OPTIMISATION OF COOLING LATTICE BASED ON BUCKED COILS FOR THE NEUTRINO FACTORY

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Abstract

The ionisation cooling technique will be used at the Neutrino Factory to reduce the transverse phase space of the muon beam. For efficient cooling, high average RF gradient and strong focusing are required to be applied in the cooling channel. However, high magnetic field at the position of the RF cavities induces electric field breakdown and therefore, a novel configuration, the Bucked Coils lattice, has been proposed to mitigate this problem. The Bucked Coils lattice has significantly lower magnetic field in the RF cavities by using coils of different radius and opposite polarity. This paper presents the optimisation of this lattice, its cooling performance, together with the preliminary conceptual engineering design.

INTRODUCTION

The Neutrino Factory [1] aims to study the neutrino oscillations by measuring the mixing parameters in unprecedented precision. This future facility will produce the most intense and high purity neutrino beam ever achieved by the decays of stored muons. However, muons are produced as tertiary particles, and as such occupy a large transverse phase-space. Their transverse emittance therefore needs to be decreased in order for the beam to be efficiently transported into downstream accelerator systems. Since muons decay in a very short time (less than 2.2 μs when at rest), the only viable technique that can reduce the muon emittance in time is *ionisation cooling* [2].

In a single ionisation cooling channel, the muons pass through absorbers, where their momentum is decreased in every direction. In following RF cavities, the muons lost energy is restored, in the longitudinal direction. With a repetition of this cooling channel, the muon transverse emittance is reduced.

The reference ionisation cooling channel of the Neutrino Factory, called FSIIA [3], reduces significantly the transverse emittance of the muon beam. However, this lattice has a large magnetic field at the position of the RF cavities, which cal lead to RF breakdown [4]. It is therefore necessary for an alternative cooling lattice to be found, that will achieve a comparable cooling performance and muon transmission to the reference lattice, reducing at the same time the magnetic field at the RF position.

A *novel* lattice was designed, called the "Bucked Coils lattice" [5], that presented a significant magnetic field reduction at the RF position while also achieving a comparable transmission and cooling dynamics performance to the FSIIA lattice. A brief description of the lattices is given, together with the detailed results of a Bucked Coils optimisation.

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METHODOLOGY

Lattice Layout

The Bucked Coils lattice makes use of a *new* coil configuration, named "Bucked Coils": two coils of opposite polarity and different radii, placed at the same position along the beam-axis (homocentric coils). With every repeat of this coil configuration, the coils' polarity alternates, effectively reducing, or even cancelling out, the magnetic field at off-axis positions at desired locations.

The layouts of a full FSIIA and Bucked Coils cells are given in fig. 1. Both cells have similar components: they start with a coil (or pair of coils), followed by one RF cavity that has a Lithium Hydride (LiH) absorber on each side. The coils' polarity alternates with every repeat.

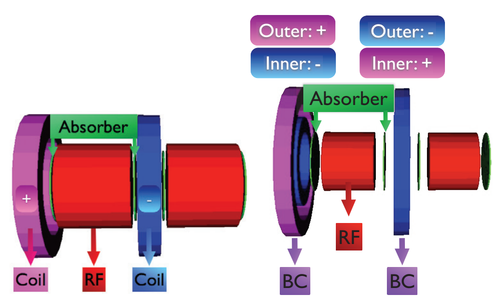

Figure 1: (Left) FSIIA and (right) Bucked Coils layouts.

The main characteristics of the FSIIA and Bucked Coils lattices are given in table 1. For the purpose of this paper, six Bucked Coils versions are presented, named BC-I, -II, -III, -IV, V, and -VI. These versions *only* differ in the full-cell length and current densities of their inner and outer coils. The differences between the six Bucked Coils versions are summarised in table 3. The RF cavities of all lattices were 50 cm long. The thickness and length of all coils were 15 cm. The inner radius of FSIIA was 35 cm; the inner radius of the inner and outer coils of BC lattices were 30 and 60 cm.

The lattices presented in [5] have been optimised: the current densities and lengths were altered aiming to find lattices with significantly lower magnetic field at the RF position, comparable cooling efficiency to the FSIIA lattice, and hoop stress less than 200 MPa (i.e. the stress limit found in literature). The six versions presented here are

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Table 1: Main Characteristics of FSIIA and BC-I

Lattice	**FSIIA**	**BC-I**
Full-cell Length [m]	1.50	2.10
Number of RF cavities	2	2
Number of Absorbers	4	4
Number of Coils	2	4 (2 pairs)
RF Cavities		
Peak Electric Field [MV/m]	15.000	16.585
Phase [degrees]	40	30
Absorbers		
Length [m]	0.0115	0.0100
Radius [m]	0.25	0.30
Coils		
Current Density [A/mm^2]	106.667 N/A	IC: 120.000; OC: 90.240

Table 2: Summary of the Differences Between the BC versions. "IC" and "OC" Correspond to the Current Densities of Inner and Outer Coils.

Lattice	**IC [A/mm^2]**	**OC [A/mm^2]**
FSIIA	106.667	N/A
BC-I	120.000	90.240
BC-II	97.200	77.140
BC-III	87.480	66.730
BC-IV	132.000	99.260
BC-V	120.000	90.000
BC-VI	87.480	66.730

therefore considered to be a summary of the best results found to date.

Simulation Description

All lattices were simulated using the G4MICE software [6]. A beam of 1,000 muons was input in each lattice having the same initial transverse and longitudinal emittance (10 mm and 0.07 ns respectively), and matched transverse beta and alpha functions to the lattice. The beam was matched using the Optics application of G4MICE. Each lattice included an appropriate number of cells, such that a 150 m lattice was formed.

RESULTS

Magnetic Field

The magnetic field was calculated for different radii at the walls of the RF cavities, as this is the most sensitive z-position with respect to the RF breakdown [4].

The total and longitudinal magnetic field, B_{tot} and B_z, with respect to the radius are shown in fig. 2. As can be easily seen, the B_{tot} of FSIIA exceeds 4 T, whereas all BC versions shown here achieve a magnetic field value from two, to up to five times smaller. The same colour code is used for all the plots of this paper.

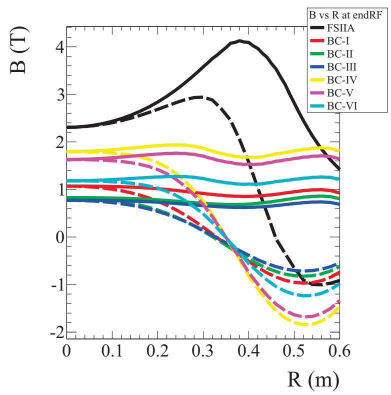
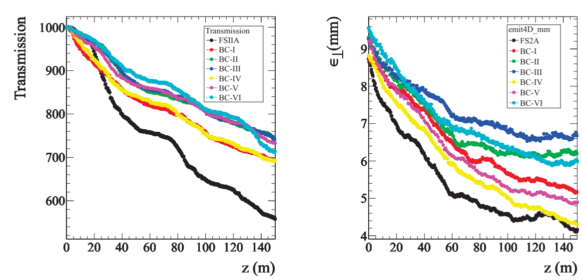


Figure 2: Total (continuous line) and axial (dashed line) magnetic field (B_{tot}, B_z) along the radius, at the walls of the RF cavities (black: FSIIA; red, green, blue, yellow and cyan correspond to BC-I, -II, -III, IV, V and VI respectively). All BC versions achieve from two to as high as five times smaller B_{tot} than FSIIA. All BC's have virtually zero B_z at the iris.

Most importantly, close to the radius corresponding to the iris (∼30 cm)[1], all BC versions have virtually zero B_z[2], whereas FSIIA has ∼3 T. At ∼35 cm the B_z of all BC lattices is completely cancelled out.

Simulation

The number of muons that manage to reach the end of a 150 m lattice is shown in fig. 3a. All BC versions achieve ∼15-20% better muon transmission than FSIIA.



(a) (b)

Figure 3: (a) Transmission along the beam-axis. All BC versions achieve as high as 15-20% better transmission than FSIIA; (b) Transverse emittance along the beam-axis. The best cooling overall is obtained by FSIIA and BC-IV.

The transverse emittance reduction, $\epsilon_\perp$, along the beam-axis is illustrated in fig. 3b. The best emittance reduction (lowest equilibrium emittance) is achieved by FSIIA and BC-IV. The other BC versions, especially BC-II, -III, and -VI, do not show as good cooling as the other lattices. It

[1] The radius corresponding to the iris of the RF cavity is the most sensitive radius with respect to RF breakdown [4].

[2] B_z is the component considered to be responsible for the RF breakdown.

should be noted that for this plot, only particles that managed to reach the end of the lattice were taken into account.

Fig. 4 shows the number of muons within 30 mm of transverse acceptance[3], $A_\perp$. The best transmission overall is achieved by BC-II and -V at ∼90 m. The maximum transmission of FSIIA is found at ∼70 m. What is of great importance to note is that at this point, where FSIIA has its maximum, BC-I, -II, and VI, achieve a comparable transmission to FSIIA; these lattices achieve 3.5 to 5 times smaller magnetic field than FSIIA (see fig. 2). Finally, BC-III, which achieves five times smaller B_{tot} than FSIIA, has an insignificantly lower transmission than FSIIA at 70 m.

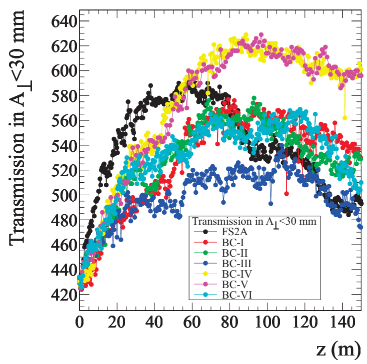


Figure 4: Transmission within $A_\perp < 30$ mm. All BC lattices achieve a better, comparable, or insignificantly lower transmission than FSIIA, at the z-position where FSIIA has its maximum.

Feasibility

The feasibility of each lattice was calculated with respect to the superconducting design (quench limit) and the maximum tolerances they can accept due to the hoop stress. All lattices apart from BC-III and BC-VI were found to exceed the 200 MPa hoop stress limit (see table 3) [7, 8]. The critical behaviour of a superconductor can be described by a critical surface: for a specific temperature there is a current density, that can turn a superconducting magnet to a normal conducting when applied at a specific magnetic field [9]. All lattices were found to be within the limits of superconducting design (fig. 5).

Table 3: Maximum Hoop Stress (in MPa) For Each Lattice.

Lattice	Hoop stress
FSIIA	238.9
BC-I	345.3
BC-II	249.9
BC-III	188.2
BC-IV	416.9
BC-V	304.0
BC-VI	187.4

[3] $A_\perp$ =30 mm is the acceptance of the downstream accelerator.

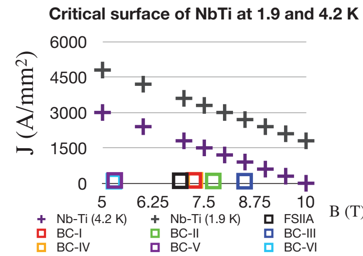


Figure 5: Critical surfaces of Nb-Ti for 1.9 and 4.2 K. All lattices are within the limits of superconducting operation.

CONCLUSIONS

Six versions of the Bucked Coils (BC) lattice were presented, compared to the reference Neutrino Factory cooling lattice (FSIIA). All BC lattices reduced the magnetic field significantly at the RF position (from two to as high as five times, see fig. 2). The transmission within 30 mm of $A_\perp$ of these lattices at the position where FSIIA had its maximum transmission (70 m) was higher, comparable, or insignificantly lower (fig. 4). Only two lattices were found to be within the 200 MPa hoop stress limits; both of them are Bucked Coils (BC-II and BC-VI). Finally, all the lattices were found to be within the limits of superconducting operation.

ACKNOWLEDGMENT

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