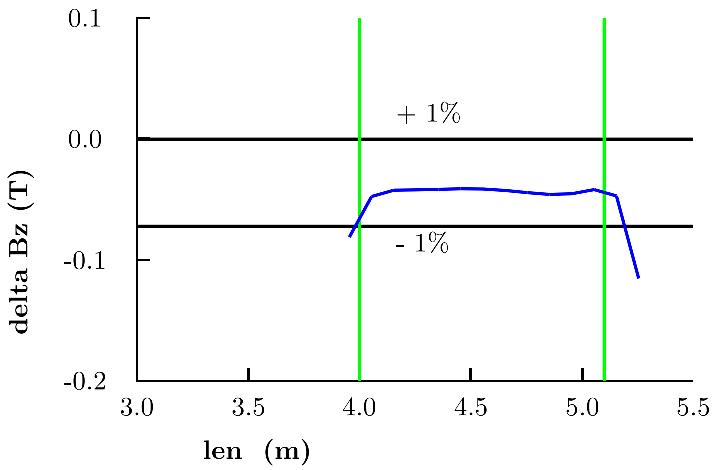
The geometry given here corresponds to 'geometry B' of my earlier note. i.e. it has 3 flips.

len1 m	gap m	dl m	rad m	dr m	I/A A/mm^2	n I A	n I l A m
0.000	0.000	0.200	0.300	0.050	-91.20	0.91	1.86
0.200	0.000	1.400	0.300	0.035	-83.84	4.11	8.20
1.600	0.000	0.200	0.300	0.050	-74.00	0.74	1.51
1.993	0.193	0.177	0.250	0.120	-39.34	0.84	1.63
2.365	0.195	0.177	0.240	0.120	-79.10	1.68	3.17
2.872	0.165	0.177	0.240	0.120	79.10	1.68	3.17
3.882	0.833	0.400	0.750	0.100	73.00	2.92	14.68
5.115	0.833	0.177	0.240	0.120	79.10	1.68	3.17
5.622	0.165	0.177	0.240	0.120	-79.10	1.68	3.17
6.632	0.833	0.400	0.750	0.100	-73.00	2.92	14.68
7.865	0.833	0.177	0.240	0.120	-79.10	1.68	3.17
8.372	0.165	0.177	0.240	0.120	79.10	1.68	3.17
8.743	0.195	0.177	0.250	0.120	39.34	0.84	1.63
9.113	0.193	0.200	0.300	0.050	74.00	0.74	1.51
9.313	0.000	1.400	0.300	0.035	83.84	4.11	8.20
10.713	0.000	0.200	0.300	0.050	91.20	0.91	1.86

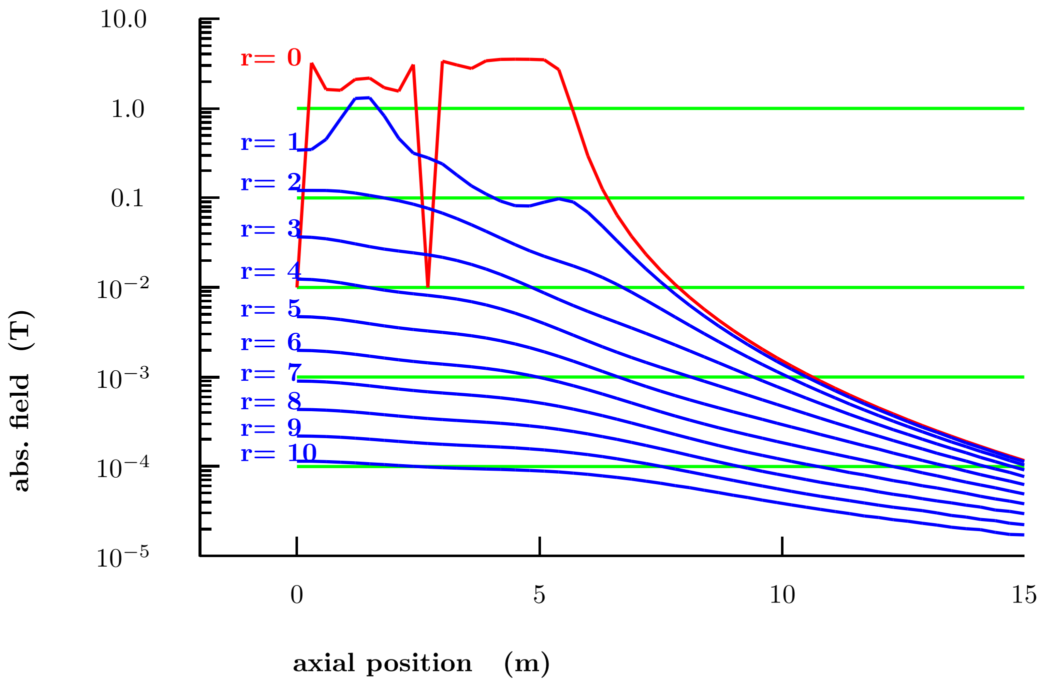




The following figure shows differences of the axial field from its nominal value of 3.6 T. It is seen to be very flat over about 1.2 m.

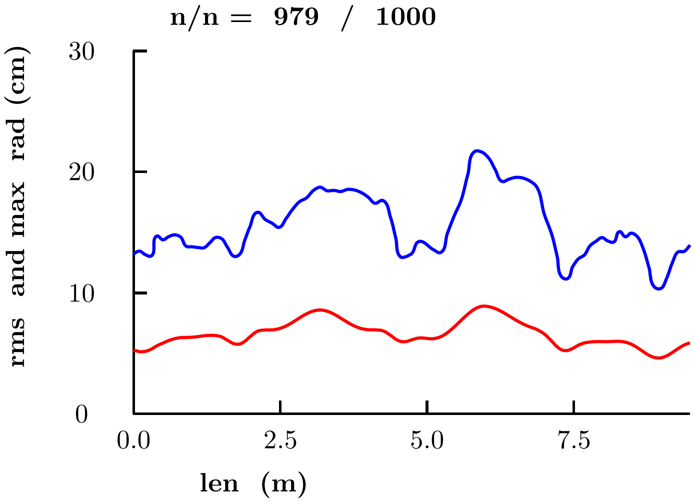


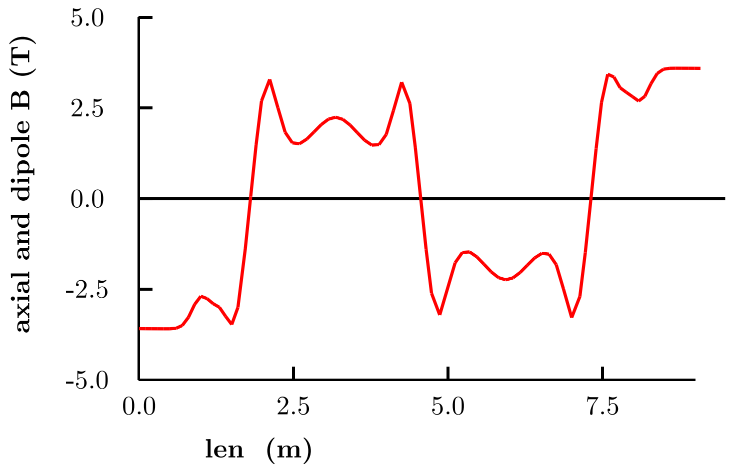
The stray fields from the full experiment are:

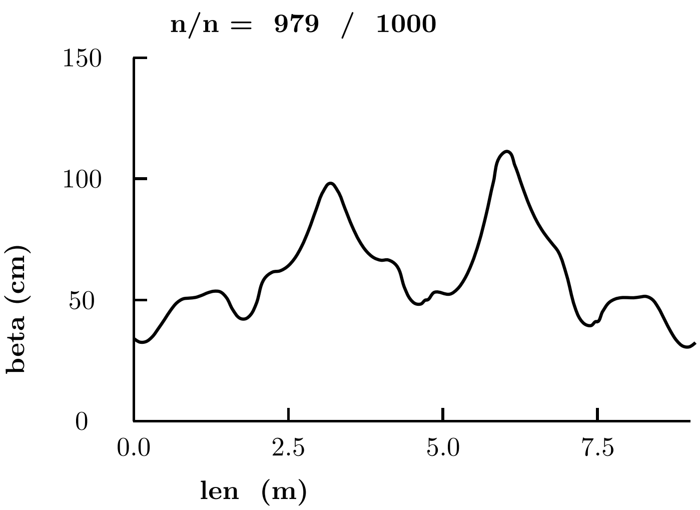


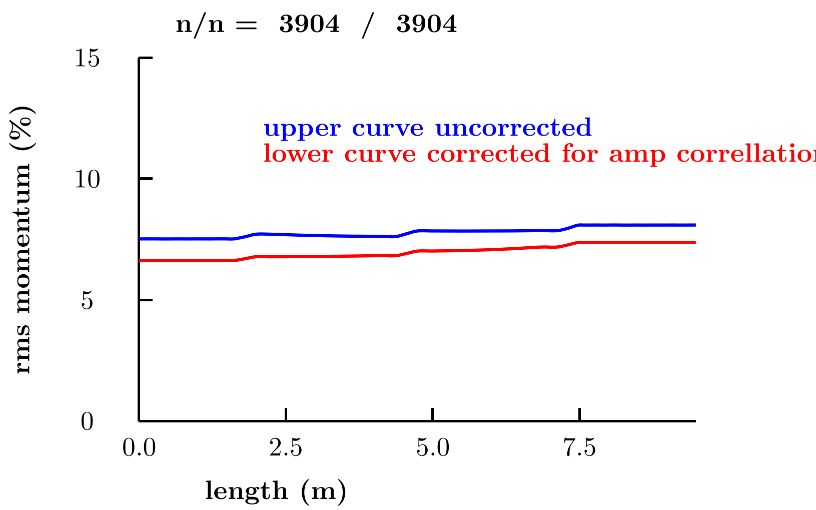
5 Simulation of experment (d)

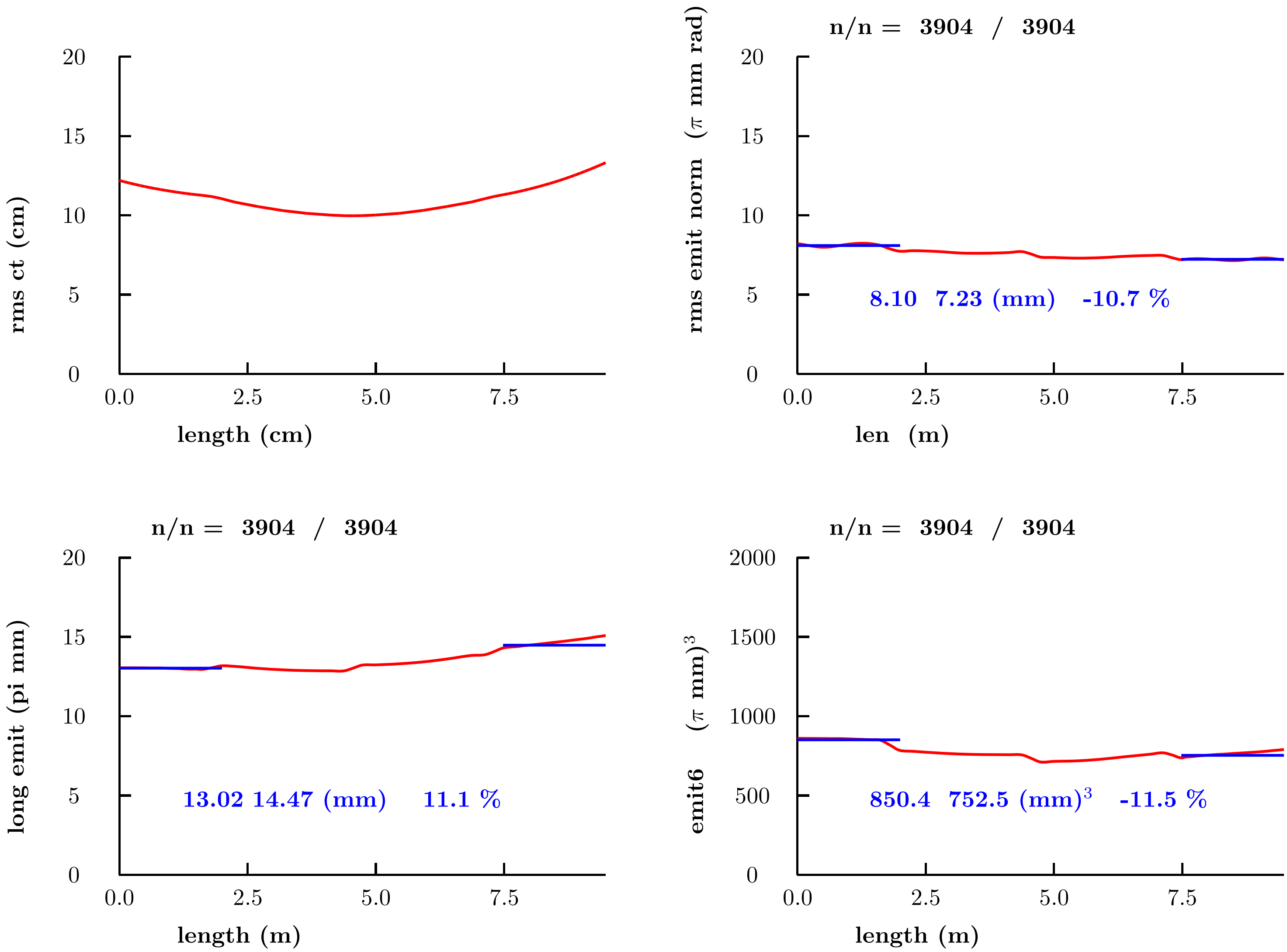
The experiment simulated here corresponds to experiment (d) of my prvious note (draft 2, attached). i.e. there are 3 full absobers, the initial energy higher than the final, and the rf running on crest.

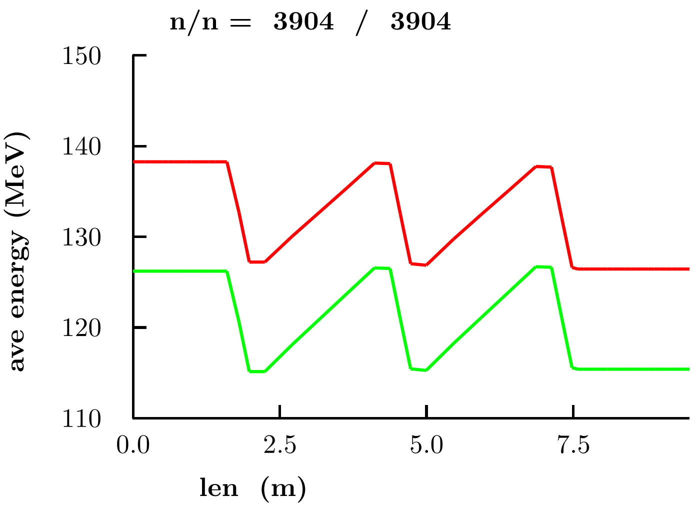


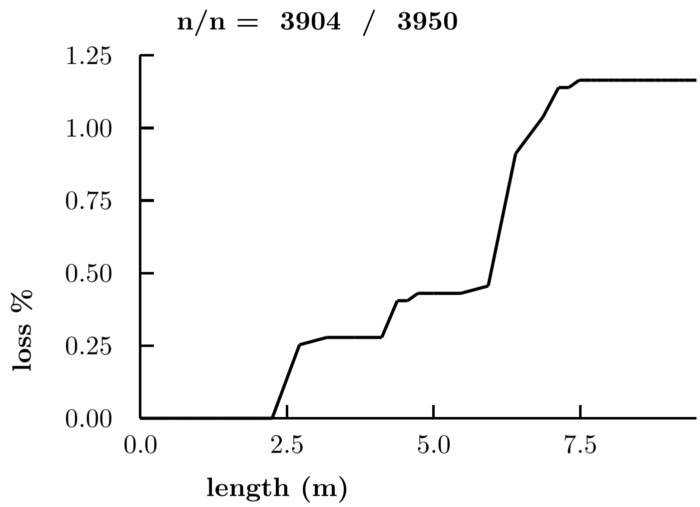







rms ct (cm)
length (cm)
n/n = 3904 / 3904
rms emit norm (π mm rad)
len (m)
8.10 7.23 (mm) -10.7 %
n/n = 3904 / 3904
long emit (pi mm)
length (m)
13.02 14.47 (mm) 11.1 %
n/n = 3904 / 3904
emit6 (π mm)³
length (m)
850.4 752.5 (mm)³ -11.5 %





The nominal transverse cooling is expected to be 12 %. We observe 10.7 %.

The longitudinal emittance should rise by about 6%, but is seen to rise by 11.1% (the excess is a matching problem and is observed even with no material or rf present) .

The 6 D emittance is seen to fall by 11.5 %.

6 appendix from Previous note (draft 2)

7 introduction

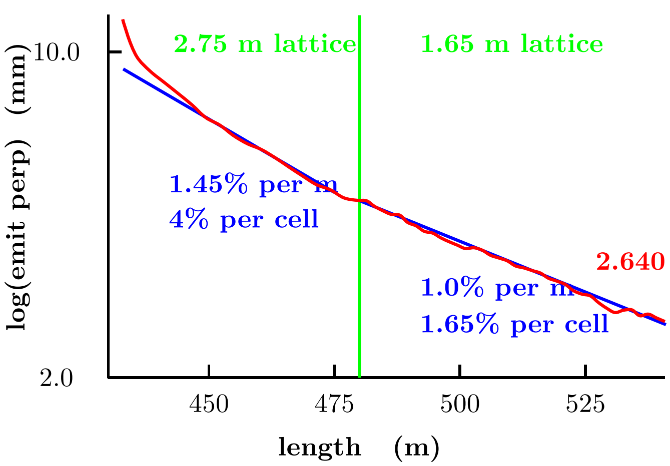
An ideal cooling experiment would involve a section of a cooling channel that could be used in a real neutrino factory. The second Feasibility Study provides two such channels: the tapered SFOFO and the double flip. This paper looks at an experiment that would test a part of the baseline SFOFO channel.

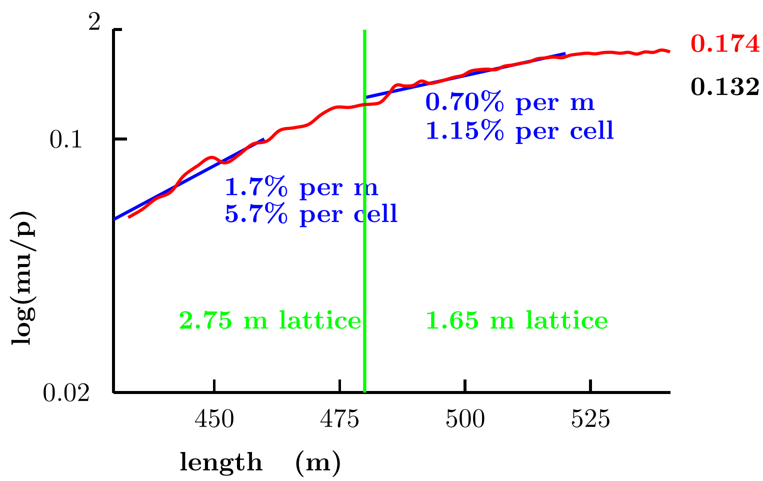
8 Choice of cell

The following figures show the rates of cooling, and rates of increase in accepted mu/p, in a simulation of the Study 2 system. We see that at the start, in the 2.75 m lattice, with an initial emittance of 10 mm rad, the transverse cooling is 4.0 % per cell (1.45 %/m). This rate may be compared to the maximum theoretical rate ($\Delta\epsilon/\epsilon$=Δp/p) of 5.6 %.

The numbers for the 1.65 m cells are lower, partly because of the condition of the beam where it is used, partly because the lattice has a 20% poorer acceleration packing factor, and, per cell, because it is shorter. We therefore consider an experiment using a cell, or cells, from the 2.75 m lattice.

In Study 2, there are tree different current setting for this cell: setting that adjust the minimum beta, and are thus matched to differing transverse emittances, as the emittance drops. In the following discussion I will assume the settings corresponding to the start of the channel. This allows cooling from the largest emittance ($\approx$ 10 π mm) which, it is assumed, would be the easiest to measure.





9 proposed experimental geometries

We want, initially, to test the shortest section that will give a sufficiently significant result. If we can measure emittances to about 0.5 % [Janot] then one absorber yielding 4 % might be considered sufficient. At full gradient, one rf section (cavities) would be enough to restore the lost energy and demonstrate un-normalized cooling (no re-acceleration is needed to show normalized cooling). But at full gradient, 16 MW of rf power is required, and the X-ray production may well prove too much for the measurement technology now being considered (fiber scintilators). We therefor propose a minimum system including two rf sections. Full energy recovery then requires only half gradient: the rf power required is only 8 MW and the X-radiation is down by 3 orders of magnitude ($\propto$ (gradient)^{10}). It is then tempting to add the possibility of two additional absorbers at the ends, allowing more cooling if a) more rf power comes available, b) we operate on crest [Zissman], or c) we drop the requirement of full energy recovery [Kaplan]. We will consider two magnetic geometries.

For emittance measurement, we assume [Janot, Blondell] planes of detectors in continuous solenoids. In the examples shown here, a field of 3.1 T, radius of 33 cm, and length 2 m, were chosen, but this could be changed. A betatron match is provided between the measurement solenoids and the cooling cells.

In all cases, the rf cavity, stepped Be window, hydrogen absorber, and Al window, dimensions are all assumed identical to those given in Study 2.

9.1 geometry A (1.5 cells)

In this, the lower cost geometry, there is only a single pair of high gradient "focus coils" at the center, and two large diameter "coupling" coils over the rf sections. Beyond these, at either end, there are single matching coils followed by the solenoids in which the detector planes measure the beam parameters. The focus coil dimensions and current will be identical to those in Study 2. The coupling coils would have the identical dimensions, but be operated at slightly lower current to aid the match into the experimental solenoids. In the following simulations, the dimensions are from a slightly earlier version, but will be updated in the next round.

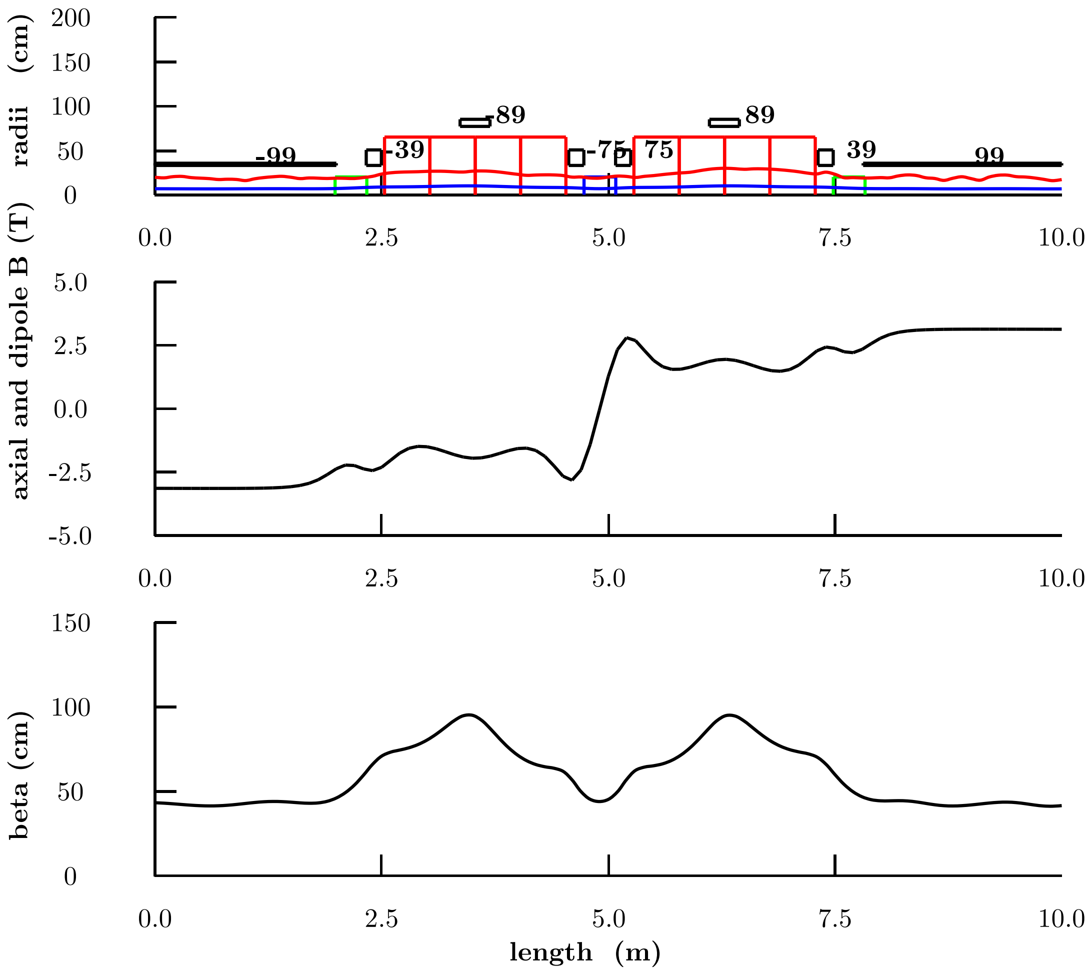
A single absorber (in blue in the following figure) placed at the center can operate in all respects like the absorbers in the study 2 case, and with the two rf sections at 1/2 full gradient, give the same cooling as a cell in that study. This is found to be approximately 4% transverse cooling, 2 % longitudinal heating, yielding 6 % 6-dimensional cooling.

If more cooling is desired then 1/2, or full, length absorbers can be placed at the ends of the rf sections. Full length absorbers are indicated in green in the following figure. It is seen that the focus beta at these locations is almost identical to that inside the "focus coils" at the center. With full rf gradient and 1/2 length end cells, we would now obtain 8 % transverse cooling.

With full length end cells we would get 12 % transverse cooling, but in this case, even with full rf gradient, the initial and final energies would be different.

The main objection to this geometry is that the fields over the end absorbers, and the angular momenta of the trajectories are not at all like those in the continuous cooling channel. As a simple demonstration of cooling, this is irrelevant; but it is not a test of cooling in a usable cooling lattice.

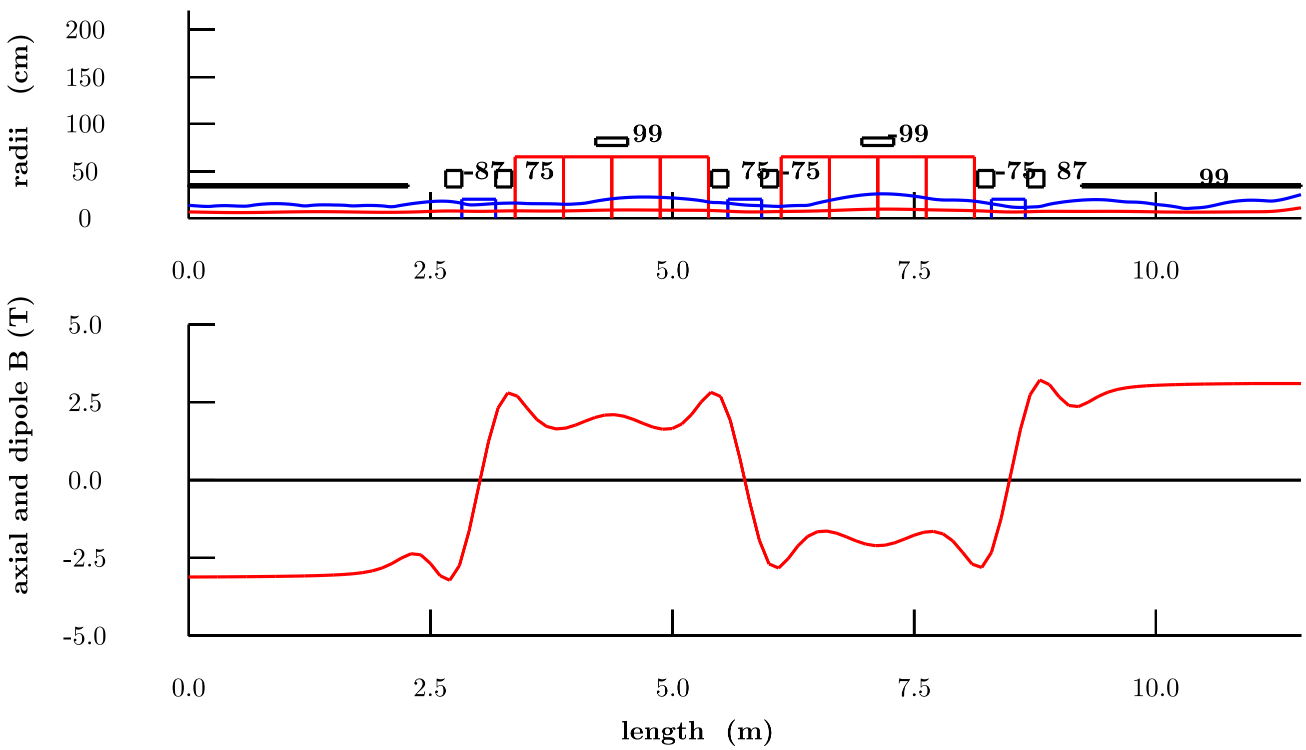
The geometry A, with rms and maximum orbits, followed by the axial fields and beta functions:



9.2 geometry B (2.5 cells)

In this, slightly more expensive, geometry there are three "focus coils" over the three absorbers, and all three are operating in the same fields as in the continuous geometry. Less work has been done on the matching in this case, but it will probably be as good as in the first case.

The geometry and axial fields are:



The matching is not yet final in these parameters, but they would provide starting values for a comparison in cost between this and geometry A.

10 Experimental Options

With either of the above geometries, we could do a number of different tests, a sample of which we list in the following table.

The examples are given in pairs: in the first of which the initial and final energies are required to be the same; in the second, they are not (which some might object to, since the un-normalized emittance cooling is not the same as that of the normalized).

Examples a) and b) use full gradient and represent 2 or 3 cell respectively. In c) and d) the rf power and gradient are reduced, but the same acceleration is achieved by running on crest (which some may object to since this cannot be done in a continuous channel). In e) and f) the rf power is lowered some more to obtain exactly half the gradient, but the phase is maintained equal to that in the continuous channel. In g) and h) the power is lowered yet more to give acceleration, on the crest, equals half the continuous value. Finally, in examples i) and j) we note that cooling of normalized emittance will be achieved even without any rf, but again, it may be objected that there is in this case, no cooling of un-normalized emittance.

Three of these examples have been simulated; that of example a0 is given in section ***.

From the study 2 simulation we saw that there was 4.1 % transverse cooling per stage. Simulations of continuous cooling with Gaussian input gives 4.6 %/cell (see section ***), while simulations of the cooling experiment (e.g. section ***) give a little less than 4%. Taking 4%/cell as the approximate cooling expected to be observed, we can list the cooling and required rf power in a number of cases:

	$E_1 = E_2$?	$n_{absorbers}$	rf grad MV/m	rf phase deg	$\Delta\epsilon_\perp$ %	rf Power MW	simulated
a	yes	1/2+1+1/2	15.5	30	8	32.3	yes
b[1]	no	1+1+1	15.5	30	12	32.3	
c	yes	1/2+1+1/2	8.7	90	2	10.3	yes
d	no	1+1+1	8.7	90	12	10.3	
e	yes	0+1+0	7.7	30	4	8.1	yes
f	no	1+0+1	7.7	30	8	8.1	
g	yes	0+1+0	4.4	90	4	2.6	
h	no	1+0+1	4.4	90	8	2.6	
i	no	0+1+0	0	0	4	0	
j	no	1+1+1	0	0	12	0	

In addition to these variants, the experiment, offline, could observe cooling from different initial emittances; and online, try different beta functions by adjusting the lattice coil currents. In the following simulations, we restrict ourselves to a transverse emittance slightly less than that at the start of the Study 2 cooling (9 mm vs. 12 mm); and longitudinal emittance significantly less (11 mm vs. 30 mm). These smaller emittances give good transmission (97%) making the study of the cooling easier, but as noted above, an actual experiment could, offline, make many differing initial assumptions.