A 3 Pass, Dog-bone Cooling Channel

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Introduction

Studies for the ISS:
1. Proton booster and driver rings for 50 Hz, 4 MW and 10 GeV.
2. Pairs of triangle and bow-tie, 20 (50 GeV) $\mu^\pm$ decay rings.

Studies after the ISS:
1. A 3 - 5.45 MeV electron model for the 10 GeV, proton NFFAG.
2. An alternative proton driver using a 50 Hz, 10 GeV, RCS ring.
3. A three pass, $\mu^\pm$ cooling, dog-bone re-circulator.
Schematic of Dog-bone Re-circulator

Muon Cooling Channel

K1 off/on

K2 on/off

Solenoids, S

μ±

μ±
Mode Of Operation

- Solenoids match the $\mu^\pm$ beams between the input and output transport lines and the cooling channel.

- Additional solenoid matching is needed between the cooling channel and the re-circulator end loops.

- The kickers contribute to the beam matching and are integral parts of the first (last) lattice cell of the rings.

- Initially, kicker K1 is off, and it is switched on after a bunch train is in the cooling channel, but before it returns to K1.

- Kicker K2 is kept on until it is turned off for beam extraction. Ring operation is close to but below its transition energy.
Potential Advantages

- Compatibility with the trains of 80 \( \mu^+ \) and 80 \( \mu^- \) bunches
- Common, dispersion free, input and output \( \mu^\pm \) beam lines
- Lower power kickers for field rise and fall times > 300 ns
- Single transits of the end loops for three channel passes
- Enhanced cooling due to the three (or 5) channel transits
- Cooling ahead of entry into the down and upstream loops
- Improved \( \mu \) to \( \nu \) divergence angle ratio in the decay rings
End Loop Lattice Requirements

- Entry and exit ring closure after completion of a 180° bend
- Mirror symmetry about the input or the output $\mu^\pm$ beam lines
- Zero dispersion at entry must transform to zero $(D,D')$ at exit
- Equal $\beta_h, \beta_v$ values at entry must match to same $\beta$ at exit
- Equal $\alpha_h, \alpha_v$ at entry must change sign, but not value, at exit
- Lattice functions must not vary too much around the rings
- Optimisation for the design of the K1 and K2 kickers
Re-circulator End Loop

Bend sequence:

- **Kicker** $- 9^\circ$
- **BN** $- 42^\circ$
- **BP** $+ 51^\circ$
- **BR** $- 45^\circ$
- **BD** $+ 45^\circ$
- **BD** $+ 45^\circ$
- **BD** $+ 45^\circ$

Mirror symmetry for return bends
End Loop Geometry

BD (45°, n<1) are asymmetric in the μ = 60°, cells C4, C5, C6.
End Loop Matching

- Kicker requirements set inputs at $\beta = 4.0$ m and $\alpha = 0.82$
- BD (and BR) require an $n = 0.5886$ to obtain $\mu = 60^\circ$ cells
- Need $\alpha_v = \alpha_h = D'_h = 0$ at 3-BD $\pi$ section and half way point
- Variables are $n$ and $\theta_{\text{bend}}$ of BN, BP, and straights next to BP
- Ring closure and approximate matching sets the $\theta_{\text{bend}}$ values
- This leaves four parameters to find a three parameter match
- Ring closure is restored via asymmetry of BD cell positions
- Input-output matching obtained but not cell to cell matching
Lattice Parameters

- Zero dispersion on entry becomes negative after kicker but positive after BR magnet & then continues to increase until halfway around the ring, where \( D = 3.4216 \text{ m} \) and \( D' = 0 \).

- Functions change in a mirror symmetric way on return to the kicker. Due to \( \pi \) phase shift for 3 adjacent BD cells, the point between \((- + -)\) and \((+ + +)\) sections also has \( D' \) (and \( \alpha \)) zero.

- Beta functions are matched from input to output but not from cell to cell, due to asymmetric BD cells and other effects. The kicker deflection is over a region of reducing \( \beta_h \) (4.0 to 2.3 m).

- The \( \beta_v \) variation over the kicker is similar (4.0 to 2.4 m), and the maximum value of \( \beta_v \) around the ring reaches 4.102 m, while the maximum value for \( \beta_h \) in the ring is 4.757 m.
Loop Betatron and Dispersion Functions

The diagram shows the behavior of betatron functions $\beta_x$ and $\beta_y$ as a function of distance. The red line represents $\beta_x$ and the blue line represents $\beta_y$. The dispersion function, shown in the lower graph, varies periodically with distance.

The x-axis represents distance in meters, ranging from 0 to 35 meters. The y-axis for $\beta$ functions ranges from 0 to 4, while the y-axis for the dispersion function ranges from -2 to 2.
### Magnet Parameters

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Length (m)</th>
<th>Angle</th>
<th>$B_o$ (T)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1,2</td>
<td>1.800</td>
<td>– 9°</td>
<td>0.07947</td>
<td>0.00000</td>
</tr>
<tr>
<td>BN</td>
<td>0.672</td>
<td>+ 42°</td>
<td>0.99334</td>
<td>0.65624</td>
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<tr>
<td>BP</td>
<td>0.816</td>
<td>– 51°</td>
<td>0.99334</td>
<td>0.59333</td>
</tr>
<tr>
<td>BR</td>
<td>0.720</td>
<td>– 45°</td>
<td>0.99334</td>
<td>0.58863</td>
</tr>
<tr>
<td>BD</td>
<td>0.720</td>
<td>+ 45°</td>
<td>0.99334</td>
<td>0.58863</td>
</tr>
</tbody>
</table>
Isochronous Position

- For an isochronous point ahead of the end loop, its gamma-t must be < the muon gamma of 2.7705462 (at 273 MeV/c)

- The isochronous path length for the gamma-t of 2.621948 is 
  \((2.7705462 / 2.621948)^2 \times 39.125404 \text{ m (ring path length)} \)

- Thus, the isochronous position ahead of the end loop is at a distance of 2.321435 m from the input end of the kicker

- The path length from and back to the point is 43.68592 m while 63 \((\beta \lambda / 2)\) for the 201.25 MHz cavities is 43.76085 m
Kicker Magnets

- Max. normalised input emittances at K1: 45,000 \((\pi)\) mm mr
- Max. normalised input emittances at K2: 30,000 \((\pi)\) mm mr

- The beam size is reduced for the first K1 pass (when it is off) and this requires an extra pulsing system for the focusing

- K1,2 have 9° kick, 435 mm gap, 794.7 G field, 300 ns fall time and 51.9 kV /section for push-pull drives & subdivision in two

- Each of eight pulse systems need 428.3 J of energy per pulse, while earlier coolers needed 10,000 J, and typical kickers. 20J

- Kicker R and D remains an important issue, because of the required high level of the pulse currents at 27.509 kA
Future Work

- Chromatic correction for the end loops \((B = B_0 (r/r_0)^{-n})\)
- Inclusion of cooling channel in re-circulator (C Rogers)
- Input and output matching for re-circulator (C Rogers)
- Muon tracking studies for the three channel transits
- Determine losses, emittance and momentum acceptance
- Study the possibility of adding an end loop to MICE