The LEGEND Experiment

Nuclear Physics Community meeting 2023

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LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Brunel University London, King's College London, Lancaster University, UKRI STFC Boulby Underground Laboratory, UKRI STFC Daresbury Laboratory, University College London, University of Edinburgh, University of Liverpool, University of Sheffield, University of Warwick, University of York

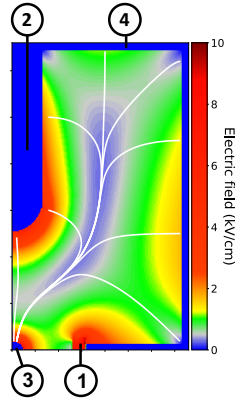
Introduction to LEGEND

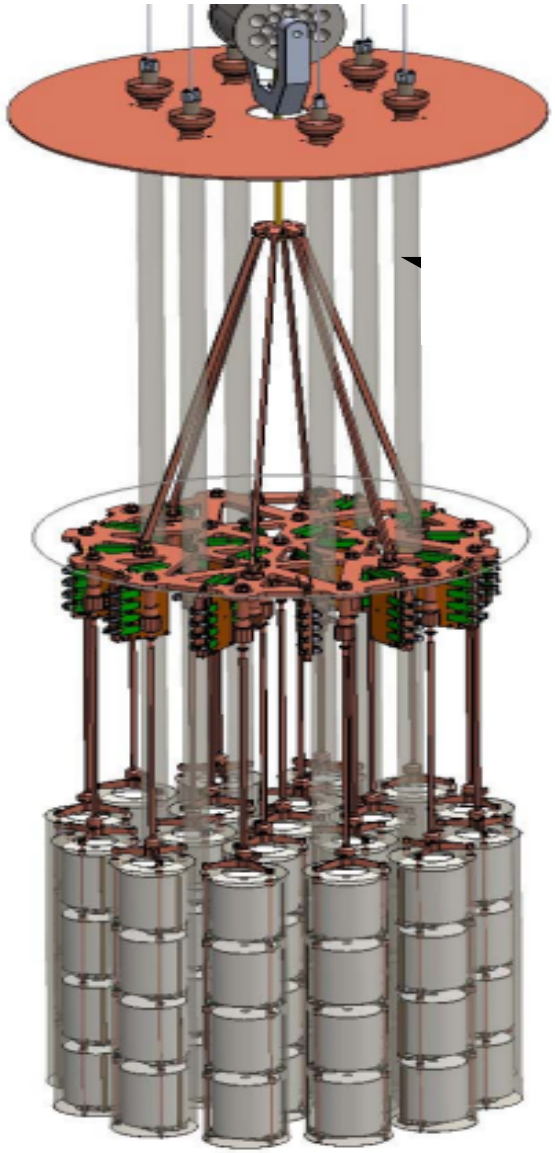
- The LEGEND collaboration proposes a 0νββ decay search experiment, using a 1 tonne of ^{76}Ge enriched detectors
- The programme follows a staged approach:
  - **LEGEND-200**: a 200 kg mass experiment, installed in the GERDA LAr cryostat at LNGS, Gran Sasso
  - It is an approved experiment at LNGS, with first commissioning in progress
  - **LEGEND-1000**: a 1T experiment will require a new underground infrastructure and additional R&D to further reduce backgrounds
  - LEGEND-1000 to start running later this decade

LEGEND 200 Overview

- A merger of the GERDA and MJD demonstrators @LNGS
- Re-use GERDA LAr cryostat: optimise geometry
- Low-background MJD front-end electronics, further from detectors
- Refinements to:
  - Veto system
  - Calibration systems
  - DAQ
- Trial PEN
- Installation in progress
- STFC Experiment support for M&O

New detectors for LEGEND:
P-type Inverted-Coaxial Point Contact
Larger mass : > 2 kg/detector



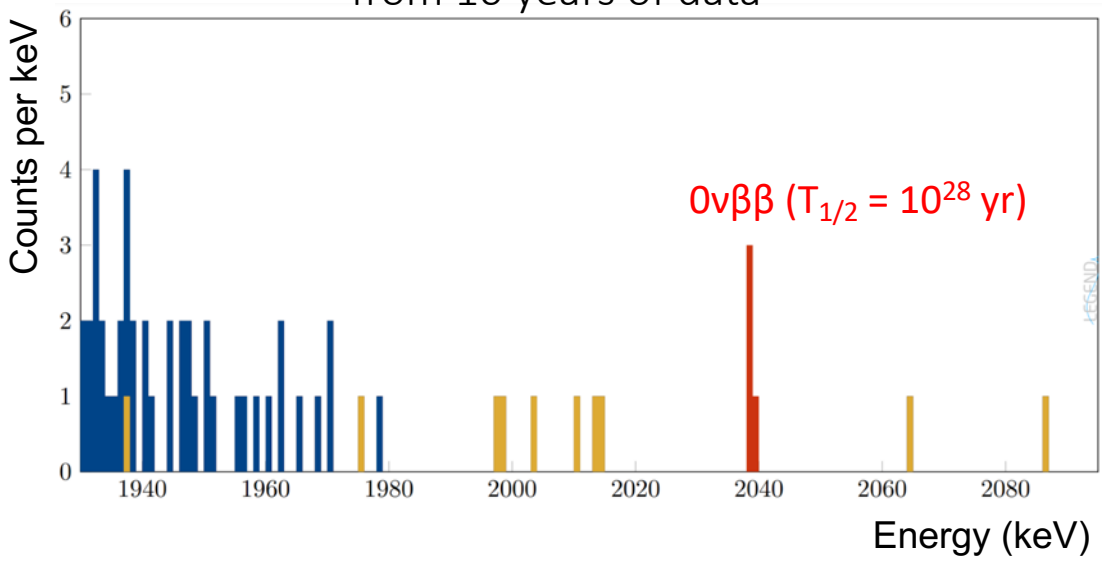


The LEGEND-1000 Discovery Sensitivity

"The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years..."

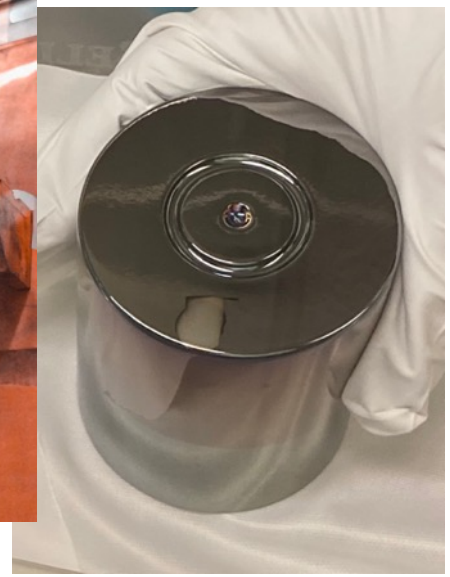
- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event rate**
    - The best possible **energy resolution**

Simulated example spectrum, after cuts, from 10 years of data

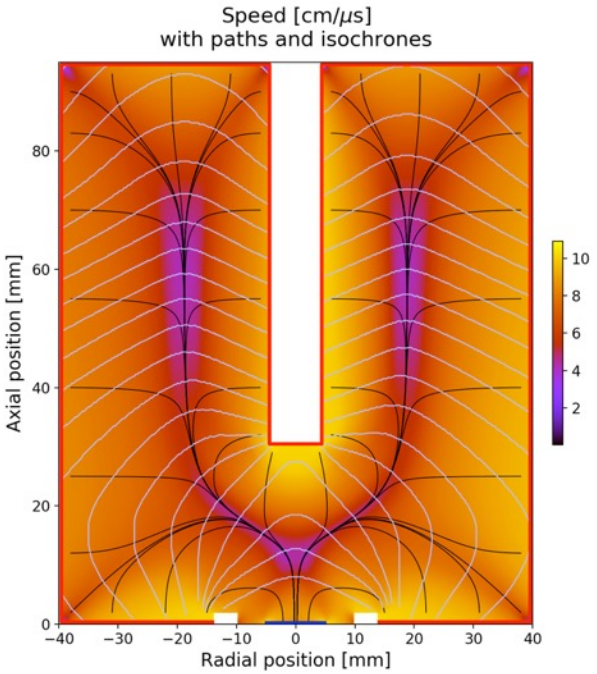


Innovation toward LEGEND-1000: ^{enr}Ge Detectors

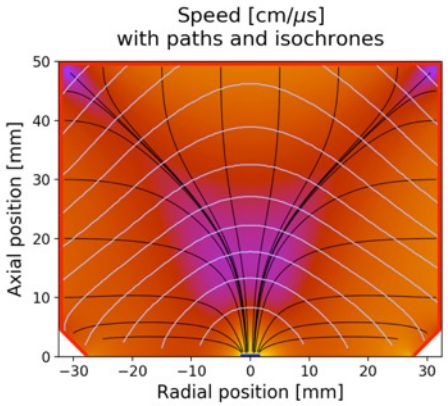
- Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
- P-type detectors: Insensitive to alphas on n^+ outer contact
- Pulse-shape discrimination against background events
- Large-mass ICPC detectors: About 4 times lower backgrounds compared to BEGes / PPCs
- Proven long-term stable operation in LAr



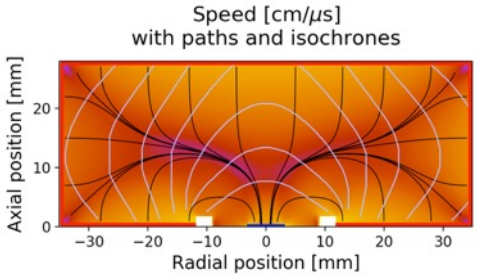
LEGEND (ICPC)

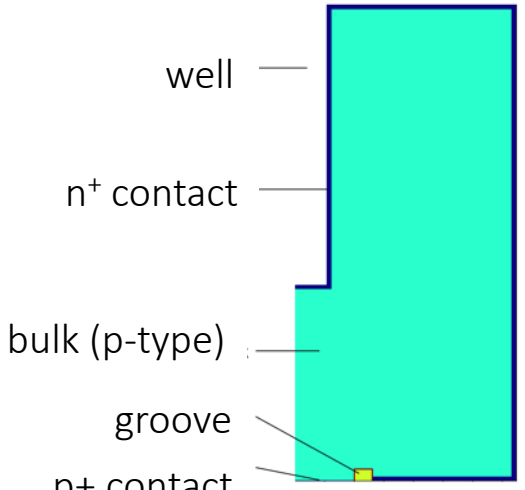


MAJORANA (PPC)



GERDA (BEGe)

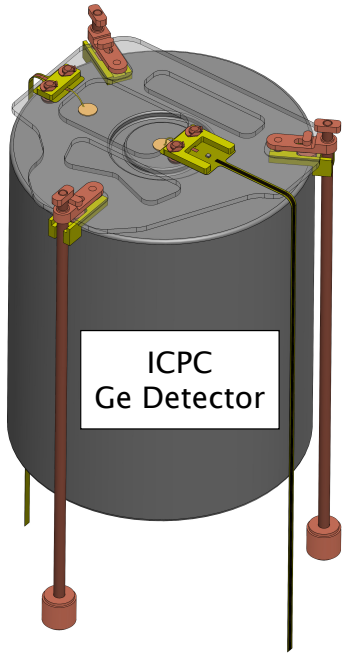




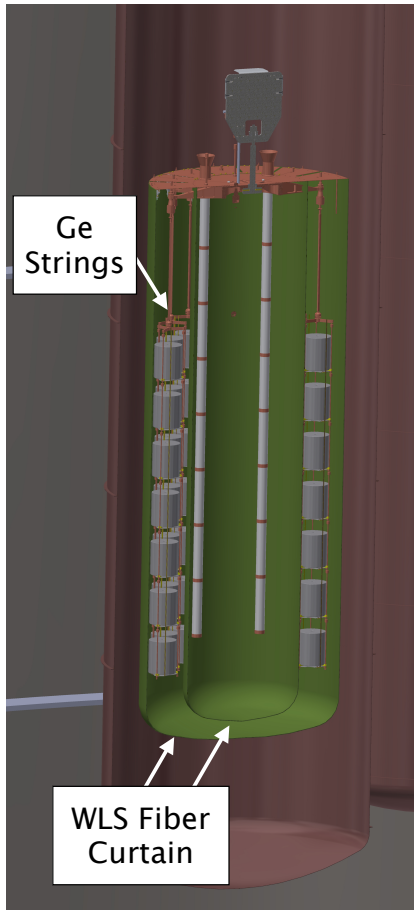
The LEGEND-1000 Experiment: Overview

1000 kg of enriched Ge detectors (92% ^{76}Ge)

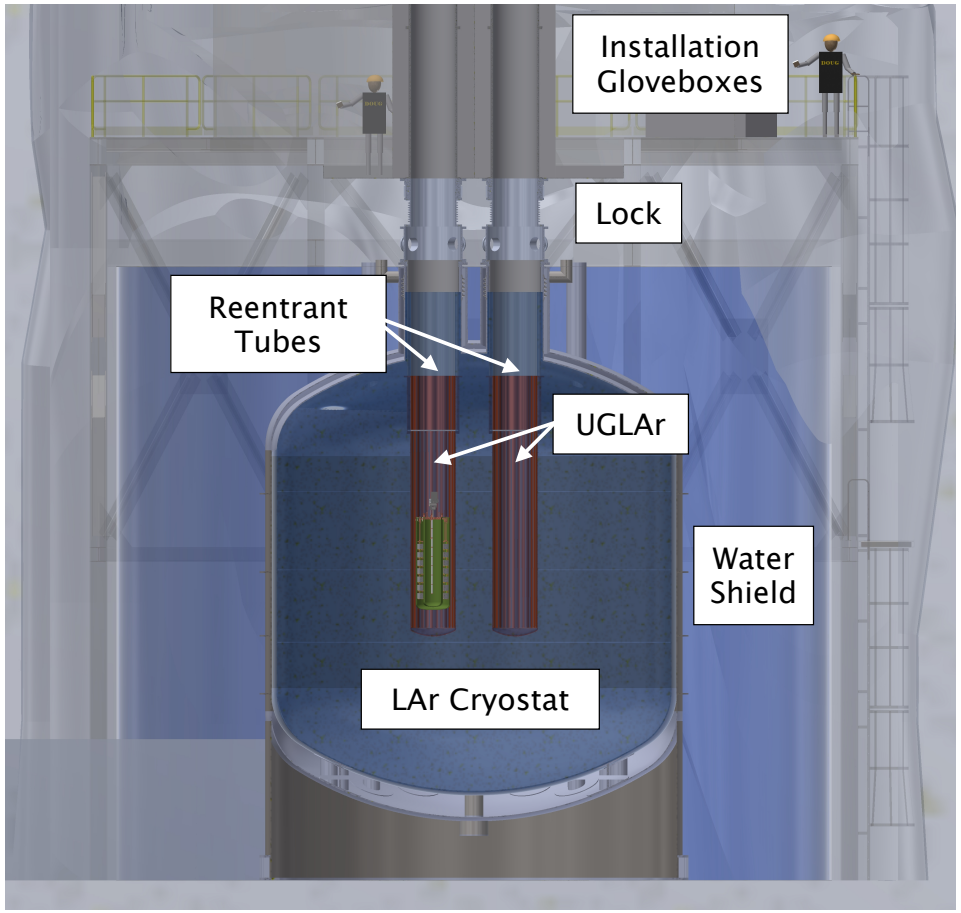
- 2.6 kg average mass
- Mounted in “strings” using components made from electro-formed Cu and scintillating plastic, PEN



- Arranged in 4 modules
- ~100 detectors per module

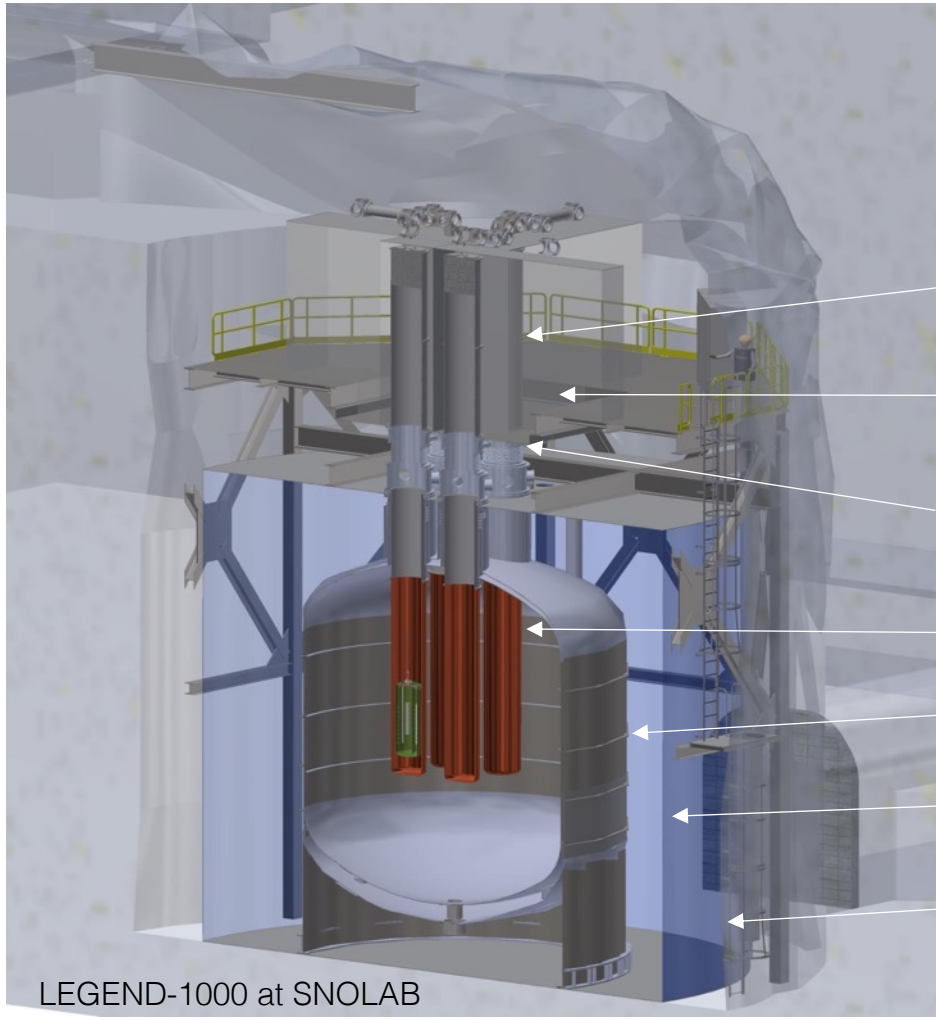


- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- EFCu Reentrant tubes



LEGEND-1000 Baseline Design: Underground Site

- A deep-underground site is needed to shield the experiment from backgrounds generated by cosmic rays
- Baseline site: The SNOLAB “Cryopit”
  - 2 km underground (6000m water equivalent)
  - In an active nickel mine in Sudbury, Ontario
  - Vertical access through mine shaft
- Alternative site: LNGS (Italy)
  - 3500m water equivalent depth
  - Lower overburden somewhat increases background
  - Horizontal access reduces cost/schedule risk
- Staff at both sites are actively involved in planning
- We are currently assuming that we need to carry both sites forward through CD-1



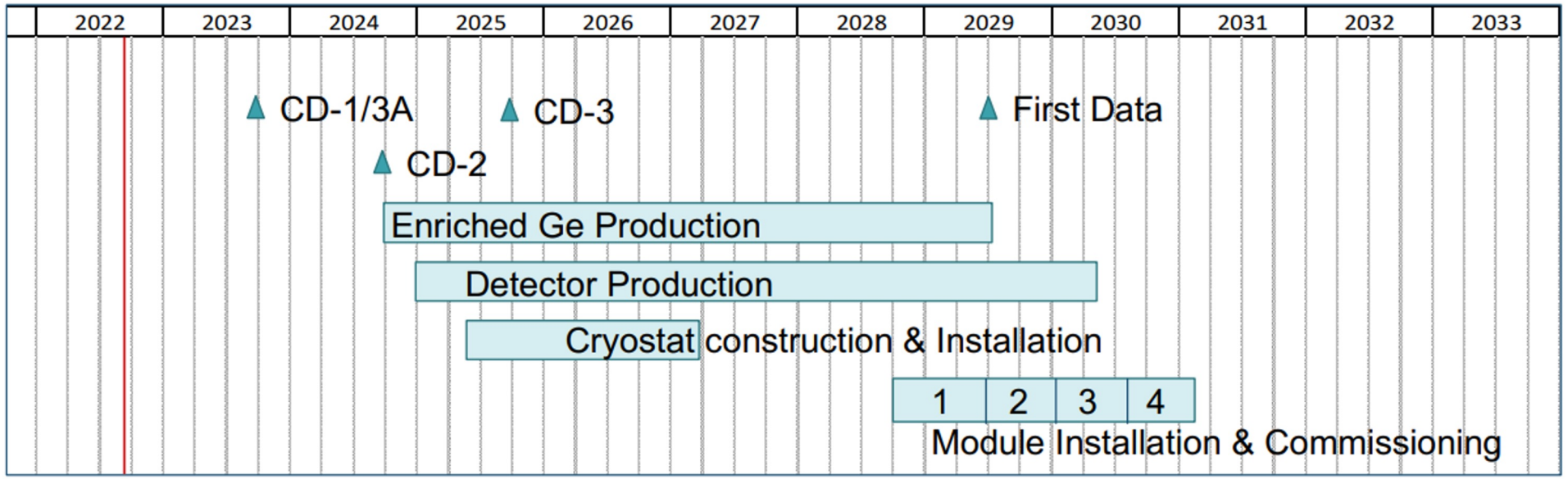
LEGEND-1000 at SNOLAB

The US Portfolio Review

- The U.S. DOE Office of Nuclear Physics has adopted as part of its mission the building of a ton-scale neutrinoless double beta decay experiment.
- Timeline:
  - **April 2016:** LEGEND Collaboration formed
  - **Nov 2018:** Approval of generic ton-scale CD-0 (“Mission Need”)
  - **Dec 2019:** ORNL selected as U.S. Lead Lab for LEGEND
  - **Nov 2020:** DOE-NP announces a “**DBD portfolio review exercise** … to inform U.S. investment strategy”
  - **18 April 2021:** DOE instructions and charge received
  - **1 June 2021:** Proposal submitted to DOE-NP
  - **13-16 July 2021:** DOE-NP Portfolio Review of three experiments: LEGEND-1000, nEXO, CUPID
- *LEGEND performed exceedingly well, and emerged as the unambiguous leader*
  - DOE-NP has however stated that all three experiments were found to be worthy of support, and they would like to support a “DBD programmatic effort” if sufficient funding can be made available
- LEGEND-1000 is now being supported by DOE-NP to proceed to the next step, “CD-1”

Notional Technically Driven Schedule

Calendar year



Critical Decision	Date
CD-0	**FY19 Q1**
CD-1/3A	FY23 Q4
CD-2	FY24 Q4
CD-3	FY25 Q4
CD-4	FY34 Q2

- Assumes technically driven funding profile
- Key Dates:
  - CD-1: Q4 FY23
  - **Module 1 Commissioning Complete: Q3 FY29 69 months (relative to CD-1)**
  - Early Finish: Module 4 Commissioning Complete: Q2 FY31 89 months
  - Late Finish (36 months of float): Q2 FY34 125 months

The UK in LEGEND

- LEGEND Collaboration formed in 2016 with an initial meeting in Atlanta between the GERDA and MJD collaborations and other interested parties.
- LEGEND was formed with the goal of a 1-tonne experiment with the discovery reach for an effective neutrino mass above 18meV
- The University of Liverpool and UCL were the first UK institutions to join LEGEND
- UK was invited to participate in LEGEND in the basis of internationally recognised expertise in HPGe detector development and neutrino physics

The UK in LEGEND

- Warwick University, Lancaster University and STFC Daresbury Laboratory subsequently joined in the following years to bring experience in simulations, PEN, cryogenics and electronics.

- A **joint** effort of nuclear and particle physics community.

- Funding to develop the collaboration in the UK was a priority. A bid was put together for the STFC PPRP Opportunities call in 2019.

- Emphasis on community building and industrial applications

The UK in LEGEND

- PPRP Opportunities support 2019 - 2022
- Open UK LEGEND meeting March 2022 @ UCL
- PPCG support + successful Experiment bid for M&O from October 2022
- DATUM UKRI Infrastructure bid September 2022
- SOI for LEGEND 1000 construction December 2022

- Ideal project start date in 2024

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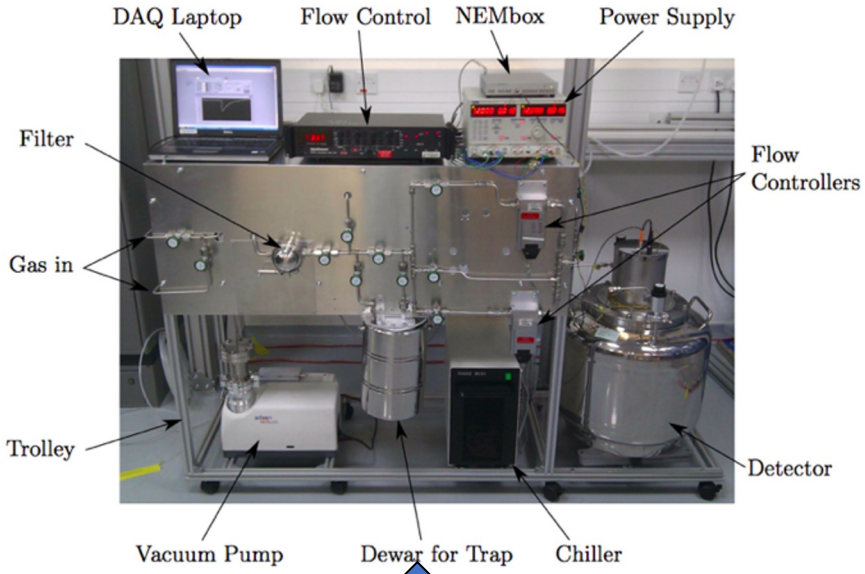
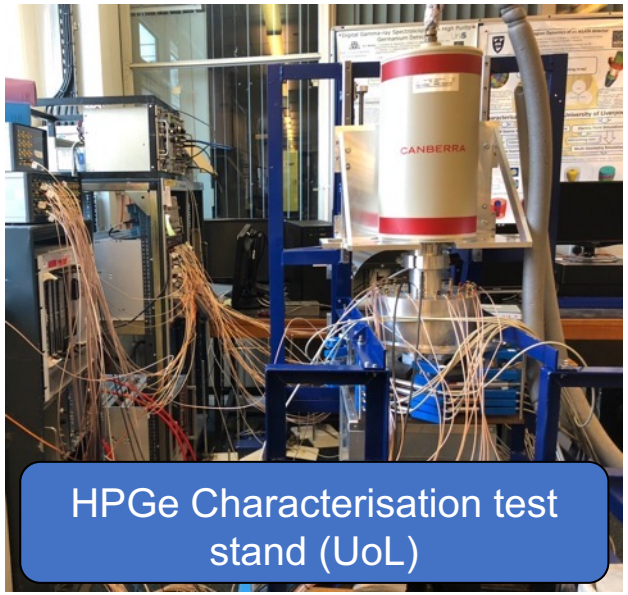
LEGEND the UK contribution

- Funded through an STFC PPRP Opportunities project (Q1 2020 – Q4 2021):
  - WP1 HPGe Characterisation and Technology Development
  - WP2 Simulation Studies for Tonne-Scale 0νββ Experiments
  - WP3 Radio-purity Assay Campaign for LEGEND
  - WP4 Novel Scintillating Material Development for LEGEND
- LEGEND-design HPGe detectors have a broad range of applications (environmental monitoring, ^{210}Pb dating, nuclear decommissioning) Working in collaboration with Mirion Technologies

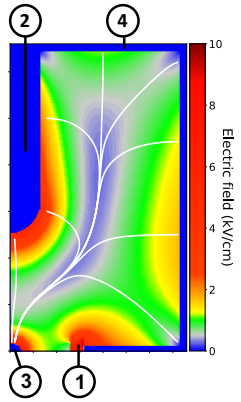


Radon Concentration Line & ICP-MS facility (UCL)



HPGe Characterisation test stand (UoL)

Proposed new detectors for LEGEND:
P-type Inverted-Coaxial Point Contact
Larger mass : > 2 kg/detector



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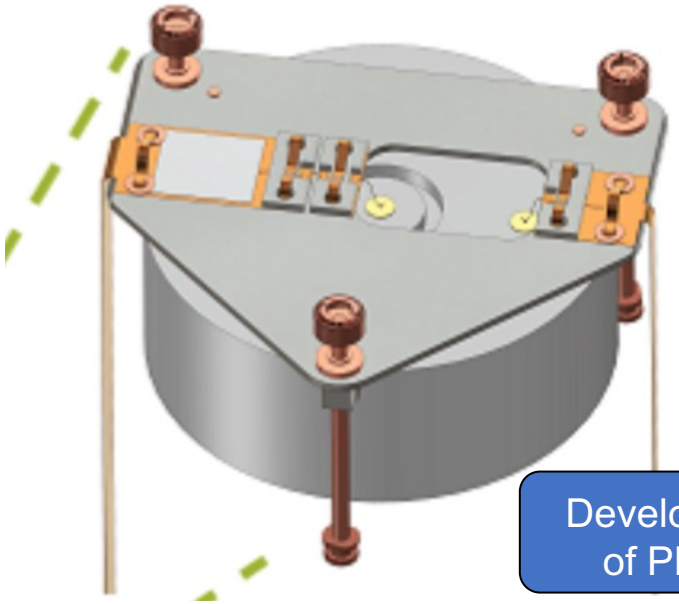
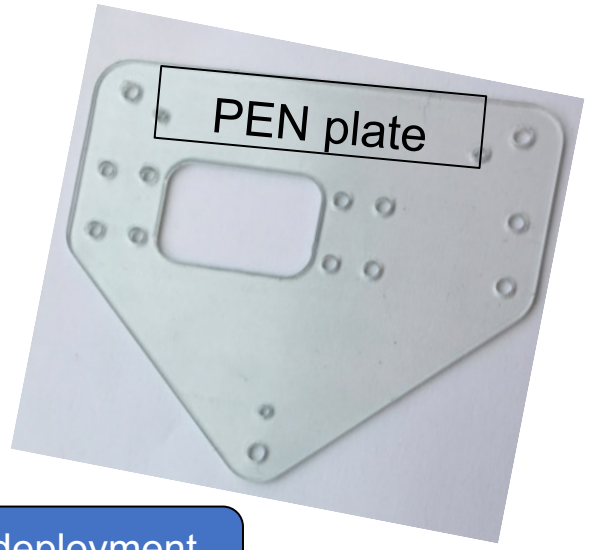
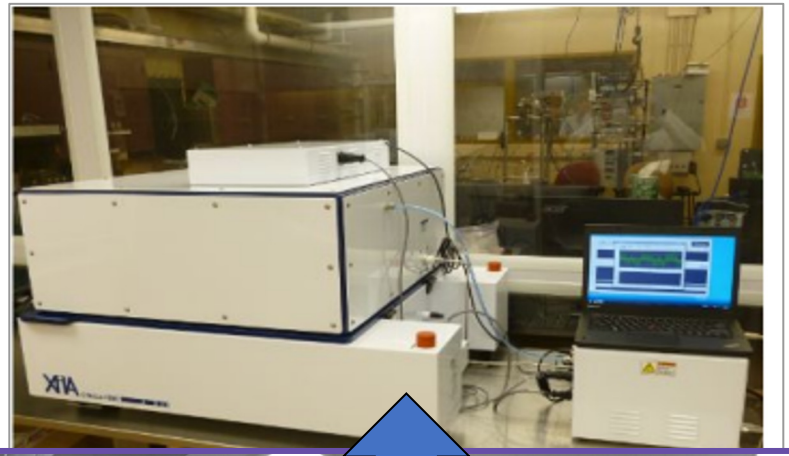
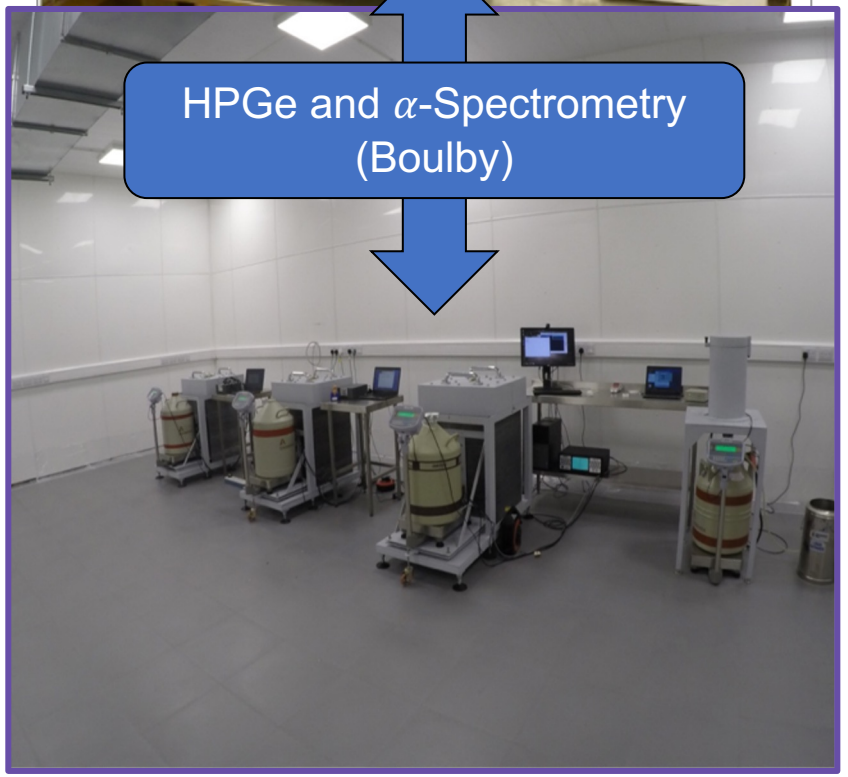




Development and deployment of PEN plates (Lancaster)





HPGe and α-Spectrometry (Boulby)

DATUM UKRI Infrastructure proposal (£3.1M)

- Detector Assembly, Testing and Underground Manufacture:
  - Design and prototype of a custom-built cryostat and a scanning station for automatic HPGe characterisation at Daresbury Laboratory (DL).
  - Development of techniques and procedures for large scale HPGe characterisation.
  - Commissioning of a scanning station at Boulby Underground Laboratory (BUL).
  - Design and prototype of an underground assembly line for semiconductor/cryogenic detector units at BUL.
  - Developing procedures for manufacturing ultra-clean components underground.
  - Technical design and costs of a one-stop infrastructure for detector assembly, characterisation and radio-assaying integrated “under one roof” capable of large-scale detector production at BUL.
- LEGEND 1000 first ”customer”
- AGATA and NP community HPGe detector M&O

SOI for LEGEND 1000 project

- A joint effort of nuclear and particle community along with industrial partners with a 2024 start for:
  - Contributing to enriched Ge and detector production
  - HPGe Detector Development & Characterisation
  - Material Screening & Assays – Boulby Underground Laboratory
  - Active Veto Liquid Argon Detectors
  - Software & Analysis including theory support
  - Design, test and build large hardware items
- Industrial requirements for improved gamma-ray detector performance
- The UK has the opportunity to play a leading role in a global next generation experiment.
- Ambition for an equal UK, Italian and German contribution.

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