Towards an end-to-end design of cooling for a muon collider

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- Introduction
- Sub-systems
  - Phase Rotation
  - Ionization Cooling
  - Bunch merge
  - Final cooling in high field solenoids
- System performance
- R&D
  - rf in magnetic fields
  - towards 50 T solenoids
- Conclusion
Why a Muon Collider?

• Point like interactions as in linear $e^+e^-$
• Negligible synchrotron radiation:
  Acceleration in rings  Small footprint  Less rf  Hopefully cheaper
• Collider is a Ring
  $\approx 1000$ crossings per bunch  Larger spot  Easier tolerances  2 Detectors
• Negligible Beamstrahlung  Narrow energy spread
• 40,000 greater S channel Higgs  Enabling study of widths

LHC $pp$ (1.5 TeV)

ILC $e^+e^-$ (.5 TeV)

CLIC $e^+e^-$ (3 TeV)

Mu-Mu (4 TeV)

FNAL site

10 km
## Current Baseline Parameters (Y Alexahin)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Example 1</th>
<th>Example 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>C of m Energy</td>
<td>1.5</td>
<td>3</td>
<td>TeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1</td>
<td>4</td>
<td>$10^{34}$ cm$^2$sec$^{-1}$</td>
</tr>
<tr>
<td>Beam-beam Tune Shift</td>
<td>0.087</td>
<td>0.087</td>
<td></td>
</tr>
<tr>
<td>Muons/bunch</td>
<td>2</td>
<td>2</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Total muon Power</td>
<td>9</td>
<td>15</td>
<td>MW</td>
</tr>
<tr>
<td>Ring $&lt;$(bending field)$&gt;$</td>
<td>6</td>
<td>8.4</td>
<td>T</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>2.6</td>
<td>4.5</td>
<td>km</td>
</tr>
<tr>
<td>$\beta^*$ at IP $= \sigma_z$</td>
<td>10</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>rms momentum spread</td>
<td>0.1</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Required depth for $\nu$ rad</td>
<td>13</td>
<td>135</td>
<td>m</td>
</tr>
<tr>
<td>Muon per 8 GeV p</td>
<td>0.008</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>15</td>
<td>12</td>
<td>Hz</td>
</tr>
<tr>
<td>Proton Driver power</td>
<td>$\approx 4$</td>
<td>$\approx 4$</td>
<td>MW</td>
</tr>
<tr>
<td>Muon Trans Emittance</td>
<td>25</td>
<td>25</td>
<td>pi mm mrad</td>
</tr>
<tr>
<td>Muon Long Emittance</td>
<td>72,000</td>
<td>72,000</td>
<td>pi mm mrad</td>
</tr>
</tbody>
</table>

- Emittance and bunch intensity requirement same for both examples
- 3 TeV luminosity ($4 \times 10^{33}$) compared to CLIC’s ($2 \times 10^{33}$ for dE/E < 1%)
Emittances vs. Stage

1) Proton driver and Buncher
2) Hg Target and Capture solenoid
3) Phase rotation
4) Separation
5) 6D Cooling
6) Bunch Merging
7) 6D Cooling
8) Recombination
9) 4D cooling in 50 T
10) Acceleration
11) Collider ring

Initial

Final

Transverse emittance (mm)

Longitudinal emittance (mm)

6) Merge to single bunches
3) Phase Rotate to 12 bunches
4) Charge separation
5) 6D Cooling before merge
7) 9)

9) Trans Cooling in 50 T Solenoids

Charge recombination

6) 7) 8)
Phase Rotation

- 110 m Drift
- 51 m rf to bunch
- 52 m Shift phases to rotate

red (21 bunches)/all (pz 0.226 ± 0.1) = 0.697
Ionization Cooling

\[ \epsilon_{\perp}^{\text{(equilib)}} \propto \frac{\beta_{\perp}}{\epsilon_v} \frac{1}{dE/dx} L_x \]

- Best Material is Hydrogen
- Best momentum to avoid blow up of \( dp/p \approx 200 \text{ MeV/c} \)

- For Long cooling we require Emittance Exchange

- Dispersions in magnet
- Path length difference in magnet
- Angular dispersion
  - and wedge
  - and path lengths in slab
6D Cooling  Several methods under study

a) ”Guggenheim” Lattice

- Lattice arranged as 'Guggenheim' upward helix
- Bending gives dispersion
- Higher momenta pass through longer paths in wedge absorbers giving momentum cooling (emittance exchange)
- Starting at 201 MHz and 3 T, ending at 805 MHz and 10 T

e.g. 805 MHz 10 T cooling to 400 mm mrad
b) Snake (Y Alexahin)

- Tilted alternating solenoids generate dispersion
- Higher momenta pass through absorbers at steeper angles giving momentum cooling (emittance exchange)
- Lattice accepts both signs
- Starting at 201 MHz and 2.5 T, ending at 805 MHz and 10 T
c) Helical Cooling Channel (HCC)  Derbenev

- Muons move in helical paths in high pressure hydrogen gas
- Higher momentum tracks have longer trajectories giving momentum cooling (emittance exchange)

- Engineering integration of rf difficult
- Possible problem of rf breakdown with intense muon beam transit
Cooling system simulation

- Use Guggenheim lattices
  They can cover the widest span of emittances
  Snakes would be cheaper: both signs at once, but not to such low emittance
  HCC ok for earlier part, but looks expensive

- This (and HCC) requires charge separation immediately after phase rotation
  alternatives are simple 4D cooling or Snake before separation

- Fernow separation using bent solenoids 85% transmission
  but apparent miss-matching that needs work
  this is NOT included in this study
Tapered lattices
As emittance falls, focusing beta should fall too
Beta can also be reduced by lowering all dimensions and raising the axial fields
We choose to reduce cells from 275 cm to 68.75 cm,
With axial fields rising from $\approx 3$ T to $\approx 12$ T

- Range of betas from 68 cm to 2.37 cm (29:1) as required
- 22 stages with betas decreasing by 15%/stage
• Some beta "bounce" at changes could be fixed by fine tuning
• Frequency should have fewer steps and phase matching
• Later stages have local $\approx 20$ T fields & must use $\text{Nb}_3\text{Sn}$
dp/p vs length

- Equilibrium dp/p ≈ 3% approached at end
- Over most of length dp/p ≫ equilibrium giving efficient longitudinal cooling
- Acceptance > 3 sigma over most of length
ICOOL Simulation of Guggenheim

- Skip all later stages
- Use matrices rather than bends and wedges
  reproduces full simulation for given lattices

<table>
<thead>
<tr>
<th>trans % emit (mm)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
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<tr>
<td>length (m)</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>1.0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>10</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

| HFOFO Snake       | 201 | 402 | 805 |
| Flat              | 44.5 |

| RFOFO Guggenheim  | long 1.67 (mm) | perp 1.23 |
| Flat              | 44.5 |

14
6D bunch merge  21→1

Longitudinal Merge 21→7

Transverse merge 7→1
Cooling after Merge

- less initial emittance after merging than initial
- Skip first 4 stages
Final Transverse Cooling in High Field Solenoids

- Use the highest field possible
- Lowering momentum helps:
  - Focusing is stronger
  - Energy loss is greater
- Slope of $dE/dx$ vs $E \rightarrow$ increased $dp/p$ & Long Emittance
- But this is now ok
ICOOOL Simulations

- Need $\approx 15$ solenoids

- Simulation of re-acceleration & matching only for last two stages
- Simulations of other stages without matching and re-acceleration
- Design using 40 T achieves same emittance but with losses to be studied
Simulation of production, to end of cooling

- 'Continuous' simulation from target to start of 30-50 T
- Emit exchange in 6D simulated with matrix
- Matching between 30-50 T solenoids not simulated
- Length and losses in 50 T are approximate
Longitudinal vs transverse emittances

- Meets requirements
Transmission

<table>
<thead>
<tr>
<th></th>
<th>transmission</th>
<th>cumulative</th>
<th>mu/p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best 21 bunches</td>
<td>0.7</td>
<td>0.7</td>
<td>0.153</td>
</tr>
<tr>
<td>Charge separation</td>
<td>0.85*</td>
<td>0.59</td>
<td>0.129</td>
</tr>
<tr>
<td>6D Cooling before merge</td>
<td>0.468</td>
<td>0.28</td>
<td>0.061</td>
</tr>
<tr>
<td>Merge</td>
<td>0.88</td>
<td>0.25</td>
<td>0.055</td>
</tr>
<tr>
<td>6D Cooling after merge</td>
<td>0.48</td>
<td>0.12</td>
<td>0.026</td>
</tr>
<tr>
<td>50 T Cooling</td>
<td>0.7*</td>
<td>0.08</td>
<td>0.018</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.7</td>
<td>0.06</td>
<td>0.013</td>
</tr>
</tbody>
</table>

* These values approximate

- Transmission less than previous (7→6.0 %) due to including charge separation
- But initial production is better, from 8 GeV and MARS 15 vs MARS 14

For $2 \times 10^{12}$ muons $1.54 \times 10^{14}$ protons/bunch
Power at 15 Hz: 2.95 (MW) less than previous (4 MW)
R&D on rf breakdown in Magnets

- **Theory:**
  - Electrons from field emission accelerated to \( \approx 1 \) MeV
  - Focused by field, fatigue damage from cyclical heating to \( T > 100 \) deg.

- **Solutions ?**
  - Use high pressure gas    Question in beam    Difficulty for low beta
  - Magnetically insulate
  - Use beryllium
Magnetic Insulation

Accelerating Cavity

Box cavity Exp

New result form Box Exp
Use of Beryllium

- No damage on Be
- Low density and strength
- Ongoing design at LBNL
- Hybrid uses less Be
- More eff than Mag-ins
R&D towards 50 T solenoid
PBL Phase II SBIRs with BNL Magnet Div

- 10 T YBCO outer solenoid
  first SBIR
- 12 T YBCO inner solenoid
  second SBIR
- Nested for \( \approx 20 \) T
- In NHMFL 19T: \( \approx 40 \) T

13 of 28 Coils for outer 10 T
each tested at 70 deg
4 deg test when all finished
Conclusion

• Phase rotation well established
• Guggenheim Lattices chosen for this study
  – simulated with several codes (ICOOL, G4-Beamline, Balbakov)
  – allow very low betas by focusing
  – Snake may be preferred for early stages
• For maximum efficiency taper betas as emittance falls
• Bunch merging (6D) after initial 6D cooling
• Final cooling in 30 (rising to 40 or 50) T solenoids
• Appears to meet requirements, but
  – Need charge separator
  – Need matching and re-acceleration for between final cooling solenoids
  – Then full simulation
• R&D
  – Problem with rf in magnetic fields - Magnetic insulation looks good
  – SBIR program towards 40 T
• We are getting close
Graph showing the critical current density \( J_c \) (A/mm²) as a function of applied field (T) for various superconducting materials. The graph includes data points and lines representing different materials such as YBCO, Nb-Ti, MgB₂, and \( \text{Nb}_3\text{Sn} \). The graph legend indicates specific data sources and conditions, such as CERN LHC Nb-Ti strand production, MgB₂ 19Fil 24% Fill (HyperTech), NbTi LHC Production 38% SC (4.2 K), \( \text{Nb}_3\text{Sn} \) RRP Internal Sn (OI-ST), and more. The graph also highlights the performance of YBCO B|| Tape Plane, YBCO B⊥ Tape Plane, RRP \( \text{Nb}_3\text{Sn} \), and bronze \( \text{Nb}_3\text{Sn} \) with high Sn Bronze Cu:Non-Cu 0.3.
Collider Ring
1.5 TeV lattice (Y Alexahin, E Gianfelice-Wendt)

- $\beta=1$ cm is VERY SMALL (RHIC $\approx 3$ m)
- 4.5 sigma dynamic aperture
- 0.8% dp/p
Collider Ring Magnets

BNL Open Mid-plane Dipole

Lorentz Forces:
Vertical: down
Horizontal: out

Beam

Lorentz Forces:
Vertical: up (small)
Horizontal: out

Warm dumps

radiation
electrons

FNAL Open Mid-plane Dipole

MARS simulation
• Sophisticated shielding of decay electron background designed for 1996 4 TeV
• GEANT simulations then indicated acceptable backgrounds
• Would be less of a problem now with finer pixel detectors

BUT

• Tungsten shielding takes up 10-20 degree cone
• Simulation now re-started
Layout of 3 TeV Collider using pulsed synchrotrons
R&D
MERIT Experiment

• MERIT demonstrated liquid mercury target for multi-megawatt beams
• Splash velocities moderate and reduced by magnetic field
• Remaining need to improve jet quality
Muon Ionization Cooling Experiment (MICE)
International collaboration at RAL, US, UK, Japan  (Blondel)

- Will demonstrate transverse cooling in liquid hydrogen, including rf re-acceleration
- Uses a different version of 'Guggenheim’ lattice

- Early Experiment to demonstrate Emittance Exchange
  - Dispersion by weighting
  - Cooling in all dimensions
  - But no re-acceleration
4) MuCool, and MuCool Test Area (MTA) at FNAL
International collaboration US, UK, Japan (Bross)

- Liquid hydrogen absorber tested
- Open & pillbox 805 MHz cavities in magnetic fields to 4 T
- 201 MHz cavity tested in stray magnetic field of 0.7 T
  Later, with coupling coil, to 2T
- High pressure H2 gas 805 MHz pillbox cavity tested
- Soon: 805 MHz gas Cavity with proton beam
rf
201 MHz warm L=0.37 G=15.5 MV/m P=4.0 MW
Acc 1.3 GHz 30 MV/m 10% loading