1. Ionization cooling
2. 6D Cooling
3. RFOFO and Guggenheim parameters
4. 5 layer layout, no shielding
5. Acceptance analysis (ongoing)
6. Particle losses: Detailed
7. Technical Issues
8. Engineering issues
9. Summary
Ionization cooling is a process by which the beam emittance of a beam of particles may be reduced. In ionization cooling, particles are passed through some material. The momentum of the particles is reduced as they ionize atomic electrons in the material. Thus the normalized beam emittance is reduced. By re-accelerating the beam, for example in an RF cavity, the longitudinal momentum may be restored without replacing transverse momentum. Thus overall the angular spread and hence the geometric emittance in the beam will be reduced.
A consequence of the transverse cooling is an increase of the longitudinal phase space caused by energy straggling in the material.

The momentum spread can be reduced if dispersion is introduced and a wedge-shaped absorber is placed such that high momentum particles pass through more material than low momentum particles.

When this procedure is carried out the beam width is increased.

Emittance exchange between the longitudinal and transverse dimensions.

When combined with transverse cooling in the material, all three dimensions can be cooled.
6D Colling Channels

- HCC
- Quadrupole channel
- RFOFO
RFOFO Channel

- RFOFO considered one of the most realistic designs (does not mean there are no technical issues).
- The FOFO part of the name refers to the focusing-drift-focusing nature of the solenoid lattice, in analogy to the FODO lattice for quadrupole channels.
- The prefix R designates a particular type of FOFO lattice where the axial field changes polarity in the middle of the cell.
## RFOFO vs Guggenheim

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R.</th>
<th>G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Cells</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Max Bz (T)</td>
<td>2.77</td>
<td></td>
</tr>
<tr>
<td>Coil Tilts (deg)</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Ave Momentum (MeV/c)</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Min Trans. Beta (cm)</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Max. Dispersion (cm)</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>0.0037</td>
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</tr>
<tr>
<td>Wedge Absorber Material</td>
<td>H2</td>
<td></td>
</tr>
<tr>
<td>Wedge Angle (deg)</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Wedge Vertex position (cm)</td>
<td>12.7</td>
<td>9.5</td>
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<tr>
<td>Frequency (MHz)</td>
<td>201.25</td>
<td></td>
</tr>
<tr>
<td>Gradient (MV/m)</td>
<td>12</td>
<td>12.33</td>
</tr>
<tr>
<td>Phase (deg) from 0-crossing</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>
Longitudinal Emittance

![Graph of Longitudinal Emittance](Image)
Transverse Emittance
Guggenheim Update
RFOFO and Guggenheim parameters

6D emittance

$\varepsilon_{6D}$ goes from $3 \cdot 10^{-6}$ to $2 \cdot 10^{-8}$
5-layer layout, no shielding

- 5 layers - more realistic, no re-injection after each turn
- No shielding - more realistic, less complex
- Extra pair of coils on each side to compensate for the asymmetry
- Increase efficiency by tuning the parameters (reference particle, RF gradient, magnetic coil field, etc.)
Particle losses in the channel

After 5 turns we have

- 26% particles lost with decay/stochastic processes off
- 42% particles lost with decay/stochastic processes on
- 16% particles lost due to decay over 5 turns (165 m)
### Particle loss with decay on/off

<table>
<thead>
<tr>
<th>Turn #</th>
<th>Decay off Stochastics off</th>
<th>Decay off Stochastics on</th>
<th>Decay on Stochastics on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>89.2% (10.8%)</td>
<td>88.0% (12.0%)</td>
<td>85.0% (15.0%)</td>
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<tr>
<td>2</td>
<td>81.0% (19.0%)</td>
<td>78.5% (21.5%)</td>
<td>75.2% (24.8%)</td>
</tr>
<tr>
<td>3</td>
<td>77.8% (22.2%)</td>
<td>75.0% (25.0%)</td>
<td>70.9% (29.1%)</td>
</tr>
<tr>
<td>4</td>
<td>76.2% (23.8%)</td>
<td>67.5% (32.5%)</td>
<td>63.2% (36.8%)</td>
</tr>
<tr>
<td>5</td>
<td>74.5% (25.5%)</td>
<td>64.5% (35.5%)</td>
<td>58.0% (42.0%)</td>
</tr>
</tbody>
</table>
Distribution vs. acceptance for average $p_z, (x - p_x)$
Distribution vs. acceptance for average $p_z$, $(y - p_y)$
Distribution vs. acceptance for average $p_z, (x - y)$
Distribution vs. survivors, \((x - p_x)\)
Distribution vs. survivors, \((y - p_y)\)
Guggenheim Update
Acceptance analysis (ongoing)

Distribution vs. survivors, $(x - y)$
Distribution vs. survivors, \((x - y)\), large \(p_z\)
Full acceptance analysis

- $x, y$ width of $\pm 150$ mm
- $p_x, p_y$ width of $\pm 100$ MeV/c
- $p_z$ length of 130 to 320 MeV/c
Tech. Issues: RF in magnetic field

- need at least 3 T @ 12 MV/m
- MTA experiment results
- Tests in the framework of MICE experiment
Tech. Issues: Shielding

- Shielding problem should be addressed
- Studies by A. Klier show that adding shielding does not influence the dynamics significantly

Effect of “shielding”

- Tighter shielding ➔ less current needed
- Almost negligible effect on field at the beam
Engineering issues

- Vertical 3D layout
- Support structures
- Infrastructure connection
- Going from 201 MHz to 805 MHz
Summary

- RFOFO vs Guggenheim
- Particle losses
- Acceptance, initial beam mismatch
- Technical issues
- Further studies