

# Performance study of the Bucked Coils cooling lattice for the Neutrino Factory

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**Abstract.** In a Neutrino Factory (NF), neutrinos are produced from the decays of muons. The muon beam itself is produced with large emittance at the NF front-end and in order to be efficiently transported to downstream accelerator systems, the beam emittance needs to be cooled using ionisation cooling. The reference ionisation cooling channel of the NF reduces the transverse emittance by a factor of  $\sim 3$ . However, this lattice has a large magnetic field at the position of the RF cavities and therefore its feasibility has come under question when recent studies indicated high external magnetic field may lower the maximum achievable gradient of the RF cavities. The present work summarizes the performance of a new lattice named “Bucked Coils”, designed to mitigate the magnetic field issue of the reference lattice of the NF while aiming to achieve similar cooling performance and transmission. This new lattice offers solution by reducing the longitudinal component of the magnetic field to almost 0 T while at the same time achieving a transmission comparable to the reference lattice within the transverse acceptance of 30 mm. Detailed comparison between the Bucked Coils lattice and the reference lattice of the NF follows with respect to the magnetic field reduction, cooling performance and transmission.

## 1. Introduction

The Neutrino Factory is the ultimate tool to study neutrino oscillations and search for leptonic CP violation. This future accelerator complex will produce the most intense and high-quality neutrino beam that has ever been achieved, using decays of stored muons [1]. As the muon beam in the Neutrino Factory is produced from pions decaying in flight, its initial transverse emittance is too large to be efficiently transported to further accelerator systems and therefore muon beam cooling is essential. Because of the short muon lifetime ( $2.2 \mu s$ ), traditional cooling techniques cannot be applied and hence, the only viable cooling technique is *Ionisation Cooling*: the muons pass through absorbers where they lose momentum in every direction and the lost energy is restored only in the longitudinal direction, when the beam passes through RF cavities.

The reference ionisation cooling channel for the Neutrino Factory, FSIIA (Feasibility Study 2a) [2], performs well with respect to cooling and transmission but at the same time presents a large magnetic field at the end of the RF cavities. Studies have shown [3] that the higher the external magnetic field is, the lower the maximum achievable gradient becomes and therefore the feasibility of FSIIA has come under question.

This paper presents the *Bucked Coils* lattice, a new lattice design created to significantly reduce the magnetic field at the position of the RF cavities while simultaneously achieving a

cooling performance and transmission comparable to FSIIA. The geometrical descriptions of FSIIA and the Bucked Coils lattice are given in detail below and the comparison of the achieved magnetic field together with cooling performance and transmission is presented.

## 2. Methodology and lattice geometry

Using G4MICE version 2-3-0 [4], a beam of 1,000 muons was generated with 10 mm normalized transverse emittance ( $\epsilon_{\perp}$ ). Different initial transverse beta ( $\beta_{\perp}$ ) was found for every lattice using the Optics application of G4MICE. The initial momentum followed a Gaussian distribution, centered at 232 MeV/c with rms of 18 MeV/c.

### 2.1. FSIIA

A half-cell of the Neutrino Factory reference cooling channel consists of a coil, followed by a 200 MHz RF cavity that has a LiH absorber on each side. The coil's polarity alternates with every half-cell repeat. A full-cell of 1.50 m is shown in fig. 1 (left).

### 2.2. Bucked Coils

A pair of coils with different radius and opposite polarity are placed homocentrically at the same position along the beam-axis,  $z$ . One 200 MHz RF cavity with a LiH absorber on each side, follows the pair of coils, forming a half-cell of the Bucked Coils lattice. The polarity of every coil alternates with every half-cell repeat, as shown in the full-cell depicted in fig. 1 (right). In this paper, three versions of the Bucked Coils lattice, that differ in cell-length and current density, will be presented: BC-I, -II and -III. Table 1 presents the main parameters of FSIIA and the three versions of the Bucked Coils lattice.

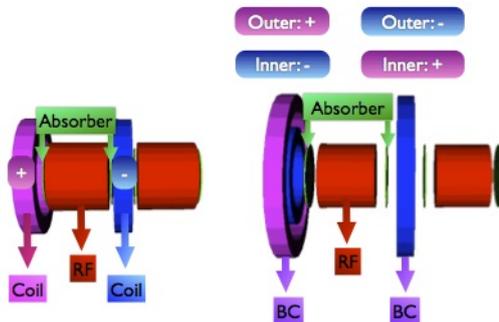


Figure 1: Layout of FSIIA (left) and BC-I (right) full-cell.

## 3. Results

### 3.1. Magnetic field

The total magnetic field ( $B_{tot}$ ), together with the transverse ( $B_r$ ) and longitudinal ( $B_z$ ) components of the magnetic field are plotted as a function of the radius in fig. 2a, 2b and 2c respectively for all four lattices. The results for FSIIA are shown in black, whereas the results for BC-I, -II and -III are given in red, green and blue respectively. This colour code is used for all the results shown in this paper. The magnetic field is only plotted at the end of the RF cavities as this is the most sensitive place with respect to RF breakdown [5].

The total magnetic field decrease is obvious in the case of the Bucked Coils lattices. In fig. 2a, FSIIA has a magnetic field that exceeds 4 T at 35 cm radius, whereas BC-I achieves a four times smaller magnetic field. Both BC-II and -III, for the same radius, produce more than two times smaller magnetic field than FSIIA.

In order to gain a better understanding of the magnetic field reduction,  $B_r$  and  $B_z$  are plotted at the end of the RF cavities, as a function of the radius,  $R$ . The transverse component of the

Table 1: Main parameters of the FSIIA and Bucked Coils lattices. “IC” and “OC” correspond to “Inner Coil” and “Outer Coil” respectively.

Lattice	FSIIA	BC-I	BC-II	BC-III
Full-cell Length (m)	1.50	2.10	1.80	1.80
Number of RF cavities	2	2	2	2
Peak Electric Field (MV/m)	15	16	16	16
Phase (degrees)	40	30	30	30
Number of Absorbers	4	4	4	4
Number of Coils	2	4	4	4
IC, Inner Radius (m)	0.35	0.30	0.30	0.30
IC, Outer Radius (m)	0.50	0.45	0.45	0.45
OC, Inner Radius (m)	<i>N/A</i>	0.60	0.60	0.60
OC, Outer Radius (m)	<i>N/A</i>	0.75	0.75	0.75
IC, Current Density ( $A/mm^2$ )	106.67	90.24	128.10	128.10
OC, Current Density ( $A/mm^2$ )	<i>N/A</i>	120.00	112.80	132.00

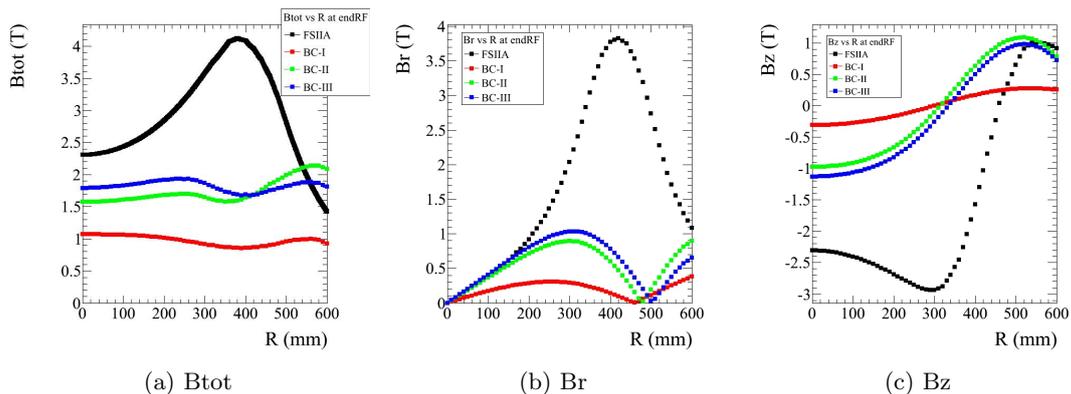


Figure 2: Magnetic field at the end of the RF cavity as a function of radius,  $R$ .

magnetic field (see fig. 2b) is as low as 0.1 T for BC-I at 42 cm, i.e. where FSIIA has its maximum (3.83 T). For the same radius, the magnetic field is 38 times smaller in BC-I, and 7 and 6 times smaller in BC-II and -III respectively. The iris of the RF cavity, which is at  $\sim 25$  cm, is a sensitive location with respect to the RF breakdown, and although the maximum  $B_r$  of BC-I is achieved at 24 cm (0.31 T), it is still four times smaller than that of FSIIA.

The magnetic field decrease is apparent in fig. 2c. FSIIA has its maximum  $B_z$  (absolute value 3 T) at 30 cm, where BC-I has virtually 0 magnetic field. At this location both, BC-II and -III have three times smaller  $B_z$  than FSIIA.

### 3.2. Optics and cooling performance

Fig. 3 presents the transverse betatron function with respect to  $z$ . Although BC-III has the lowest betatron function at the RF position, closely followed by FSIIA, the amplitude of the FSIIA betatron function is smaller than BC-III and therefore the FSIIA cooling performance is expected to be better than that of BC-III. The equilibrium emittance of BC-I and -II will be higher than that of FSIIA and BC-III as can be deduced from their betatron function amplitude.

However, the betatron functions of BC-I and -II are still within the cooling limit.

One of the most important results is the transmission (the number of muons) within the transverse acceptance of 30 mm, the nominal accelerator acceptance defined in the baseline Neutrino Factory design [1]. The best transmission over all is achieved by BC-III at 120 m. What is important to note is that at 70 m, where FSIIA achieves its maximum, all three BC lattices achieve a very similar transmission. Most importantly BC-I, the lattice with the best magnetic field reduction, achieves less than 10% smaller transmission in comparison to the FSIIA lattice at 70 m, and this transmission difference is insignificant.

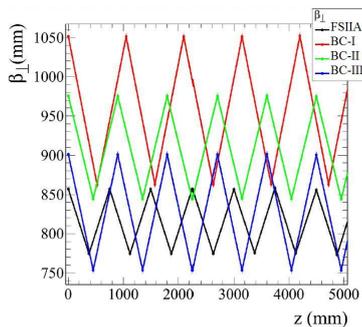


Figure 3: Transverse betatron function with respect to the beam-axis,  $z$ .

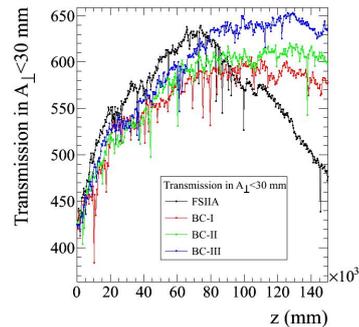


Figure 4: Transmission within the transverse acceptance of 30 mm along  $z$ .

#### 4. Conclusions

Several versions of the Bucked Coils lattice were designed with the aim of reducing the magnetic field within the RF cavities. Three versions, BC-I, -II and -III were presented in this paper and compared to the FSIIA lattice with respect to the magnetic field reduction and transmission. When Bucked Coils are used, the magnetic field reduction is clear: BC-I has 4 times smaller  $B_{tot}$  and 38 times smaller  $B_r$  than FSIIA. At 30 cm the  $B_z$  of BC-I is virtually 0 whereas in FSIIA is as high as 3 T. Transmission within the transverse acceptance of 30 mm (fig. 4), shows BC-III to have the best transmission over all the lattices at 120 m. Most importantly, at 70 m, where FSIIA achieves its maximum transmission, BC-I, which achieves the best magnetic field reduction, has a very similar transmission to FSIIA. Bucked Coils lattices not only decreased significantly the magnetic field but also achieved a comparable transmission and cooling performance to the FSIIA lattice.

The Bucked Coils lattice is now one of the three alternative cooling channels for the Neutrino Factory. Optimization of the lattice will be beneficial and further work is planned investigating the feasibility of the lattice with regards to engineering design.

#### References

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