Revised Step IV MICE Optics in the Absence of M1 SSD

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1 Introduction

During magnet commissioning in September 2015, the leads on coil M1 of the downstream spectrometer solenoid failed. The coil will not be operational for MICE Step IV. Revised settings for the Step IV data taking are reviewed.

1.1 Aims of MICE Step IV

MICE Step IV aims to

- Measure material properties of lH_2 and LiH.
- Observe normalised transverse emittance reduction.

The MICE collaboration seeks to make measurements, over a range of momenta, a variety of different optical β functions and emittances, with and without field flips available in the magnets.

1.2 The MICE Lattice

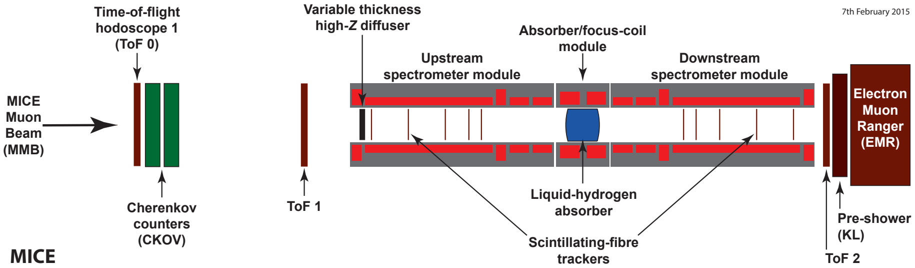


Fig. 1: Schematic of MICE at Step IV.

The MICE lattice was designed to provide a good performance over these various settings. A schematic of the MICE channel is shown in figure 1. The function of each lattice element is described below.

- The diffuser provides a variable thickness scatterer in the beam, enabling experimentalists to select different emittances.
- The outer 3 coils of the spectrometer modules are, from outermost to innermost, End2 coil, Center coil and End1 coil (ECE). The Center coil provides a constant solenoidal field to enable helix fitting in the trackers. End2 and End1 are trim coils used to improve field quality in the tracker region.
- The inner 2 coils of the spectrometer modules are Match2 and Match1. The Match coils provide matching from the constant solenoidal field to the absorber region. Two coils enable independent selection of β and $d\beta/dz$.
- The Focus coil provides a final focus on the absorber.

The coil geometries used in this note are summarised in MICE Note 474 version 1.

1.3 Measurements in the MICE Lattice

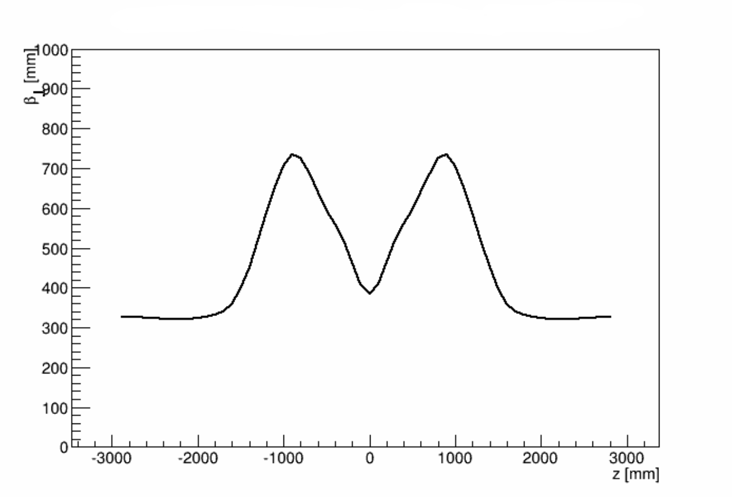


Fig. 2: Baseline β function as a function of z, with M1 and M2 available at upstream and downstream spectrometers.

Measurement of emittance reduction requires that the beam should transport in a satisfactory manner from the upstream Tracker Reference Plane (TRP), where the beam is measured, to the absorber and to the corresponding downstream TRP. The β function should be sufficiently small and acceptance sufficiently large that a beam with emittance greater than the equilibrium emittance is transported. Emittance growth from non-linearities should not be too large.

Measurement of material physics processes requires that a sufficient number of beam particles can be transported to the absorber and downstream TRP and is insensitive to the beam optics.

An indirect measurement of emittance reduction can be made by projecting beam particles to the absorber and calculating beam emittance before and after the absorber.

A baseline optical β function and corresponding B_z is shown in figure 2. The β function is symmetric about the absorber, not too large in the Match coil region and flat in the spectrometer solenoid region. While these properties are not essential, they result in a good acceptance and suppress high order non-linearities that are present for such a high emittance beam. These non-linearities can result in emittance growth that is significant with respect to the emittance reduction produced at the absorber.

1.4 Baseline-Like Optics Settings Without M1

In the absence of M1 the range of available optics solutions, given the boundary conditions outlined above, is greatly reduced.

In figure 3 a selection of available optics functions are shown. The equilibrium RMS emittance, below which the beam heats rather than cools, is shown as a function of β in figure 4. For acceptances typical of the MICE lattice, β functions below around 1 m are required. The β function in all cases is too high to transport a beam with the MICE equilibrium emittance through the cooling channel, so in these circumstances MICE would heat the beam rather than cool it.

It is clear that in order to make a lattice that cools, the constraints must be relaxed.

2 Material Physics Measurements

It is noted that measurement of material physics processes in the MICE absorbers and indirect measurement of emittance reduction is still possible, even without further optimisation.

For example, during data taking on Wednesday 7th October 2015, SSU End1 coil, Center coil and End2 coil (ECE) were powered. SSD was not powered. In this configuration, 13000 particles per hour traversed the experiment to TOF2 running in a 200 MeV/c muon mode. This corresponds to more than 20 % of the hits in TOF1. It is expected that the transport efficiency will be improved if SSD ECE were powered, with further improvements achieved by powering the match coils and focus coils and reoptimising the beamline for the available coils.

This should be compared with 2.3e6 and 1.1e6 events that MuScat measured on 109 mm and 159 mm liquid Hydrogen targets respectvely [?]. To achieve comparable statistics to MuScat, assuming no further rate optimisation, would require 1-2 weeks of data taking on each absorber.

MICE will also make a measurement of multiple scattering with no fields in the trackers. In this configuration, resolutions in transverse angle are expected

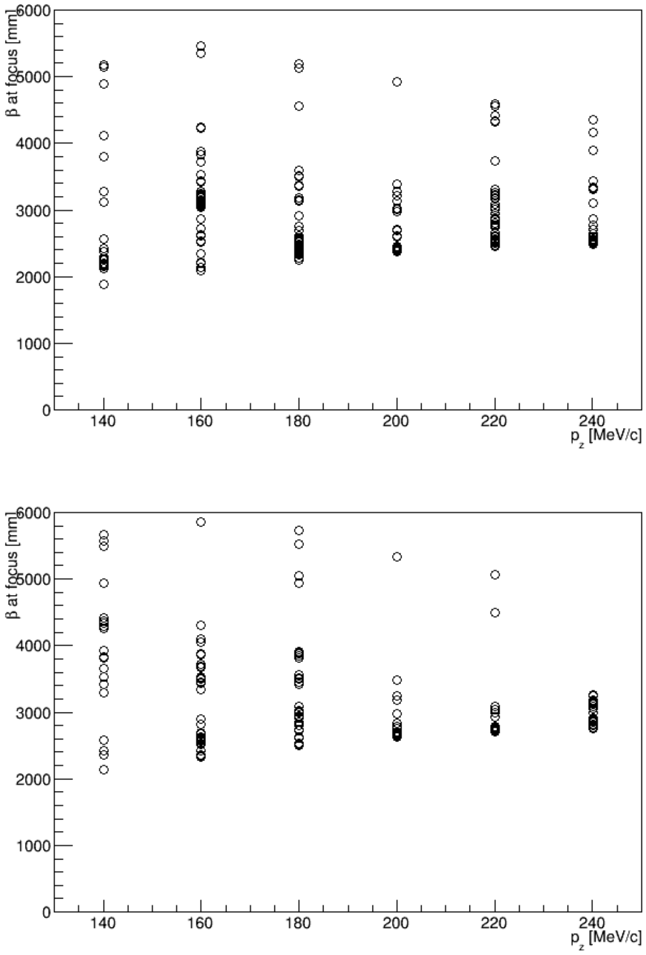


Fig. 3: Available β at the focus coil, given "baseline" constraints on MICE (top) in flip mode, with field antisymmetric about the lattice centre, and (bottom) in solenoid mode, with field symmetric about the lattice centre.

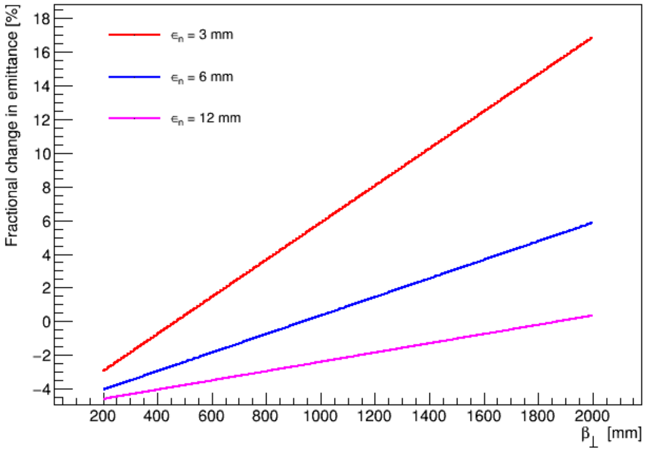


Fig. 4: Fractional emittance reduction for various input emittances and optical β functions.

to be better, but resolutions in energy (required for particle selection) are expected to be worse. Clearly such a configuration is unaffected by the presence of fields.

3 Available Optics

In order to achieve an optics that can reduce emittance in MICE, one of the boundary conditions must be relaxed. Various different constraints are relaxed and the resultant optics solutions are discussed.

3.1 Asymmetric Optics with β Constant in Tracker

In this section the requirement that the optics is symmetric about the absorber is relaxed. The constraint that β is constant in the spectrometer is maintained. In order to achieve sufficient focussing at 200 (and 240) MeV/c, the magnetic field in the solenoids must be reduced. Reasonable solutions are available at 140 MeV/c without reducing the magnetic field in the solenoids.

In figures 5 and **??** the optical β function at the absorber is shown as a function of magnetic field in the spectrometer solenoids. Here the upstream and downstream spectrometer solenoid field are constrained to be identical and β in the spectrometers is held constant.

It is noted that an optics is available for 140 MeV/c at 4 T. In order to recover a good optics at 200 MeV/c, the field in the spectrometer solenoid must be degraded to around 1.2 T. There are two consequences to this; the

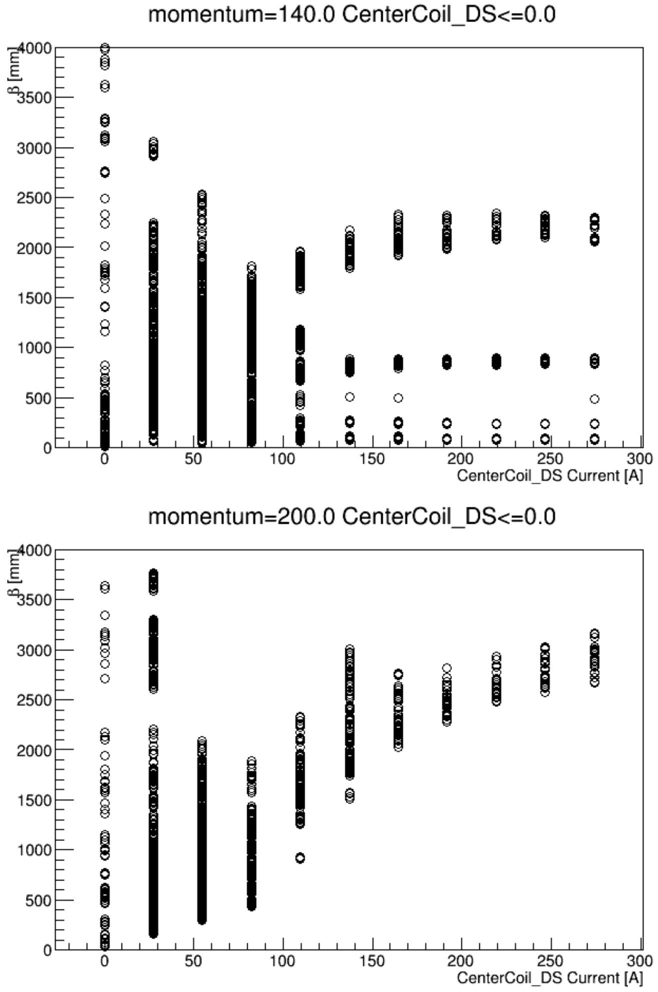


Fig. 5: Flip mode optical functions at the absorber, as a function of CenterCoil current for (top) 140 MeV/c (bottom) 200 MeV/c. At 4 T the downstream Center Coil, CenterCoil_DS, operates at 274 A.

performance of the tracker is reduced; and the acceptance in the tracker region is reduced.

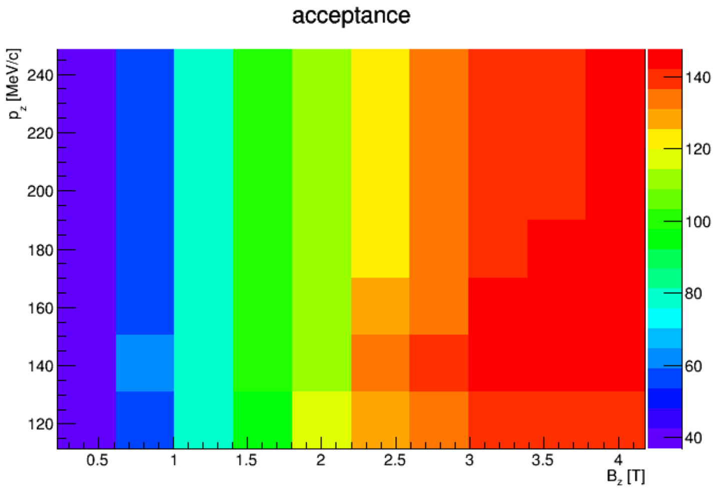


Fig. 6: Acceptance [mm] in a tracker as a function of B_z and p_z. The 150 mm tracker fiducial volume and constant optical β function is assumed.

The acceptance in a 1.1 m long constant field region is shown in figure 6 as a function of momentum and magnetic field. Here the 150 mm fiducial radius of the tracker has been assumed. Note that in the lattices considered here, the tracker is the limiting aperture; previously the region around the match coil was limiting.

The linear optics β function for a 200 MeV/c optic is shown in figure **??**. The focus is closer to the upstream end of the cooling channel, as greater focussing is available upstream of the absorber.

3.2 Symmetric Lattice with Beta-Beating in Spectrometer

Instead of relaxing the symmetry of the optics in the cooling channel, one may relax the requirement that β is constant in the spectrometer region. The field in the spectrometer is maintained at 4 T and the optics are required to be symmetric about the absorber, with the field either symmetric or antisymmetric.

In figure 7 the minimum achievable β with non-constant β in the spectrometer region is shown as a function of β and α at the tracker reference plane.

One consequence of a non-constant β in the spectrometer is that the acceptance in the tracker region will be reduced. The acceptance in a 1.1 m long constant field region is shown in figure 8 as a function of the initial β and α. The time-reversal symmetry ensures that the acceptance will be the same upstream and downstream, barring a sign flip in alpha.

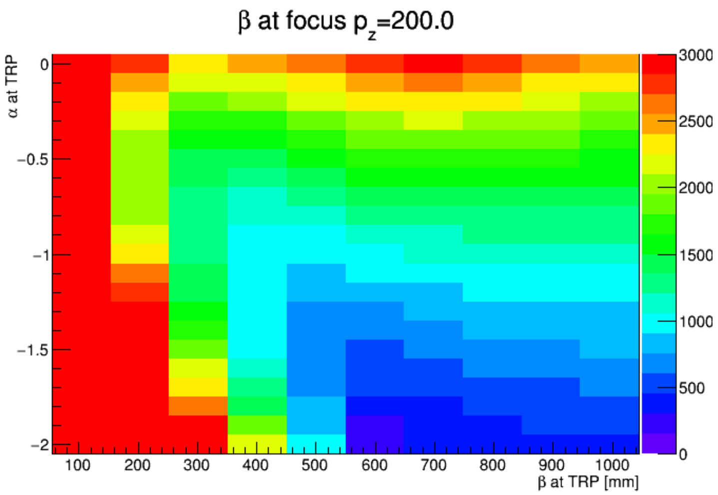


Fig. 7: Minimum achievable β with non-constant β in the spectrometer region as a function of β and α at the tracker reference plane. Magnets were in an antisymmetric configuration and beam was at 200 MeV/c.

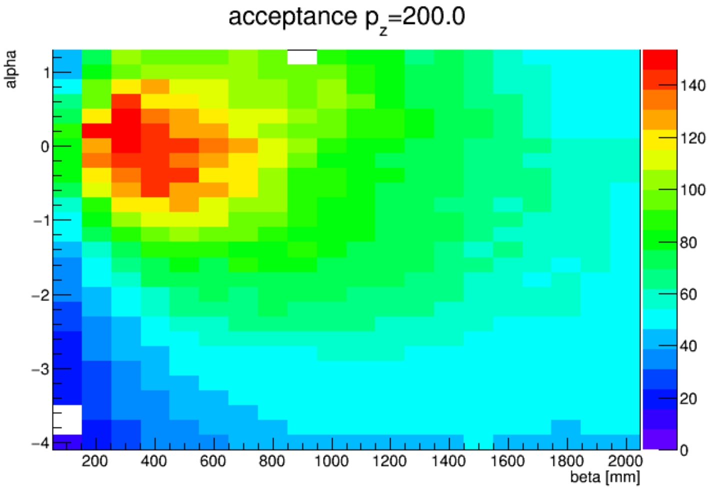


Fig. 8: Acceptance in a tracker as a function of β and α at the tracker reference plane. Acceptance was found by tracking a beam through a constant B_z region and removing particles that had radius more than 150 mm, the fiducial volume of the tracker. Particles were binned in acceptance and the bin where the number of surviving particles in an acceptance bin was less than 50 % was considered the acceptance. All particles in the beam had p_{tot} of 200 MeV/c.

3.3 Asymmetric Lattice with Beta-Beating in Spectrometer

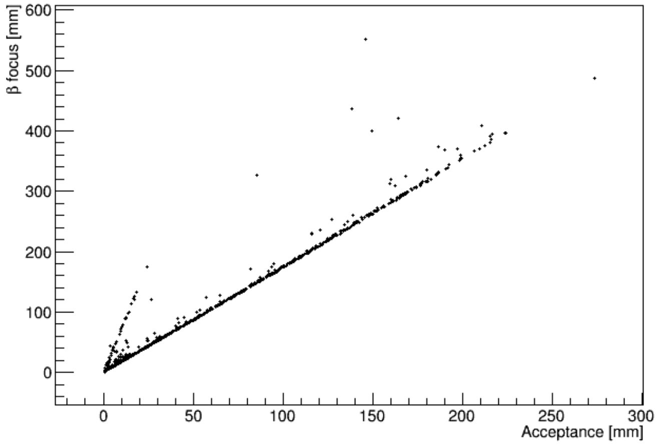


Fig. 9: Minimum achievable β at the absorber focus as a function of β and α at the tracker reference plane. Magnets were in an antisymmetric configuration and beam was at 200 MeV/c.

It is also possible to abandon both the constraint of a symmetric optics and the boundary condition that β is constant in the solenoid.

In this general case, the lattice is optimised by minimising the ratio of equilibrium emittance to acceptance. In the paraxial, thin absorber approximation the acceptance is given by

$$A_{max} = \frac{r^2 p_z}{\beta_\perp m} \tag{1}$$

and the equilibrium emittance is given by

$$\epsilon_{eqm} = \frac{1}{2m} \frac{13.6^2}{L_R} \frac{\beta_\perp}{\beta_{rel} < dE/dz >}. \tag{2}$$

The ratio is minimal when the ratio $\beta_\perp(z)\beta_\perp(absorber)/r^2(z)$ is minimal for all z. A minimising routine was used to find optimum conditions for the lattice given these constraints. Initial conditions were chosen randomly and the optimising routine was allowed to converge. The population of minimal solutions is shown in figure 9 as a function of β at the absorber and minimum scraping aperture acceptance.

It is noted that optimal solutions have the Focus coil running at the maximum achievable current, M2 in SSD operating at the maximum achievable current and the limiting aperture is at the downstream end of the downstream tracker.

Lattice Index	p MeV/c	β_{abs} mm	β_{in} mm	α_{in}	E2 [A]	CC [A]	E1 [A]	M2 US [A]	M1 US [A]	FC [A]	M2 DS [A]
1	140	423	233	0	253.00	274.00	234.00	0.68	218.92	185.0	-276.39
2	200	447	1102	0	75.90	82.20	70.20	107.8	250.9	225.0	-231.6
3	200	574	600	-1.5	253.00	274.00	234.00	279.99	0.0	189.45	-279.99
4	200	687	600	-1.5	253.00	274.00	234.00	255.05	0.0	149.26	-255.05
5	200	411.	743.19	-0.748	253.00	274.00	234.00	0.0	277.53	224.83	-279.71

Tab. 1: Summary of lattices simulated below. In all cases the ECE downstream coils were simulated with the same current as the ECE upstream currents bar a factor -1. The downstream Focus coil was simulated with the same current as the upstream focus coil bar a factor -1. The downstream Match coil 1 was not powered.

4 Reconstruction in Reduced Field

5 Tracking Performance Comparison and Normalised Emittance Reduction

In this section the tracking performance of the lattices described above is compared.

Several optics solutions are studied, as summarised in Table 1. Beams were simulated travelling from the upstream tracker reference plane to the downstream tracker reference plane. The absorber was included for some simulations but the tracker Helium window and associated Helium was not included. This may introduce some additional heating that has not been properly accounted for in these simulations.

In figure 10 the optical β is calculated for a selection of beams propagating through each of the lattices. The effect of such aberrations is also clearly visible when the propagation of emittance is considered as shown in 11. Due to the extremely large beam emittances involved and relatively small cooling provided by a single absorber, optical emittance growth is significant.

The cooling performance as a function of input beam emittance and momentum spread is shown in figure 12. Lattice 3 performance is poor due to optical aberrations and it barely cools. Lattice 4 and 5 give at best 2 % cooling. Around half of the cooling effect is disguised by optical emittance growth.

6 Conclusions

A revised optics has been studied following failure of the Match1 coil in the downstream spectrometer solenoid. Several situations have been studied.

- β is constant in the solenoid field; the lattice optics are allowed to be asymmetric and the tracker region of the spectrometer is derated.

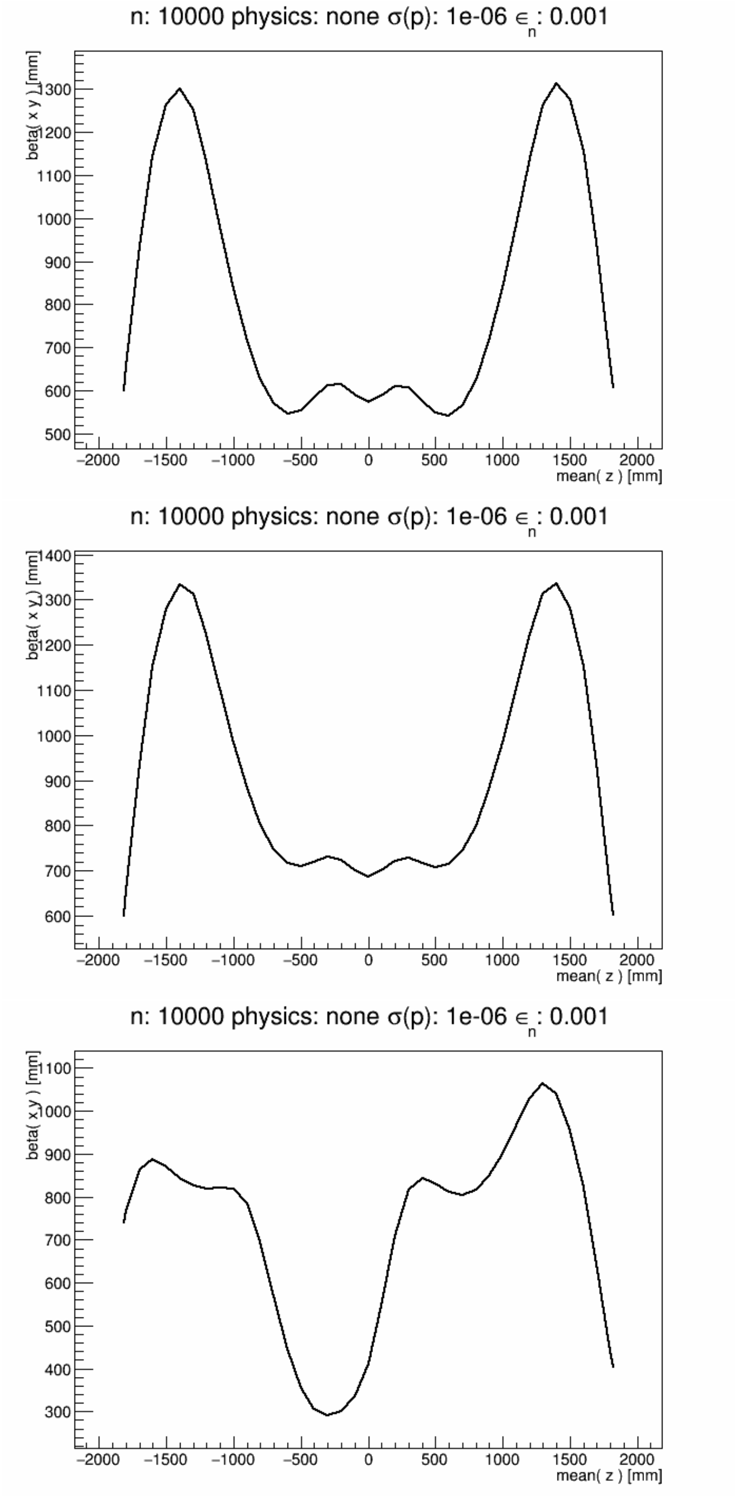
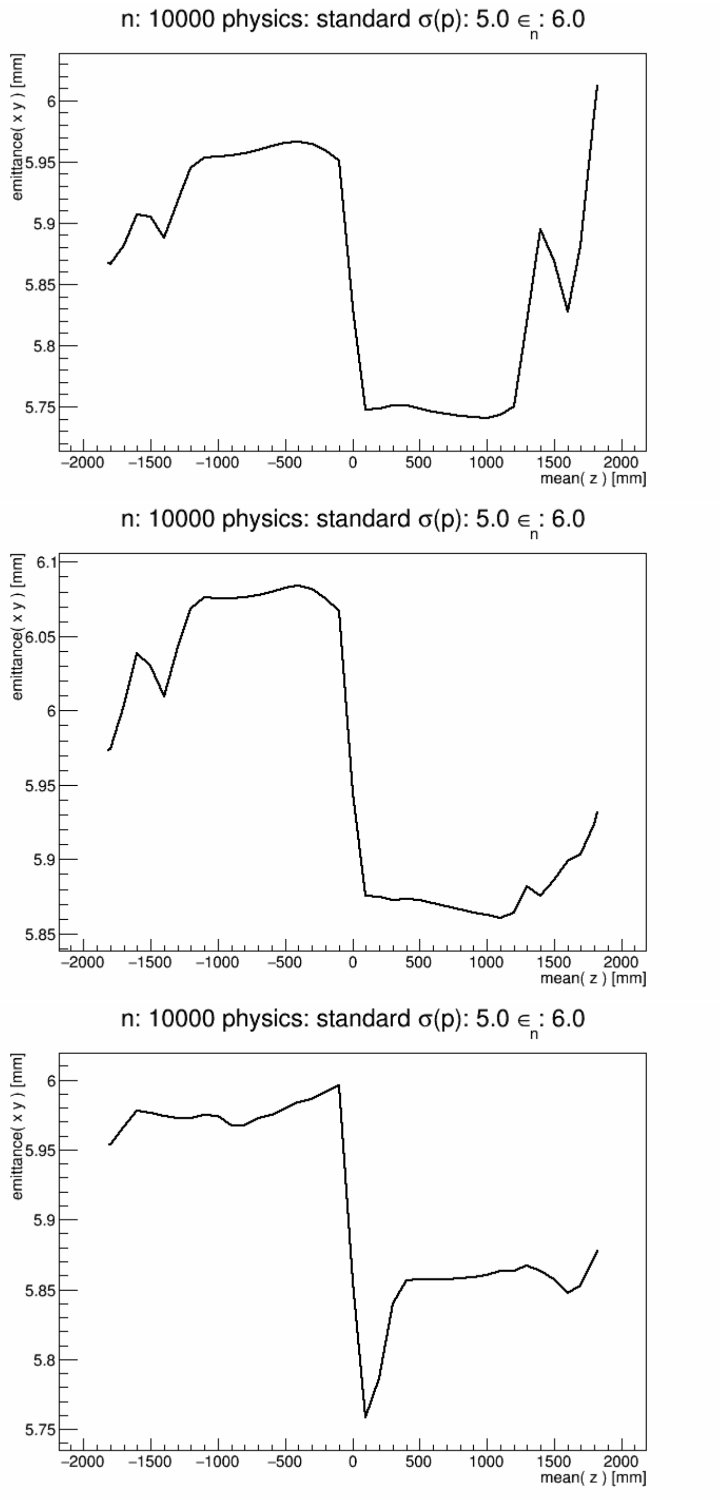


Fig. 10: β function for lattices 3 to 5.


n: 10000 physics: standard σ(p): 5.0 ϵ_n: 6.0

n: 10000 physics: standard σ(p): 5.0 ϵ_n: 6.0

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Fig. 11: Emittance change as a function of z for lattices 3 to 5. In all cases the beam had an initial momentum spread of 5 MeV/c RMS and emittance of 6 mm.

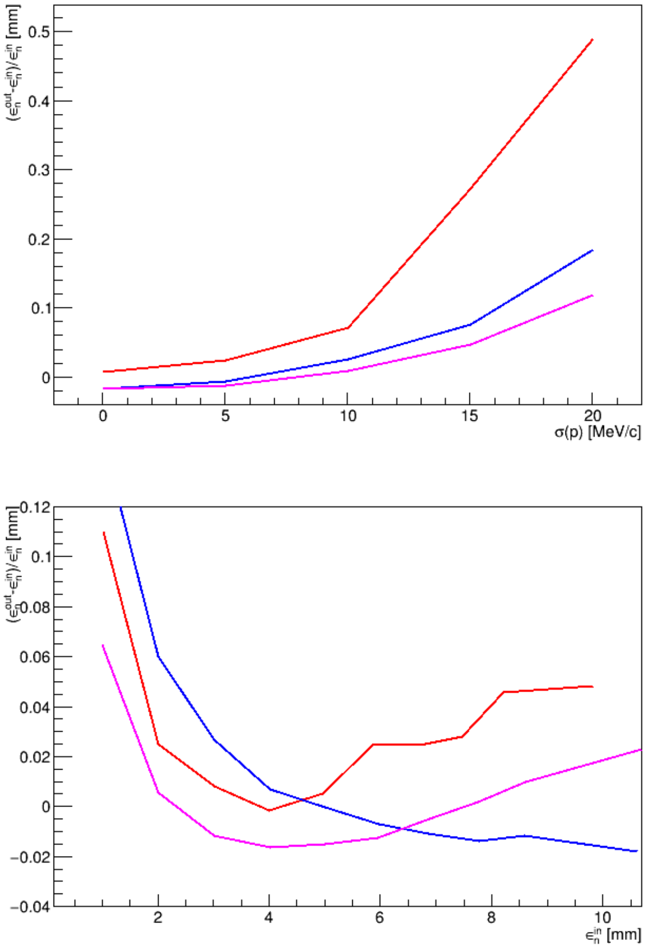

Fig. 12: Emittance change for lattices 3 to 5. Lattice 3 is shown in red, lattice 4 in blue and lattice 5 in pink.

- β beats in the solenoid field; the lattice optics are constrained to be symmetric, and the tracker field is maintained at 4 T.
- β beats in the solenoid field; the lattice optics are asymmetric, and the tracker field is maintained at 4 T.

In the first instance, cooling performance is maintained but the reconstruction is degraded. In the second and third instance, cooling performance is degraded due to non-linear effects, but reconstruction resolution is maintained.