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Possible 200 MHz Cooling Experiment Designs

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1 introduction

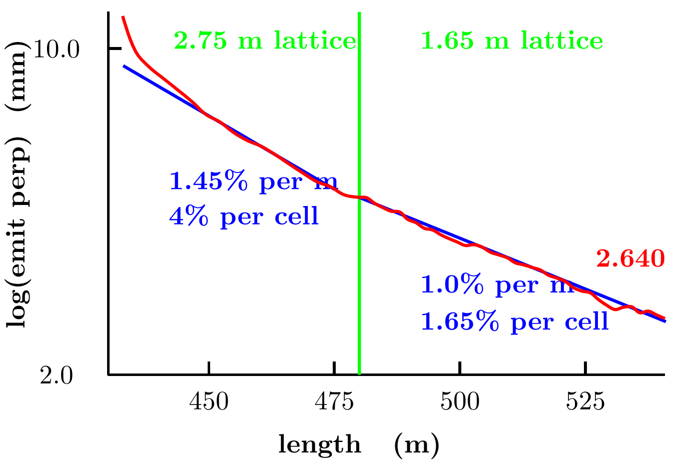
An ideal cooling experiment would involve a section of a cooling channel that could be used in a real neutrino factory. The second Feasibility Study provides two such channels: the tapered SFOFO and the double flip. This paper looks at an experiment that would test a part of the baseline SFOFO channel.

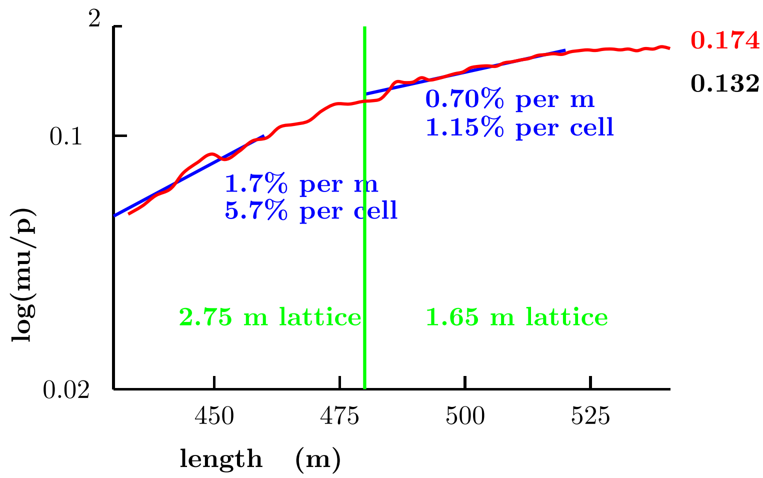
2 Choice of cell

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.





3 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.

3.1 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.

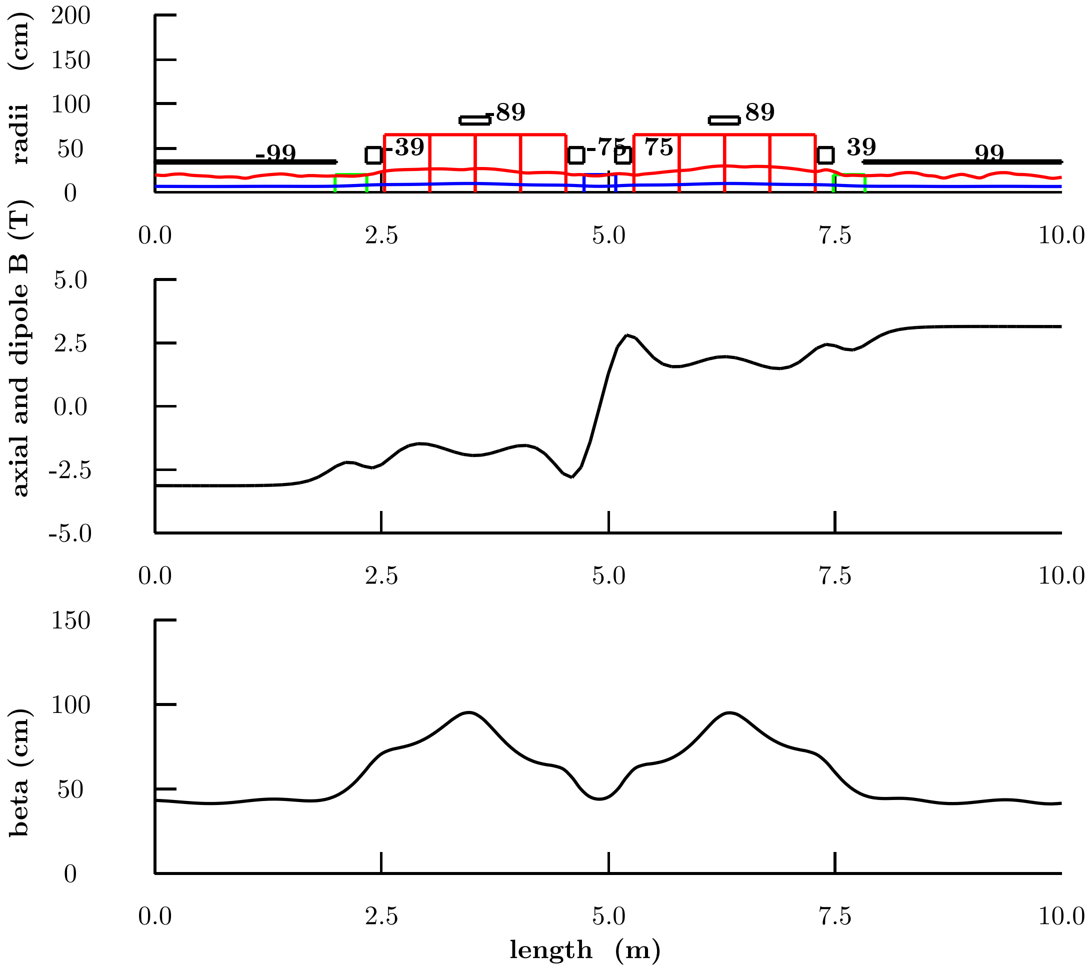
A single absorber (in blue in the following figure) placed at the center can operate in all respects like the absorbers in the study 2 case, and with the two rf sections at 1/2 full gradient, give the same cooling as a cell in that study. This is found to be approximately 4% transverse cooling, 2 % longitudinal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



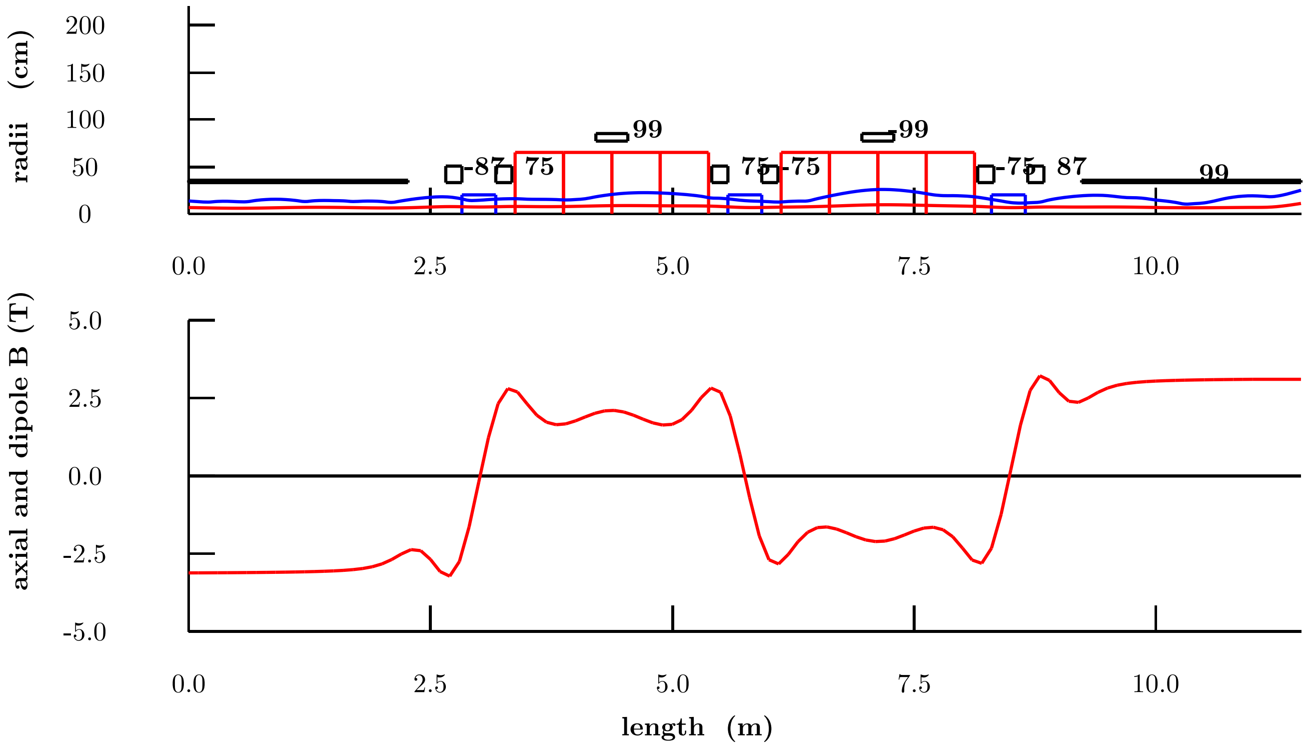
The coil Parameters for geometry A are:

len1	gap	dl	rad	dr	I/A	n I	n I l
m	m	m	m	m	A/mm^2	A	A m
4.000	0.000	2.000	0.330	0.025	-100.00	5.00	10.76
6.330	0.330	0.167	0.330	0.175	-39.11	1.14	3.00
7.365	0.868	0.330	0.770	0.080	-89.39	2.36	12.01
8.563	0.868	0.167	0.330	0.175	-75.96	2.22	5.82
9.080	0.175	0.167	0.330	0.175	75.96	2.22	5.82
10.115	0.868	0.330	0.770	0.080	89.39	2.36	12.01
11.313	0.868	0.167	0.330	0.175	39.11	1.14	3.00
11.810	0.330	2.000	0.330	0.025	100.00	5.00	10.76

3.2 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 coil dimensions and currents are:

len1	gap	dl	rad	dr	I/A	n I	n I l
m	m	m	m	m	A/mm^2	A	A m
4.000	0.000	2.000	0.330	0.025	-100.00	5.00	10.76
6.390	0.390	0.167	0.330	0.175	-87.44	2.56	6.70
6.907	0.175	0.167	0.330	0.175	75.96	2.22	5.82
7.942	0.868	0.330	0.770	0.080	99.24	2.62	13.33
9.140	0.868	0.167	0.330	0.175	75.96	2.22	5.82
9.657	0.175	0.167	0.330	0.175	-75.96	2.22	5.82
10.692	0.868	0.330	0.770	0.080	-99.24	2.62	13.33
11.890	0.868	0.167	0.330	0.175	-75.96	2.22	5.82
12.407	0.175	0.167	0.330	0.175	87.44	2.56	6.70
12.964	0.390	2.000	0.330	0.025	100.00	5.00	10.76

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.

4 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.

5 ICOOL Simulations

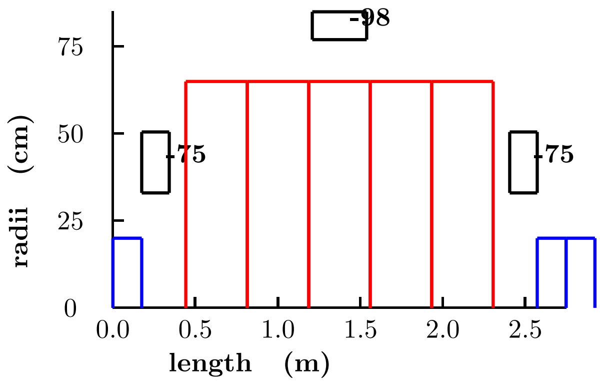
5.1 Continuous Cooling Lattice

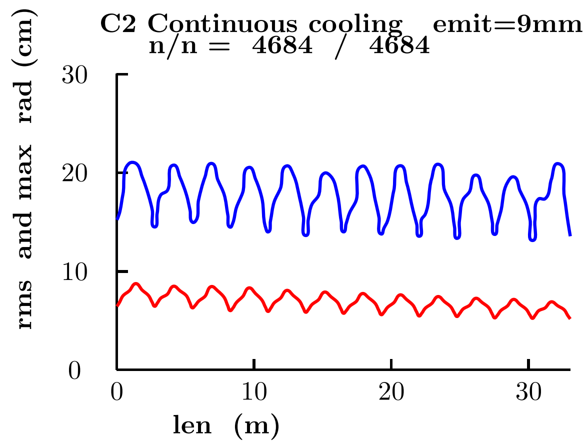
For a comparison with the cooling experiment, it is desirable to have a "clean" simulation of the cooling channel using the same Gaussian initial distributions as will be used in the experiments. The parameters used here are:

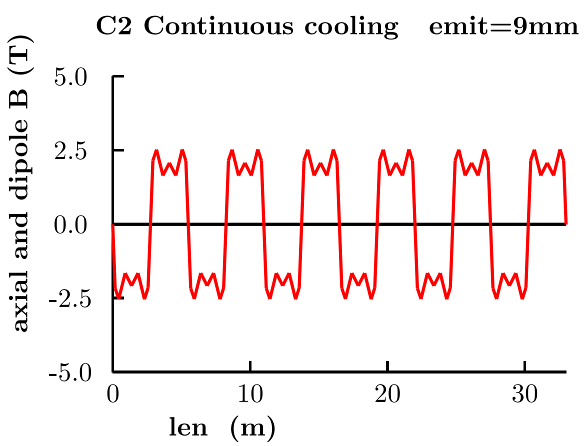
particles		5000
uncorrelated momentum	MeV	200
Transverse emittance	π mm	9
Longitudinal emittance	π mm	11
uncorrelated dp/p	%	7
rms ct	cm	9
mom-amp^2 correlation	GeV/c	0.34

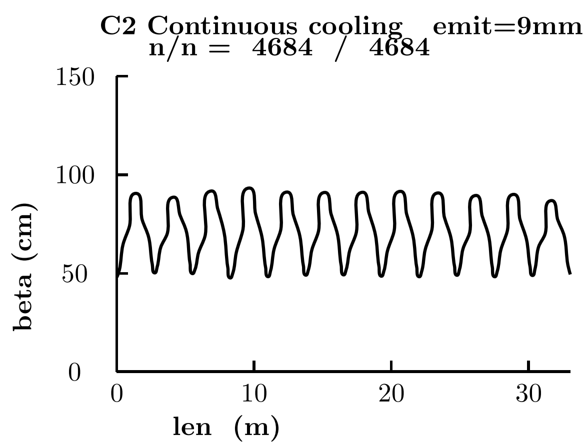
If no cuts are applied to the transmitted particles, then the longitudinal emittance was found to rise rapidly. This was found to be due to a few particles not captured by the rf. We thus apply the following cuts, treating the particles outside these cuts as lost:

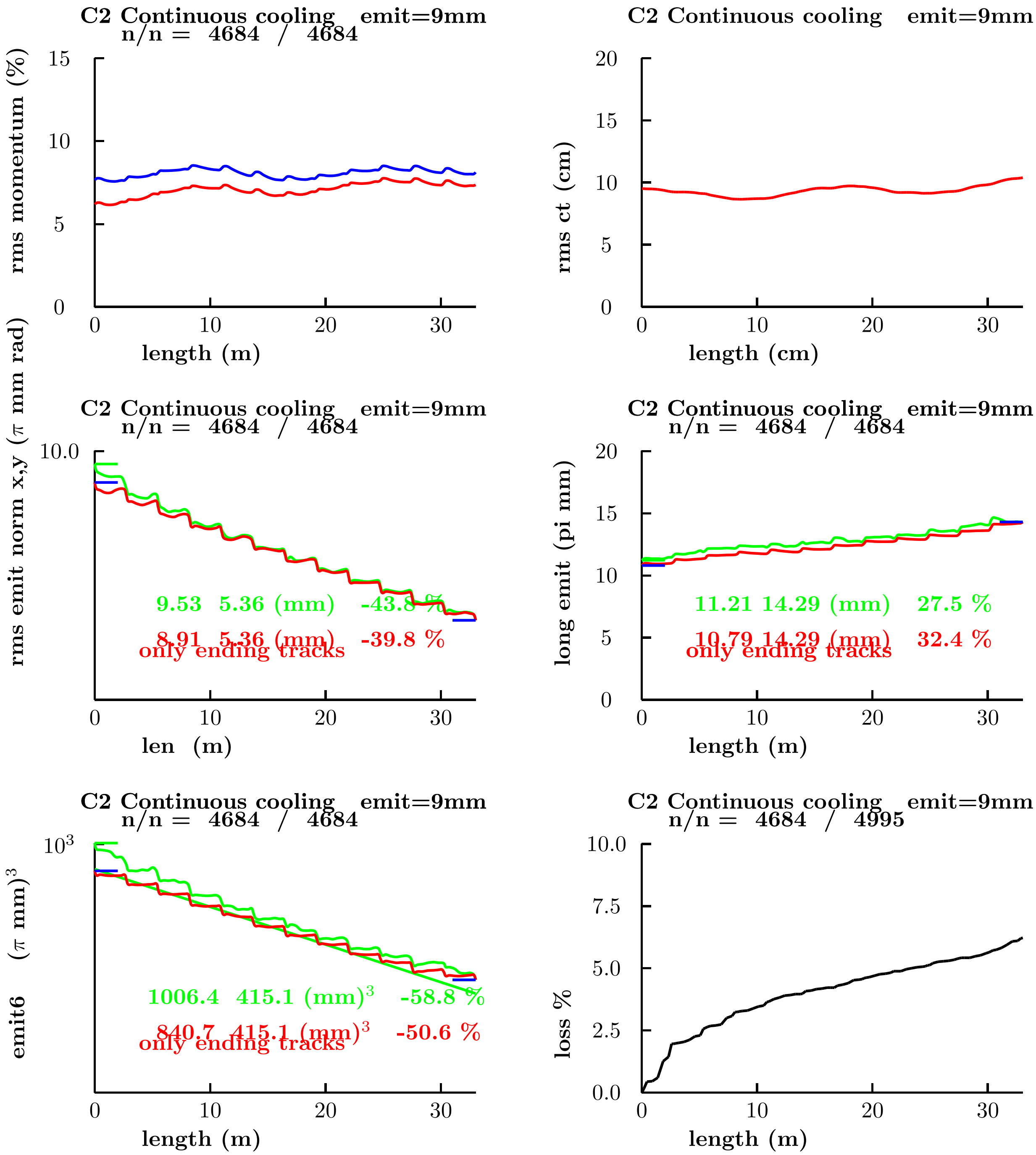
ct cuts	+/- 30 cm
pmax cut	315 MeV
pmin cut	95 MeV

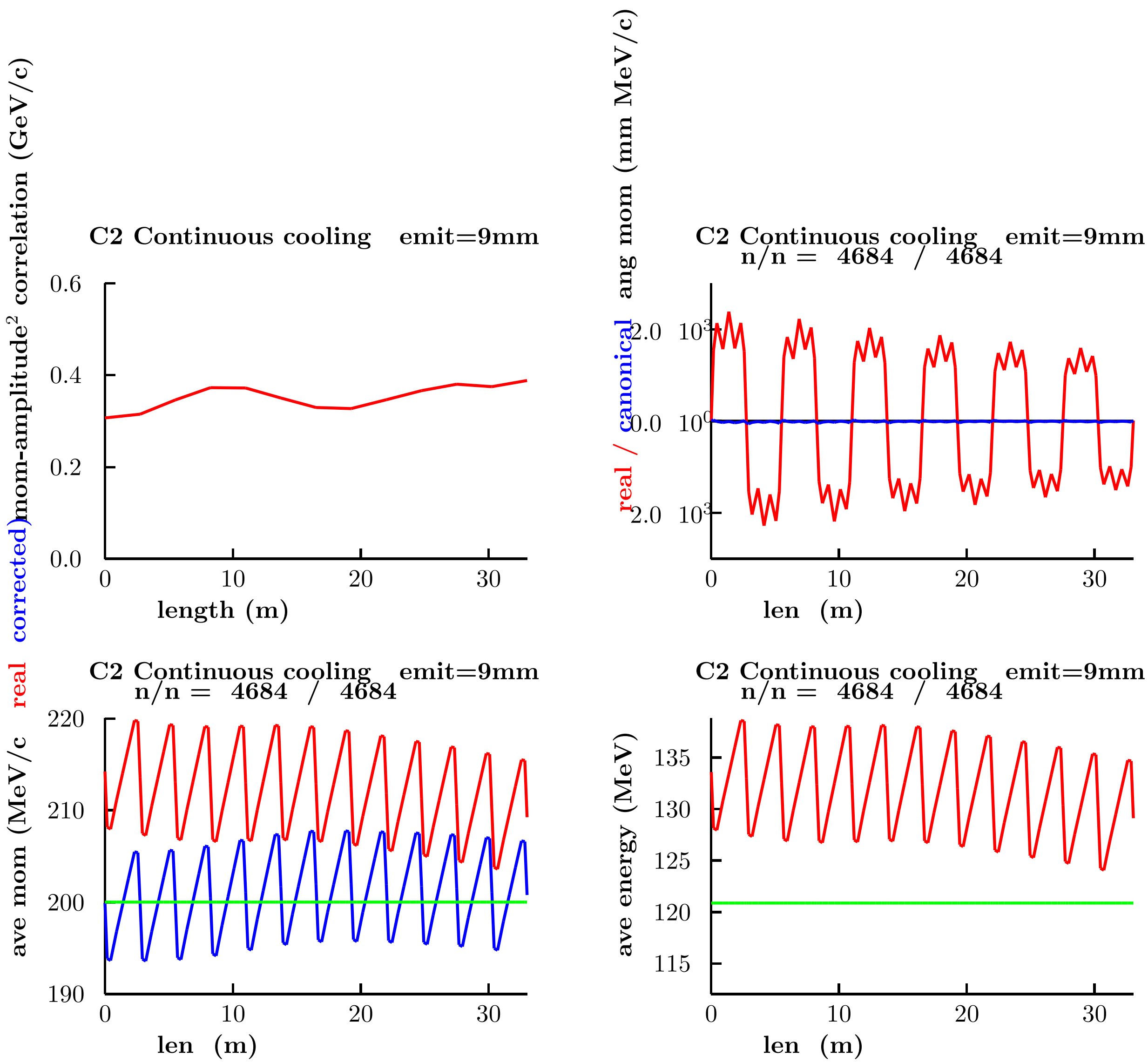









C2 Continuous cooling emit=9mm
n/n = 4684 / 4684
rms momentum (%)
length (m)
C2 Continuous cooling emit=9mm
rms ct (cm)
length (cm)
C2 Continuous cooling emit=9mm
n/n = 4684 / 4684
rms emit norm x,y (π mm rad)
9.53 5.36 (mm) -43.8 %
8.91 5.36 (mm) -39.8 %
only ending tracks
len (m)
C2 Continuous cooling emit=9mm
n/n = 4684 / 4684
long emit (pi mm)
11.21 14.29 (mm) 27.5 %
10.79 14.29 (mm) 32.4 %
only ending tracks
length (m)
C2 Continuous cooling emit=9mm
n/n = 4684 / 4684
emit6 (π mm)³
1006.4 415.1 (mm)³ -58.8 %
840.7 415.1 (mm)³ -50.6 %
only ending tracks
length (m)
C2 Continuous cooling emit=9mm
n/n = 4684 / 4995
loss %
length (m)



Transmission is:

Transmission through 4 cells	96 %
Transmission through 12 cells	94 %

The observed initial rate of changes of emittances per cell are:

Transverse emittance	-4.6 %
Longitudinal emittance	+2.0 %
6-D emittance	-6.9%

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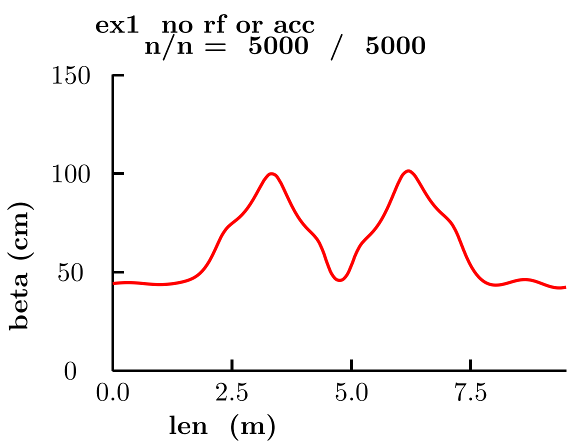
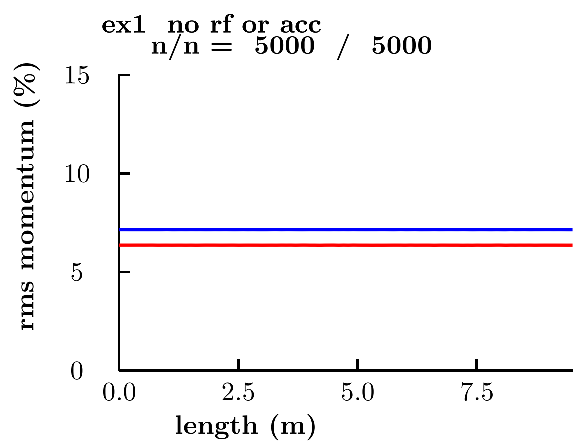
5.2 Experiment without rf or absorber

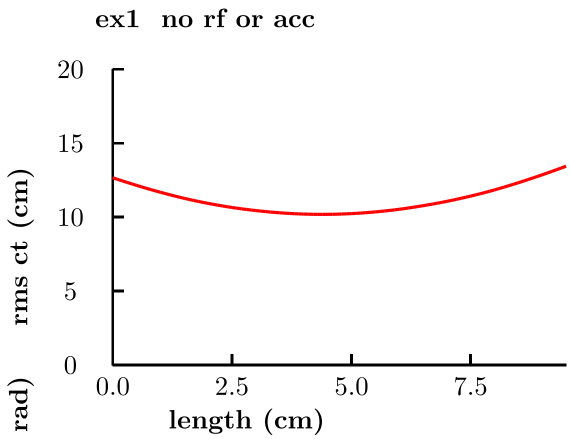
In order to observe unperturbed emittances, it is necessary to introduce and correct for 3 correlations: 1) the familiar (momentum) - (betatron amplitude)^2 correlation needed because the forward velocities of large amplitude particles are otherwise slower than for small amplitudes, resulting in mixing between longitudinal and transverse planes; 2) a correlation between angular momentum and time. This second correlation is not large, and does not rise, if the axial magnetic field alternates reasonably frequently, but in the experiment case, this is not well satisfied and correction is needed; and 3) an initial time-momentum correlation corresponding to a finite synchrotron α_o.

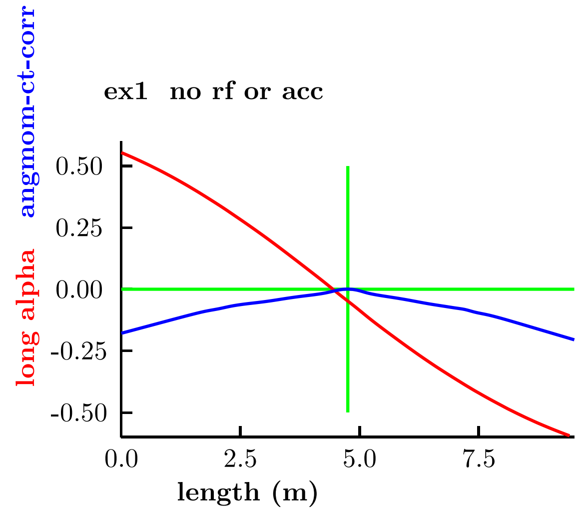
The initial conditions used were:

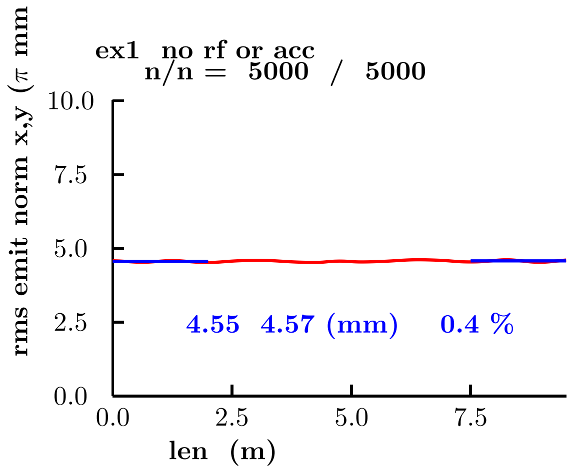
particles		5000
uncorrelated momentum	MeV	200
Transverse emittance	π mm	9
Longitudinal emittance	π mm	11
uncorrelated dp/p	%	7
rms ct	cm	9
mom-amp^2 correlation	GeV/c	.34
ct-angmom correlation	GeV^{-1}	-35
ct-dp/p correlation	m	1.14

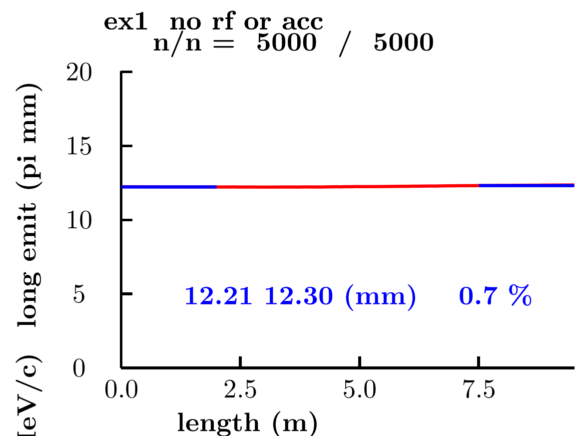


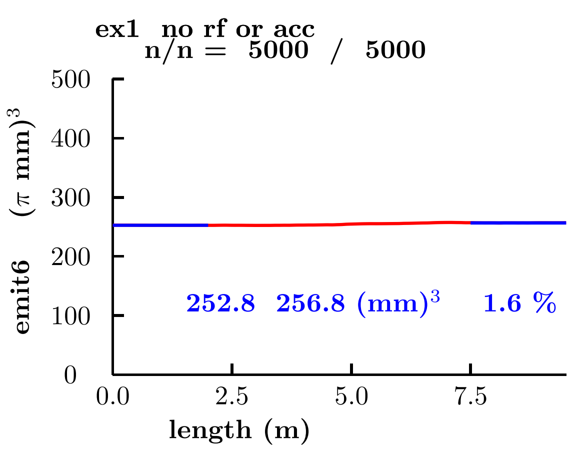


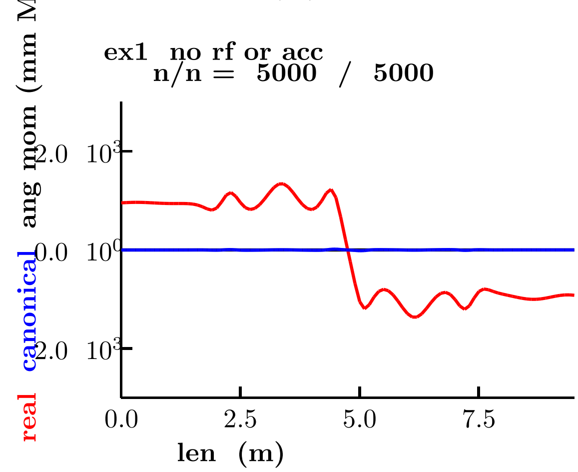

ex1 no rf or acc
rms ct (cm)
20
15
10
5
0
0.0
2.5
5.0
7.5
length (cm)

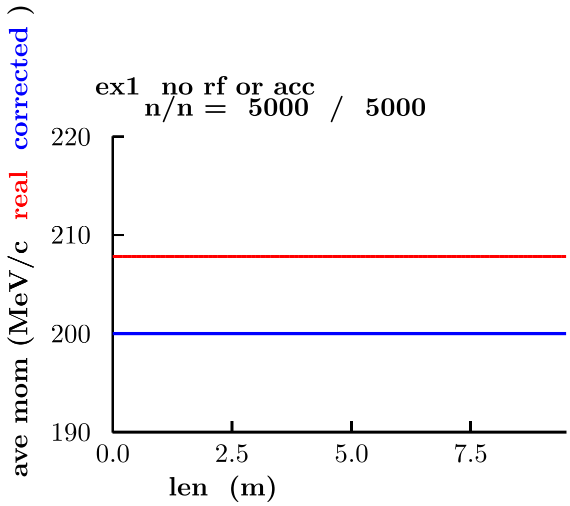

ex1 no rf or acc
long alpha
angmom-ct-corr
0.50
0.25
0.00
-0.25
-0.50
0.0
2.5
5.0
7.5
length (m)

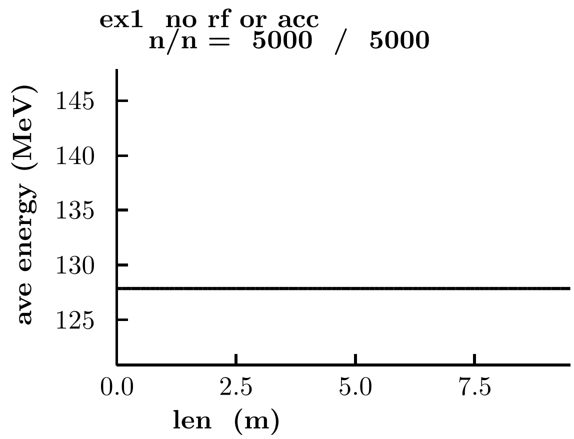

ex1 no rf or acc
n/n = 5000 / 5000
rms emit norm x,y (π mm rad)
10.0
7.5
5.0
2.5
0.0
4.55 4.57 (mm) 0.4 %
0.0
2.5
5.0
7.5
len (m)


ex1 no rf or acc
n/n = 5000 / 5000
long emit (pi mm)
20
15
10
5
0
12.21 12.30 (mm) 0.7 %
0.0
2.5
5.0
7.5
length (m)


ex1 no rf or acc
n/n = 5000 / 5000
emit6 (π mm)^3
500
400
300
200
100
0
252.8 256.8 (mm)^3 1.6 %
0.0
2.5
5.0
7.5
length (m)


ex1 no rf or acc
n/n = 5000 / 5000
real canonical ang mom (mm MeV/c)
2.0 10^3
0.0 10^0
-2.0 10^3
0.0
2.5
5.0
7.5
len (m)





Although the simulation needs to be done with more statistics, it does already show statistically significant heating due to various higher order effects.

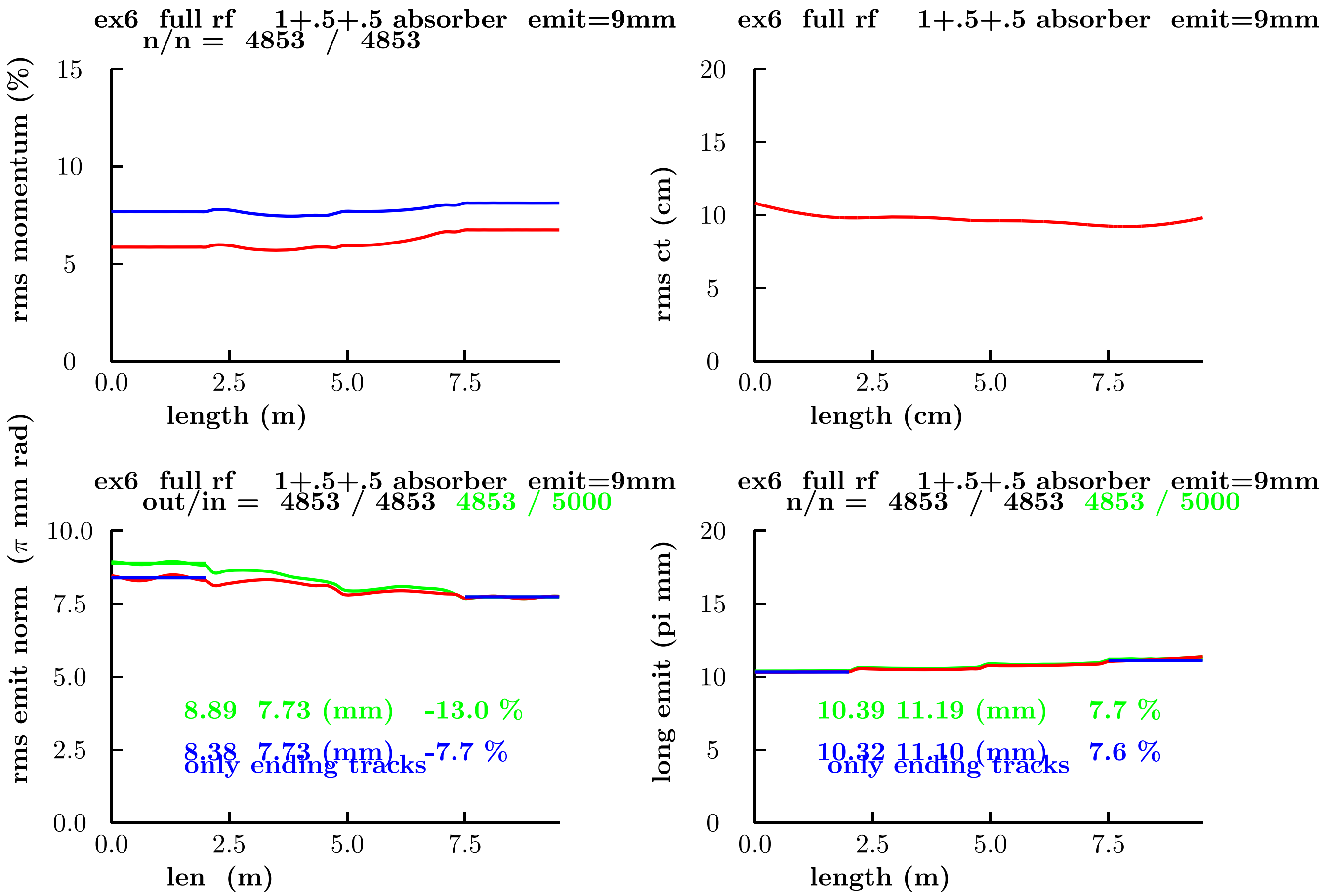
particle loss	0 %
Transverse emittance change	+ .4%
Longitudinal emittance change	+ .7%
6-D emittance change	+ 1.6%

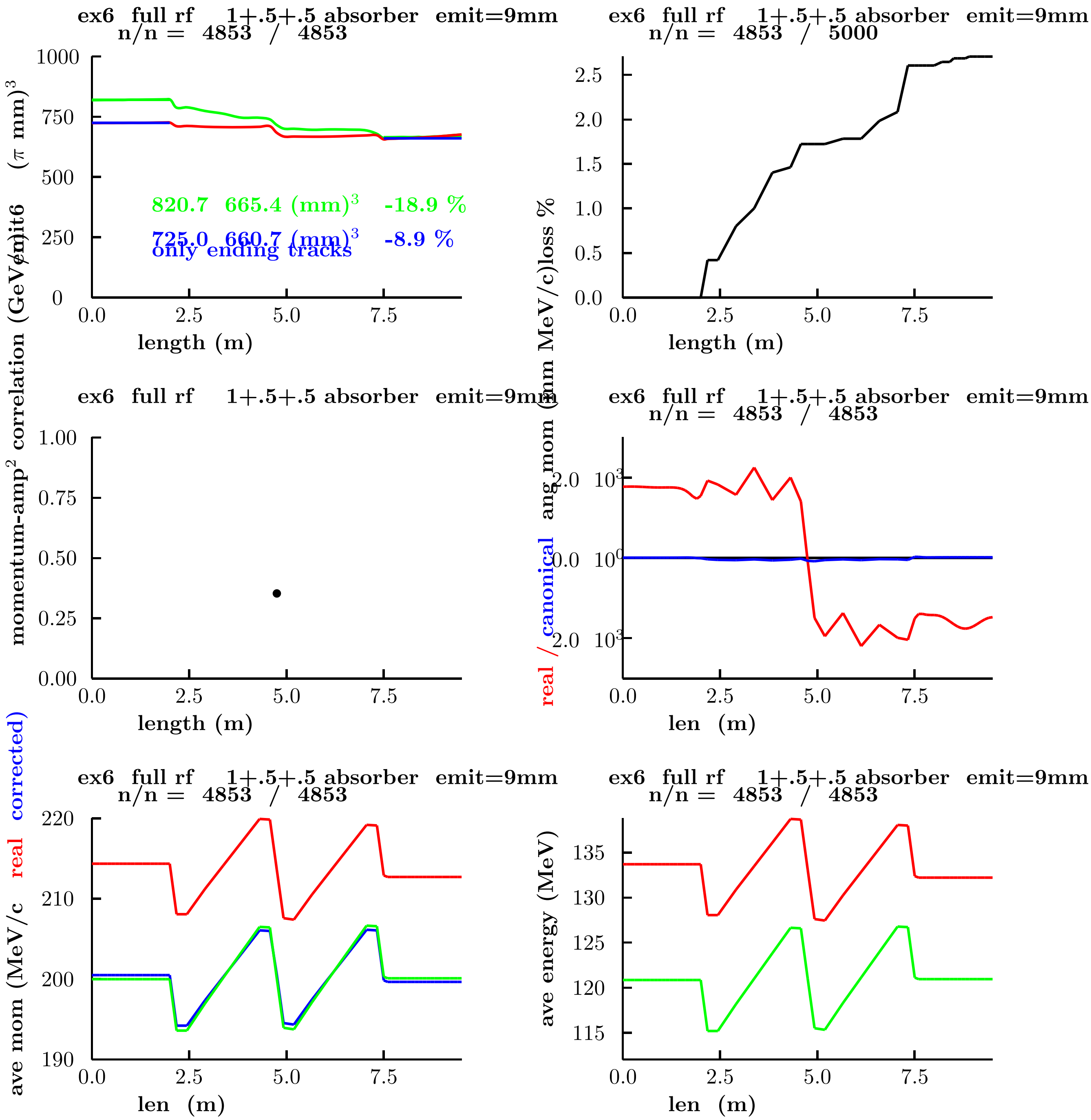
Clearly more work could be done to correct for these, but it is unlikely that all effects can be easily identified. It is probably fair to deduct these growths from the emittance changes observed with material, but I will refrain from doing so here.

5.3 Example with rf and absorbers

This is the example a) in the above table, with full rf gradient, a full absorber in the center and half length absorbers at the front and back. It is thus an experiment with 2 full cells of the continuous lattice. The initial conditions are :

particles		5000
uncorrelated momentum	MeV	200
Transverse emittance	π mm	9
Longitudinal emittance	π mm	11
uncorrelated dp/p	%	7
rms ct	cm	9
mom-amp^2 correlation	GeV/c	.34
ct-angmom correlation	GeV^{-1}	-35
ct-dp/p correlation	m	1.14




ex6 full rf 1+.5+.5 absorber emit=9mm
n/n = 4853 / 4853
820.7 665.4 (mm)^3 -18.9 %
725.0 660.7 (mm)^3 -8.9 %
only ending tracks
emit6 (π mm)^3
length (m)
ex6 full rf 1+.5+.5 absorber emit=9mm
n/n = 4853 / 5000
loss %
length (m)
ex6 full rf 1+.5+.5 absorber emit=9mm
momentum-amp^2 correlation (GeV/c)
length (m)
ex6 full rf 1+.5+.5 absorber emit=9mm
n/n = 4853 / 4853
real / canonical ang mom (mm MeV/c)
len (m)
ex6 full rf 1+.5+.5 absorber emit=9mm
n/n = 4853 / 4853
ave mom (MeV/c real corrected)
len (m)
ex6 full rf 1+.5+.5 absorber emit=9mm
n/n = 4853 / 4853
ave energy (MeV)
len (m)

When material and rf are introduced, there is significant particle loss (2.6 %. The lost particles are mostly in the transverse amplitude tails that are collimated by the rf windows. In order to separate emittance reduction due to this collimation from that due to cooling, we determine the emittance changes for only those particles that arrive at the end.

The observed emittance changes (2 cells), with and without the selection, are:

	all tracks	ending tracks	
Transverse emittance change	-13	-7.7	%
Longitudinal emittance change	+7.7	+7.6	%
6-D emittance change	-18.9	8.9	%

The longitudinal heating is a little more than that for 2 cells in the continuous lattice (7.6% vs. 4%), and the transverse cooling is somewhat less (7.7% vs. 8.2%), the differenced being probably due to failure to provide perfect matching.

6 Conclusion

Much work is still needed, but the two geometries proposed here may be a good start for the design of 200 MHz experiment. The simulations suggest that such a short section should provide easily verifiable cooling, providing the detectors can measure transverse and longitudinal emittance to better than 1 %.