NUSTRAP
Nuclear Structure, Reactions & Applications

RAMONES

Geant4 simulations of two types of CdZnTe-based γ-ray spectrometers for the monitoring of the radioactivity in the marine environment

Varvara Lagaki
Post-Doctoral Associate
Department of Physics, University of Athens, Greece

Receives funding from European Union under Horizon 2020 FET Proactive Programme via grant agreement No. 101017808

Outline

- Motivation
- GR1 spectrometer
- μSPEC4000 spectrometer
- Simulations
- Conclusions

Radioactivity in the marine environment

- Radioactivity exists in the marine environment (natural or artificial origin)
- Significantly **under-sampled**, **unmeasured**, and **understudied**
- Radioactivity monitoring in the marine environment with current instrumentation is **relatively limited on both short and long-term periods**
- The massive ocean volume acts as **a protective shield** to the human population from radioactivity sources deep inside the water but this is not the case for ocean ecosystem

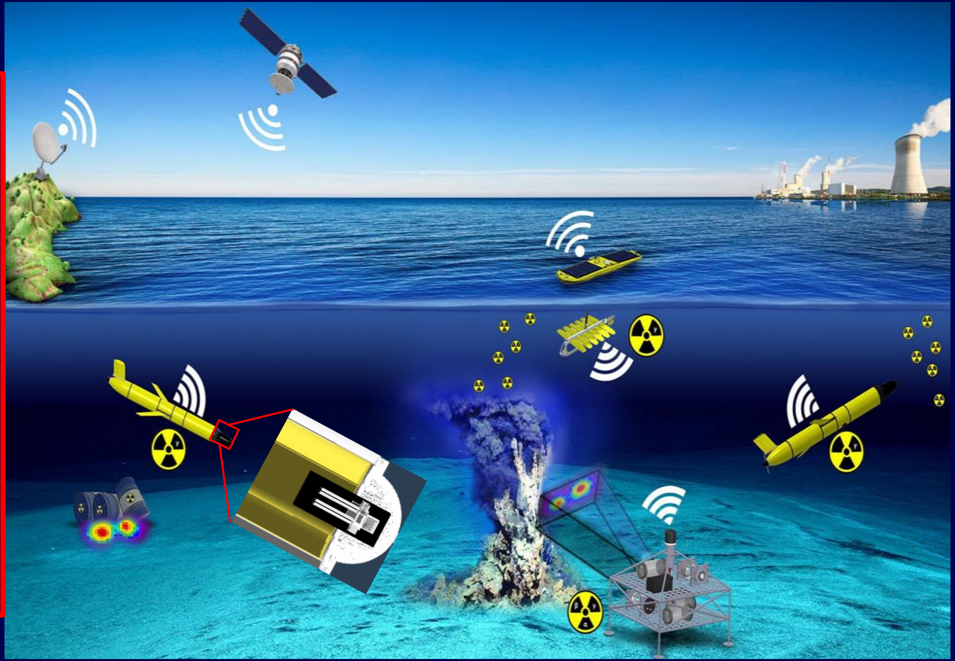
↓

Need for innovative solutions for better marine radioactivity monitoring

RAMONES: RAdioactivity Monitoring in OceaN EcosystemS

Basic idea: Offer a **new generation of radiation sensing instruments** for *in situ*, continuous and long-term monitoring of natural and artificial radioactivity in harsh underwater environments

- γ-Sniffers
  - Gamma spectrometers (CdZnTe crystal) inside AUG
  - Perform surveys of extended areas and volumes of the ocean waters in order to detect hot spots of radioactivity



- Stationary Benthic Lab:
  - Gamma Spectrometer
  - Gamma Imager
  - Alpha Spectrometer
  - Cherenkov Imager

GR1 spectrometer

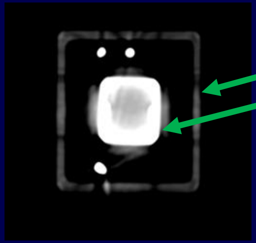
1 cm^3 CZT crystal (Kromek/Canberra)

Nominal crystal's dimensions: 10 x 10 x 10 mm

Evaluation of the detector's geometry and response through different scenarios

Internal structure determination

CT scan images:

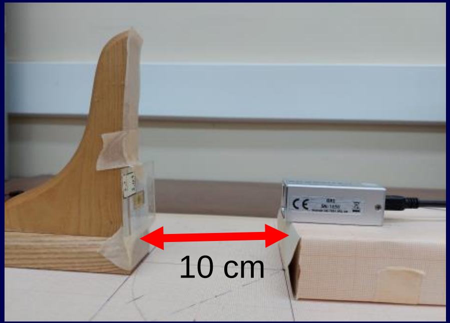


CT scan images
Specification sheet

→

1. Detector's geometry
2. Crystal dimensions: 10 x 10 x 9 mm

Nominal value: 10 x 10 x 10 mm

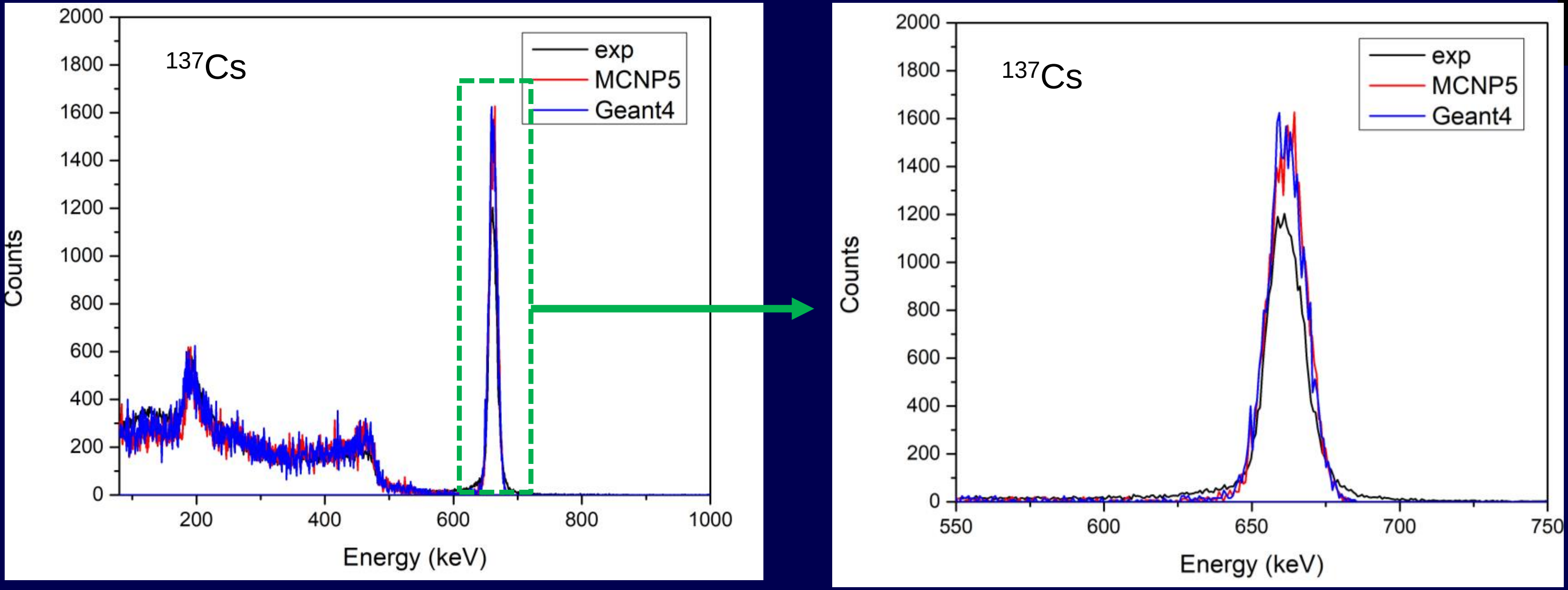


Experimental measurement at 10 cm distance with a point-like standard calibrated source

Simulations with Geant4:

- Match simulated results to the experimental ones → Simulate reliably any new situation

Internal structure determination



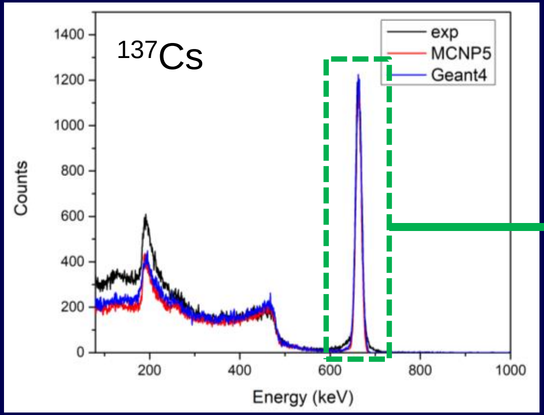
18% difference between experiment and simulations

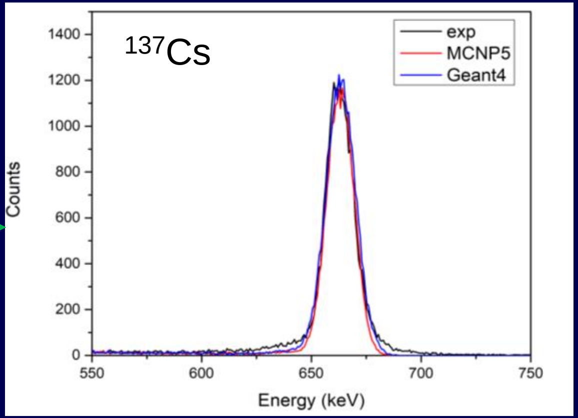
Internal structure determination

Crystal dimensions:
- Specification sheet → 10 x 10 x 10 mm
- CT scan → 10 x 10 x 9 mm
- Simulations → 10 x 10 x 9 mm (physical volume) and 9.5 x 9.5 x 8.25 mm (effective volume)

↓

Inactive layer phenomena (physical volume ≠ effective volume)





Discrepancies:
1. Approximation of the electronic components
2. Approximation of the lab's surroundings
3. Incomplete charge collection phenomena

S. Mohamad Tajudin, et al. (2019), doi: 10.11113/mjfas.v15n4.1254
Bolotnikov, A. et al. (2012), doi:10.1016/j.nima.2011.10.066
Kim, K., -O., et al. (2009), doi: 10.5516/NET.2009.41.5.723
Linxiang LI et al. (2022), https://doi.org/10.1016/j.nima.2022.166922.

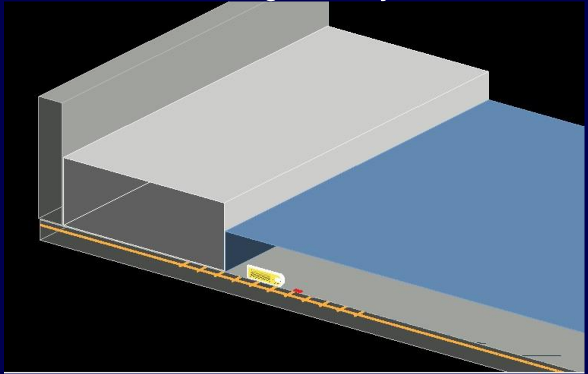
Simulations in aquatic environment

RAMONES

Water tank of the Laboratory of Harbor Works in National Technical University of Athens

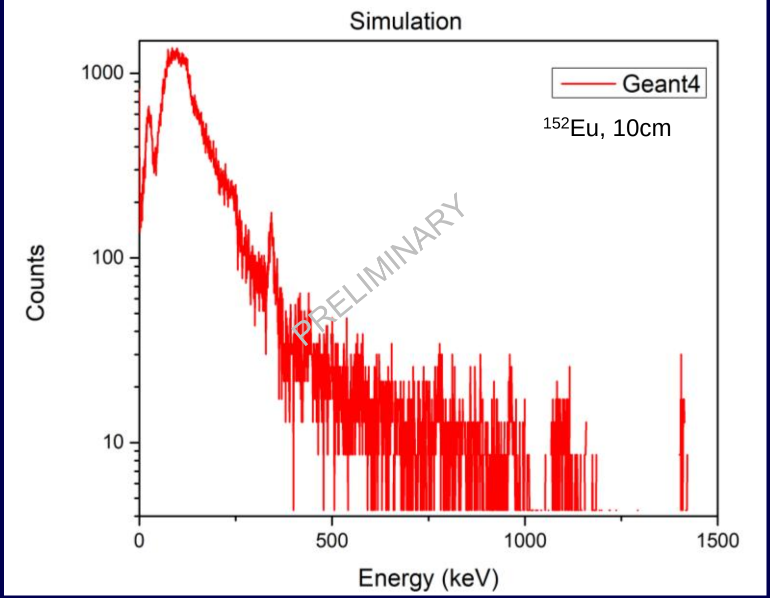
- Varied the distance between a ^{152}Eu point source and the detector:

Geant4 geometry



Blue: Water
Orange: Fe grid
White: Housing
Red: Source

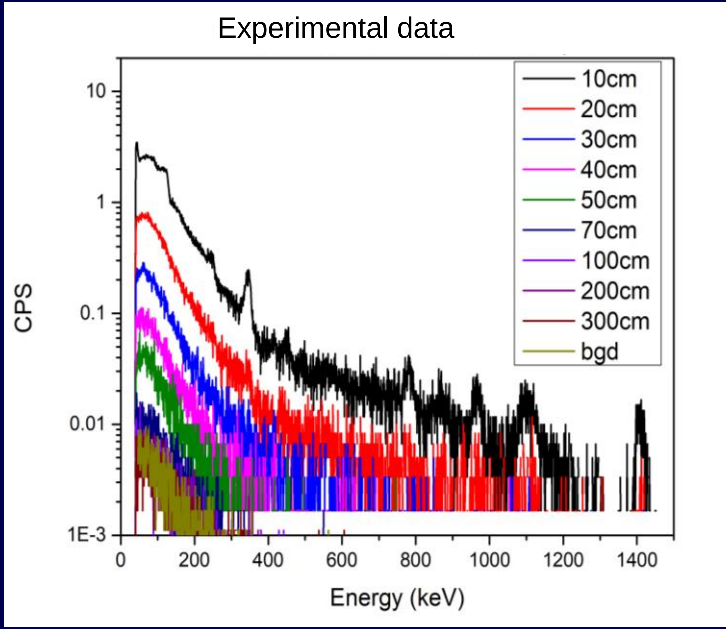
Yellow: Styrofoam
Grey: Concrete
Light grey: Carbonate rocks
Black: CZT shielding



First tests in aquatic environment

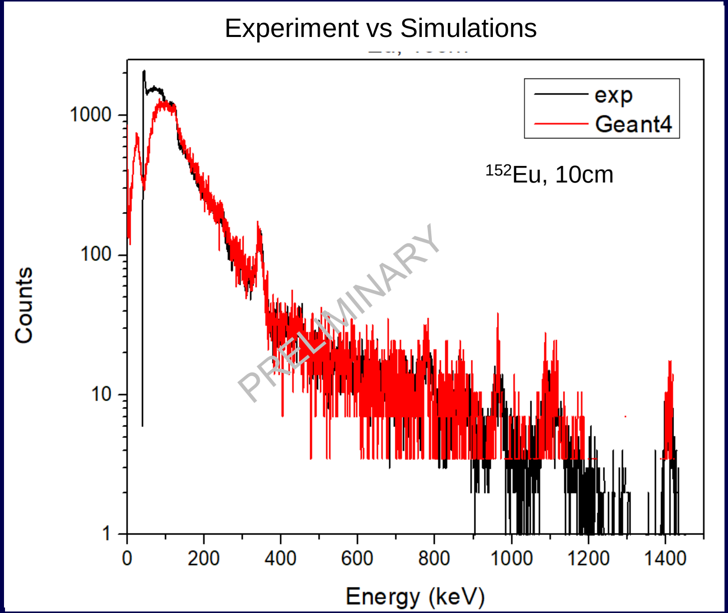
Water tank of the Laboratory of Harbor Works in National Technical University of Athens

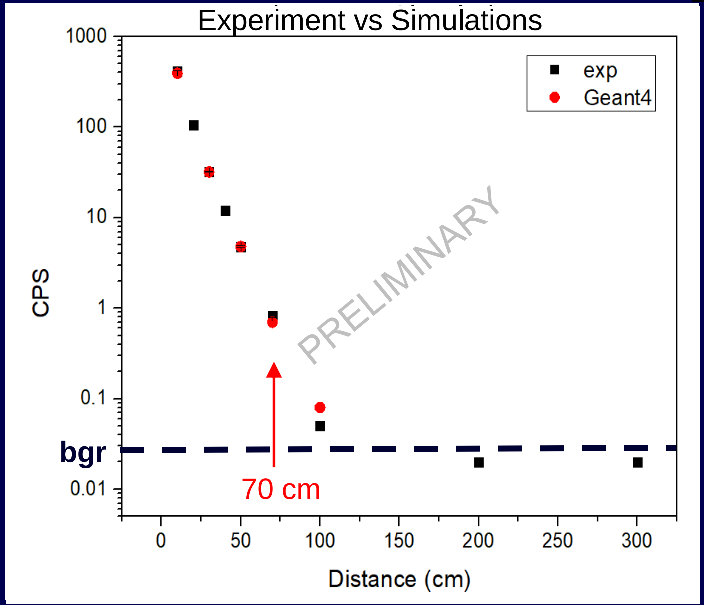
- Water tank's depth: ~30 cm
- Plexiglass housing with thickness ~4 mm
- ^{152}Eu point-like standard calibrated source



First tests in aquatic environment

Water tank of the Laboratory of Harbor Works in National Technical University of Athens





Very good agreement between experiment and simulations

μSPEC4000 spectrometer

4 cm^3 CZT crystal (Ritec)

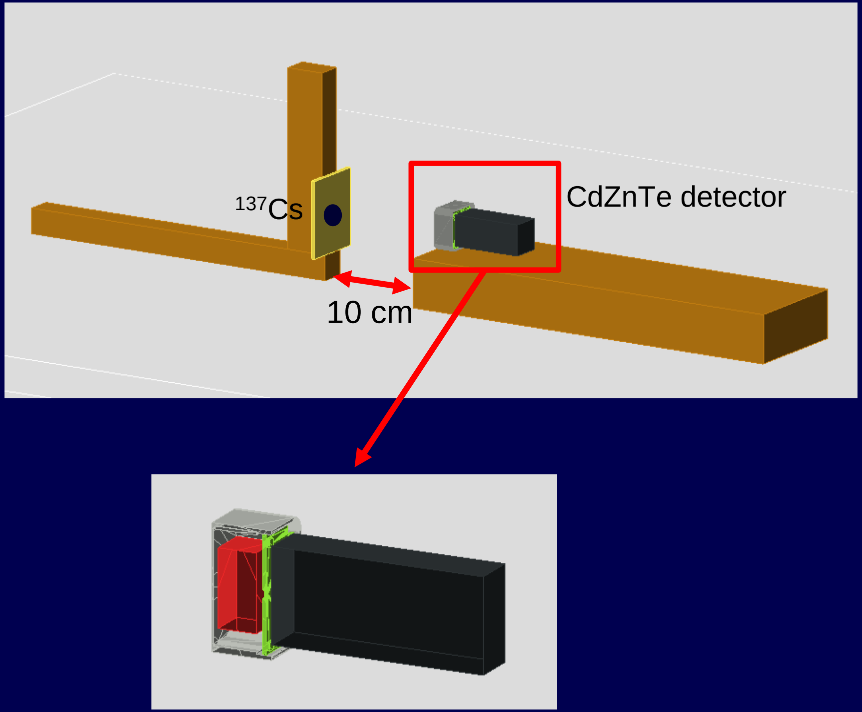
Nominal crystal's dimensions: 20 x 20 x 10 mm

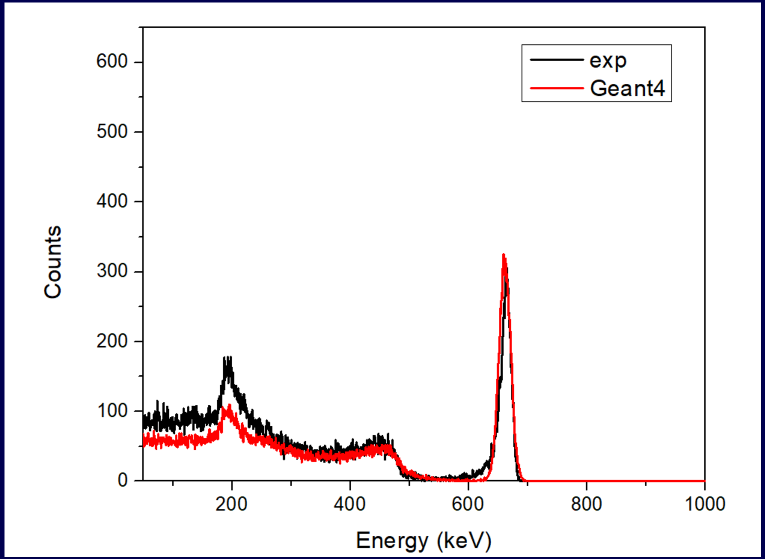
Evaluation of the detector's geometry and response through different scenarios

Internal structure determination

- ^{137}Cs point source placed 10 cm away from the detector at the lab:

Geant4 geometry

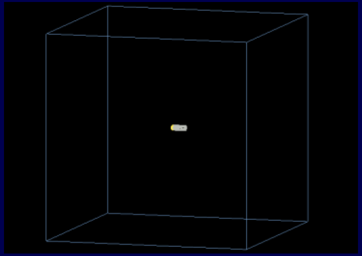


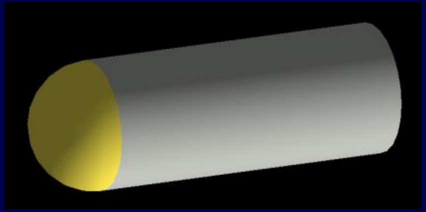


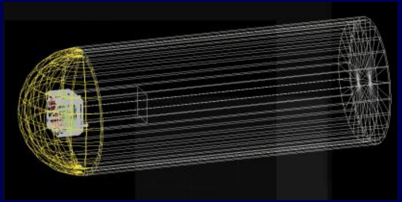
Simulations in aquatic environment

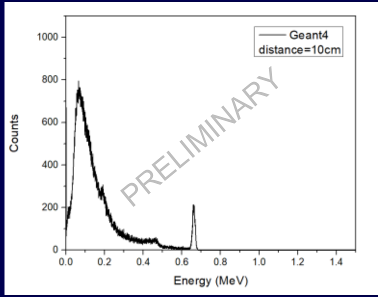
- Varied the distance between a ^{137}Cs point source and the detector:

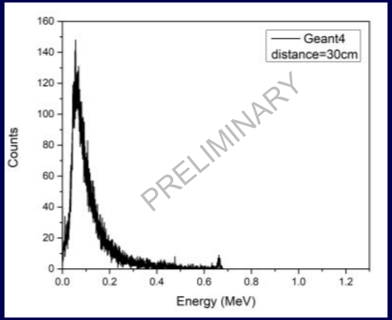
Marine environment : 2 x 2 x 2 m

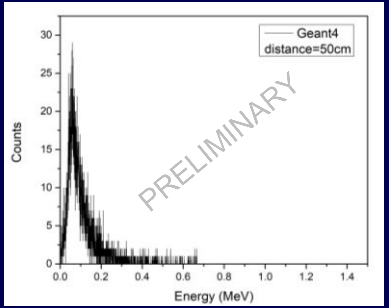


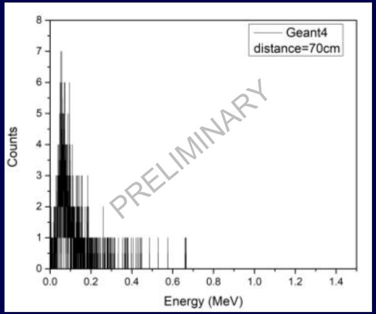


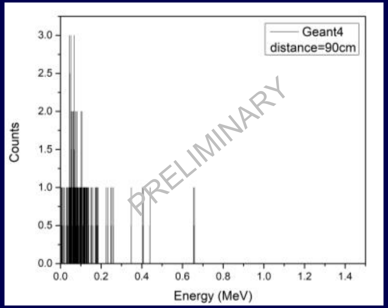


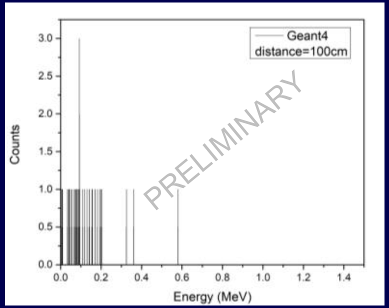






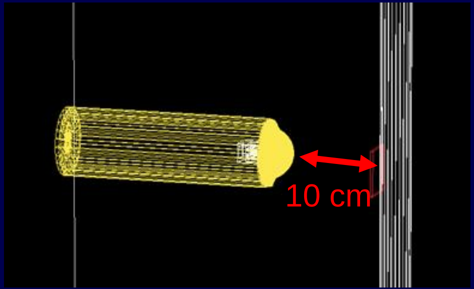


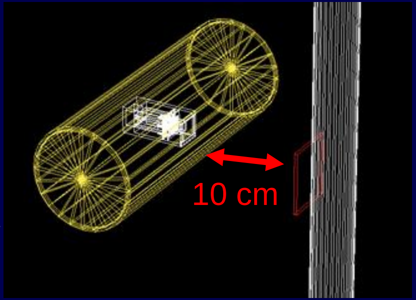


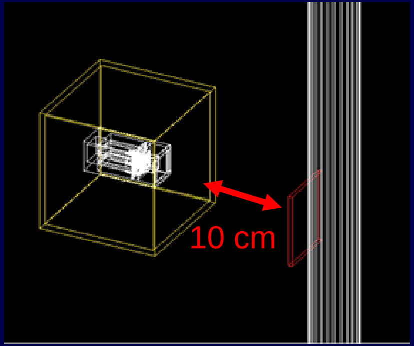


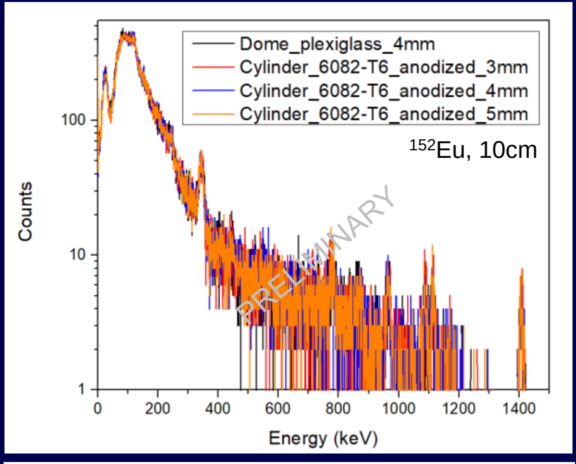
Simulations in aquatic environment

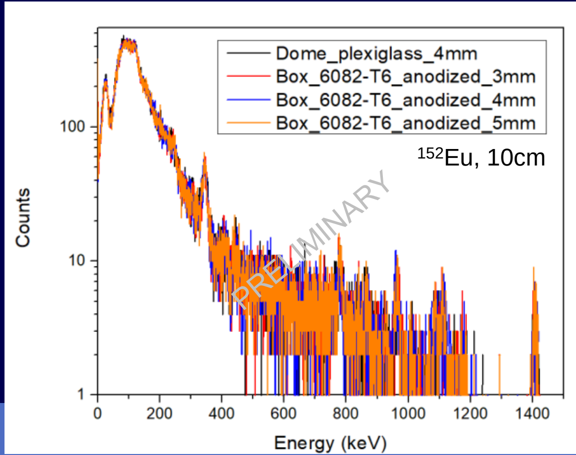
- Housing's geometry, material and thickness



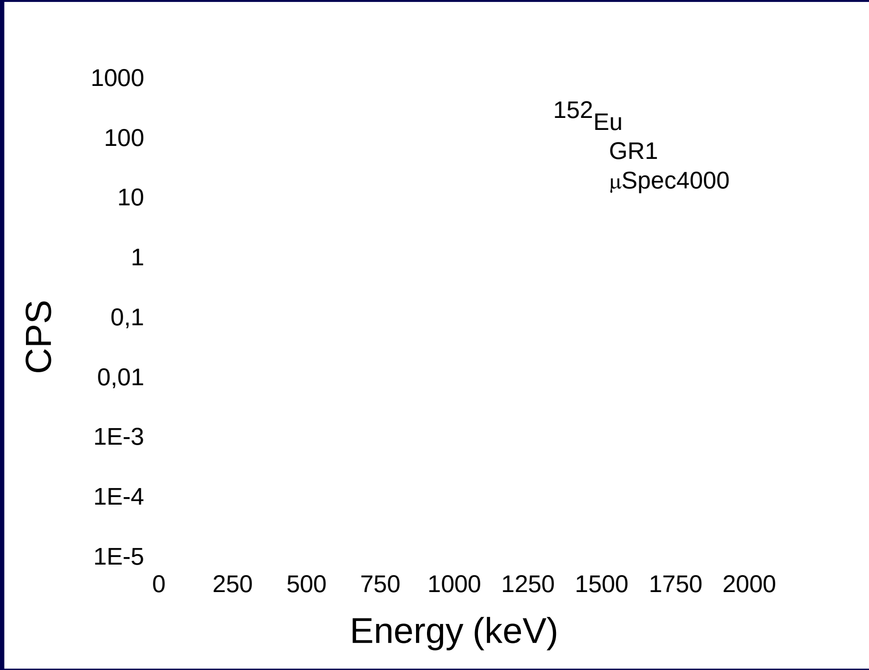








GR1 vs µSPEC4000



GR1: 1 cm^3 crystal

µSPEC4000: 4 cm^3 crystal

$$\frac{Integral_{\ \mu SPEC4000}}{Integral_{\ GR1}} = 5.2$$

Conclusions

- RAMONES: development of innovative instrumentation for enhanced monitoring of the radioactivity in marine ecosystems

- Mobile (γ-sniffers) and stationary platforms (benthic lab)

- γ-sniffers → CZT spectrometers inside AUG will perform surveys of ocean volumes for the detection of radioactivity hot spots

  - ➢ **GR1** (1 cm^3 CZT crystal) :
    - ✓ Simulations results → Nominal GR1 crystal's dimension ≠ Actual GR1 crystal's dimensions
    - ✓ Very good agreement between simulations and experiment for the detection range
    - ✓ Detection range ~ 70 cm → supplementary instrument for benthic lab or potential surface vehicle

  - ➢ **μSPEC4000** (4 cm^3 CZT crystal) :
    - ✓ Very good agreement between simulations and experiment
    - ✓ Detection range ~100 cm and higher detection efficiency compared to GR1→ more suitable for γ-sniffers

Thank you for your attention!

Our consortium:

HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

Institute for Systems and Robotics | LISBOA

EvoLogics®

ENS | PSL

National Technical University of Athens

PLOATECH
engineering marine science

Durham University Business School

LPC
Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

Backup slides

Materials composition

RAMONES

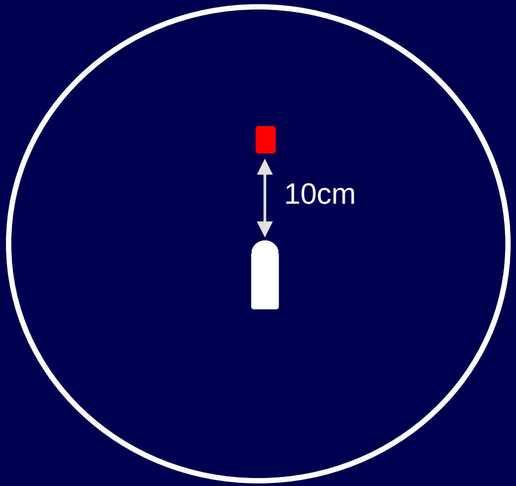
Sea water composition (salinity 3.5%):

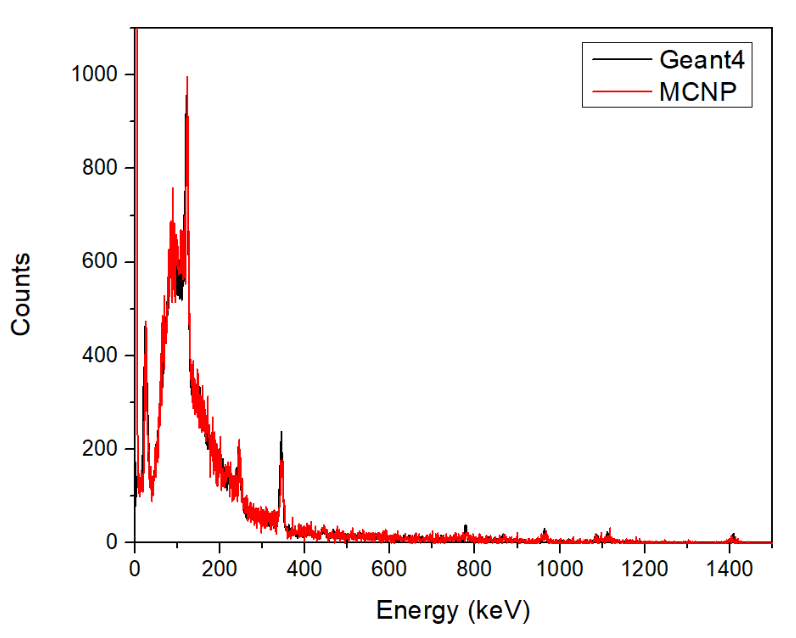
Air (ρ=0.001205 g/cm^3)	
Element	**Weight Fraction (%)**
C	0.0124
N	75.5268
O	23.1781
Ar	1.2827

Element	Percent by mass
Oxygen	85.84
Hydrogen	10.82
Chlorine	1.94
Sodium	1.08
Magnesium	0.1292
Sulfur	0.091
Calcium	0.04
Potassium	0.04
Bromine	0.0067
Carbon	0.0028

Geant4 vs MCNP in aquatic environment

- Water tank of d=146cm and depth=30cm
- Filled with water (H_2O)
- ^{152}Eu source 10cm away from the detector

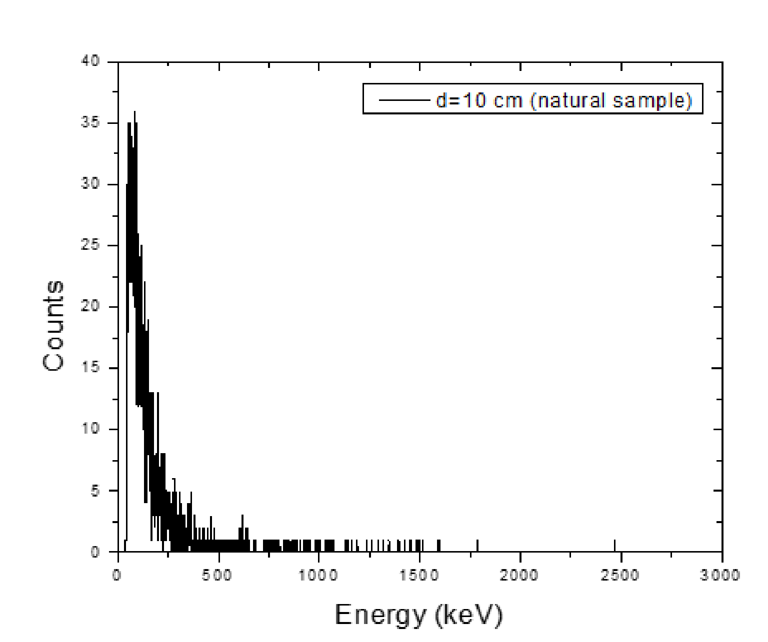




Field tests

1. Water tank of the Laboratory of Harbor Works at National Technical University of Athens

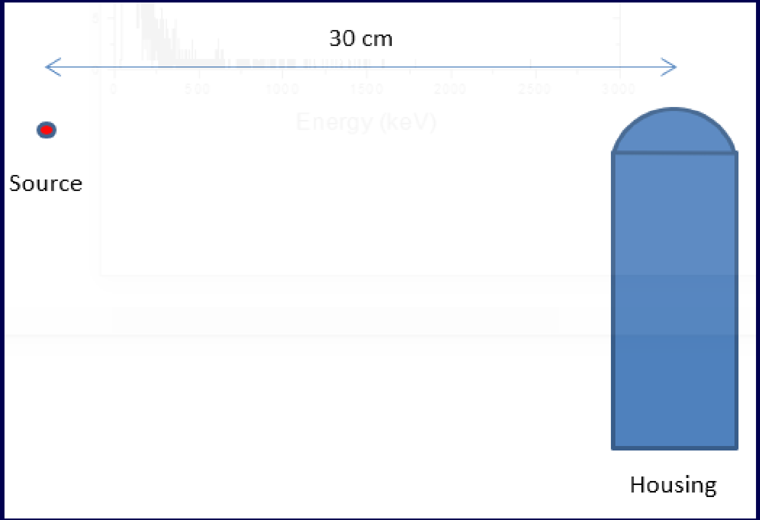
Sample of granite rock known to have natural uranium content

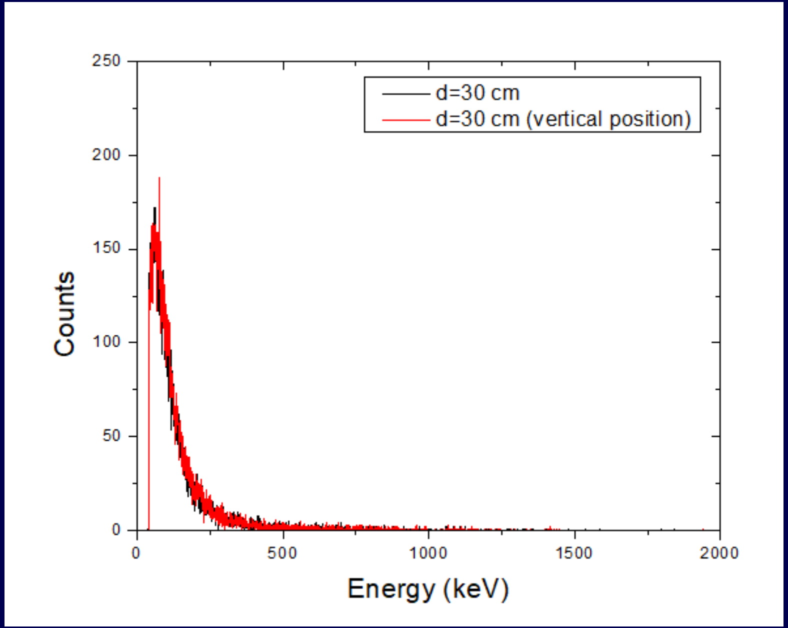


Field tests

1. Water tank of the Laboratory of Harbor Works at National Technical University of Athens

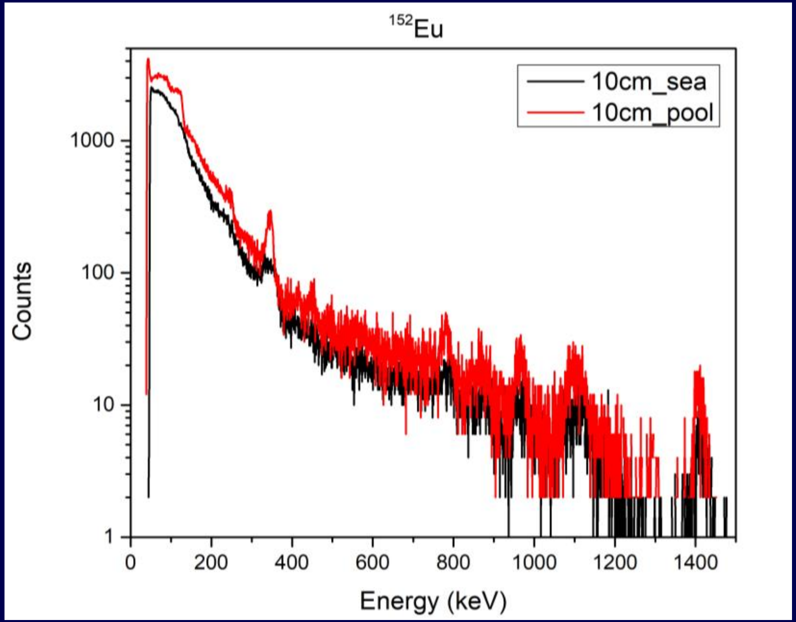
Angular dependency on the detector's response





Field tests (Static)

Sea vs Pool environment



Semiconductors operation

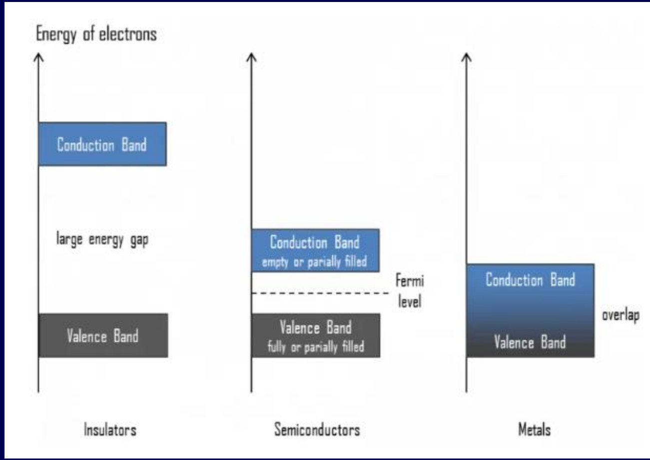
The operation of semiconductor detectors is summarized in the following points:

- **Ionizing radiation enters** the sensitive volume of the detector and interacts with the semiconductor material.

- Particle passing through the detector ionizes the atoms of semiconductor, producing the **electron-hole pairs**. The number of electron-hole pairs is proportional to the energy of the radiation to the semiconductor. As a result, a number of electrons are transferred from the valence band to the conduction band, and an equal number of holes are created in the valence band.

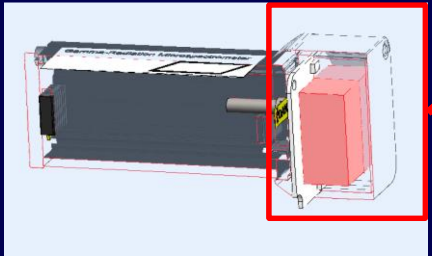
- Under the influence of an electric field, electrons and holes travel to the electrodes, where they result in a **pulse** that can be measured in an outer circuit

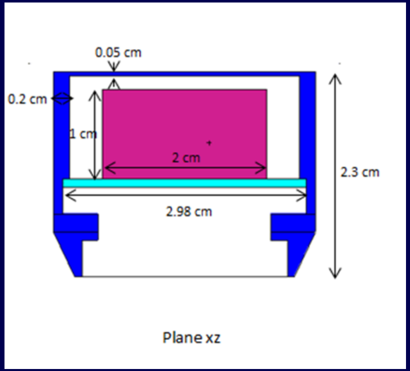
- This pulse carries information about the energy of the original incident radiation. The number of such pulses per unit time also gives information about the intensity of the radiation.

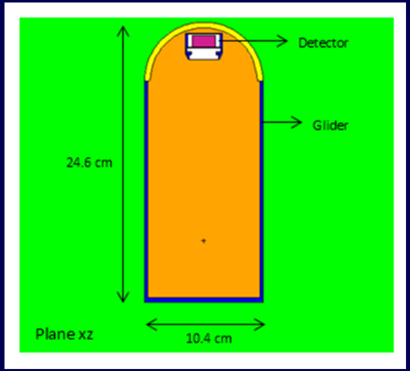


µSPEC4000 geometry

MCNP5 geometry







Green: Sea water
Blue: Aluminum
Orange: Air
Pink: CdZnTe crystal
Yellow: Acetal or Acryl
Light Blue: Silicon
White: Void

Evaluation of the detector's response through 6 different scenarios at marine environment

Nominal crystal's dimensions: 20 x 20 x 10 mm

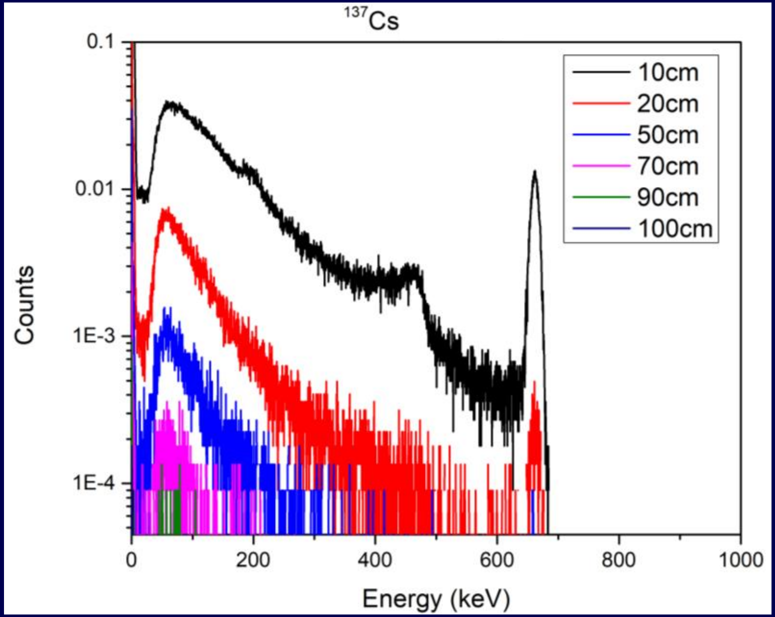
Different scenarios in the marine environment

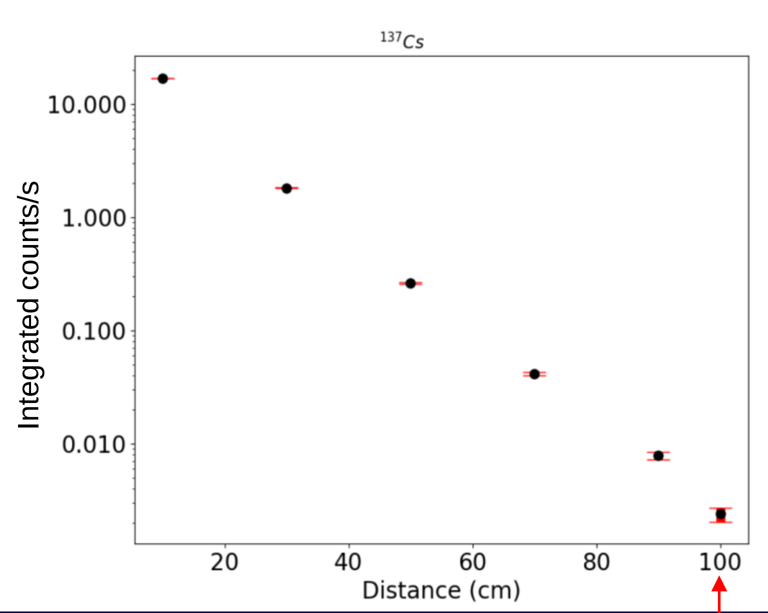
RAMONES

- **Scenario 1:** Varied distance between detector and a point source (^{137}Cs)
- **Scenario 2:** Different isotropic spherical volume of ^{226}Ra and daughter nuclides with R=10, 50 and 100 cm
- **Scenario 3:** Isotropic spherical volume source of ^{226}Ra with R=50 cm for different seawater's salinity
- **Scenario 4:** Two-point source (^{137}Cs) situation with the detector moving alongside to them ($A_1=A_2$, $A_1=A_2/2$)
- **Scenario 5:** Two-point source (^{137}Cs) situation with the detector moving perpendicular to them ($A_1=A_2$, $A_1=A_2/2$)
- **Scenario 6:** Two-point source (^{137}Cs) situation with the detector moving diagonally to them with different θ angles ($A_1=A_2$)

Scenario 1

- Varied distance between detector and a point source:



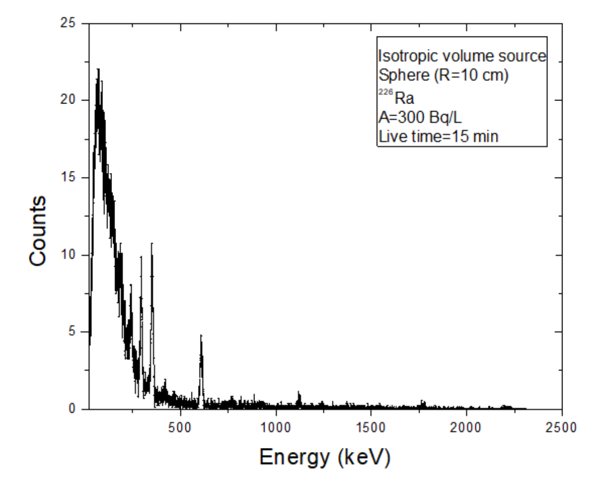


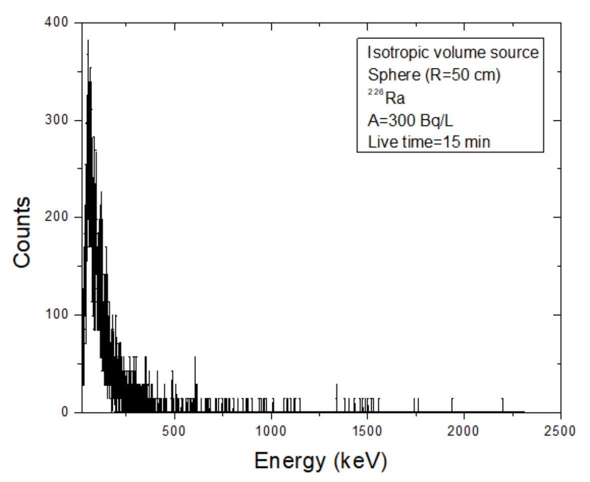
For distances higher than 100 cm zero counts were detected from the crystal

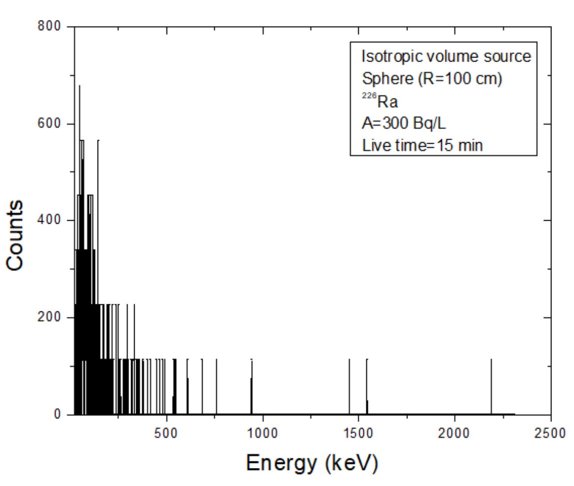
100 cm

Scenario 2

- Different isotropic spherical volume of ^{226}Ra and daughter nuclides with R=10, 50 and 100cm

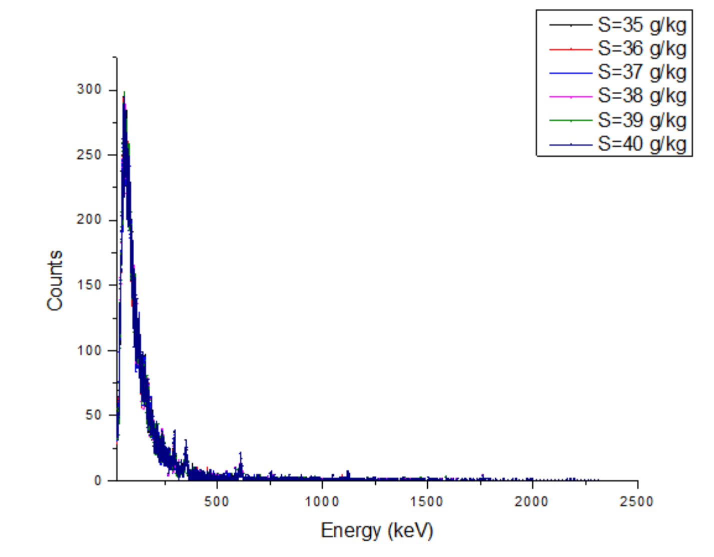


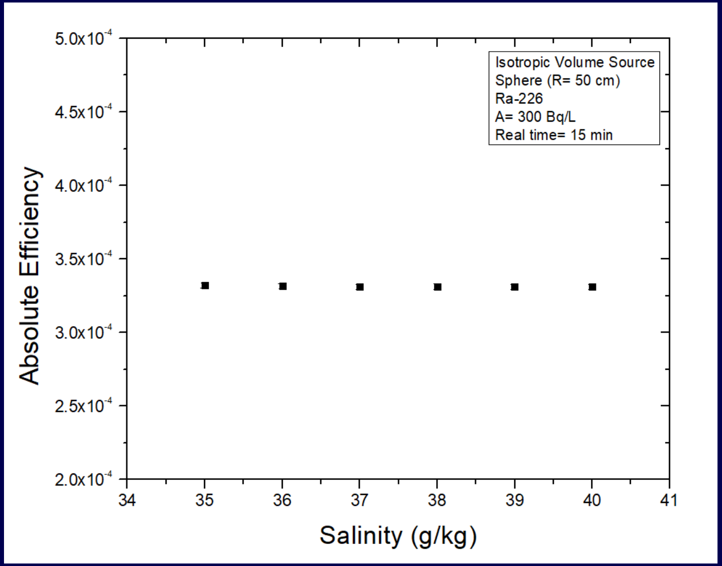




Scenario 3

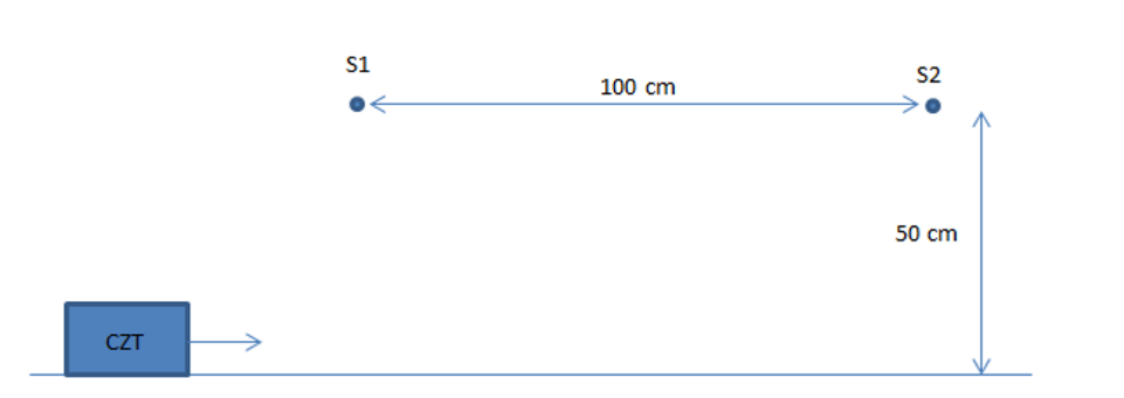
- Isotropic spherical volume source of ^{226}Ra with R=50 cm for different seawater's salinity





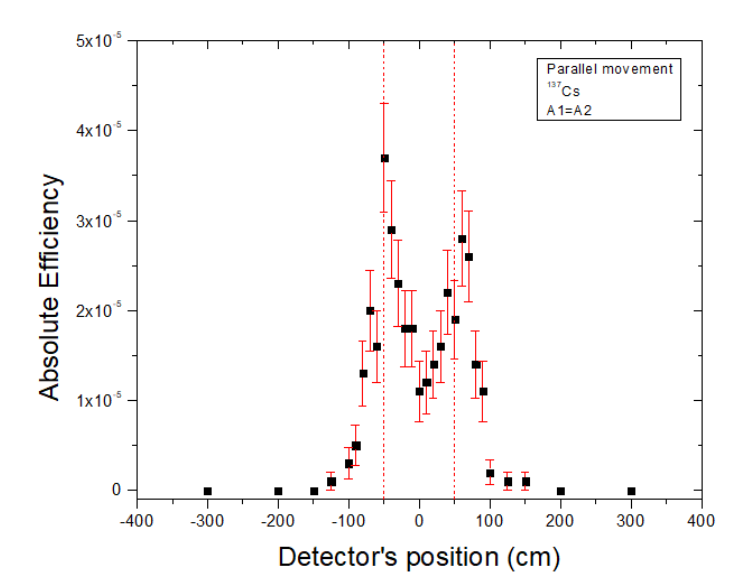
Scenario 4

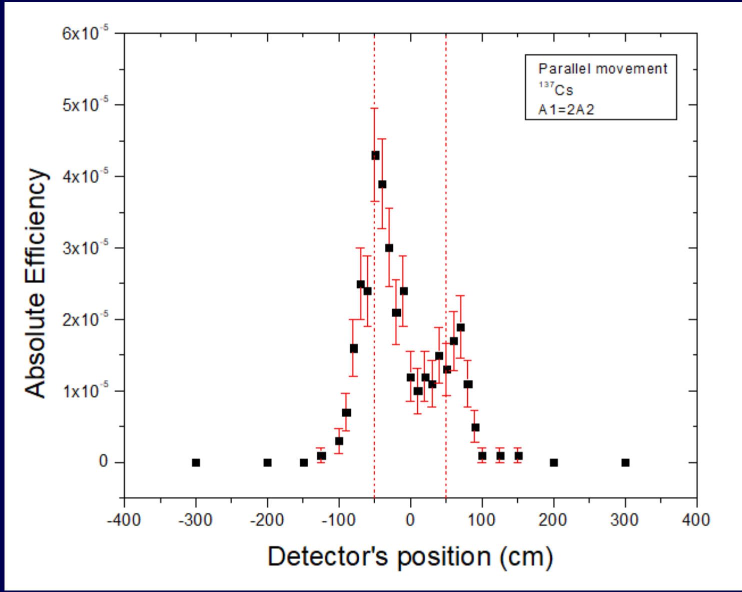
- Two-point source (^{137}Cs) situation with the detector moving alongside to them:



Scenario 4

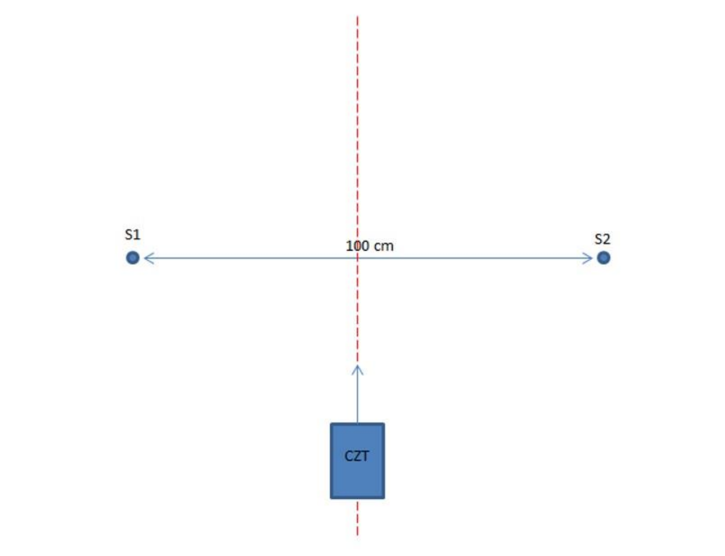
- Two-point source (^{137}Cs) situation with the detector moving alongside to them:

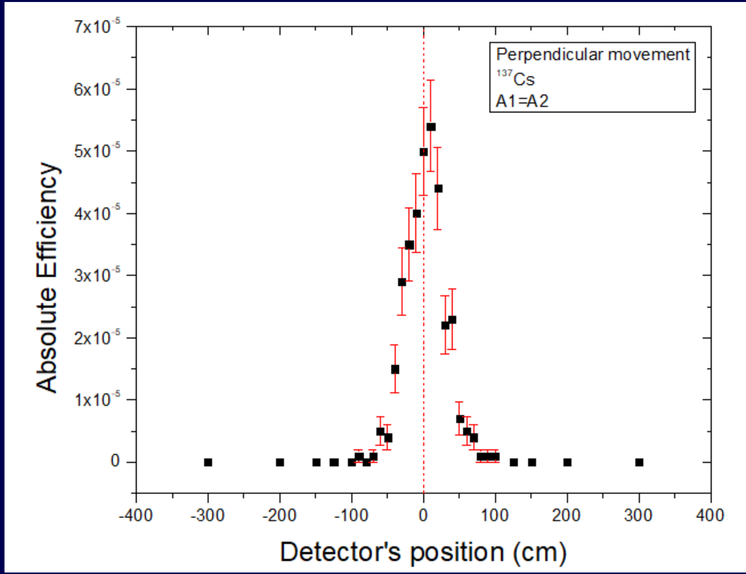




Scenario 5

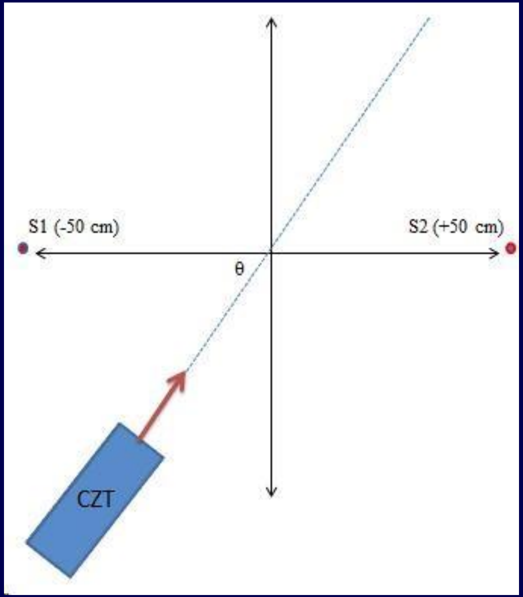
- Two-point source (^{137}Cs) situation with the detector moving perpendicular to them

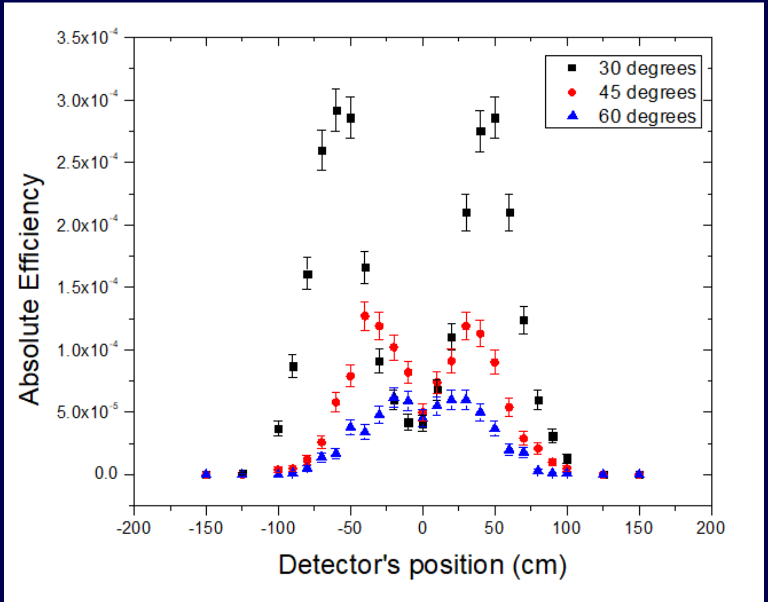




Scenario 6

- Two-point source (^{137}Cs) situation with the detector moving diagonally to them with different θ angles:





Simulations vs experiments