WBS 1.02.04 Light Detectors

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CUPID LBNL Project Review
December 16-17, 2024

UC Berkeley

Outline

- Scope
- High-level system requirements
- Conceptual Design
- Maturity
- Plan to complete R&D validation
- Risks
- Interfaces
- Budget
- Schedule
- Summary

Scope

- 1.0 CUPID Project
  - 1.01 Project Management
  - 1.02 Detector Components
    - 1.02.04 Light Detectors
      - 1.02.04.01 LD Procurements
      - 1.02.04.02 SiO coating and Al electrode deposition
      - 1.02.04.03 Gluing
      - 1.02.04.04 Light Detector Validation runs
  - 1.03 Detector Structure
  - 1.04 Host lab Infrastructure and Cryogenic systems
  - 1.05 Data Readout
  - 1.06 Background Control

- Shared scope between the US and France
  - Both deliver 1000 detectors each for the whole project

High-level system requirements

CUPID

Requirements	Value
Pile up background	$< 5 \times 10^{-5}$ ckky
Alpha/Beta discrimination (< 100 eV baseline RMS at 0V)	> 0.996
Light detector rise time	< 0.5 ms
Light detector S/N (σ) after NTL	> 140
Light Collection	> 0.36 keV/MeV
Deliverable quantity	2000 (US scope: 1000)
Fraction of working LDs	> 98%
Radiopurity	226-Ra (238-U) < 20 uBq/kg 228-Th (232-Th) < 10 uBq/kg
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Interfaces with WBS 1.02.05 (risetime depends on NTD-Ge resistance and heat capacity)

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CUPID

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Interfaces with WBS 1.04 (Noise depends on Lab infrastructure and cryogenic system)

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CUPID

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Interfaces with WBS 1.02.03 (Light yield depends on the crystal quality)

WBS 1.02.04 KPP

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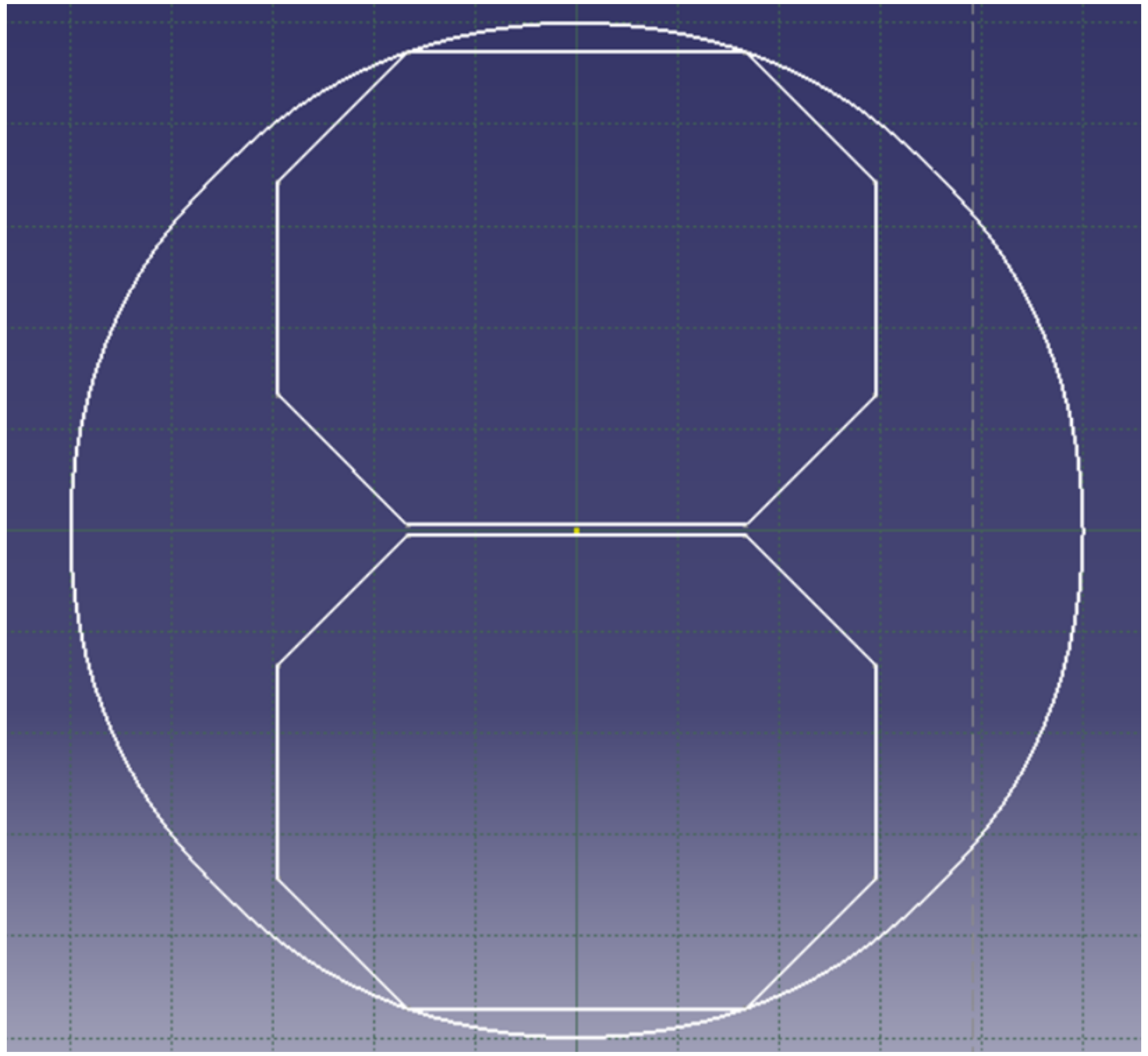
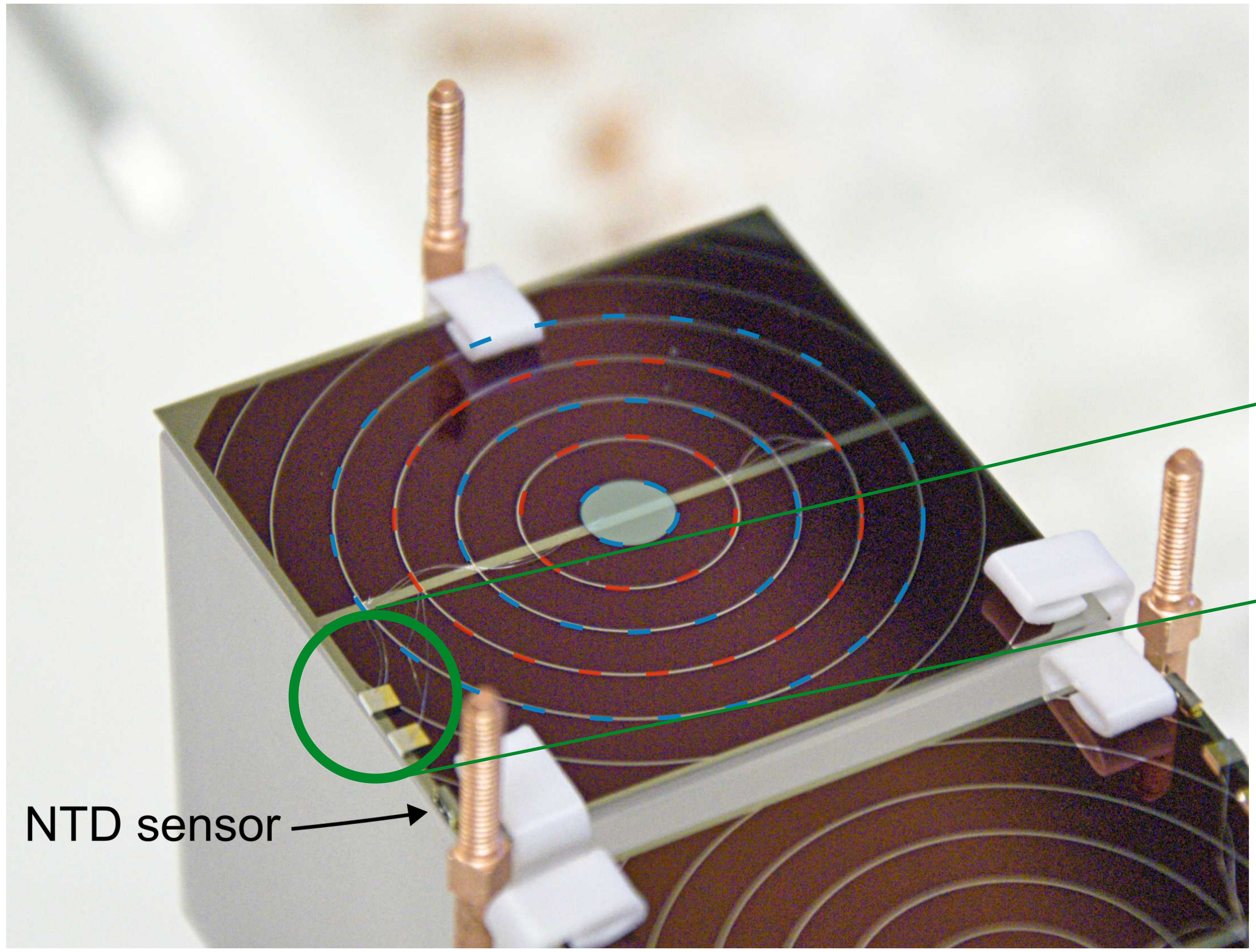
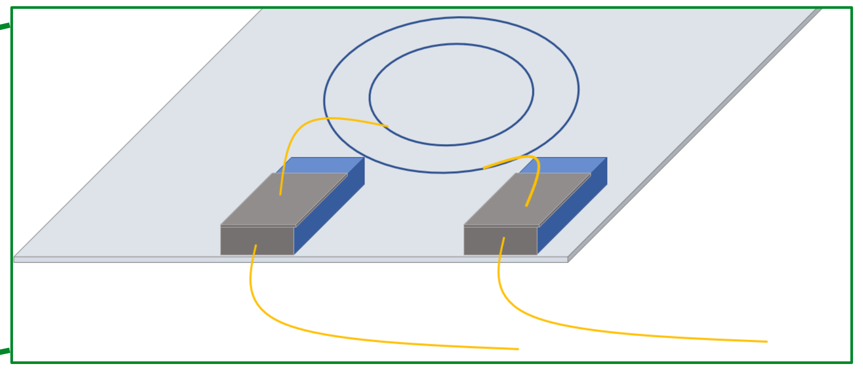
Key performance parameters identified which drive project success

Description	Threshold	Objective
WBS 1.02.04 Light Detectors	Delivery to LNGS of the required set of LDs meeting or exceeding technical requirements on energy and time resolution as demonstrated on a 5% sample of delivered detectors	Delivery to LNGS of the required set of LDs meeting or exceeding technical requirements on energy and time resolution as demonstrated on a 30% sample of delivered detectors

Conceptual Design







100 mm wafer, 2 LDs max
Dice out 1000 wafers to make 2000 detectors

Concentric rings of Al electrode
+ Anti-reflective coating

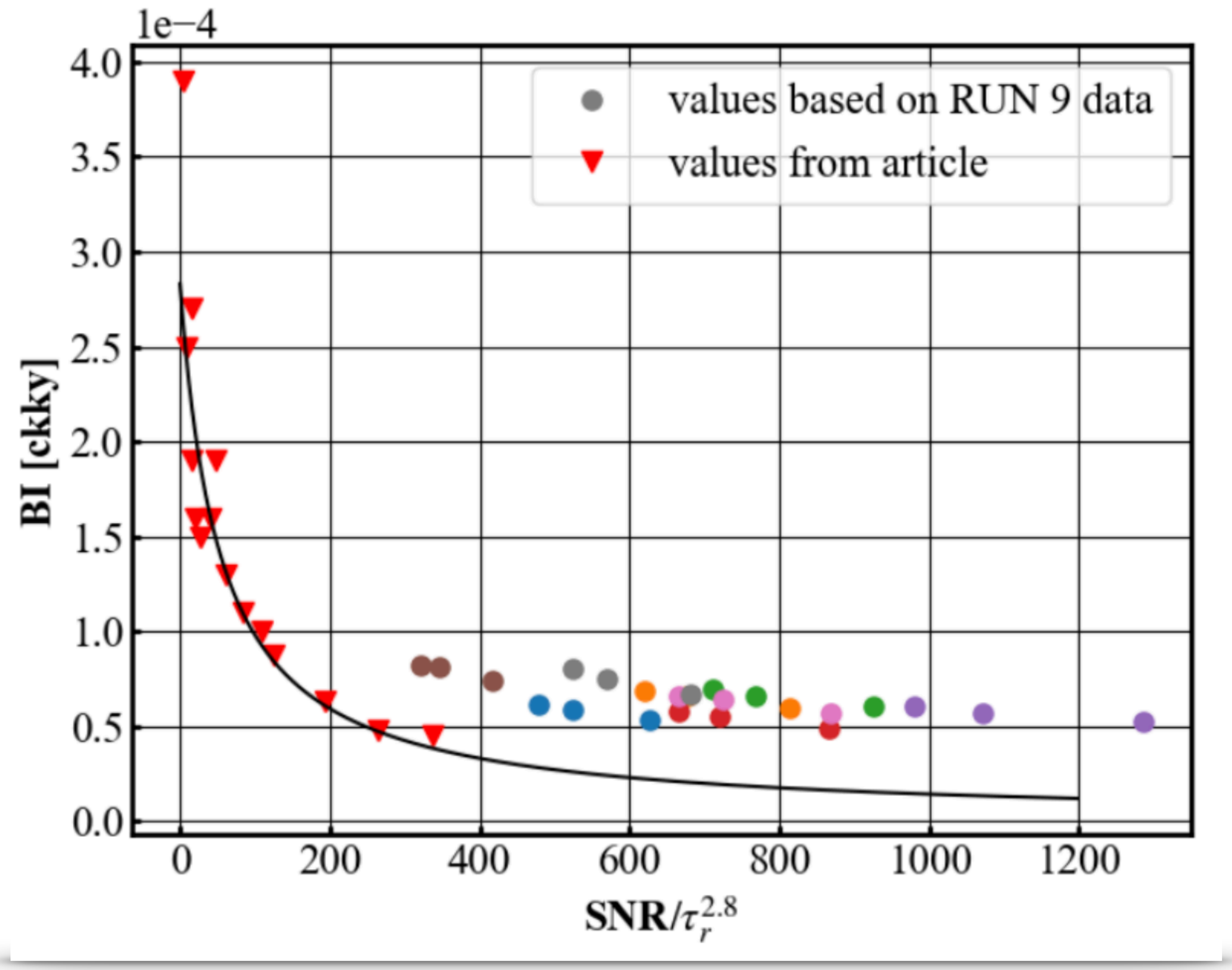
Transition pieces for bonding

Technical Specifications

- **High-Purity Germanium:** Detectors utilize high-purity germanium with minimal impurities (10^{10} atoms/cc) to reduce leakage current and enable higher bias voltage for improved performance.
- **Octagonal Shape:** Wafers are cut into an octagonal shape to maximize the active detector area.
- **Aluminum Electrodes:** Aluminum electrodes are applied to the germanium surface to create the necessary conditions for phonon-assisted detection (NTL effect)
- **Anti-Reflective Coating:** A 70nm SiO/SiN anti-reflective coating layer minimizes light loss (<10% reflectance) by optimizing light collection from the LMO scintillator.
- **Thin Wafers:** The use of 300 µm wafers to minimize heat capacity.

Maturity

- Existing NTL-assisted Ge light detectors have demonstrated the viability of this technology for CUPID.



Note:

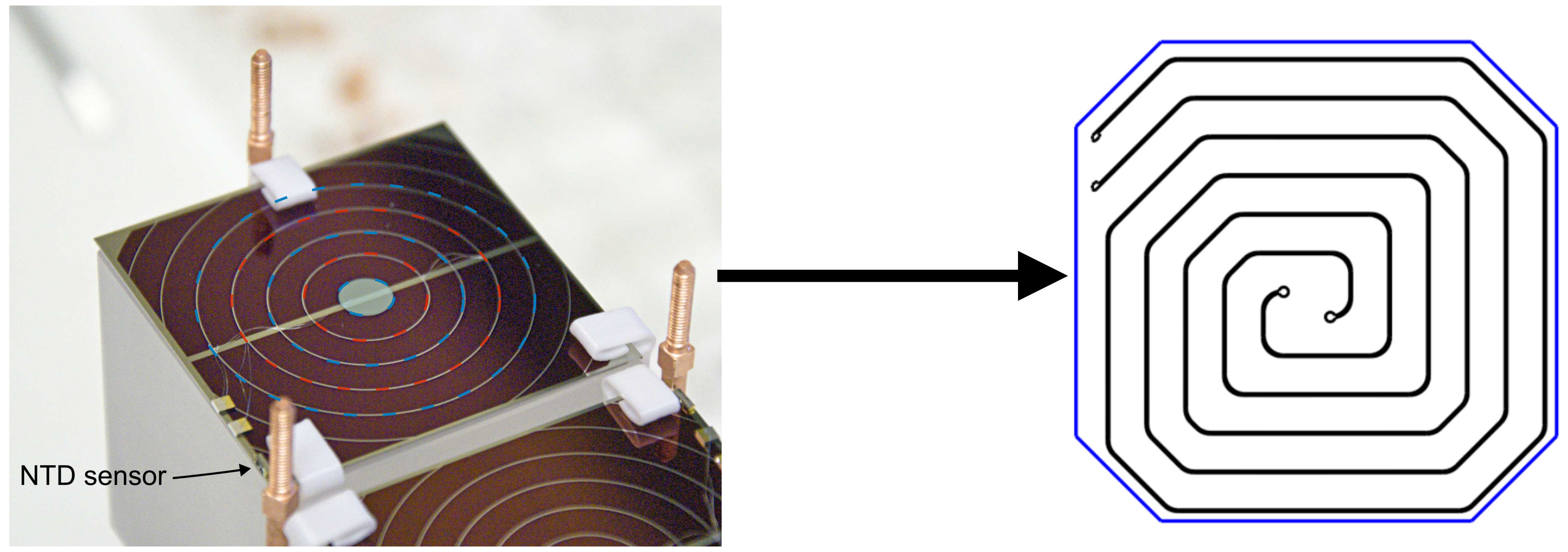
- Data uses the scaled value of SNR to account for the geometrical coverage of electrodes for CUPID-like detectors and Light Yield.

Maturity

- **Large-Scale Validation:** Planned tests with Vertical Slice Test Tower (VSTT), the CROSS demonstrator, and the BINGO demonstrator will provide extensive data from hundreds of LDs, confirming reliability and performance on a large scale.
- **Rigorous Testing:** A pre-screening process involving testing at 4K will identify and eliminate unreliable detectors before deployment in CUPID, minimizing failure rates.
- **Continuous Improvement:** Ongoing R&D efforts focus on optimizing electrode design, crystal surface polishing, noise reduction, and advanced analysis techniques to enhance detector performance beyond the baseline.
- **Redundancy:** CUPID's design incorporates redundant light detectors (upper and lower) in its towers, providing backup in case of individual detector failures.

Plan to complete

- **Improved NTL electrode design:** Full surface coverage for a ~33% SNR improvement.



- **Crystal surface optimization:** Polished surface to maximize light output, potentially improving SNR by ~20%.
- **Noise mitigation:** Reduce noise within the LD signal risetime bandwidth.
- **Optimized NTD sensor:** Improved doping and geometry for better LD risetime and SNR.
- **Advanced analysis techniques:** Denoising, novel analysis, and machine learning for enhanced pile-up rejection and background reduction.
- **Dual LD pile-up rejection:** Utilize both upper and lower LDs for pile-up rejection.

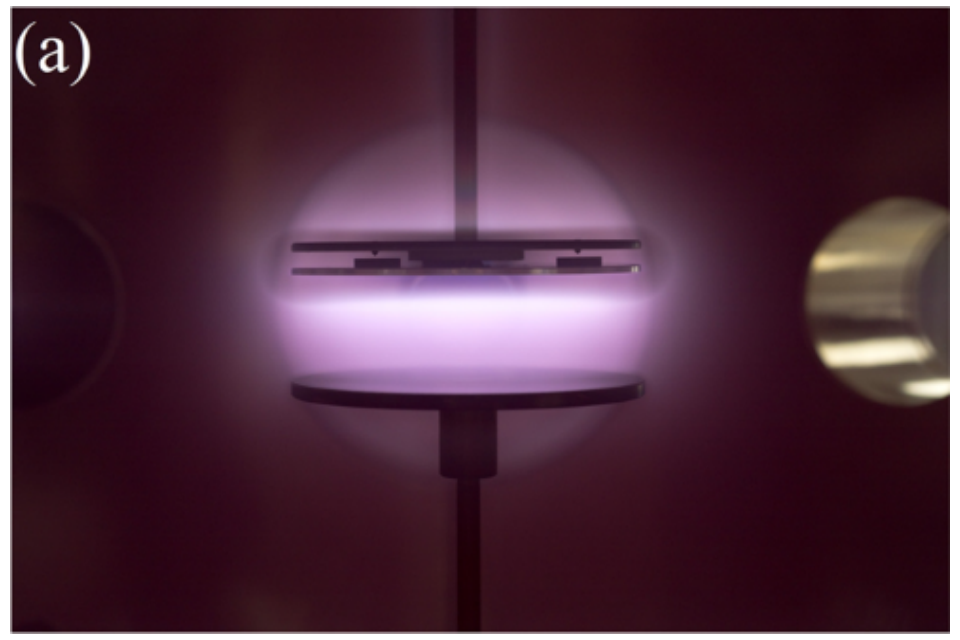
Plan to complete

- **“150 mm electronic grade” Umicore wafers**: Potential Cost savings, need to validate performance.
- **ANL-produced detectors need validation**: significant R&D effort to get the recipe right.
- **Regeneration of detectors and long-term stability:** will have more statistics from VSTT, CROSS, and BINGO demonstrators)

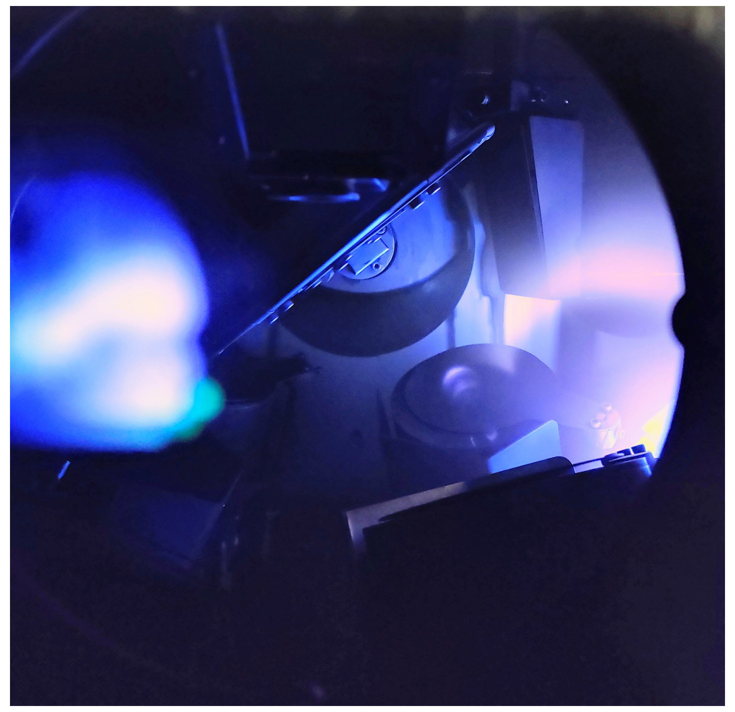
Production Status in the US (ANL)

- Clean wafers
  - RF Plasma and/or Ion Gun Plasma

RF Plasma



Ion Gun Plasma

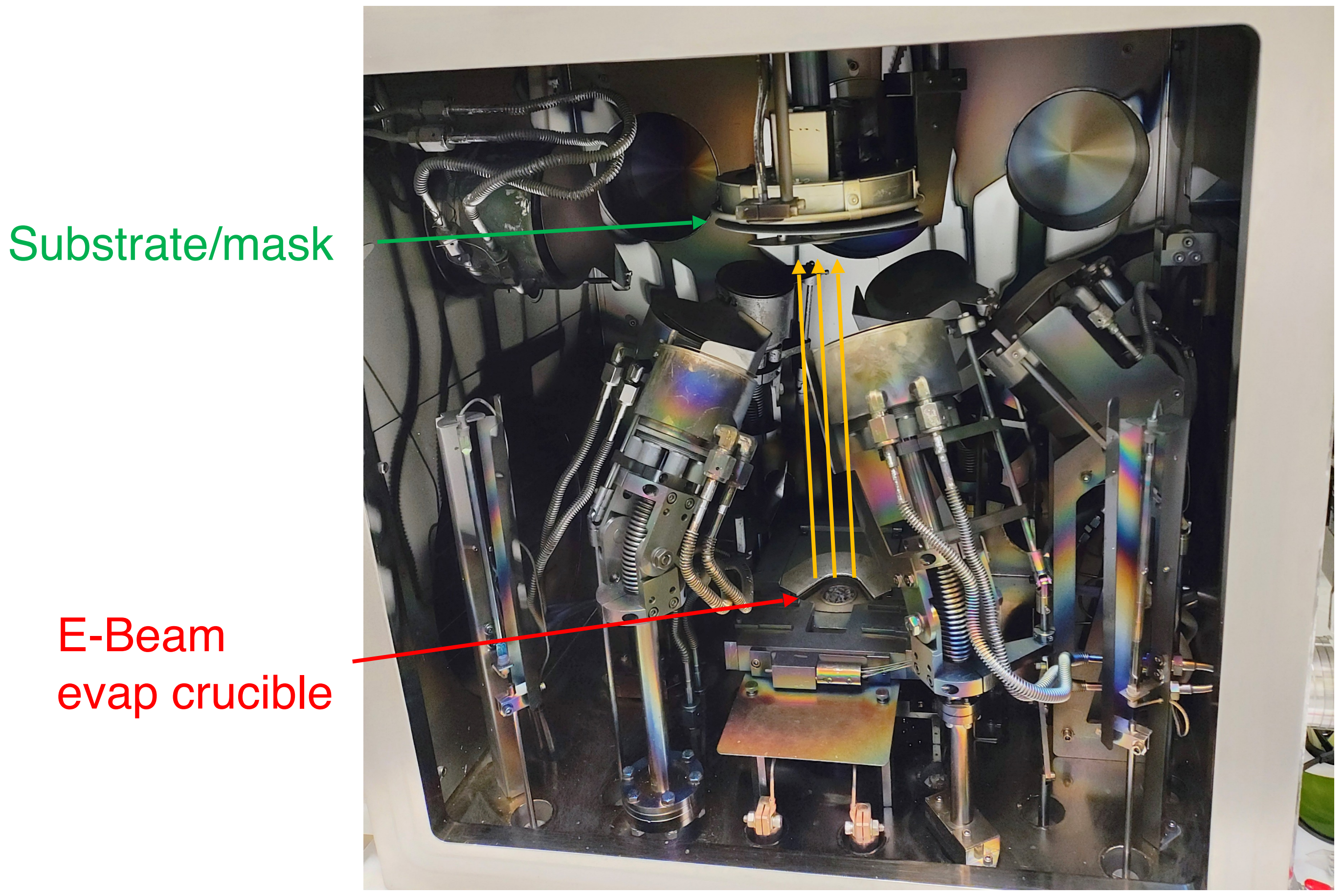


- Deposit Layers
  - Sputtering and/or E-beam evaporation

Sputtering
Done in AJA/Angstrom Engineering System

and/or

E-Beam Evap
Done in Angstrom Engineering System



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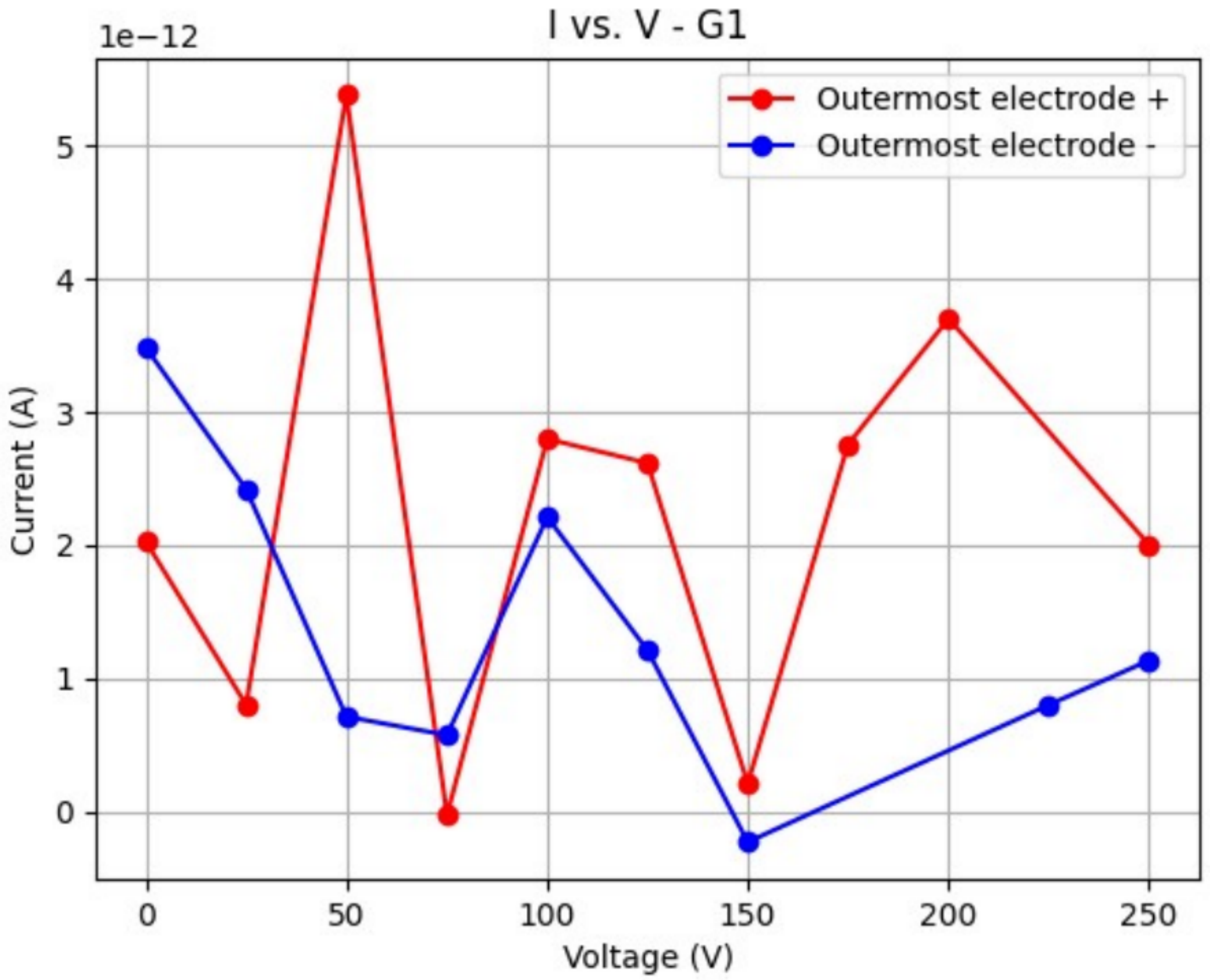

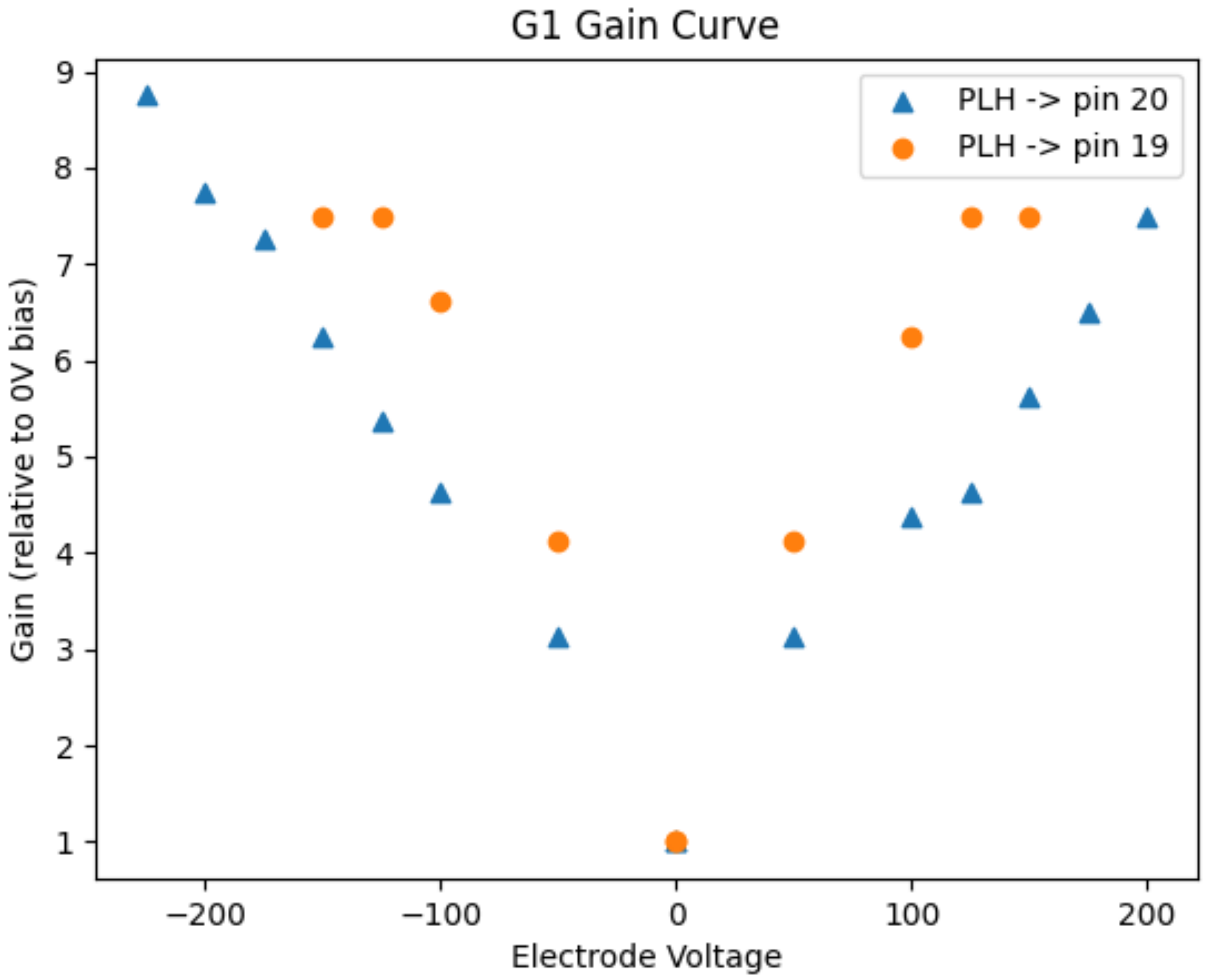

- Successfully operated ANL fabricated prototype detectors
  – Can withstand > 150 V
  – with reasonable gain.

Risks

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Risk ID	L2	L3	Description	Consequence	Likelihood	Cost Impact	Schedule Impact	Technical Scope	Impact Ranking	Mitigation
202040004	2	4	Delay in setting up the AR coating facility that meets all technical specifications at ANL.	The production schedule of Light detectors will be severely impacted if the facility is not timely setup and does not meet the clean room spec.	Likely	Critical (C)	Critical (C)	Critical (C)	Critical (C)	Procurement and setup should be done as soon as funds are available.
202040007	2	4	More than 2% of the detectors are found to be inoperable after installation and cooldown.	We will have to open the cryostat again and replace the detectors. This is non trivial.	Unlikely	Significant (S)	Critical (C)	Critical (C)	Critical (C)	We will check and recheck our installation procedure to ensure this does not happen. We have the experience of CUORE, where we lost only 4 channels out of 988.
202040009	2	4	Loss of personnel at ANL	The LD fabrication process will either have to move out of ANL or will go very slowly.	Unlikely	Significant (S)	Critical (C)	Marginal (M)	Critical (C)	France and Italy both have coating facilities, and we can move the scope to them.

Interfaces

Interface	Description
WBS 1.02.03 LMO Crystals	Crystal quality determines the absolute light yield incident on the light detectors.
WBS 1.02.05 NTD-Ge thermistors	The energy and timing resolution of the light detectors is critically dependent on the size, quality, and coupling of the sensors to the LDs.
WBS 1.02.06 Heaters	The LDs will be equipped with heaters to correct the thermal gain drift.
WBS 1.03.02 Detector Structure Design	The shape and size of LDs affect the LY and shape of electrodes, which affect the gain. In addition, it dictates how they are positioned in a tower and the positioning of the electrode contacts and terminals for wire bonding.
WBS 1.03.06 Tower Bonding	use of transition pieces to be able to bond the tower horizontally
WBS 1.03.07 Gluing	The gluing of NTDs and heaters will happen in a dedicated assembly line in an external cleanroom at LNGS.
WBS 1.04.02 Wiring	The detectors need separate wirings for NTD-Ge readout, Heater readout, and HV bias. Wire capacitance can have a contribution to the rise time. The heaters and HV will be connected in parallel for each column at the
WBS 1.04.10 Optical Injection System	The optical injection system will regenerate the LDs. It can also be used for thermal gain drift without heaters.
WBS 1.05.04 Electronics: Filters and Digitizers	The light detectors' bandwidth determines the filters' bandwidth and the sampling rate of the DAQ. This has an impact on pile-up rejection.
WBS 1.06.xx Background Control	The pre-production LDs need to be counted and validated to ensure the fabrication process does not introduce radio impurities.

Budget

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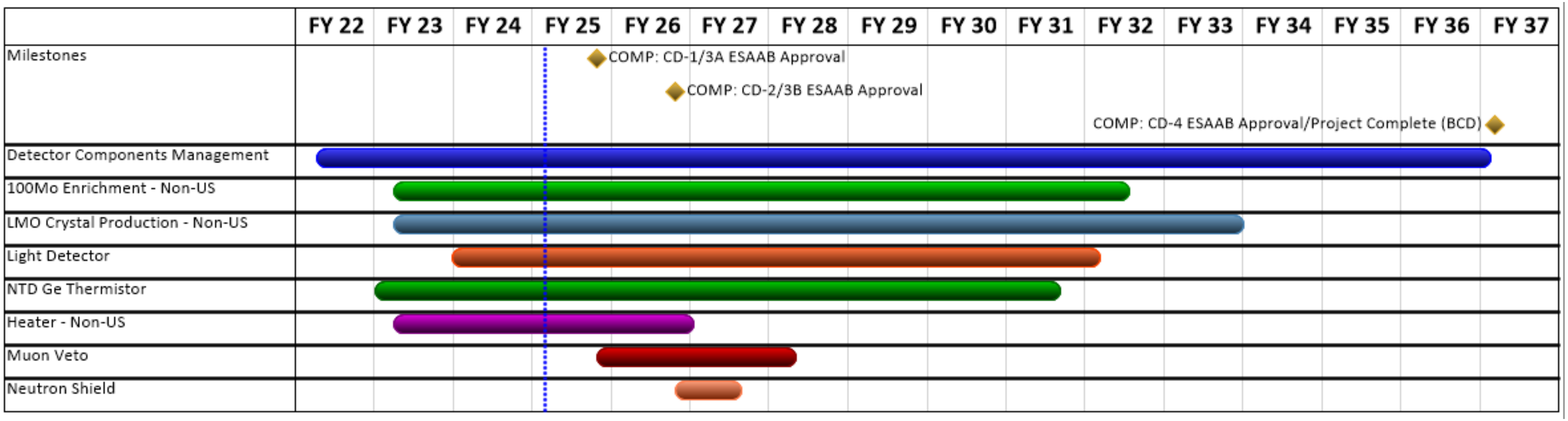
Units: kilo-hours and kilo-dollars

Sum of Value	Column Labels		
Row Labels	HOURS	DOLLARS	Total_$
US	10.9	1555.4	4011.4
Phase 1	7.1	1318.4	3089.9
1.02 Detector Components	7.1	1318.4	3089.9
1.02.04.01 LD Procurements	.5	1247.6	1602.0
1.02.04.02 SiO Coating and Al Electrode Deposition	2.7	25.5	753.0
1.02.04.03 Gluing	1.2	.0	371.8
1.02.04.04 Light Detector Validation Runs	.6	.0	55.7
1.02.04.05 OPC: LD Procurements	2.1	45.3	307.4
Phase 2	3.8	237.0	921.5
1.02 Detector Components	3.8	237.0	921.5
1.02.04.01 LD Procurements	.8	193.3	513.4
1.02.04.02 SiO Coating and Al Electrode Deposition	1.5	43.7	188.8
1.02.04.03 Gluing	.7	.0	125.7
1.02.04.04 Light Detector Validation Runs	.9	.0	93.6
Grand Total	10.9	1555.4	4011.4

Schedule



FY 22
FY 23
FY 24
FY 25
FY 26
FY 27
FY 28
FY 29
FY 30
FY 31
FY 32
FY 33
FY 34
FY 35
FY 36
FY 37
Milestones
COMP: CD-1/3A ESAAB Approval
COMP: CD-2/3B ESAAB Approval
COMP: CD-4 ESAAB Approval/Project Complete (BCD)
Detector Components Management
100Mo Enrichment - Non-US
LMO Crystal Production - Non-US
Light Detector
NTD Ge Thermistor
Heater - Non-US
Muon Veto
Neutron Shield

Procurement and Production Status

- Ge wafers vendor identified
  - 100 mm high-purity Ge wafers from Umicore
- Vendor for dicing the wafers identified
  - American Precision Dicing (APD)
- The deposition process is well-established and validated by the French group.
- ANL is close to getting the recipe correct; recent results have been very promising.

Procurement and Production Status

- France purchasing a new evaporator (CryoVap)
  – tentatively in 2026
- New deposition tool at ANL
  – whenever funding is made available (Vendor identified)
- We estimate a production rate of 40 detectors per week
- Leakage current tests at 4K for detector preselection to be done in parallel with the production

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CDR Review recommendation

WBS 1.02.04: Light Detector

- **Comments:**
  1. The TES light detector technology seems quite promising, providing excellent time resolution without the risk of problematic leakage currents that could negatively impact the experiment. Bringing the TES technology to sufficient maturity to allow an informed technology choice should be a priority for the collaboration.
- **Recommendations:**
  R4. Before the CD-1 review, establish and document a plan for LD development, assessment vs. requirements, and selection of baseline vs. alternative technology.

Alternative Technology: Transition Edge Sensors (TES) with Frequency Domain Multiplexing (FDM) are being developed as an alternative to the baseline technology.

- **Advantages of TES:**
  - **Improved pile-up rejection:** TES sensors are faster than NTDs, allowing for better pile-up discrimination.
- **R&D Efforts:**
  - Successful prototype of a 10-channel FDM readout.
  - Ongoing focus on noise reduction, cryogenic cabling optimization, and component radiopurity.
- **Impact:**
  - **Baseline technology (NTL+NTD sensors) is currently deemed more mature. Alternative technology (TES sensors) is being developed outside of the project scope to mitigate project risks. Project estimated costs of deploying alternative technology. LD technology has to be selected by CD-2.**

Summary

- The technical scope is known, and the detector design meets the physics requirements.
- Multiple integration tests are planned to identify and mitigate operational risks.
- The US fabrication facility is demonstrating its capability to produce high-quality detectors, with performance approaching that of the French facility.
- The scope, budget, and schedule are well understood.