Liquid Argon Dielectric Strength Measurements

Sarah Lockwitz
Fermilab

LArTPC R&D Workshop
July, 9 2014
Fermilab
Recent Interest in LAr High Voltage (HV)

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**Table 6.2: Electric strengths of liquefied gases**

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- Topics included:
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  - Insulator studies (& more)
  - and LAr breakdown tests
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- Resnati presented HV R&D work for GLACIER
HV in Noble Liquids

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- Included a plan for a LAr dielectric strength test
- Used Rogoski profile to create a uniform 100 kV/cm electric field between two 20 cm² plates separated by 1 cm
HV in Noble Liquids

- Resnati presented HV R&D work for GLACIER
- Included a plan for a LAr dielectric strength test
- Used Rogoski profile to create a uniform 100 kV/cm electric field between two 20 cm² plates separated by 1 cm
- Since then, published their result
  - 100 kV/cm sustained between the profiles (4 hours)
  - Breakdowns as low as 40 kV/cm in boiling liquid

HV in Noble Liquids:
LHEP University of Bern
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- At the workshop, T. Strauss highlighted
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  - A dielectric constant measurement
  - Breakdown field measurements between two spheres
Work at LHEP University of Bern
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- Since then,
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• Since then,
  • Published on dielectric strength measurements up to the cm scale
  • Breakdown measurements between 1 ppb - 20 ppm
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- Since then,
  - **Published** on dielectric strength measurements up to the cm scale
  - Breakdown measurements between 1 ppb - 20 ppm
  - **Published** a study using a cathode coating to suppress discharges

---

**Table 1.** Summary of the breakdown test measurements with 200 μm and 450 μm thick polyisoprene layers coating 5 cm and 4 cm diameter spherical cathodes, respectively.

<table>
<thead>
<tr>
<th>Gap width</th>
<th>Max. field strength</th>
<th>Sphere diameter</th>
<th>Polyisoprene thickness</th>
<th>Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td>298 kV/cm</td>
<td>4 cm</td>
<td>450 μm</td>
<td>no</td>
</tr>
<tr>
<td>4 mm</td>
<td>358 kV/cm</td>
<td>4 cm</td>
<td>450 μm</td>
<td>no</td>
</tr>
<tr>
<td>3 mm</td>
<td>412 kV/cm</td>
<td>4 cm</td>
<td>450 μm</td>
<td>yes</td>
</tr>
<tr>
<td>5 mm</td>
<td>296 kV/cm</td>
<td>5 cm</td>
<td>200 μm</td>
<td>yes</td>
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This is significantly higher from the previous BD measurement.
Work at Fermilab
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- We wanted to measure the dielectric strength of LAr as it relates to:
Work at Fermilab

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  - **Geometry**: Not only distance but also the size of features

Use different sized cathode probes:

- 3 in
- 5 mm
- 1.3 mm
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• We plugged into MicroBooNE’s phase 1 cryosystem at LArTF

*Use different sized cathode probes:*  
3 in  5 mm  1.3 mm
Work at FNAL: LArTF?
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  - Could provide **pure argon** to a cryostat before MicroBooNE cryostat installation
  - Access to **gas analyzers** and an upstream **purity monitor** for measurements
    - **Gas Analyzers** read from cryostat liquid
    - Liquid sent to **purity monitor** vessel after use
Test Setup

- Mirrors angled to see breakdown space from viewports
- Grounded plate
- HV Probe
- Reflection of top plate
- Translator can move the probe vertically
- This goes into the cryostat

Mention of cryostat and breakdown space viewports as part of the test setup.
Test Setup

- Cryostat was a vacuum jacketed cryostat

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  - Distance read out by a digital linear scale

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2.125” OD, 0.065” Wall

86”
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  - Accomplished by interference of materials
- Electrical connection is made by a spring tip attached to the end of the FT
  - Allows for shrinking/movement
Test Setup:
The MicroBooNE HV Feedthrough

The max E field on the cathode is ~28 kV (~4in to ground)
Test Setup: The MicroBooNE HV Feedthrough

- Longer than the ICARUS feedthrough
- Because cryostat is cylindrical, we have to extend the ground sheath deeper to avoid high fields with the cryostat wall

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  - Reduce electric field here
- Tested at -128 kV in pure LAr (500 ppt O₂) for 63.5 hours
  - Time was limited by LAr boil off
Test Procedure
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• Find zero point
Test Procedure

- Find zero point
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- Find zero point
- Go to desired distance
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• Ramp voltage until breakdown

• Normally obvious; current trip level was set to a few micro-Amps
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• Repeat ~5x for each distance
A Sample: Data from 02/27/2014

- Plot of voltage vs distance (1.3 mm sphere):

![Breakdown Voltage vs. Distance](image-url)
Disclaimer
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- With the 3 in and 5 mm probes, we saw breakdown along the FT for some points above 1 cm, and 1.5 cm respectively.
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- We did not see this with the 1.3 mm probe
Disclaimer

• With the 3 in and 5 mm probes, we saw breakdown along the FT for some points above 1 cm, and 1.5 cm respectively.

• We did not see this with the 1.3 mm probe

• We found we could mitigate this by adding more liquid, but to ensure that we are not including FT breakdown data points, we have excluded points beyond 1 cm for the 3 in probe, and 1.5 cm for the 5 mm probe.
Width of Data
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- We used the same probe over and over again
Width of Data

- We used the same probe over and over again
- The literature mentions that breakdown is a stochastic process
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- Breaking down many times at a fixed distance yields

![Breakdown Voltage at 7 mm Spacing (3 in Ball)](chart.png)
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We can fit this with a Weibull function (as the literature suggests)
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\[ \frac{x^2}{ndof} = 0.82 \]
Data Collected

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<tr>
<th>Date</th>
<th>Probe</th>
<th>O₂ (ppb)</th>
<th>N₂ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/24/14</td>
<td>3 in</td>
<td>1400⁺0⁻0</td>
<td>1.4⁺0⁻1</td>
</tr>
<tr>
<td>01/31/14</td>
<td>5 mm</td>
<td>1300⁺0⁻0</td>
<td>2.2⁺0⁻1</td>
</tr>
<tr>
<td>02/18/14</td>
<td>1.3 mm</td>
<td>1200⁺0⁻0</td>
<td>1.7⁺0⁻2</td>
</tr>
<tr>
<td>02/27/14</td>
<td>1.3 mm</td>
<td>744⁺2⁻0</td>
<td>3.1⁺0⁻2</td>
</tr>
<tr>
<td>03/04/14</td>
<td>1.3 mm</td>
<td>1.8⁺1⁻0.7</td>
<td>6.0⁺0⁻5</td>
</tr>
<tr>
<td>03/11/14</td>
<td>1.3 mm</td>
<td>0.35⁺0.15⁻0.15</td>
<td>5.2⁺0⁻2</td>
</tr>
<tr>
<td>04/01/14</td>
<td>3 in</td>
<td>70⁻20⁺100</td>
<td>3.2⁺0⁻5</td>
</tr>
<tr>
<td>04/07/14</td>
<td>3 in</td>
<td>10.2⁺0.0⁻3.0</td>
<td>5.5⁺0⁻5</td>
</tr>
<tr>
<td>04/11/14</td>
<td>3 in</td>
<td>0.60⁺0.10⁻0.10</td>
<td>5.0⁺0⁻5</td>
</tr>
<tr>
<td>04/16/14</td>
<td>3 in</td>
<td>&lt;0.23⁺†</td>
<td>5.9⁺0⁻5</td>
</tr>
<tr>
<td>04/22/14</td>
<td>3 in</td>
<td>&lt;0.13⁺†</td>
<td>5.9⁺0⁻5</td>
</tr>
<tr>
<td>04/28/14</td>
<td>1.3 mm</td>
<td>200⁺20⁻0</td>
<td>5.5⁺0⁻2</td>
</tr>
<tr>
<td>05/01/14</td>
<td>1.3 mm</td>
<td>&lt;0.29⁺†</td>
<td>6.4⁺0⁻2</td>
</tr>
<tr>
<td>05/07/14</td>
<td>1.3 mm</td>
<td>1400⁺100⁻0</td>
<td>28⁺2.0⁻0</td>
</tr>
<tr>
<td>05/14/14</td>
<td>3 in</td>
<td>1500⁺100⁻0</td>
<td>24⁺2.0⁻0</td>
</tr>
<tr>
<td>05/19/14</td>
<td>5 mm</td>
<td>&gt;900⁺50⁻50</td>
<td>22⁺5.0⁻5</td>
</tr>
<tr>
<td>05/30/14</td>
<td>5 mm</td>
<td>775⁺50⁻50</td>
<td>22⁺5.0⁻5</td>
</tr>
</tbody>
</table>

Purity Monitor Data:

<table>
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Purity Monitor Data:

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<tr>
<td>01/24/14</td>
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<td>1400⁺0⁻0</td>
<td>1.4⁻0.1⁺0.1</td>
</tr>
<tr>
<td>01/31/14</td>
<td>5 mm</td>
<td>1300⁺0⁻0</td>
<td>2.2⁻0.1⁺0.1</td>
</tr>
<tr>
<td>02/18/14</td>
<td>1.3 mm</td>
<td>1200⁺2⁻0</td>
<td>1.7⁻0.2⁺0.2</td>
</tr>
<tr>
<td>02/27/14</td>
<td>1.3 mm</td>
<td>744⁺2⁻2.0</td>
<td>3.1⁻0.5⁺0.5</td>
</tr>
<tr>
<td>03/04/14</td>
<td>1.3 mm</td>
<td>1.8⁻0.1⁺0.7</td>
<td>6.0⁻0.2⁺0.2</td>
</tr>
<tr>
<td>03/11/14</td>
<td>1.3 mm</td>
<td>0.35⁻0.15⁺0.15</td>
<td>5.2⁻0.2⁺0.2</td>
</tr>
<tr>
<td>04/01/14</td>
<td>3 in</td>
<td>70⁻0⁺100</td>
<td>3.2⁻0.2⁺0.2</td>
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<td>5.5⁻0.5⁺0.5</td>
</tr>
<tr>
<td>04/11/14</td>
<td>3 in</td>
<td>0.60⁻0⁺0.10</td>
<td>5.0⁻0.2⁺0.2</td>
</tr>
<tr>
<td>04/16/14</td>
<td>3 in</td>
<td>&lt;0.23⁺5.9⁻0.5</td>
<td>5.9⁻0.5⁺0.2</td>
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<td>04/28/14</td>
<td>1.3 mm</td>
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<tr>
<td>05/01/14</td>
<td>1.3 mm</td>
<td>&lt;0.29⁺6.4⁻0.2</td>
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<td>05/19/14</td>
<td>5 mm</td>
<td>&gt;900⁻22⁻5.0</td>
<td>22⁻5.0⁺5.0</td>
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- Some “high” $N_2$ data at the end.

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**$V_{\text{Breakdown}}$ vs. Distance**

- Plotted average $V_{\text{bd}}$ at a given distance for a given date’s data (specific purity and probe)

**Average Breakdown Voltage vs. Distance**

![Graph showing the relationship between voltage and distance for different oxygen purity levels and probe sizes.]
\( V_{\text{Breakdown}} \) vs. Distance

- Plotted average \( V_{bd} \) at a given distance for a given date's data (specific purity and probe)

Average Breakdown Voltage vs. Distance

[Diagram showing breakdown voltage vs. distance for different spheres and oxygen concentrations.]

- 1.3 mm sphere
- 5 mm sphere
- 3 in sphere

Average of these would be one point.
**$V_{\text{Breakdown}}$ vs. Distance**

- Plotted average $V_{\text{bd}}$ at a given distance for a given date’s data (specific purity and probe)

![Graph showing average breakdown voltage vs. distance for different ranges of oxygen purity and sphere sizes.](image)

- Average of these would be one point

200-1400 ppb $O_2$

0.29-1.8 ppb $O_2$
$E_{\text{Max}}$ vs Distance

- Doesn’t appear to be just $E_{\text{max}}$

**Average Peak Breakdown Field vs. Distance**

- 1.3 mm sphere
- 5 mm sphere
- 3 in sphere

---

LAr Dielectric Strength

July 9, 2014

S. Lockwitz et al.
Comparison to Others’ Data

Plot inspired from LHEP Bern. Earlier data provided by LHEP Bern
Other Quantities of Interest

Gerhold et al., Cryogenics (1994)

The impact of an area effect on LHe breakdown has been recognized by several authors. It is generally accepted that LHe breakdown is triggered at weak-links adjacent to the cathode, i.e., protrusions. The area
Other Quantities of Interest

• Literature suggests a dependence of breakdown voltage on area

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Stressed area, peak field is at the star, shaded pink has $E > 0.80 \times E_{\text{max}}$

*Gerhold et al., Cryogenics (1994)*
Other Quantities of Interest

- $E_{\text{max}}$ vs Area (80% $E_{\text{max}}$ left; 90% right)
Comparison with another test...
Comparison with another test...

- Last summer we did a breakdown test in LAPD
Comparison with another test...

- Last summer we did a breakdown test in LAPD
- We had a 2.5” sphere within a grounded cylinder with a ~4.9 mm gap
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- We had a 2.5” sphere within a grounded cylinder with a ~4.9 mm gap
- We recorded data with this fixed distance, but...
- There was an issue where a screw was found to be broken after removal
Comparison with another test...

- Last summer we did a breakdown test in LAPD
- We had a 2.5” sphere within a grounded cylinder with a ~4.9 mm gap
- We recorded data with this fixed distance, but...
- There was an issue where a screw was found to be broken after removal
  - (so we likely will not publish this)
Comparison with another test...
Comparison with another test...

- If we assume the device was ok during the testing,
  - We have something with an order of magnitude more stressed area
Comparison with another test...

- If we assume the device was ok during the testing,
  - We have something with an order of magnitude more stressed area
- *(80%: 37.6 cm\(^2\), 90%: 24.7 cm\(^2\); \(E_{\text{max}}\): ~52 kV/cm)*
Closing Thoughts
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- While I’ve highlighted FNAL’s dielectric strength work here, other topics and other groups are producing interesting work
Closing Thoughts

- While I’ve highlighted FNAL’s dielectric strength work here, other topics and other groups are producing interesting work.

- While a lot of work has been done in the past year on understanding the dielectric strength of LAr, there’s still much to be worked out.
  - Stressed area seems to be a more general parameter of interest.
  - Hints at purity effects but there’s more work to do here.
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• Our group will have a paper on the arXiv later this month

• We plan to continue HV R&D efforts with an LDRD grant:

  • **Blanche**: Breakdown (or Big) liquid argon cryostat for high-voltage experiments
HVC Thank You's

- Cryo design and operation: M Zuckerbrot
- Data collected by B. Carls, R. Acciarri, & S. Lockwitz
- Lots of design & construction work by H. Jostlein
- Task Force members & others with helpful discussions: B. Lundberg, G.P. Zeller, G. Rameika, J. Raaf, and C. James
Looking Closer at Purities...

O$_2$<10 ppb

Average Maximum Breakdown Field vs. Area with $E>0.8E_{\text{Max}}$

O$_2$>800 ppb

Average Maximum Breakdown Field vs. Area with $E>0.8E_{\text{Max}}$
Breakdown in gas is understood: a Townsend process, as described by Paschen in 1905:

\[
\alpha \left( \frac{E}{\rho} \right) = A \rho e^{\frac{b \rho}{E}}
\]

\[
V_B = \frac{B d \rho}{\log[Ad\rho] - \log[\log[1 + \frac{1}{\gamma}]]}
\]

Breakdown in cryogenic liquids is NOT understood: it depends on thermodynamic state, surface effects, purity and much else. See J. Gerhold, *Properties of cryogenic insulators*, Cryogenics 38 (1998) 1063: “discharge voltages can only be measured as a function of the overall electrode/liquid system; extrinsic parameters have an important effect”

Breakdown Field for LAr at ~89K

“Our measurement” = A. Blatter, et al., *Experimental study of electric breakdowns in liquid argon at centimeter scale*, arXiv: 1401.6693
A Purity Note from C. Thorn

The mean free path for attachment to O2 at 10kV/cm is 0.15 cm for 1ppm and 150 cm for 1ppb (these increase by ~2x per decade of field). Thus below ~10ppb there should be no change in breakdown voltage for gaps greater than a few cm, if the mechanism for the purity dependence is attachment.

Average Breakdown Voltage vs. Distance

- 1.3 mm sphere
- 5 mm sphere
- 3 in sphere

Legend:
- Open blue triangle: 800 < O2 < 3000 ppb
- Dotted blue line: 10 < O2 < 800 ppb
- Solid black circles: 0.01 < O2 < 10 ppb
- Solid red circles: 0.01 < O2 < 10 ppb
A Purity Note from C. Thorn

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Test Setup

- Voltage was supplied by a Glassman LX150N12 capable of up to -150 kV

- Same filter pot as uB
  - filters ripple
  - isolates energy

- Voltage controlled by a LabView program (monitoring voltage, and some current)

- Current additionally monitored by analog outputs on the back of the supply
HV Line Drawing

This keeps going...

C = 1.3 nF
C = 3 GΩ

C = 200 pF
R = 75 MΩ

C = 200 pF

C = 400 pF for a 25’
cable (we will use a
shorter cable in uB)

Cathode

This keeps going...