



Abstract

The Comprehensive Nuclear Test-Ban Treaty (CTBT) International Monitoring System (IMS) provides a network of 120 Radionuclide detection systems, strategically positioned around the globe with the aim of detecting radionuclide emissions from nuclear explosions. The UK CTBT laboratory (GBL15, based at the Atomic Weapons Establishment, UK) routinely monitors this network for the UK government, assessing events, reviewing data, and re-measuring IMS samples from around the world. The laboratory also undertakes substantial research, with the aim of increasing the overall sensitivity of the monitoring regime.

The Current State of the Art

Detection limits are generally defined by three aspects of a system, the detector efficiency, the level of background (noise), and the choice of signal to be measured. A number of approaches have been used to improve detection limits, including:

- Graduated shielding, including low-background lead
- Detectors built using low-background material
- Cosmic Veto systems to actively reduce the background
- Nitrogen purge systems to reduce Radon concentrations

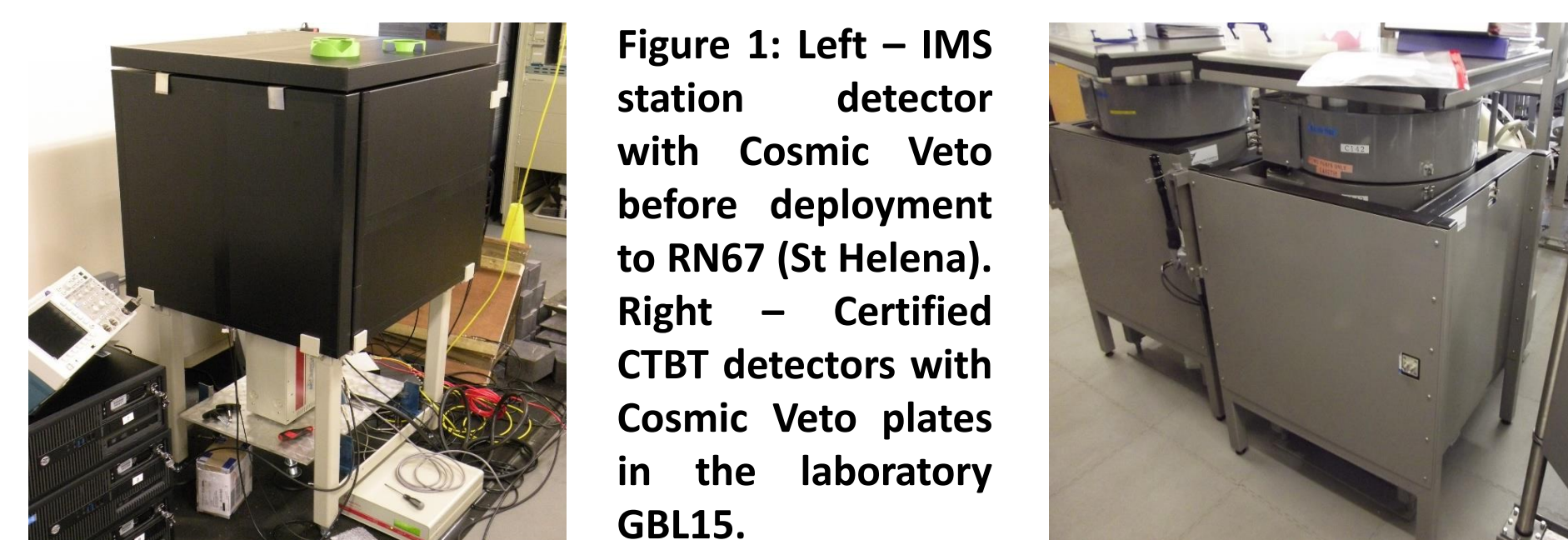


Figure 1: Left – IMS station detector with Cosmic Veto before deployment to RN67 (St Helena). Right – Certified CTBT detectors with Cosmic Veto plates in the laboratory GBL15.

Ultimately, there is a limit what can be detected. Certified laboratory systems typically achieve the level of 5-30 $\mu\text{Bq.m}^{-3}$ of ^{140}Ba with a 7 day measurement.

To push past these limits, a number of laboratories have been working on advanced coincidence systems, something that GBL15 pioneered. GBL15 have a number of operational coincidence systems, including two fully shielded BEGe 6530 detectors that can achieve ultra-close geometries, a field deployable system based on two IDM-200 ruggedised detectors, and a remote system currently deployed within Boulby Underground Laboratory.

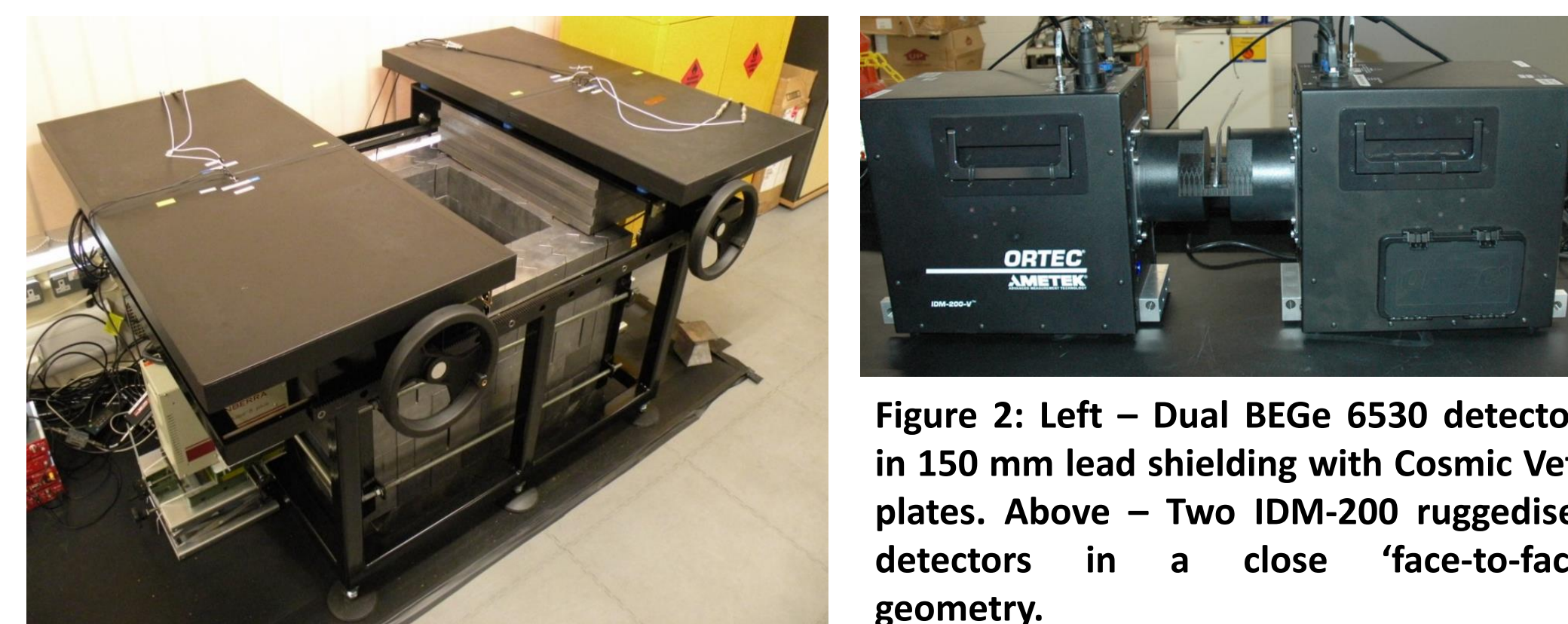


Figure 2: Left – Dual BEGe 6530 detectors in 150 mm lead shielding with Cosmic Veto plates. Above – Two IDM-200 ruggedised detectors in a close 'face-to-face' geometry.

Validating Advanced Systems

Advanced dual detector systems have not yet been widely adopted due to the challenges in operationally quantifying the signals they capture. This requires a detailed knowledge and understanding of Nuclear Structure data, and efficient software to generate an appropriate library for your system.

Monte-Carlo techniques have been used to calculate the required factors on an ad-hoc basis, but require a new simulation for every new sample geometry. To solve this issue, GBL15 developed RIMMER¹⁻⁴, which calculates all factors automatically from peak and total efficiencies (the same input data required for traditional measurements). This has been validated using a number of Proficiency Test Exercises (PTEs) and in peer reviewed publications¹⁻⁴.

Current Performance

Advanced dual detector systems can greatly improve the sensitivity possible, often by over an order of magnitude. This is due to the massive reduction in background signal (by factors of up to 10^6).

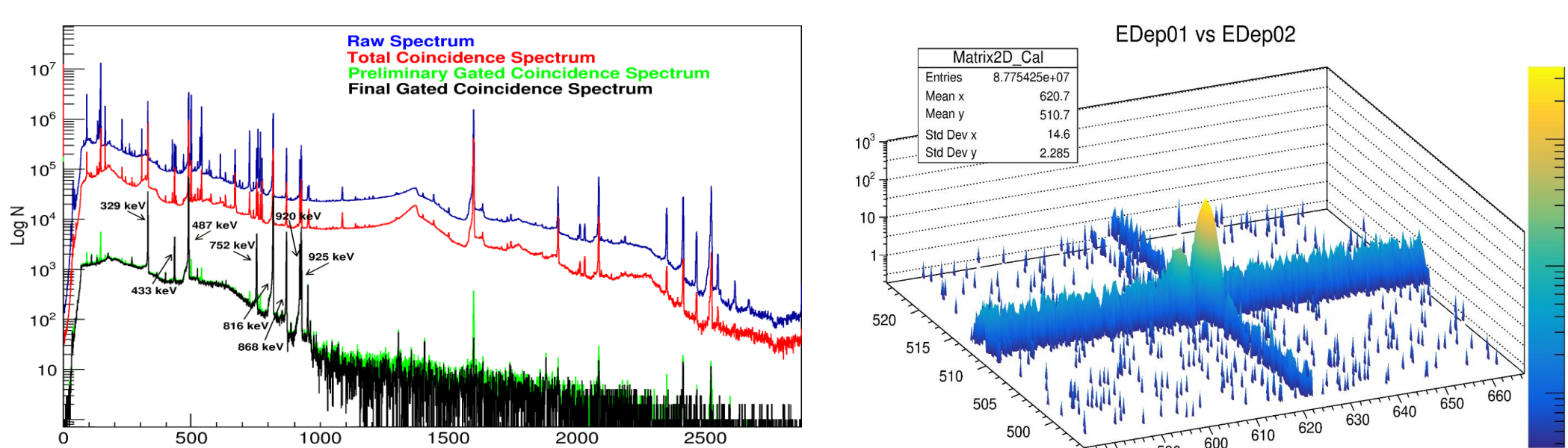


Figure 3: Left – Traditional spectrometry (raw spectrum) and a 1596.2 keV gated extraction using the full coincidence capability of the system. The background (anything that isn't ^{140}La) is reduced by a factor of 10^6 , and an extremely clean ^{140}La signature is extracted. Right – Coincidence signatures from ^{106}Ru , with almost zero background despite a 30 day acquisition.

The ability to almost completely separate the signal from any background is due to the uniqueness of the γ cascade. The γ emissions are correlated in time, and with fast electronics timestamping all events, these coincidences can be extracted during post-processing of the data.

Nuclide	Singles MDC (Bq.m^{-3})	Gate Energy (keV)	Projection Energy (keV)	RIMMER Factor	Background (projected)	Coincidence MDC (Bq.m^{-3})	Ratio to Singles
^{134}Cs	3.38E-07	605	796	2.02E-03	2	4.85E-08	0.143
^{133}Ba	4.41E-07	30.6	356	7.10E-01	54	8.48E-10	0.002
^{108m}Ag	4.76E-07	24.0	434	2.37E-04	61	2.69E-06	5.646
^{60}Co	5.14E-07	1173	1332	8.73E-04	1	5.61E-08	0.109
^{110m}Ag	4.33E-07	658	885	1.04E-03	3	1.10E-07	0.254
^{152}Eu	8.23E-07	40.1	245	2.08E-02	40	2.52E-08	0.031
^{125}Sb	1.99E-06	27.2	408	9.01E-03	34	5.40E-08	0.027
^{46}Sc	4.71E-07	889	1120	1.31E-03	1	3.74E-08	0.079
^{102}Rh	1.08E-06	21.8	475	1.64E-04	30	2.80E-06	2.597
^{59}Fe	9.00E-07	192	1100	1.81E-04	9	1.44E-06	1.603
^{140}La	1.15E-06	329	487	1.08E-03	11	2.72E-07	0.237
^{136}Cs	1.30E-06	31.8	1240	1.82E-03	7	1.17E-07	0.090
^{126}Sb	1.01E-06	415	666	1.81E-03	5	9.02E-08	0.089

Table 1: A selection of detection limits for both traditional and coincidence processing of the same dataset. The ratio of the MDC in coincidence to that in singles is also shown. Not all nuclides benefit from coincidence processing, however the detection limits for several (^{46}Sc , ^{60}Co , ^{125}Sb , ^{126}Sb , ^{133}Ba , ^{134}Cs , ^{136}Cs , ^{152}Eu) are improved by an order of magnitude.

The detection limits achieved in Table 1 refer to the measurement of an air filter collected during a series of ^{106}Ru detections across Europe, and was measured for 30 days. Note that some of the detection limits approach nBq.m^{-3} , a factor of 1000 lower than the CTBT laboratory requirement for ^{140}Ba .

Minimising Background

Advanced systems require advanced shielding. In a surface laboratory, little can be done to protect the system from the high flux of Cosmic muons and charged particles streaming through the atmosphere. Fortunately the UK has an established world-class facility with the Boulby Underground Laboratory, an 1100 m deep clean room facility.



Figure 4: The STFC funded Boulby Underground Laboratory is a clean room facility 1100 m underground within a working mine in the north of England. A wide range of science is undertaken here, from NASA equipment testing to Dark Matter research.

A collaborative effort between the Boulby Underground Laboratory and GBL15 has established a prototype coincidence system, and the first tranche of funding is secured to develop a permanent system. This will create a unique measurement capability for the UK, with the first fully operational, large volume, high-resolution multi-detector spectrometer to be fielded in such a low-background regime.

Reducing Noise

Once the background is reduced, the majority of noise in the system originates in the sample itself. Compton scattering of γ emissions creates a noise continuum, which can be suppressed by capturing the scattered radiation. An on-going collaboration with PNNL is developing the technology to effectively suppress Compton scattered events for both traditional and coincidence measurements, with prototypes at AWE and a fully engineered solution at PNNL (the Advanced Radionuclide Gamma-spectrometer - ARGO) utilising up to 12 NaI(Tl) based guard detectors (see talk T3.2-02 by Davies et al).

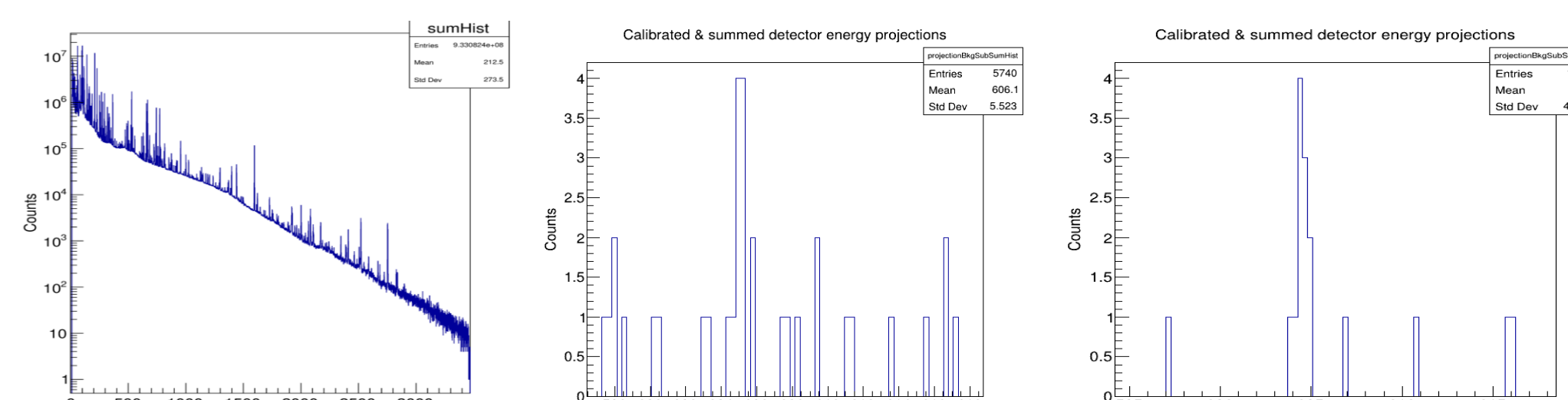


Figure 5: Left - signal vs noise for traditional γ spectrometry (with gain-matched summed signals from each detector). Centre – signal vs noise for energy gated gain-matched and summed coincidence projections. Right – Compton suppressed energy gated gain-matched and summed coincidence projections.

Maximising Efficiency & Selectivity

Current designs use the most advanced COTS detectors available. Work is ongoing to create bespoke detector designs that maximise the efficiency, energy resolution and timing resolution of the signal. The timing window alone can offer up to an order of magnitude improvement over the current selectivity of the coincidence window. Work is also being undertaken to explore how additional detectors could be incorporated to improve the efficiency further. Calculations suggest that efficiency could be improved by up to 50% in the current design. Further improvements would require moving to a 26+ detector array.

Maximising Signal

Through the use of RIMMER, GBL15 have been able to automate selection, analysis and quantification of both traditional and coincidence signals. Particularly in the coincidence plane, however, there are opportunities to improve the signal extracted due to the unique, (near)zero-background regime in which these systems operate.

GBL15 have developed a software package, MUGS (MUlti-Gamma Surveyor), that automatically combines signals if it favourably improves the signal-to-noise ratio. This Multi-Signal (MS) approach has improved potential signal strength by up to a factor of three for nuclides such as ^{136}Cs and ^{140}La , and reduced the MDC of ^{60}Co in singles mode by ~30% (which could greatly help the reduction of false-positives during IDC and NDC processing of IMS data).

Nuclide	MDC (nBq.m^{-3})						Best Technique	Improvement Factor
	Single	MS	Dual	MS	Coinc.	MS		
^{108m}Ag	329	272	233	192	7.6	4.8	Coinc. MS	69
^{110m}Ag	412	360	291	254	19.9	8.47	Coinc. MS	49
^{133}Ba	3960	2870	2800	2030	501	494	Coinc. MS	8
^{140}Ba	1010	846	713	598	195	-	Coinc.	5.2
^{144}Ce	639	-	452	-	21100	12800	Dual det.	1.4
^{60}Co	489	359	345	253	24.8	-	Coinc.	20
^{134}Cs	358	278	253	197	9.97	8.01	Coinc. MS	45
^{136}Cs	487	381	344	269	14.3	5.22	Coinc. MS	93
^{152}Eu	2980	-	2100	-	330	270	Coinc. MS	11
^{156}Eu	1040	-	738	-	235	65.1	Coinc. MS	16
^{59}Fe	726	597	513	422	105	99.6	Coinc. MS	7.3
^{140}La	605	446	427	315	35.6	17	Coinc. MS	36
^{102}Rh	558	-	394	-	116	96.3	Coinc. MS	5.8
^{125}Sb	708	674	500	476	1620	1100	Dual det. MS	1.5
^{126}Sb	434	329	307	233	19.3	11.5	Coinc. MS	38
^{46}Sc	390	306	275	216	15.7	-	Coinc. MS	25

Table 2: Current limits of detection utilising MUGS and RIMMER for a measurement within GBL15 (figure 2, left). It takes under 10 minutes for an analyst to fully process raw list-mode data, generate quantification factors using RIMMER, evaluate detection opportunities / limits using MUGS, and quantify what is in the sample. Note that the detection limit for ^{140}Ba is 195 nBq.m^{-3} , a factor of 25 lower than the best IMS laboratories.

Whole Signal Spectrometry

By developing and utilising automated analysis packages such as RIMMER and MUGS, GBL15 can now focus on the optimisation of the hardware components to capture as much signal as possible in these unique (near)zero background systems. With the efficient processing of high-multiplicity coincidence data at GBL15 now routine, we are also well positioned to incorporate additional detection technologies such as β - γ systems (see poster T3.2-P2 by Matthew Goodwin).

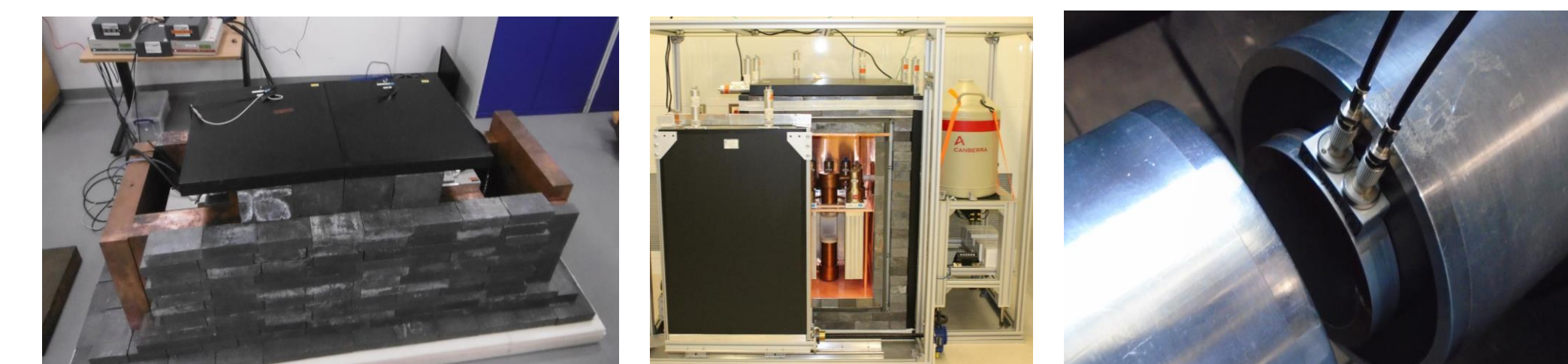


Figure 5: Left – prototype system at Boulby Underground Laboratory. Centre – ARGO in the shallow underground laboratory at PNNL. Right – testing of a PIPSBOX™ sandwiched between two BEGe 6530 detectors.

Applications

Recent Nuclear Weapons tests are typically carried out underground to minimize the release of material to the atmosphere. These advanced systems can greatly increase the sensitivity of the IMS to any signatures that may escape, such as ^{140}Ba and ^{140}La that are produced from the decay of ^{140}Xe .

Re-measurement of IMS samples during special studies could also lower MDCs, and increase the number of detections (and locations) available for source location via Atmospheric Transport Modelling.

Measurement of complex samples using these systems have also proved beneficial, with detection limits greatly improved for in-field systems and when measuring fresh fission products in exercises.

Summary and Future work

GBL15 has developed a number of operational coincidence systems, pushing detection limits into the nBq.m^{-3} range.

Automated data processing, including coincidence quantification, detection limit evaluation and the combination of signals to maximise the detection probability has been developed and validated, allowing analysts to routinely use these advanced systems.

The ultimate limits of γ spectrometry have also been evaluated using MUGS, and a roadmap developed to get closer to these. This includes development of a number of multi-detector prototypes in collaboration with several institutes and National Laboratories, and a permanent facility within a unique deep underground environment.

Acknowledgements

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References

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