200 MHz Cooling Experiment Design

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1 Introduction

Since Version 2, I have:

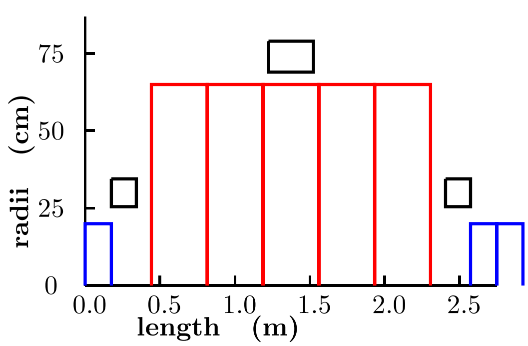
- Used the 9 cm thickness for the focus coils as introduced in 'Version 2'
- Increased the coupling coil thickness to 10 cm
- Decreased the sizes of the matching Coils
- Obtained matches for a higher momentum case and all the lower beta cases

2 Lattice

The parameters for a single cell of the lattice with currents for the standard 42 cm minimum betas, and a momentum of 200 MeV, are given below:

	z_1 m	gap m	$z_2 - z_1$ m	r_1 m	$r_2 - r_1$ m	I/A A/mm^2	n I MA	n I l MA m
focus	0.175	0.175	0.167	0.255	0.090	-117.76	1.77	3.34
coupling	1.225	0.883	0.300	0.690	0.100	-90.00	2.70	12.55
focus	2.408	0.883	0.167	0.255	0.090	-117.76	1.77	3.34

The coil dimensions for one cell are:



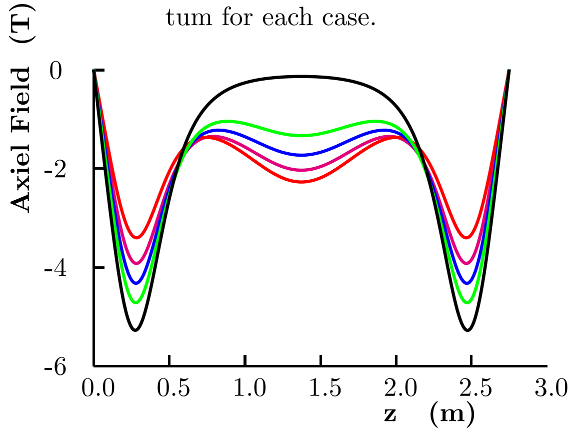
With the same coil dimensions, changing the currents can change the minimum $\beta_\perp$'s. In the following table the current densities, for a beam momentum of 200 MeV/c, are given for 5 different cases:

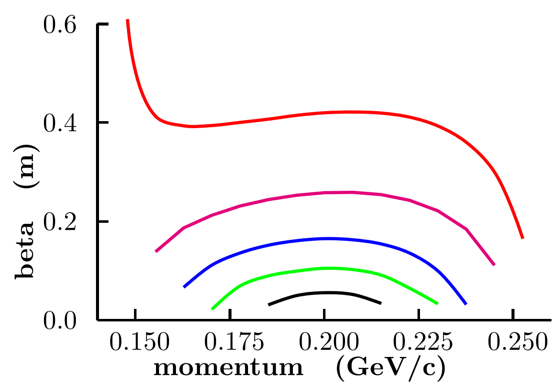
	jfocus A/mm^2	jcoupling A/mm^2	beta cm	dp/p $\pm$ %	ref. mom MeV/c
1	115	105	44	25	200
2	139	93	26	20	200
3	155	67	16	18	200
4	171	50	10	14	200
5	196	0	5.5	8	200

It will be noted that the current densities in the focus coils increase as the lattice is re tuned for lower beta. In a real channel, the lower beta solutions would only be used when the beam had already been cooled, and when the beam would thus have smaller dimensions. The coils could then be brought in and their current densities reduced. For the MICE experiment however, we could explore these cases by lowering the momentum and all currents by the same factor. The betas will remain unaffected and the transverse cooling rate will increase as the relative momentum loss in the absorbers is greater.

In a real lattice, one might also be able to lower the momentum and allow the lower betas and faster cooling, but such cases have not yet been explored. At lower momenta, it is hard for the RF to hold a bunch with the Study 2 initial momentum spread. However, as noted in the above table, and shown below, the momentum spread must anyway be reduced for these cases. In practice, this means that such low beta solutions will only be used in, or after, emittance exchange. But such a conclusion in no way reduces the interest in testing them in the experiment, where the momentum spread can be arbitrarily controlled by off line selection.

The following figures give the axial fields vs length and the betas vs momentum for each case.

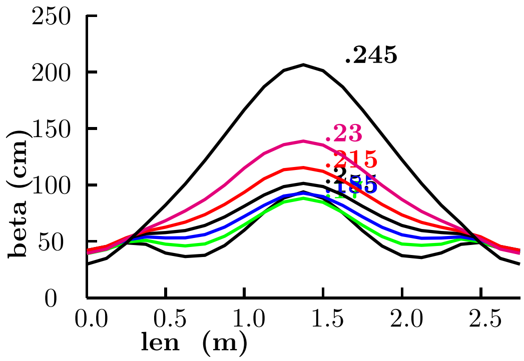




These plots show that the momentum acceptance falls as the beta is reduced. The approximate half momentum acceptances are also given in the above table.

The beta functions as a function of length for the five cases are:

1)



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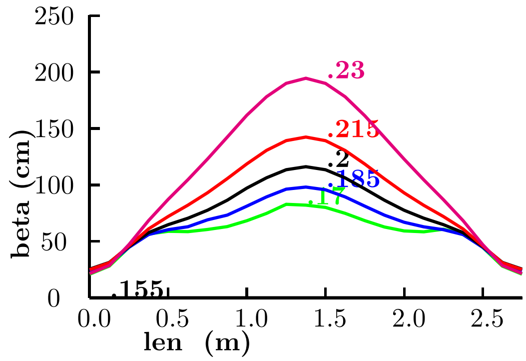

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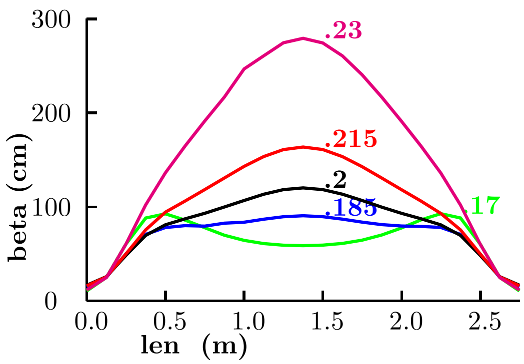

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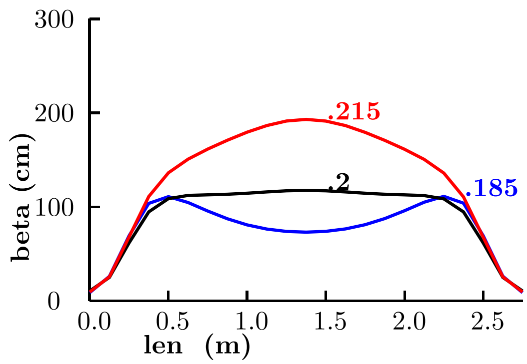

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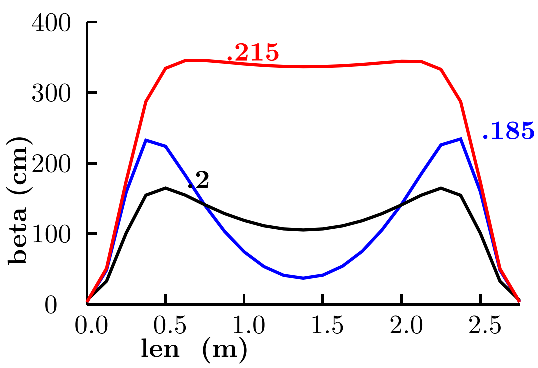


The maximum beta functions for the lowest beta minimum cases are a little higher. But this does not mean that larger apertures are required because the low minimum betas would be used only for low emittance beams.

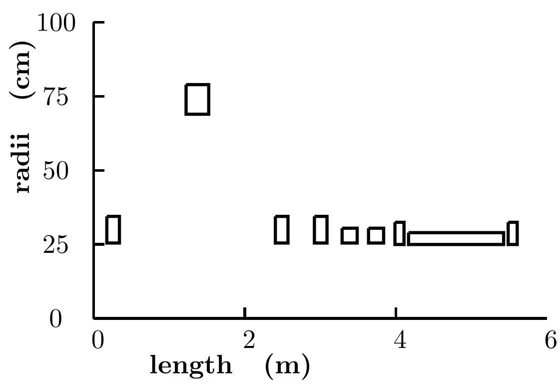
3 Standard Matching to Detector

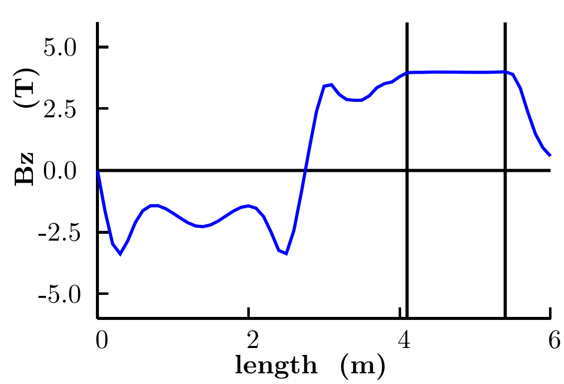
To match the central momentum into the detector, two variables are needed to set the entering $\beta_\perp$ to its required value in the solenoid, and to set its rate of change to zero. To avoid having to move any coils for different matching, two matching coils are introduced between the cells of the lattice and the detector solenoid, and the currents in these are adjusted. An attempt was also made to use only one matching coil and use the last focus coil as the other variable element, but this required higher currents and fields in this element and thus seemed a poor solution.

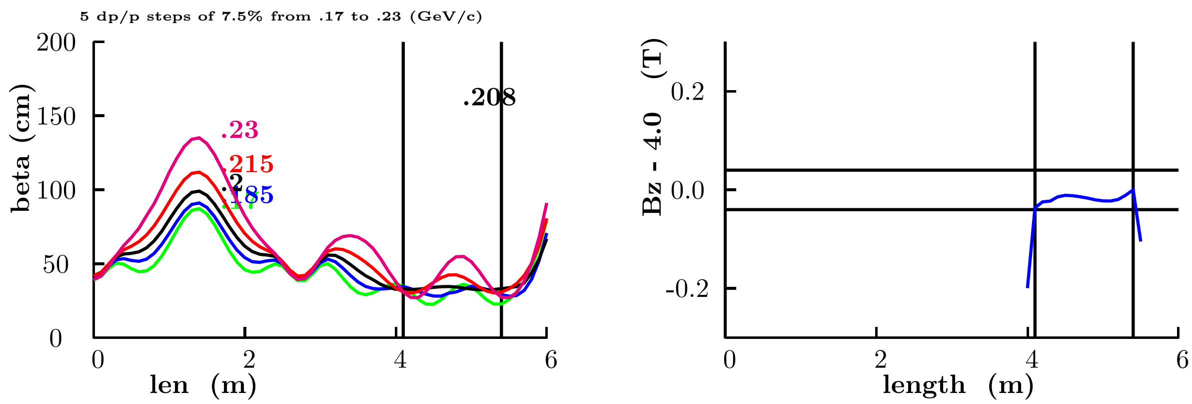
The coil dimensions, starting at the center, for one half of the experiment, and the current densities for the 'standard case' are given below.

	z_1 m	gap m	$z_2 - z_1$ m	r_1 m	$r_2 - r_1$ m	I/A A/mm^2	n I MA	n I l MA m
focus	0.175	0.175	0.167	0.255	0.090	-117.76	1.77	3.34
coupling	1.225	0.883	0.300	0.690	0.100	-90.00	2.70	12.55
focus	2.408	0.883	0.167	0.255	0.090	-117.76	1.77	3.34
focus	2.925	0.350	0.167	0.255	0.090	117.76	1.77	3.34
match	3.292	0.200	0.200	0.255	0.050	65.04	0.65	1.14
match	3.642	0.150	0.200	0.255	0.050	97.25	0.97	1.71
end	3.992	0.150	0.120	0.250	0.075	100.00	0.90	1.63
solenoid	4.172	0.060	1.260	0.250	0.040	80.95	4.08	6.92
end	5.492	0.060	0.120	0.250	0.075	128.89	1.16	2.10

Plots follow of the coils positions, axial field, betas vs length, and an expanded plot of the axial field difference in the solenoid.







It is seen that this case is not achromatically matched: momenta other than the central one oscillate in the detector solenoid. A measure of the quality of the match is δ: the sum in quadrature of the maximum relative beta errors:

$$\delta \;=\; \sqrt{\frac{\sum_1^n \left(\frac{\beta_{\rm max} \;-\; \beta_{\rm min}}{\beta_{\rm max} \;+\; \beta_{\rm min}}\right)^2}{n}}$$

In this case, for the central three momenta (0, and $+/-$ 7.5%), it is 11%, which is reasonably good. If the σ_p used is such that the maximum momentum acceptance is at $3 \times \sigma_p$, then $\sigma_p \;=\; 8\%$, so the above criterion reflects the magnitude of error in the Gaussian case. A far more chromatically matched solution has been found, but it has more coils, is almost 3 m longer, and would not allow achromatic matching for other than this single case.

It is proposed therefore to stick with the simpler match and, if it is needed, to use software to correct for the chromatic abberations.

4 Matching for Other Cases

Central momentum matches have also been obtained for a number of other cases tabulated below with the approximate current densities of the different coils.

Two versions of the 42 cm beta case : #1a operates at the standard 200 MeV/c, #1b operates at the highest momentum consistent with the assumed coil current capabilities. In this case, the match was modified to keep the detector solenoid operation at the standard 4 T value. Operation at lower momenta can be obtained by lowering all currents, including those of the detector solenoid, by the same factor.

Case #2 with a beta of 26 cm, is the lowest beta that can be obtained without exceeding the current specifications. Higher momenta are not possible at this beta, but lower momenta can be tried by scaling the currents.

In cases #3 - #5 the operating momentum and detector solenoid fields have been reduced to keep the current desities within reaonable bounds. An example was tried for case #2, in which the match was made to the detector solenoid running at full field, but the match was slightly more chromatic, and there seems little reason to do it.

#	Mom MeV/c	β cm	B_{sol} T	$\delta_{7.5\%}$ %	$\delta_{3\sigma}$ %	j_{foc}	j_{couple}	j_{m1}	j_{m2} A/mm^2	j_{end1}	j_{sol}	j_{end2}
1a	200	42	4	11	12	117.76	90.00	65.04	97.25	100.00	80.95	128.89
1b	240	42	4	10	11	141.32	108.00	74.34	103.61	97.87	80.95	128.89
2	200	25.4	4	17	12	139.72	79.33	66.73	74.42	104.44	80.95	128.89
3	175	16.7	3.5	25	14	136.23	58.92	53.15	47.81	97.22	70.83	112.78
4	150	10.5	3.0	39	13	128.74	37.50	40.89	14.03	89.67	60.71	96.67
5	140	5.7	2.8	65	10	137.21	0	20.82	-18.90	91.78	56.67	90.22

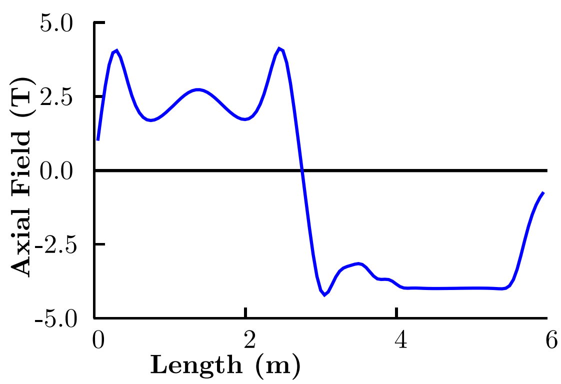
The two figures for the chromatic abberation are given:

1. $\delta_{7.5\%}$ is the function as defined above for the three smallest calculated momentum deviations: 0, and $+/-$ 7.5%.

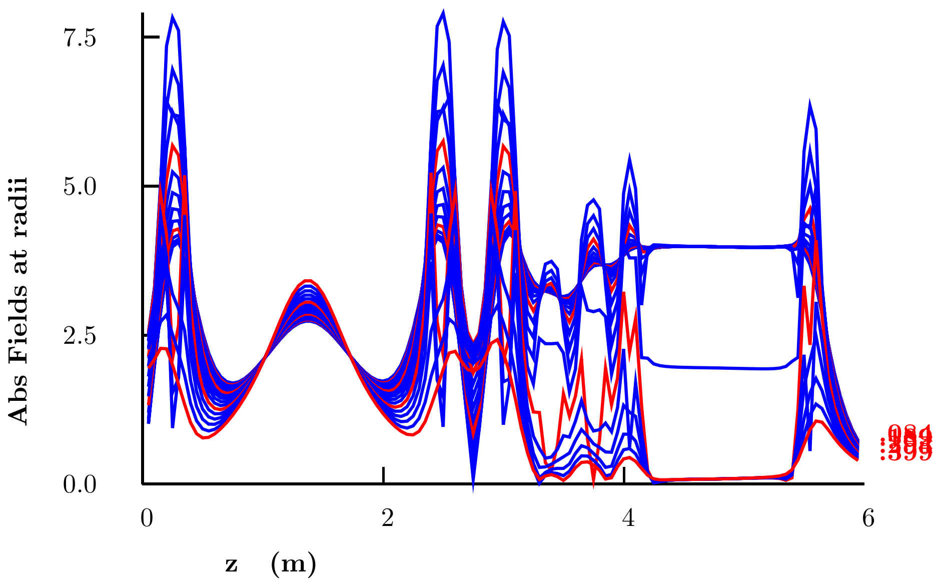
2. $\delta_{3\sigma}$ is scaled from the above to provide an estimate of the error at one sigma of a Gaussian beam that has been chosen to give 3 sigma at the maximum acceptance.

It is seen that the first definition implies a deterioration in the chromatic effects for the lower beta cases, but the more reaonable definition for a momentum spread that fits in the acceptance, gives an effect that is substantially independent of the case. Note that a 10% change in beta corresponds to an only 5% change in beam size.

The current densities for all cails are highest for case #2. So if the magnets are designed for this case, then they will be able to run all the other cases too. The axial fields for case #2 are:



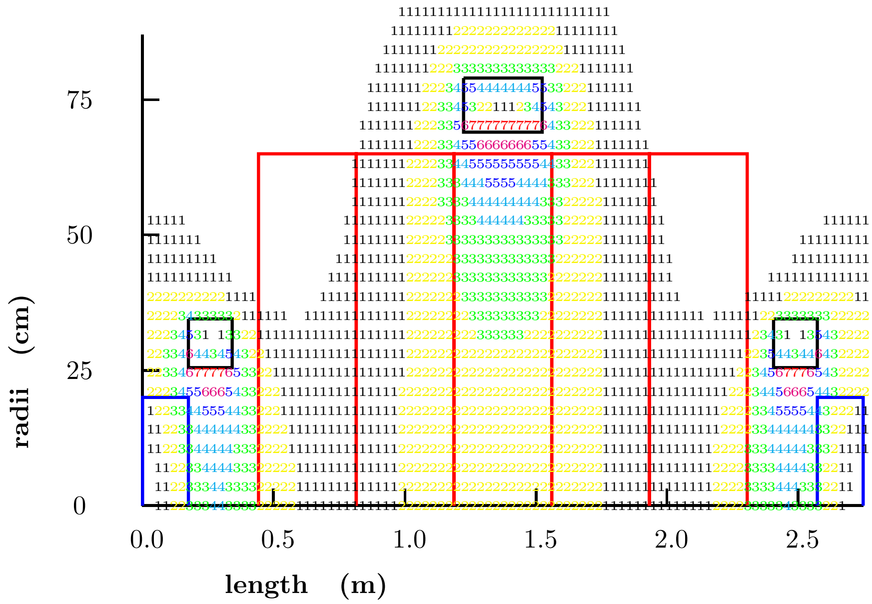
The fields at radii stepped by 2.1 cm are:

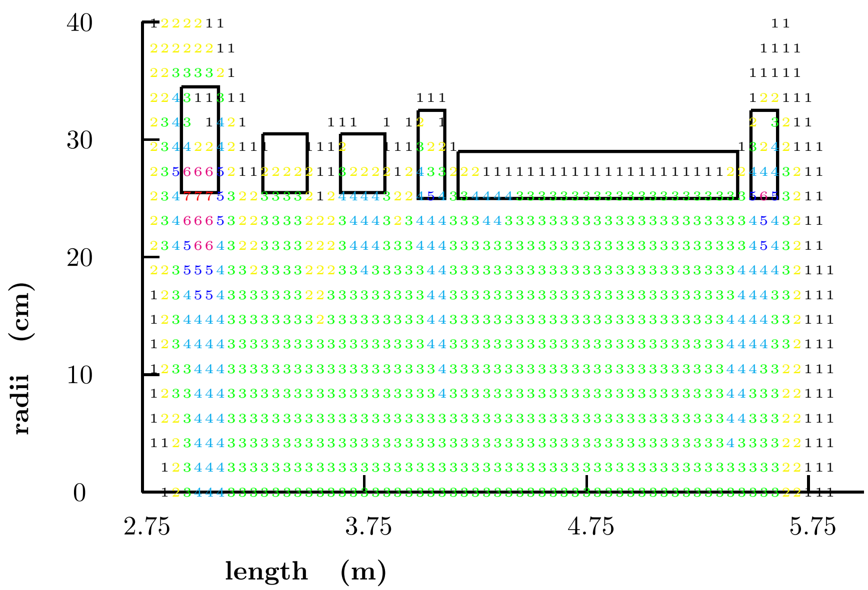


From this plot we can obtain approximate maximum fields seen by the conductors. These fields, together with the other coil specifications are given below:

	len1 m	gap m	dl m	rad m	dr m	I/A A/mm^2	n I MA	n I l MA m	Bmax T
focus	0.175	0.350	0.167	0.255	0.090	-141.32	2.12	4.00	7.95
coupling	1.225	0.883	0.300	0.690	0.100	-108.00	3.24	15.06	3.4
focus	2.408	0.883	0.167	0.255	0.090	-141.32	2.12	4.00	7.95
focus	2.925	0.350	0.167	0.255	0.090	141.32	2.12	4.00	7.8
match 1	3.292	0.200	0.200	0.255	0.050	74.34	0.74	1.31	3.75
match 2	3.642	0.150	0.200	0.255	0.050	103.61	1.04	1.82	4.8
end 1	3.992	0.150	0.120	0.250	0.075	97.87	0.88	1.59	5.5
solen	4.172	0.060	1.260	0.250	0.040	80.95	4.08	6.92	4.0
end 2	5.492	0.060	0.120	0.250	0.075	128.89	1.16	2.10	6.4

The integer parts (i.e. '7' means a B between 7 and 8 T) of these fields are ploted in two parts below. It is seen that in all cases, the highest fields occur on the inside surfaces of the coils.





5 Conclusion

We have shown a coil set that will allow central momentum matching into the 4T, or lower, detector for:

1. The standard 42 cm beta lattice (similar to that at the beginning of Study 2) at 200 MeV/c (being the reference momentum in the study 2 case).

2. the same lattice but operating at 240 MeV/c

3. A 25 cm beta lattice (similar to that in the third part of the study 2 cooling) at 200 MeV/c.

4. 3 other lattices with betas of 16, 10, and 5 cm, but with momenta at 175, 150 and 140 MeV/c respectively.

5. The fields seen by the conductors are given for the worst case.

6. Chromatic abberations in the match are estimated for all cases and appear reasonable if the momentum spreads are chosen to correspond with the acceptances in each case. If necesary, software correction of these abberations will be possible.