Highlights of Emittance Exchange talks from Riverside

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BNL

MC Friday Meeting
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Outline

1. Linear precoolers
   R. Palmer  LiH channel with bends
   R. Fernow  helical channels

2. Ring coolers
   A. Garren  dipole ring - designs
   H. Kirk    dipole ring – hard edge
   S. Kahn    dipole ring with realistic fields
   R. Godang  RFOFO ring with Geant
   A. Klier   RFOFO ring with Geant

3. Final cooling
   Y. Fukui   Li lens ring cooler
Longitudinal Cooling is observed
## Summary

<table>
<thead>
<tr>
<th></th>
<th>Linear</th>
<th>Curved</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trans (π mm)</td>
<td>10.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Long (π mm)</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>6 D (π mm)</td>
<td>13.5 k</td>
<td>13.5 k</td>
</tr>
<tr>
<td><strong>50 m</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trans (π mm)</td>
<td>9.2 (1/2.1)</td>
<td>12.7 (1/1.5)</td>
</tr>
<tr>
<td>Long (π mm)</td>
<td>39.9 (1/9)</td>
<td>30.5 (1/1.2)</td>
</tr>
<tr>
<td>6 D (π mm)</td>
<td>3.39 k (1/4.0)</td>
<td>4.9 k (1/2.7)</td>
</tr>
<tr>
<td><strong>100 m</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trans (π mm)</td>
<td>5.9 (1/3.3)</td>
<td>10.1 (1/1.9)</td>
</tr>
<tr>
<td>Long (π mm)</td>
<td>43.4 (1/8)</td>
<td>21.9 (1/1.6)</td>
</tr>
<tr>
<td>6 D (π mm)</td>
<td>1.52 k (1/8.9)</td>
<td>2.3 k (1/5.9)</td>
</tr>
</tbody>
</table>


Balbekov helical cooling channel

72 m long, 40 x 1.8 m cells  
\( B_S = 5 \, \text{T}, \, b_0 = 0.3 \, \text{T} \)  
201 MHz, 14 MV/m, 30° phase  
14.7° LiH wedge absorbers  
dipole field tapered on/off over 8 cells  
simulations described in MC146 and MC193

Input beam parameters  
\( \sigma_X = \sigma_Y = 3.25 \, \text{cm} \)  
\( \sigma_Z = 10 \, \text{cm} \)  
\( \sigma_{P_X} = \sigma_{P_Y} = 48.7 \, \text{MeV/c} \)  
\( \sigma_{P_Z} = 18 \, \text{MeV/c} \)  
\( L_Z \) for 5 T solenoid  
momentum – transverse amplitude
ICOOL cooling performance with Gaussian beam

include stochastics
\[ \alpha_W = 14.74^\circ, \text{optimized } U_W \]
100< \( p < 320 \) MeV/c cut in ECALC9
initial emittances
\[ \varepsilon_{TN} = 11.0 \text{ mm} \]
\[ \varepsilon_{LN} = 28 \text{ mm} \]

<table>
<thead>
<tr>
<th>helix model</th>
<th>phase model</th>
<th>( U_W ) [cm]</th>
<th>( \varepsilon_{TN} ) [mm]</th>
<th>( \varepsilon_{LN} ) [mm]</th>
<th>Tr [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>7</td>
<td>8.0</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>7</td>
<td>7.8</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>2 (D)</td>
<td>3</td>
<td>7</td>
<td>7.8</td>
<td>22</td>
<td>65</td>
</tr>
</tbody>
</table>

• channel performs very poorly !!!
• sheet field has better transmission

• clear problems keeping beam bunched
ICOOL cooling performance

include stochastics
initial emittances
\[ \varepsilon_{TN} = 11.0 \text{ mm} \]
\[ \varepsilon_{LN} = 28 \text{ mm} \]

<table>
<thead>
<tr>
<th>helix</th>
<th>phase</th>
<th>P [atm]</th>
<th>( \varepsilon_{TN} ) [mm]</th>
<th>( \varepsilon_{LN} ) [mm]</th>
<th>Tr [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>140</td>
<td>4.9</td>
<td>26</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>160</td>
<td>5.1</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>2 (D)</td>
<td>3</td>
<td>160</td>
<td>5.2</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>2 (D+Q)</td>
<td>3</td>
<td>160</td>
<td>5.5</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>

- slightly better performance than channel with LiH wedges
- no evidence for longitudinal cooling
- adding quad term to sheet model makes it worse
Parameters of 6-Sector Rings

\( \rho = R_c, \theta = 30^\circ, \epsilon = 15^\circ \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum, GeV/c</td>
<td>0.25</td>
</tr>
<tr>
<td>Magnetic field, T</td>
<td>2.62</td>
</tr>
<tr>
<td>Magnet half length (L_B)</td>
<td>0.167</td>
</tr>
<tr>
<td>Gap half length (L_S)</td>
<td>0.159</td>
</tr>
<tr>
<td>(\rho)</td>
<td>0.318</td>
</tr>
<tr>
<td>(R_c)</td>
<td>0.318</td>
</tr>
<tr>
<td>Cell length</td>
<td>0.637</td>
</tr>
<tr>
<td>Circumference</td>
<td>3.82</td>
</tr>
<tr>
<td>(R_S)</td>
<td>0.594</td>
</tr>
<tr>
<td>(R)</td>
<td>0.615</td>
</tr>
<tr>
<td>(B_x, \text{max})</td>
<td>0.719</td>
</tr>
<tr>
<td>(B_y, \text{max})</td>
<td>0.645</td>
</tr>
<tr>
<td>(D, \text{max})</td>
<td>0.637</td>
</tr>
</tbody>
</table>
12 Cell Ring without Drifts
Layout of 1 Cell

\[ k = nd = -nf = 2.7 \]
\[ B/B_0 = (R/R_0)^k = (\rho/\rho_0)^{-n} \]
\[ P/P_0 = (R/R_0)^{k+1} \]
\[ (R/R_0) = (P/P_0)^{1/(k+1)} \]

\[ D = dR/d(\rho/\rho_0) = R/(k+1) = 0.2581 \text{ m} \]
\[ L_f = 0.3333 \text{ m} ; \quad L_d = 0.1667 \text{ m} \]
\[ L_{\text{cell}} = 0.5 \text{ m} ; \quad \text{Circumference} = 6 \text{ m} \]

\[ \rho_0 = 0.3183 \text{ m} ; \quad R_0 = 0.9549 \text{ m} ; \quad B_0 = 2.620 \text{ T} \]
\[ p_c = 0.25 \text{ GeV} ; \quad B_\rho = 0.8339 \text{ m} \]
Gas Filled Dipole Wedge Rings

Key parameters at r = 60 cm

\[ \beta_x = 53 \text{ to } 72 \text{ cm} ; \quad \beta_y = 60 \text{ to } 64 \text{ cm} \]

Dispersion = 60 to 64 cm

Circumference = 3.91 m

Harold G. Kirk
Introduce Skew Quadrupoles

- Bracket dipoles with thin (3cm) skew quadroles
- Skew quadrupoles real estate at 9% circumference
- Test various gradients.
- X/Y Coupling achieved
An FFAG-like Lattice

Lattice consists of alternating Horz. Defocusing and Horz. Focusing with $L_{HD} = \frac{1}{2} L_{HF}$.
No drift cells between dipole elements.

Parameters
12 cells
Bend angles $30^\circ$ and $-15^\circ$
Circumference = $6m$
$B_0 = 2.6T$ and $P_0 = 250$ MeV/c
Dispersion = $25$ cm

Harold G. Kirk
FFAG Lattice Performance

12 Sector Oct. 21, 03 Lattice: 250 MeV/c

- Invariant Emittance
- RF at 25 MV/m over 60% of circumference

Horizontal Emittance Reduction Factor 10
Vertical Emittance Reduction Factor 11
Longitudinal Emittance Reduction Factor 2

Harold G. Kirk
A Demonstration Scenario

- Merit factor of ~ 10 is sufficient
- Muon decay ignored
- RF frequency at 800 MHz
- Beam aperture at ±7 cm
- Gas density at 10 atmos at 77° K
- DC dipole field at 1.5T
- Pulsed dipole field ~ 3T
Field Along the Reference Path

- Figure shows $B_y$ along the 250 MeV/c reference path.
  - The blue curve indicates the field from the Tosca field map.
  - The red curve is the hard edge field.
- Note the –0.5 T field in the gap mid-way between the magnets.
$b_n$ along the path
Horizontal Dynamic Aperture (x vs. $p_x$)

Kirk’s Hardedge model

My Hardedge model

Realistic Field Model

Realistic Model with no sex
Vertical Dynamic Aperture ($y$ vs. $p_y$)

Kirk’s Hardedge Model

Realistic Field Model

Realistic field w/ no sex

My Hardedge Model

Dipole Cooler Ring

27 January 2004

Steve Kahn
The table below shows the Twiss Parameters as seen in ICOOL for both the *realistic* and *hardedge* models. These were calculated in a manner similar to those shown before.

Both ICOOL models look reasonably comparable to the original SYNCH and TOSCA models.

- This is extremely encouraging and says that the realistic fields do not significantly alter the lattice!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A. Garren Synch</th>
<th>Tosca</th>
<th>Icool Realistic</th>
<th>Icool Hardedge</th>
<th>Icool with No Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_x$</td>
<td>99.8784°</td>
<td>98.38°</td>
<td>105.496°</td>
<td>103.626°</td>
<td>106.313</td>
</tr>
<tr>
<td>$\beta_x$</td>
<td>37.854 cm</td>
<td>32.3099 cm</td>
<td>34.293 cm</td>
<td>38.8635 cm</td>
<td>33.6023 cm</td>
</tr>
<tr>
<td>$\alpha_x$</td>
<td>0</td>
<td>-0.00124</td>
<td>-0.000461</td>
<td>-0.000576</td>
<td>-0.00593</td>
</tr>
<tr>
<td>$\mu_y$</td>
<td>92.628°</td>
<td>100.62°</td>
<td>100.619°</td>
<td>94.9662°</td>
<td>100.865</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>56.891 cm</td>
<td>53.9188 cm</td>
<td>54.086 cm</td>
<td>56.9616 cm</td>
<td>53.844 cm</td>
</tr>
<tr>
<td>$\alpha_y$</td>
<td>0</td>
<td>0.0009894</td>
<td>0.000652</td>
<td>-0.000001</td>
<td>0.00597</td>
</tr>
</tbody>
</table>
GEANT Simulation

Geometry and Material

- RFOFO geometry and material in GEANT are identical as in ICOOL
  - Overall dipole $B$ is 0.125 Tesla
  - Alternating Solenoids $B$ is $\pm 3.0$ Tesla
- RFOFO's circumference is $\sim 33$ m

GRID Magnetic Fields

- We determine the particle closed orbit using constant magnetic fields (shown)
- We generate $1\text{cm} \times 1\text{cm} \times 1\text{cm}$ GRID fields map with tilt angle of 53 mrad (S. Bracker, MU COOL-271)
- Satisfy fundamental Maxwell’s equations $\nabla \cdot B = 0$ and $\nabla \times B = 0$
- We use FINT interpolation routine with result of $10^{-4}$ Tesla differences compared to the real fields
- It is a very good resolution!
- We apply the GRID fields into GEANT with satisfying the geometry boundary condition
The 

- beam vertexes in x, y and z direction

- beam is circulating in the RFOFO Ring with the RF, wedges and B fields on!
3-D view of the RFOFO ring
Closed orbits in a single cell

Solid line – the reference orbit

- E = 200 MeV
- 200 MeV
- 227 MeV
- 250 MeV
- 270 MeV

Arc length (cm)
The beam in 15 turns (no muon decay)
Cooling performance: transmission, 2-D emittances
### Lithium Lens Ring Cooler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon momentum</td>
<td>250 MeV/c</td>
</tr>
<tr>
<td>Circumference</td>
<td>42.1 m</td>
</tr>
<tr>
<td>straight section length</td>
<td>5.9 m (x 2)</td>
</tr>
<tr>
<td>Structure of half cell</td>
<td>2 dipoles with edges</td>
</tr>
<tr>
<td>number of bending cells</td>
<td>8</td>
</tr>
<tr>
<td>bend cell length</td>
<td>3.6 m</td>
</tr>
<tr>
<td>length of Lithium lens</td>
<td>34.5 cm (x 2)</td>
</tr>
<tr>
<td>Lowest/highest $\beta$ in Li</td>
<td>1.0 cm /16 cm</td>
</tr>
<tr>
<td>$dE/dx$</td>
<td>35 MeV/turn (x 2)</td>
</tr>
<tr>
<td>dipole bend angles</td>
<td>44.2, -21.7 degree</td>
</tr>
<tr>
<td>dipole edge angles</td>
<td>30/-3, -11/-11 degree</td>
</tr>
<tr>
<td>dipole magnetic field</td>
<td>6.5, -3.2 tesla</td>
</tr>
<tr>
<td>Cell tunes bend cell</td>
<td>0.72/0.70</td>
</tr>
<tr>
<td>Cell tunes straight cell</td>
<td>4.0</td>
</tr>
</tbody>
</table>

![Diagram of Lithium Lens Ring Cooler](image)
Lithium Lens Ring Cooler
Li lens Ring Cooler with matrix solenoid, matrix pole face rotation

\[ \varepsilon_x, \varepsilon_y \quad (\text{mm}^2\cdot\text{rad}) \]

Transmission

\[ z \quad (\text{m}) \]

9.2\% loss with No Decay

\[ \text{scatt + stragg} \]

42 mm/turn

\[ \varepsilon_z \quad (\text{mm}) \]

RMS of \( \Delta P \)

RMS of \( \Delta z \)

\[ z \quad (\text{m}) \]