MUON COOLING PERFORMANCE IN VARIOUS NEUTRINO FACTORY COOLING CELL CONFIGURATIONS USING G4MICE*

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Abstract

The Neutrino Factory is a planned particle accelerator complex that will produce an intense, focused neutrino beam, using neutrinos from muon decay. Such high neutrino intensities can only be achieved by reducing the muon beam emittance using an ionization cooling system. The G4MICE software is used to study the performance of various cooling cell configurations. A comparison is drawn between the cooling in the MICE-like, the baseline Neutrino Factory, Singlet and Doublet cooling channels. The beam dynamics in each of cooling channels are presented. The lattices are compared with respect to the equilibrium emittance, muon transmission and evolution of emittance along the channel. Conclusions for a possible optimisation of the future muon cooling channel for the Neutrino Factory are presented.

INTRODUCTION

The Neutrino Factory is a proposed accelerator system that will produce the most intense, narrow, high-energy neutrino beam ever achieved, from the decay of stored muons. Using this intense neutrino beam, precise measurements of the parameters that describe neutrino oscillations and leptonic CP-violation can be made [1]. However, muons in the Neutrino Factory are produced with a large initial emittance and large energy spread, therefore in order for the beam to be injected into the muon accelerator systems its emittance needs to be reduced. As the muon lifetime is only 2.2 μs, the only viable cooling technique is ionization cooling. The present work, which is conducted within the International Design Study for the Neutrino Factory (IDS-NF) [2], compares the performance of various cooling cell-configurations, using G4MICE [3]–a custom software package with extensive capabilities, designed especially for the needs of the Muon Ionization Cooling Experiment (MICE) [4]. The cooling cell-configurations that are compared are a MICE-like cell, the baseline Neutrino Factory cell (FS2A) [5], a Singlet and a Doublet cell.

METHODOLOGY

In this study, the G4MICE software was used for all simulations. G4MICE provides a set of applications for simulation and analysis of a variety of accelerator and detector configurations, as well as a set of field map, physics modelling and analysis libraries on which the user can build specific new applications.

The characteristics of each component of the lattices are summarized in Table 1. The first and second values of the current density in the MICE-cell column represent the current density of the focusing and coupling coils respectively.

Table 1: Summary of the Components Properties

Type of cell	MICE	FS2A	Singlet	Doublet
Cell Length [m]	5.50	0.75	3.90	3.85
RFs per cell	8	1	5	5
Absorbers per cell	2	2	1	1
Coils per cell	6	1	2	2
RFs				
P.E.F. [MV/m]	12.46	13.026	8.620	16.500
Phase [degrees]	40	40	45	45
Length[cm]	46	50	46	50
Radius [cm]	64.5	30.0	25.0	70.0
Absorbers				
Length [cm]	37.5	1.0	7.0	14.0
Radius [cm]	64.5	25.0	25.0	70.0
Coils				
Length [cm]	21	15	20	20
Radial Thickness [cm]	8.4	15.0	20.0	20.0
Inner Radius [cm]	26.3	35.0	30.0	30.0
Current Density [A/mm2]	113.9 96.2	106.7	47.5	47.5

In each configuration, the peak electric field (P.E.F.) of the RF cavities was chosen to keep the mean energy of the reference particle constant (i.e. the gained energy from the RFs to be approximately equal to the energy lost in

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the absorbers). This technique increased the possibility for all the particles to reach the end of the lattice.

The initial longitudinal and transverse emittance used for all the lattices was 0.067 ns and 10 mm respectively. The initial momentum of all the lattices was chosen to be P=232 MeV/c, except for the MICE-like cell which had P=200 MeV/c due to the presence of resonances at 150 and 250 MeV/c.

MICE-like Lattice

The MICE-like cell consists of two liquid Hydrogen (LH2) absorbers alternating with two sets of four 201.25 MHz RF cavities. In between two consecutive absorbers there are three coils: a focusing, a coupling and then a focusing coil again.

FS2A Lattice

The cell begins with a coil, followed by a 200 MHz RF cavity. The polarity of the coil alternates with each repeat of the cell. The cooling in each cell is obtained by two Lithium Hydride (LiH) absorbers. The LiH absorbers are coated with Beryllium which electromagnetically seals the cavity, acting in this way as ionization cooling element.

Singlet Lattice

As with the Doublet lattice, the Siglet lattice was designed in order to obtain a low magnetic field in the RF cavities, and therefore to keep the transverse betatron function small at the absorbers position. The Singlet cell consists of one LiH absorber, five 200 MHz RF cavities and two coils of opposite polarity. The first RF cavity is immediately after the absorber. The coils follow, with three more RF cavities in between them. The fifth RF cavity comes after the second coil.

Doublet Lattice

Although the Doublet lattice has the same components as the singlet lattice, its length is shorter by 5 cm. As a result of this, the distance between the opposite-polarity coils is 1.875 m, i.e. different than the distance between the coils of same polarity (3.85 m).

BEAM OPTICS

The transverse beta with respect to the momentum of the beam is presented in Figure 1. As can be seen, the resonance of the MICE-like cell is at approximately 250 MeV/c, explaining the choice of P=200 MeV/c for the mean input beam momentum. The transverse beta function presented in this section (see figure 2) was calculated analytically. Note that the lowest beta at the absorbers position is obtained by the MICE-like cell, which can be explained by the extra coil. Doublet offers a low beta at the position of the absorbers as well; however, the Doublet and the MICE-like cells do not have a good momentum acceptance.

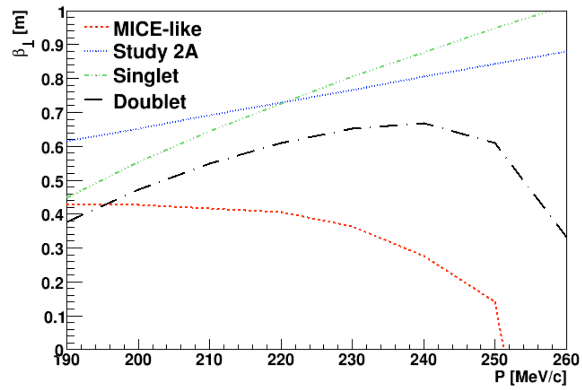

Figure 1: Plot of the transverse beta with respect to the mean total momentum of the beam.

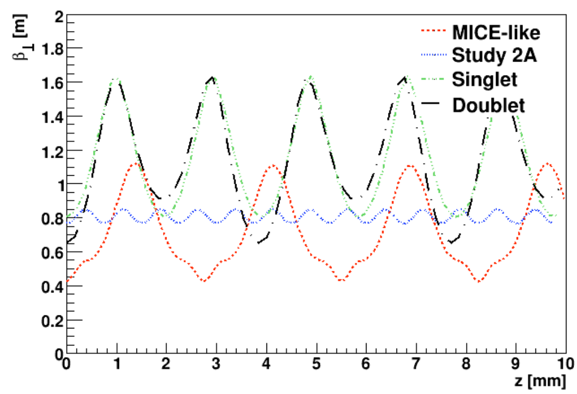

Figure 2: Plot of the analytical transverse beta along the z-axis.

TRACKING

The plots presented in this section were obtained using the particles that make it through the total length of lattices, with momentum 130<P<330 MeV/c, and within a radius of R<30 cm.

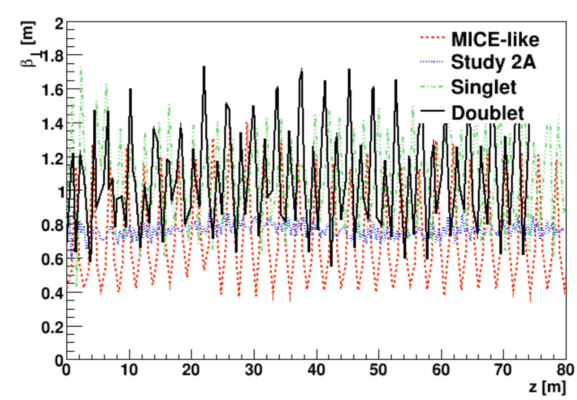

Figure 3: The transverse betatron function along the z-axis.

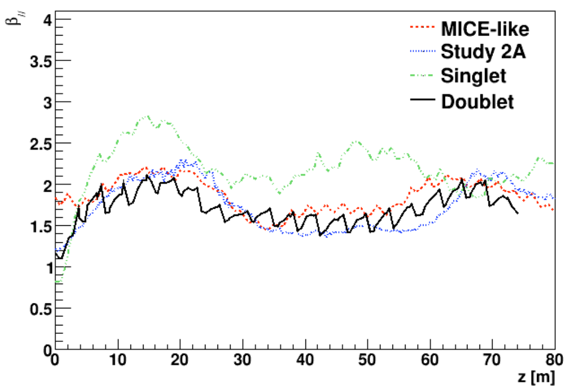

Figure 4: The longitudinal beta along the z-axis.

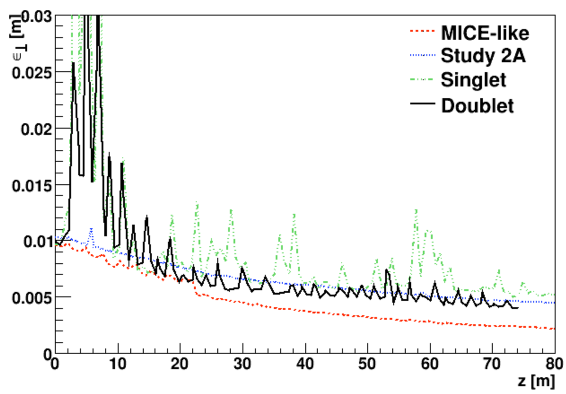

Figure 5: The transverse emittance of the beam along the cooling lattices.

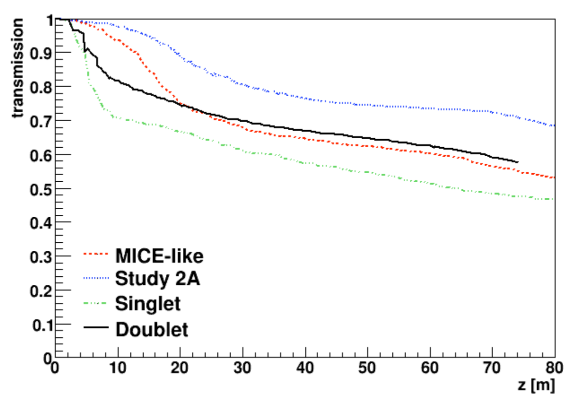

Figure 6: The transmission of the particles along the cooling channels. Note how dramatically the transmission of the first 10 m of both, the Singlet and Doublet cells, decreases.

As with the optics section, the lowest transverse betatron function is of the MICE-like lattice, resulting from the extra (coupling) coil each cell has. However, as can be seen in figure 6, this cell was designed as one part of a tapering scheme so transmission is somewhat poorer than might be desired. FS2A on the other hand, is obviously the lattice which offers the best transmission for approximately the same decrease as the other lattices of transverse emittance. The Singlet cell does not provide a good number of particles to the end of the lattice (less than 50%) and, together with the Doublet, they have a dramatic increase of their transverse emittance in the beginning of the lattice, resulting to the drastic decrease of transmission within approximately the same length (0-8 m, see fig. 5 and fig.6).

CONCLUSIONS

In this study, the MICE-like, FS2A, Singlet and Doublet cells were compared with respect to the cooling dynamics each provides, in order to find the optimum cooling lattice for the Neutrino Factory.

As the Siglet and Doublet lattices were designed in order to obtain a low magnetic field in the RF cavities, and therefore to keep the transverse betatron function small at the position of the absorbers, the distance between the coils was larger than in the other lattices. This increase of distance though caused an increase of the betatron function at the position of the coils, leading to a higher beam size modulation with respect to FS2A lattice.

The lowest beta is obtained by the MICE-like cell; however, as with the case of the Doublet cell, the momentum acceptance for these two lattices is low. Although the beta function of the FS2A lattice is higher than the other lattices, transmission is better and emittance reduction is acceptable. It is therefore clearly obvious that out of these four lattices, the most suitable lattice for the needs of the Neutrino Factory is the FS2A lattice.

Future work that will focus on new configurations still needs to be done. It would be very useful to study lattices in which the focusing at the position of the absorbers is very good, while keeping at the same time the magnetic field as low as possible within the RF cavities. The introduction of longitudinal cooling may be beneficial to reduce the muon losses, stabilise the dynamics in the longitudinal plane and facilitate the matching with the downstream accelerators. This requires introduction of the dispersion function into the lattice, which can be achieved by tilting the solenoidal coils or introducing additional windings to generate the dipole filed component.

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