Performance Comparison Between FSIIA and Bucked Coils for the Neutrino Factory Cooling Lattice

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Layout

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• New Alternative Lattice: Bucked Coils, BC
• FSIIA vs BC:
  • Magnetic Field
  • Cooling Dynamics & Transmission
• Towards Engineering Design
• Summary & Future Plans
Neutrino Factory:

- Proposed next generation neutrino physics facility and possibly a front-end of the Muon Collider
- Will **produce** the most intense and high-energy neutrino beam ever achieved, from stored muon decays:
  \[ \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
- Key to: discover leptonic CP violation, mass hierarchy, precise determination of mixing parameters
Muon beam produced at Neutrino Factory has large initial emittance which needs to be reduced (cooled)

Muons life-time very short (~2.2 μs)

**Ionization Cooling:**

- Muon momentum decreases in every direction by ionising absorber’s material
- Momentum is restored only longitudinally when beam passes through RF cavities

Only viable technique for muon emittance reduction: Ionization Cooling

Transverse phase-space reduced
Current Baseline Cooling Channel: FSIIA

FSIIA: Feasibility Study IIA

- Coil-LiH absorber-RF-LiH absorber
- Coil’s polarity alternates with every repeat
- Good transmission & emittance reduction
Current Baseline Cooling Channel: FSIIA

**FSIIA: Feasibility Study IIA**

- **Coil-LiH absorber-RF-LiH absorber**
- **Coil’s polarity alternates with every repeat**
- **Good transmission & emittance reduction**

**BUT**

- **Recent studies indicate RF performance may be limited when external magnetic field is applied**
- **FSIIA has large magnetic field at RF position (>4 T)**

**Feasibility of FSIIA is questioned!**

*We are searching for a new solution mitigating the RF breakdown by lowering the magnetic field at the RF cavities while also keeping good transmission and cooling performance*

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*“Effects of high solenoidal magnetic fields on rf accelerating cavities”, A. Moretti, et. al, Physical Review Special Topics - Accelerators and Beams 8, 072001*
New Alternative Lattice: Bucked Coils, BC

- The magnetic field at the RF cavities can be decreased by:
  - Increasing cell’s length
  - Using **Bucked Coils**:
    - Pair of different radius & opposite polarity coils
    - The pair of coils is placed at the same position along the beam axis (homocentric coils)
New Alternative Lattice: Bucked Coils, BC

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- BC configuration:
  - Pair Of Coils - LiH absorber - RF - LiH absorber
  - Pair Of Coils’ polarity interchanges with every repeat
New Alternative Lattice: Bucked Coils, BC

- Three different versions: BC-I, -II, -III
- BC-I, -II, -III: same configurations except for:
  - Full-cell’s length
  - Current densities of inner-outer coils

<table>
<thead>
<tr>
<th>Lattice</th>
<th>BC-I</th>
<th>BC-II</th>
<th>BC-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-cell Length (m)</td>
<td>2.10</td>
<td>1.80</td>
<td>1.80</td>
</tr>
<tr>
<td>Inner Coil Current Density (A/mm²)</td>
<td>90.24</td>
<td>128.10</td>
<td>99.26</td>
</tr>
<tr>
<td>Outer Coil Current Density (A/mm²)</td>
<td>120.00</td>
<td>112.80</td>
<td>132.00</td>
</tr>
</tbody>
</table>
FSIIA vs BC: Magnetic Field

Area with ZERO magnetic field

Centre of Coil
Centre of RF
FSIIA vs BC: Magnetic Field

- **FSIIA**: $>4$ T !!!
- **BC-I**: 4 times lower than FSIIA
- **BC-II** and **BC-III**: 2 times lower than FSIIA
Betatron Function

\[ \beta_\perp \]

- FS2A
- BCI
- BCI
- BCIII

\[ z \text{ (mm)} \]

\[ \beta_\perp \text{ (mm)} \]

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Beam initial characteristics

Lattices were compared using the same initial beam:

- Simulated using G4MICE software
- 1,000 muons
- 10 mm Transverse Emittance
- 0.07 ns Longitudinal Emittance
- P: Gaussian distribution centred at 232 MeV/c
Better cooling for FSIIA and BC-III
FSIIA vs BC: Transmission in $A_T < 30$ mm

- BC-III: best transmission over all at 120 m
- FSIIA maximum at 70 m
- BC-I: less than 4% lower transmission than FSIIA at 70 m (BC-II and BC-III less than 3%)
Towards Engineering Design

- We started looking into the Hoops Stress of Bucked Coils → Larger than FSIIA but within technological limits!
- Superconducting design: BC’s look feasible with Nb-Ti
- Still more studies needed including realistic beam losses that could deposit energy into the coils
Summary

• FSIIA:
  • Current Neutrino Factory baseline cooling channel
  • Good transmission and transverse emittance reduction
  • Large magnetic field at RF position
  • Recent studies indicate RF performance can be limited when external magnetic field applied \( \Rightarrow \text{Is FSIIA feasible?} \)

• Bucked Coils (BC):
  • New lattices (BC-I, -II, -III), designed to reduce B at RF position
  • BC-I:
    • 4 times lower magnetic field than FSIIA at RF position
    • Less than 4% smaller transmission within 30 mm \( A_T \) than FSIIA

Future Plans

• BC optimisation: lower B & much better transmission than FSIIA
• Paper preparation
Thank you
Current Density vs $B_{\text{max}}$ in Cooling Lattices

![Graph showing current density vs magnetic field strength for cooling lattices with different labels: FSIIA, BC-I, BC-II, BC-III.](image-url)
Buckup

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β⊥(mm)

β⊥

- FS2A
- BCI
- BCII
- BCIII

z (mm)

0 1000 2000 3000 4000 5000

750 800 850 900 950 1000 1050
Neutrino Factory Front End:
1. Protons on target $\rightarrow$ Pions production
2. Drift: Pions decay to muons and bunch lengthens (high energy “head”, low energy “tail”)
3. Buncher: RF voltages applied to beam $\rightarrow$ string of different-energy bunches
4. Rotator: Lower energy reference particle moved to accelerating phase