PERFORMANCE OF THE BUCKED COILS MUON-COOLING LATTICE FOR THE NEUTRINO FACTORY*

A. Alekou#, Imperial College London, London, U.K
J. Pasternak, Imperial College London, London/STFC-RAL ISIS, Chilton, Didcot, UK
C.Rogers, RAL ASTeC, Chilton, Didcot, UK

Abstract

Ionization cooling is essential to the Neutrino Factory in order to decrease the large emittance of the tertiary muon beam. Strong focusing and large RF gradient in the cooling channel are required for efficient cooling. However, the presence of strong magnetic field at the position of the RF cavities limits their performance by lowering the breakdown limit. In order to mitigate this problem a new lattice configuration, the Bucked Coils, is proposed: Two solenoidal coils of different radius and opposite polarities are placed along the channel at the same z-positions. The Bucked Coils lower the magnetic field in the RF cavities while also providing strong focusing. This paper presents the results of the beam dynamics simulations in the new lattice, using G4MICE code. The comparison on the achieved cooling performance and transmission between the currently proposed Neutrino Factory baseline lattice (FSIIA) and the new configuration, is provided in detail.

INTRODUCTION

The Neutrino Factory is a proposed accelerator complex that will produce the most intense and high-energy neutrino beam ever achieved, by using muons decaying in storage rings with long straight sections pointing towards far detectors. The performance of this facility is a key to the discovery of leptonic CP violation, the precision studies of the mass hierarchy and the mixing parameters including the presently unknown θ_{13} [1].

The muon beam produced at the Neutrino Factory has a very large initial emittance, therefore, in order to fall efficiently within the acceptance of downstream accelerator components it requires cooling (emittance reduction). Due to the short muon lifetime (~2.2 μs), the only viable technique for such emittance reduction is *ionization cooling*. At ionization cooling, muon momentum decreases in every direction by ionizing the absorber's material and the longitudinal momentum is restored when the beam passes through RF cavities.

Although the baseline solution for the Neutrino Factory cooling channel, FSIIA [1], has been established, recent studies indicate that the maximum gradient achievable in the RF cavities may be limited when an external magnetic field is applied [2]. Therefore, although FSIIA obtains acceptable transmission and good transverse emittance reduction in simulations, the magnetic field within the RF cavities must be significantly reduced or its effect on the achievable RF gradient mitigated in order to ensure the cooling performance.

Bucked Coils (BC) is a configuration that includes a pair of opposite polarity and different radius coils placed at the same position along the beam axis. This paper presents the results and detailed comparison of the muon beam dynamics between FSIIA and various configurations of BC. Future plans on possible further modifications of the BC configuration are also discussed.

LATTICE GEOMETRY

Recent studies indicate that the magnetic field within the RF cavities can limit their performance by lowering the breakdown limit, which results in smaller achievable mean gradient. Using the Optics and Simulations applications of the G4MICE software [3], a detailed comparison was made of FSIIA and the various configurations of BC called BC-I, BC-II and BC-III. The aim of this comparison was to find a lattice that provides a substantially lower magnetic field within the RFs while also keeping the transmission within 30 mm transverse acceptance high. The characteristics of each lattice are given below in Tables 1 and 2. The Optics application is used for the analytical evolution of beams whereas Simulation is used for Monte-Carlo tracking of particles.

FSIIA

The FSIIA half-cell begins with a coil followed by an RF cavity which has a LiH absorber on each side. A repetition of this 0.75 m cell, with opposite coil polarity to the first coil, forms a full 1.5 m FSIIA cell.

Bucked Coils (BC)

BC is a configuration which includes two coils with different radius and opposite polarities, placed at the same position along the beam axis. BC cell can have different current densities in the inner and outer coils. Due to the different magnetic field produced by the coils, the achieved magnetic field within the RF cavities is significantly lower than that of FSIIA (see Fig. 2 in the Simulation Results section).

Similarly to the FSIIA lattice, BC-I has a pair of coils followed by an RF cavity which has a LiH absorber on each side. This 1.05 m half-cell is repeated, with opposite polarity to the first pair of coils, to form a 2.10 m full-cell of BC-I. Two versions of the BC lattice with 0.9 m half-cell length were also investigated (BC-II and BC-III). Fig. 1 illustrates the BC configuration and table 1 summarizes the main parameters of FSIIA and BC-I. The differences of BC-I, BC-II and BC-III are summarized in Table 2.

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#androula.alekou08@ic.ac.uk

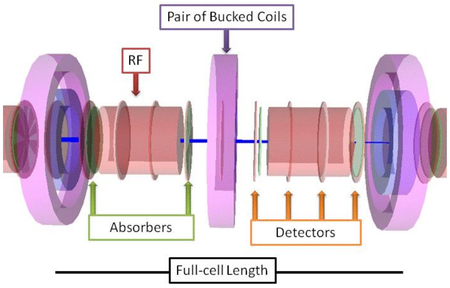

Figure 1: Bucked Coil (BC) lattice layout.

Table 1: Lattice Characteristics.

Lattice	FSIIA	BC-I
Full-cell Length (m)	1.50	2.10
Number of RF Cavities	2	2
Peak Electric Field (MV/m)	15	16
Phase (degrees)	40	30
Number Of Absorbers	4	4
Material	LiH	LiH
Number Of Coils	2	4
Inner Coil; Inner Radius (m)	0.35	0.30
Inner Coil; Outer Radius (m)	0.50	0.45
Outer Coil; Inner Radius (m)	N/A	0.60
Outer Coil; Outer Radius (m)	N/A	0.75
Inner Coil; Current Density (A/mm^2)	106.67	90.24
Outer Coil; Current Density (A/mm^2)	N/A	120.00

Table 2: Characteristics of BC-I, BC-II and BC-III.

Lattice	BC-I	BC-II	BC-III
Full-cell Length (m)	2.10	1.80	1.80
Inner Coil Current Density (A/mm^2)	90.24	128.10	99.26
Outer Coil Current Density (A/mm^2)	120.00	112.80	132.00

A beam of 1000 muons was generated in the G4MICE code with initial normalised rms emittances of 10 mm and 0.07 ns, in the transverse and longitudinal phase space respectively. The beam had a Gaussian distribution in momentum and was centred at 232 MeV/c. In order to improve the final transmission, the peak electric field in the RF cavities was kept constant but the absorber's length for each lattice was chosen such as to keep the energy of the reference particle approximately constant throughout the lattice. The G4MICE Optics application was used to match the initial transverse beta and alpha beam twiss parameters for all lattices.

SIMULATION RESULTS

Total Magnetic Field Comparison

Fig. 2 presents the total magnetic field as a function of radius at the end of the RF cavities for the four lattices. It should be stressed that this position represents the approximate position of the cavity walls, which are the most sensitive place for the occurrence of the RF breakdown induced by the presence of the magnetic field. As shown in this figure, at a 40 cm radius in the FSIIA lattice the magnetic field exceeds 4 T, whereas for all BC configurations the magnetic field is less than 2.2 T. The lowest magnetic field at the end of the RF cavities is achieved by BC-I, with a maximum of 1.1 T, i.e. almost a factor of four smaller than the FSIIA maximum. BC-II and BC-III obtain magnetic field of around 2 T, a factor of two smaller than FSIIA. All the plots follow the same colour code: black represents the results of FSIIA whereas red, green and blue represent BC-I, BC-II and BC-III respectively.

It is apparent that at the end of the RF cavities, within a 0-60 cm radius, the three new configurations obtain lower magnetic field compared to FSIIA, where the magnetic field is very large, something that raises a question of its feasibility with respect to high gradient operation. For all three lattices the external RF cavity radius corresponds to 60 cm and the radius of the Be beam window, which seals electromagnetically the RF cavities, to about 30 cm.

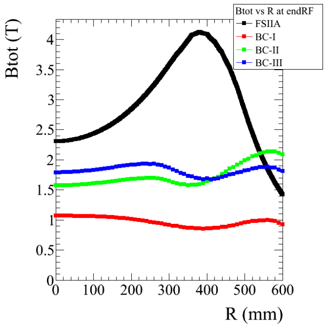

Figure 2: Total magnetic field with respect to radius at the end of the RF cavities for the four lattices.

Beam Dynamics

The evolutions of the betatron function and the transverse emittance as a function of the longitudinal position, z, have been calculated using the G4MICE code.

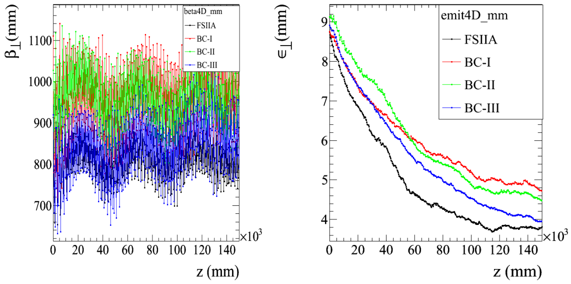

Figure 3: (Left) Betatron function and (right) transverse emittance reduction along z.

As can be seen in Fig. 3 (left), FSIIA and BC-III have the lower beta out of the four lattices, and therefore better cooling is obtained since their equilibrium emittances are lower (see Fig. 3, right). The equilibrium emittances obtained by the BC-I and BC-II configurations are very similar. In the above calculations, the results of which are shown in Fig. 3 (left and right), there were no radial or momentum cuts used. The only particles that were taken into account for these plots were those that were propagated to the end of the lattice.

Transmission

A very important parameter that needs to be studied is transmission. Both radial and momentum cuts were used for the transmission calculations, the results of which are shown in Fig. 4 (left). Particles recorded at a virtual detector having radius larger than 30 cm were not taken into account further downstream. Particles recorded at a specific detector with momentum outside the momentum cuts were not taken into account for that position, but were still taken into account further downstream. The momentum cuts used were 232±100 MeV/c. Transmission within the transverse acceptance of 30 mm, which is required by the Neutrino Factory design [1], was also calculated and is shown in Fig. 4 (right). In this case no radial or momentum cuts were used.

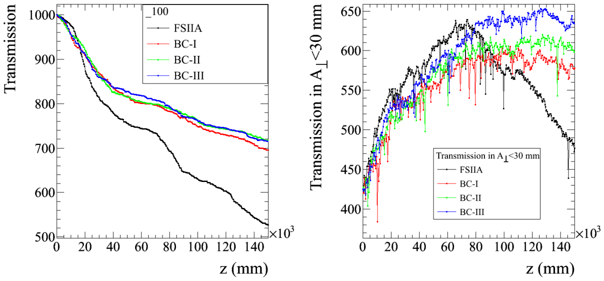

Figure 4: (Left) Transmission of the muon beam through the lattices within a 232±100 MeV/c momentum cut, and a radial cut of 30 cm. (Right) Transmission within the transverse acceptance of 30 mm along z.

As can be seen in Fig. 4 (left), the overall transmission is better for BC-II and BC-III, where 72% of the particles reach the end of the lattice within the applied cuts. BC-I has a very similar transmission (only 2% lower). On the other hand, only 53% of the particles reach the end of the FSIIA lattice.

Fig. 4 (right), where the transmission within 30 mm transverse acceptance for the four lattices is compared, shows the best transmission is obtained by BC-III which at 120 m reaches 65%. For FSIIA the maximum is 63% at 70 m; BC-II and BC-III have only 3% lower transmission than FSIIA at this position. A very important result is that BC-I, the lattice which achieves the lowest magnetic field at the position of the RF cavities (as shown in Fig. 2), also transmits a very good percentage of particles: BC-I has only 4% less particles than FSIIA at 70 m.

CONCLUSION

Recent studies have indicated that the RF cavity performance depends strongly on the external magnetic field. Although the baseline cooling lattice of the Neutrino Factory, FSIIA, has been established, the achieved magnetic field of this lattice at the position of the RF cavities is large. Lattices based on BC were designed using two coils of different radius and opposite polarity placed at the same position along the beam axis of the lattice. This new coil geometry allows a significant reduction of the magnetic field at the position of the RF cavities (see Fig. 2). Furthermore, although the transverse emittance reduction is better in FSIIA, BC-I, which obtains the lowest magnetic field out of these four configurations, has only 4% lower transmission than FSIIA at the z position which corresponds to the maximum transmission of FSIIA, i.e. at 70 m. BC-III obtains the highest transmission of these four lattices at 120 m; BC-II and BC-III have only 3% lower transmission than FSIIA at 70 m.

BC configurations, BC-I, BC-II and BC-III, not only provide a lower magnetic field at the position of the RF cavities but also obtain a very similar or better transmission within 30 mm transverse acceptance than FSIIA. The magnetic field achieved in BC-I is approximately a factor of four smaller than that present in FSIIA and the obtained transmission within 30 mm transverse acceptance in BC-I is only 4% lower than that of FSIIA.

FUTURE PLANS

BC results are promising and therefore future work should focus on further optimisations that can be applied to these lattices. A study of modifications of BC could offer a lower magnetic field at the position of the RF cavities together with an acceptable transverse emittance reduction and an improved transmission within 30 mm of transverse acceptance.

REFERENCES

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