The MAJORANA DEMONSTRATOR: Concept, Design, Status

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Meeting on the Next Generation ^{76}Ge Experiment

Munich, Germany

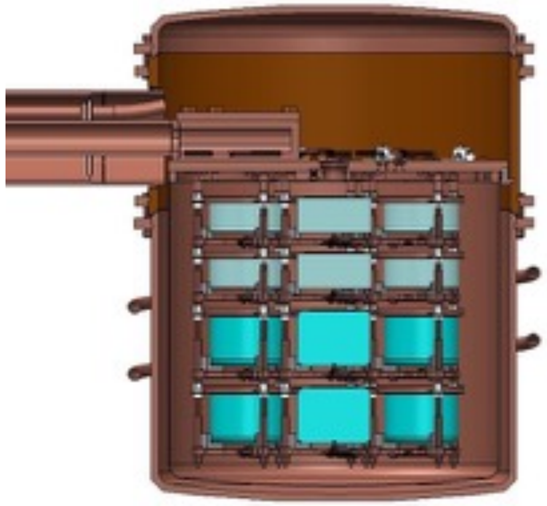
25 April 2016

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

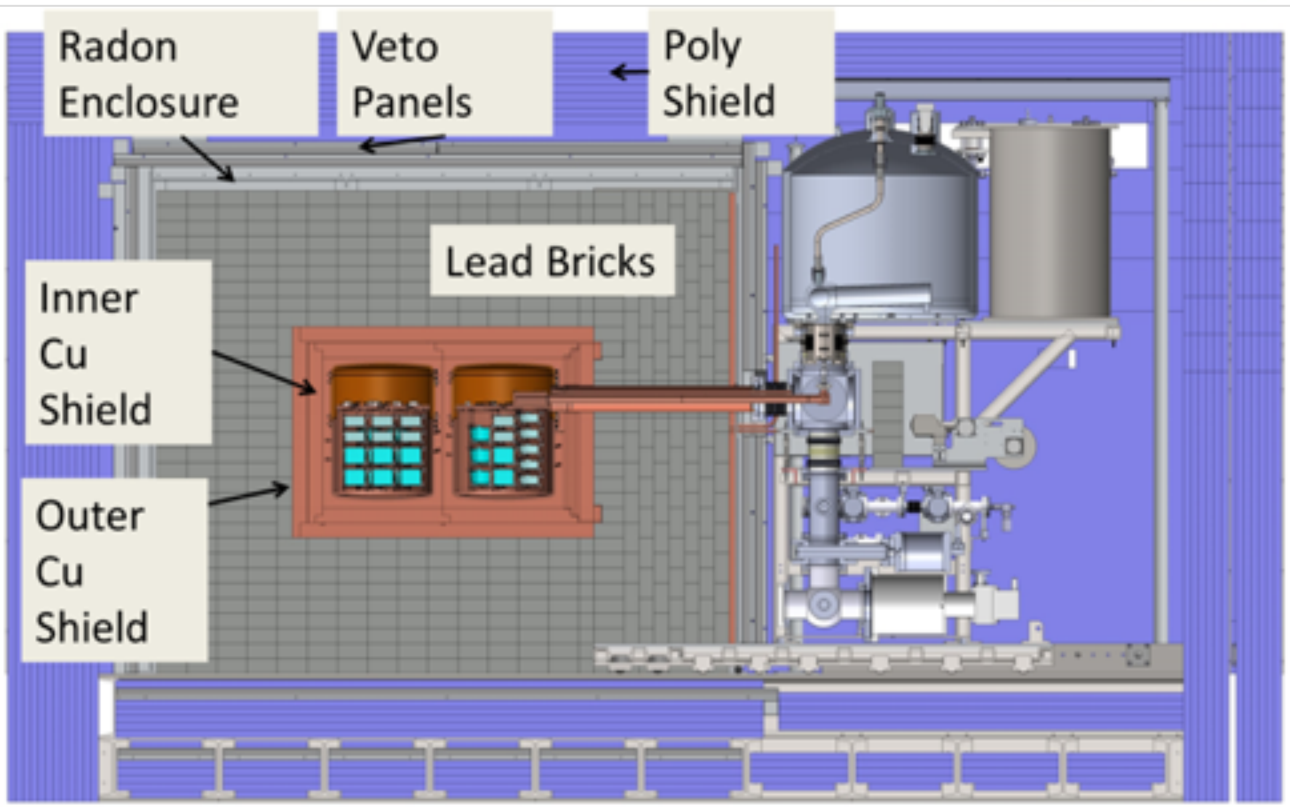


Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
scales to 1 count/ROI/t/y for a tonne experiment

44-kg of Ge detectors
- 29 kg of 87% enriched ^{76}Ge crystals
- 15 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



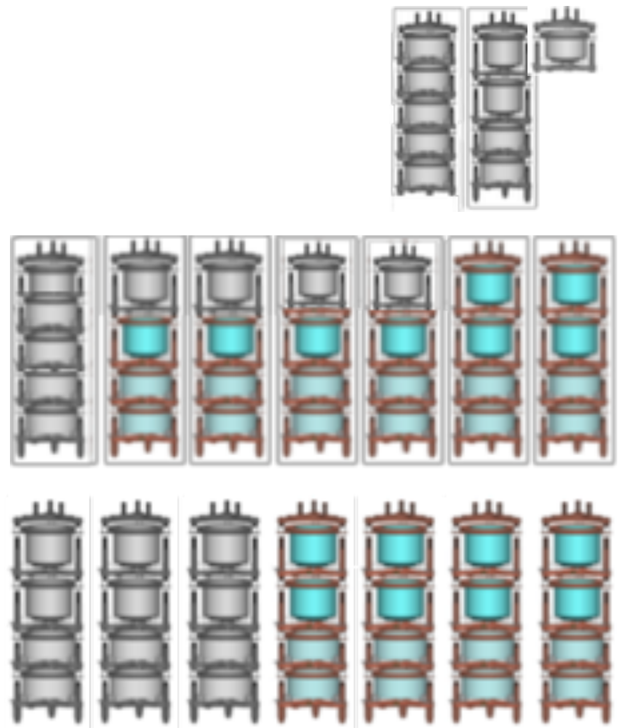
MAJORANA DEMONSTRATOR Implementation

Three Steps

Prototype cryostat: 7.0 kg (10) ^{nat}Ge

Module 1: 16.8 kg (20) ^{enr}Ge
5.7 kg (9) ^{nat}Ge

Module 2: 12.8 kg (15) ^{enr}Ge
9.4 kg (14) ^{nat}Ge

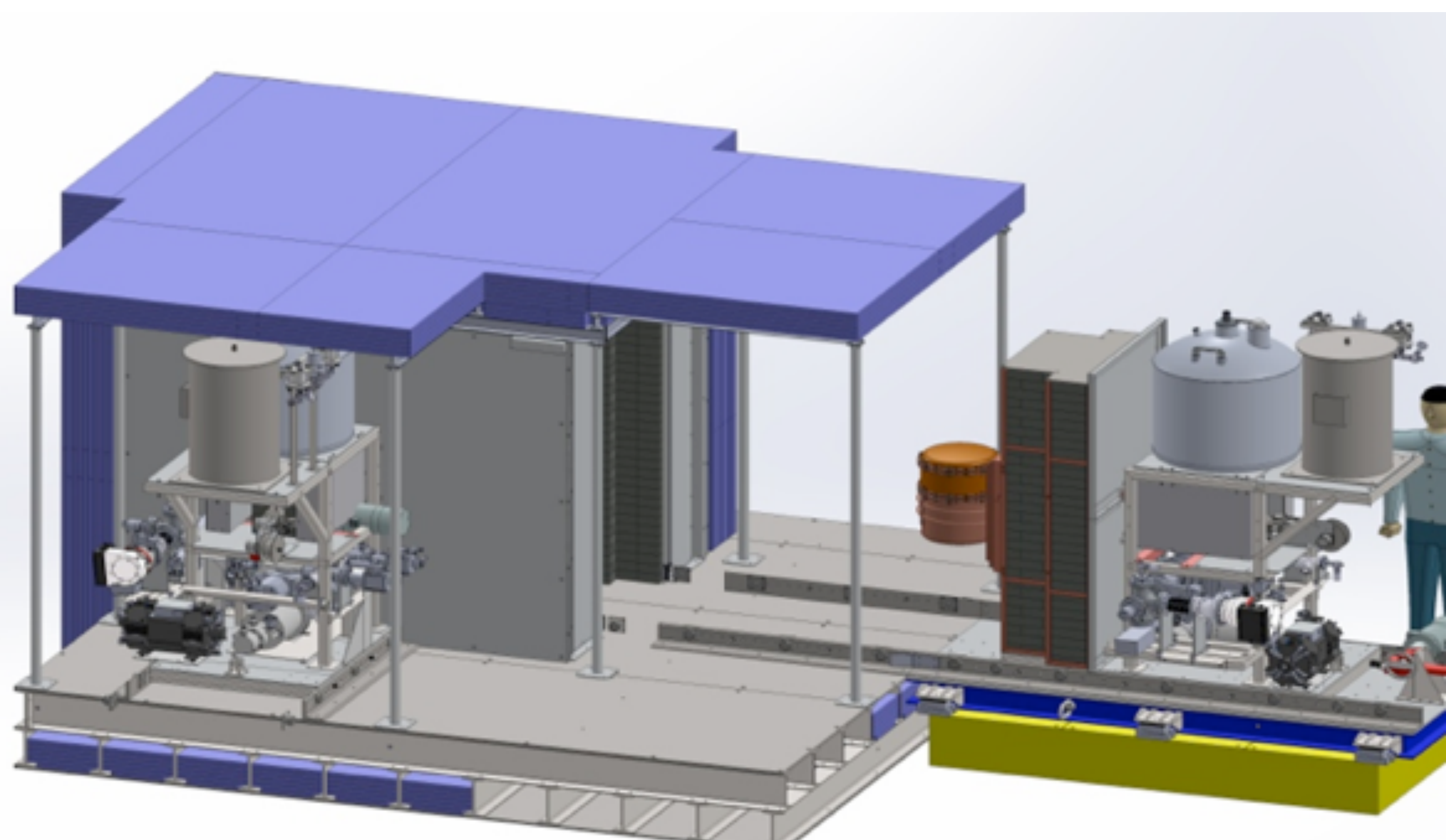


In shield Operation

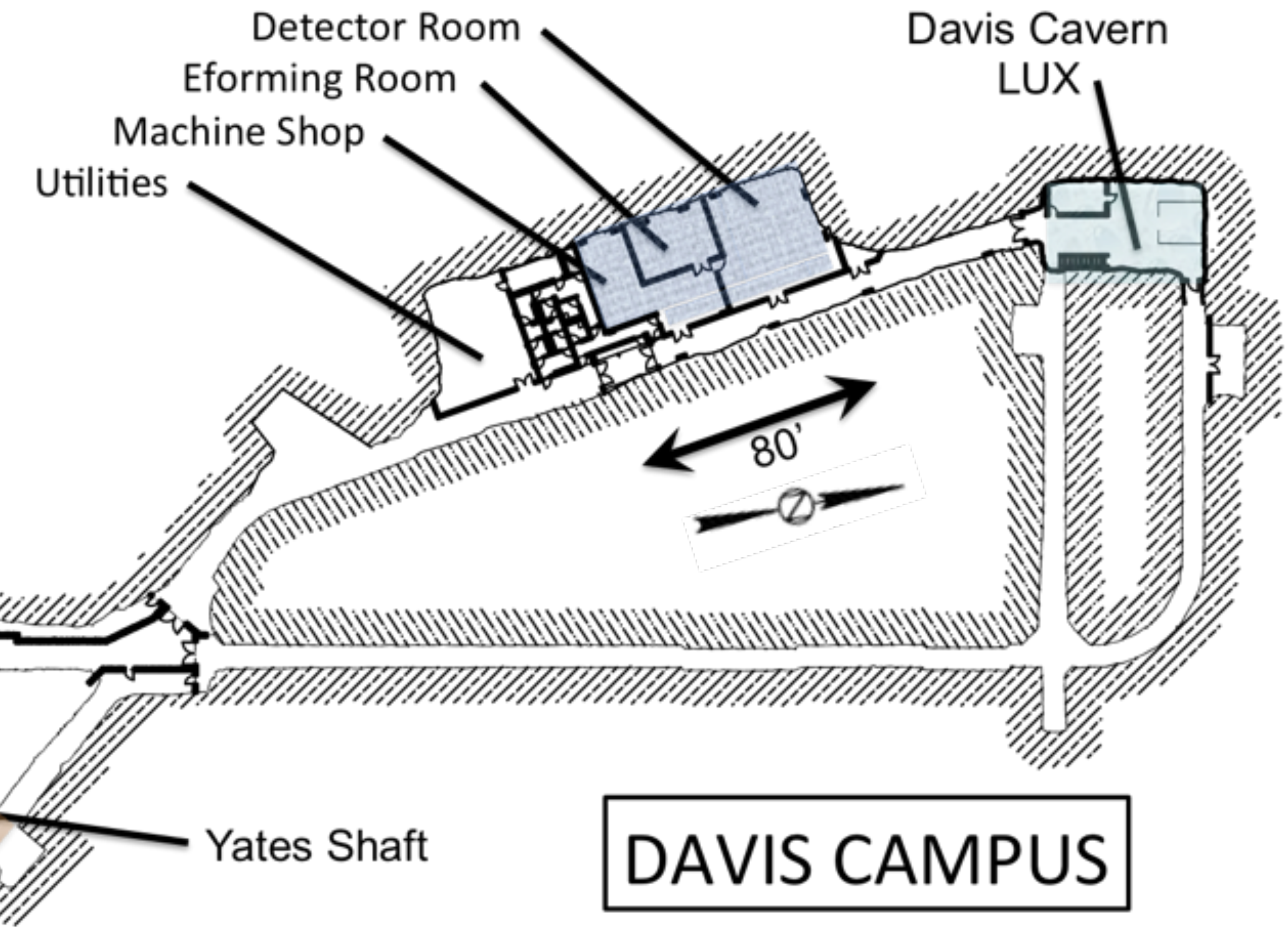
June 2014-June 2015

May–Oct. 2015,
Upgraded: Fall 2016
Jan 2016 - present

May 2016

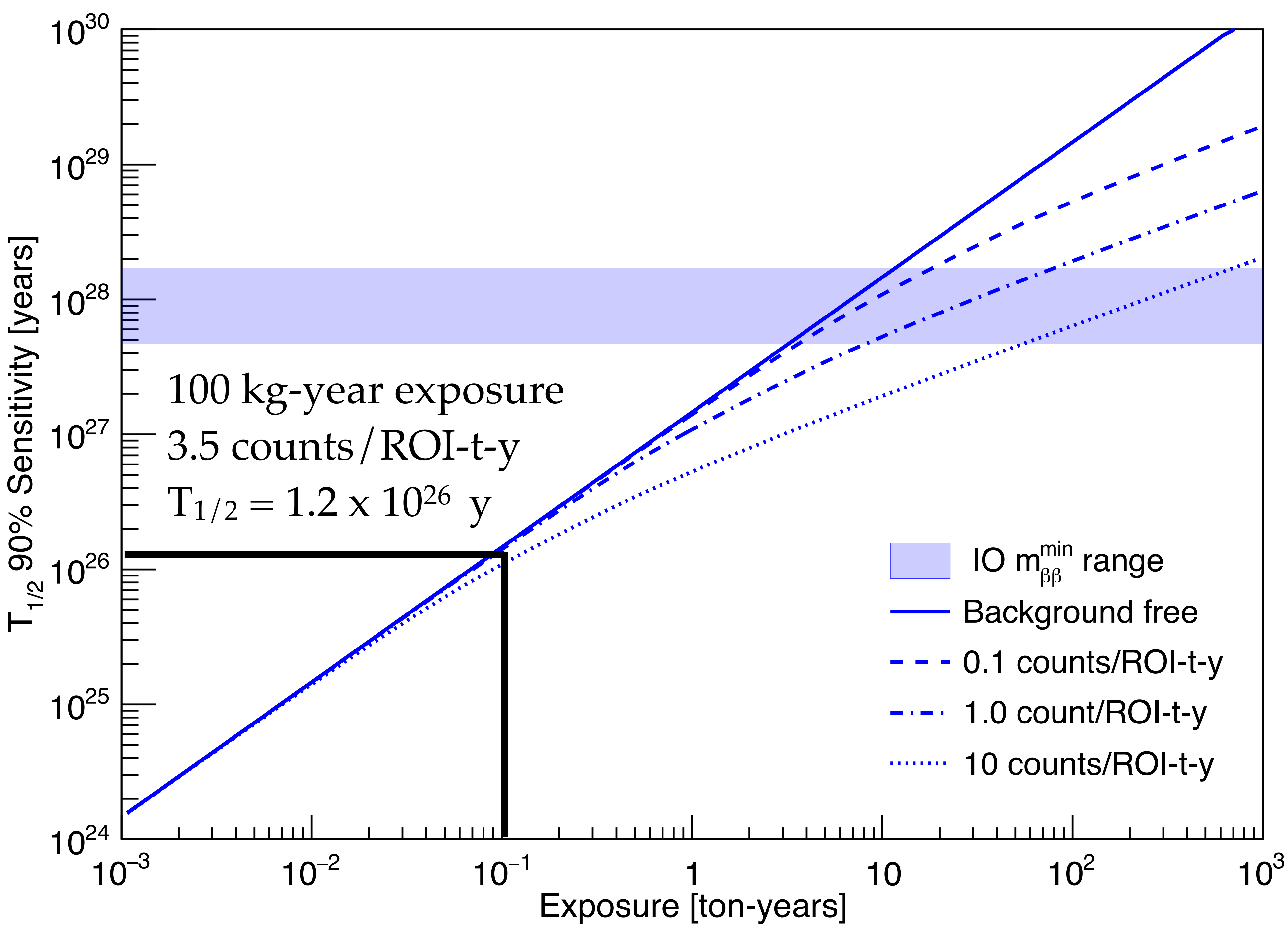


MAJORANA Underground Laboratory



Sensitivity vs. Exposure ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

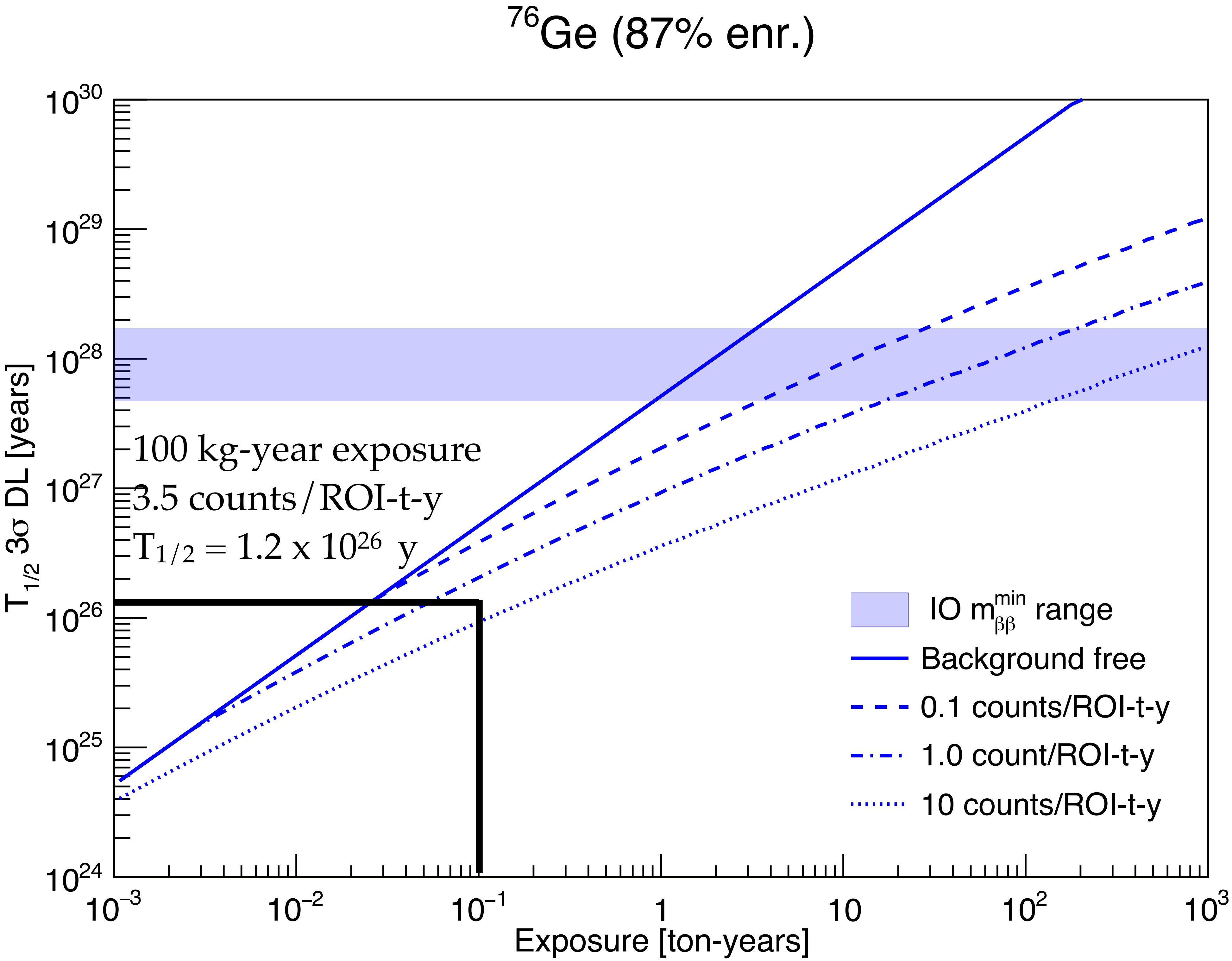
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

3σ Discovery vs. Exposure for ^{76}Ge

J. Detwiler



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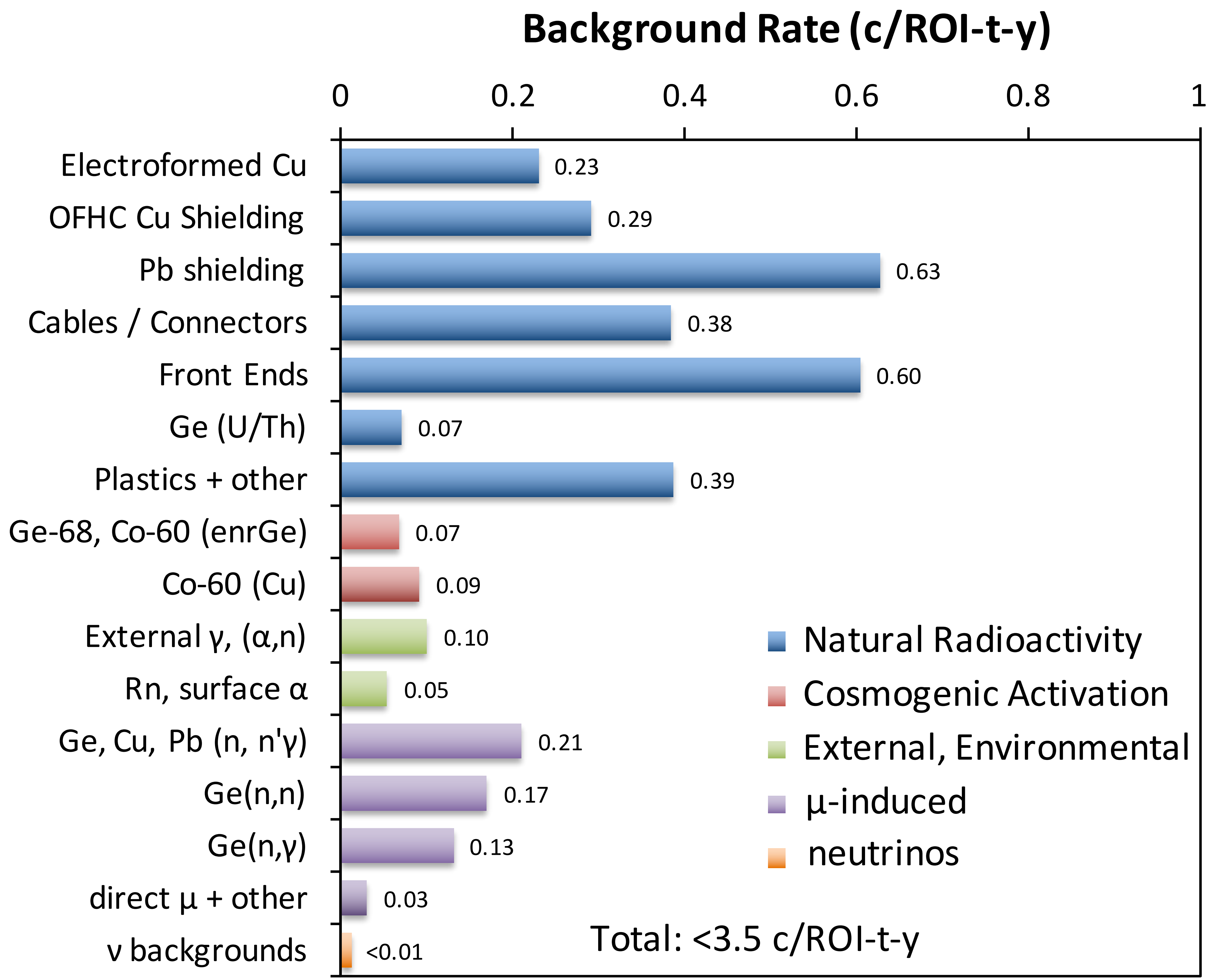
DEMONSTRATOR Background Model

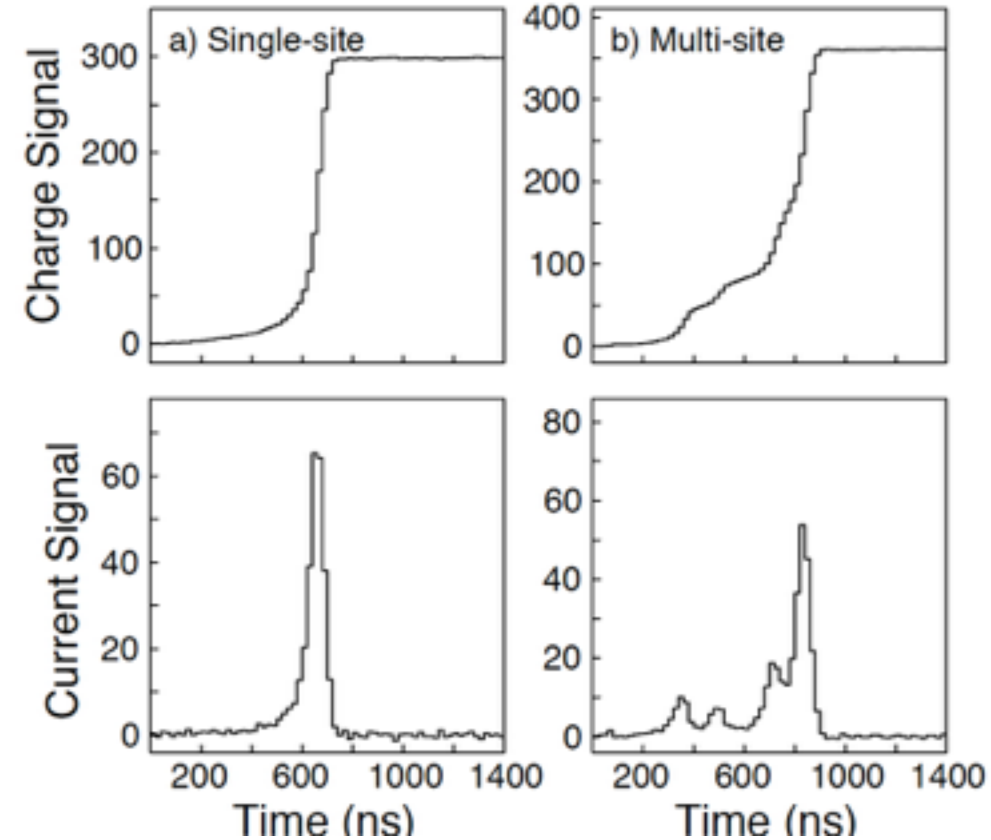


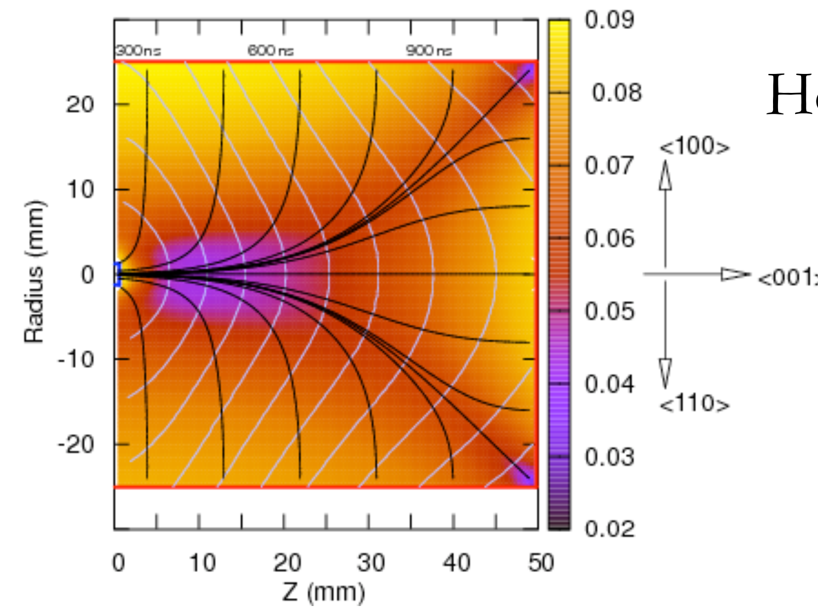
P-type Point Contact Detectors

Ultra-low background rate requires a pulse shape analysis (PSA) rejection of multi-site gamma events

P-type Point-Contact (PPC) detectors
- No deep hole; small point-like central contact
- Length is shorter than standard coaxial detector
- Simple, cost-effective, low background
- Localized weighting potential gives excellent multi-site rejection
- Low capacitance (~ 1 pF) gives superb resolution at low energies

Rising edge "stretched" in time
⇒improved PSA





Hole v_{drift} [mm/ns] with paths and isochrones

MAJORANA Detector Choice

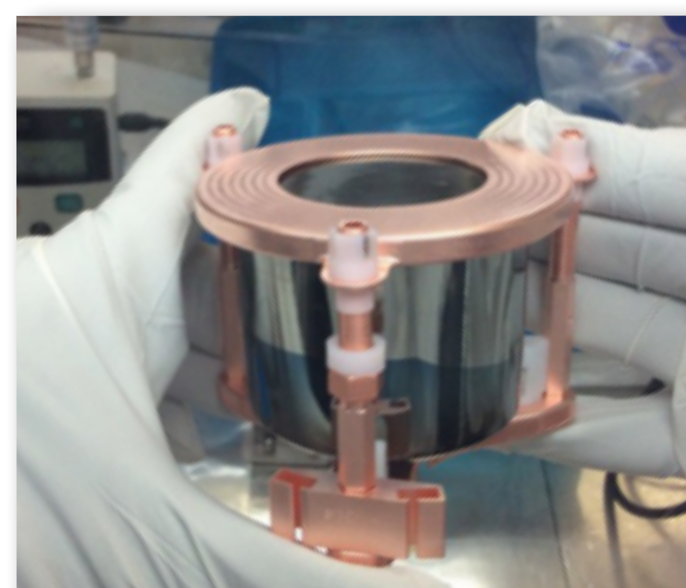
MAJORANA DEMONSTRATOR

Natural Detectors

- CANBERRA modified BEGe
- ~ 70 mm x 30 mm
- ~ 650 g each
- Made in Meriden, CT, USA; different from the Olen-type used in GERDA

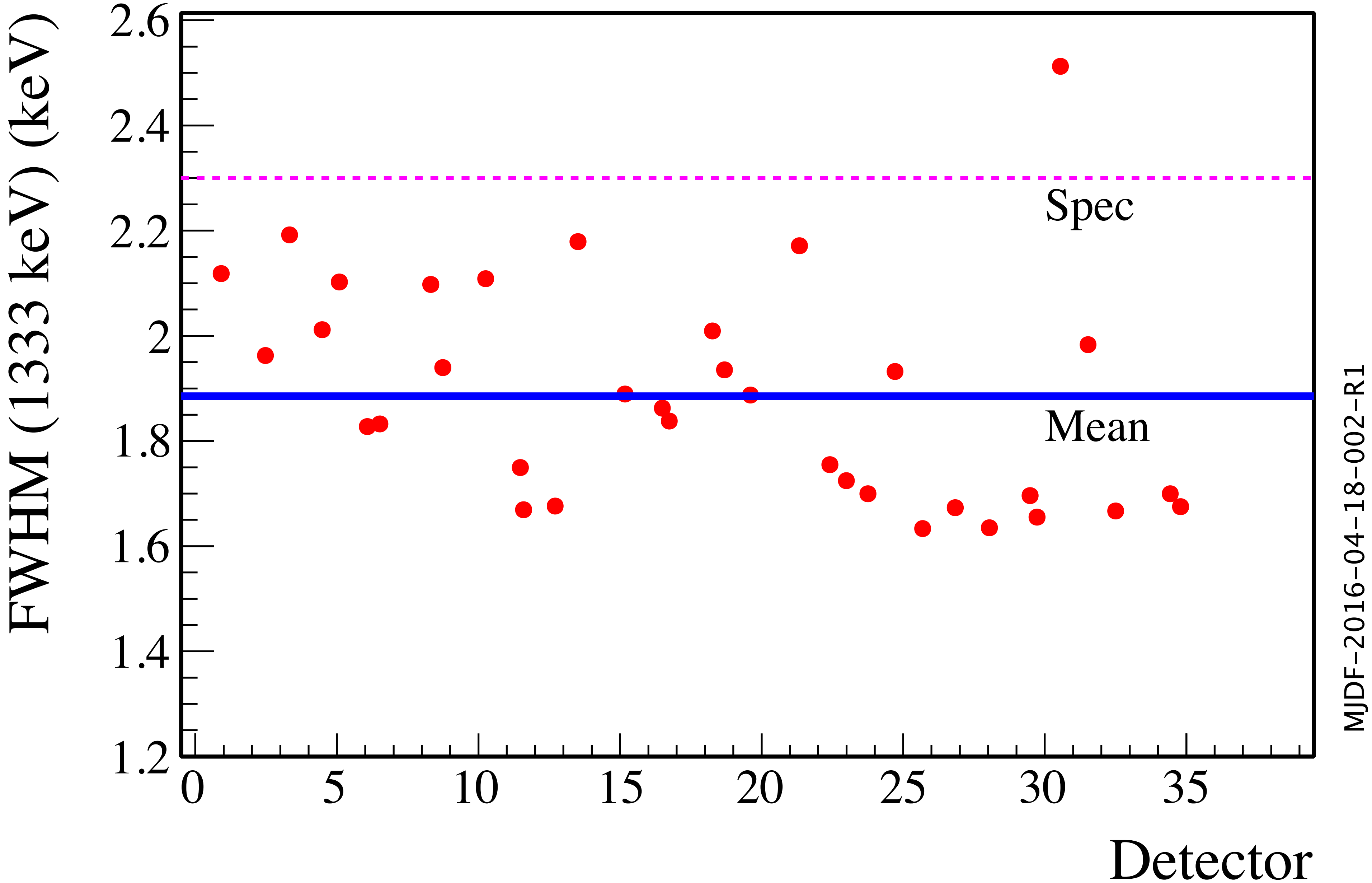
Enriched Detectors

- ORTEC PPC
- ~ 70 mm x 50 mm
- ~ 900 g each
- All production (zone refinement, crystal pull and diode production) in Oak Ridge, TN, USA
- Production began in Nov. 2012

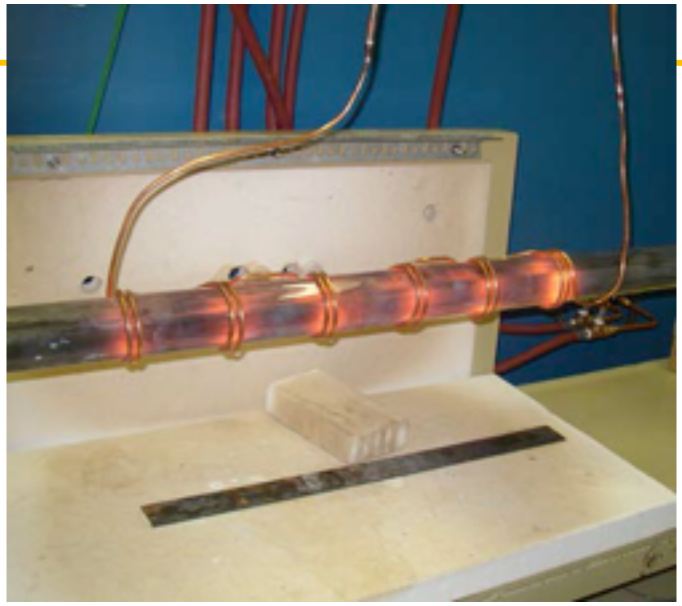


Delivered ^{enr}Ge Detectors

Vendor: AMETEK/ORTEC
Enriched detector production completed in June 2015
Total enriched detector mass = 29.683 kg / 35 detectors
Mean FWHM at 1333 keV = 1.88 keV



Material Purity



The detector

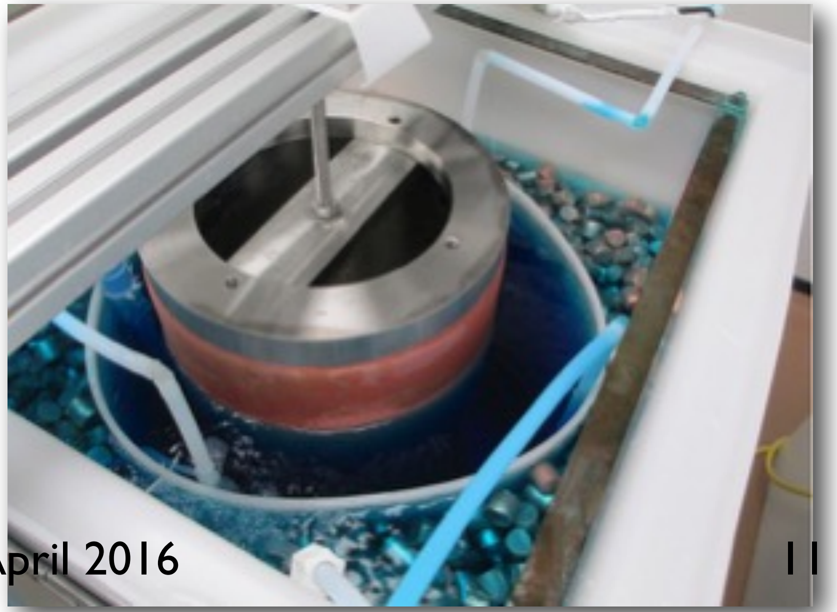
- Ge metal zone refined and pulled into a crystal that provides purification
- Limit above-ground exposure to prevent cosmic activation
- Deep underground operation

Detector mounts

- Ultra-pure plastic and electro-formed Cu
- Low mass design
- Custom cable connectors and front-end boards
- Carefully selected plastics (PTFE, PEEK, Vespel)
- Fine Cu coaxial cables

Cryostat and inner shielding

- Underground electro-formed Cu



MAJORANA Electroformed Cu

MAJORANA operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850′ level and 6 baths at a shallow UG site at PNNL. All copper was machined at the Davis campus.

The electroforming of copper for the DEMONSTRATOR successfully completed in May of 2015 but we continued to operate baths in the TCR for additional material until March 2016.

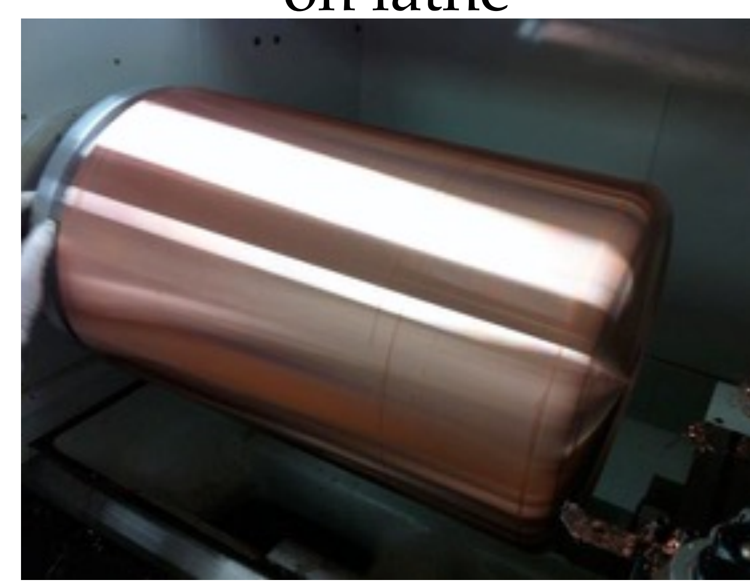
- 2654 kg of electroformed copper produced.
- 1196 kg was installed in the Demonstrator.

Electroforming Baths in TCR

Inspection of EF copper on mandrels

Th decay chain (ave) ≤ 0.1 μBq/kg
U decay chain (ave) ≤ 0.1 μBq/kg

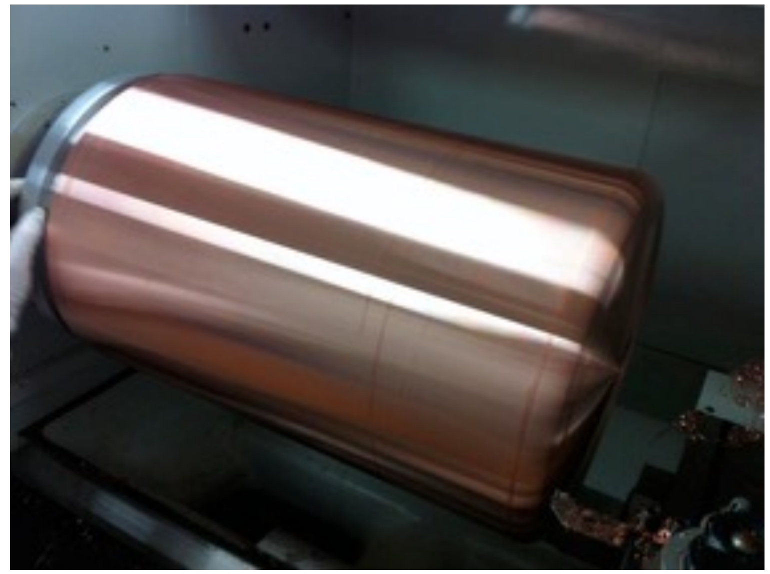
EF copper after turning on lathe

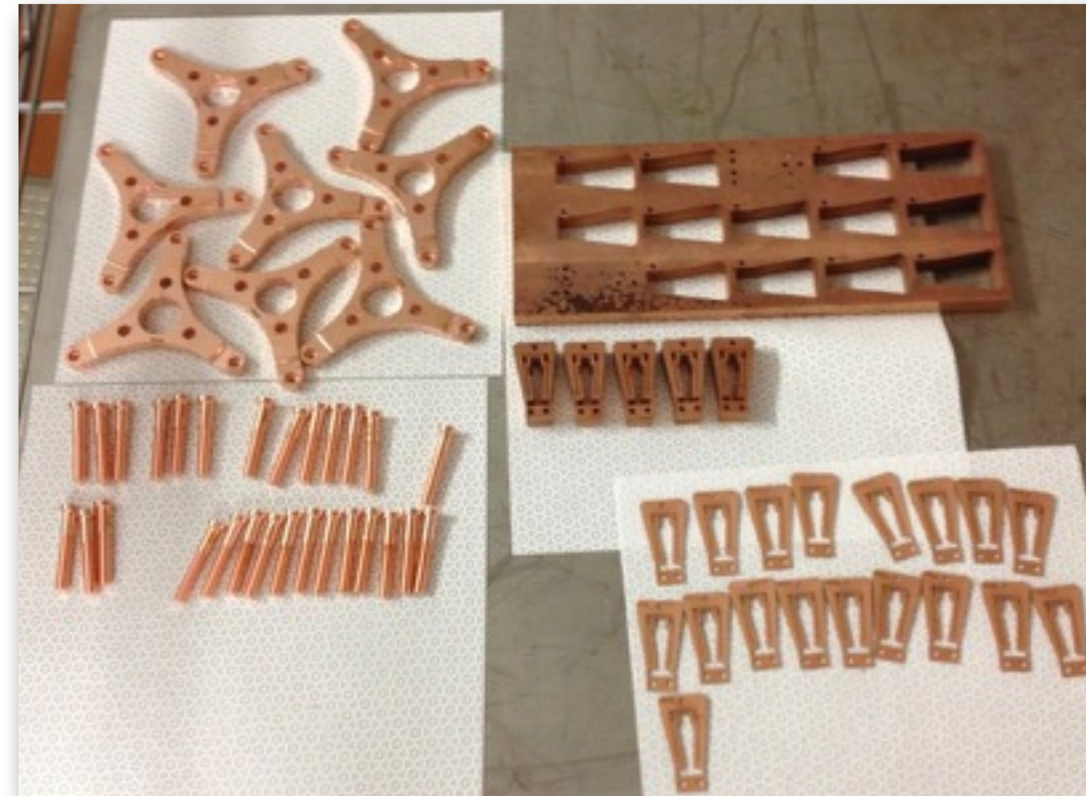


Cu Production and Machining

Underground Cu electro-forming laboratory produces all of the ultra-pure inner Cu

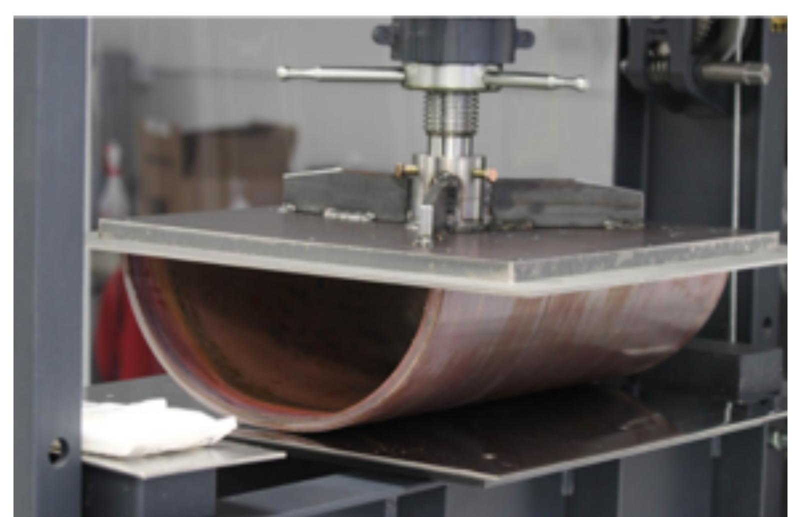
Cu Production and Machining

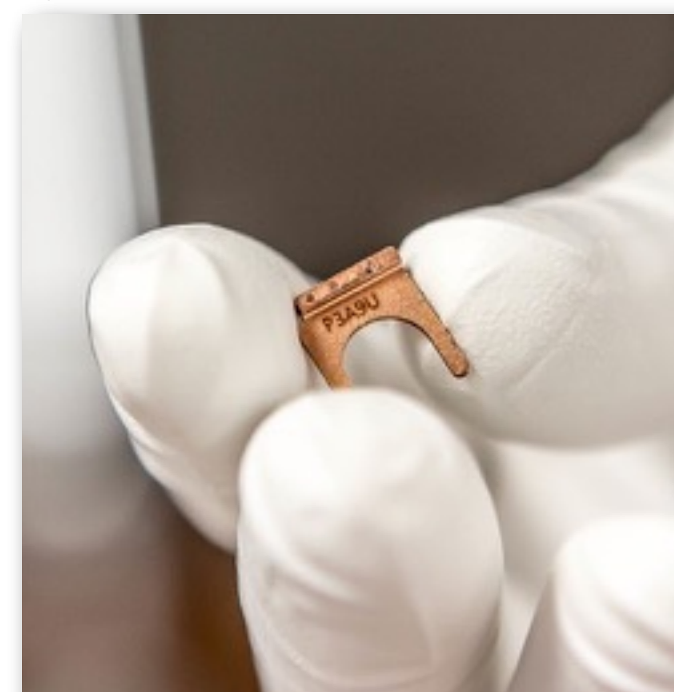




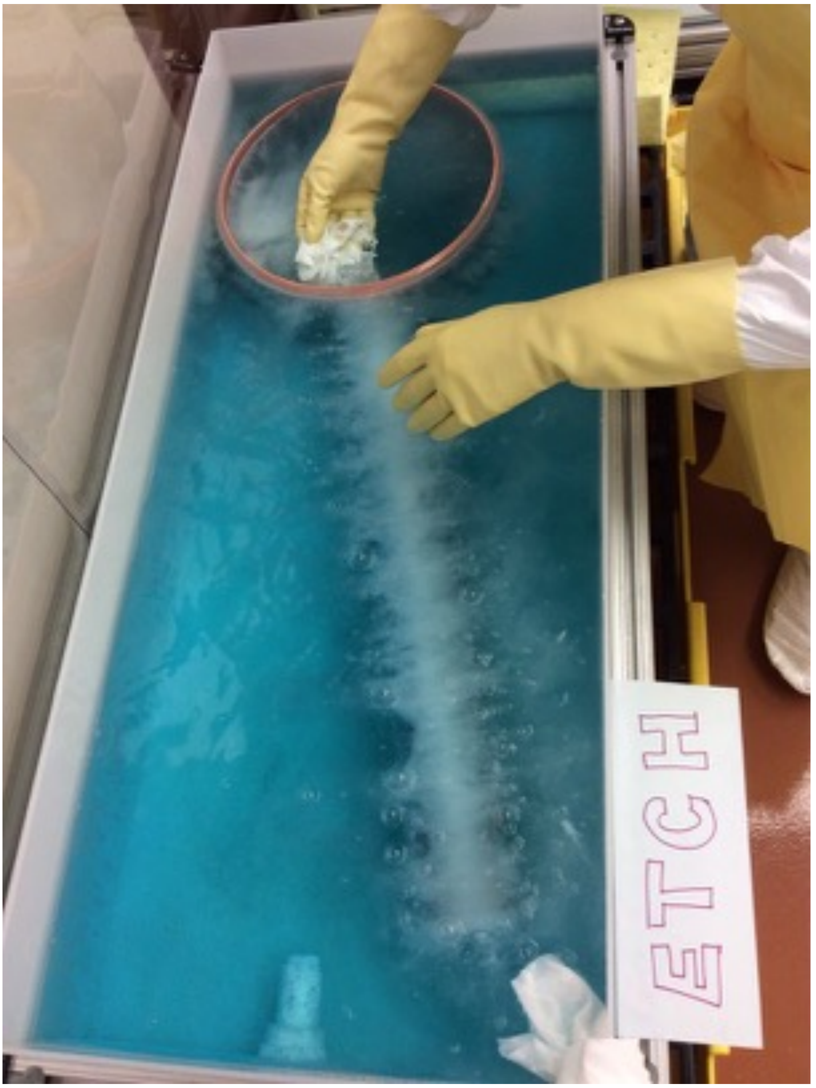
Cu machining in an underground clean room machine shop complete April 2016

All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database.



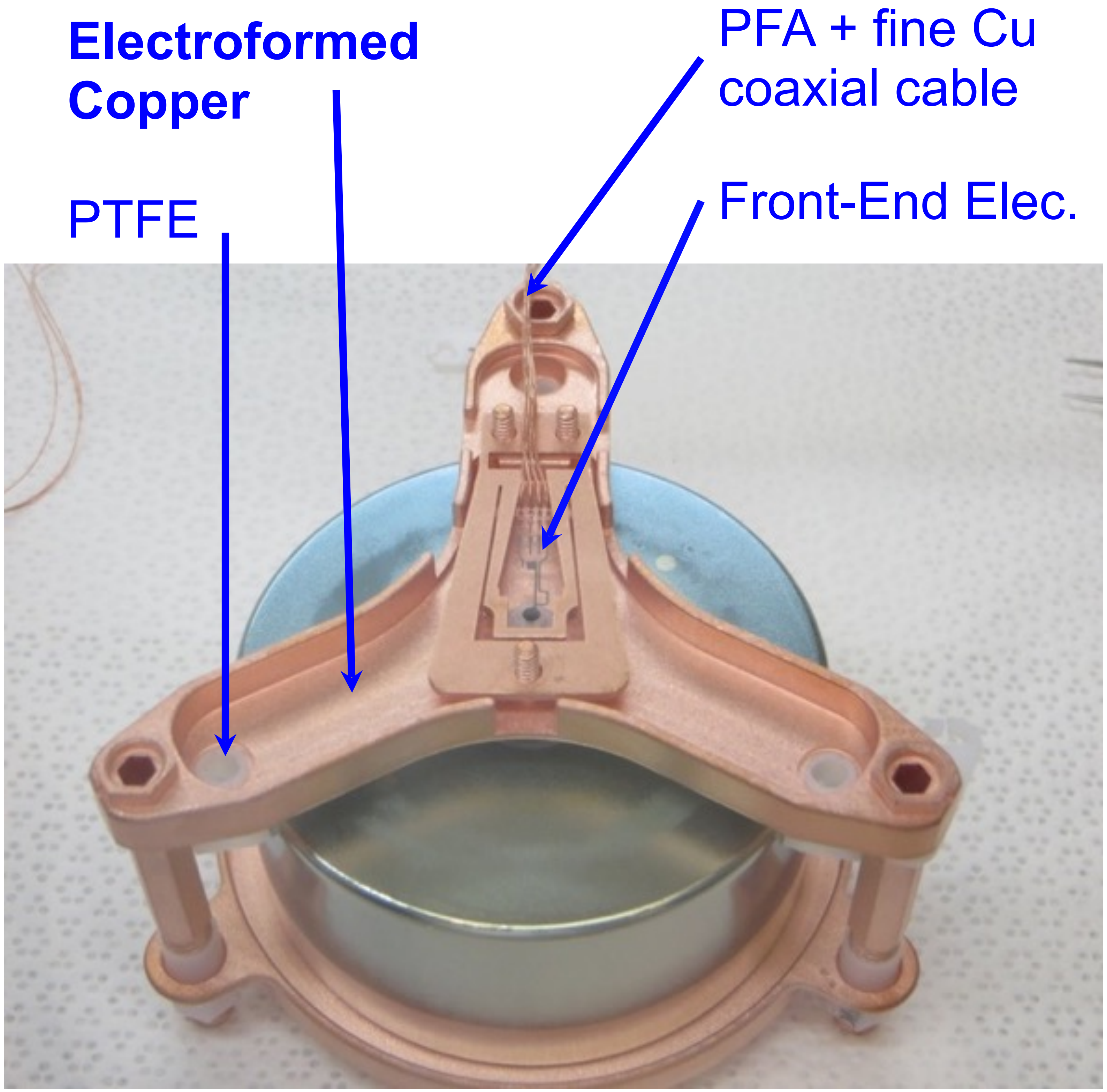


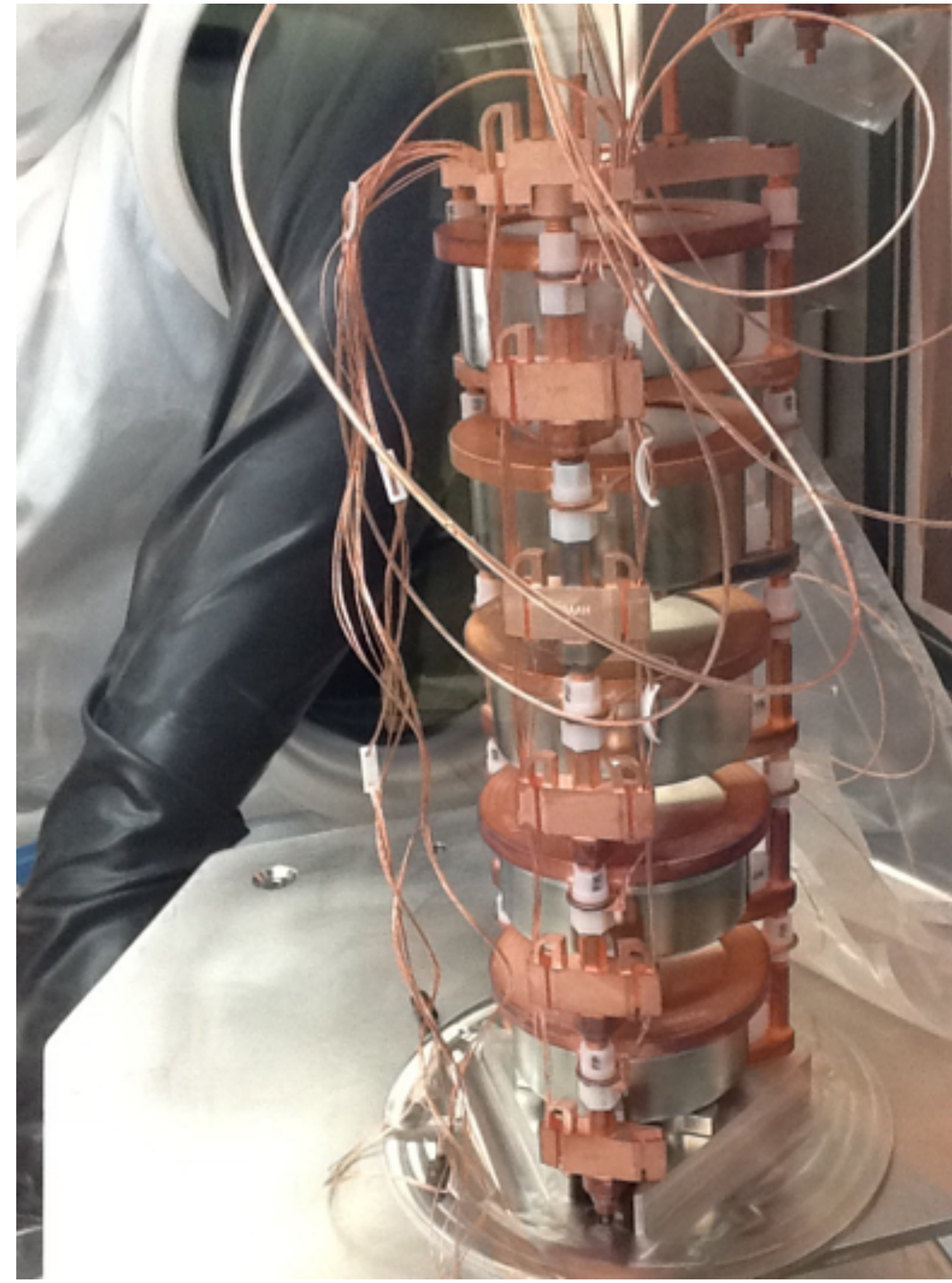
Cu Part Cleaning



Cleaning of Cu parts by acid etching and passivation

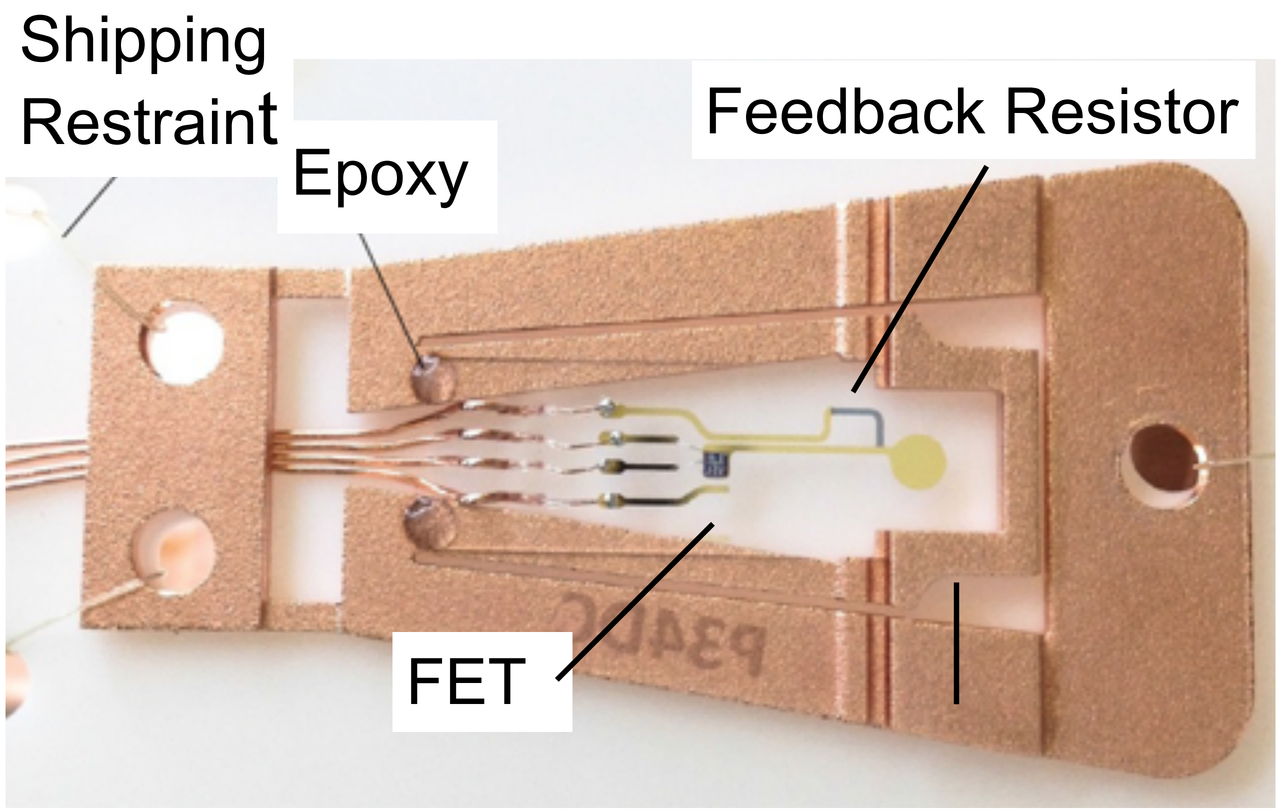
Assembled Detector Unit and String





String Assembly

Detector Readout Components



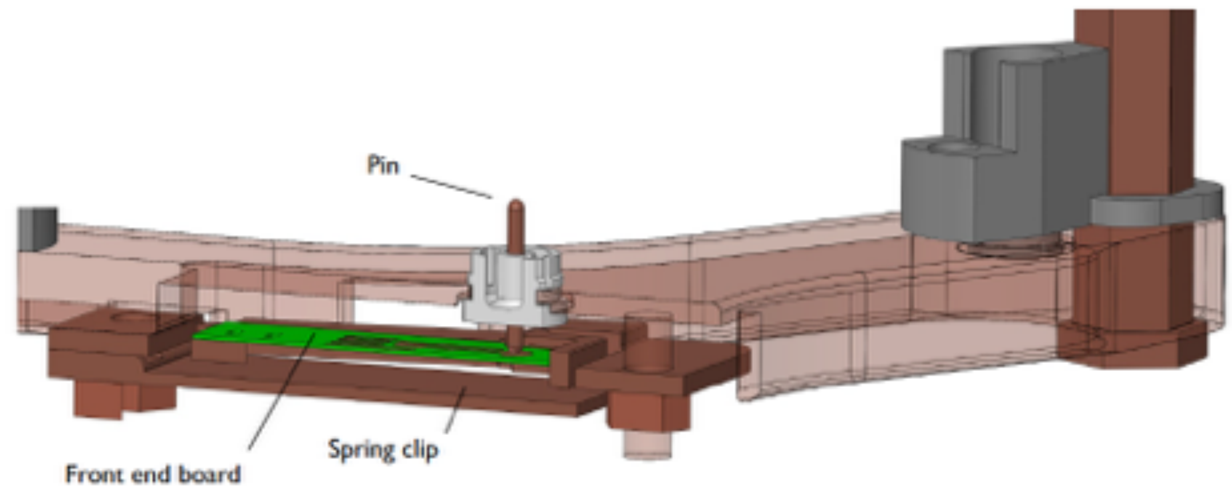
Custom low mass front-end boards

Clean Au+Ti traces on fused silica

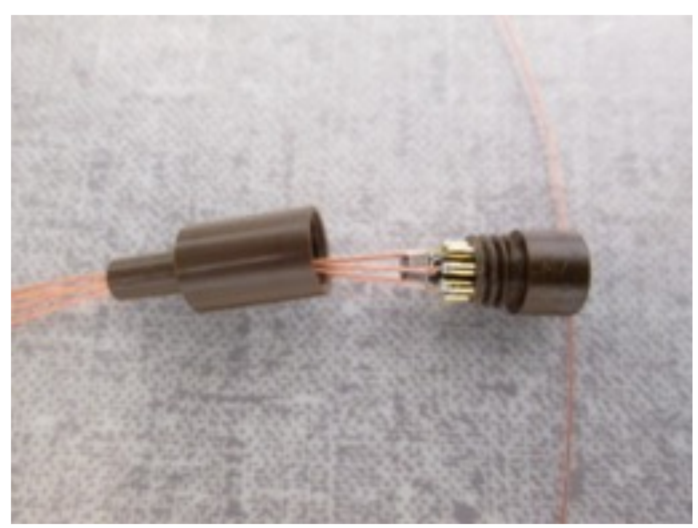
Amorphous Ge resistor

FET mounted with silver epoxy

EFCu + low-BG Sn contact pin



Fine Cu coaxial cable and clean connectors



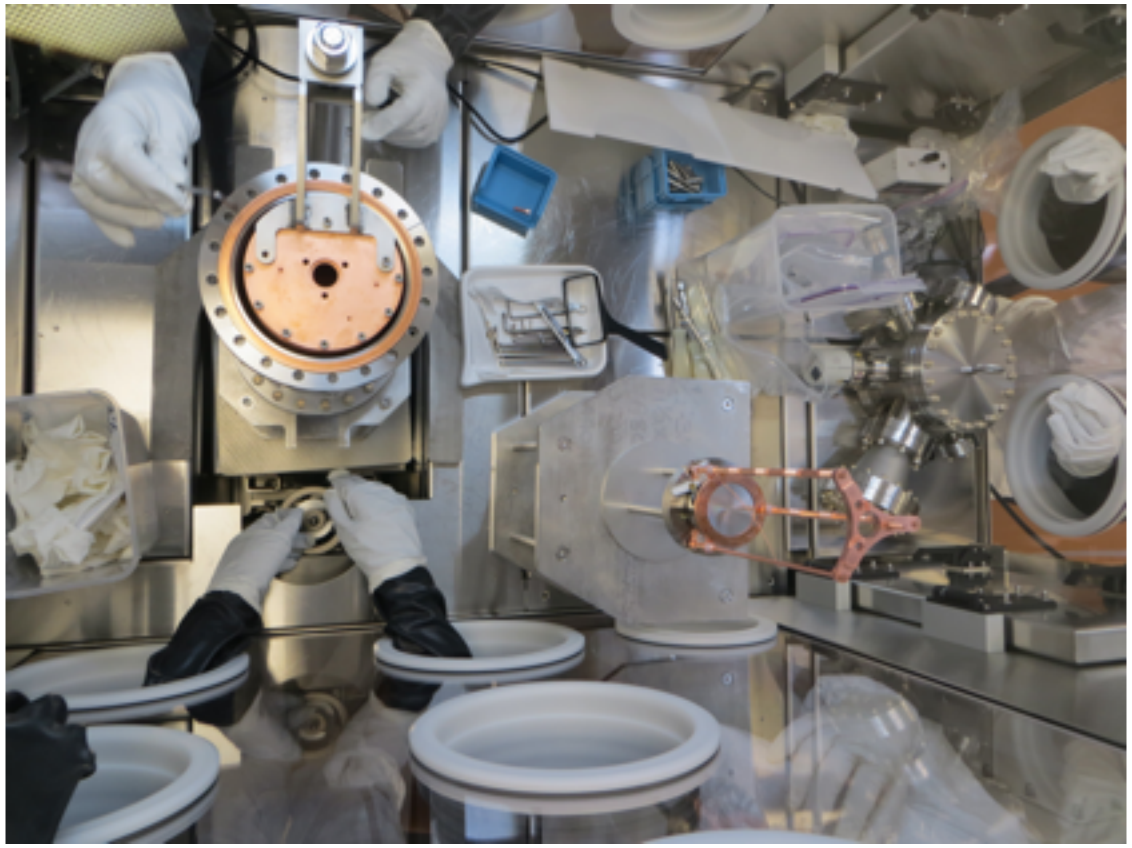
Connectors reside on top of cold plate.

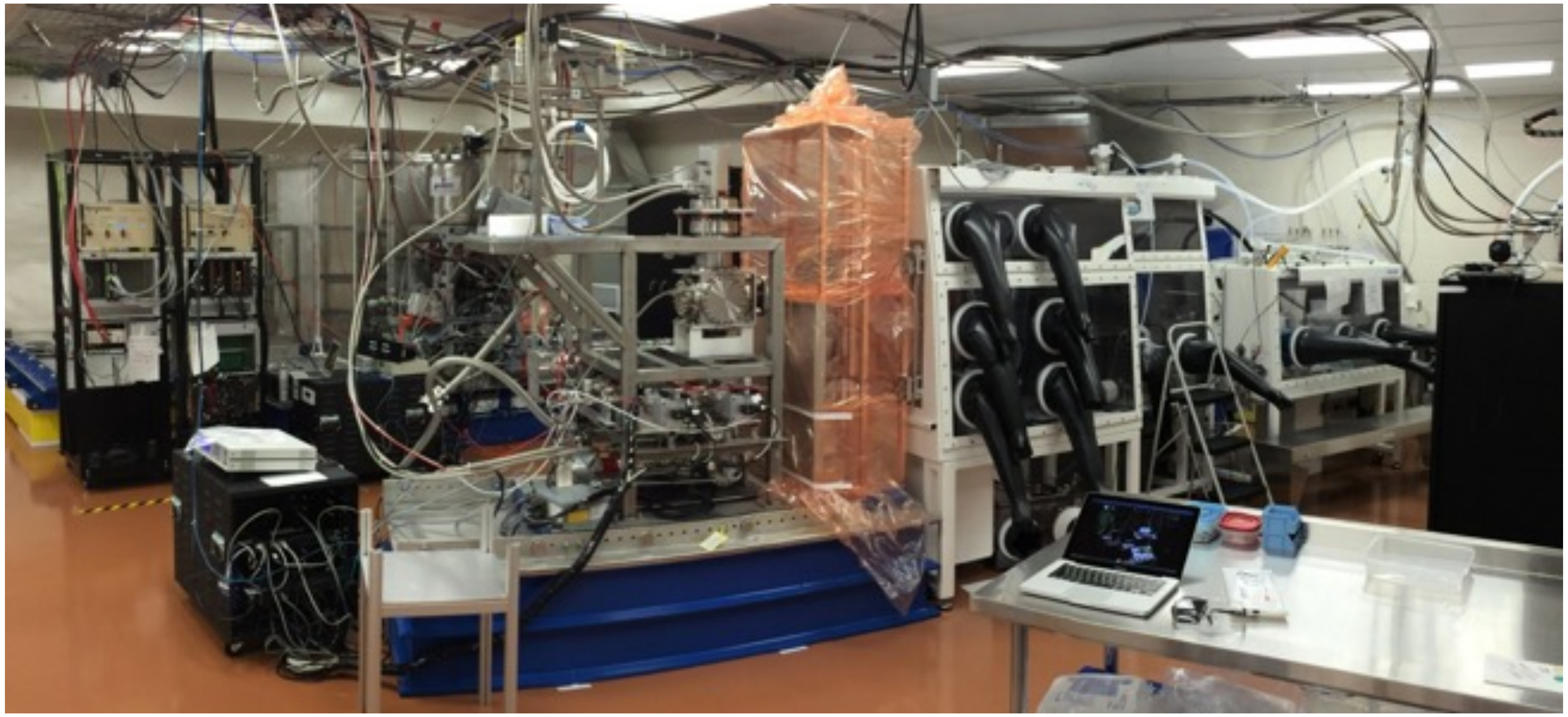
In-house machined from Vespel.

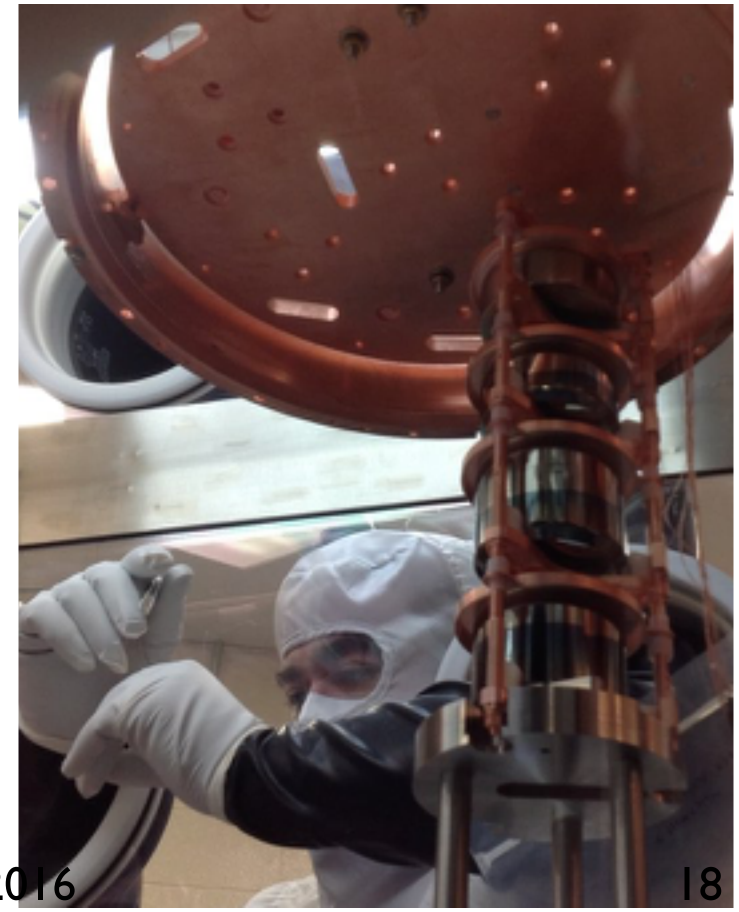
Axon' pico co-ax cable.

Low background solder and flux.

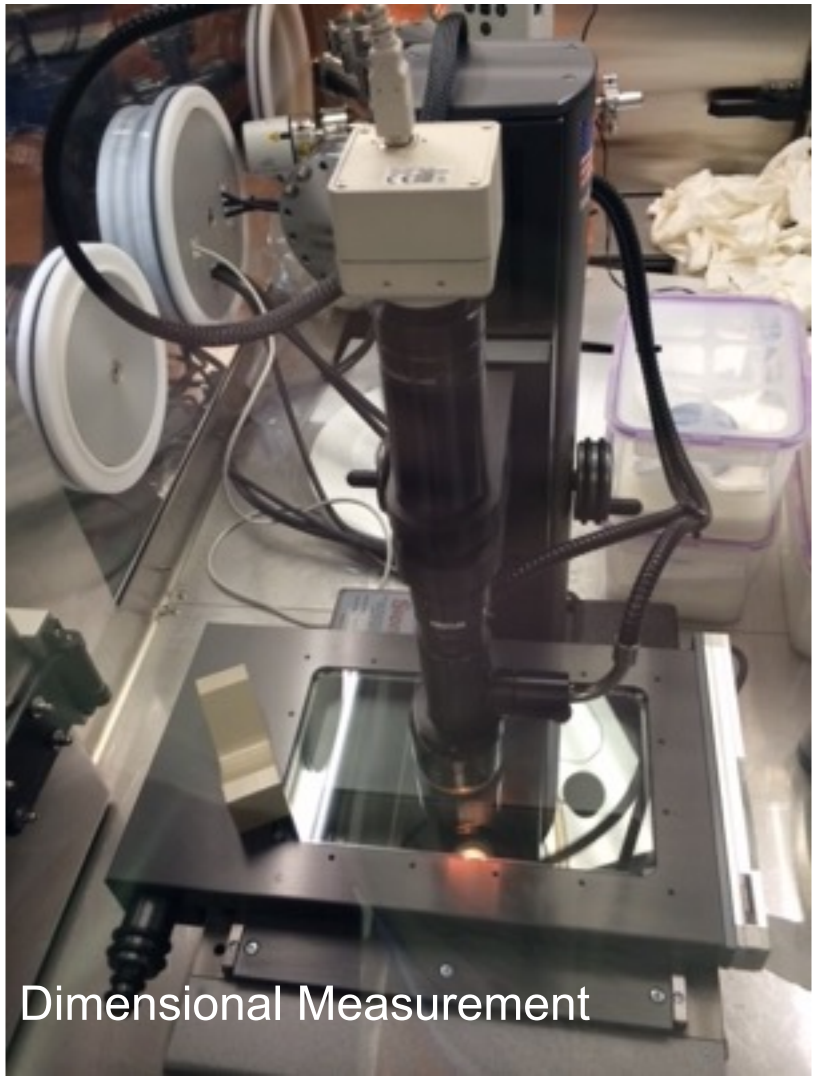
Glovebox Assembly

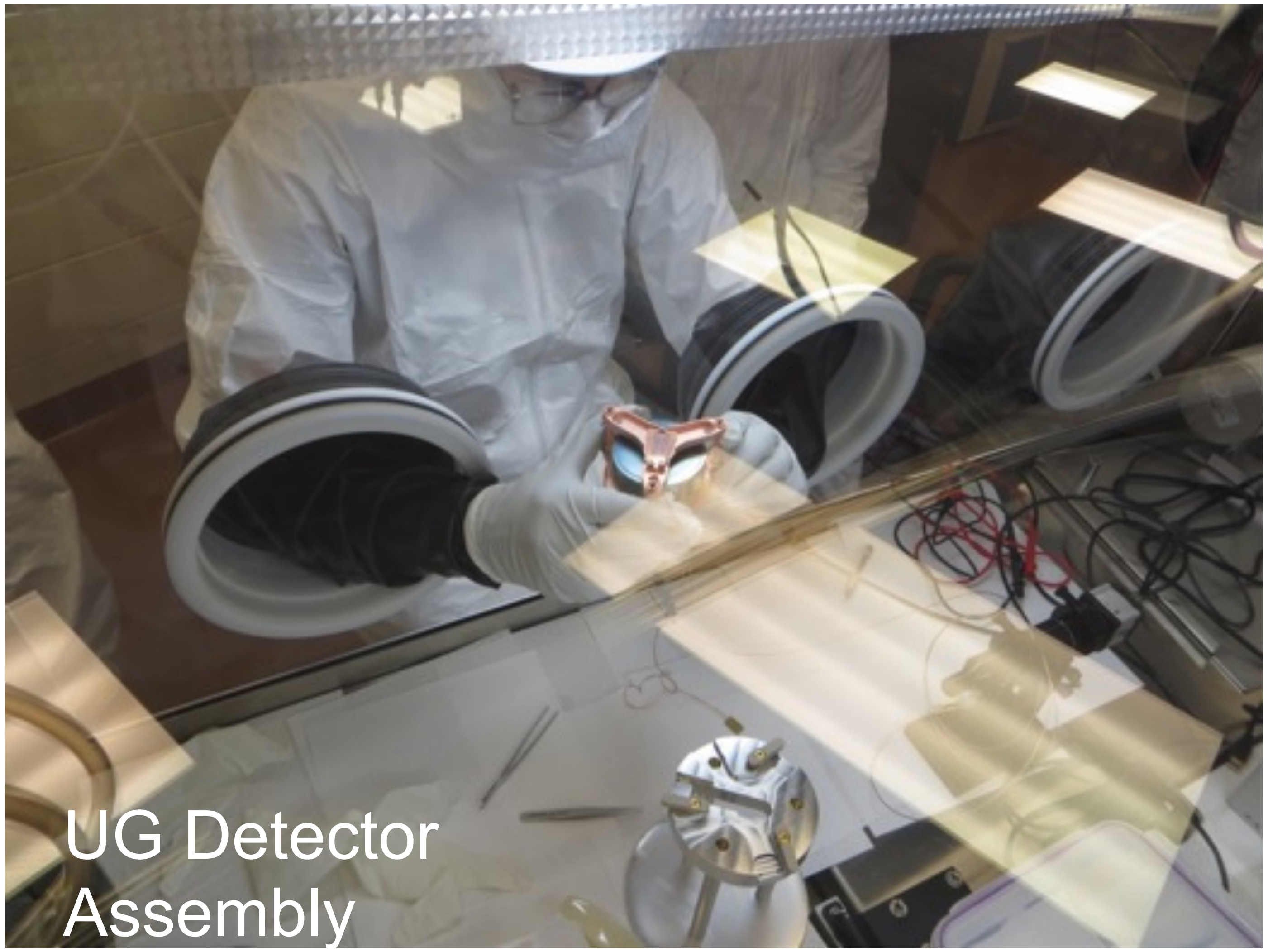






Detector Units

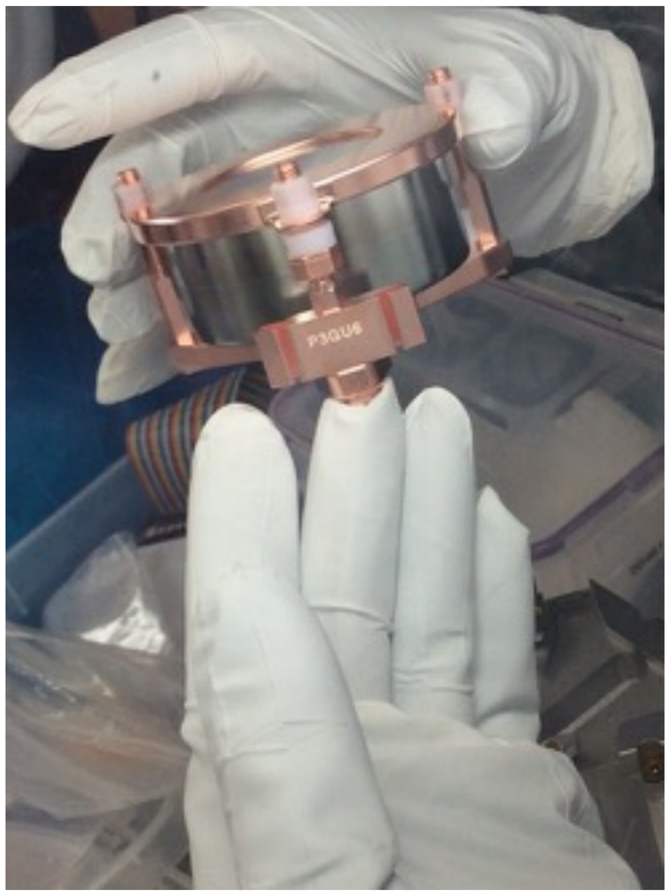


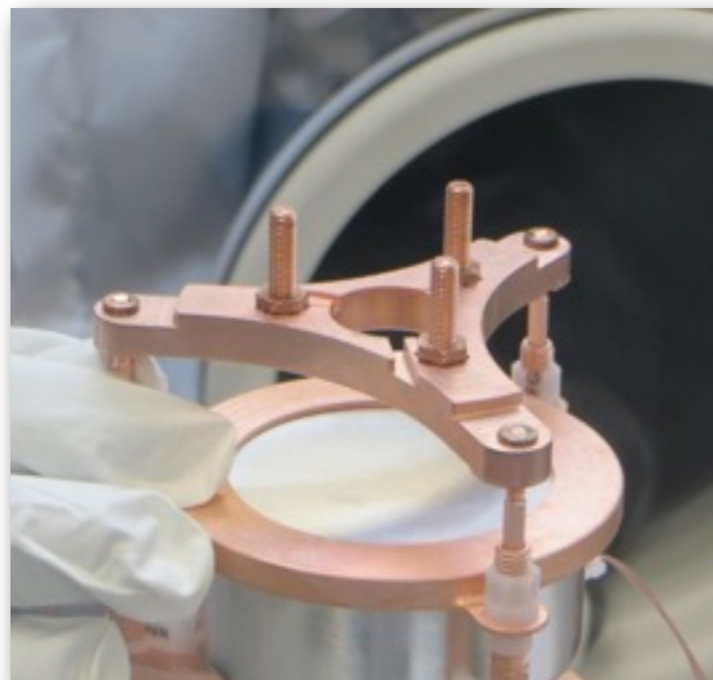


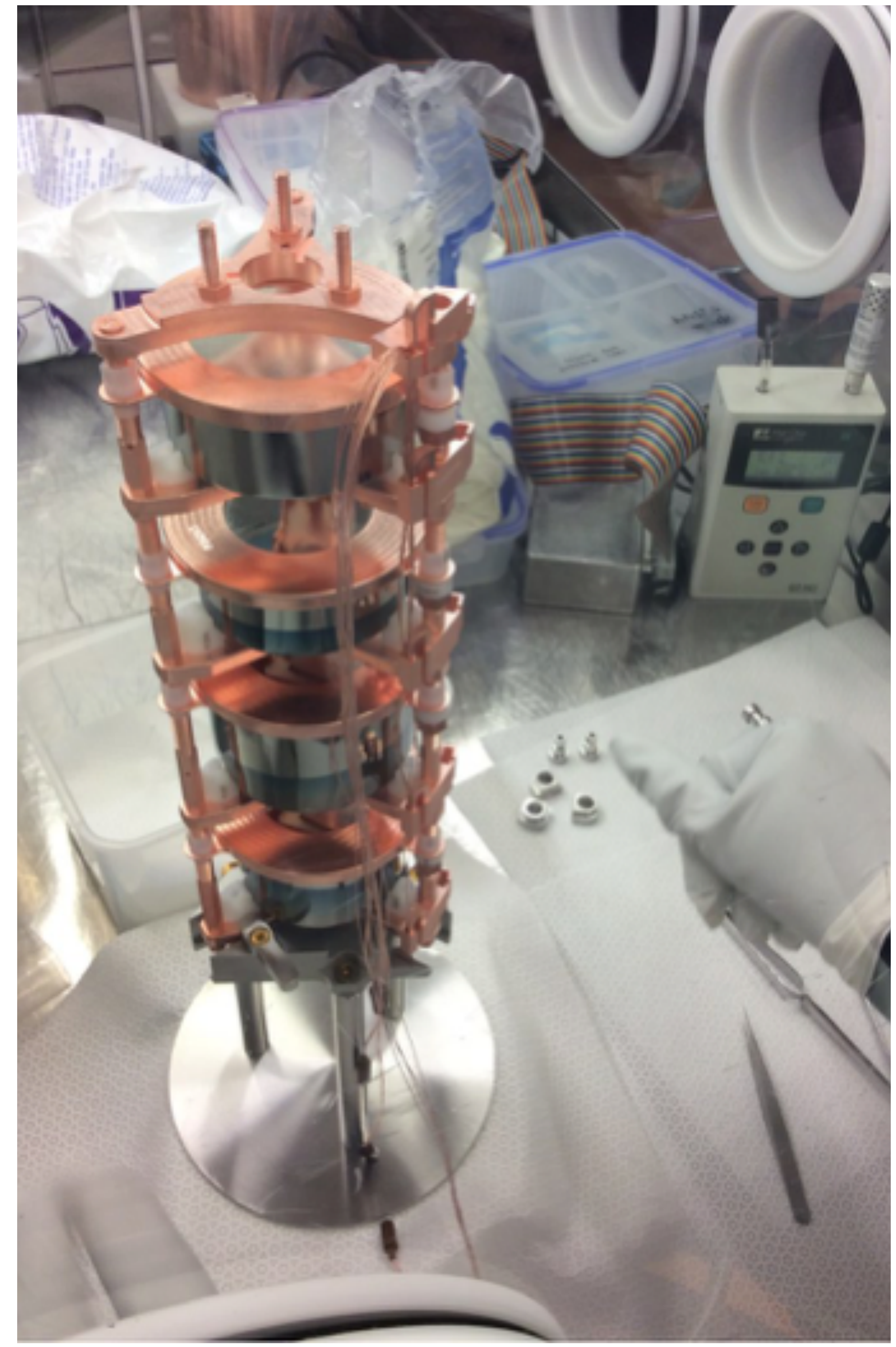
- All detector related assembly performed in N_2 purged gloveboxes.
- All detectors' dimensions recorded by optical reader.

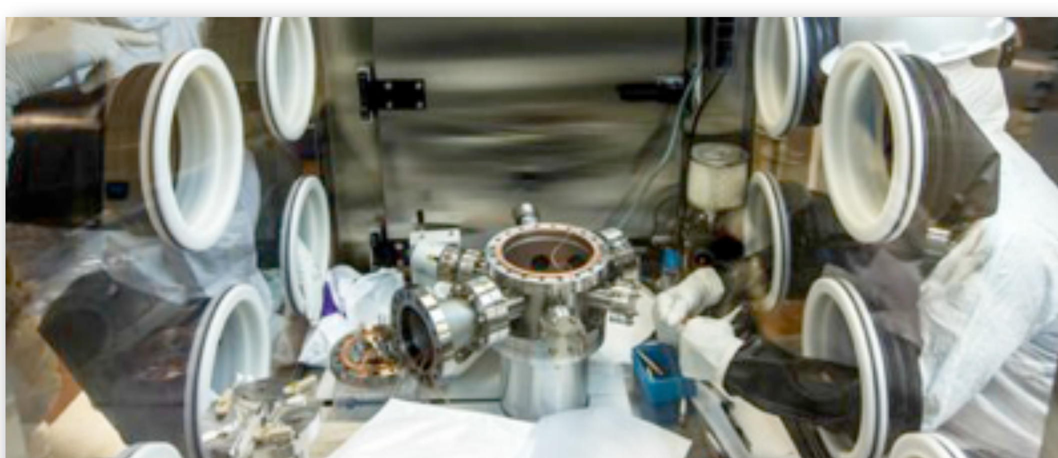
Detector Units and Strings

Detector units and strings built inside a glovebox with a radon-reduced, dry N_2 environment



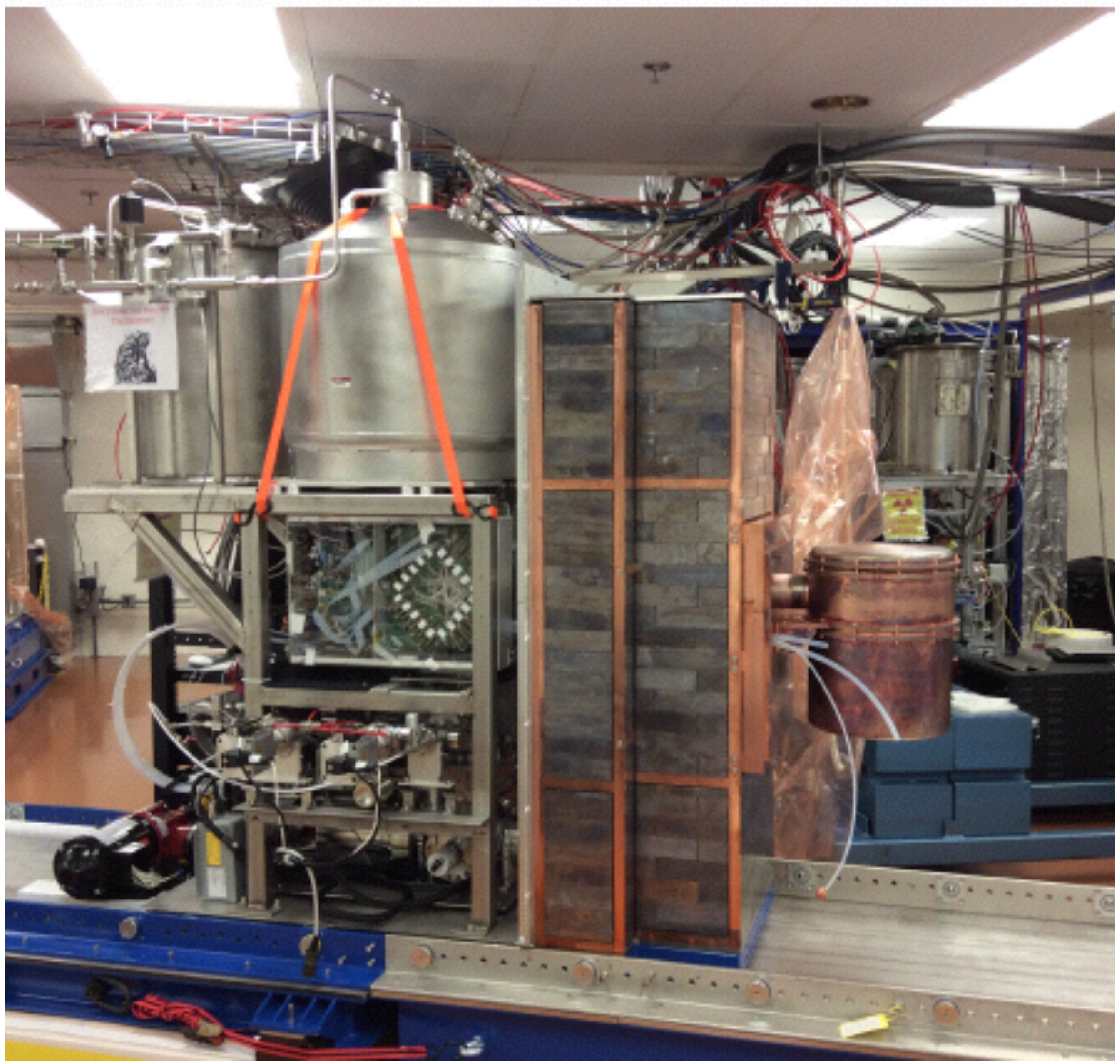






Detector Module

- A self contained vacuum and cryogenic vessel
- Contains a portion of the shielding
- Can be transported for assembly and deployment



Cryostat mated to the glovebox for string installation

Detector Module

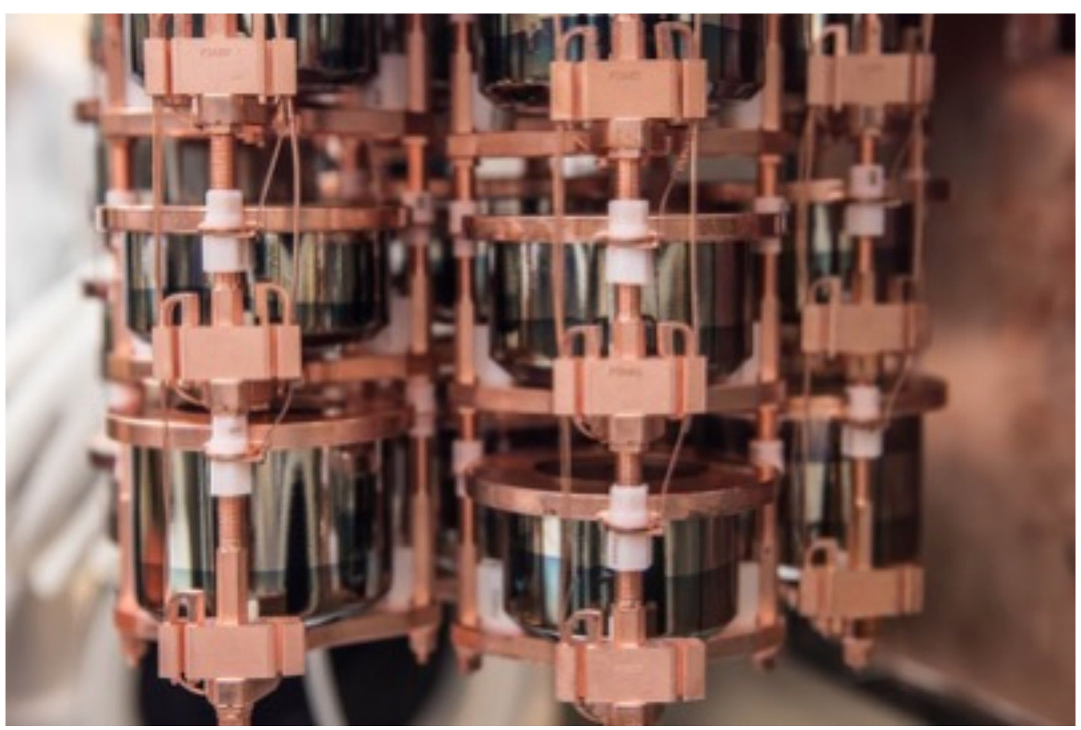
Cabling on top of cold plate

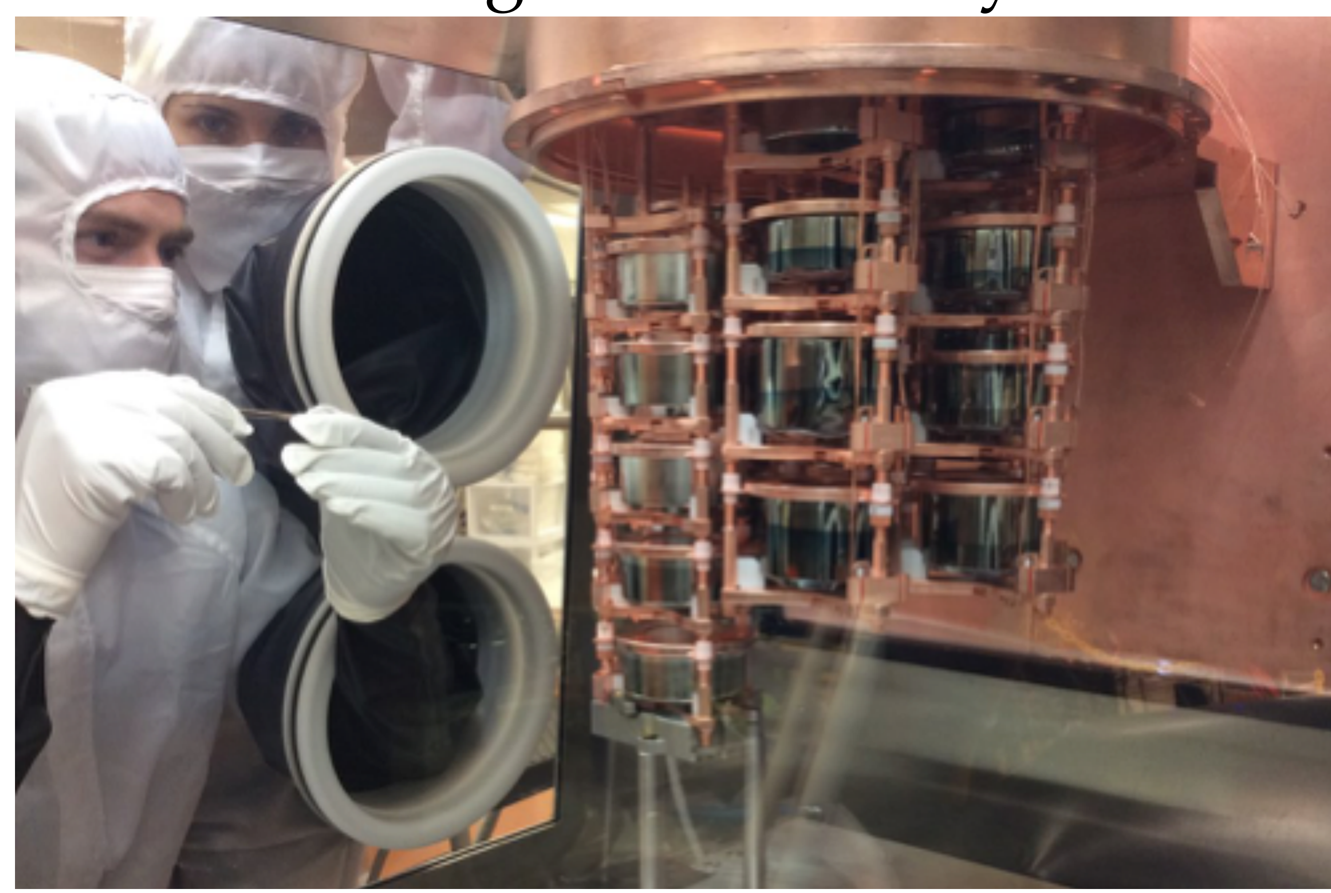
First string of ${}^{enr}Ge$ in Cryostat 1

Detector Module

Loading of ^{enr}Ge in Cryostat 2

Loading of ^{enr}Ge in Cryostat 1

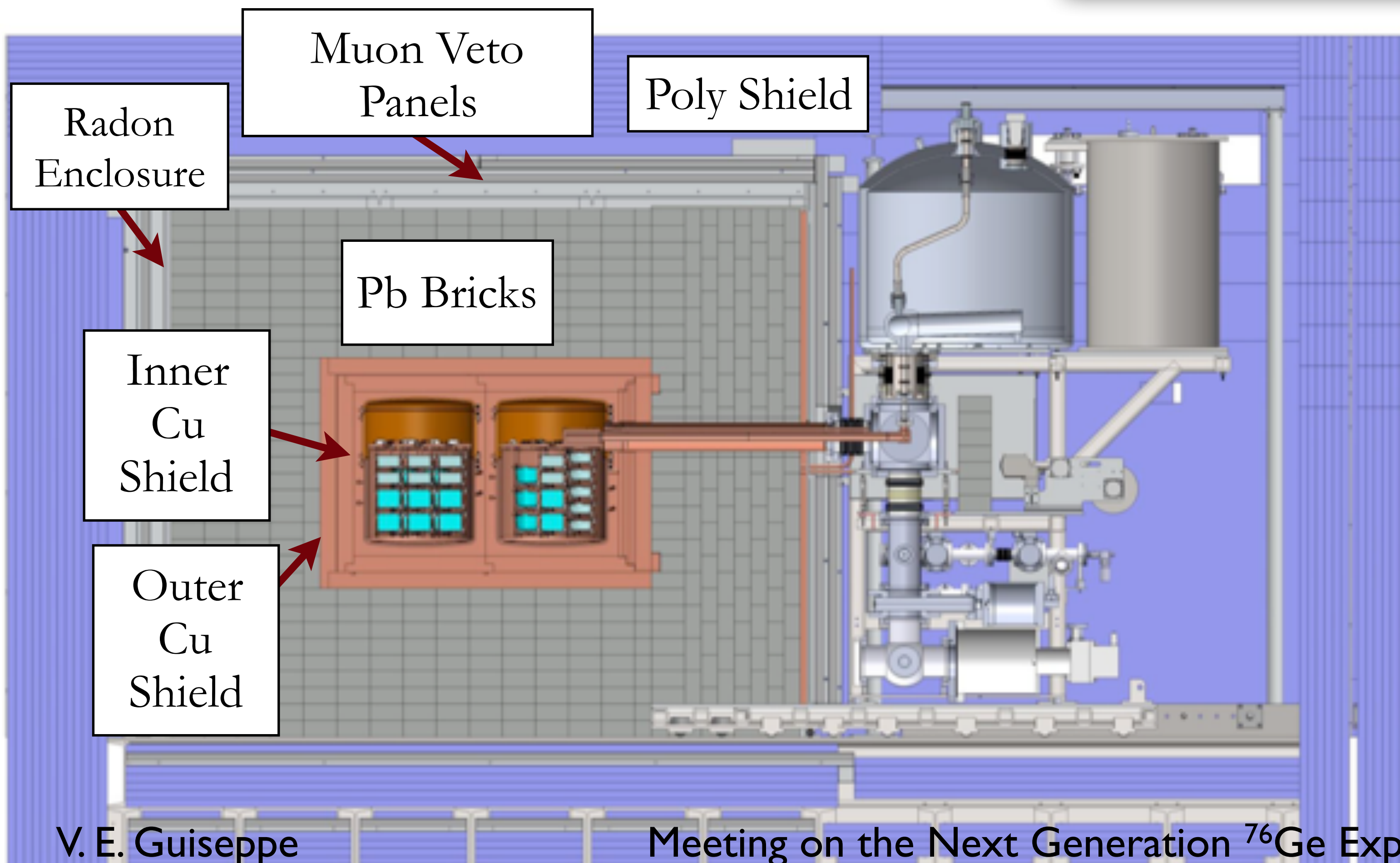




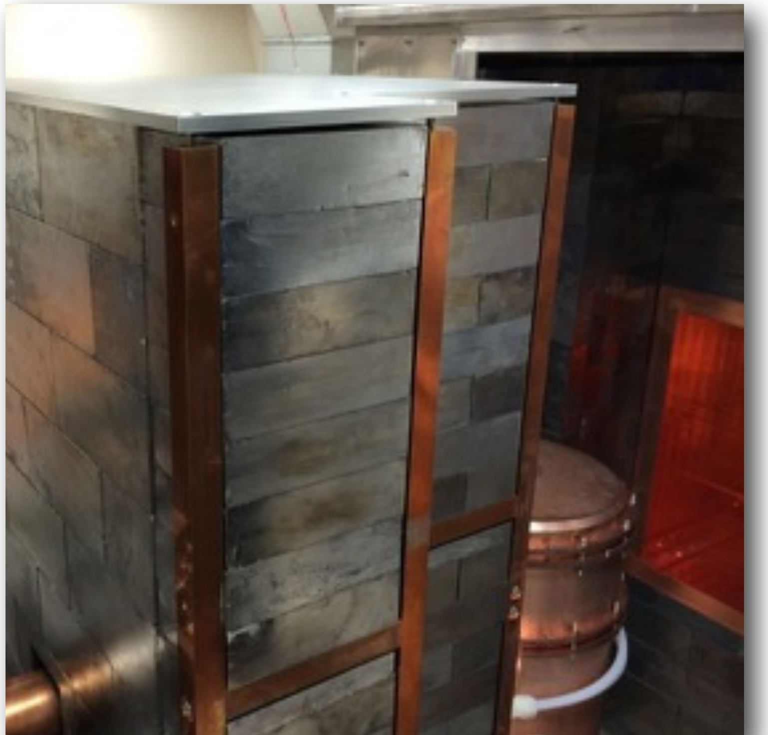
Passive Shielding and Muon Veto

Pb and outer Cu shield installed

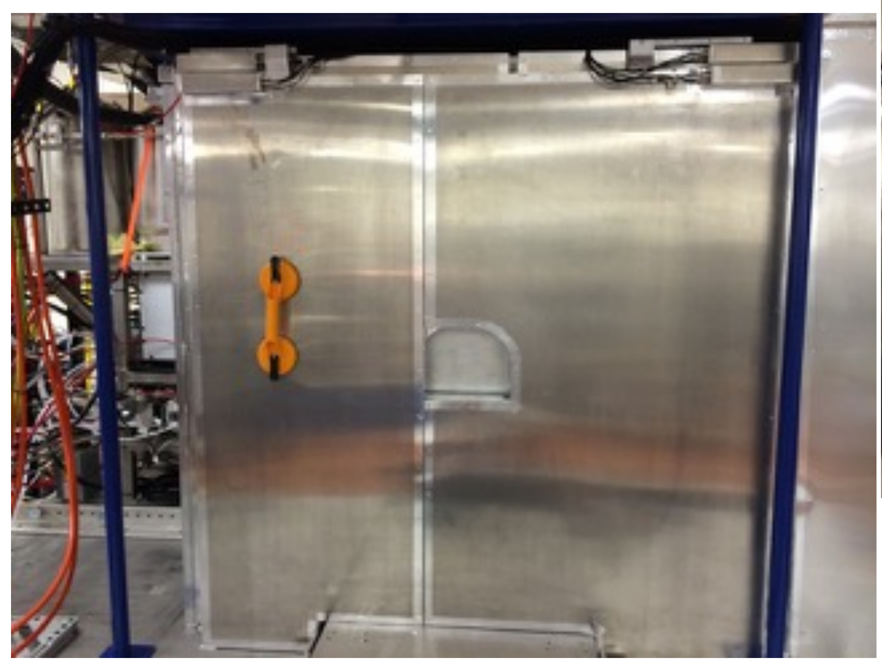
Module deployment



Passive Shielding and Muon Veto

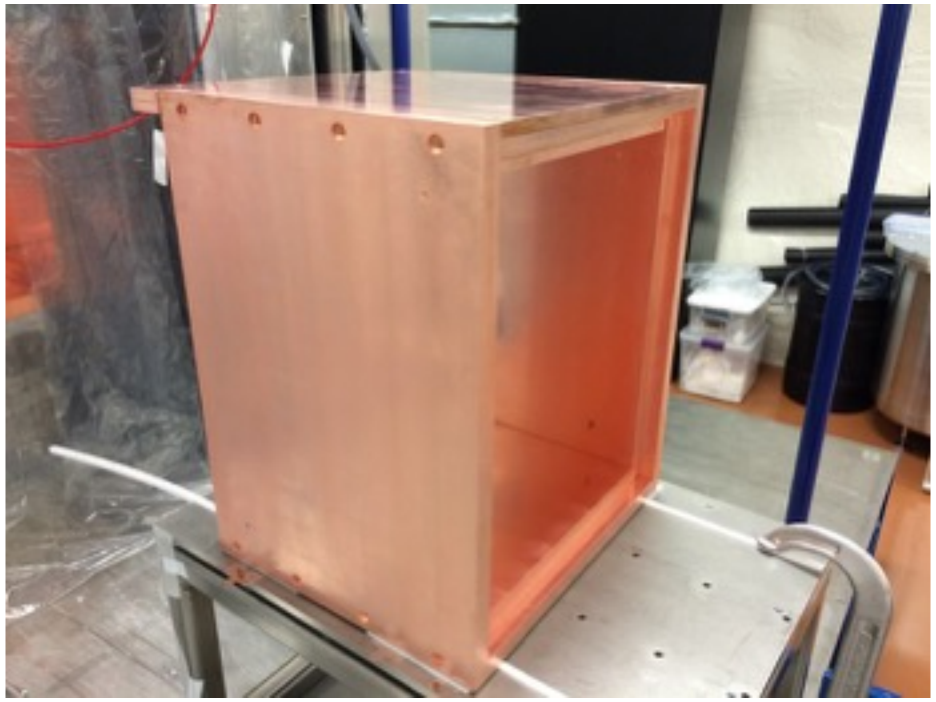


Module deployment



Muon panels

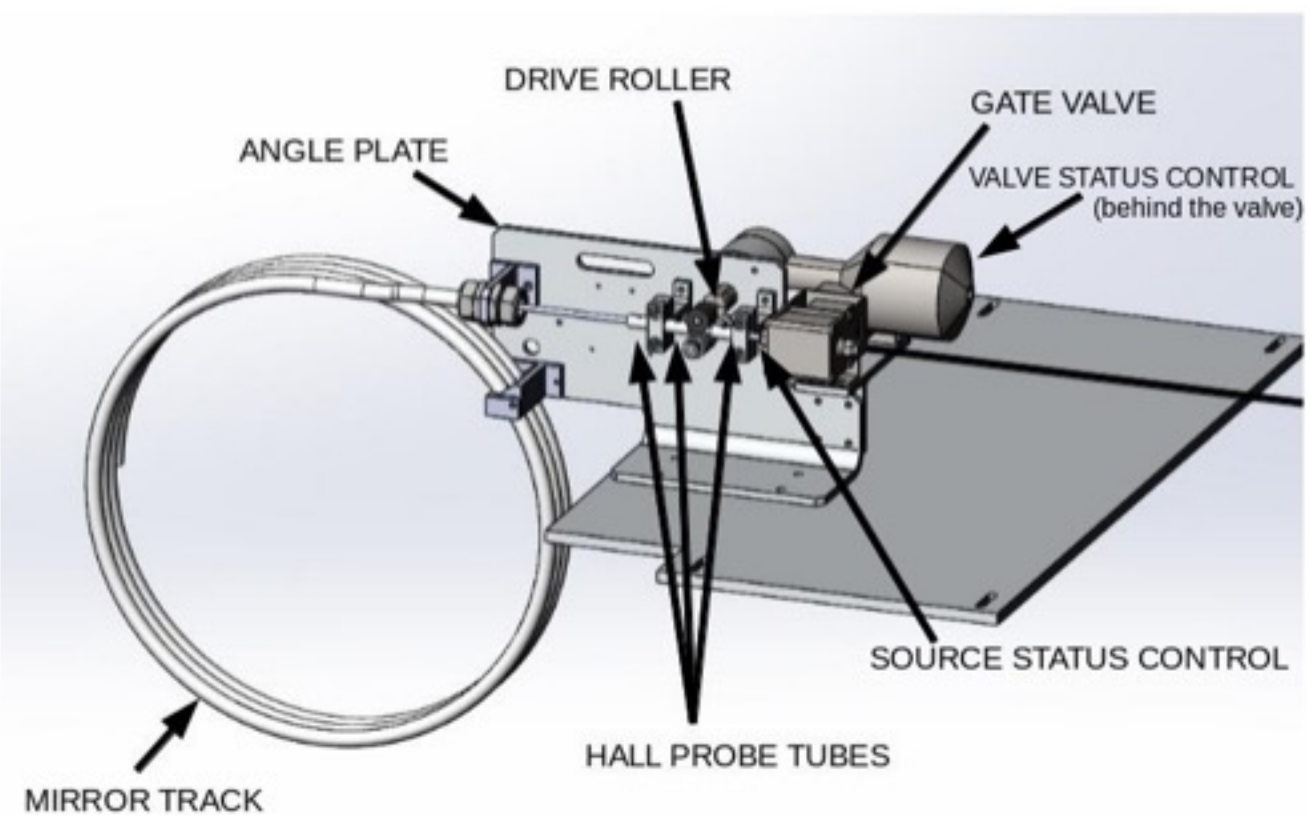
The Inner Copper Shield



- Extensive time to electro-form the Cu parts.
- String parts higher priority for machining.
- Hence installed after shield constructed.
- Expect x10 reduction in background from other shield materials.

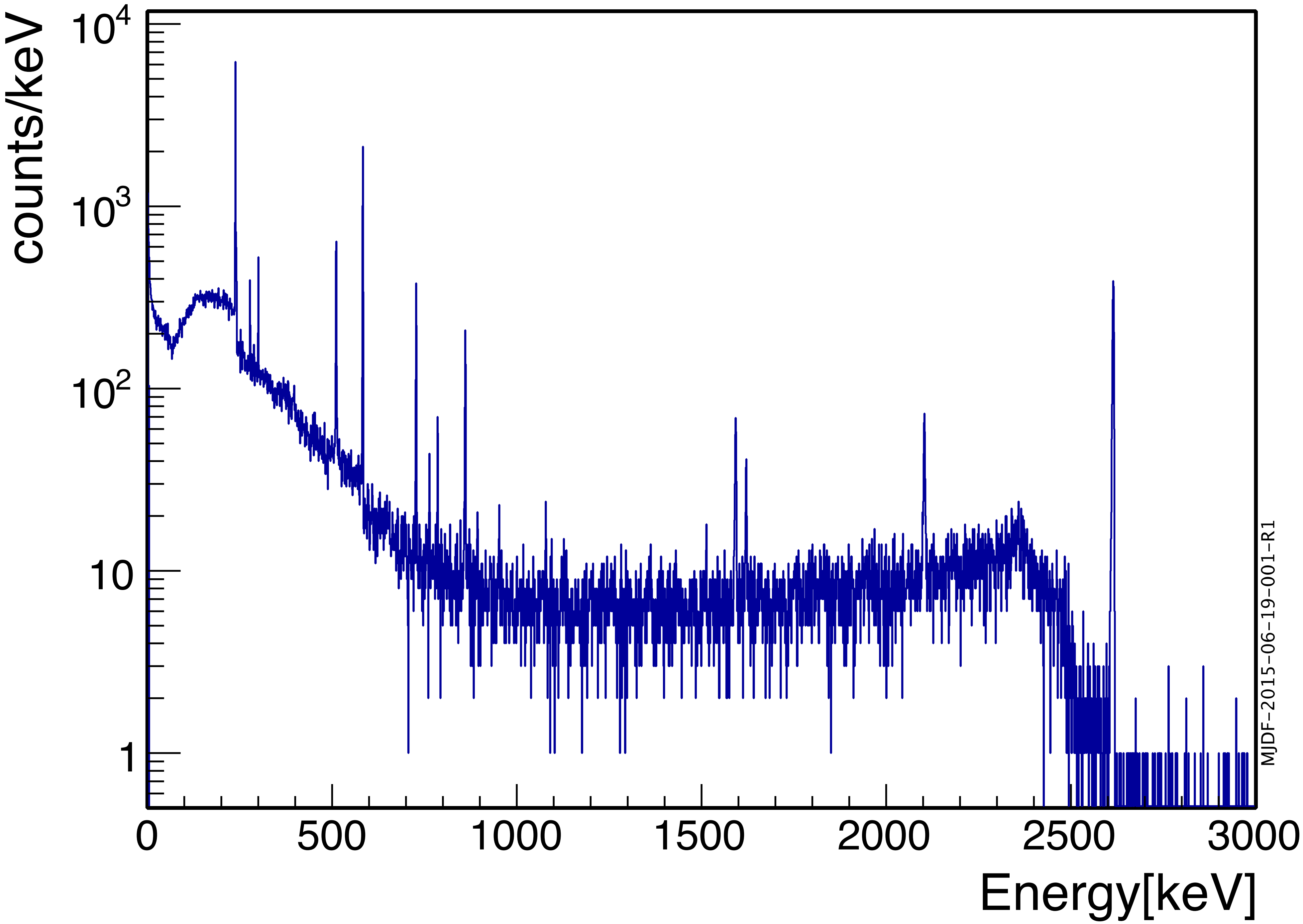
The MAJORANA Calibration system

- Line sources are deployed from outside the shielding within a tube that surrounds each cryostat.
- ^{228}Th (11.6 kBq) and ^{60}Co (6.3kBq) sources available.
- Calibration tube is externally purged during calibration.
- Several sensors monitor the position of the source and the status of the system.

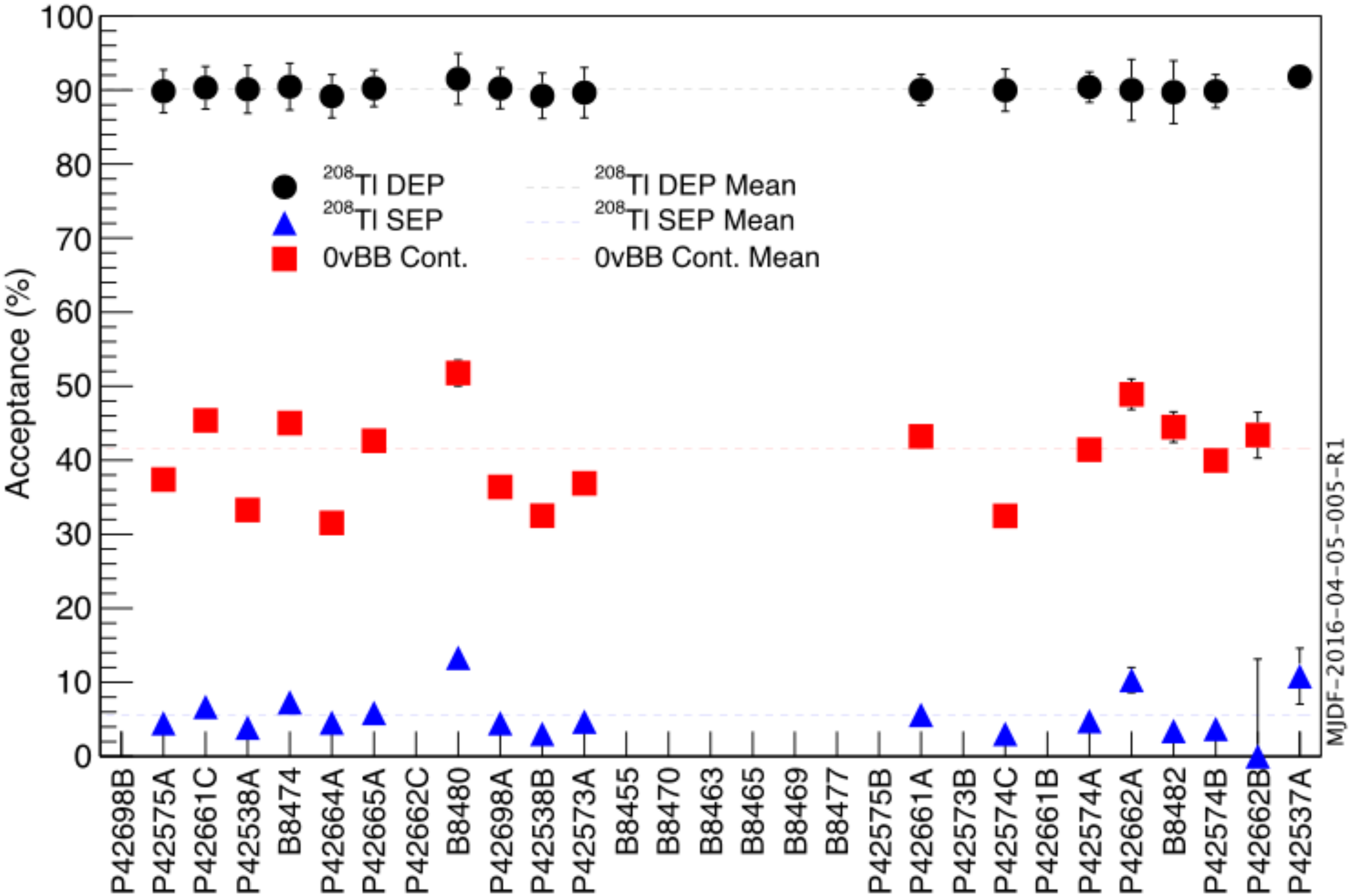


^{228}Th Calibration Spectrum in Module 1 (DS0)

One enriched detector spectrum within a string mounted in Module 1 and inside shield. FWHM 3.6 keV at 2.6 MeV



Ge Detector PSD Performance in Module 1 (DS1)



^{208}Tl DEP (single site events) fixed to 90%

^{208}Tl SEP (multi-site events) reduced to 10%

Data Set Parameters

Data Set	Prototype Module	Module 1 no inner shield	Module 1 with inner shield
mnemonic	DS-PM	DS0	DS1
Operation Dates	9/18/14 – 4/17/15	6/26/15 – 10/7/15	12/31/15 – 4/14/16*
Run Time	211 d	103.15 d	104.68 d
Live Time	138.22 d	47.73 d	54.70 d
Fraction Live	0.65	0.46	0.52
Enriched Ge Exposure	0 kg d	510.2±1.1 kg d	650.41±0.30 kg d
Natural Ge Exposure	701.7 kg d	186.6±0.6 kg d	91.35±0.15 kg d

*Data taking ongoing

Dry-run of analysis and data production
Found known backgrounds and addressed
2 observed backgrounds

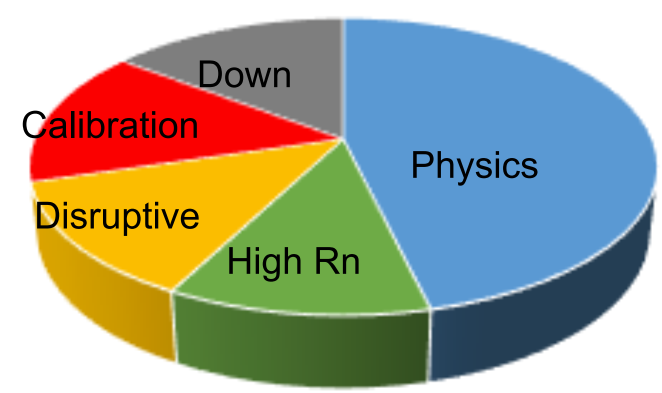
Module 1 Data Set Duty Cycles

Break for Module 1 planned improvements

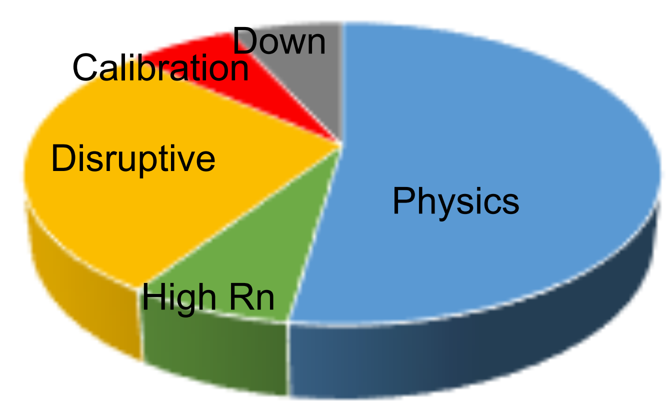
		DS0 (days) No inner shield June 26, – Oct. 7, 2015	DS1 (days) with inner shield Dec. 31, 2015 – Apr. 14, 2016*
Total		103.15	104.68
Total acquired		88.04	97.49
Physics	(blue)	47.73	54.70
High radon	(green)	11.76	7.32
Disruptive Commissioning tests	(yellow)	13.10	28.61
Calibration	(red)	15.44	6.86
Down time	(grey)	15.11	7.19

*Data taking ongoing

DS0



DS1



Module 1 Improvements – Fall 2015

Operated in-shield June 2015 - Oct. 2015

- Partial shielding and some high-background components

During Oct.- Dec. 2015 performed planned improvements to Module 1.

- Installed inner Cu shield: Decrease background contribution from outer Cu shield and Pb by factor of about 10.
- Replaced Kalrez O-rings in cryostat: These o-rings contributed to our background. Replaced with PTFE.

    Kalrez: Th ~ 2000-4000 ppt. Expect about 80 c/ROI t y.

    PTFE sheet: significant reduction in BG compared to Kalrez.

Crossarm Shielding: Added to decrease background contributions from electronics-breakout box region.

Repaired non-operating detectors and upgrade cables:

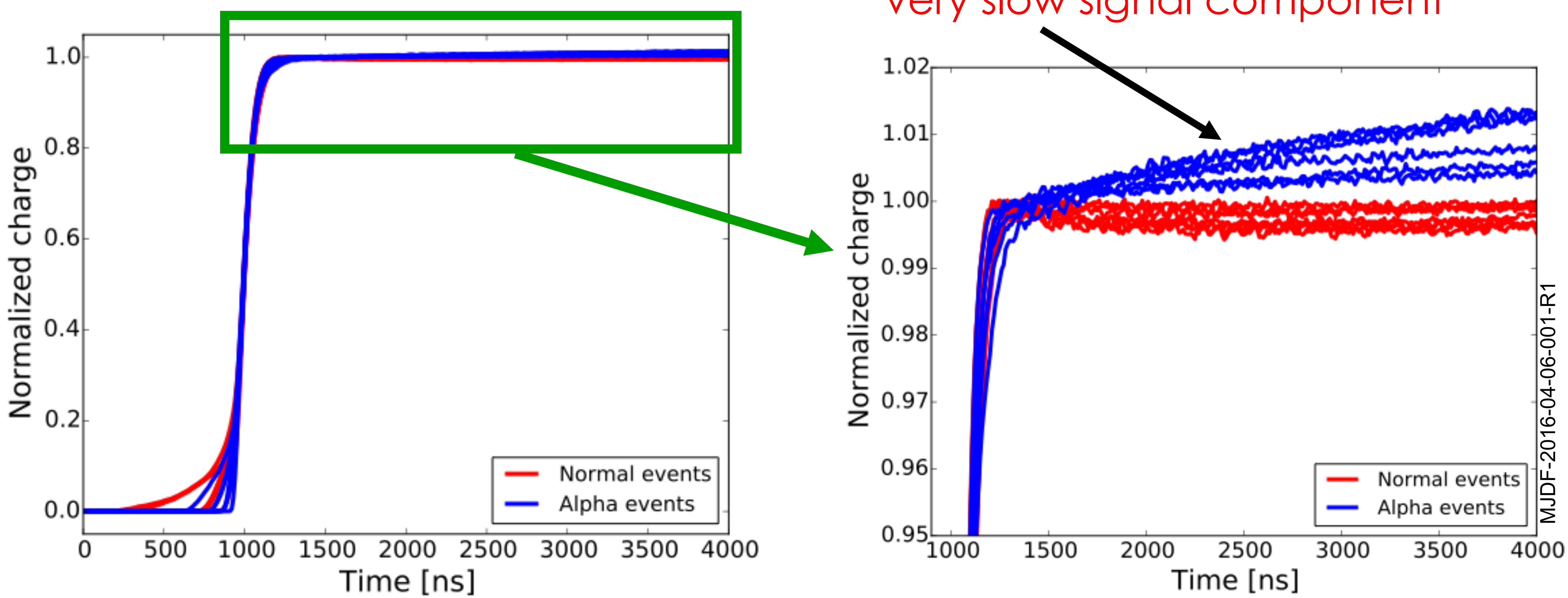
- Repairing non-operating detectors (cable connection, HV connection, LMFE replacement, …)

Delayed Charge Recovery and Alphas

- Alpha background response observed in Module 1 commissioning (DS0)
  - Identified as arising from alpha particles impinging on passivated surface
- Results in prompt collection of some energy, plus very slow collection of remainder
- Enables a powerful PSA rejection of alpha events
- "Delayed Charge Recovery" parameter related to slope of tail

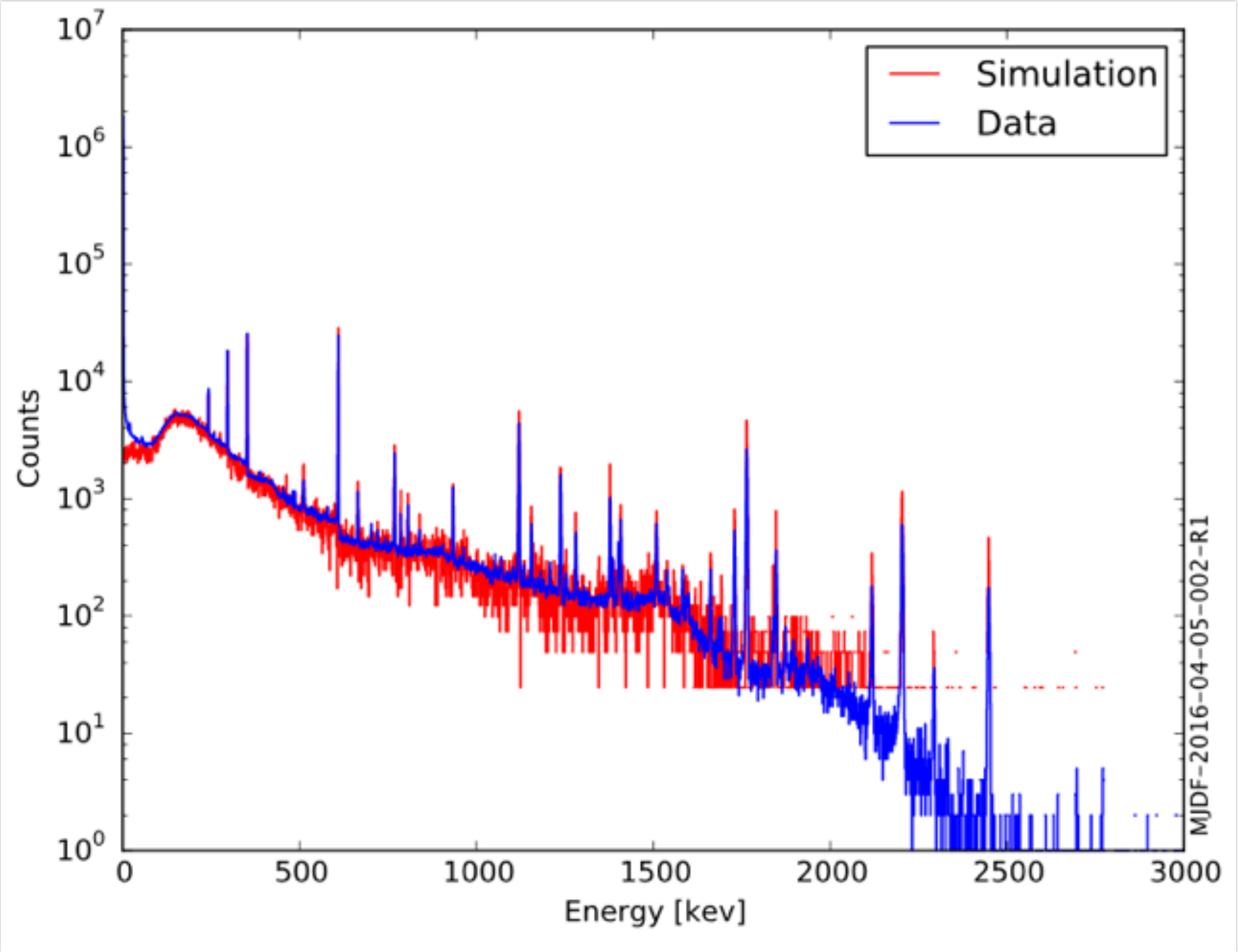
Example pole-zero corrected waveforms

Slow drift of charges along passivated surface results in very slow signal component

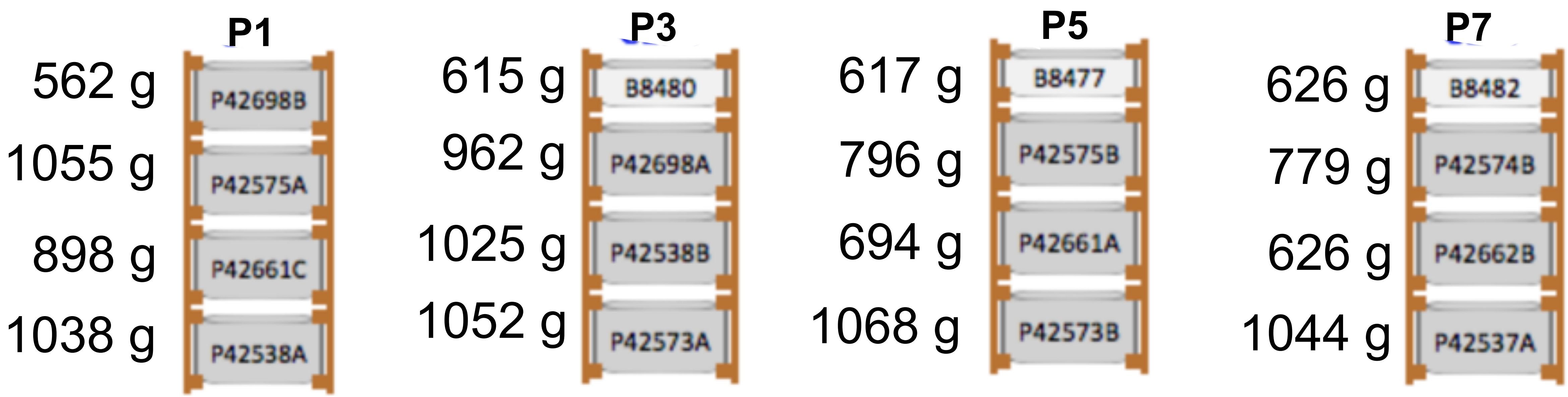


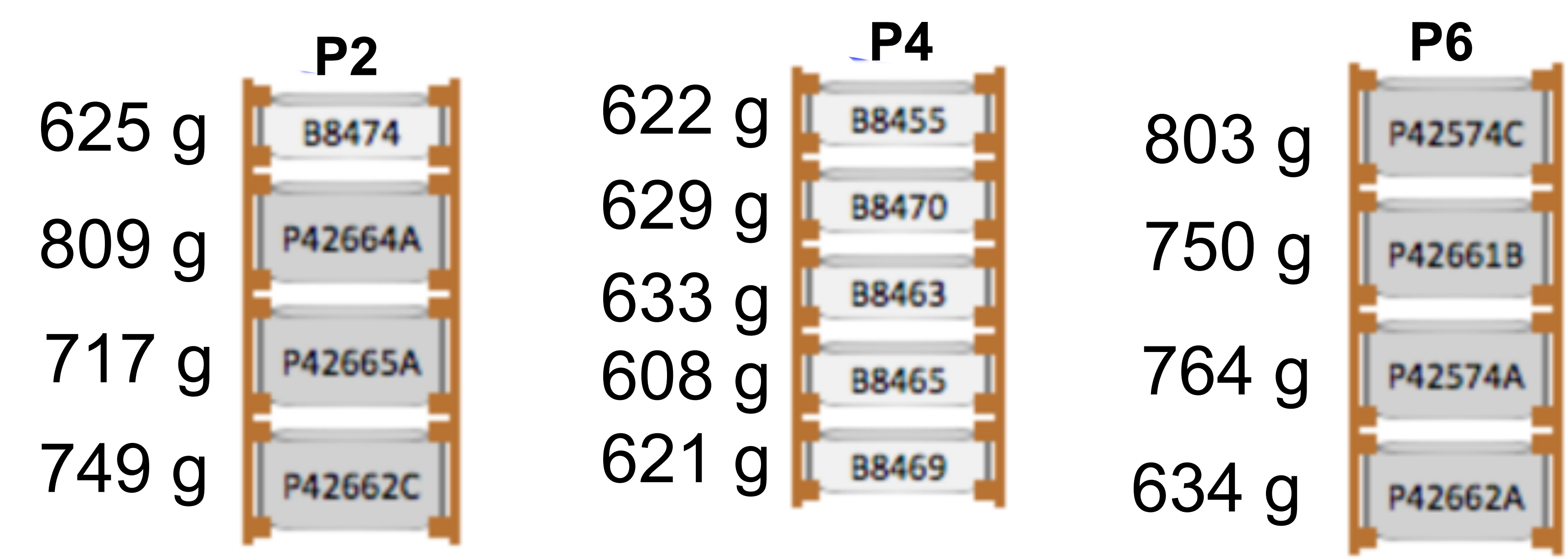
Rn Simulation Compared to Data

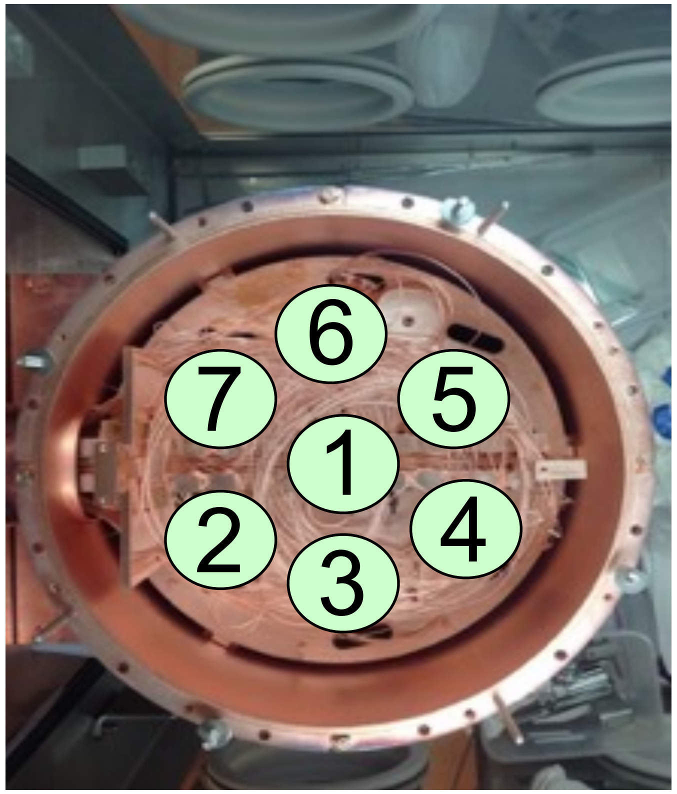
Rn purge-off test Sept. 2015, during Module 1 commissioning (DS0).
Rn simulation compared to data. Fit around 609-keV peak.
Fit is 8.5 pCi/L, near room value of 6.91±0.06 pCi/L. No shield-level value.



Module 1 String Layout







P#####L ORTEC PPC, enriched, detector mass 16.8 kg
B#### Canberra BEGe, natural, detector mass 5.7 kg
29 total detectors

Module 1 Detector Status

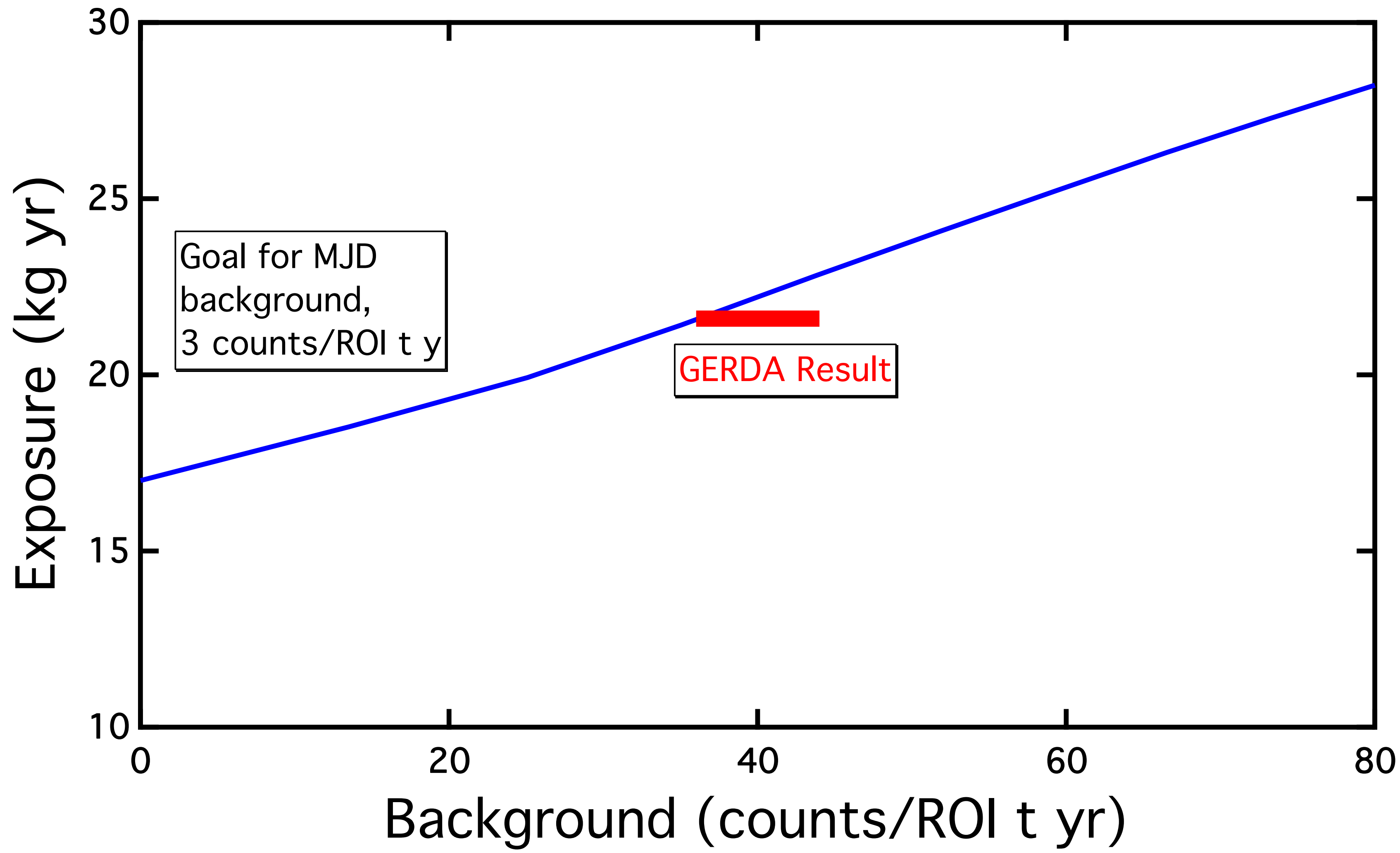
	6/26/15 – 10/7/15	12/31/15 – Present
mnemonic	DS0	DS1
Total Number of Detectors Installed	29	29
Enriched Detectors Num. used in Analysis	20 14	20 15
Natural Detectors Num. used in Analysis	9 7	9 3
Active Natural Mass	3.9 kg of 5.7 kg	1.7 kg of 5.7 kg
Active Enriched Mass	10.7 kg of 16.8 kg	11.9 kg of 16.8 kg

Unbiased Detectors - Lost connections, leakage current, noisy response, HV instability

May re-work Module 1 as Module 2 commissioning progresses

The MAJORANA Blindness Plan

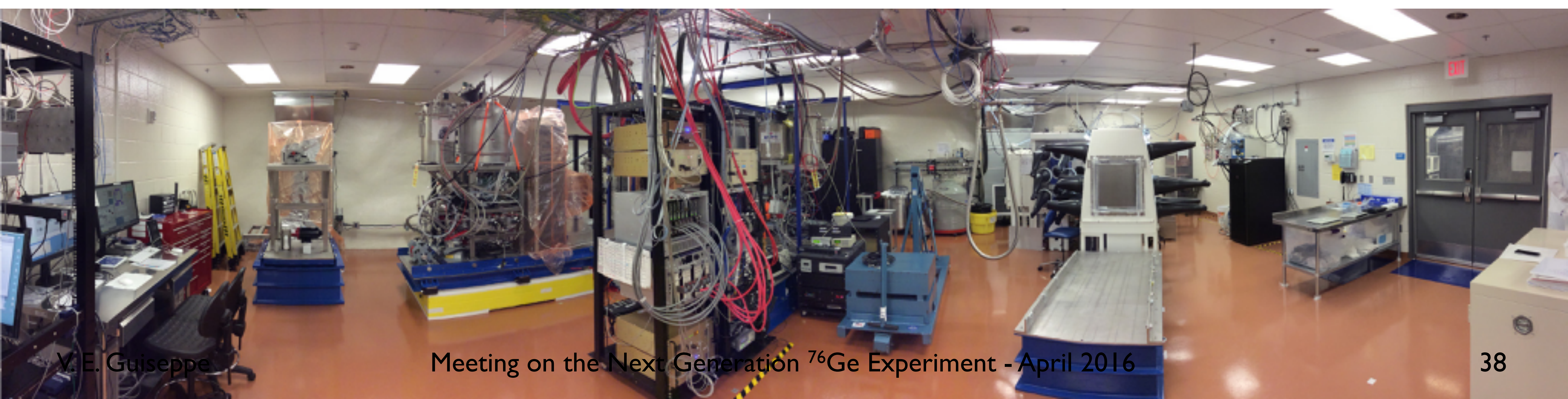
Minimum exposure to reach 2.1x10^{25} yr half-life limit as a function of background.



- Data pre-scaling scheme, 25% open. 31 h open followed by 93 h blind.
- If background is near goal, require 15-20 kg yr of exposure to reach present half-life limit in Ge. Hence plan to remove blindness after 15 kg yr.
- Specialized physics analyses (dark matter, e.g.) will have different blind exposure requirements based on physics goals. A certain region of the spectrum may have blindness removed at a lower exposure, for example.

MJD Summary

- Assembly and construction concluding at Sanford Davis Campus laboratory.
- Based on assays, material backgrounds projected to meet cleanliness goals.
- Successful reduction and refinement of ^{enr}Ge with 98% yield.
- Electroformed copper completed at SURF and PNNL.
- AMTEK (ORTEC) produced 35 detectors, 29.7 kg, from the ^{enr}Ge.
- All detectors underground at SURF.
- Shield nearly complete. Some poly layers are not yet installed
- Module 1, in-shield running from June – Sept. 2015. Final installations complete and re-installed in shield Dec. 2015. Module 1 operating in shield
- Module 2 construction and assembly proceeding. Scheduled to start commissioning in May 2016.
- Predict $T_{1/2} = 1.2 \times 10^{26}$ y (90% Sensitivity) and $T_{1/2} = 1.2 \times 10^{26}$ y (3σ Discovery)
  - MJD 100 kg-year at 3.5 counts/ROI-t-y



The MAJORANA Collaboration

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This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

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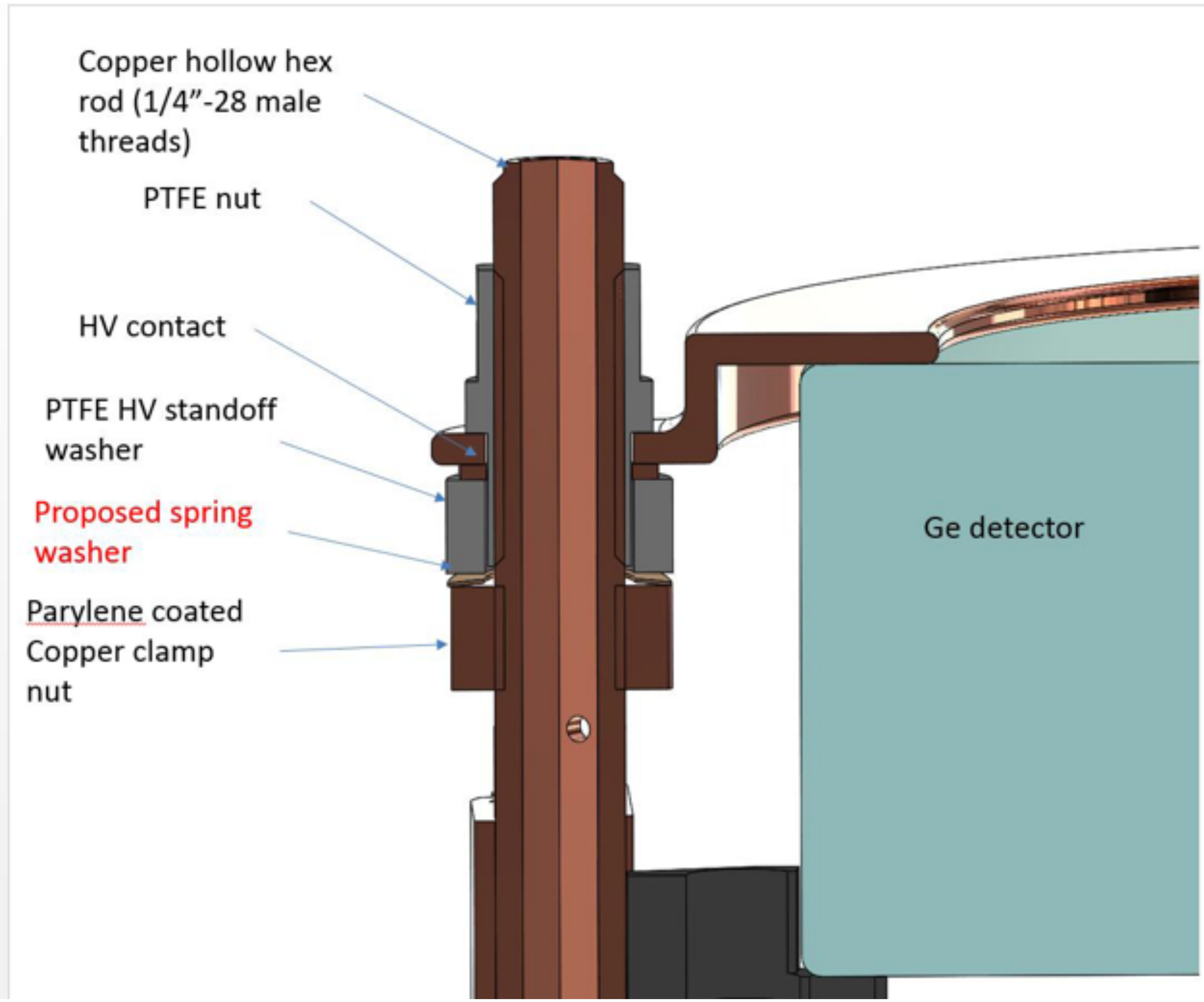
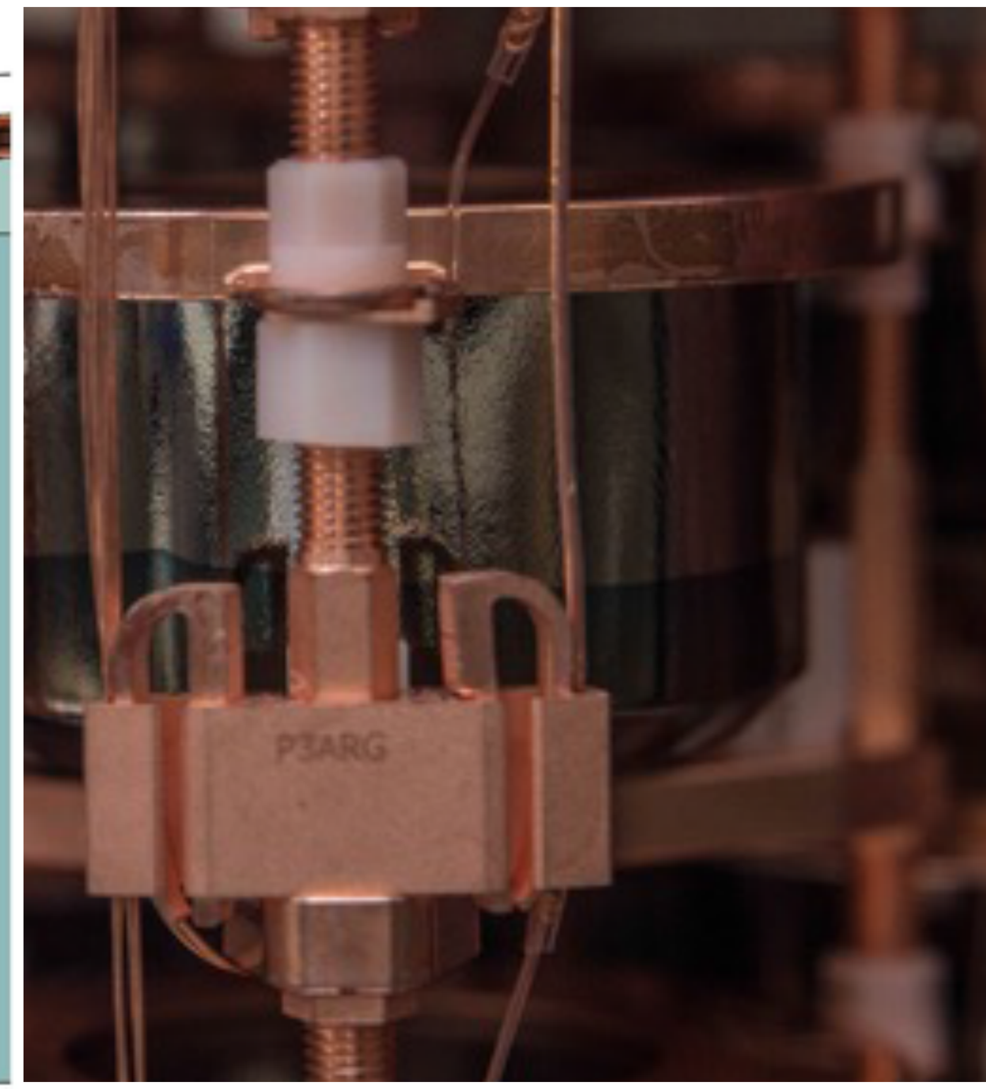
Backup Slides

HV Connection Updates





Plan to add clamp nut and spring washer.

email to send Group Résumés slides

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