

The LEGEND Experiment

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Andy Boston, Andy Mehta, Laura Harkness-Brennan, Dan Judson, Chris Everett

 LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ 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

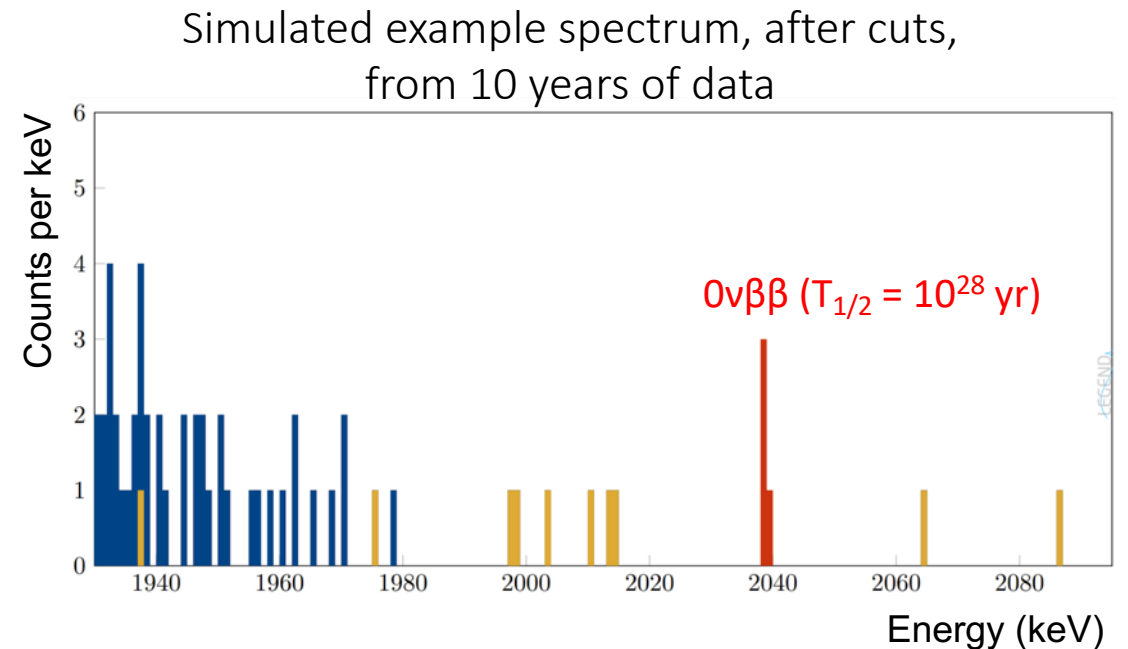
Introduction to LEGEND

- The LEGEND collaboration proposes a $0\nu\beta\beta$ 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 data taking 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

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...”

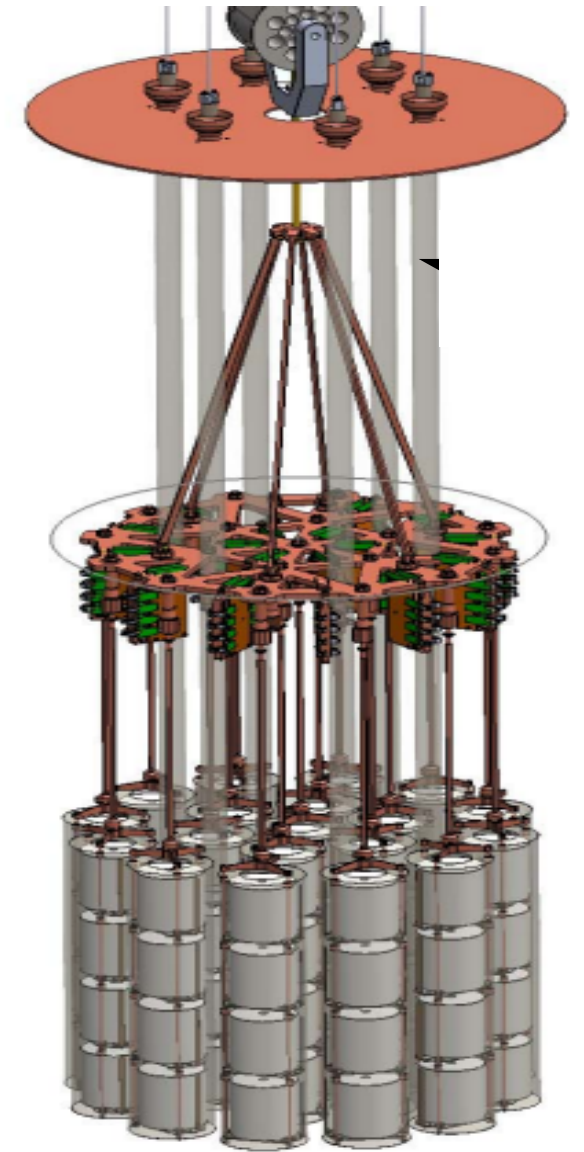
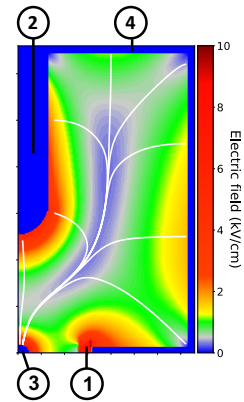
- What is required for a discovery of $0\nu\beta\beta$ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
 - Need 10 ton-years of data to get a few counts
 - Need a good signal-to-background ratio to get statistical significance
 - A very low **background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

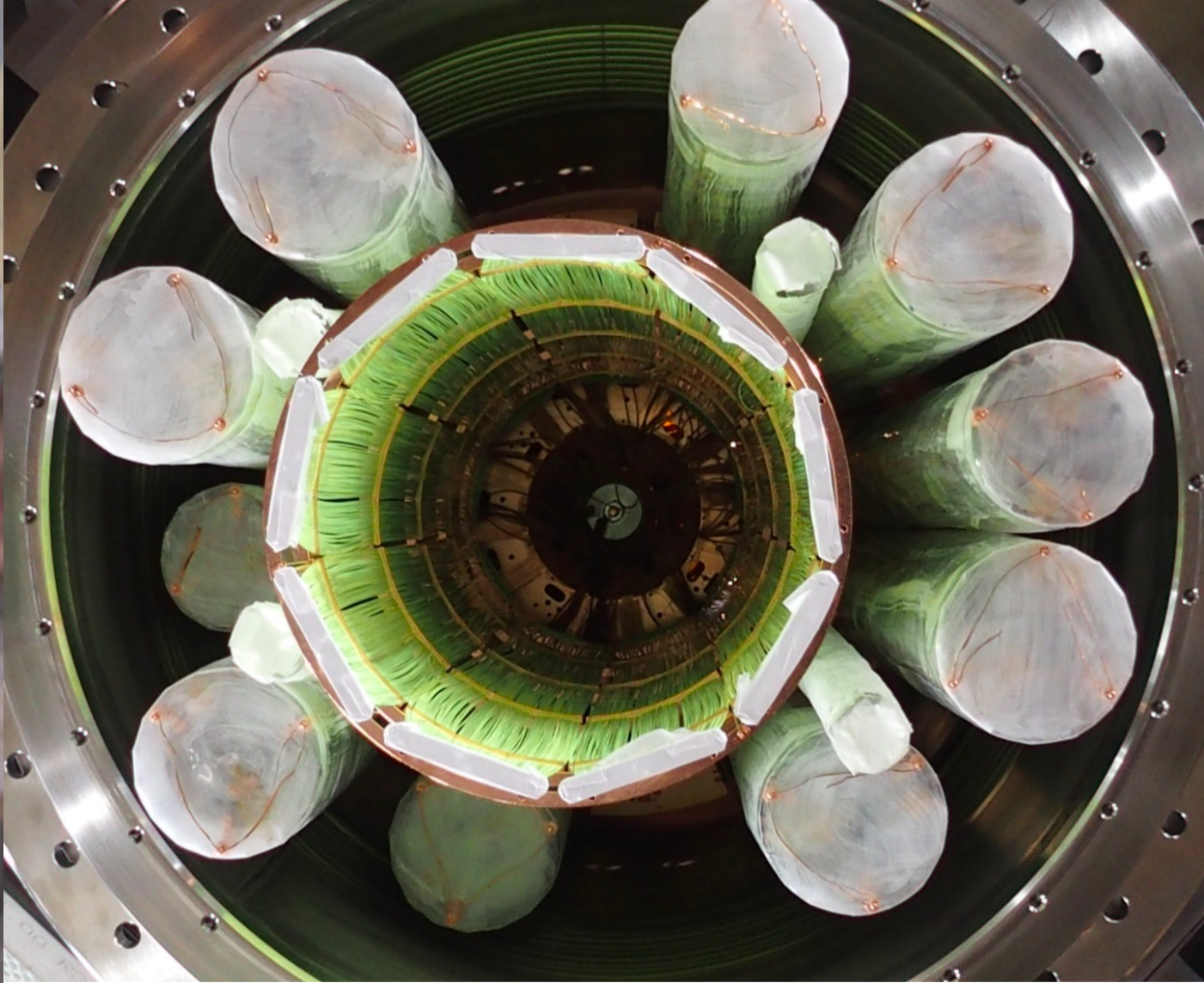
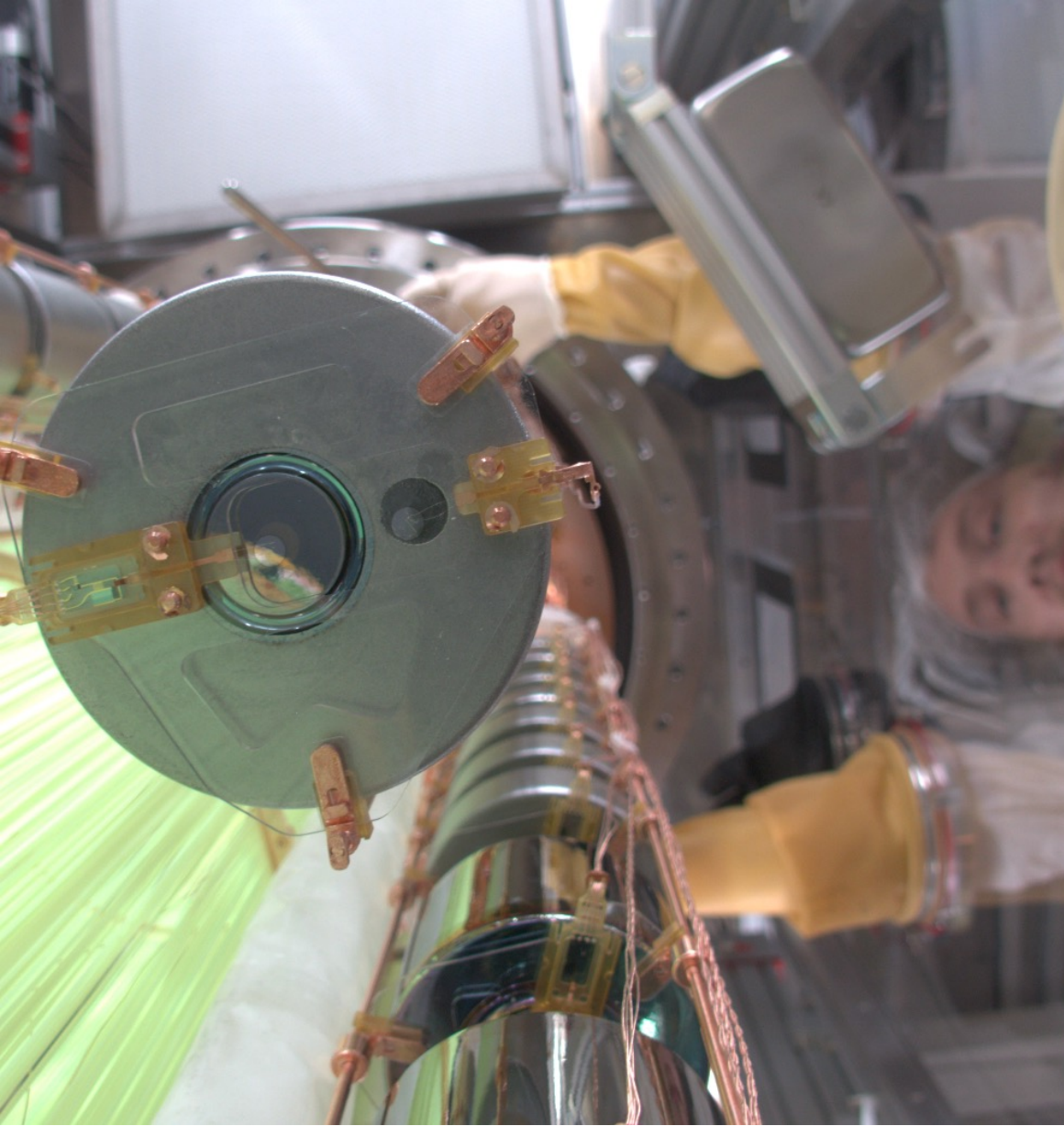


LEGEND 200 Overview

- 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
- Physics data taking in progress
- STFC Experiment support for M&O

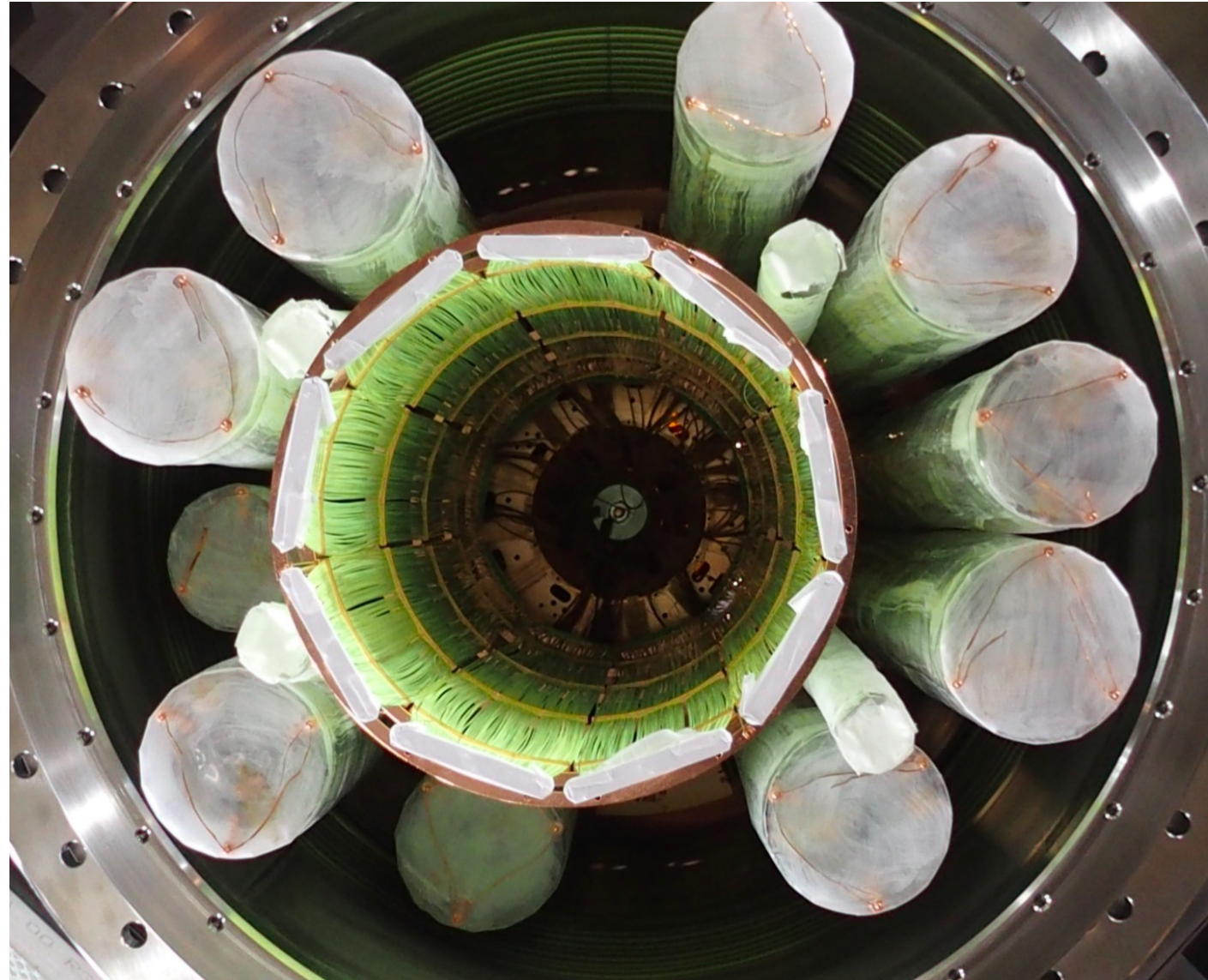
New detectors for LEGEND:
P-type Inverted-Coaxial Point Contact
Larger mass : > 2 kg/detector





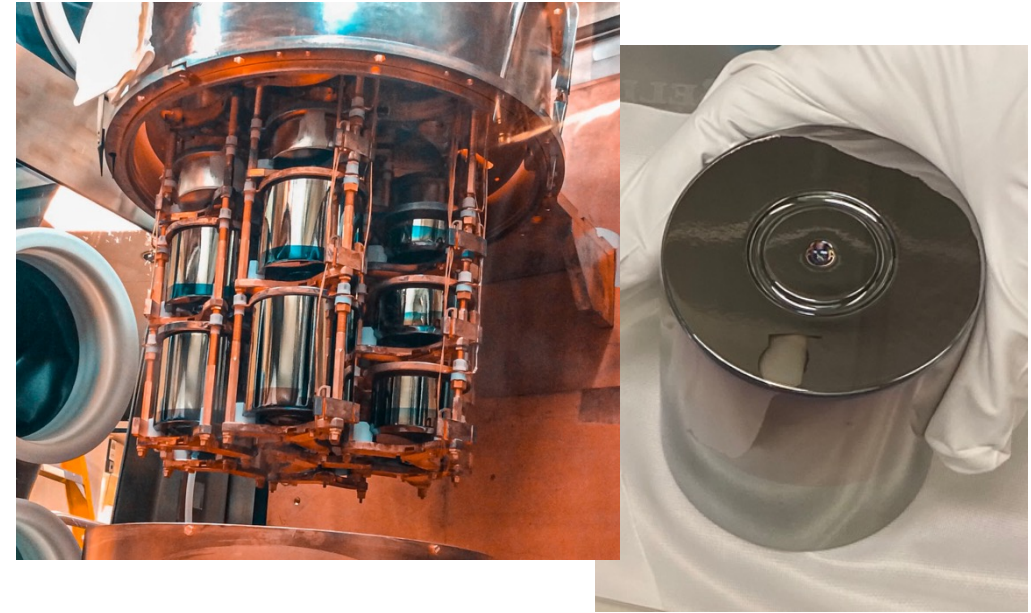
LEGEND 200 Status

- 101 Ge detectors mounted in 10 strings
 - 22 detector with reduced HV
 - PPC, BEGe, GERDA ICPC,
 - ORTEC ICPC, Mirion ICPC
- 140kg Ge installed
- 50kg to be installed
- LAr instrumentation:
 - 18 inner fiber SiPM channels ok,
 - 31 of 40 outer SiPM working



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

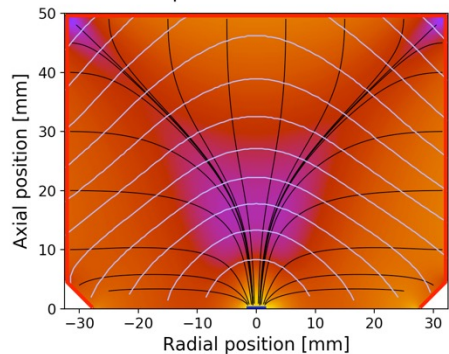


LEGEND (ICPC)

Speed [$\text{cm}/\mu\text{s}$]
with paths and isochrones

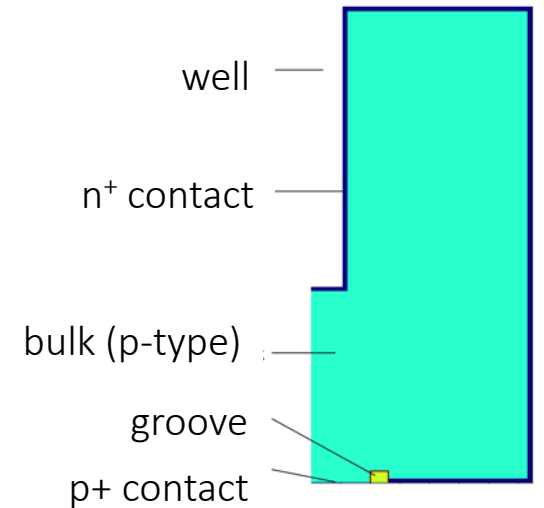
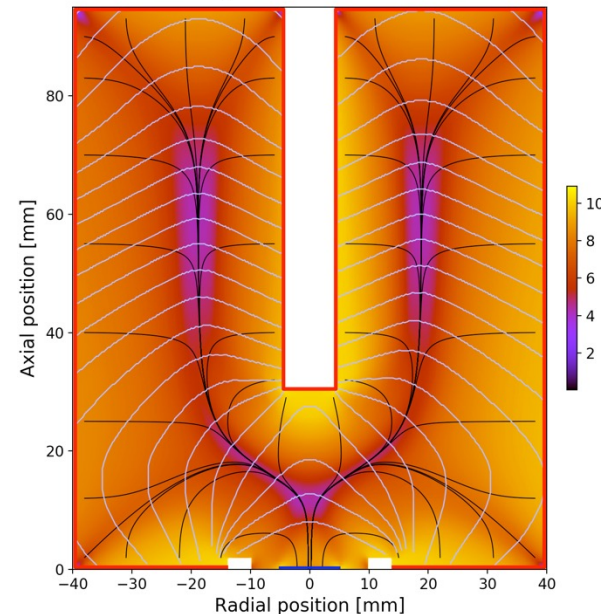
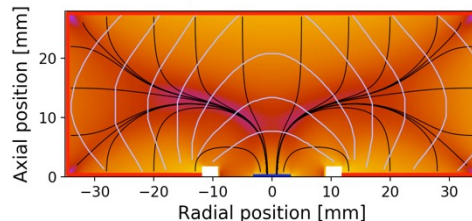
MAJORANA (PPC)

Speed [$\text{cm}/\mu\text{s}$]
with paths and isochrones



GERDA (BEGe)

Speed [$\text{cm}/\mu\text{s}$]
with paths and isochrones

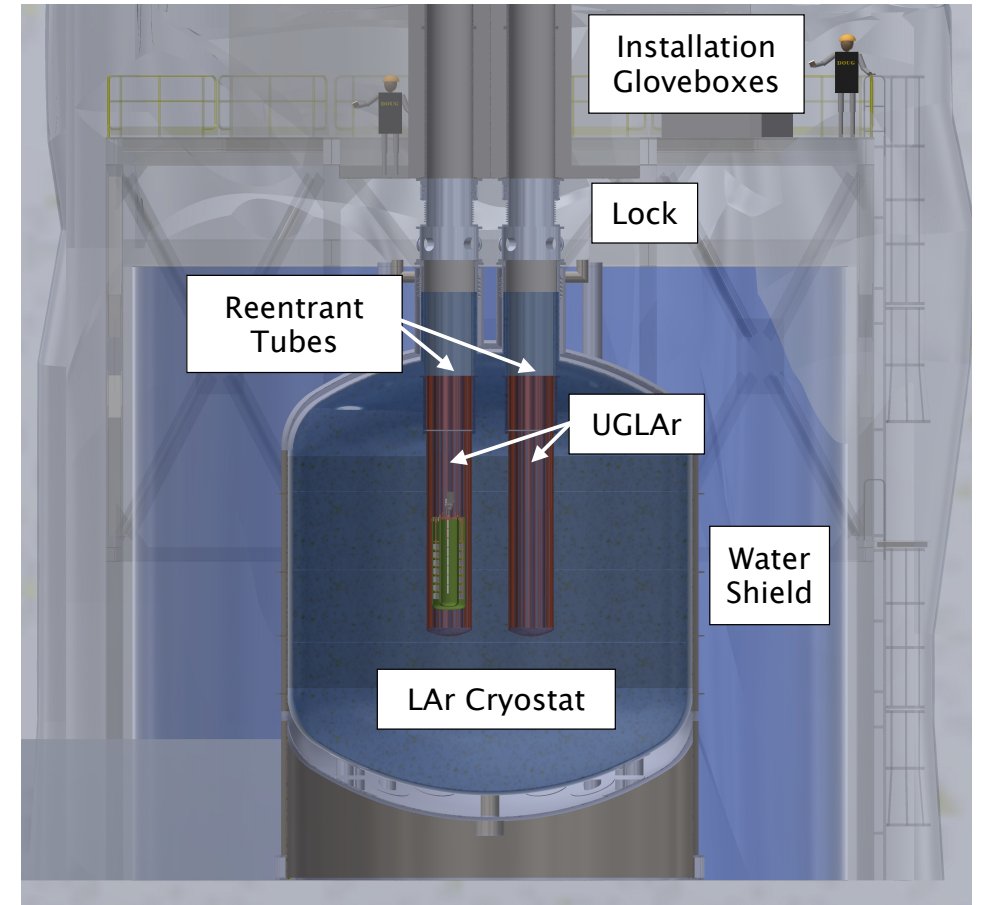
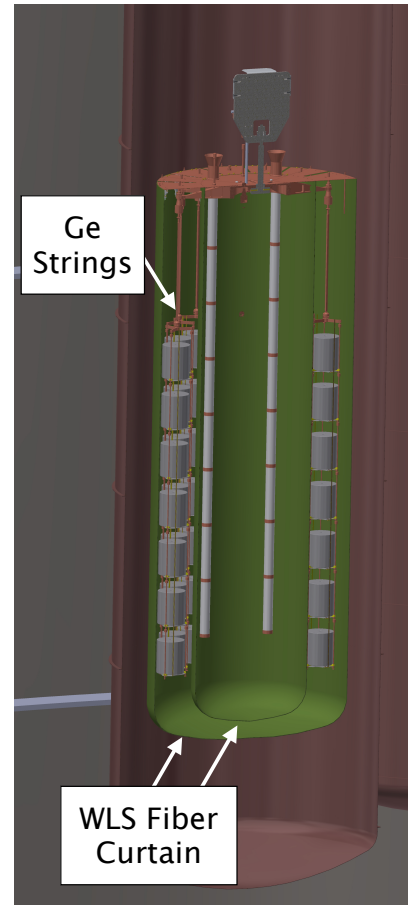
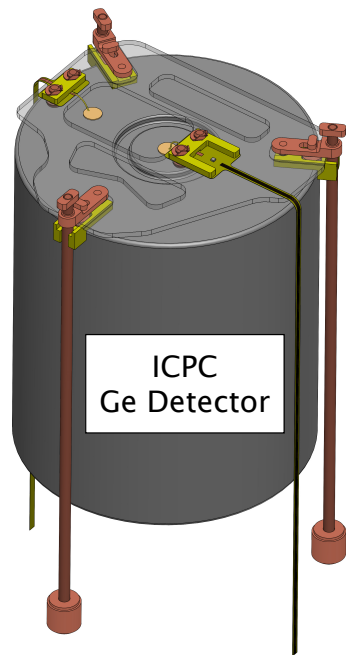


The LEGEND-1000 Experiment: Overview

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

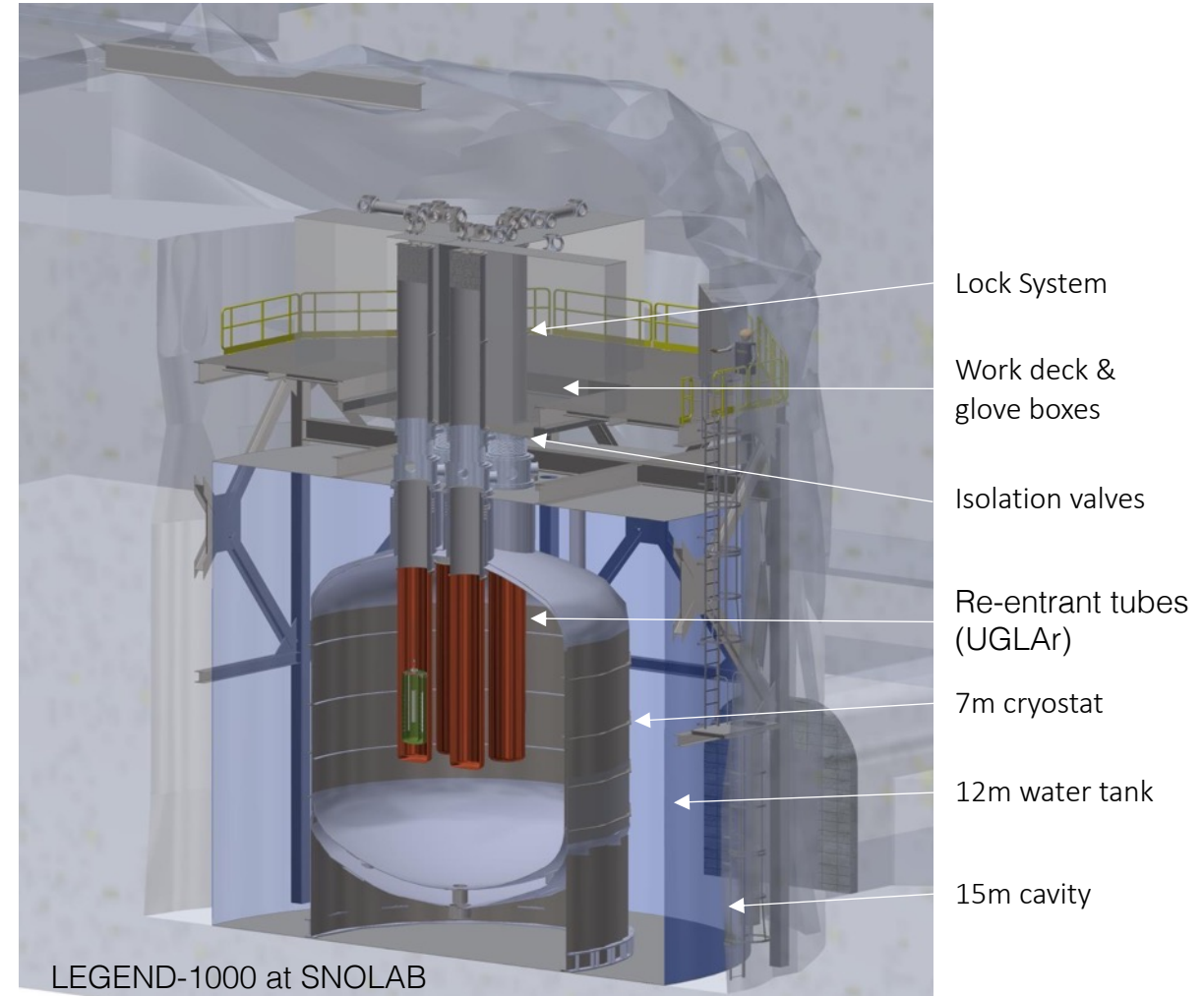
- 2.6 kg average mass
- Mounted in “strings” using components made from electro-formed Cu and scintillating plastic, PEN
- Arranged in 4 modules
- ~100 detectors per module

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

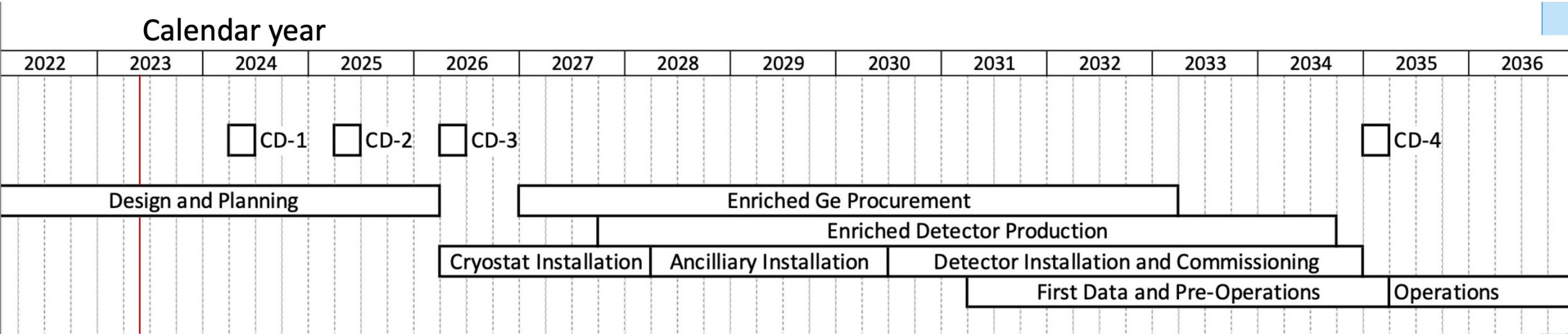


LEGEND-1000 Baseline Design: Underground Site

- 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



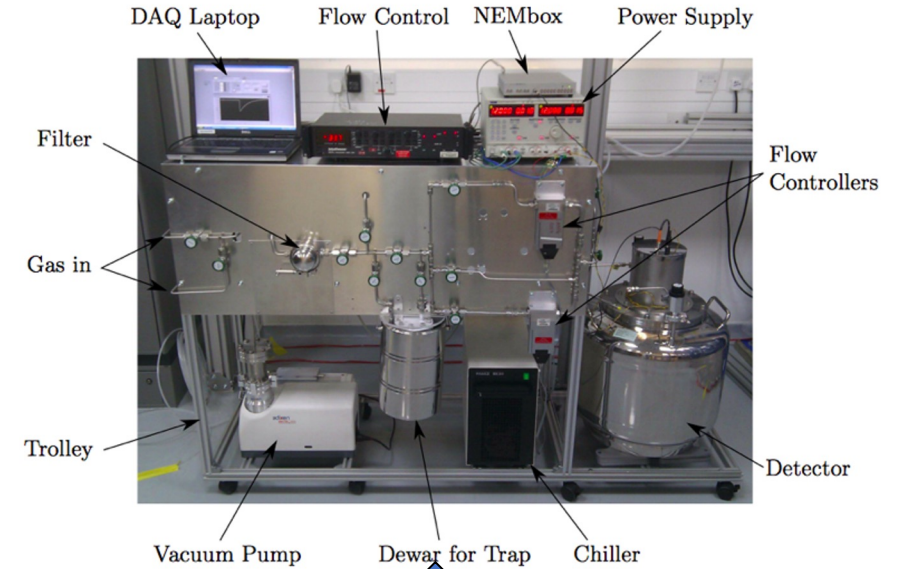
Technically Driven Schedule: LEGEND 1000



- Assumes technically driven funding profile
- Key Dates:
 - CD-1 final approval Q2 2024
 - First 250 kg Commissioning Complete (start of physics data) Q2 2031 – Q3 2032
 - Early Finish: Commissioning Complete: Q1 2035
 - Late Finish (36 months of float): Q1 2038

LEGEND the UK contribution

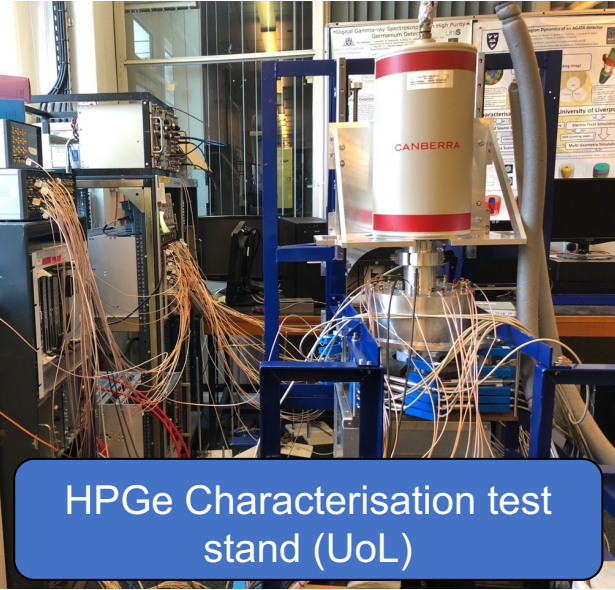
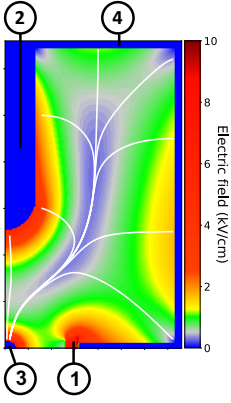
- Funded through an STFC PPRP Opportunities project (Q1 2020 – Q4 2021):
 - WP1 HPGe Characterisation and Technology Development
 - WP2 Simulation Studies for Tonne-Scale $0\nu\beta\beta$ Experiments
 - WP3 Radio-purity Assay Campaign for LEGEND
 - WP4 Novel Scintillating Material Development for LEGEND
- 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)



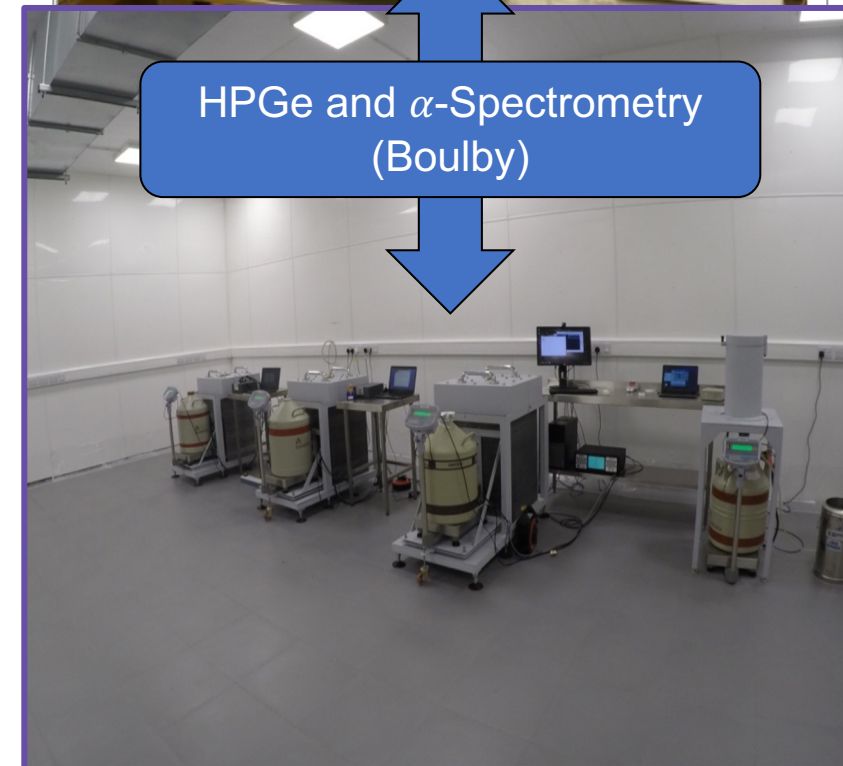
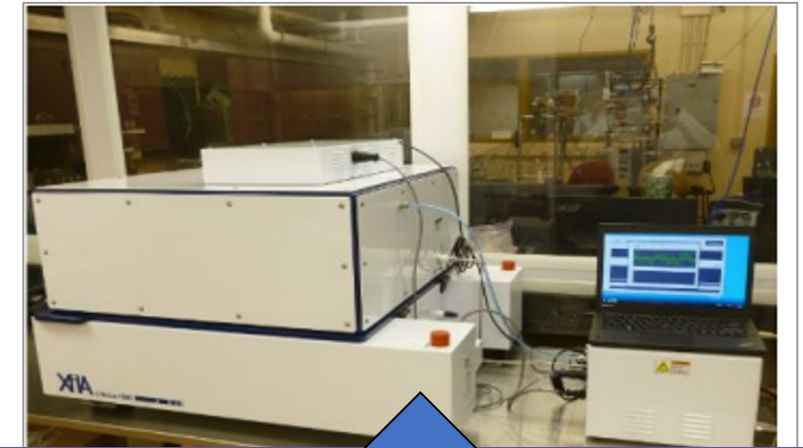
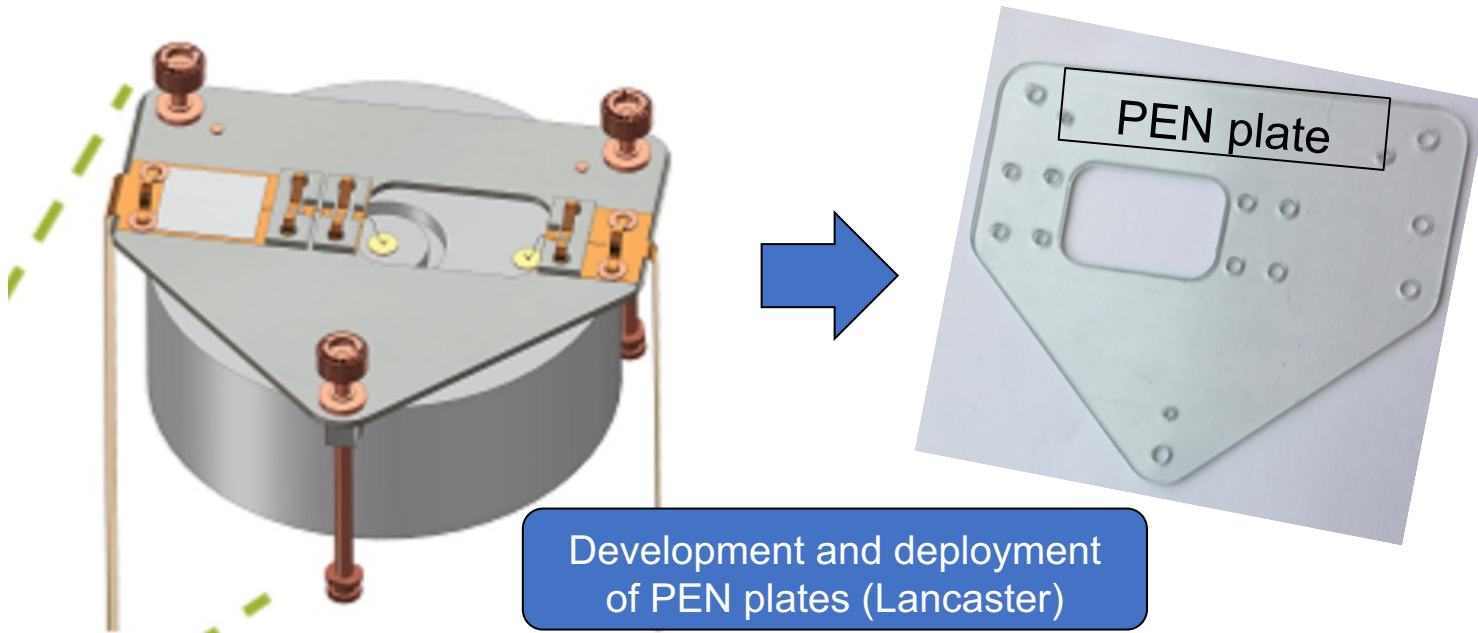
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Larger mass : > 2 kg/detector



HPGe Characterisation test stand (UoL)

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LEGEND UK Leadership and Liverpool contribution

- LEGEND Collaboration formed in 2016
 - A. Boston - detector coordinator 2017-2018, UK PI
 - D. Waters/R. Saakyan - IB chair
 - M. Agostini - analysis coordinator (current)
 - D. Muenstermann - PEN-Veto coordinator (current)
- Liverpool
 - Germanium detector characterisation
 - Detector calibration/data quality enhancement
 - Data taking in LEGEND-200
 - Detector procurement and characterisation for LEGEND-1000

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 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.

LEGEND UK future plans

- STFC Daresbury Laboratory Design/build of Liquid Argon infrastructure & Possible leadership of DAQ (STFC funding and future project)
- UCL – Data analysis lead (CG) and bid for screening WP (future project)
- For the future project Liverpool will:
 - Design and deliver multiple detector characterisation stands for installation at Boubly
 - Characterise inverted coaxial germanium detectors
 - Optimise the analysis algorithms and analyse the characterisation data

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