Low Background materials and fabrication techniques for cables and connectors of the MAJORANA DEMONSTRATOR

Matthew Busch
TUNL / Duke University
The MAJORANA Collaboration

Black Hills State University, Spearfish, SD
Kara Keeter

Duke University, Durham, North Carolina, and TUNL
Matthew Busch

Joint Institute for Nuclear Research, Dubna, Russia
Viktor Brudanin, M. Shirchenko, Sergey Vasilyev, E. Yakushev, I. Zhitnikov

Lawrence Berkeley National Laboratory, Berkeley, California and the University of California - Berkeley
Nicolas Abgrall, Yuen-Dat Chan, Lukas Hehn, Jordan Myslik, Alan Poon, Kai Vetter

Los Alamos National Laboratory, Los Alamos, New Mexico
Pinghan Chu, Steven Elliott, Ralph Massarczyk, Keith Rielage, Larry Rodriguez, Harry Salazar, Brandon White, Brian Zhu

National Research Center ‘Kurchatov Institute’ Institute of Theoretical and Experimental Physics, Moscow, Russia
Alexander Barabash, Sergey Konovalov, Vladimir Yumatov

North Carolina State University, and TUNL
Matthew P. Green

Oak Ridge National Laboratory
Fred Bertrand, Charlie Havener, Monty Middlebrook, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, Washington
Isaac Arnquist, Eric Hoppe, Richard T. Kouzes

Princeton University, Princeton, New Jersey
Graham K. Giovanetti

Queen’s University, Kingston, Canada
Ryan Martin

South Dakota School of Mines and Technology, Rapid City, South Dakota
Colter Dunagan, Cabot-Ann Christofferson, Anne-Marie Suriano, Jared Thompson

Tennessee Tech University, Cookeville, Tennessee
Mary Kidd

Technische Universität München, and Max Planck Institute, Munich, Germany
Tobias Bode, Susanne Mertens

University of North Carolina, Chapel Hill, North Carolina, and TUNL
Thomas Caldwell, Thomas Gilling, Chris Haufe, Reyco Henning, Mark Howe, Samuel J. Meijer, Christopher O’Shaughnessy, Gulden Othman, Jamin Rager, Anna Reine, Benjamin Shanks, Kris Vorren, John F. Wilkerson

University of South Carolina, Columbia, South Carolina
Frank Avignone, Vince Guiseppe, David Tedeschi, Clint Wiseman

University of South Dakota, Vermillion, South Dakota
Wenqin Xu

University of Tennessee, Knoxville, Tennessee
Yuri Efremenko, Andrew Lopez

University of Washington, Seattle, Washington
Sebastian Alvis, Tom Burritt, Micah Buuck, Clara Cuesta, Jason Detwiler, Juliesta Gruszko, Ian Guinn, David Peterson, Walter Pettus, R. G. Hamish Robertson, Tim Van Wechel

25 May 2017
The **MAJORANA DEMONSTRATOR**

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

**Goals:**
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

- Located underground at 4850’ Sanford Underground Research Facility
- Background Goal in the peak region of interest (4 keV at 2039 keV)
  - 3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
    scales to 1 count/ROI/t/y for a tonne experiment

- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched $^{76}$Ge crystals
  - 14.4 kg of nat Ge
  - Detector Technology: P-type, point-contact.

- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable

- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

1.02 m LRT Korea
Detector unit and string

Electroformed Copper

PFA + fine Cu coaxial cable

PTFE

Front-End Elec.
In vacuum Cables

40 channels wired in cross arm to provide spares

29 detectors installed and connected at cold plate

1 piece 40 HV cables 85” (2.16 m) w/ fork end
4x40 signal 65” (1.65 m) w/ 40 Vespel connectors

4x29 signal w/Vespel connectors fed to coldplate, 24” (0.6 m)
1x29 clamping nuts for HV at detector
2008-2014 development

Cables: in house ribbon

4-wire cable
(~0.5 mil parylene on both sides)

5 nm Ti, 100 nm Cu

signal connection

HV connection

Cables: custom Axon’ Picocoax
MAJORANA DEMONSTRATOR cable

- **Signal cable**
  - $50 \, \Omega$, 87pF/m, 0.4 g/m
  1. Conductor AWG 40 Dia. 0.076 mm
  2. Dielectric FEP OD 0.254 mm
  3. Spiral shield wires AWG 50 ~30 strands
  4. Jacket FEP OD 0.4mm

- **HV Cable**
  - Outer Diameter: 1.2mm
  - Approx mass: 3 g/m
  - 5kV DC

Custom production from Axon’ cable
Signal connectors at detector

- 0.7 mm elastic deflection at nut
- 400g force applied to pin
HV fork connection

Installed signal wires

Phosphor Bronze spring washer

Installed HV fork

29 detectors installed under coldplate
Internal signal connectors 2015-2016
Wired cryostat w/ existing connectors

13” ID vacuum enclosure, 40 connectors available above coldplate
Vacuum feedthrough

Reduced radiopurity requirements, but unique cables still require unique connectors

HV cable custom feedthrough connectors with commercial pins

Signal cable customized commercial 50 pin D-sub
Vacuum side of 8” Conflat flange wired
## Radiopurity performance

<table>
<thead>
<tr>
<th>component</th>
<th>$^{232}\text{Th} \times 10^{-12} \text{g/g}$</th>
<th>$^{238}\text{U} \times 10^{-12} \text{g/g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axon’ cable</td>
<td>0.54 +/- 0.05</td>
<td>11.7 +/- 1.2</td>
</tr>
<tr>
<td>Vespel SP-1 connectors</td>
<td>&lt;49</td>
<td>&lt;45</td>
</tr>
<tr>
<td>Brass pins</td>
<td>1500 +/- 400</td>
<td>310 +/- 70</td>
</tr>
<tr>
<td>Brass pins w/CuBe inserts*</td>
<td>9900 +/- 300</td>
<td>64000 +/- 100</td>
</tr>
<tr>
<td>Phosphor Bronze</td>
<td>6.08 +/- 1.0</td>
<td>10.8 +/- 2.5</td>
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<tr>
<td>Silver epoxy (example)</td>
<td>56.7 +/- 7</td>
<td>67 +/- 8</td>
</tr>
<tr>
<td>solder</td>
<td>&lt;100</td>
<td>&lt;300</td>
</tr>
<tr>
<td>FEP heat shrink</td>
<td>&lt;34</td>
<td>&lt;100</td>
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</tbody>
</table>

*not used in experiment

Excerpted from: The Majorana Demonstrator radioassay program [N. Abgrall et al. NIM A828 (2016) 22]
Functional performance

- 44 of 58 biased
  - 7 unbiased detectors have signal connection issues
  - 6 unbiased detectors have HV connection issues
  - 1 unbiased detector needs reprocessing

- 35 of 58 used in analysis thus far
  - Poor AvsE performance, maybe due to damaged HV cables that prevent full depletion

- Installed spare cables
  - 2 of 11 spare HV cables functional. HV fork clamp ineffective.
  - 0 of 11 spare signal cables functional. Poor connection quality at cold plate or feedthrough.
HV breakdown testing

- Pinching HV cables reproduces field observed breakdown behavior
- Replacement cables should be more robust or better protected from damage.
Various commercial small HV cables drawn to scale

Rated voltage: 

Below 5kV | 5kV | 13.5kV | 18 kV
---|---|---|---
HABIA (used by ATLAS?)
RG 179 used by GERDA
Axon’ in use MJD
T_R 178-5135
T_R 178-5138
T_R 178-6653

Dia. 1.2 mm REF

In use MJD and GERDA
Samples tested at UNC

Note: aluminized Mylar shield, no response to RFQ from vendor, HV rating unknown

No ground shield, considered risky for noise performance
Too massive to fit in MJD design, likely to fail purity requirements
Failed initial HV breakdown test

Best Option is to produce more robust custom cable with known clean copper. Most cost effective short term option is to use existing Axon’ cable and protect it better during fabrication and installation

25 May 2017
LRT Korea
HV cable protection

- Baffle plates guide cable and protect cable bundles during installation, and shield detectors from backgrounds originating outside of shield
Test plates for improved cable routing

Proposed new design

Installed design

PTFE overwrapped signal bundle

PTFE overwrapped HV bundle

Messy bundle of signal cables

~single layer of HV cables.

NOTE: overlapping may cause pinching. We took precautions to avoid this at assembly, but repeated installs and thermal cycling may make this worse.

New shielding design improves shield effectiveness near thermosyphon tube

25 May 2017

LRT Korea
HV Fork

• Eliminates drilling holes and Vespel clamp plug
• Works with initial HV discharge testing
• Strain relief quality to be tested
Commercial signal connector options

Nano twist pins: vendors unwilling to work with Axon’ cable without a PCB interface, doesn’t work with existing hardware form factors, no assay history but is CuBe free.

Micro IDT (Insulation Displacement Technology): vendor unwilling to make any customization for form factor or cleanliness without $100k minimum order, doesn’t work with existing hardware form factors. No good assay history but is CuBe free.

Fuzz Buttons: vendor is very helpful with custom solution that fits within current hardware form factor using assayed materials. Good assay history with CDMS experiment.
Replacement signal connectors

- Fuzz buttons from Custom Interconnects solve connector reliability issues so far in testing
Feedthrough connectors

MIL SPEC and Space rated from Glenair (will be tested for vac compatibility, but meets NASA outgassing requirements)
Micro-TIG and resistance welding

• Similar to wire bonding, but higher power density.
• Used in industry for battery terminals, solar panels, magnet wire and micro motor windings, and specialty aerospace applications.
• Will be tested for MJD upgrade and LEGEND, may provide more flexibility than wirebonding, solder, or silver epoxy
LEGEND cables and connectors

Wirebonding uses ultrasonic energy and light pressure to weld contacts

25 µm Al wires work well at detector, worked in the end for GERDA but some development difficulties at cable end related to inconsistencies in cables

76 µm Cu wires inconsistent in testing c. 2010 (resistance or Micro-TIG may work better here)
LEGEND development work

- Front end (ASIC) in flat circuit cable and/or multi conductor bundle
- Main pre-amp after L-Ar shielding, can use commercial CuBe free connectors (fuzz button, nano-twist, IDT, ZIF)

Nano twist are MILSpec and can be made hermetic for feethroughs. Requires some assay and/or custom materials

IDT and ZIF are from consumer electronics. Very low mass, but harder to customize and not as reliable or rugged.
Conclusions

• Low quality terminations and cable durability is a leading cause of detector failure in the MAJORANA DEMONSTRATOR.

• Development work is underway to upgrade cables and connectors in the MAJORANA DEMONSTRATOR.

• This cable upgrade will feed directly into design and development for LEGEND.
NASA QC process

• Read this: NASA-STD 8739.4A “Workmanship standard for crimping, interconnecting cables, harnesses, and wiring.”
• Don’t solder unless absolutely necessary to improve ruggedness and repeatability
• Pull-out strength and QC procedures for crimped connectors
• Overwrap and/or ties and installation guidelines for harness assembly
Wire Crimp pull testers

• Required for production QA to meet many test standards including NASA, UL, ISO, ASTM, SAE
Overwrap: work in progress

Previously assayed Clean PTFE film is not securable

Un-assayed PTFE monofilament sample is ineffective

Un-assayed PTFE spiral wrap is effective, but massive and requires restraint at ends
Quality Assurance

- Vespel machining: hand de-burr and test fit of connector body and threads for back shell
- Visual inspection at pin insertion
- Connectivity after soldering in air
- Paired connectivity with 4+ connections, \( \frac{3}{4} \) must pass
- Samples dunked in LN (~3/4 pass)
- Complete harness pin-pin connectivity test (90% pass)
- Field installed in apparatus (75% pass)
- 44 of 58 installed detectors operating. Most failures are due to connectors and cables.
- HV breakdowns after installation indicated damaged HV cables on ~8 detectors
Cable and connector upgrade for Majorana Demonstrator

• Goal is to improve fraction of operating detectors from ~76% to 90%+

• Strategy:
  ✓ Determine root cause of HV breakdowns
  ✓ Revisit commercial cable options
  ✓ Revisit commercial connector options
  □ Test best options (in process)
  □ Develop detailed production plan and QC process
  □ Fabricate and test complete harnesses (late 2017)
  □ Install in Majorana Demonstrator (late 2018)