Progress of Front End Design and FOFO Snake

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Outline

• Front end design
  – Baseline configuration
  – Buncher Phase Rotator
  – Cooler options

• HFOFO “Snake” properties
  – Design Concepts
  – Example (IBS)
  – Simulation

• Variations
  – cold muon source
• **From target to end of initial cooling**
  
  – capture and bunch $\pi \rightarrow \mu$; initial cooling for downstream
  
  – captures & cools both signs ($\mu^+$ and $\mu^-$)

• **Same system can be used for both $\nu$ factory and $\mu^+\mu^-$ collider**
IDS Neutrino Factory Buncher and φ-E Rotator

- **Drift** ($\pi \rightarrow \mu$)
- “Adiabatically” bunch beam first (weak 320 to 232 MHz rf)
- **Φ-E** rotate bunches – align bunches to ~equal energies
  - 232 to 202 MHz, 12MV/m
- **Cool beam 201.25MHz**
- Captures and Cools both $\mu^+$ and $\mu^-$
Buncher/Rotator Example

- **Drift** from target ~60m
  - $\pi \rightarrow \mu$
  - Beam lengthens
- **Buncher** (~30m)
  - $N=10$, $P_0=280$ MeV/c, $P_N=154$ MeV/c
  - $330 \rightarrow 235$ MHz
  - $V'=0 \rightarrow 10$ MV/m
- **Rotator** (~35m)
  - $N=10.08$ – accelerate/decelerate bunches
  - $235 \rightarrow 202$ MHz, $V'=12$ MV/m
- **Cooler** (~80m)
  - $201.25$ MHz, ASOL lattice
  - $15$ MV/m in rf cavities
  - LiH or $H_2$ cooling
- Captures both $\mu^+$ and $\mu^-$
MAP: 200→325MHz System

- **Drift**
  - 20T → 2T

- **Buncher**
  - $P_0 = 250\text{MeV/c}$, $P_N = 154\text{ MeV/c}$; $N = 12$
  - $V_{rf} : 0 → 15\text{ MV/m}$
  - $f_{RF} : 490 → 365\text{MHz}$

- **Rotator**
  - $V_{rf} : 20\text{MV/m}$
  - $f_{RF} : 364 → 326\text{MHz}$
  - $N = 12.045$

- **Cooler**
  - 245 MeV/c, 325 MHz, 25 MV/m
  - LiH absorbers

325 MHz – much more affordable than 200MHz
more compact, ~1/2 rf power
matches present/future power sources/ frequencies-ILC, PIPII
but more bunches in bunch train for collider (~12 → ~21)
Problem: Beam Losses & Activation

- Beam Loss and Activation
  - 4MW p beam
  - 100 kW secondaries ..
    - ~kW/m losses in line

- Solution: Chicane and Absorber
  - Chicane: bend out ~15\(\times\) 6.5m
  - bend back ~15\(\times\) 6.5m
    - separates high-E particles
  - Absorber
  - ~10 cm Be
    - stops p, \(\pi\), K low-E \(\pi\)

- Localizes beam-related losses to before buncher/rf
• **Add chicane**
  – .6.5m → +15°, 6.5m -15°

• **Add 30 m drift after chicane to absorber**
  – .6.5m → +15°, 6.5m -15°

• **Rematch**
  – particle 1-283 MeV/c → 250
  – particle 2-194 MeV/c → 154
    – Bunch (N=12) 0→15 MV/m :496 → 365 MHz
    – Rotate (N=12.045 )– 20 MV/m :365 → 326.5 MHz
    – Cool -325MHz -25 MV/m

• **Obtain ~0.1 \( \mu^+ \) and \( \mu^-/p \)
Compare without/with chicane

-30m
-50m

1600 GeV/c
0 GeV/c

0m (production target)
66m (after chicane/absorber)
88m (after drift)
109m (after buncher)
132m (after rotator)
190m (after cooling)

57m
79m
102m
152m
21 bunches for Collider
Cooling Section – “2-D” cooling only

- Baseline Initial cooling system
  - from IDS Neutrino Factory cooling
  - Consists of rf & LiH absorbers & Alternating Solenoid focusing

- Cools transverse emittance
  - $\sim l_t : 0.016 \rightarrow 0.0065 \text{ m}$
  - $l_L : 0.04 \rightarrow \sim 0.03 \text{ m}$
    - no longitudinal cooling (scrapping)

- $\sim 0.1 \mu / 8\text{GeV} \ p$ within acceptance
  - most beam outside acceptance scraped away

Useful cooling

$N : 0.15 < P < 0.35 \text{ GeV/c}$

$N : \epsilon_T < 0.03$; $A_L < 0.2$

$N : \epsilon_T < 0.015$; $A_L < 0.2$
Vacuum rf or Gas-filled rf?

• Initial design was for vacuum rf within B = ~2T solenoids
  – rf gradient limited within magnetic fields (?)
    • gas-filled rf does not breakdown
      – (but has plasma loading effect)

• Front end can have gas-filled rf
  – same performance as with vacuum rf
    • need a bit higher gradient to compensate energy loss in gas
      – With higher density gas and higher gradient
        • can have some cooling in buncher/rotator
          – better performance

• Would like to increase B → 3T
“FOFO Snake” initial cooling  [Y. Alexahin et al. ]

• Motivation
  – Obtain front end 6-D cooling
  – equal cooling in x and y
    • cyclotron and drift modes
  – For both $\mu^+$ and $\mu^-$
    • Dispersion+wedge would only cool one sign …
      – (we thought …)

• Principles
  – Alternating solenoid cooling
  – resonance dispersion
    • tilts in solenoids
      \[ D_x = \frac{dx_{co}}{d\delta_p} \approx -\pi Q'_x x_{co} \cot(\pi Q_x) \]
  – Longitudinal cooling from path length ($E_\mu$)
Basic Principles of “FOFO Snake”

• **Alternating Solenoid field**
  – Equal cooling of transverse modes
    • cyclotron/drift modes exchange at each flip

• **Resonance Dispersion generation**
  – solenoid tilts generate helical orbit/dispersion
    • $x_{co} \sim 1/\sin(\pi Q_x)$
    

\[
D_x = \frac{d x_{co}}{d \delta_p} \approx -\pi Q'_x \cdot x_{co} \cdot \cot(\pi Q_x)
\]

    • larger compaction factor if tune $\sim N+\delta$

• **Longitudinal cooling in flat absorbers due to D'**
  • path length ($\delta_p$)
    

\[
x = x_{co} + D_x \delta_p
\]

    • initially without wedge absorbers
Baseline  325 Mhz cooler example

- 6 cell period
  - $4.2 \text{m, } B_{\text{max}} = 3.7 \text{T}$
  - $\beta_t \approx 0.6 \text{m}$
  - 325MHz rf, 25 MV/m
  - 2.5 mrad Tilts

- Gas filled (1/5 Liquid H$_2$ density)
  - (slabs could also be used)
    - with LiH wedges
FODO snake properties

- 2.5 mrad tilts oriented at
  \[ \phi_k = \frac{4\pi}{3}, \frac{2\pi}{3}, \frac{4\pi}{3}, 0, \frac{2\pi}{3} \]
  from vertical

- Wedges follow similar rotation
  - Are placed to **cool both signs**: \( \mu^+ \) and \( \mu^- \)

- Eigen values, equilibrium \( \epsilon \)

<table>
<thead>
<tr>
<th>Mode</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tune</td>
<td>1.2271 + 0.0100i</td>
<td>1.2375 + 0.0035i</td>
<td>0.1885 + 0.0049i</td>
</tr>
<tr>
<td>Emittance (mm)</td>
<td>2.28</td>
<td>6.13</td>
<td>1.93</td>
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- not balanced in \( x, y \) – (add quad)

- Total cooling channel is
  \(~30\) cells (126 m)
Matching from upstream Rotator

- **Transverse Optics match**
  - constant solenoid to ASOL

- **Helical Orbit match**
  - tilts of solenoids 3-9

- **Longitudinal momentum match**
  - gradual deceleration

  - phases readjusted to compensate for amplitude/momentum correlation
Cooling & Transmission (G4BL)

Effect of energy - transverse amplitude correlation, but otherwise matching is O.K.

Normalized emittances (cm) from Gaussian fit:
\( \mu^+ \) - solid lines, \( \mu^- \) - dashed lines.

Transmission as a ratio of the number of muons in the Gaussian core: red solid line - \( \mu^+ \), blue dashed line - \( \mu^- \).

Final/Initial values (Gaussian fit):

<table>
<thead>
<tr>
<th></th>
<th>( N^{(\text{total})} )</th>
<th>( N^{(150&lt;p&lt;360)} )</th>
<th>( N^{(\text{core})} )</th>
<th>( p^{(\text{cnt})}, \text{MeV/c} )</th>
<th>( \varepsilon_{m\nu}, \text{cm} )</th>
<th>( \varepsilon_{6Dr}, \text{cm}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^+ )</td>
<td>5378/11755</td>
<td>5167/7998</td>
<td>5010/7329</td>
<td>208.2/248.0</td>
<td>0.19/1.19</td>
<td>0.36/2.19</td>
</tr>
<tr>
<td>( \mu^- )</td>
<td>5896/12396</td>
<td>5743/9020</td>
<td>5499/8248</td>
<td>207.7/248.8</td>
<td>0.16/1.22</td>
<td>0.46/2.10</td>
</tr>
</tbody>
</table>
Results and discussion

• **Beam phase space**
  – before (blue)
  – after (red)

• **Longitudinal distributions**
  – momentum spread reduced by factor of ~2
Comparison to 2-D cooling

• Cools in 3-D
  – $\varepsilon_1$: 2.2 $\rightarrow$ 0.4 cm; $\varepsilon_2$: 1.2 $\rightarrow$ 0.2 cm; $\varepsilon_L$: 2.4 $\rightarrow$ 0.7 cm
  – $\varepsilon_t$: 1.7 $\rightarrow$ 0.6 (2D)

• More Cooling (than 2-D baseline)
  – but longer channel & stronger focusing
    • up to 120m; $B_{\text{max}}$ 2.8 $\rightarrow$ 3.7 T

• Initial Acceptance a bit less than 2-D cooling channel
  – $\sim$10%

• Better match to downstream systems
  – from longitudinal cooling …
Front End with Helical FOFO cooler preferred

- Smaller momentum spread bunches will fit into downstream components more easily
  - Acceleration transition 325→650 MHz can occur earlier
    - at ~1 GeV/c for nu-Factory → “NuMAX” scenario
  - Cooling transition 325→650 for collider sooner …
  - losses reduced; separation of $\mu^+$ and $\mu^-$ easier …

- Deceleration to a lower energy muon beam (mu2e?) easier, with fewer losses
To Do

- Write-up current status for JINST volume
- Variations / Improvements -- ?
- Scale back to low-energy applications
  - smaller, lower field system capturing at 150 MeV/c
    - 50m → 25m
    - → 100 MeV/c
    - ~0.05 μ/p
Summary

This might look like an ordinary PowerPoint slide.

But it is actually a portal to another dimension in which energy and position have traded places.

Stop playing with my slides.

Beware the beast that crosses over.
Backup slides
Low-E capture

- Capture at low momentum
  - prepare beam for low-E $\mu$ experiment
- Somewhat scaled back version of front end
  - 30.4m drift
  - shorter buncher /rotator
    - 12m / 13.5m
    - 0→15 MV/m, 15 MV/m
      - vacuum rf
  - B=2T

- Parameters
  - 150 MeV/c … 100 MeV/c reference particles
  - 77.8 // 39.8 MeV
- Bunch to 150 MeV/c

- Cooling at 2T (1-D cooling)
simulation of low-E buncher

- Used Ding initial beam
  - initial beam cut off at ~70 MeV/c
    - 21 MeV kinetic energy
  - bunch train formed

- Cooling from 60m to 100m
  - longitudinal antidamping
    - $g_L = \sim -0.5$
  - $B=2T, 2cm$

- more used to separate captured from uncaptured beam

- $\sim 0.05 \mu/p$ within acceptance ??
  - not sure what acceptance criteria to use