Flow Absorber Possibilities

C. Darve
Fermi National Accelerator Laboratory
Batavia, IL, 60500, USA

Neutrino Factory & Muon Collider Collaboration Meeting
@ IIT
03/12/06
Flow Absorber possibilities

From simulations to experiments...

Headlines:

- Materials and fluids for Muon ionization cooling
- Disadvantages of the LH\textsubscript{2} choice
- Review of the basic LH\textsubscript{2} Absorbers designs
- Design philosophy for a hostile environment
- Implementing SAMPLE cryo-loop
- Cryo-system to support the LH\textsubscript{2} absorber tests at MTA
- Concluding comments
Materials and fluids for Muon ionization cooling

Ionization cooling

Bethe-Blücher multiple scattering

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>A</th>
<th>(Z/A)</th>
<th>Nuclear collision interaction length $\lambda_r$ [g/cm$^2$]</th>
<th>Nuclear collision interaction length $\lambda_i$ [g/cm$^2$]</th>
<th>Nuclear dE/dx at min [MeV/g/cm$^2$]</th>
<th>Fusion reaction X$_{0}$ [g/cm$^2$]</th>
<th>Refractive density [g/cm$^3$]</th>
<th>Liquid boiling point at 1 atm (K) [°F]</th>
<th>Refractive index n</th>
<th>for gas (g/L)</th>
<th>Point at (n-1)x10$^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ gas</td>
<td>1</td>
<td>2</td>
<td>0.99212</td>
<td>43.3</td>
<td>50.8</td>
<td>1.0103</td>
<td>61.28</td>
<td>0.0988</td>
<td>0.0099</td>
<td>139.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$ liquid</td>
<td>1</td>
<td>2</td>
<td>0.99212</td>
<td>43.3</td>
<td>50.8</td>
<td>1.0103</td>
<td>61.28</td>
<td>0.0988</td>
<td>0.0099</td>
<td>139.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D$_2$</td>
<td>1</td>
<td>2</td>
<td>0.99632</td>
<td>43.7</td>
<td>50.7</td>
<td>1.0103</td>
<td>61.28</td>
<td>0.0988</td>
<td>0.0099</td>
<td>139.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>0.9968</td>
<td>49.9</td>
<td>65.1</td>
<td>1.0103</td>
<td>61.28</td>
<td>0.0988</td>
<td>0.0099</td>
<td>139.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
<td>18</td>
<td>0.9595</td>
<td>56.0</td>
<td>75.2</td>
<td>1.0103</td>
<td>61.28</td>
<td>0.0988</td>
<td>0.0099</td>
<td>139.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Source: NASA, Glenn Research Center Safety Manual |
Disadvantages of the LH$_2$ choice

- Stringent safety requirements for mech. & elec. designs (25 liters of LH$_2$ released into the air with a 10% yield = 4 kg of TNT)
- Need Cryogenic plant to supply LHe flow and subcooled LH$_2$ to 17 K
- None standard thin Aluminum windows to contain LH$_2$
  - On-going effort to comply with safety requirements
  - Supported by photogrammetry: Innovative none intrusive technique

### Cryogenic Properties of Various Gasses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He</th>
<th>N$_2$</th>
<th>H$_2$</th>
<th>CH$_4$</th>
<th>C$_3$H$_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triple point temperature $T_t$ (K)</td>
<td>2.177*</td>
<td>63.15</td>
<td>13.81*</td>
<td>90.69</td>
<td>91.46</td>
</tr>
<tr>
<td>Heat of fusion @ $T_t$ (J g$^{-1}$)</td>
<td>-NA-</td>
<td>25.3</td>
<td>59.5*</td>
<td>58.41</td>
<td>79.97</td>
</tr>
<tr>
<td>Boiling temp. $T_b$ @ 1 bar (K)</td>
<td>4.222</td>
<td>77.35</td>
<td>20.28*</td>
<td>111.67</td>
<td>230.46</td>
</tr>
<tr>
<td>Liquid density $\rho$ @ $T_b$ (kg m$^{-3}$)</td>
<td>124.9</td>
<td>807</td>
<td>70.8*</td>
<td>422.4</td>
<td>585.3</td>
</tr>
<tr>
<td>Gas density $\rho_v$ @ $T_b$ (kg m$^{-3}$)</td>
<td>16.89</td>
<td>4.622</td>
<td>1.339*</td>
<td>1.816</td>
<td>2.497</td>
</tr>
<tr>
<td>Gas to liquid volume ratio at $T_b$</td>
<td>7.395</td>
<td>175.6</td>
<td>52.87*</td>
<td>232.6</td>
<td>298.0</td>
</tr>
<tr>
<td>Gas $V_{293}$ to Liquid $V_b$ Ratio</td>
<td>699.4</td>
<td>645.6</td>
<td>792.9</td>
<td>591.4</td>
<td>379.0</td>
</tr>
<tr>
<td>Gas $C_p$ @ $T_b$ (J g$^{-1}$ K$^{-1}$)</td>
<td>9.144</td>
<td>1.341</td>
<td>12.24*</td>
<td>2.218</td>
<td>1.642</td>
</tr>
<tr>
<td>Heat of vaporization @ $T_b$ (J g$^{-1}$)</td>
<td>20.7</td>
<td>198.8</td>
<td>445*</td>
<td>510.8</td>
<td>424.8</td>
</tr>
<tr>
<td>Heat flux for $\Delta T=300-T_b$ (kWm$^{-2}$)</td>
<td>-200</td>
<td>-27</td>
<td>-93</td>
<td>-47</td>
<td>-NA-</td>
</tr>
<tr>
<td>Broken vacuum heat flux (kWm$^{-2}$)</td>
<td>-35</td>
<td>-1.6</td>
<td>-19</td>
<td>-0.31</td>
<td>-NA-</td>
</tr>
<tr>
<td>Critical temperature $T_c$ (K)</td>
<td>5.195</td>
<td>126.2</td>
<td>32.98</td>
<td>190.6</td>
<td>368.8</td>
</tr>
<tr>
<td>Critical pressure $P_c$ (MPa)</td>
<td>0.228</td>
<td>3.39</td>
<td>1.29</td>
<td>4.59</td>
<td>4.36</td>
</tr>
</tbody>
</table>

$^*$ The lambda point temperature for helium. For helium liquid, gas, and solid can't coexist.

$^*$ This data is for para hydrogen. Ortho hydrogen changes to para hydrogen at < 100 K.
Effort is on-going within two schemes

**LH2: Convection scheme**: Advantage of limit LH$_2$ inventory for MICE: energy deposition ~100 W

- [IIT Internal Report-Cassel et al. 2001]
- [NUFACT'01 – S. Ishimoto et al.]
- [PAC'05 – M.A. Cummings and S. Ishimoto]
- [Cryocooler ~ 20 W]

**LH2: forced-flow scheme**: Advantage of maximum energy removed for MuCool (energy deposition larger than 300 W)

- [ICEC19, 2002 –C. Darve et al.]
- [Research instruments & methods in physics research,1996-E.J. Beise et al.]
Review of the basic LH$_2$ Absorbers designs - Convection scheme

Numerical simulation (K. Cassel/IIT)
- Natural transverse convection
- Self regulating

Orders of magnitude:
{L=0.3m; R=20cm; Q=150 W}
\[ \text{Ra}=7.25 \times 10^{13} \]

Convection heat transfer coefficients:
{Thein/out=14K/15 K; T$_{\text{LH}_2}$=18.5 K}
\[ h_{\text{LHe}}=1580 \text{ W/m}^2\text{K} \]
\[ h_{\text{LH}_2}=210 \text{ W/m}^2\text{K} \]

Proposal:
\[ \Rightarrow \text{Heat transfer area}=0.2\text{m}^2 \]
\[ \Rightarrow \text{mdot}=28 \text{ g/s} \]

Design by S. Ishimoto [see MAC’s talk]
Review of the basic LH$_2$ Absorbers designs - Convection scheme

Experimental test (FNAL/KEK) 6.2-liter of LH$_2$
LHe test @ KEK; LH$_2$ tests @ KEK run 1 & 2

KEK Run1: some Lessons learned
• Safety review process and design requirements
• Operating procedures and flow sensitive
• Cryo-system and LH$_2$ absorber stabilities
• Instrumentation precision (TT, FT)
• Data interpretation: heater element influence
• Numerical simulations to valid test <-> prototype?

[FNAL Internal report-11/05 “Reflections on Initial MTA Tests“, B.Norris, C.Darve, L.Pei]
Effort is on-going within two schemes

**LH2: Convection scheme**: Advantage of limit LH$_2$ inventory for MICE: energy deposition $\sim$100W

- [IIT Internal Report-Cassel et al. 2001]
- [NUFACT’01 – S. Ishimoto et al.]
- [PAC’05 – MA.Cummings and S.Ishimoto]

(Cryocooler $\sim$ 20 W)

**LH2: forced-flow scheme**: Advantage of maximum energy removed for MuCool (energy deposition larger than 300 W)

- [ICEC19, 2002 –C. Darve et al.]
- [Research instruments & methods in physics research,1996-E.J. Beise et al.]
Review of the basic LH$_2$ Absorbers designs – Forced-flow scheme

External cooling loop for the LH$_2$ forced-flow absorber

- Cryo-loop design with minimum of 25-liter
- Nozzle design and flow distribution to validate by a prototype test
- Since 2001 few numerical simulations have permitted to optimize the windows geometry while complying with safety requirements - maximum allowable working stress in the aluminum (P$_{\text{LH}_2}$ = 1.2 atm)
  - minimize thickness => to reduce multiple scattering
  - modify windows curve => to improve heat transfer

[Design by E. Black, W.Lau, S.Yang]
Review of the basic LH$_2$ Absorbers designs – Forced-flow scheme

- LH$_2$ absorber geometry
  - Several models and configurations:
    - w/ and w/o inner channel
    - A: 11 inlet/15 outlet; B: 15/19

- Beam simulation
  - $\phi$ 10 mm, 300 W

- LH$_2$ properties (17 K, 1.2 atm)

- Field distributions
  - Velocity
  - Temperature

- CFX solver (Ansys)
  - Heat $\rightarrow$ mdot $\rightarrow$ Velocity at inner chamber

Need optimal flow mixing in absorber, but LH$_2$ pump:
$\Delta P = 0.365$ psi @ m=450 g/s

Pressure drop in LH$_2$ circuit

- 19.7%
- 9.2%
- 19.7%
- 5.2%
- 36.4%
Review of the basic LH$_2$ Absorbers designs – Forced-flow scheme

MuCool ~300W

- Numerical simulation by Oxford Univ.:
  - Holding/Lau using Algor 2D (2002)

<table>
<thead>
<tr>
<th>Model</th>
<th>Inlet velocity</th>
<th>Initial Temp.</th>
<th>Heater</th>
<th>Reynolds Number</th>
<th>Temp. increase</th>
<th>Max. Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>8+12</td>
<td>2 m/s</td>
<td>17K</td>
<td>150W</td>
<td>4.2547E5</td>
<td>0.16K</td>
<td>279 Pa</td>
</tr>
<tr>
<td>11+15</td>
<td>0.5 m/s</td>
<td>17K</td>
<td>150W</td>
<td>9.0158E4</td>
<td>1K</td>
<td>13.7 Pa</td>
</tr>
<tr>
<td></td>
<td>2 m/s</td>
<td>17K</td>
<td>150W</td>
<td>3.49E5</td>
<td>0.38K</td>
<td>217 Pa</td>
</tr>
</tbody>
</table>

Table: Model configurations and performance metrics

<table>
<thead>
<tr>
<th>config.1 velocity</th>
<th>0.5m/s</th>
<th>1m/s</th>
<th>2m/s</th>
<th>3.3m/s</th>
<th>4.4m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>11+15</td>
<td>8.6K</td>
<td>5K</td>
<td>0.96K</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>With Chamber</td>
<td>13+19</td>
<td>-</td>
<td>5.3K</td>
<td>2.47K</td>
<td>-</td>
</tr>
<tr>
<td>15+19</td>
<td>6.1K</td>
<td>3K</td>
<td>1.8K</td>
<td>0.86K</td>
<td>0.63K</td>
</tr>
<tr>
<td>Without Chamber</td>
<td>11+15</td>
<td>-</td>
<td>-</td>
<td>0.45K</td>
<td>-</td>
</tr>
<tr>
<td>13+19</td>
<td>-</td>
<td>-</td>
<td>0.93K</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15+19</td>
<td>-</td>
<td>-</td>
<td>0.39K</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Review of the basic LH$_2$ Absorbers designs – Forced-flow scheme

- Influence of flow symmetry and number of active nozzles
- Configuration with 15 inlet nozzles and 19 outlet nozzles; velocity 2 m/s at inner chamber inlet

These results are still waiting to be validated by experiment!!

Ex: 11+15 config _without channels_ inlet velocity at 2m/s, heater at 300W
Review of the basic LH$_2$ Absorbers designs – Forced-flow scheme

- Structural analysis
- Thermal analysis
- Hydraulic analysis (w/ Oxford Univ.)
- Process and Instrumentation Diagram
- Venting considered
- Oxygen Deficiency Hazard

Cryo-system development

25-liter of LH$_2$
27 g/s of helium @ 14 K, 1.2 atm
Design philosophy for a hostile environment

- Electrical components located in the experimental hall must be rated Class 1, Div. 2 Gp B or considered as intrinsically safe: e.g. He guard, N\textsubscript{2} purge, specific equipments, etc...
- Venting system designed to account for H\textsubscript{2} gas released from thermal expansion
- Building equipment: flammable gas, Oxygen Deficiency Hazard system, ventilation, audio and visual alarm
- Operating Procedures, interlock, Safety PLC, Personnel safety training

Additional instrumentation and materials requirements:
- Operate at cryogenic temperatures (physical properties)
- High magnetic field (absorber sits inside the 4 Tesla SC solenoid magnet)
- Radiation-hard (able to withstand more than 300 mS/hr)

Design guidelines:


LH\textsubscript{2} expertise from FNAL, SAMPLE, E158, G0...

LHC experiences: Cernox use
Implementing SAMPLE cryo-loop

SAMPLE Heat exchanger:
- 1 kg/sec LH$_2$ flow
- Counterflow
- Cu hose and SS housing
- dim: 85 cm, $\phi$ 15 cm

Modified to account for the SAMPLE cryostat

Same:
Implementing SAMPLE cryo-loop

Permit to save fabrication cost (heat exchanger, operational LH$_2$ pump and motor) to help get the forced-flow system online, but the current engineering design must reflect these modifications.
<table>
<thead>
<tr>
<th>Cryo-systems to support LH₂ absorber tests at MTA [see B.Norris’s-talk]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- MTA facility equipped with Hydrogen test capacity</td>
</tr>
<tr>
<td>- MTA building: practicality of cryogenic cooling in hazardous environment</td>
</tr>
<tr>
<td>- Safety PLC (QUADlog), ODH, fan, vent, etc...</td>
</tr>
<tr>
<td>- First MTA helium distribution using helium and nitrogen Dewars to operate KEK convective-type LH₂ absorber test and the SC solenoid magnet</td>
</tr>
<tr>
<td>- Future Helium facility (compressor, refrigerator and transfer line) operating in switch-over mode [COOL’05]</td>
</tr>
<tr>
<td>- 4 K mode – to SC MTA solenoid magnet and other cryo-components.</td>
</tr>
<tr>
<td>- 14 K mode – to forced-flow, convective type LH₂ absorbers</td>
</tr>
<tr>
<td>Use Tevatron satellite components ➔ Expected liquefaction rate is 78 liter/hr</td>
</tr>
<tr>
<td>- Expander test has been performed to ensure the supply of 27 g/s of helium at 14 K, 15 psig (0.2 MPa) required for removing 300 W of heat deposition from the forced-flow absorber cryo-loop (ΔT of 1 K)</td>
</tr>
</tbody>
</table>

[COOL’05 – “Cryogenics for the MuCool Test Area (MTA)” C.Darve, B.Norris, L.Pei]
What exist and what we need?

**What exist for future LH$_2$ absorber tests?**
- Numerical models to simulate test results (convective and forced-flow schemes)
- More precise numerical model to account for experimental imperfections?
- Adequate instrumentation type, number and position to correlate data?
- Expertise from KEK run 1: value of designing safety into the system from scratch …
- Cryo-system design & fabrication, KEK cryostat analysis & test and finally operation
- Towards a continuous supply of LHe [See B.Norris’s talk]
  - Installation of compressors
  - Completion of the warm piping for the compressor room

**What is needed for future LH$_2$ absorber tests?**
- Towards a continuous supply of LHe
  - Complete design, install and test transfer lines
  - Complete design, install and test the refrigeration system
  - System review documentation and finally commissioning…
How things might proceed – convective-type LH$_2$ test

- Structural analysis, pressure tests, safety document preparation
- Instrumentation and DAQ updated
- Safety Review approval
- Test the LH$_2$ convective type: KEK run 2
  - Using temporary infrastructure like during summer 2004 test
How things might proceed – Forced-flow LH$_2$ absorber test

- Completed LH$_2$ cryo-loop design by integrating SAMPLE equipments
  - Safety Review approval
  - Fabricate and assemble parts
  - Test the LH$_2$ forced-flow absorber at MTA (in SC solenoid magnet)

Complete the helium cryo-plant:
- Refrigerator room: Complete design and manufacture (mechanical + electrical)
- Compressors room: Complete the compressors refurbishing as well as control & monitoring system

Satisfy the safety requirements for the thin window design: pressure and rupture tests, material certification, safety review document, etc...

Safety Review approval
### Concluding comments

On-going cryogenic efforts for the LH₂ absorbers
CFD models exist and need to be validated by experiment

- Convective-type: 2D by IIT (2001)

Safety review in-progress for the KEK convective-type run2

LH₂ cryo-loop conceptual design available since 2003
Design modification requested to implement SAMPLE heritage
Limited engineering resource available from FNAL/Cryo

- First LH₂ convective-type LH₂ absorber tested at MTA (summer 2004).
  Limited energy deposition. Lesson learned..
- Hydrogen facility was successfully designed, built and commissioned at Fermilab to support LH₂ convection absorber during summer 2004