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Bucked Coils lattice: a novel ionisation cooling lattice for the Neutrino Factory

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ABSTRACT: A successful muon ionisation cooling channel for the Neutrino Factory and Muon Collider, requires simultaneously a strong focusing and a large mean RF gradient. To date, all candidate design lattices achieved these requirements with a large magnetic field in the RF cavities, which can potentially limit the achievable gradient leading to RF breakdown. This paper presents the Bucked Coils lattice, designed to reduce the magnetic field at the RF cavities while achieving a satisfactory cooling effect and muon transmission. The Bucked Coils managed to achieve significantly reduced magnetic field components at the RF position, while also achieving a comparable transmission to the FSIIA lattice, the current reference ionisation cooling lattice of the Neutrino Factory. A detailed comparison with respect to the magnetic field reduction, cooling dynamics and transmission is given. A preliminary feasibility study taking into account the hoop stress of the coils and their superconducting operation is also presented.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam Optics; Beam dynamics; Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators)

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Contents

1 Introduction

The future Neutrino Factory facility [1] aims to address the evidence for the CP violation in the leptonic sector with the precision study of neutrino oscillations. The Neutrino Factory will produce the most intense and pure neutrino beam that has ever been achieved, using decays of stored muons. Due to the fact that the muons are produced as a tertiary beam, they occupy a large phase space which needs to be reduced using ionisation cooling [2]. The emittance reduction mechanism in ionisation cooling is based on passing muons through absorbers, where their momentum is decreased in every direction, and subsequently through RF cavities, where the lost energy is restored in the longitudinal direction.

An efficient cooling channel requires simultaneously a strong focusing and large mean RF gradient. All candidate lattices, including the current IDS-NF [1] baseline, which is based on the US FSIIA study [3], achieved these requirements by having a large magnetic field value at the position of the RF cavities. Recent results have shown that a high external magnetic field at the RF position can lead to RF breakdown [4]. Therefore the feasibility of the FSIIA lattice has come under question. A new lattice needs to be found that not only manages to reduce significantly the muon emittance and obtain an appreciable muon transmission, but that also achieves a small magnetic field at the RF position.

Several lattices were designed aiming to mitigate the RF breakdown problem in the presence of the magnetic field: a Singlet and Doublet lattice with an extended cell-length [5] as well as simulation with reduced RF field level [6]. However these configurations did not obtain satisfactory results with respect to the the muon transmission.

We propose a *novel* alternative lattice, *the Bucked Coils lattice* [7], that makes use of a new coil configuration, called Bucked Coils (BC). Bucked Coils is a pair of homocentric coils that have different radii and opposite polarity. The coils' polarity is alternated with every pair repeat, which results in a significant magnetic field reduction at desired off-axis locations. Although the idea of Bucked Coils was earlier considered [8], the results obtained in previous studies were not satisfactory.

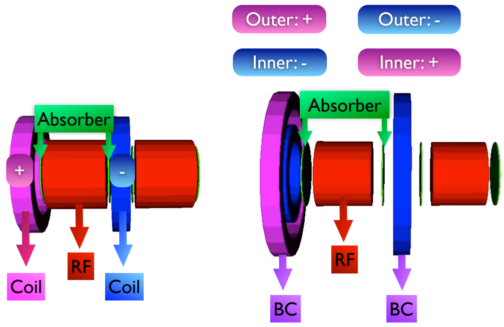


Figure 1. FSIIA (left) and Bucked Coils (right) full-cells. Both cells have similar components, apart from the fact that Bucked Coils uses a pair of coils (rather than a single one) and has a larger cell-length than FSIIA.

2 The Bucked Coils lattice configuration

The Bucked Coils lattice consists of the same components as the FSIIA lattice but has a larger cell length and uses a pair of BC rather than a single coil. The layouts of a full-cell of the FSIIA and Bucked Coils lattices are shown in figure 1. Both lattices' coils are followed by one RF cavity that has a Lithium Hydride (LiH) absorber on each side. The coils' polarities alternate with every repeat, in both cells, resulting in a complete magnetic field cancellation for on-axis positions at the centre of their RF cavities.

In this paper six versions of the Bucked Coils lattice will be presented that appear to obtain the best results with respect to the magnetic field, cooling dynamics and feasibility (feasibility is studied taking into account the hoop stress in the coils and their superconducting operation). For simplicity these versions are named: BC-I, -II, -III, -IV, -V and -VI. The only difference between these versions are the cell's length and the current densities of their inner and outer coils.

The coils' cross sections of the FSIIA and BC-I lattices along the radius and beam-axis are shown in figure 2 for a full-cell length (one period). The coils' characteristics of these two lattices are detailed in table 1, and the current densities and full-cell lengths of the different Bucked Coils versions are presented in table 2.

2.1 Magnetic field reduction

The total magnetic field, B_{tot}, of FSIIA and BC-I was calculated in G4MICE [9], from the coil's centre to the centre of the RF cavity in the z-direction, and from the coil's centre to 60 cm in radius (see figure 3). Both, FSIIA and BC-I have zero magnetic field at the centre of their RF cavities for on-axis positions, which was expected as the polarity of their coils alternates with every repeat. A significant reduction of the magnetic field at the RF cavity region has been clearly obtained: while the region of $B_{\mathrm{tot}} < 0.5$ T extends to less than 10 cm radius at the centre of the RF cavity for FSIIA, in BC-I it exceeds 60 cm, and even extends to a larger length in z. Finally the regions with $B_{\mathrm{tot}} < 0.2$ T and $B_{\mathrm{tot}} < 0.1$ T are larger in BC-I.

Figures 4a, 4b and 4c show the total, axial (B_z), and radial (B_r) magnetic field respectively, with respect to the radius for the z-position corresponding to the wall of the RF cavity. This position has been chosen as the RF wall is the most sensitive place with respect to the RF breakdown. In particular, the iris of the RF cavity (at $\sim$30 cm radius) is a very sensitive point, due to large elec-

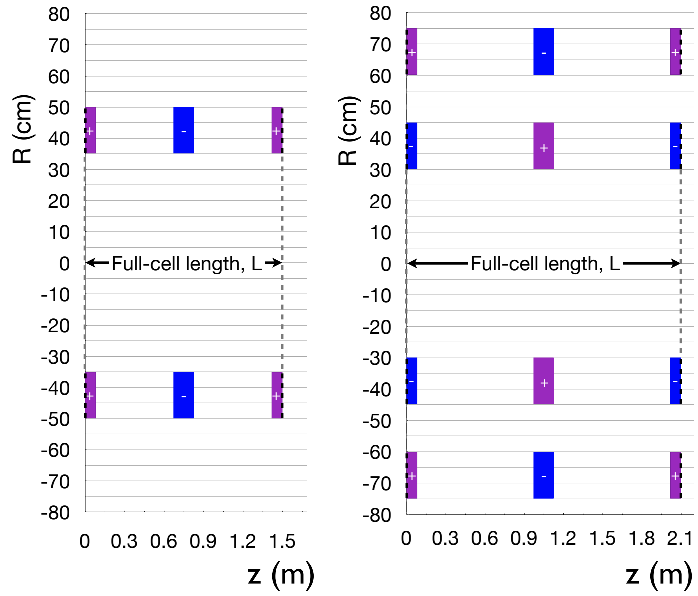


Figure 2. FSIIA (left) and BC-I (right) coils' cross section (one period). The coils' positions along the radius, R, and the beam-axis, z, are shown. Purple and blue indicate positive and negative polarities respectively.

Table 1. FSIIA and BC-I coils' characteristics. "IC" and "OC" correspond to "Inner Coil" and "Outer Coil" respectively.

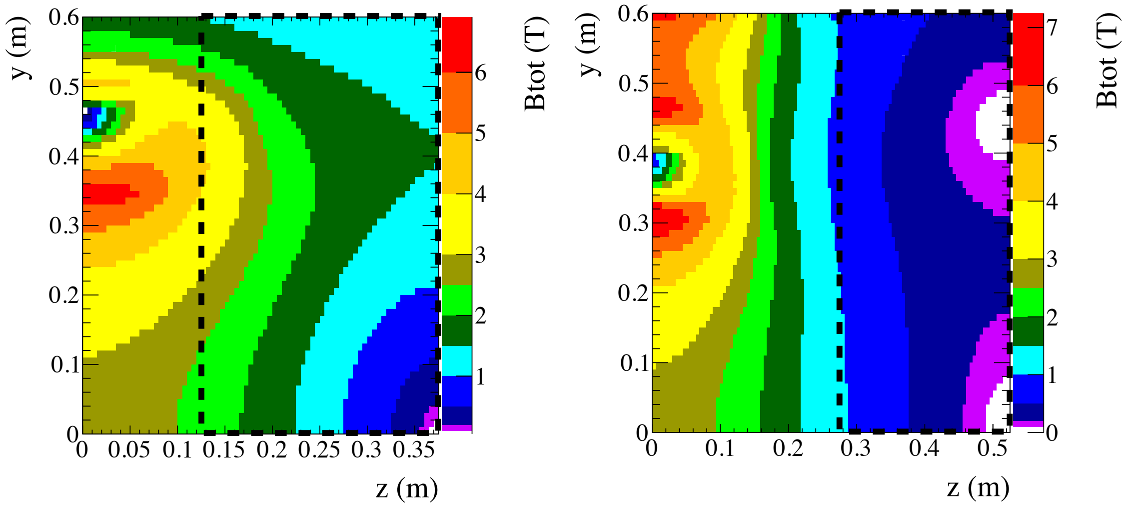
Lattice	**FSIIA**	**BC-I**
Current Density [A/mm^2]	106.667; N/A	IC: 120.000; OC: 90.240
***z*-position [m]**	0, 0.75, 1.5, ... N/A	IC: 0, 1.05, 2.10, ... OC: 0, 1.05, 2.10, ...
Inner Radius [m]	0.35; N/A	IC: 0.30; OC: 0.60
Thickness [m]	0.15; N/A	IC: 0.15; OC: 0.15
Width [m]	0.15; N/A	IC: 0.15; OC: 0.15

tric field values [4]. This plot shows that the B_{tot} of FSIIA exceeds 4 T, whereas all BC versions achieve from two to five times smaller B_{tot}. In addition, B_z, which was speculated to be the main component responsible for the RF breakdown, has been significantly reduced around the iris in all BC versions. Finally, B_r is also reduced in all Bucked Coils lattices.

The on-axis longitudinal magnetic field ($B_z(z)$) is shown in figure 4d. The curves of all the Bucked Coils lattices have been shifted in the z-direction so that their zero-magnetic field points

Table 2. Full-cell length and coils' current densities of the FSIIA lattice and the different BC versions.

Lattice	Full-cell length [m]	Inner Coil [A/mm^2]	Outer Coil [A/mm^2]
FSIIA	1.50	106.667	N/A
BC-I	2.10	120.000	90.240
BC-II	2.10	97.200	77.140
BC-III	2.10	87.480	66.730
BC-IV	1.80	132.000	99.260
BC-V	1.80	120.000	90.000
BC-VI	1.80	87.480	66.730



(a) **(b)**

Figure 3. Total magnetic field, B_{tot} (in T) of FSIIA (a) and BC-I (b), with respect to the beam-axis, z, and radius, y (x was set to zero). $z = 0$ corresponds to the z-position at the centre of the coil(s), whereas for (a) z=0.375 m and for (b) z=0.525 m correspond to the z-positions at the centre of the RF cavities of FSIIA and BC-I respectively. Blue corresponds to 0.5< B_{tot} <1 T, dark blue corresponds to 0.2< B_{tot} <0.5 T, violet to 0.1< B_{tot} <0.2 T and white to 0< B_{tot} <0.1 T. B_{tot} is significantly lower in BC-I within the area of the RF cavities (shown in dashed line).

will coincide with that of FSIIA. It is clear that all the Bucked Coils lattices have a smoother field change around the centre of the RF cavities in comparison to the FSIIA lattice.

2.2 Optics

For each lattice, a transverse betatron function, $\beta_\perp$, and transverse alpha function, $\alpha_\perp$, were calculated to match the lattice using the 4D formalism [10] implemented in G4MICE. Figure 5 shows the transverse betatron function with respect to the beam-axis, z (figure 5a), and momentum (fig-

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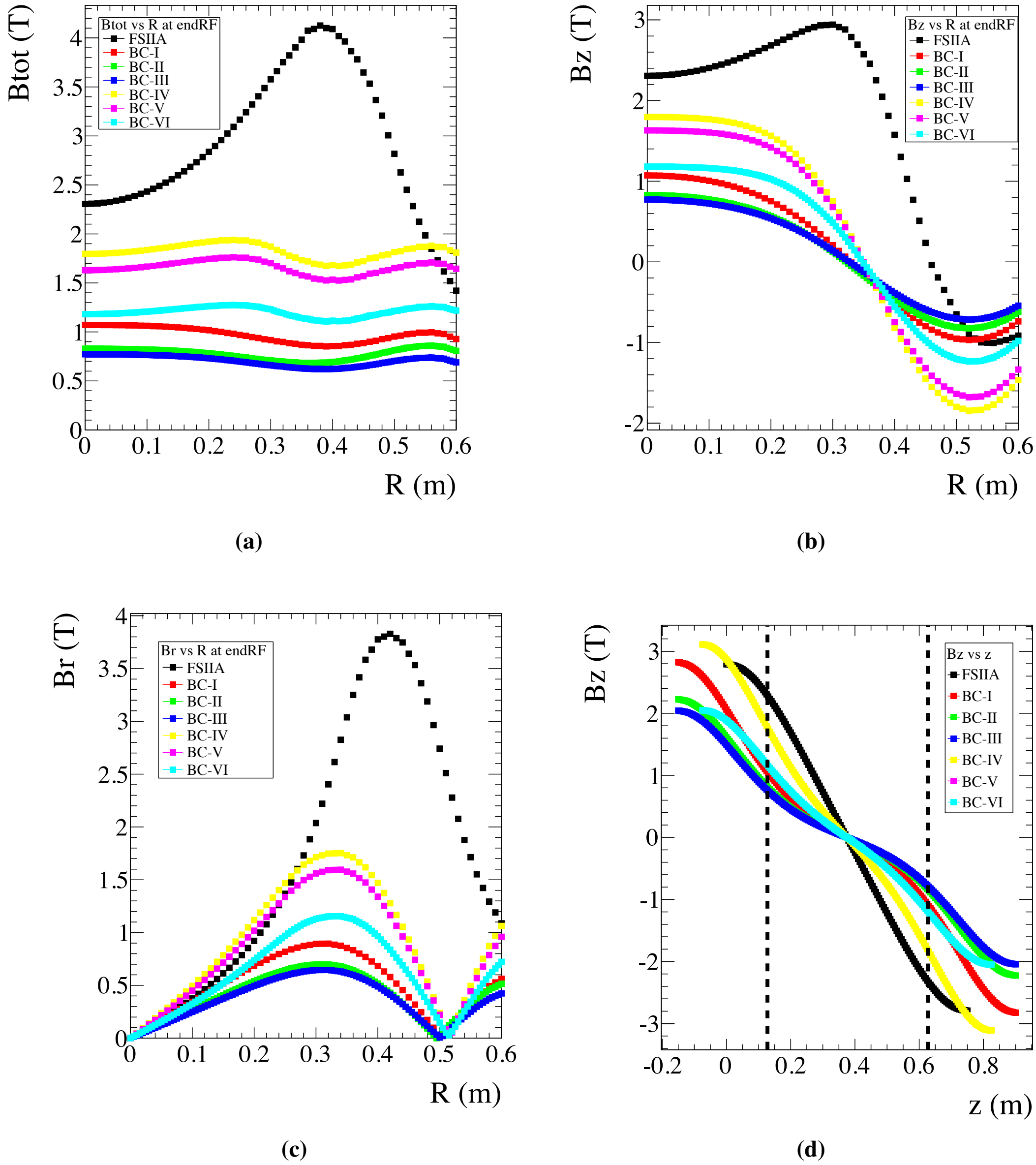
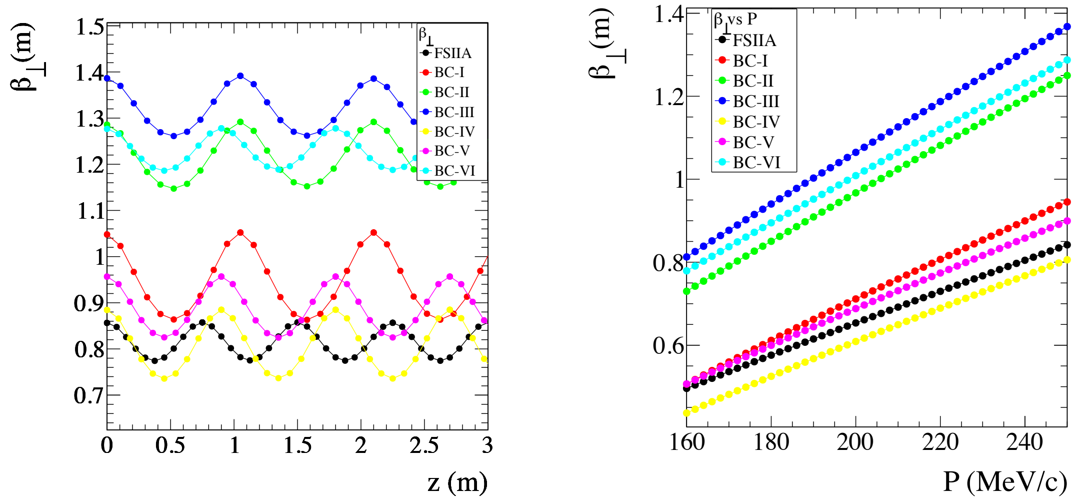


Figure 4. Total (a), axial (b), and radial (c) magnetic field with respect to the radius, R. The magnetic field is significantly reduced when the Bucked Coils are used. On-axis longitudinal magnetic field (d) with the RF z-extension indicated in dashed lines (the BC curves have been shifted in the z-direction so that the zero magnetic field point will coincide with that of FSIIA); the longitudinal magnetic field change is smoother than that of FSIIA around the RF centre. FSIIA is shown in black, whereas BC-I, -II, -III, -IV, -V and -VI are shown in red, green, blue, yellow, violet and cyan respectively.

ure 5b). In figure 5a it can be seen that the lowest beta function is achieved in FSIIA and BC-IV, which directly implies a better cooling for these lattices. The other BC lattices have higher values of $\beta_\perp$ and therefore their equilibrium emittance is expected to be higher than FSIIA and BC-IV.



(a) Transverse betatron function along the beam-axis at 232 MeV/c. FSIIA and BC-IV achieve the lowest $\beta_{\perp}$ which implies the best cooling.

(b) Transverse betatron function with respect to momentum at zero magnetic field positions. All lattices are stable for the ±20% momentum spread.

Figure 5. Transverse betatron function with respect to (a) the beam-axis and (b) momentum.

Moreover, a similar cooling behaviour is suggested by figure 5b between FSIIA, BC-I, -IV and -V. All lattices remain stable for a large momentum spread (±20%, centred at 232 MeV/c).

2.3 Tracking

The general characteristics of the RF cavities and absorbers of FSIIA and BC-I are summarised in table 3 (the other Bucked Coils versions are not present in this table since, apart from the current density and cell-length, they share the same characteristics with BC-I). The 201 MHz room temperature RF cavities for all lattices are 50 cm long, and the RF gradients of the BC lattices were chosen in order to compensate for the lattices' longer cell-length. An appropriate number of cells was used for each lattice such that they had all formed a 150 m lattice. Ten extra coils were placed before the beginning and after the end of each lattice, ensuring a perfectly symmetric magnetic field.

Using the previously found values of the periodic betatron function, a beam of 1,000 muons with 10 π·mm·rad transverse rms normalised emittance was input at the start of each lattice at a zero magnetic field position. The beam was simulated in G4MICE using the Simulation application including the beam-absorber interactions, taking into account the multiple scattering, ionisation and straggling models implemented into the code.

The muon transmission (in percentage) along the beam-axis is presented in figure 6a. No cuts were applied for this plot. As can be seen, all Bucked Coils versions achieve ∼15-20% better transmission than FSIIA. The emittance reduction is shown in figure 6b. Only particles that reached the end of 150 m lattice were taken into account. As expected, due to the smaller value of the betatron function obtained by FSIIA (see figure 5a), the lowest equilibrium emittance is achieved by FSIIA, closely followed by the BC lattices.

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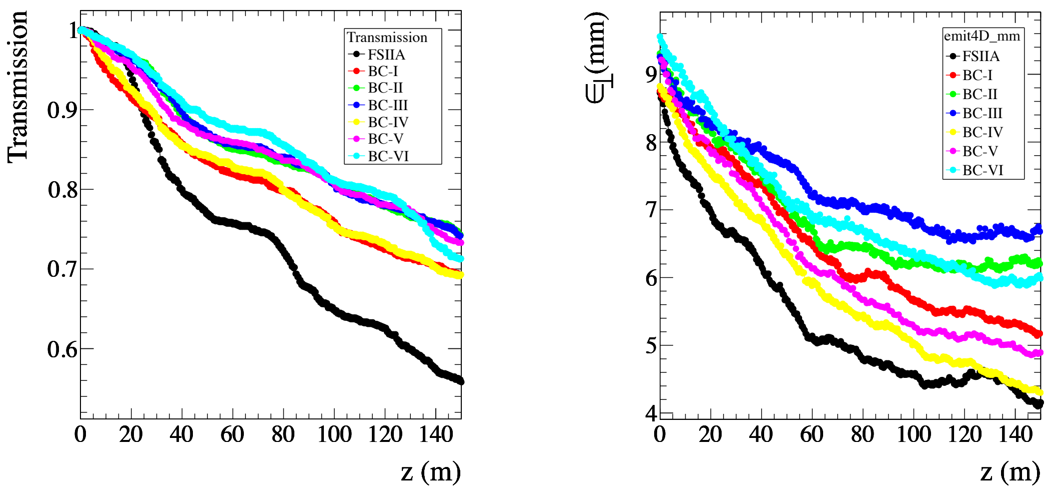
Table 3. Main characteristics of one full-cell of FSIIA and BC-I.

Lattice	**FSIIA**	**BC-I**
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



(a) Transmission (in percentage) along the beam-axis. All BC have a substantially better transmission than the FSIIA lattice.

(b) Emittance decrease along the beam-axis. FSIIA and BC-IV have practically the same equilibrium emittance.

Figure 6. Transmission (a) and transverse emittance (b) along z for the FSIIA and BC lattices.

Figure 7a presents the muon transmission (in percentage) within 30 mm of transverse acceptance, $A_{\perp}$, which is used as a figure of merit as it corresponds to the acceptance of the downstream accelerator systems ([1], page 75). No cuts were used on the longitudinal acceptance. The best transmission overall is achieved by BC-IV and -V, at ~90 m. FSIIA has its maximum transmission at ~70 m. BC-I, -II and -VI, the lattices that achieve from 3.5 to 5 times smaller magnetic field than FSIIA, obtain a comparable transmission to FSIIA. BC-III, which obtains five times smaller magnetic field than FSIIA has an insignificantly lower transmission.

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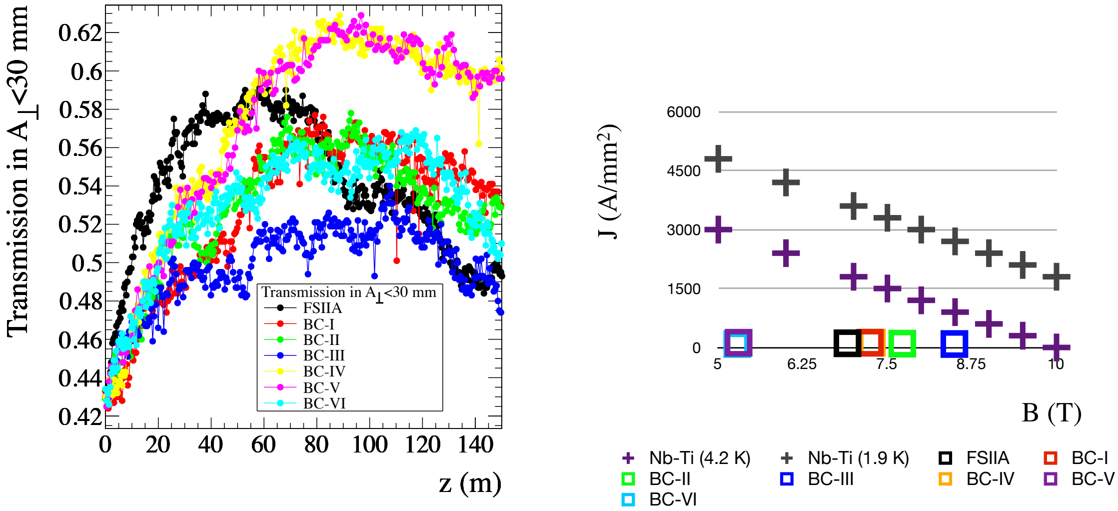

(a) Transmission (in percentage) within 30 mm of $A_\perp$. **(b)** Critical current density.

Figure 7. (a) Transmission within 30 mm of transverse acceptance, $A_\perp$, along the beam-axis, z. All the Bucked Coils lattices achieve a better, comparable or insignificantly lower transmission than FSIIA at 70 m, where FSIIA has its maximum; (b) Critical current density of Nb-Ti, and maximum magnetic field at coils for FSIIA and BC lattices with respect to the current density at 1.9 K (grey) and 4.2 K (purple). All lattices are within the limits of superconducting operation as their current densities and magnetic fields are below both critical current densities.

3 Feasibility

A precise knowledge and understanding of the forces acting on a magnet are of great importance, as they can limit the magnet's performance by the destruction of the coils themselves. The radial component of the Lorentz force acting on a solenoid generates the hoop stress, σ_t, on the magnet. Using the "current sheet approximation", where the current flows in a thin surface around the coil diameter, the approximate hoop stress acting on a solenoid is found to be [11]:

$$\sigma_t = j_t B_z r, \tag{3.1}$$

where j_t is the current density, B_z is the longitudinal magnetic field component, and r is the radius. The hoop stress limit given in the up to date literature is approximately $\sim$200 MPa [12]; this is nevertheless considered to be a conservative value.

The maximum hoop stress of FSIIA was found to be at the inner radius of its coil, whereas that of all BC lattices is at the inner radius of their outer coil. Table 4 summarises these maximum hoop stress values. As can be seen, the only two lattices that do not exceed the conservative 200 MPa hoop stress limit are BC-III and -VI, whereas FSIIA and BC-II slightly exceed it. This approximate hoop stress analysis should be followed by a rigorous mechanical engineering study.

The critical current density was plotted for two different temperatures [13, 14]. These current densities are illustrated in figure 7b, together with the maximum total magnetic field with respect

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Table 4. Maximum hoop stress of all lattices.

Lattice	Hoop stress [MPa]
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

to the current density of FSIIA and BC lattices. As can be seen, all lattices are below the critical lines. Still, a sufficient margin taking into account the beam losses needs to be evaluated.

4 Conclusions

We designed and presented a novel alternative ionisation cooling lattice for the Neutrino Factory, called the Bucked Coils lattice. This lattice was designed aiming to significantly reduce the magnetic field at the position of the RF cavities, while at the same time obtaining a comparable transmission and cooling dynamics to the reference cooling channel of the Neutrino Factory, FSIIA.

Six different versions of the Bucked Coils lattice were presented: all of them, compared to FSIIA, obtained a significantly reduced total magnetic field, from two to as high as five times. For a $\sim$70 m long channel, where FSIIA achieves its maximum transmission within 30 mm of $A_\perp$, all Bucked Coils versions obtained better, comparable or insignificantly lower transmission. A feasibility study has been performed and it was shown that only two lattices do not exceed the conservative hoop stress limit of 200 MPa; both of them are Bucked Coils lattices (BC-III and -VI). Finally, the critical current density of Nb-Ti has been drawn for two different temperatures; it was found that all lattices are within the limits of superconducting operation. A summary of the main results for the lattices studied are shown in table 5.

It is concluded that the best Bucked Coils lattice over-all is BC-II; although the conservative hoop stress limit is slightly exceeded, this lattice presents more than five times smaller total magnetic field than FSIIA at the walls of the RF cavities, a significantly lower B_z than FSIIA at the iris, and a comparable transmission within 30 mm of transverse acceptance. In the case that the hoop stress limit should not exceed the 200 MPa limit, then the best lattice is considered to be BC-VI, since it achieves more than three times smaller total magnetic field than FSIIA, a significantly lower B_z at the iris, and a comparable transmission.

Due to these positive results, our lattice offers a feasible solution and can therefore be used as a replacement of the reference cooling lattice for the Neutrino Factory. We believe that there is still a substantial room for further optimisation of the lattices based on the Bucked Coils solution. Therefore, further work is strongly recommended.

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Table 5. Results of maximum transmission within 30 mm of $A_\perp$, B_z field at the iris of the RF cavity (z=30 cm) and maximum hoop stress for the FSIIA and BC lattices.

Lattice	Maximum transmission (in %) within 30 mm of $A_\perp$ relative to FSIIA	B_z field at the iris of the RF cavity [T]	Maximum hoop stress [MPa]
FSIIA	1.00	2.94	238.9
BC-I	0.97	0.21	345.3
BC-II	0.97	0.12	249.9
BC-III	0.91	0.14	188.2
BC-IV	1.06	0.75	416.9
BC-V	1.06	0.68	304.0
BC-VI	0.96	0.49	187.4

Acknowledgments

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