DAMIC-M Cryostat Conceptual Design, ULB Materials Production and Fabrication, Recent ULB Cryostat Examples

TODD HOSSBACH
with contributions from my PNNL colleagues

DAMIC-M Collaboration Meeting – June 2018 – Paris
PNNL-SA-135464

Outline

- Review of the conceptual DAMIC-M cryostat design
- Copper electroforming capabilities
- Clean fabrication and assembly
- Examples of recent ultra-low-background cryostats produced at PNNL
  - Design, fabrication, assembly

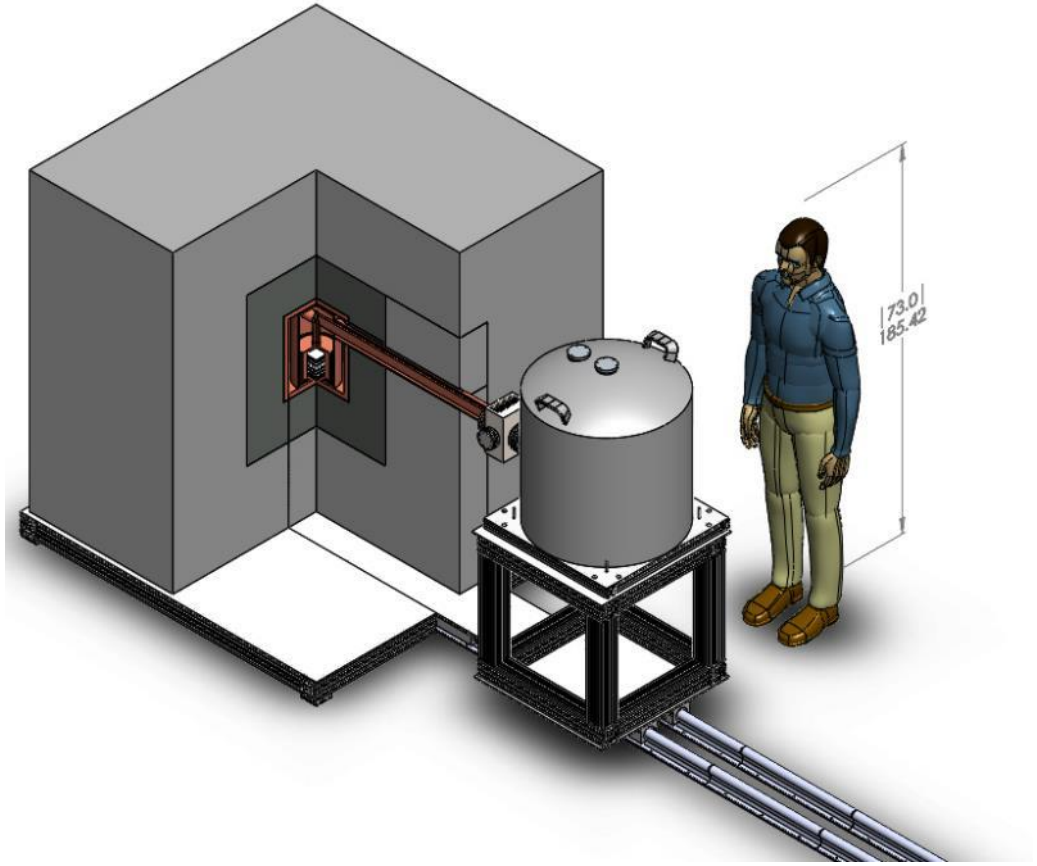
Conceptual Design Principles

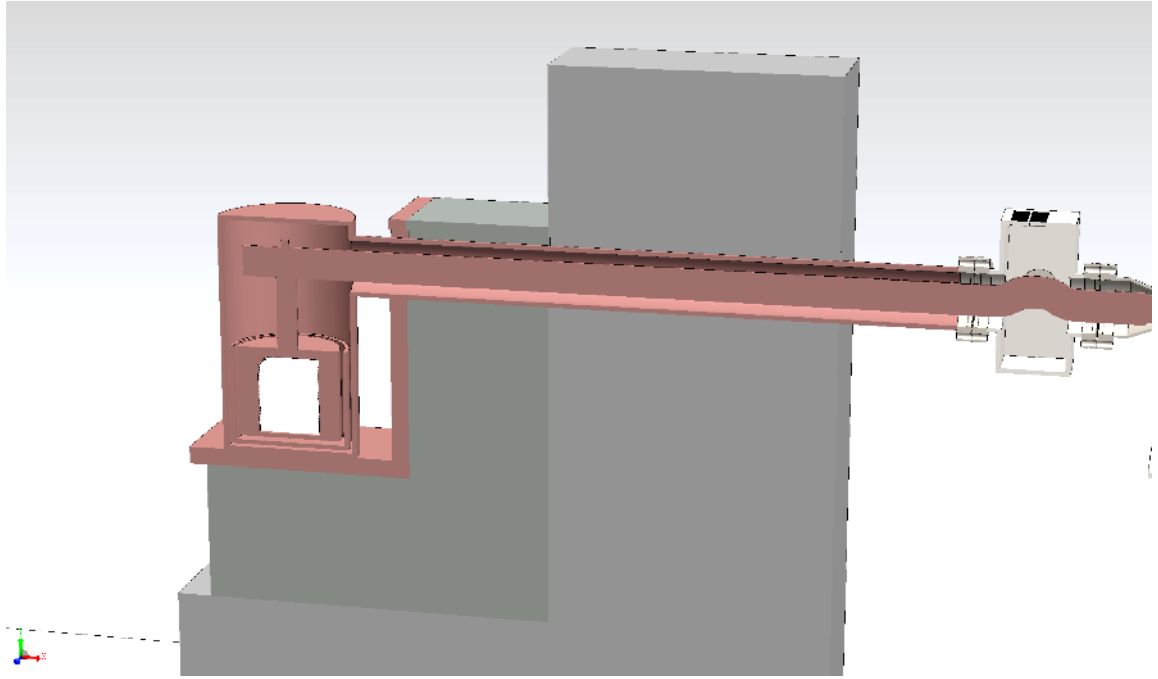
- Guiding principles
  - Begin with what we know works
  - Minimize complexity
  - Focus on background control

- DAMIC-M design particulars
  - Use of electroformed copper important in achieving background goal
  - To achieve our timeline and stay within budget (background and €/$), high-quality OFHC copper should be used in non-critical components of cryostat
  - Flex cable management and associated background mitigation
  - Vacuum feedthroughs
  - Stable experimental operation
    - Good thermal contact between CCDs and heat conductors
    - Minimize IR load on sensors
    - Re-condense N_2 boil-off gas from Dewar

- Critical for us to define the CCD packaging and detector module as soon as possible.

DAMIC-M Cryostat Design Concept –
From ERC/NSF Proposal

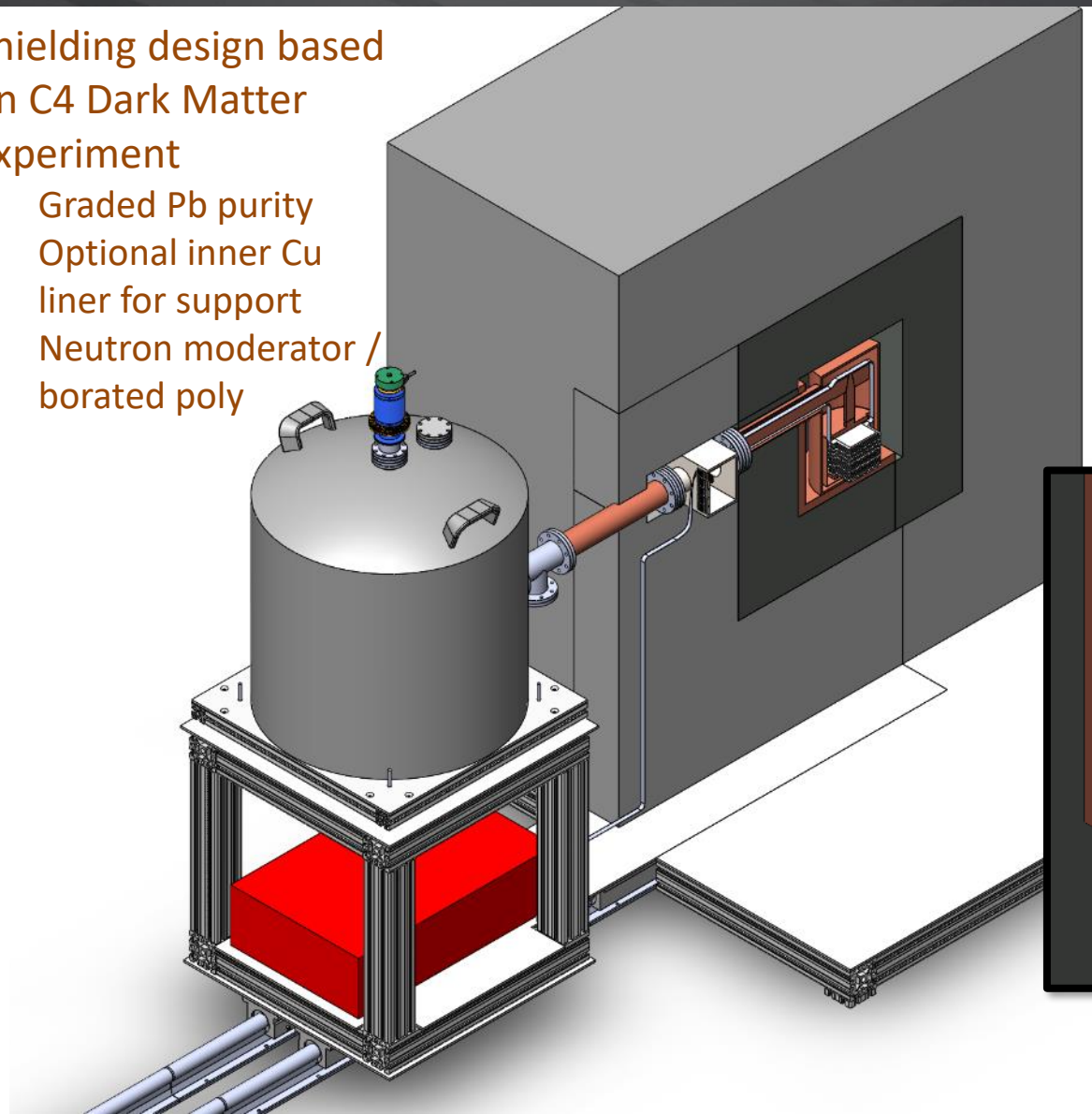




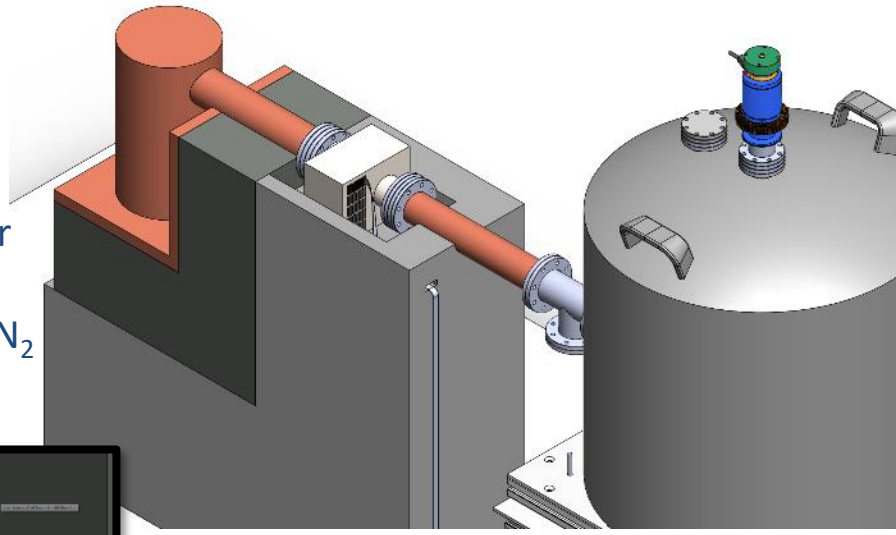
DAMIC-M Cryostat Design Concept –
Some recent updates

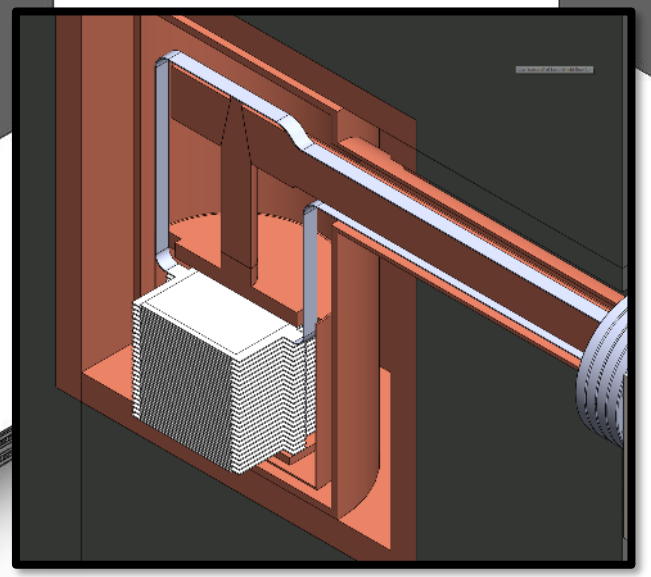
Shielding design based on C4 Dark Matter Experiment

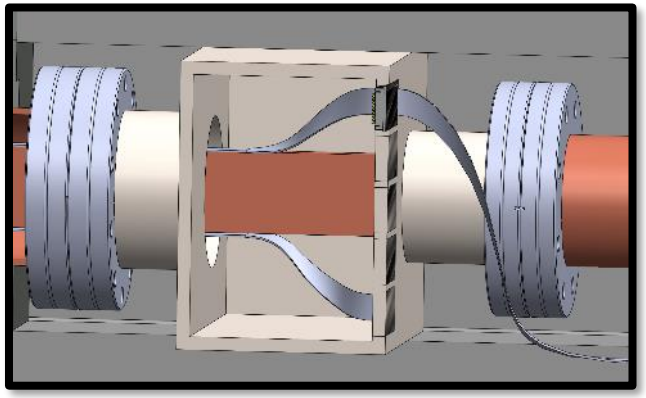
- Graded Pb purity
- Optional inner Cu liner for support
- Neutron moderator / borated poly



- 33 x 33 x 38cm inner volume
- Cu, within shield, is OFHC
- Alternative location for vacuum feedthrough
- Sterling/PT cooler for N_2 reliquification





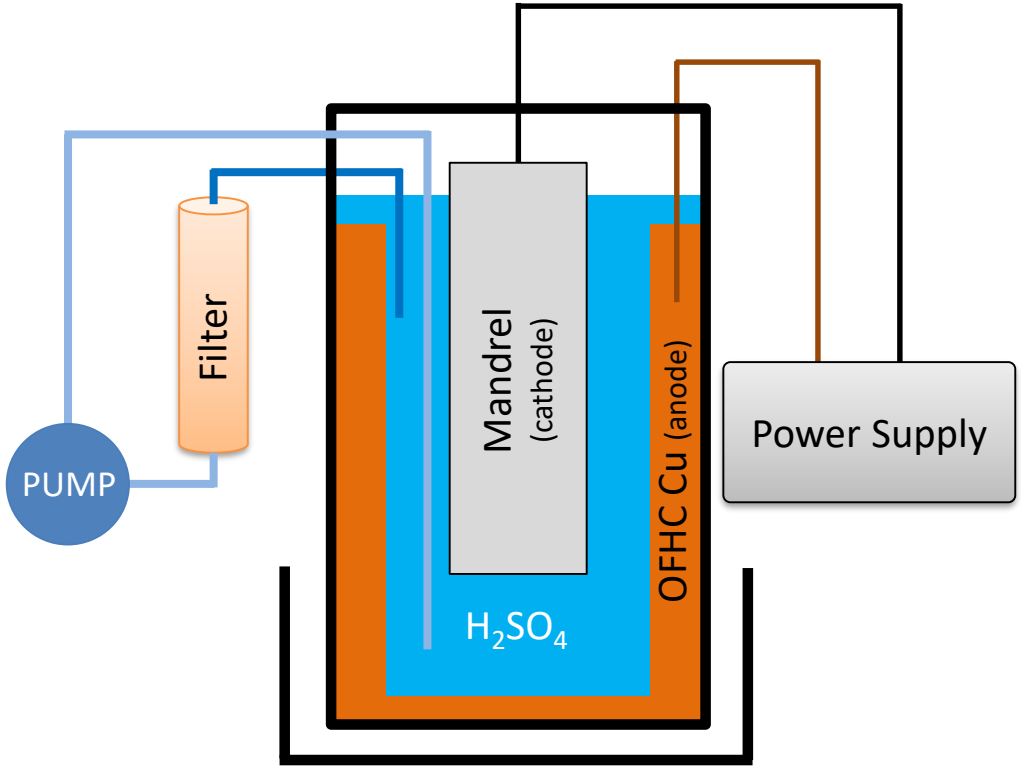


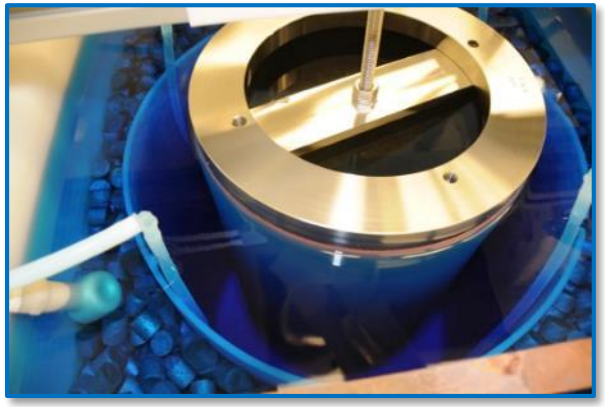
Electroforming

Electrochemical Purification of Copper

- Originally developed in the 1980's as a method to reduce trace radioactive impurities in HPGe copper cryostats
- Significant improvements to electroforming methods in early 2000's
  - Reduced U/Th levels, better materials properties, reproducible growth, new cleaning and surface passivation
- Most radiopure copper available <0.1 µBq U or Th/kg Cu

- AC plating process
  - Copper growth ~0.0015" (38 microns) per day
  - Have grown large pieces >1" (25mm) thick
- Begin with highest purity OFHC starting stock
- Uses Optima-grade acid
- Typically growth on cylindrical and hexagonal mandrels.
- Routine assay of electrolyte

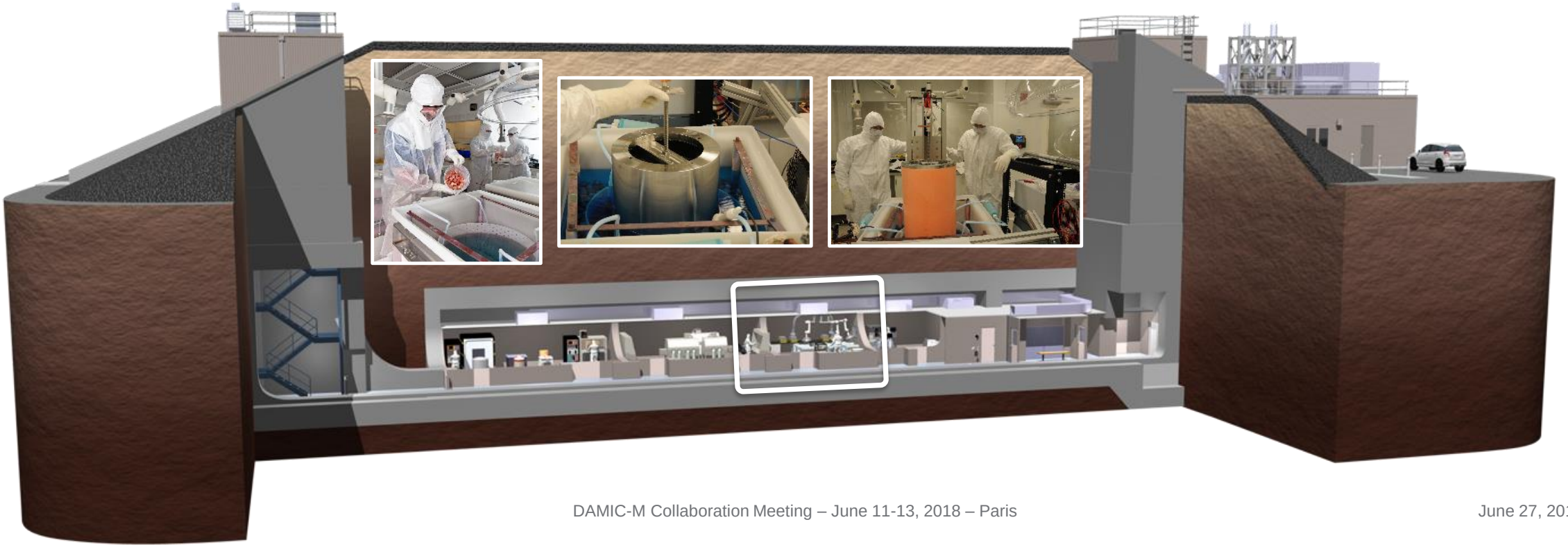




Eric Hoppe
Electroforming Lead

Copper Electroforming at PNNL

- Electroforming occurs at 35 mwe in dedicated Class 1000 cleanroom – 10x reduction in production of cosmogenics
- 14 Electroforming Baths
  - 8 small baths – mandrels up to 6” (15cm) diameter and 16” (40cm) long
  - 6 large baths – mandrels up to 13” (33cm) diameter and 24” (60cm) long

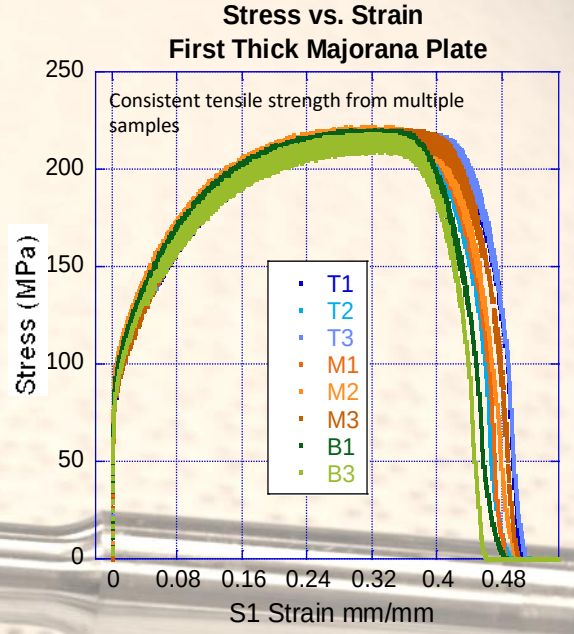


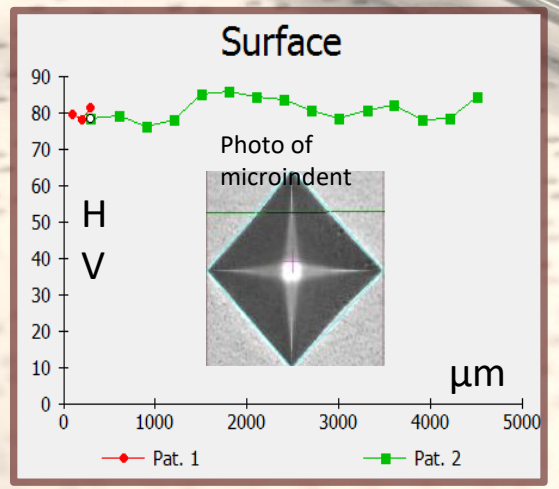
Copper Electroforming at PNNL

Physical Properties of Electroformed Copper

Electroformed copper is evaluated for grain size, hardness, and tensile strength
(most commercial OFHC copper is <10 ksi)

Yield Strength: 13.78 ± 0.58 ksi
Ultimate Tensile Strength: 31.2 ± 0.73 ksi
Young's Modulus: 9.34E3 ± 1.74E3 ksi
- Significant Strain hardening
- Significant Ductility

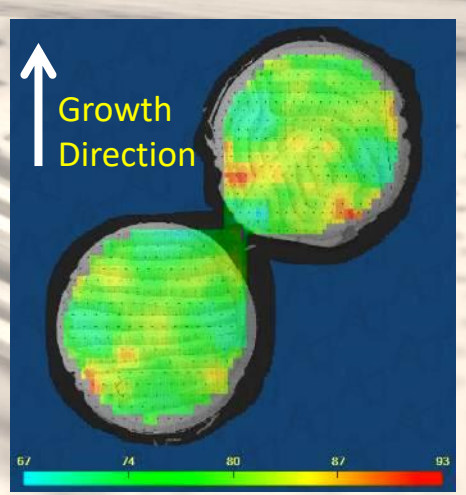




Hardness measured across a surface

Electroformed copper shows consistency in mechanical response from tensile and hardness testing on different regions across the material profile

Currently developing radiopure Cu/Cr alloy with mechanical properties of mild steel



Hardness contour map across a surface

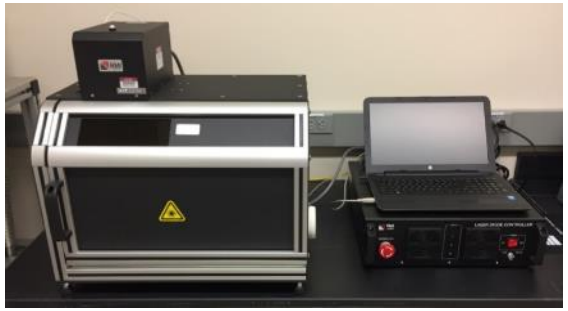
Fabrication

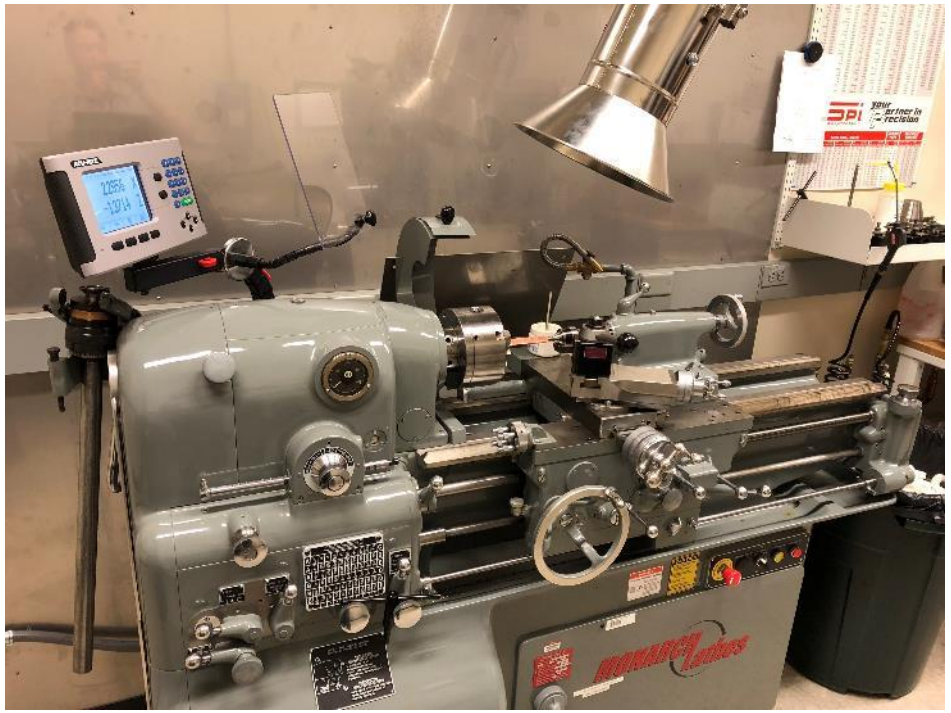
Clean Fabrication of Copper and Polymers

- Three specially trained professional machinists
  - Follow defined handling protocols – gloved hands, face masks, etc.
- Two dedicated clean (low-background) machine shops
  - CNC mill, knee mill, lathe, EDM (electrical discharge machining) hole-drilling/die-sinking
- One general purpose machine shop
  - CNC mills, knee mills, lathes, wire EDM, band saw, electron-beam welder, etc.
  - Aggressive cleaning of existing tools, tooling, fixtures, etc. prior to use in low-background applications
- Fixtures made of compatible materials (e.g. avoid Al if cutting Cu)
  - Vacuum fixtures used to produce DAMIC parts
- Alternative cutting fluids and coolants
  - Propylene glycol, cryo-machining (liquid nitrogen), vortex coolers (-46C)
- Proper storage between fabrication steps
- Post-fabrication cleaning – acidified peroxide solution (removes 1 micron/min)

Clean Fabrication of Copper and Polymers

- Machine tools located in typical laboratory environment – not a cleanroom
- Access to tools strictly controlled
- Only low-background raw materials permitted in shop
- Final parts marked with a unique identifier using laser engraving system

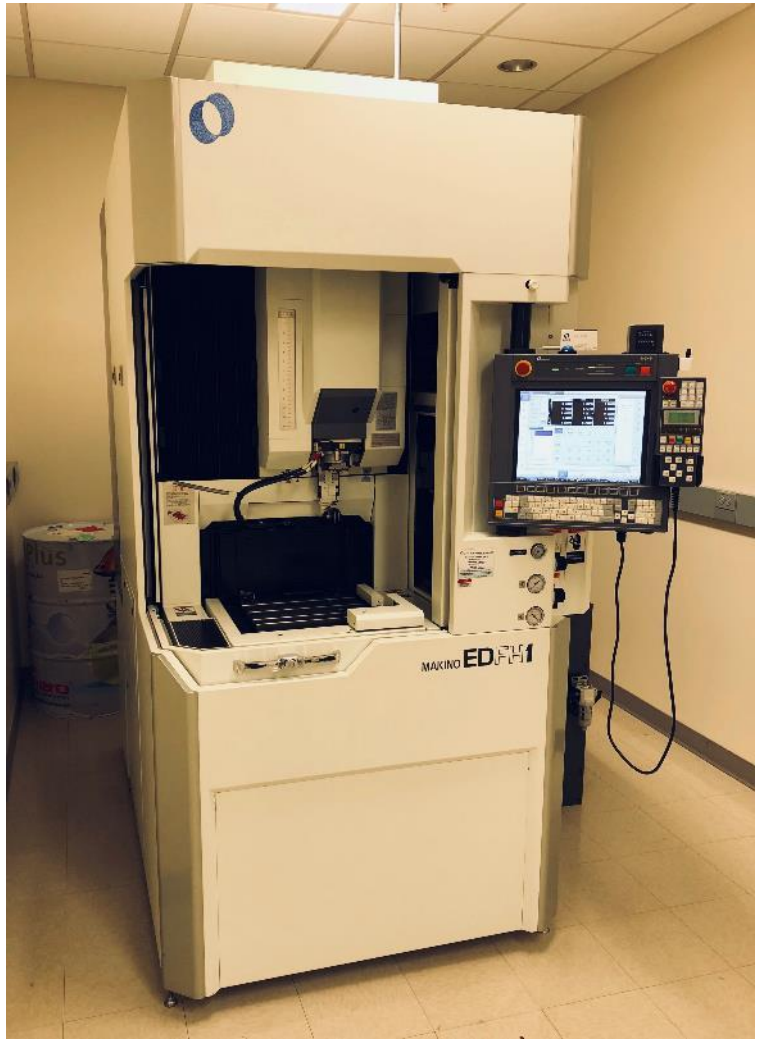


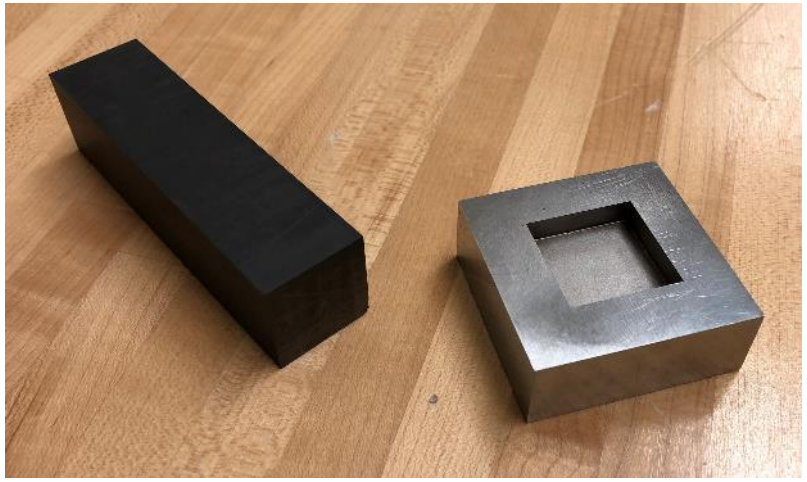


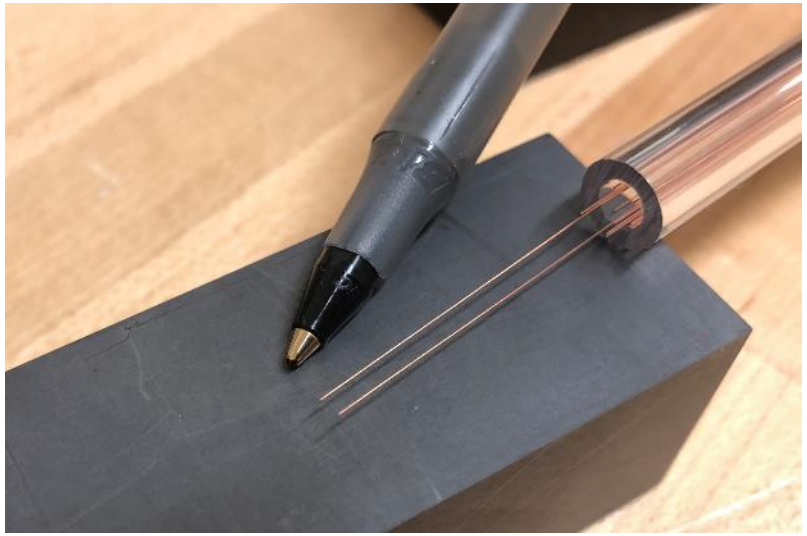
Clean Fabrication of Copper and Polymers

EDM fine-hole drilling and die sinking

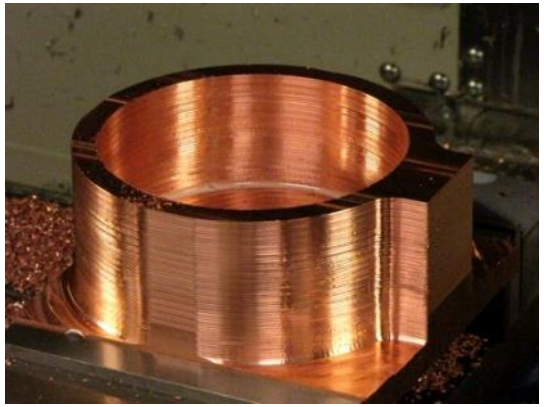
- New capability at PNNL
- EDM process can be extremely clean
- Only 75 units produced by manufacturer
- Capable of drilling extremely fine holes in all metals
- Die-sinking enables production of parts/finishes not possible with conventional machining methods
- Pipes for drilling or electrodes for die-sinking can be made from high-purity copper

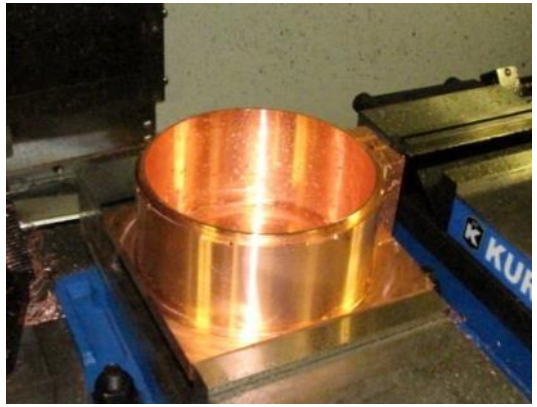


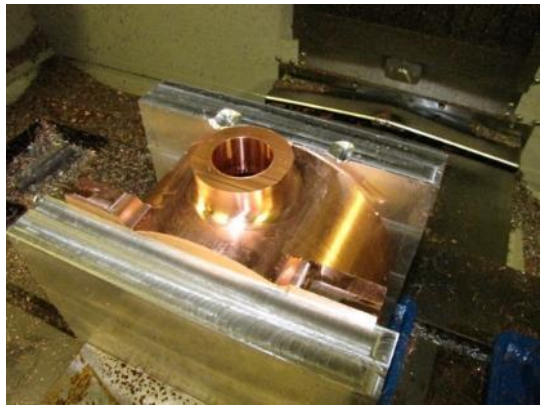


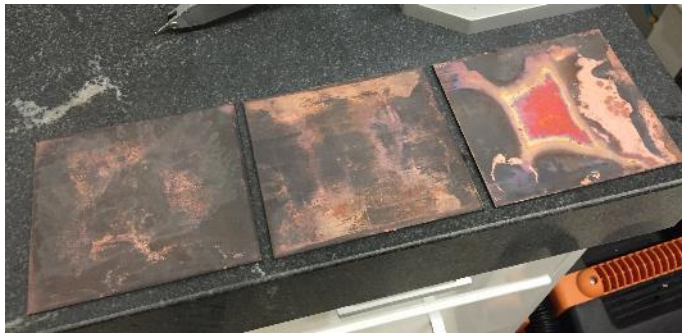


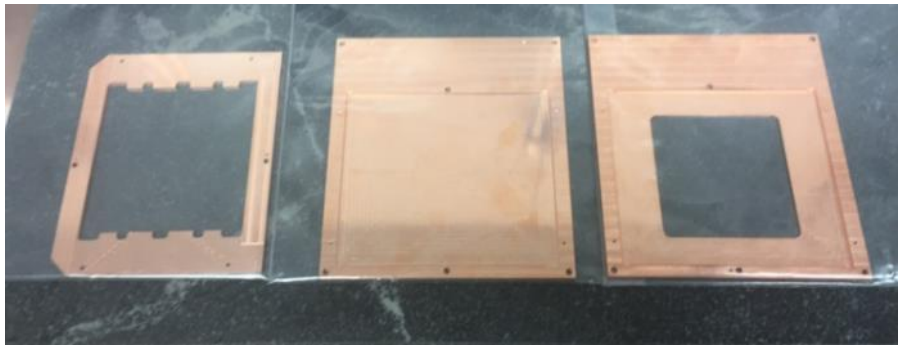
Fabrication of OFHC Copper Cryostat Parts and DAMIC Electroformed Copper CCD Modules

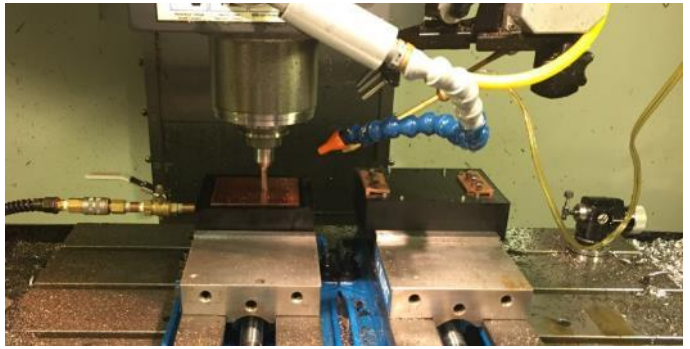




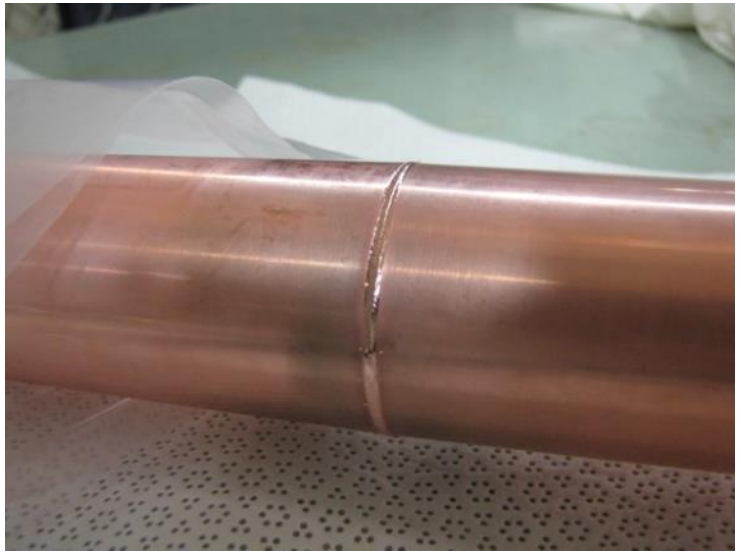


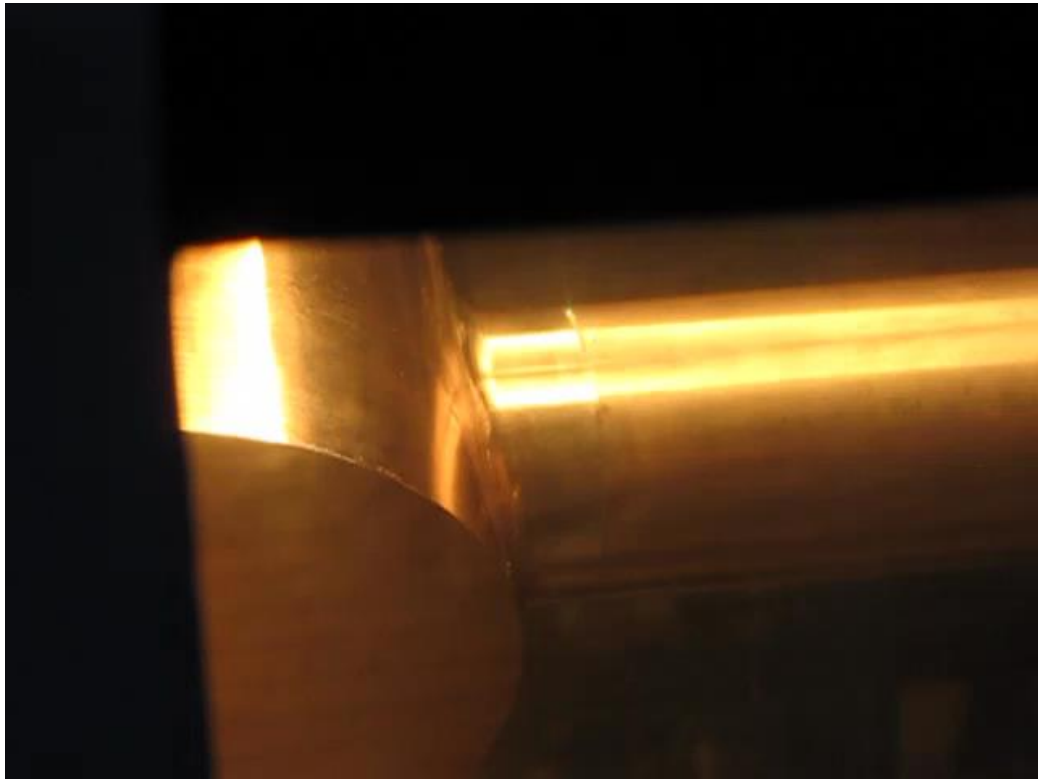


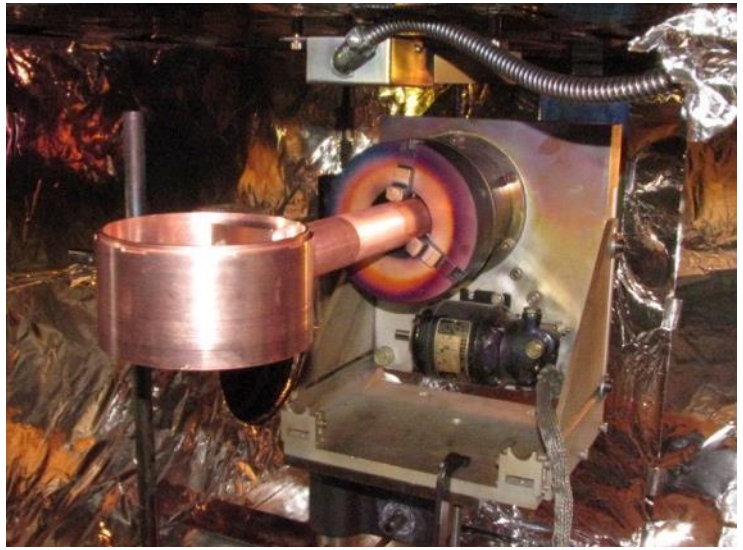


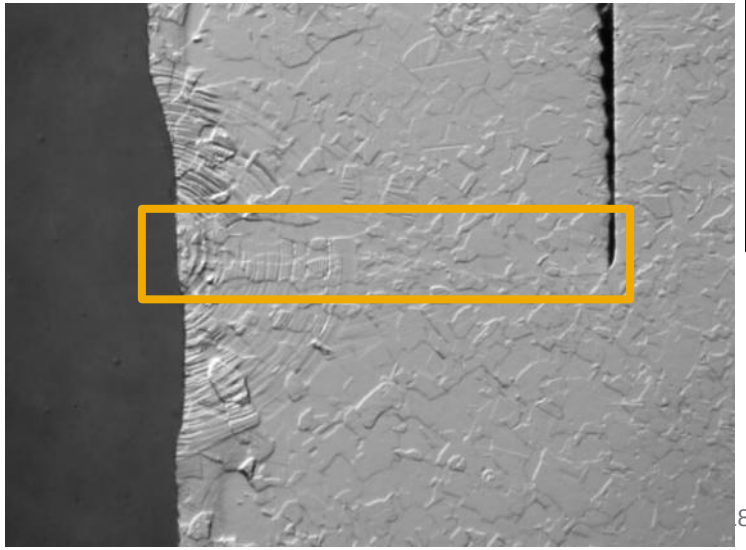


Clean Joining of Detector Elements – Electron-Beam Welding





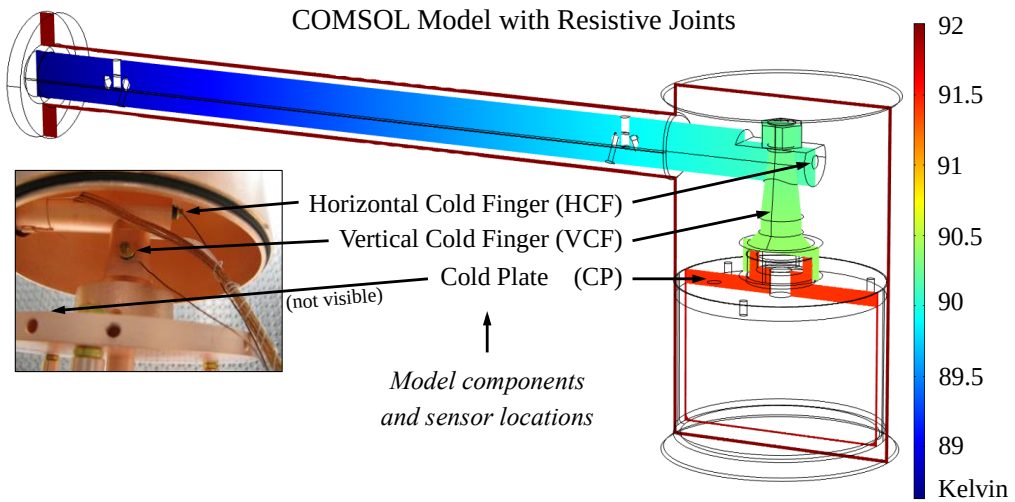


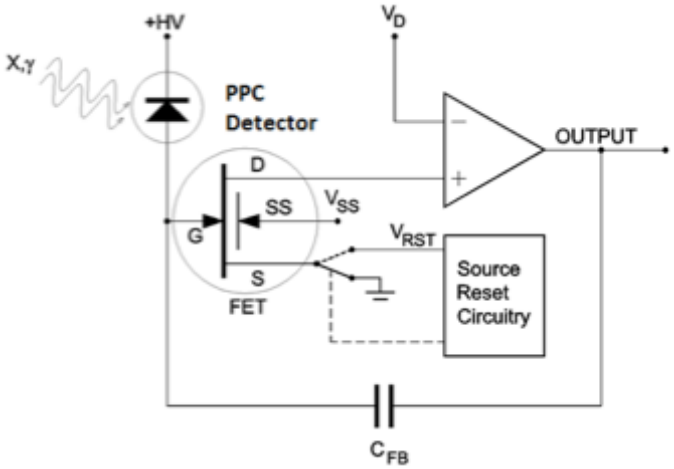


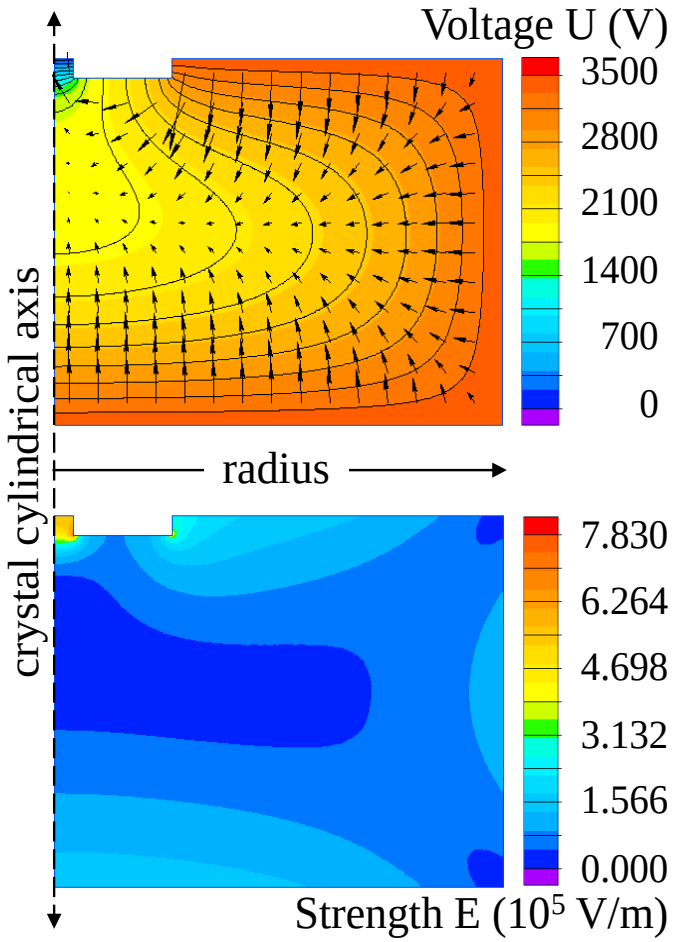
Examples of Recent ULB Germanium Spectrometer Production

RECENT PRODUCTION OF ULB HPGe SPECTROMETERS

- In 2012 and 2017, we produced two ultra-low-background HPGe spectrometers
  - C4 dark matter experiment, ULB gamma assay
- First cryostats produced at PNNL to involve significant mechanical, thermal, and electrical modeling prior to beginning production.

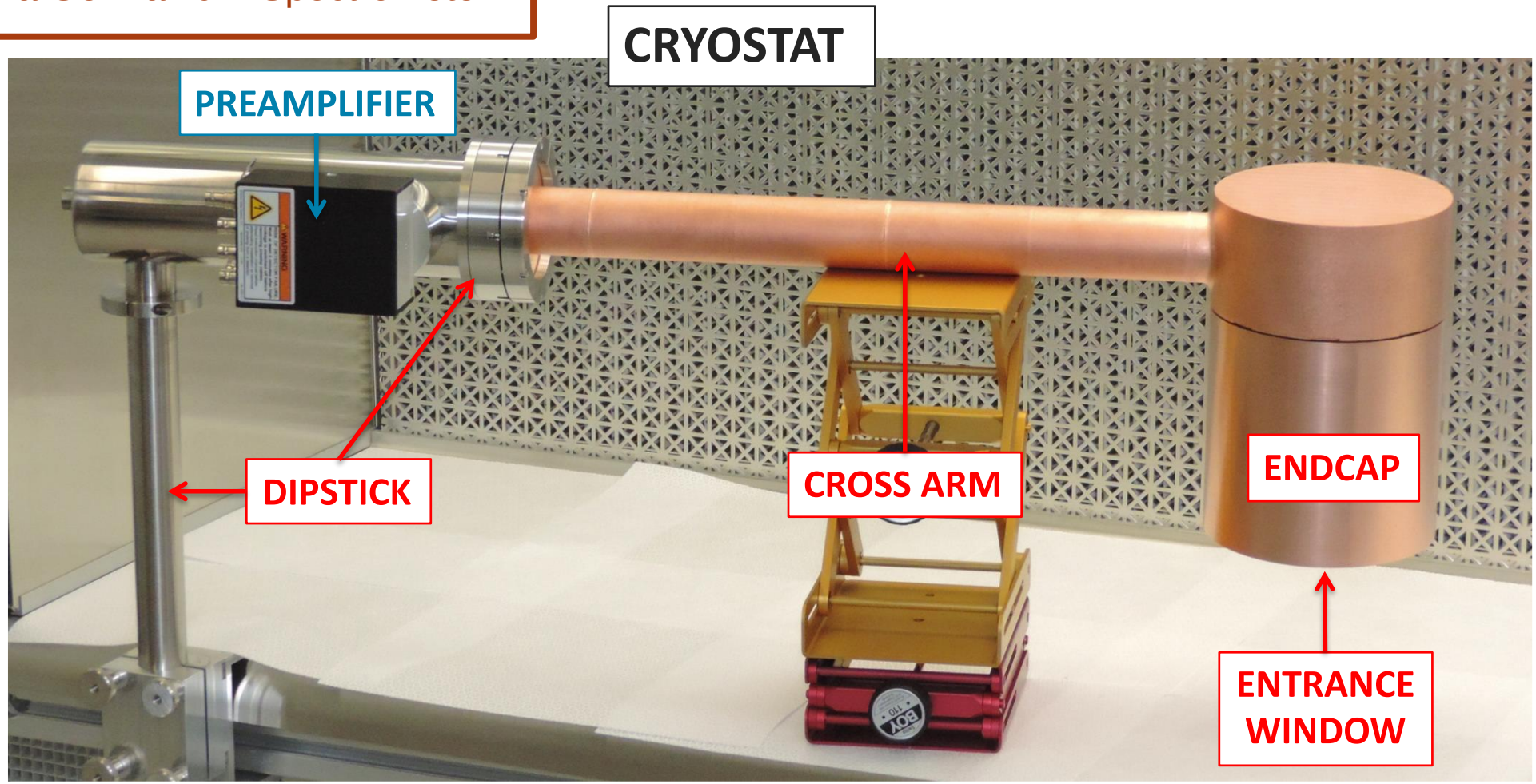






C4 Cryostat - 2012

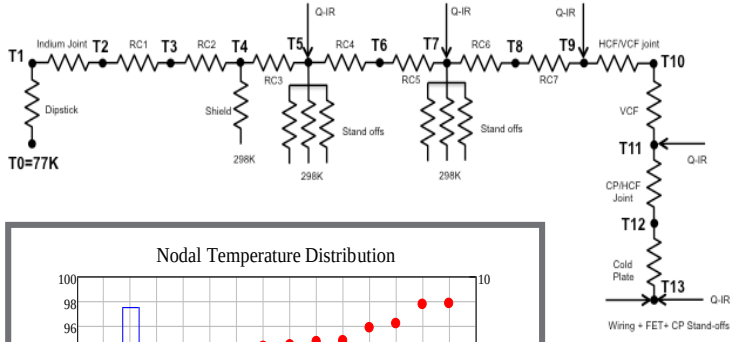
Anatomy of a Germanium Spectrometer

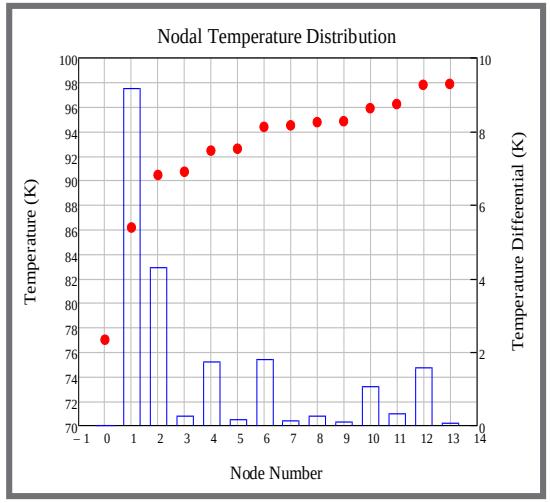


C4 Cryostat – 2012
Step 0 – Perform calculations / modeling

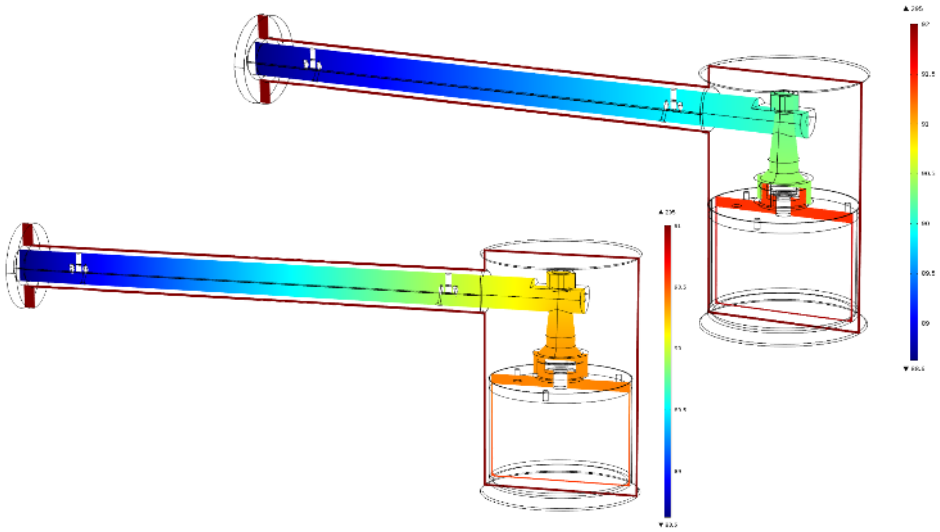
1-D Model – Electrical Analogy

A one dimensional model was used to estimate the various thermal loads and final crystal temperature.





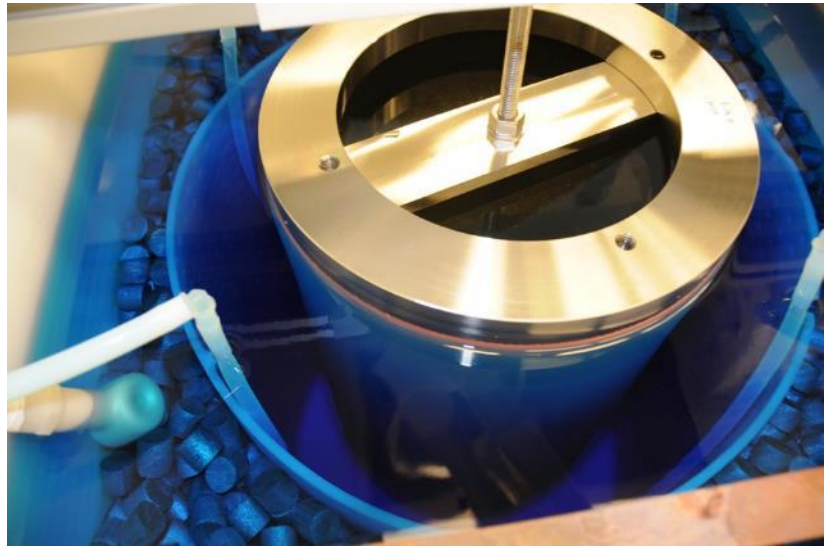
COMSOL FEM Model



COMSOL FEM modeling was used to determine how changes to the thermal path could lower the operating temperature of the crystal in future cryostats.

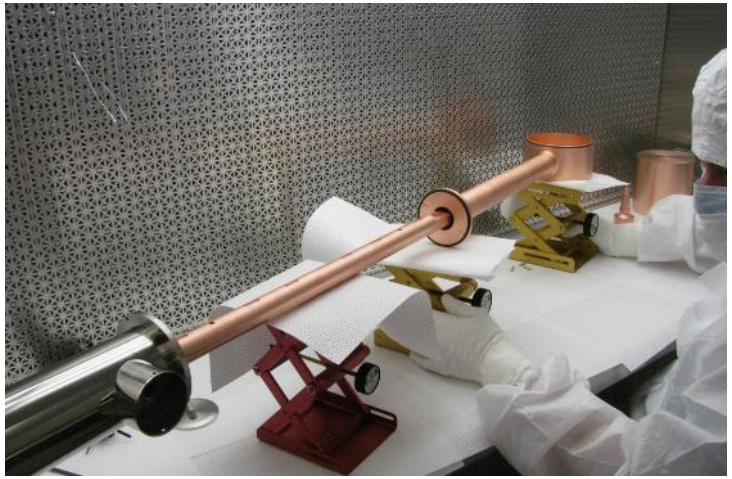
C4 Cryostat – 2012

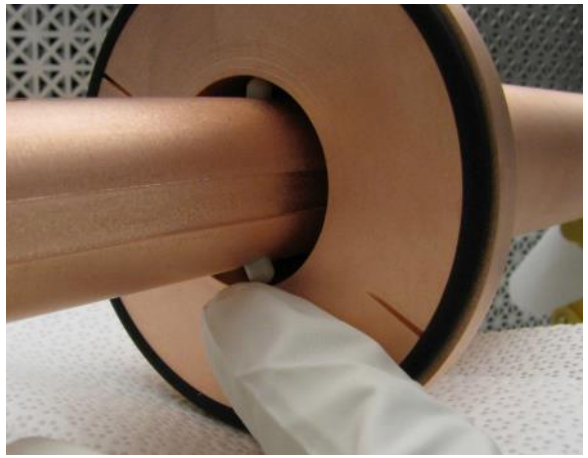
Step 1 – Electroformed copper growth, fabrication of components

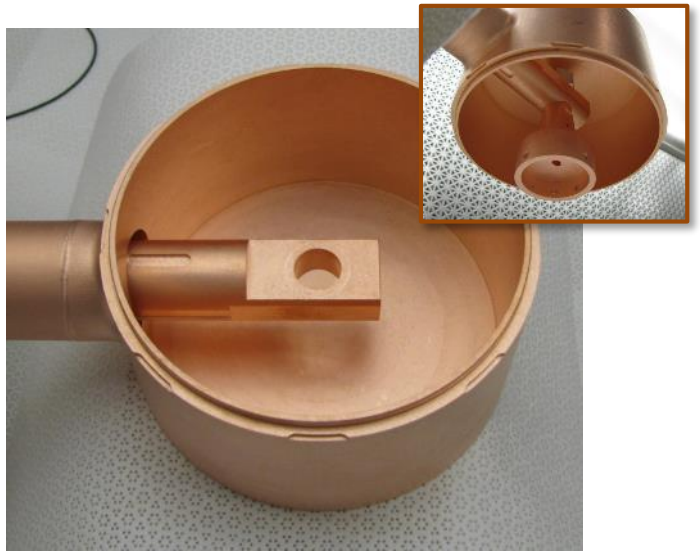


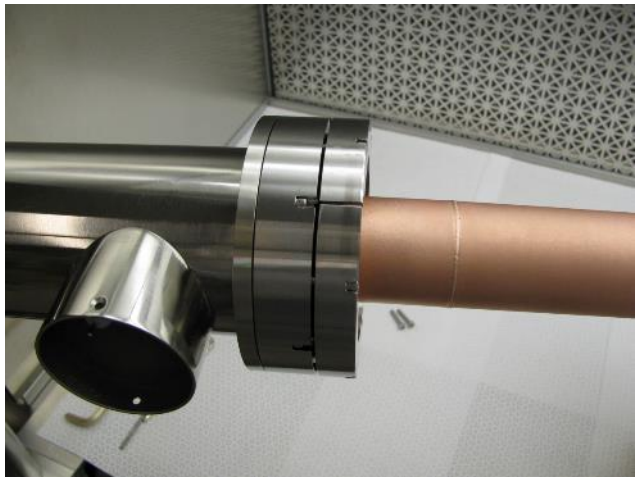
C4 Cryostat – 2012

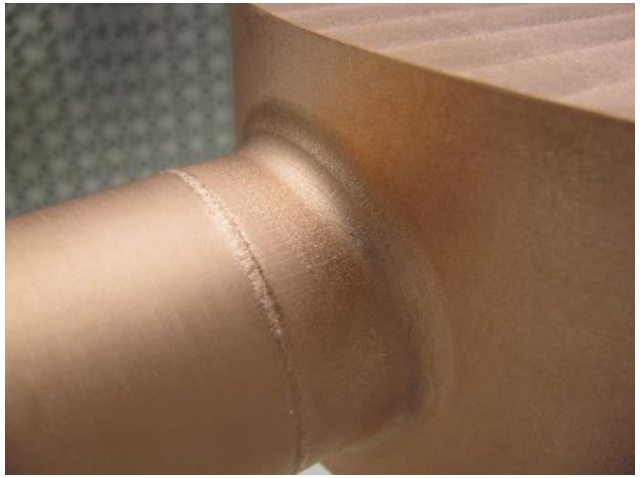
Step 2 – Test assembly of thermal path and vacuum jacket followed by leak testing





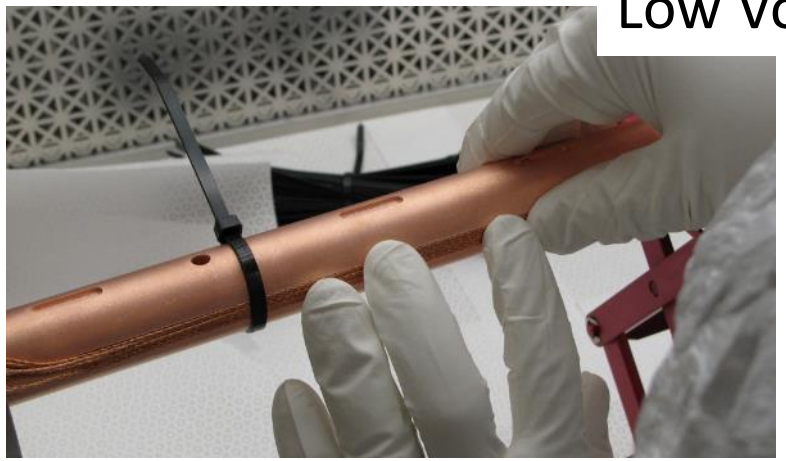


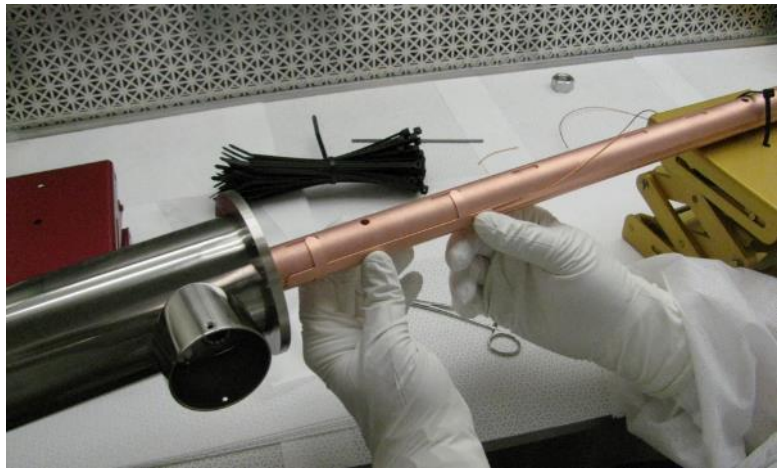


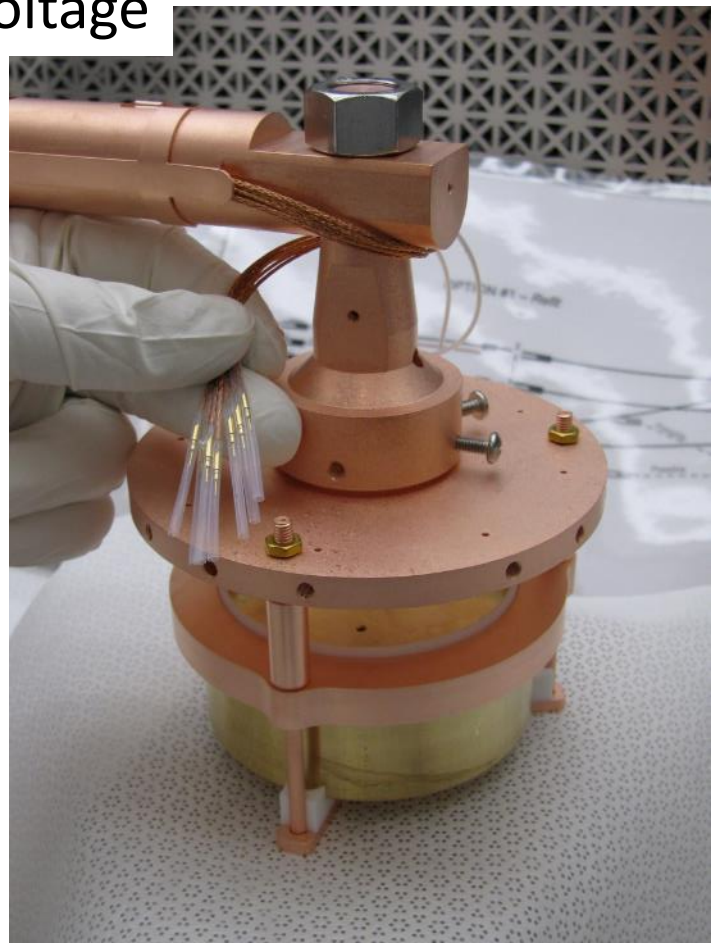


C4 Cryostat – 2012
Step 3 – Electrical wiring

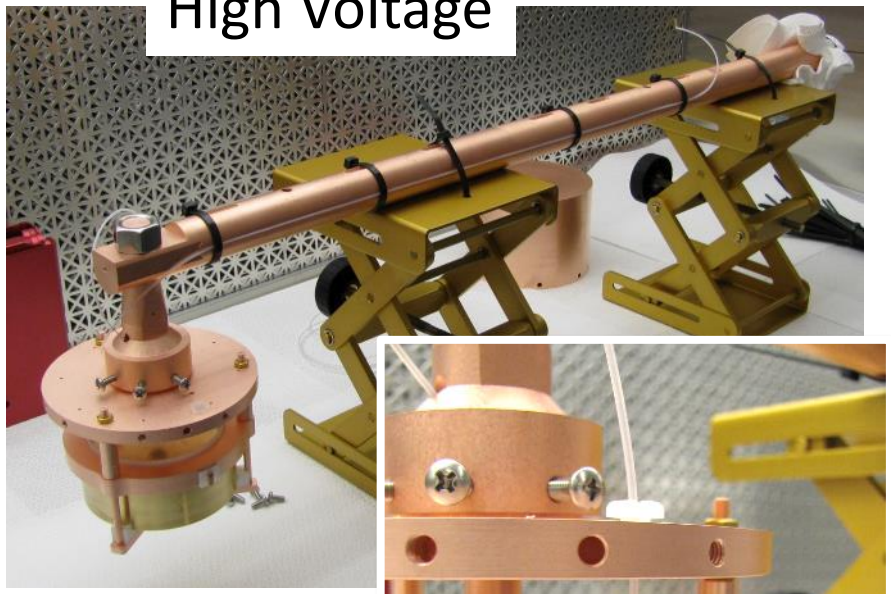
Low Voltage

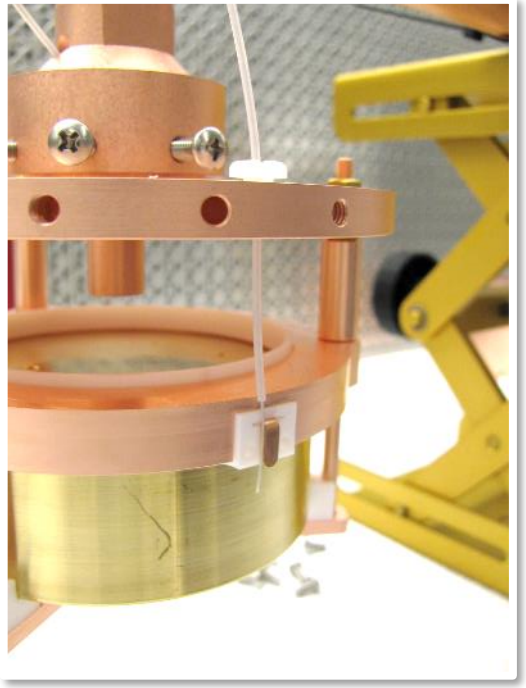






High Voltage

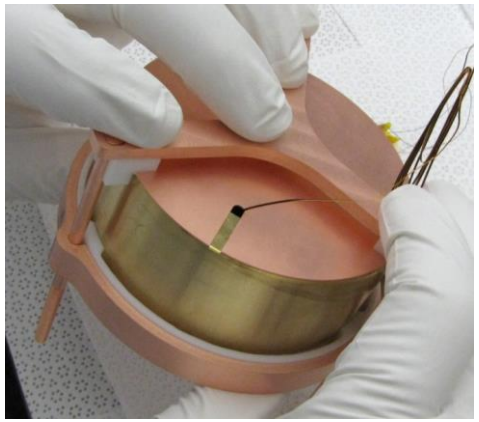


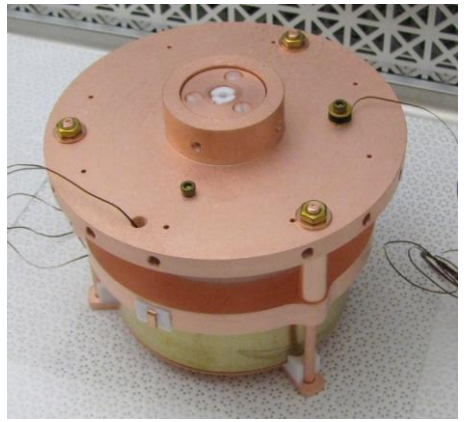


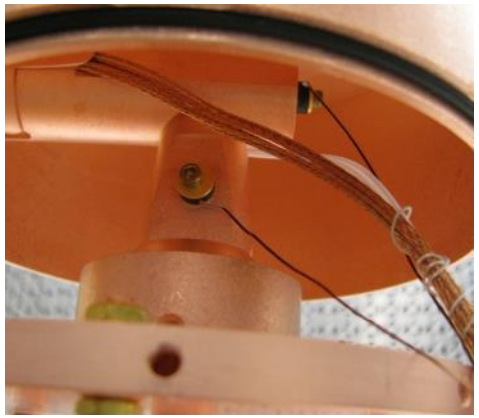
Brass blank used as surrogate for Ge crystal in test assembly.

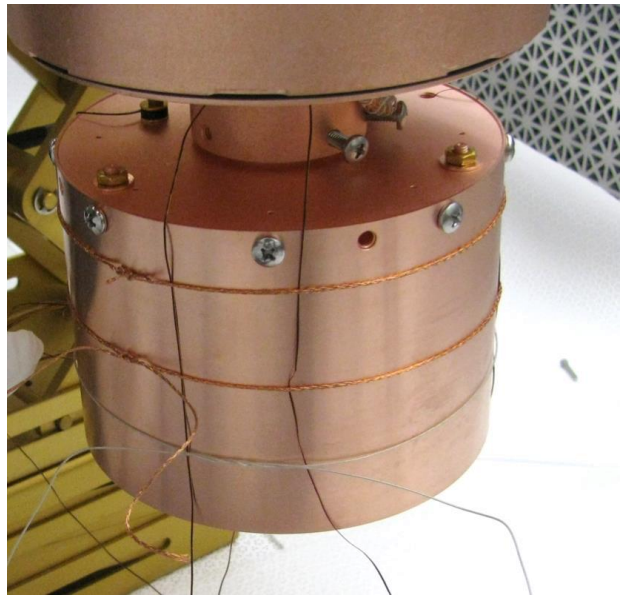
Stainless fasteners used only in test assemblies. Replaced with copper in final assembly.

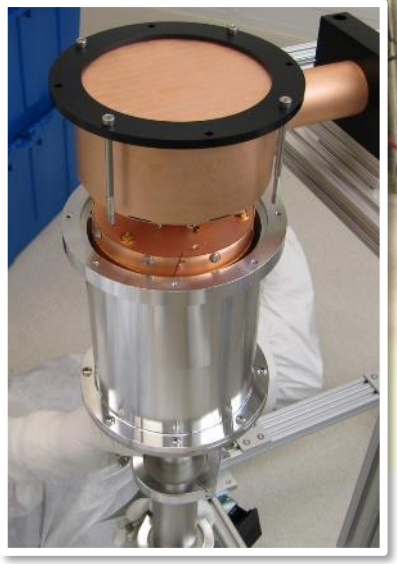
C4 Cryostat – 2012
Step 4 – Thermal testing

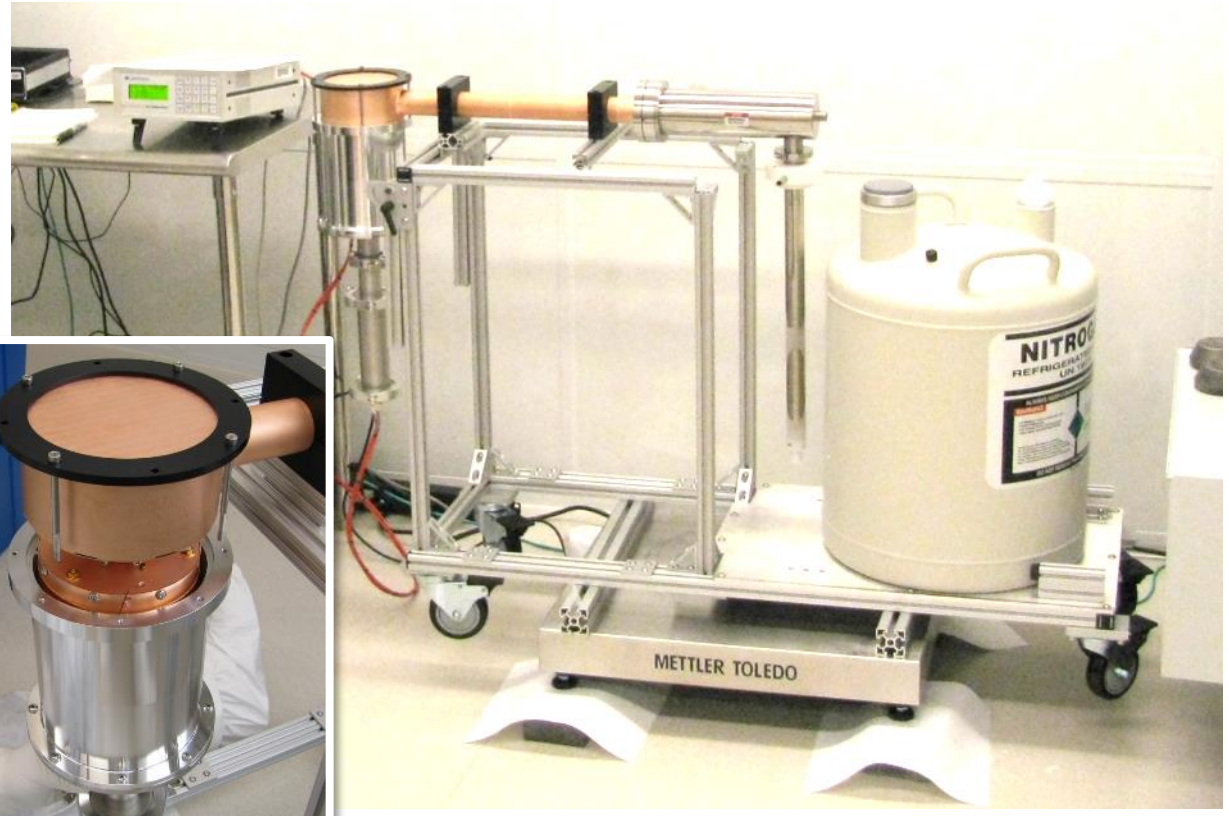




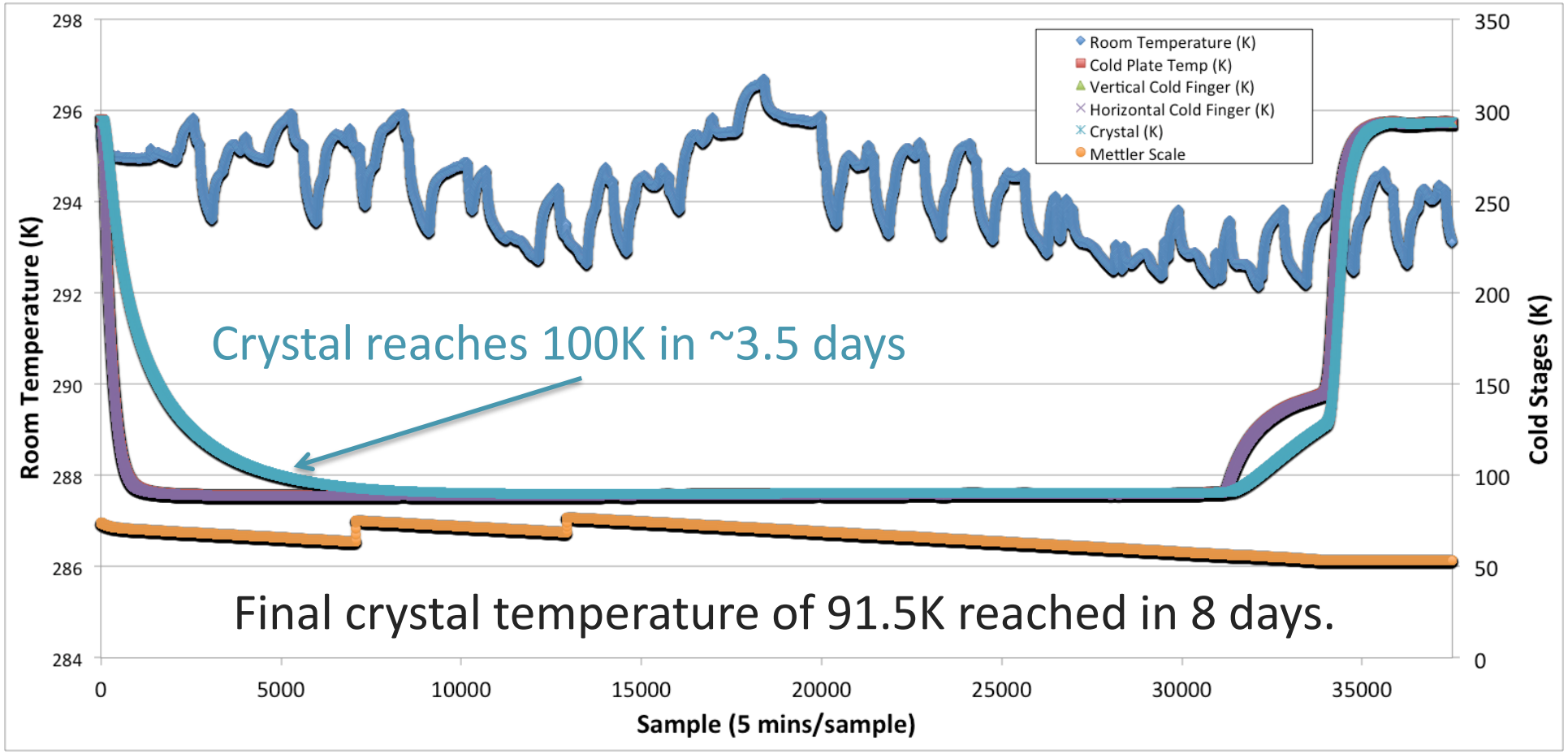




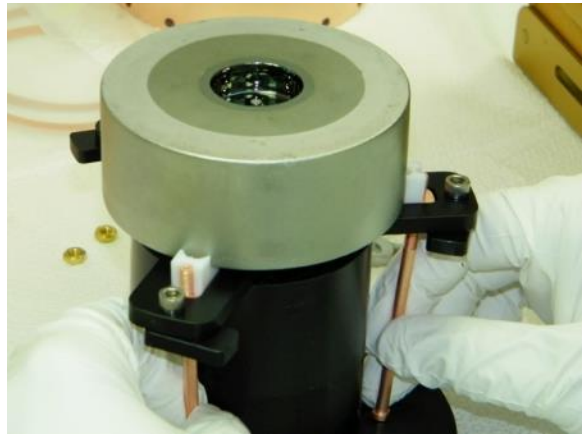


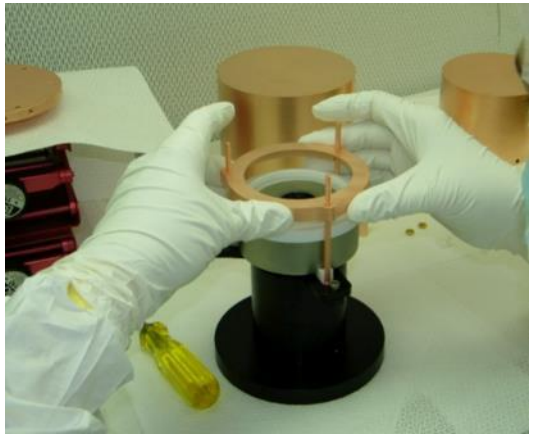


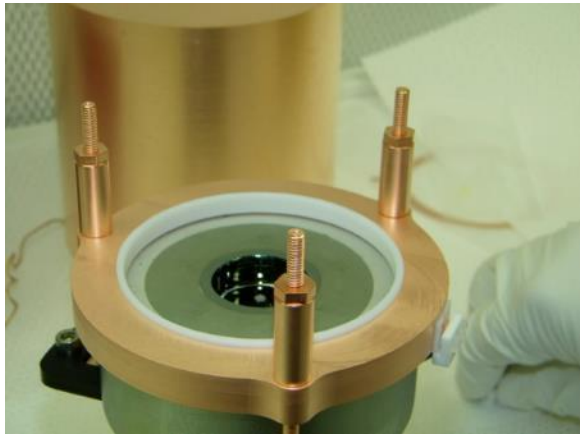
C4 Cryostat – 2012
Step 4 – Thermal testing

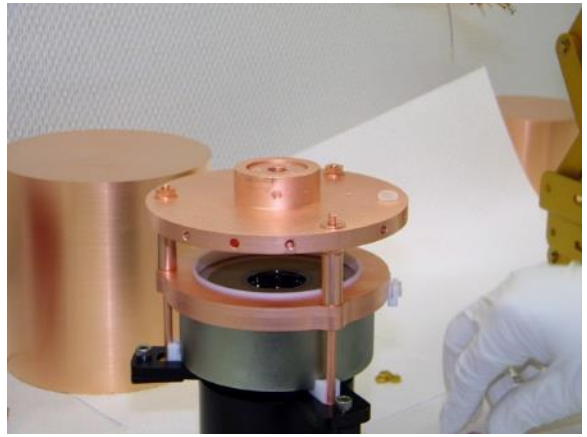


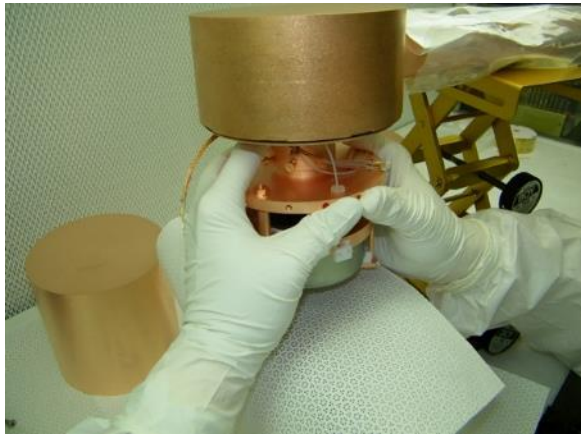
C4 Cryostat – 2012
Step 5 – Germanium integration

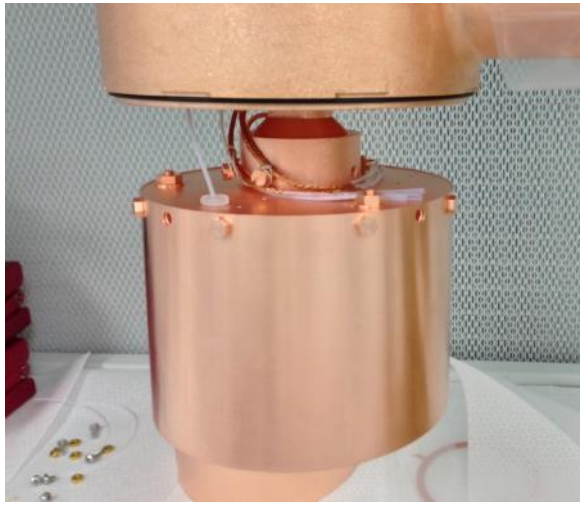




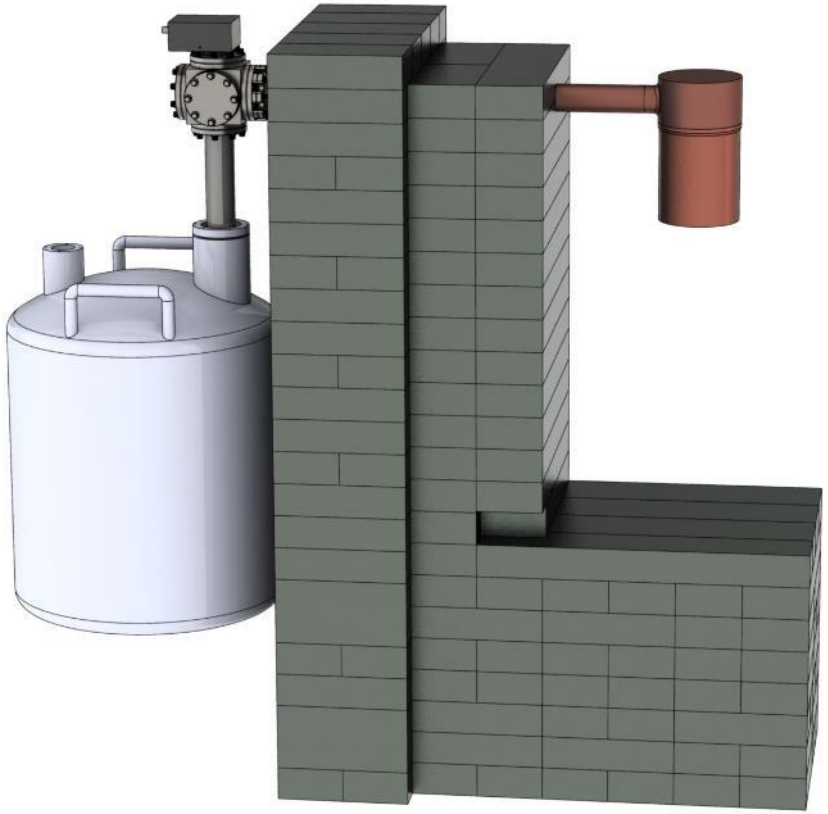








ULB Gamma Spectrometer– 2017



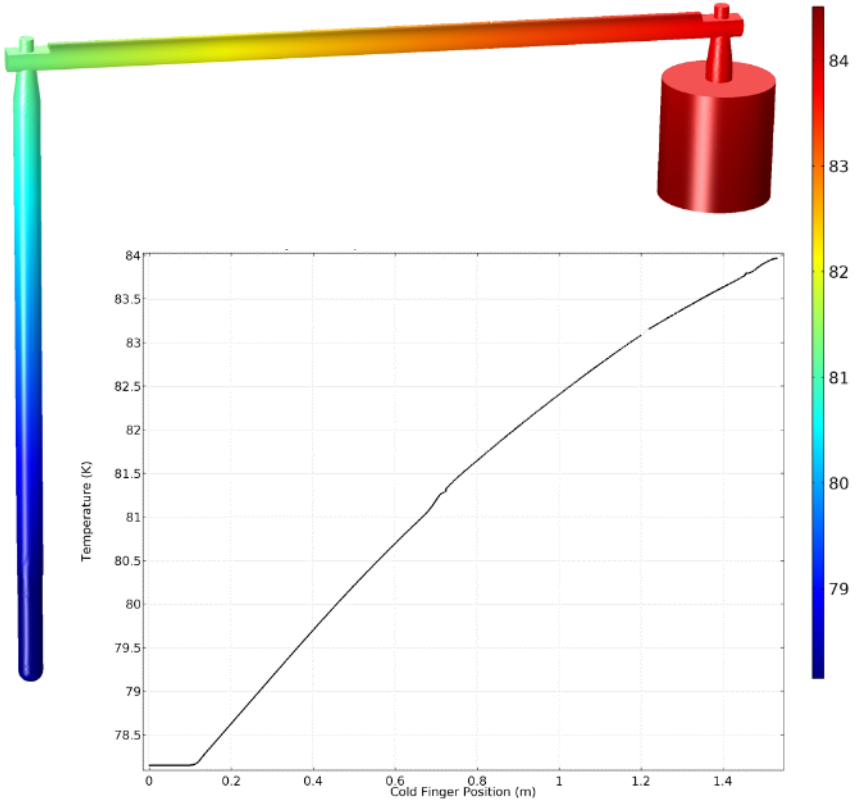
The image shown at the right is a thermal profile of the cryostat that indicates a ~6K temperature variation along the length of the cryostat.

Modeling Case:

- 1-1/8” thermal conductor diameters

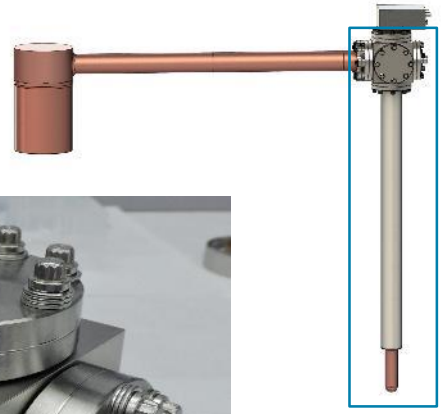
Modeling Outcomes:

- Cold-plate temperature: 84K
- IR loading: 1.6W
- Total LN load: 3.7W
  - LN Consumption: 2L/24hr



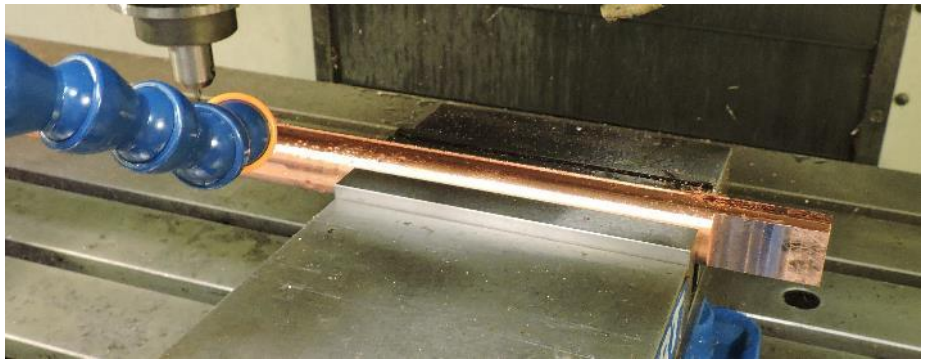
ULB Gamma Spectrometer– 2017
Improving thermal performance

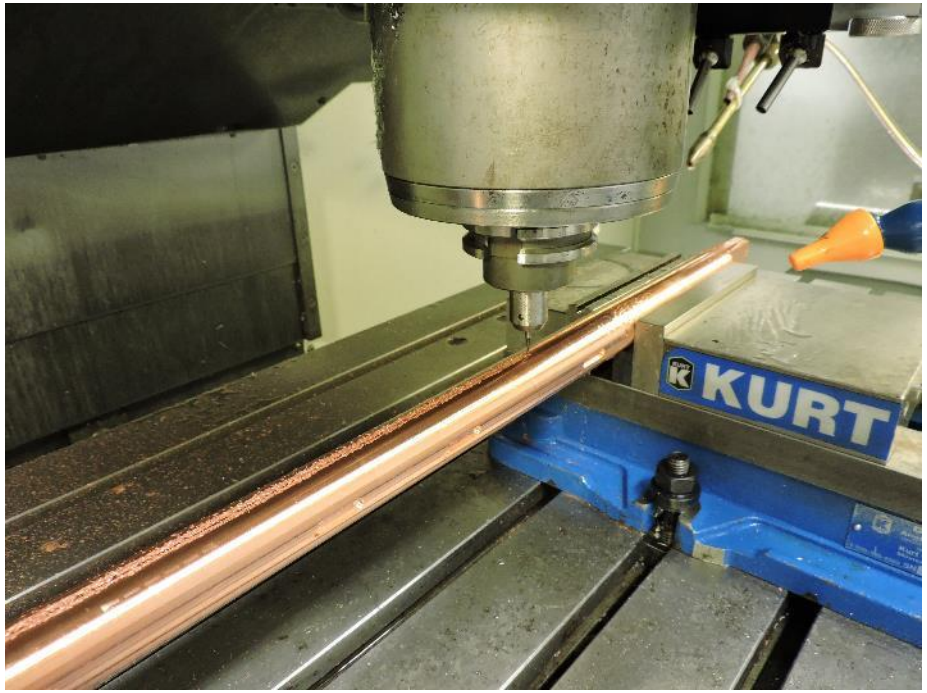
Cryostat thermal performance had to be improved due to the higher IR load (larger HPGe crystal) and longer horizontal cross arm

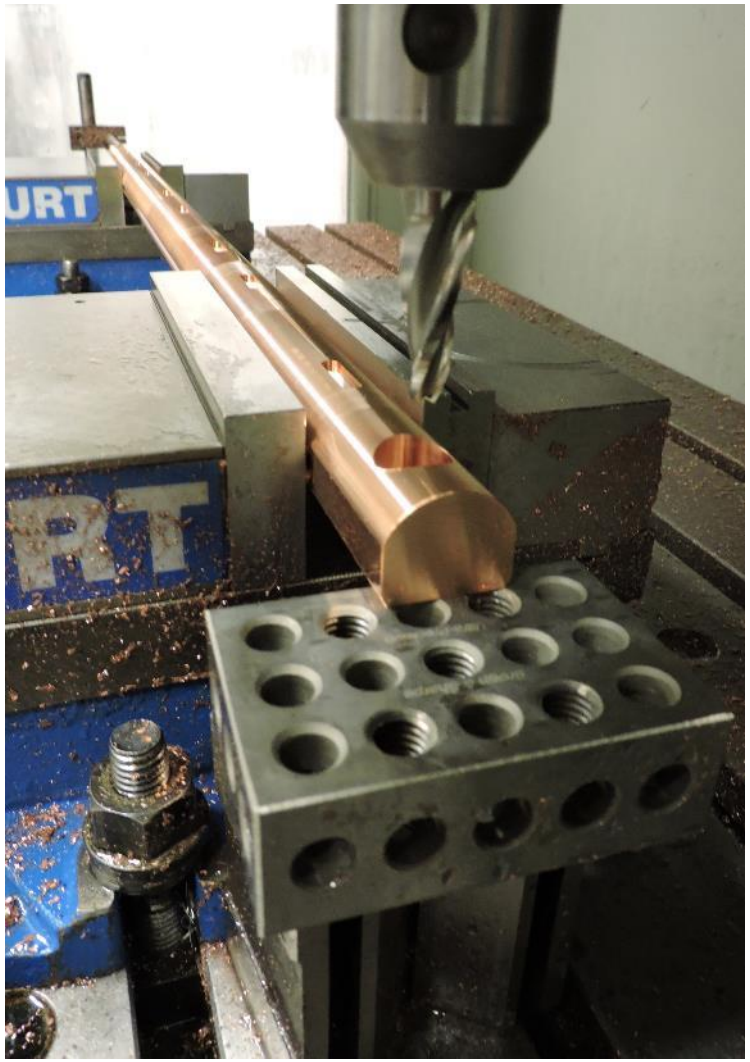


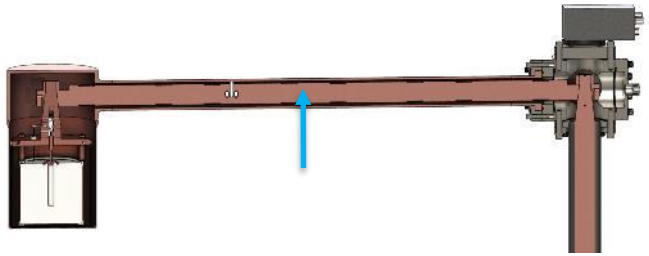
ULB Gamma Spectrometer– 2017

Critical design feature to eliminate thermal resistance of joints



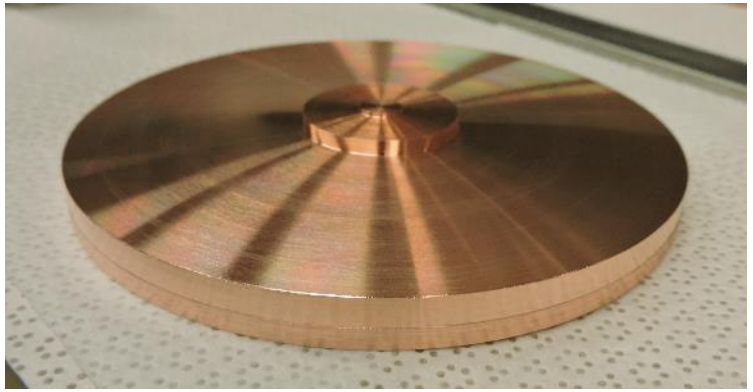


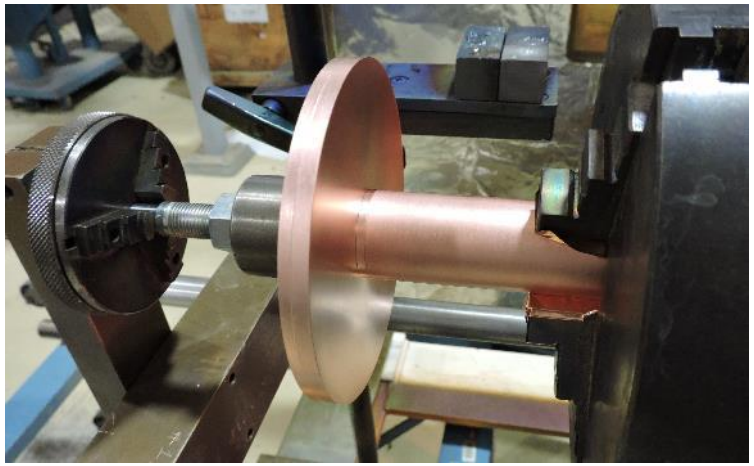


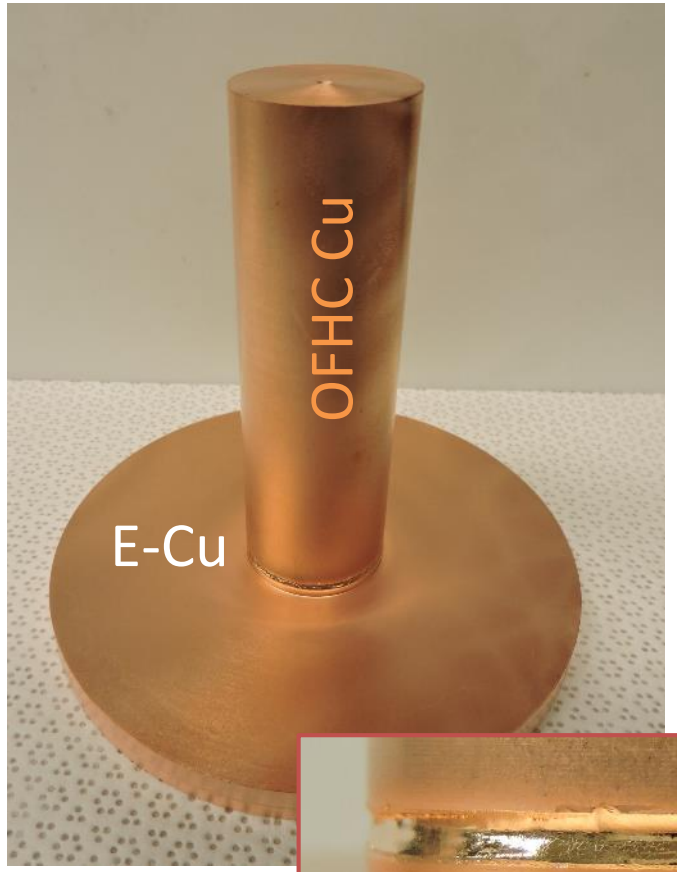


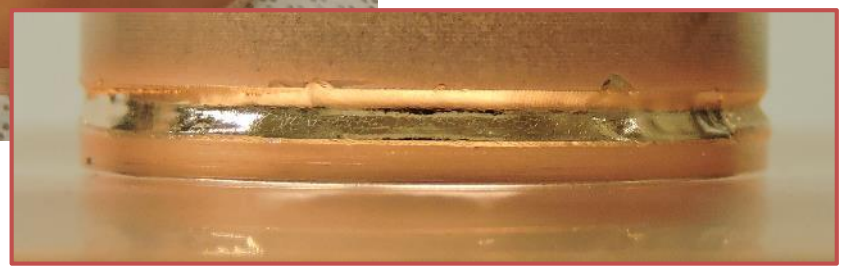
No measurable thermal resistance with tapered joints

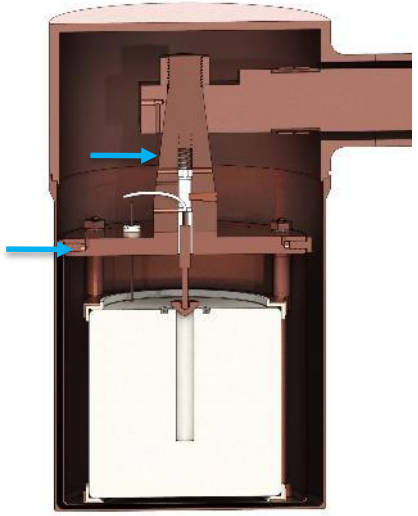
ULB Gamma Spectrometer– 2017
Blending electroformed and OFHC copper







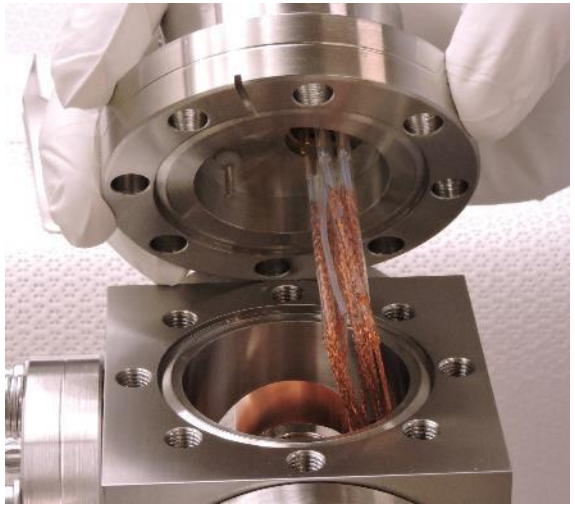


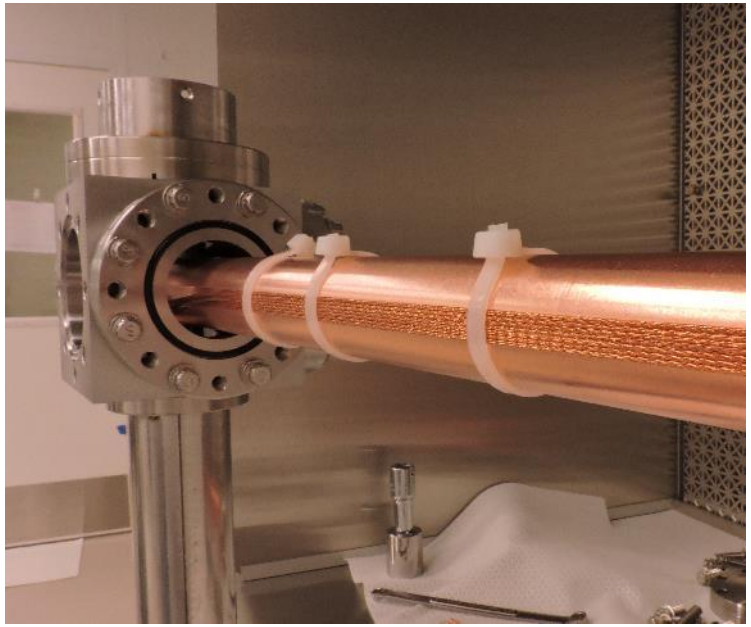


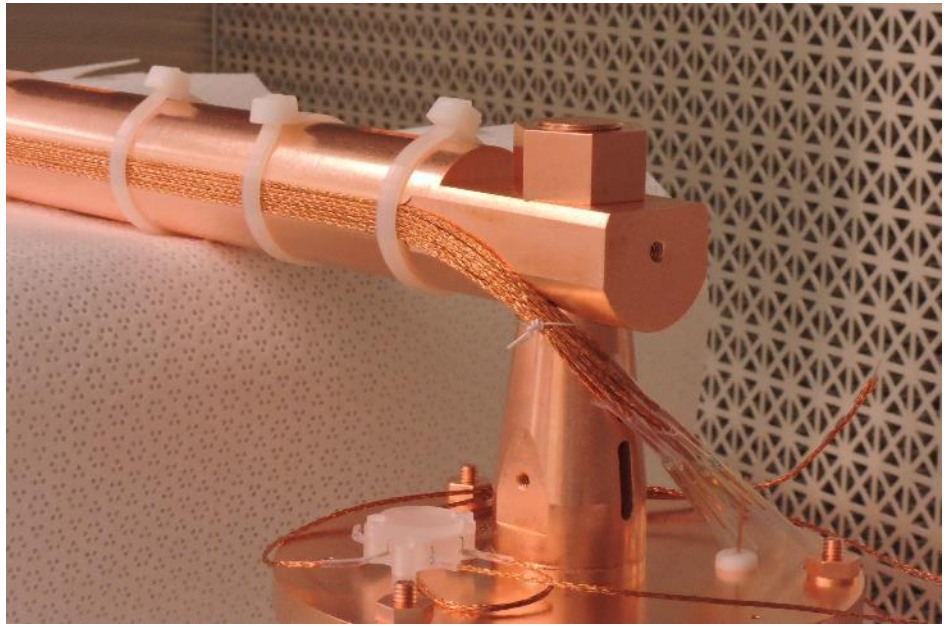
By using OFHC copper where possible, cryostat production time can be significantly reduced

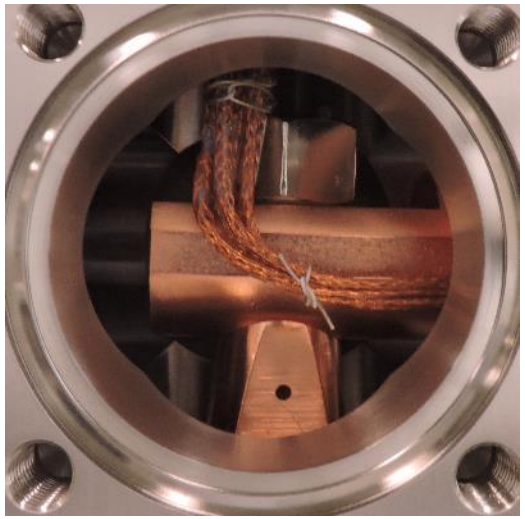
ULB Gamma Spectrometer– 2017

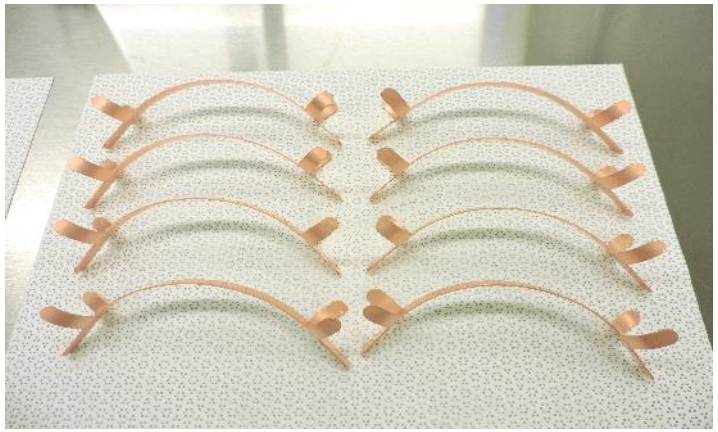
Electrical wiring

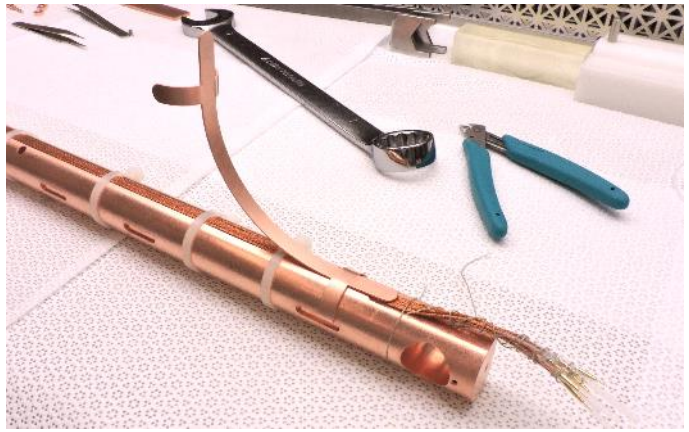






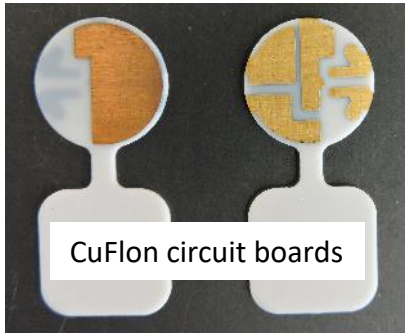


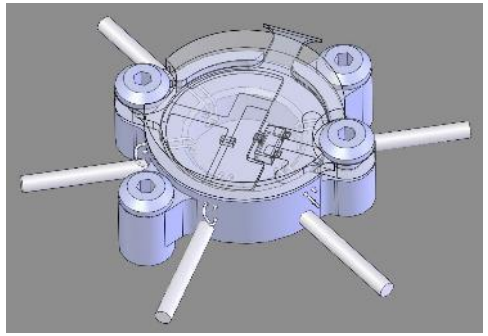


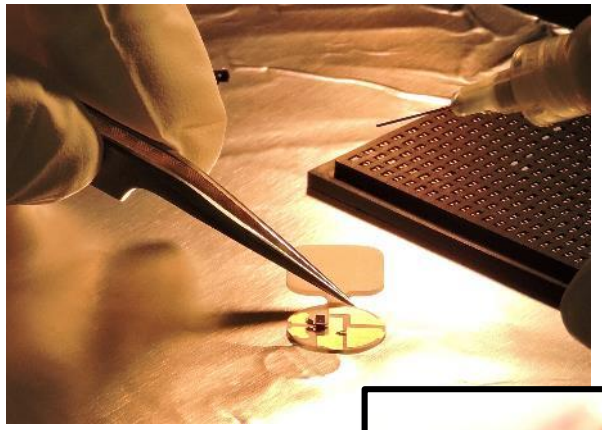


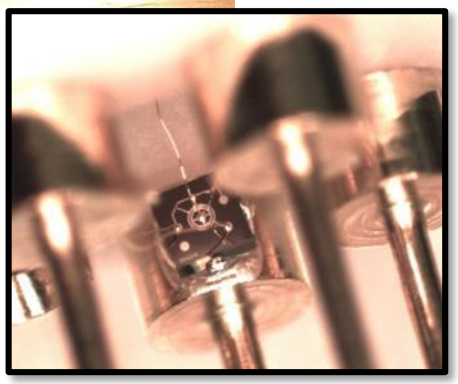
ULB Gamma Spectrometer– 2017
Lower background electronics

PNNL developed low-background front-end electronics for use in HPGe spectrometers. Use small electronic components to limit background contribution. For ultimate background performance, bare-die JFETs and wire bonding are used.

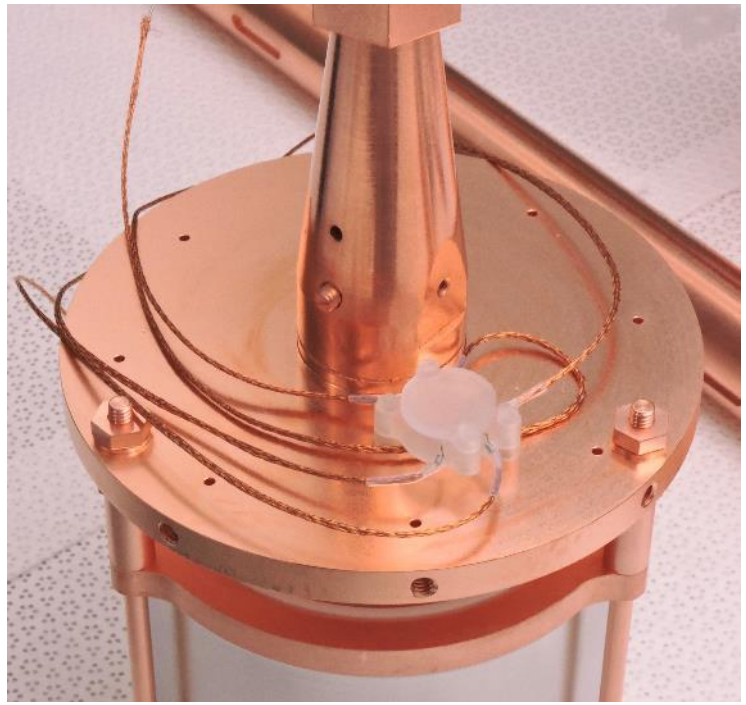


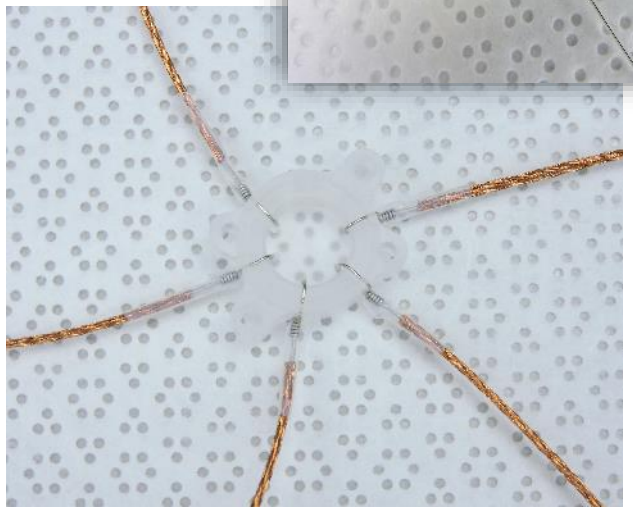






Canberra bare-die JFET configuration in C4

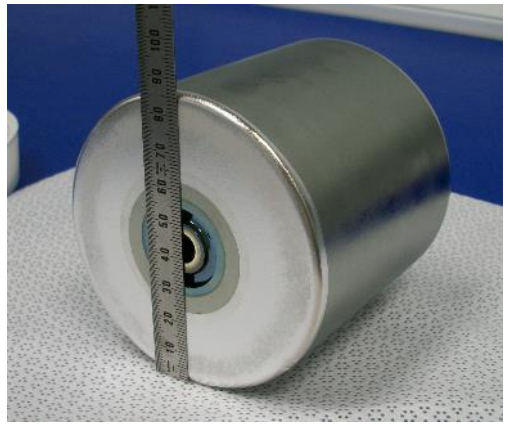


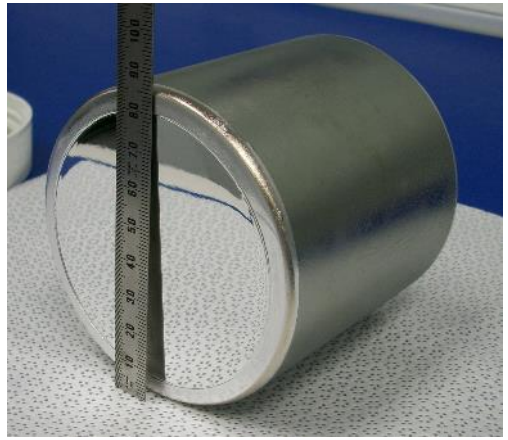


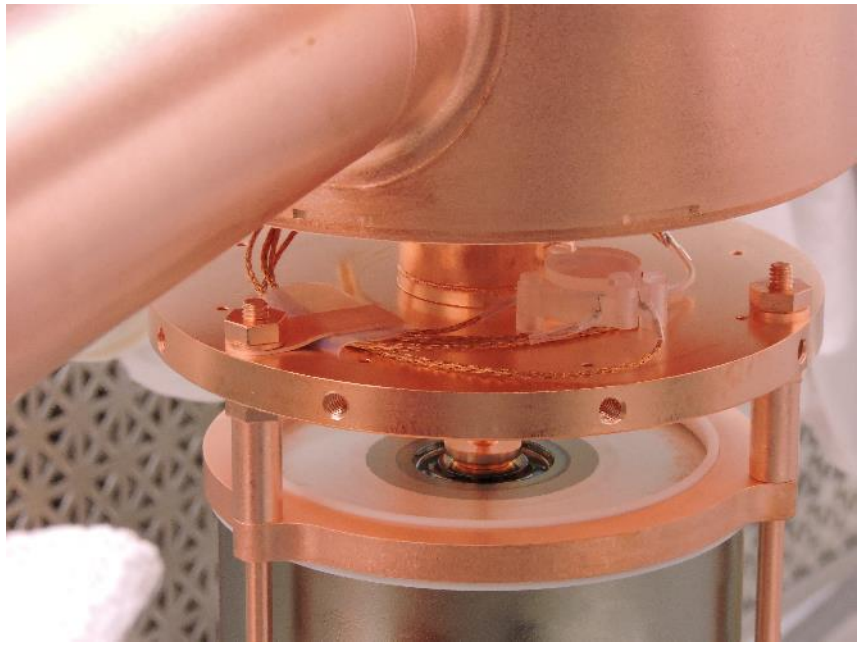
Screened polymer and cabling

ULB Gamma Spectrometer– 2017
Germanium crystal integration

- Custom 2.7kg Canberra XtRa crystal (partial wrap-around Li contact)
- 143% relative efficiency







Summary

- Recent successes with the production of HPGe cryostats gives me confidence that we (The Collaboration) can design and build a cryostat capable of achieving the background goals of DAMIC-M.
- Significant ultra-low-background capabilities and expertise exist at PNNL and are available to DAMIC-M

- There is a lot of work to be done before we will have a 90% cryostat design
- <u>For DAMIC-M to be successful the individual tasks will need to work together closely!</u>
  - cryostat, shielding, CCD packaging, and electronics tasks

Questions?

Heart of the Hill Vineyard – Red Mountain – Benton City, Washington