Introduction

Daniel M. Kaplan

Absorber Review Meeting
Fermilab
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Outline:

1. Collaboration
2. Brief review of ionization cooling
3. Choice of absorber medium
4. Power handling (linear vs. ring coolers)
5. Windows & containment
6. Summary
Absorber R&D Collaboration

E. Almasri, E. L. Black, K. Cassel, R. Johnson†, D. M. Kaplan, W. Luebke
Illinois Institute of Technology*

S. Ishimoto, K. Yoshimura
KEK High Energy Accelerator Research Organization

M. A. Cummings, A. Dychkant, D. Hedin, D. Kubik
Northern Illinois University*

Y. Kuno
Osaka University

D. Errede, M. Haney
University of Illinois at Urbana-Champaign*

M. Reep, D. Summers
University of Mississippi

W. Lau
University of Oxford

in collaboration with

D. Allspach, C. Darve, S. Geer, C. Johnstone‡, A. Klebaner, B. Norris, M. Popovic, A. Tollestrup
Fermilab

* member, Illinois Consortium for Accelerator Research  † also at Muons, Inc.  ‡ also at IIT
(Is this up-to-date?)
Ionization Cooling

Absorbers:

\[ \frac{dE}{dx} \]

\[ \frac{dE}{dx} \]

\[ \frac{dE}{dx} \]

\[ \frac{dE}{dx} \]

- Absorbers:

\[
\begin{align*}
E & \to E - \langle \frac{dE}{dx} \rangle \Delta s \\
\theta & \to \theta + \theta_{\text{space}}^{\text{rms}}
\end{align*}
\]

for thin absorber, \( \theta_{\text{space}}^{\text{rms}} = \sqrt{2} \theta_0 \), where \( \theta_0 \approx \frac{0.014 \text{GeV}}{\beta c p} \sqrt{\frac{L}{L_R}} \) (Gaussian approx.)

- RF cavities between absorbers replace \( \Delta E \)

- Net effect: reduction in \( p_\perp \) spread w.r.t. \( p_\parallel \), i.e., transverse cooling

- But energy spread increases due to energy-loss straggling \( \to \) beam losses
Longitudinal Ionization Cooling?

- At or below ionization minimum, $dE/dx$ slope zero or negative $\Rightarrow$ no negative feedback
- Above ionization minimum, $dE/dx$ slope positive
  - but too small to be useful, and
  - straggling (random fluctuations in ionization rate) significant
$\Rightarrow$ no good regime for longitudinal ionization cooling

$\rightarrow$ Emittance-exchange concept:

![Diagram of muon beam, bending magnets, and low-Z wedge absorber]
Comparing potential absorber media:

- **2D transverse-cooling rate:**

\[
\frac{d\varepsilon_{x,N}}{dz} \approx -\frac{1}{\beta^2} \frac{\varepsilon_{x,N}}{E} \left| \frac{dE}{dz} \right| + \beta_\perp \frac{(0.014 \text{ GeV})^2}{2\beta^3 E m_\mu L_R}
\]

<table>
<thead>
<tr>
<th>Mat'l</th>
<th>(\rho) (g/cm(^3))</th>
<th>(dE/dx) (MeV/g \cdot cm(^2))</th>
<th>(dE/dx) /cm (MeV/cm)</th>
<th>(L_R) (cm)</th>
<th>merit ((L_R dE/dx)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH(_2)</td>
<td>0.0708</td>
<td>4.05</td>
<td>0.29</td>
<td>866</td>
<td>1</td>
</tr>
<tr>
<td>LHe</td>
<td>0.125</td>
<td>1.94</td>
<td>0.24</td>
<td>755</td>
<td>0.51</td>
</tr>
<tr>
<td>LiH</td>
<td>0.82</td>
<td>1.94</td>
<td>1.59</td>
<td>106</td>
<td>0.44</td>
</tr>
<tr>
<td>Li</td>
<td>0.53</td>
<td>1.64</td>
<td>0.88</td>
<td>155</td>
<td>0.28</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.42</td>
<td>2.42</td>
<td>1.03</td>
<td>46.5</td>
<td>0.19</td>
</tr>
<tr>
<td>Be</td>
<td>1.848</td>
<td>2.95</td>
<td>2.95</td>
<td>65</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- “merit” \(\propto\) 4D transverse-cooling rate

\(\Rightarrow\) In the scattering-limited cooling regime, as equilibrium between cooling and heating is approached, hydrogen is best by factor \(\approx 2\)
Absorber Power Handling

• Neutrino Factory Feasibility Study II absorbers:

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Length (cm)</th>
<th>Radius (cm)</th>
<th>Window thickness (µm)</th>
<th>Number needed</th>
<th>FS-II power (kW)</th>
<th>“Rev.-FS-II” power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minicool?</td>
<td>175</td>
<td>30</td>
<td>?</td>
<td>2</td>
<td>≈5.5</td>
<td>≈22</td>
</tr>
<tr>
<td>SFOFO 1</td>
<td>35</td>
<td>18</td>
<td>360</td>
<td>16</td>
<td>≈0.27</td>
<td>≈2</td>
</tr>
<tr>
<td>SFOFO 2</td>
<td>21</td>
<td>11</td>
<td>220</td>
<td>36</td>
<td>≈0.1</td>
<td>≈0.9</td>
</tr>
</tbody>
</table>

(Not LH2)

– power dissipation w/ 4-MW Proton Driver & both µ charges at once

– First, estimate rate of bulk temperature rise if no flow:

\[
c_p = 1.1 \times 10^4 \text{ J/kg}\cdot\text{K}
\]

\[
\Delta T / s = \frac{\langle P \rangle}{c_p V \rho} = \frac{\langle P \rangle / L}{c_p A \rho}
\]

\[
= \frac{2 \text{ kW} / 0.35 \text{ m}}{1.1 \times 10^4 \text{ J/kg}\cdot\text{K} \times \pi (0.16 \text{m})^2 \times 70.8 \text{ kg/m}^3}
\]

\[
\approx 0.1 \text{ K/s}
\]

\[\Rightarrow 0.1 \text{ volume change/s sufficient to keep } \Delta T \lesssim 0.1 \text{ K}\]

\[\approx 3 \text{ l/s for SFOFO 1 (35-cm) absorber}\]

→ should be feasible if good transverse mixing, without eddies or dead zones
**Ring Cooler**

- **Ring cooler:**
  - does 6D cooling via simultaneous transverse cooling and emittance exchange
  - e.g. Palmer design:

- Requires muons to traverse each absorber 10–20 times
  \[ \rightarrow \approx 20 \text{kW/absorber power dissipation} \]

- Is this feasible?
Ring Cooler Power Handling

- \( \Delta T \) per turn at beam center neglecting heat xfer (T. Roberts, LIT):
  \[
  \Delta T \approx \frac{N \frac{dE}{dx}}{\sigma^2 c_p} = \frac{N}{\sigma^2} \frac{4.2 \text{ MeV/g} \cdot \text{cm}^{-2}}{11 \text{ J/g} \cdot \text{K} \times 1.6 \times 10^{13} \text{ MeV/J}}
  \]
  (assuming Gaussian beam centered at origin – maybe poor approx for ring cooler)

- Assume \( N = 2.8e13 @ 15 \text{ Hz} \) (4-MW 24-GeV \( p \) beam \( \times 0.2 \mu/p \times 2 \mu \) charges):

\[ \Rightarrow \text{A single cycle does not boil the hydrogen, BUT} \]
- can the heat be removed quickly enough? (need low \( \Delta P \) due to thin windows!)
- maybe better than this:
  - in some designs wedge covers only half of beam
  - 2.8e13 \( \mu/pulse \) maybe overestimate?
  - dispersion may lower peak intensity – need actual beam distribution from simulation
Absorber Windows

(E. Black, IIT, W. Lau, Oxford, M. Reep, D. Summers, UMiss)

• **R&D issue:** conventional designs for pressure-vessel windows too thick
  – especially true for ring cooler, which approaches scattering-dominated regime

→ Developing thin, tapered windows, custom-machined (with integral flange) out of a single block of material:
Established FNAL liquid-hydrogen rules are explicit:

1. must prevent oxygen contamination within hydrogen loop, AND
2. must exclude ignition sources from vacuum vessel containing absorber

Since RF cavities considered an ignition source,

⇒ must have “primary containment” vacuum vessel surrounding absorber vessel

⇒ twice as many windows as in Feasibility Study II simulation!

Fortunately,

vacuum window need not be as strong as absorber window (since not an LH$_2$ container)

⇒ total Al thickness per cell comparable to that in FS-II:

2 × 360 µm “SFOFO 1” lattice

2 × 220 µm “SFOFO 2” lattice
Even Thinner Windows?
(D. Summers, UMiss)

- “Aircraft alloys” (containing Li) are stronger & lighter than 6061:

<table>
<thead>
<tr>
<th>Al alloy name</th>
<th>Composition</th>
<th>Density</th>
<th>Yield strength @300K</th>
<th>Tensile strength @300K</th>
<th>Tensile strength @20K</th>
<th>Rad. Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% by weight</td>
<td>(g/cc)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(cm)</td>
</tr>
<tr>
<td>6061-T6</td>
<td>1.0Mg 0.6Si 0.3Cu 0.2Cr</td>
<td>2.70</td>
<td>40</td>
<td>45</td>
<td>68</td>
<td>8.86</td>
</tr>
<tr>
<td>2090-T81</td>
<td>2.7Cu 2.2Li .12Zr</td>
<td>2.59</td>
<td>74</td>
<td>82</td>
<td>120</td>
<td>9.18</td>
</tr>
</tbody>
</table>

⇒Windows could be ≈45% thinner, if
- 2090-T81 has good machinability and
- such thin windows can be reliably machined

... to be tested soon at U. Miss.

(Note latest window shape already 40% thinner than previous iteration)
Summary

- Healthy progress developing LH$_2$ absorbers with thin windows
- Need to continue iterating towards optimal, self-consistent designs
- Need to document details of absorbers for MuCool, MICE
- Need to pass safety reviews
- Need to think about wedge absorbers and limits to power handling