BUCKED COILS LATTICE FOR THE NEUTRINO FACTORY*

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Abstract

In the Neutrino Factory muon front end, ionization cooling is used to reduce the very large initial transverse muon beam emittance. The current baseline cooling channel, FSIIA, performs well in simulations with respect to the transmission and cooling. However, recent studies indicate the RF voltage may be limited when an external magnetic field is applied and therefore, as the FSIIA lattice has a large magnetic field at the position of the RF cavities, the feasibility of FSIIA may be questioned. The Bucked Coils lattice, a new cooling lattice that uses different radius and opposite polarity coils placed at the same position along the beam-axis, aims to achieve a low magnetic field at the position of the RF cavities, while obtaining comparable transmission to FSIIA. The detailed comparison between FSIIA and different versions of the Bucked Coils configuration, with respect to the magnetic field, beam dynamics and transmission, are presented in this paper.

INTRODUCTION

Neutrino Factory is a future accelerator complex that will use the decay of stored muons to produce the most intense and high-energy neutrino beam that has ever been achieved [1]. This facility is key to discovering leptonic CP-violation, the mass hierarchy and determining the PMNS mixing parameters. However, as the muon beam is produced by pion decays and has a very large initial emittance (~10^{-2} m) in order to further accelerate the muons in downstream accelerator systems, the emittance needs to be reduced, or cooled. Traditional beam cooling techniques cannot be applied to muons as their lifetime is only 2.2 microseconds. The only technique that can be used for cooling muon beams is *ionisation cooling*: the muons pass through absorbers where their momentum decreases in every direction, and then through RF cavities, where the lost energy is restored in the longitudinal direction only.

The reference cooling channel of the Neutrino Factory, FSIIA [1], has shown good transmission and transverse emittance cooling; however this lattice has a total magnetic field larger than 4 T at the end of the RF cavities. Since recent studies indicate RF performance may be limited when the cavity is placed in high magnetic field [2], the feasibility of this lattice has come under question.

This paper presents a new lattice, Bucked Coils [3], designed to lower the magnetic field at the location of the RF cavities, while also obtaining comparable transmission to FSIIA. Three versions of the Bucked Coils lattice, BC-I, -II and -III, are compared to FSIIA with respect to the magnetic field, transmission and cooling dynamics.

METHODOLOGY

The lattices presented in this paper were built and simulated using the G4MICE software and more specifically the Optics and Simulation applications [4]. The geometry of each lattice follows, together with their components' characteristics.

FSIIA

The reference cooling channel consists of a coil, the polarity of which alternates with every repeat of the cell, followed by one RF cavity that has a LiH absorber on each side. Table 1 presents the main parameters of FSIIA and Fig.1 (left) shows the FSIIA layout.

Table 1: FSIIA and BC-I Main Parameters

Lattice	**FSIIA**	**BC-I**
Full-cell length (m)	1.5	2.1
Number of RF cavities	2	2
Peak Electric Field (MV/m)	15	16
Phase (degrees)	40	30
Number of absorbers	4	4
Number of Coils	2	4
Inner Coil; Inner Radius (m)	0.3	0.3
Inner Coil; Outer Radius (m)	0.5	0.45
Outer Coil; Inner Radius (m)	N/A	0.6
Outer Coil; Outer Radius (m)	N/A	0.75
Inner Coil; Current Density (A/mm²)	106.67	128.1
Outer Coil; Current Density (A/mm²)	N/A	112.8

Bucked Coils

A pair of opposite polarity and different radius coils is placed at the same position along the beam axis, to form a pair of "Bucked Coils". The polarity of each pair alternates with every repeat. As shown in Fig. 1 (right), each pair of coils is followed by one RF cavity that has a LiH absorber on each side. The main parameters of this configuration are shown in Table 1. Several versions of the Bucked Coils lattice were simulated with different geometric parameters. For the purpose of this paper though only three versions will be presented, named BC-I, -II and -III. The differences between these three

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versions, which are the current density and the cell-length, are summarized in Table 2. Since the coils that form a pair have opposite polarity and different radii, and their polarity alternates with every repeat, it is expected that there will be a magnetic field “cancellation” at the RF position.

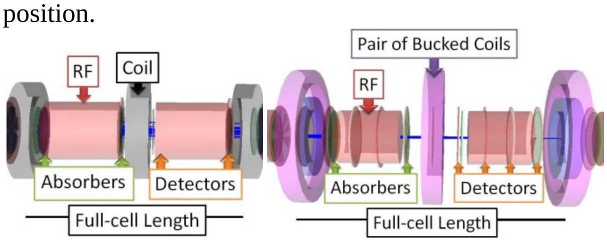


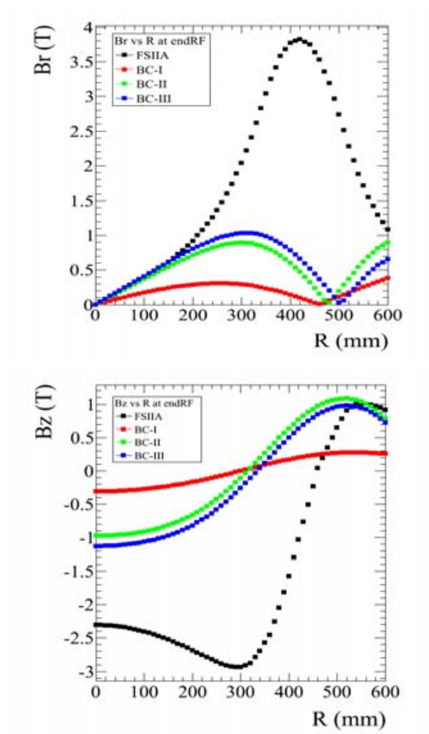
Figure 1: FSIIA (left) and Bucked Coils (right) layout.

Table 2: Summary of Differences of the Three Bucked Coils Versions, BC-I, -II, and -III

Lattice	BC-I	BC-II	BC-III
Full-cell length (m)	2.10	1.80	1.80
Inner Coil Current Density (A/mm2)	90.24	128.10	99.26
Outer Coil Current Density (A/mm2)	120.00	112.80	132.00

RESULTS

Magnetic Field



(a)

(b)

Figure 2: B_r (a) and B_z (b) as a function of z.

Fig. 2 presents the magnetic field at the end of the RF cavities. Black colour corresponds to FSIIA results, whereas red green and blue correspond to BC-I, -II and -III respectively (this colour-code applies to all the plots that follow). This position is chosen as it is the most sensitive to RF breakdown [5]. As seen in plot (a), the decrease in the radial component of the magnetic field, B_r, is apparent when Bucked Coils are used. Especially at 42 cm radius, FSIIA has B_r~3.83 T whereas BC-I has only 0.1 T, i.e. the BC-I obtains a decrease of more than 38 times in the radial magnetic field. BC-I shows a maximum B_r at 24 cm (0.31 T), which is still more than four times smaller than the B_r achieved by FSIIA (1.26 T). BC-II and BC-III both obtain a more than seven and six times respectively smaller B_r than FSIIA at 42 cm.

Plot (b) presents the longitudinal component of the magnetic field, B_z, with respect to the radius. Again, this plot shows B_z at 30 cm is virtually 0 for BC-I, whereas for FSIIA the B_z maximum (absolute value) is 3 T. BC-II and -III have a three times smaller B_z than FSIIA for the same radius. We are mostly interested in a radius of ~25 cm, as this radius corresponds to the beginning of the iris of the RF cavity.

Optics

As can be seen in Fig. 3, FSIIA has the lowest betatron function of all the lattices, closely followed by BC-III. The other lattices have a higher betatron function but, still small enough to enable ionisation cooling.

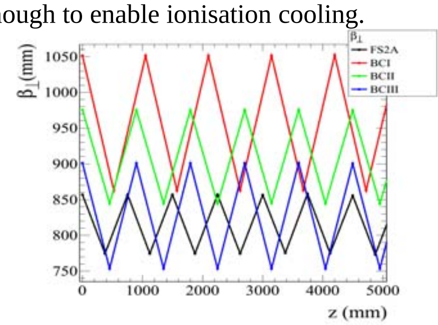


Figure 3: Betatron function with respect to the beam-axis, z.

Transmission and Cooling Dynamics

In order to compare the transmission and cooling dynamics achieved by these lattices the same beam was used, consisting of 1,000 muons with a 10 mm transverse emittance and a 0.07 ns longitudinal emittance. The momentum had a Gaussian distribution centred at 232 MeV/c, with rms momentum spread of 18.33 MeV/c.

Fig. 4 (left) presents the muon transmission that survives the momentum cuts of P±100 MeV/c, and radial cuts of 30 cm. Particles detected on a plane having radius larger than 30 cm are cut and not transmitted further downstream, whereas particles detected on a plane with momentum outside the momentum cuts are not taken into account on the specific plane, but are still transmitted further downstream. From this plot it is clear that the Bucked Coils configuration achieves a 20% better transmission than FSIIA at the end of the lattice.

Transverse emittance reduction along the lattice is presented in Fig. 4 (right). FSIIA has the lowest equilibrium emittance, closely followed by BC-III, as expected from the betatron function (see Fig. 3). For this plot the only muons taken into account were those that made it to the end of the lattice, i.e. no further cuts were used in momentum or radius.

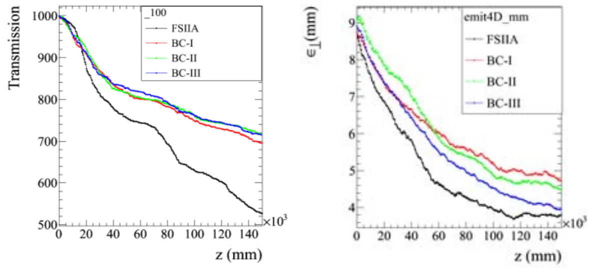


Figure 4: Transmission (left) and transverse emittance reduction (right) along the beam-axis, z.

Figure 5 presents the transmission within 30 mm of transverse acceptance. BC-III achieves the best transmission overall at 120 m. BC-I, the lattice that shows the best reduction in magnetic field over all the lattices achieves less than 4% smaller transmission at the position where FSIIA has its maximum (70 m). The other lattices, BC-II and -III achieve a similar muon transmission at 70 m, to FSIIA and BC-I.

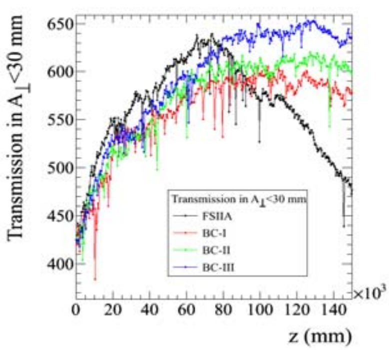


Figure 5: Transmission within 30 mm of transverse acceptance as a function of z.

FEASIBILITY

Preliminary study shows that the Hoop stress on the coils of Bucked Coils is higher than FSIIA but still within acceptable limits. In particular the maximum Hoop stress value for BC-I was estimated to be 356.4 and 346.5 MPa for the inner and outer coils respectively. Study of the maximum magnetic field in the coils shows that the construction of Bucked Coils based on the superconducting technology of Nb-Ti material is feasible: Fig. 6 presents the critical surface for Nb-Ti, drawn using an approximate linear relation [6] for two different temperatures (1.9 K and 4.2 K). The current density as a function of maximum total magnetic field of FSIIA, BC-I, -II and -III is included in the same plot in order to compare the lattices' current density to the critical surface. It is obvious from Fig. 6 that all lattices will be able to have superconducting coils as their current density is below the critical current density for the same value of magnetic field.

Further study should be performed that will include the energy deposition caused from realistic beam losses and the impact on the temperature increase in the lattices' coils.

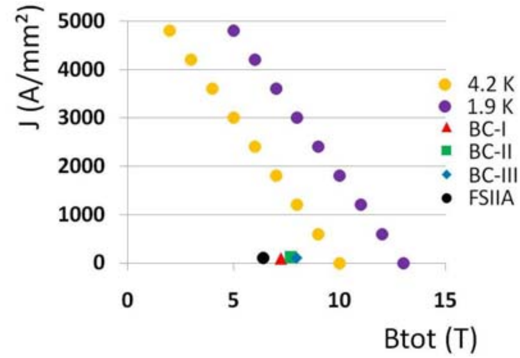


Figure 6: Critical surface for Nb-Ti.

CONCLUSIONS

The Bucked Coils lattice was designed aiming to mitigate the magnetic field issue of FSIIA, while achieving a comparable transmission within 30 mm of A_T.

This paper presents the results of a comparison between three versions of Bucked Coils (BC-I, -II, and -III) and FSIIA. BC-I not only decreased remarkably the total magnetic field at the RF position (B_r by a factor of 38 and B_z is virtually 0, see Fig. 2), but also achieved a comparable transmission within 30 mm of transverse acceptance to FSIIA: less than 4% smaller at 70 m, where FSIIA achieves its maximum transmission (see Fig. 5). Furthermore, a preliminary study on superconductivity showed that Bucked Coils are feasible (Fig. 6).

The Bucked Coils lattice is now one of the three alternative cooling lattices for the Neutrino Factory as it has shown to mitigate significantly the magnetic field issue of FSIIA without compromising cooling dynamics. Bucked Coils could also be applied not only for ionisation cooling purposes but more generally where RF performance can be affected by external magnetic field.

Further work is planned that includes an optimisation on Bucked coils and further investigation on its feasibility with regards to engineering design.

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