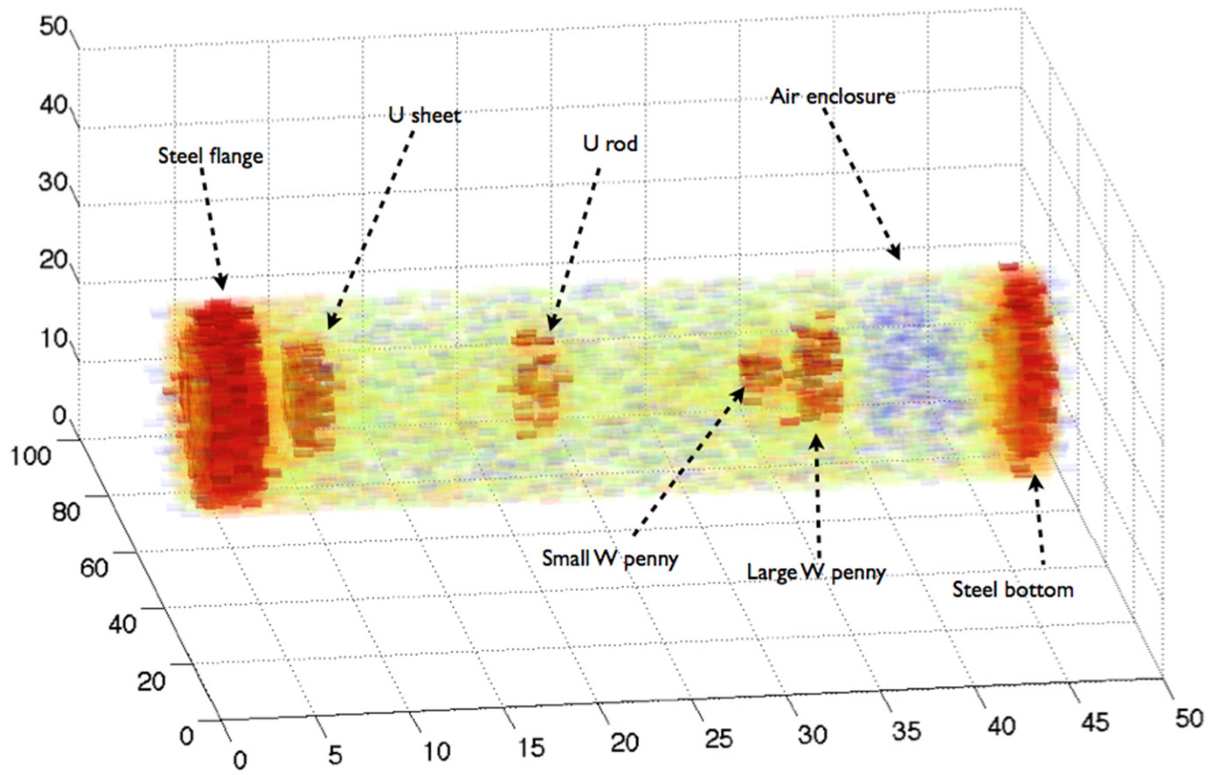

Steel flange
U sheet
U rod
Air enclosure
Small W penny
Large W penny
Steel bottom

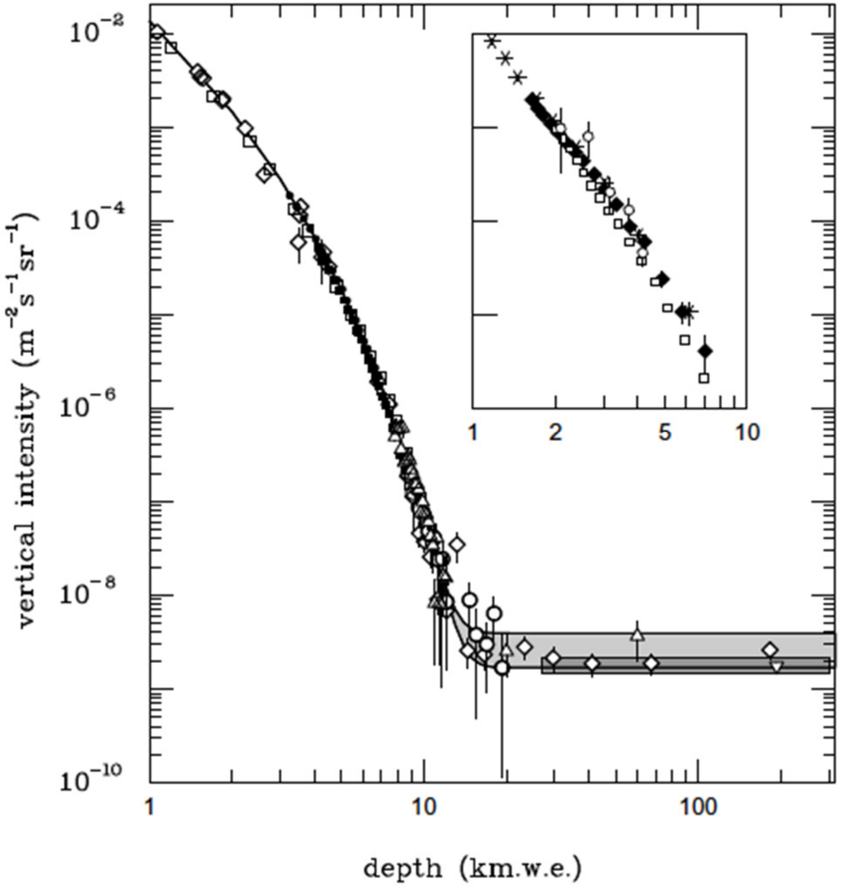
Contents

- Muon tomography
- Waste drum results
- Large drum results
- Radiography
- Thoughts on Paldiski
- Summary

Cosmic rays: muons

- Primary cosmic rays interact in the atmosphere and decay into showers of secondary cosmic rays.
- On Earth we are constantly bathed in (secondary) fundamental particles from cosmic rays.
- Naturally occurring at decent rates (~100 Hz/m^2)
  - Large angular and energy spread.
  - Flux and energy of muons depend on the zenith angle.
- Highly penetrating. Measured rate up to 10km water equivalent.

- All these combined make muons an excellent probe to study enclosed spaces from a safe distance.

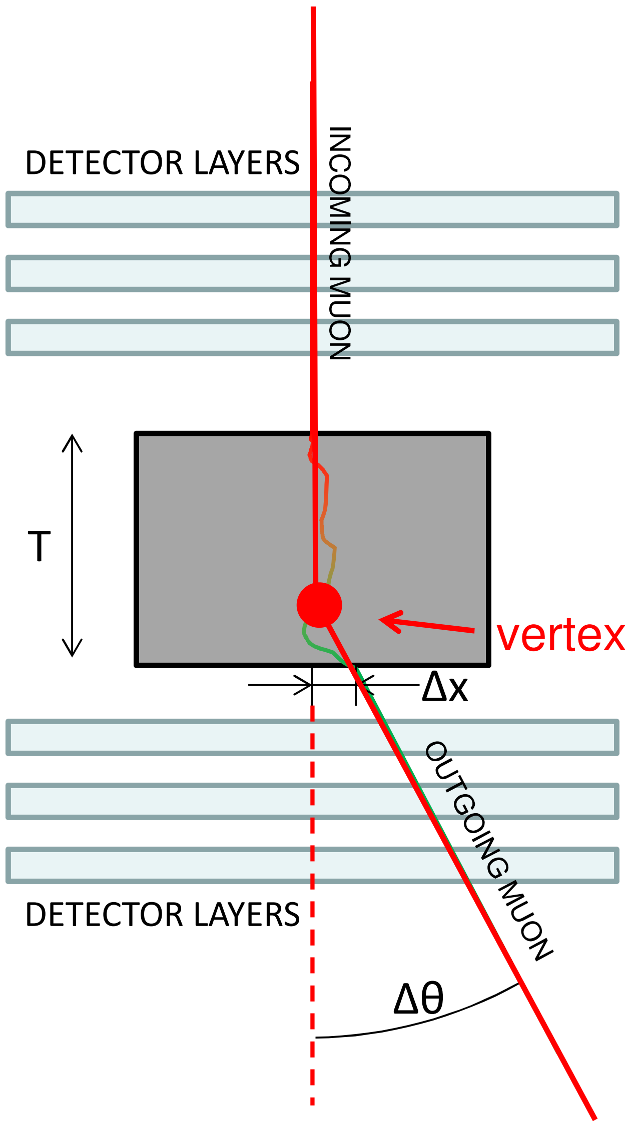


Muon scattering tomography

- Muon scattering tomography relies on multiple scattering.
- The angular distribution is Gaussian, with σ_0 depending on the radiation length X_0 and thus on Z.

$$\sigma_0^2 \approx \left(\frac{15MeV}{pc\beta}\right)^2 \frac{T}{X_0} \qquad X_0 \approx \frac{A \cdot 716.4 g/cm^2}{\rho \cdot Z \cdot (Z+1)\ln(287/\sqrt{Z})}$$

- The Z^2 means that the technique is very sensitive for high-Z materials!
- Every track yields a displacement and an angle
  - We measure an angle and a vertex.

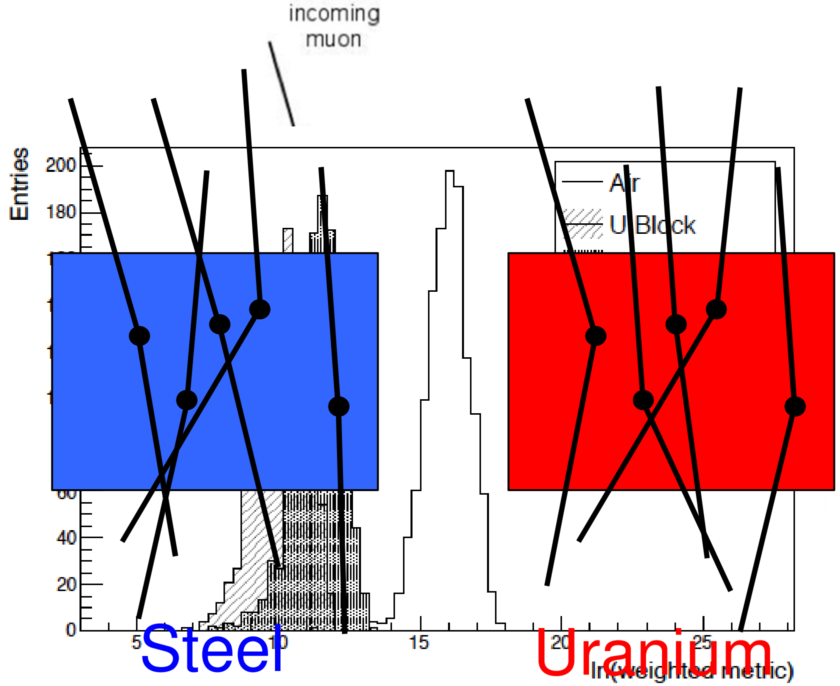


Novel reconstruction method

- Our approach for cargo containers
  - Fit each muon pair as coming from a vertex
  - Use very large voxels (25 cm edges)
  - Take in each sub-volume the 50 tracks with largest scatter and calculate median of weighted metric distance
    - Exploiting “clusteredness” high scatters

$$m_{ij} = \frac{\| v_i - v_j \|}{(\theta_i \tilde{p}_i)(\theta_j \tilde{p}_j)}$$

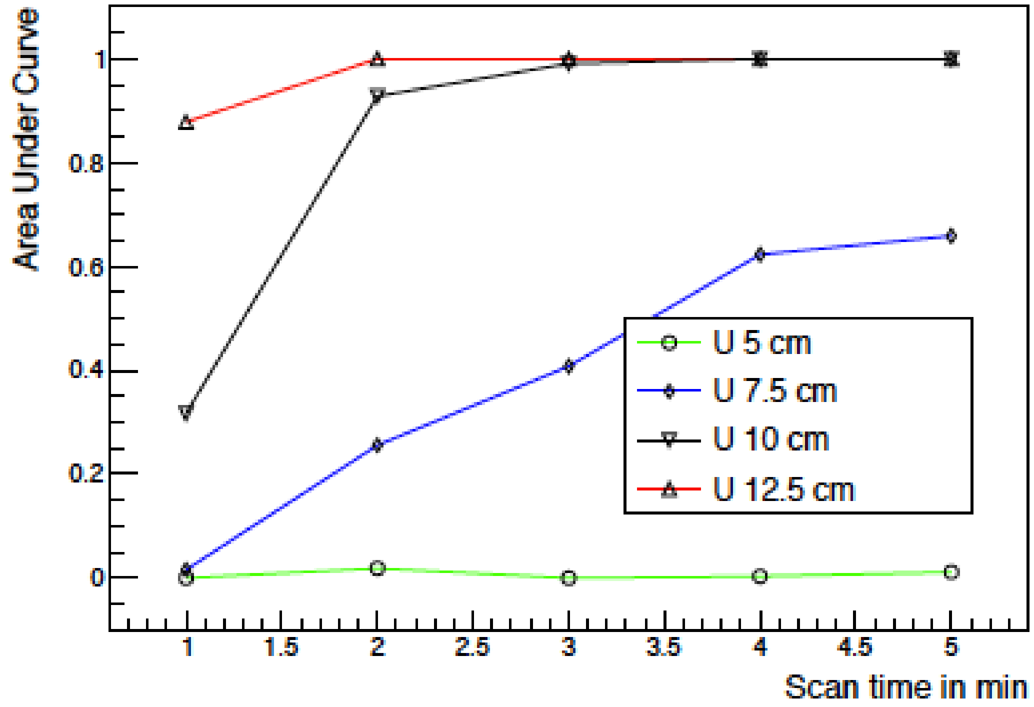
  - For 1 minute, using 10x10x10 cm³ blocks in air get very good separation



This is **our** algorithm and chosen analysis, many more groups and algorithms available.

Performance

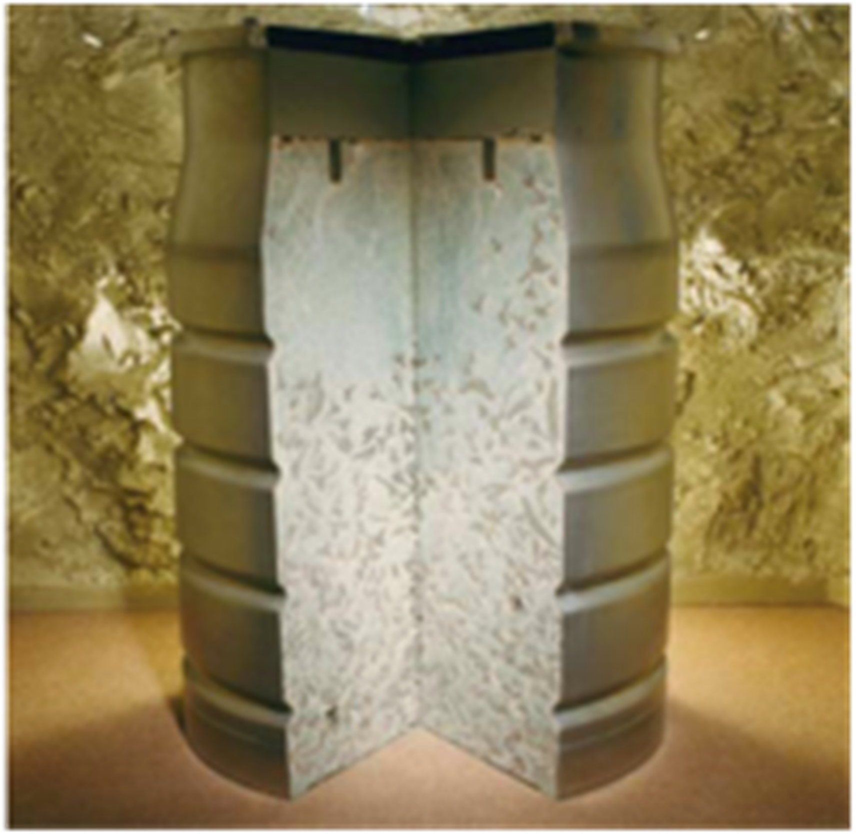
- When filling a shipping container up to maximum weight with rock around U block
  - Very good after 2 min of data taking
- And for scrap iron
  - Very good after 3 min of data taking
- Can find U block of 7.5x7.5x7.5 cm^3 or larger in very good time
  - Can optimise more for smaller blocks



Nuclear waste

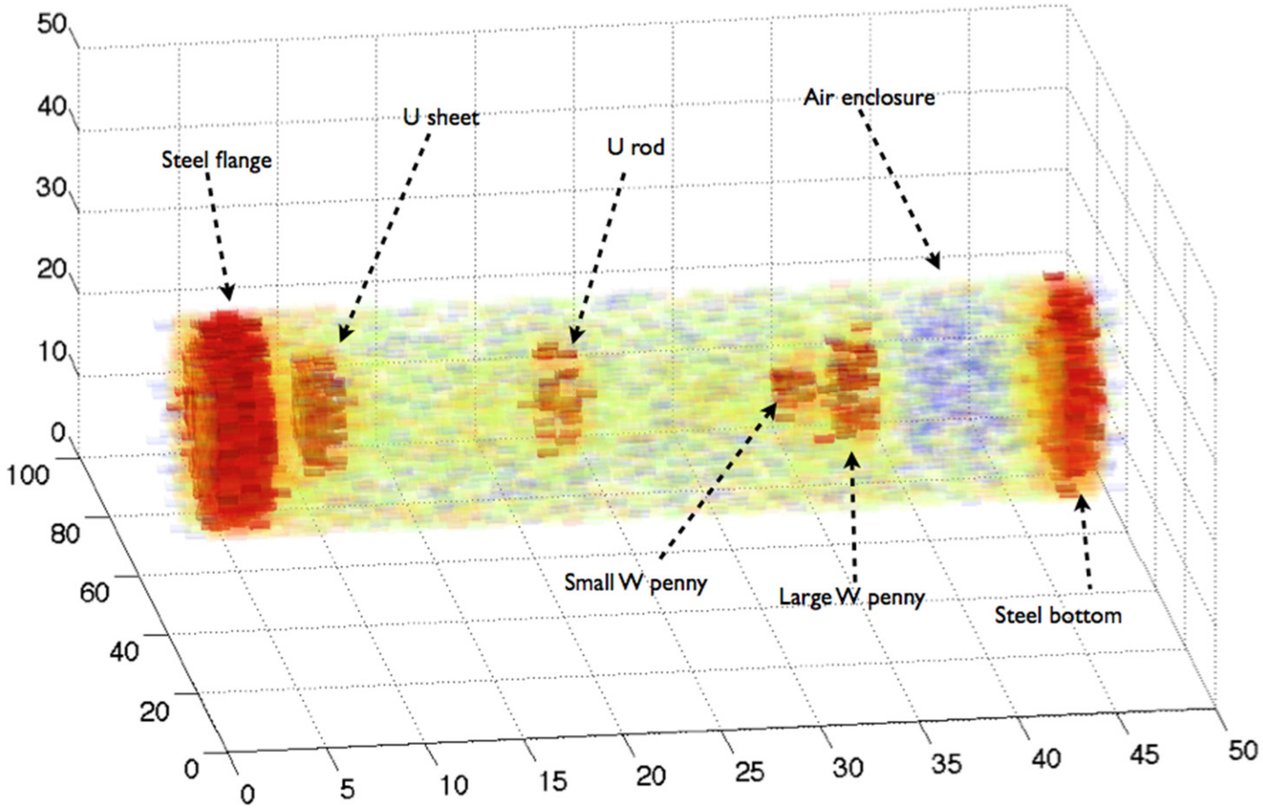
- Nuclear reactors have been and are producing waste.
- This is stored in waste containers in concrete.
- It is important to monitor what goes on inside a container over time.
  - Requires a measurement from distance with closed container

- For hazard assessment want to
  - measure the size
  - identify the material



Waste drum monitoring

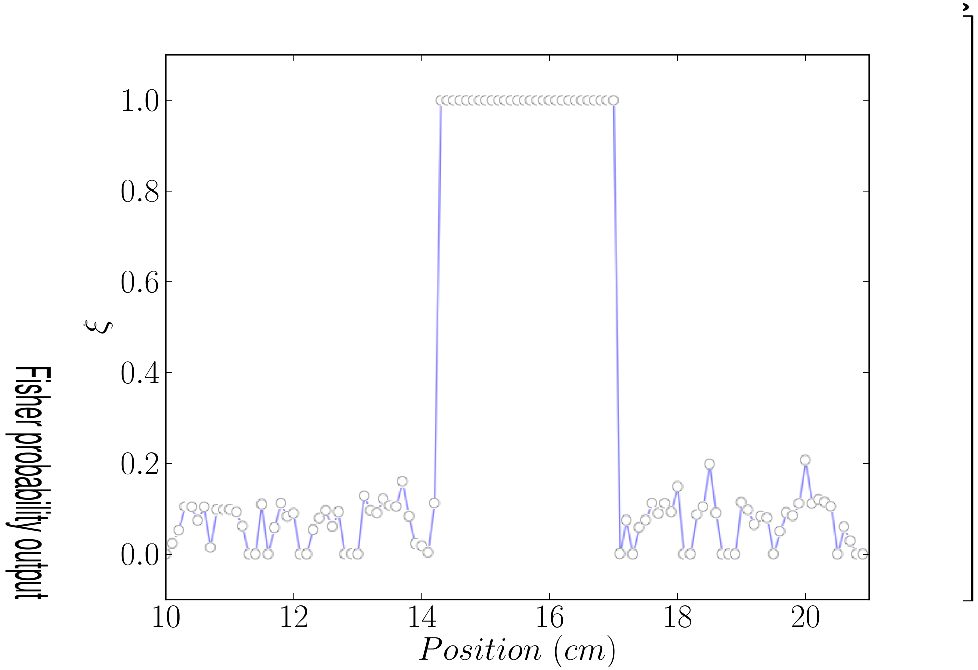
- Monte Carlo simulation of a small drum.



Top hat scans, 2 weeks of data, 50% momentum uncertainty

Edge finding

- In order to distinguish uranium from concrete at the edge, multivariate analysis (MVA) was performed using variables from the raw data and the fit:
  - Maximum value;
  - Respective bin position;
  - Widths of the Landau and Gaussian from fit;
  - Peak amplitude and position from fit.
- MVA method: Fisher linear discriminant.
- Plot output versus *x*.



5 mm uranium

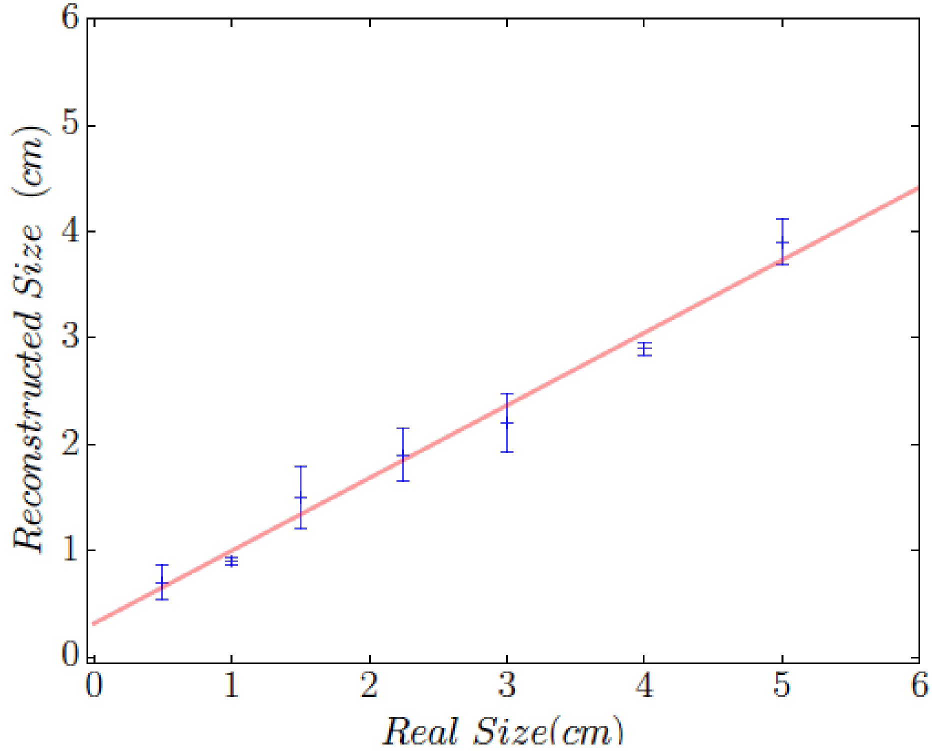
30 mm uranium

Output from the training with the Fisher linear discriminant, using samples of pure concrete and pure uranium (2 cm block).

Edge finding results

- Excellent correspondence between real and reconstructed length.
  - U blocks
  - 4 weeks of data.

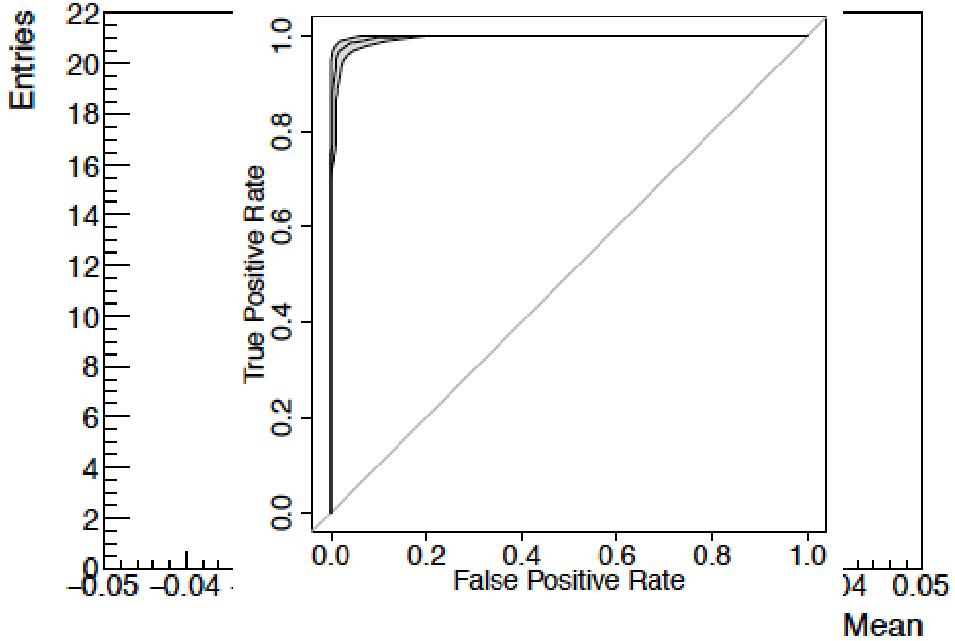
- We can define the edges of uranium blocks in concrete, measuring lengths as small as 2 mm.
- The resolution obtained was $\sigma = 2.9 \pm 0.5$ mm.



Nuclear waste: Material identification

- Want to identify the materials. Focussing on
  - Lead: $X_0 \approx 0.56$ cm
  - Tungsten: $X_0 \approx 0.35$ cm
  - Uranium: $X_0 \approx 0.32$ cm
  - Plutonium: $X_0 \approx 0.30$ cm
- All materials were embedded in a concrete cylinder, with 13 cm radius and 40 cm length.

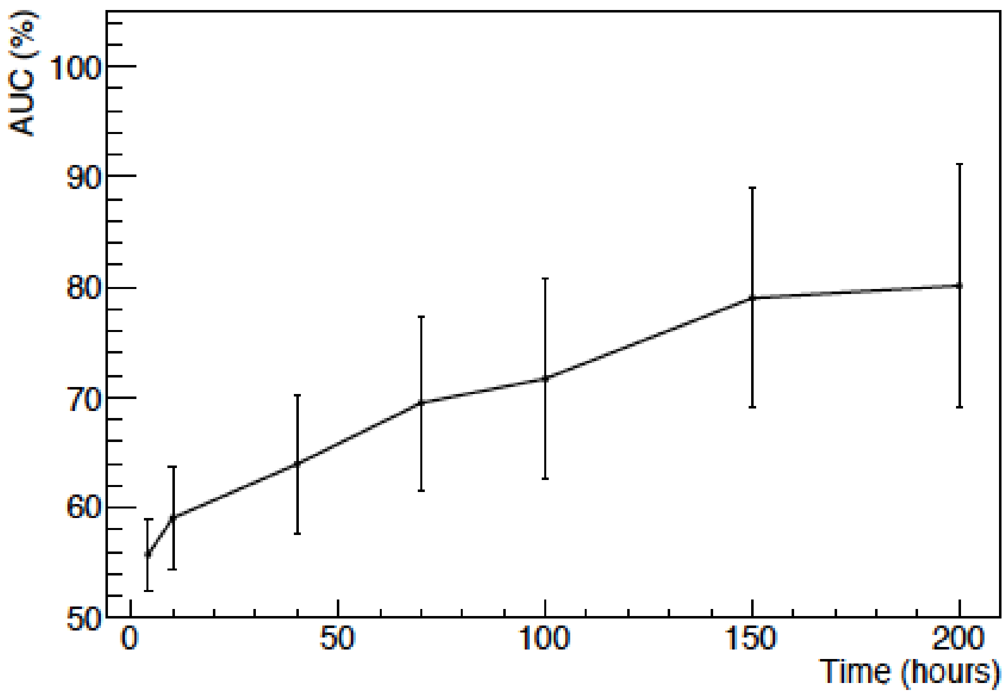
10x10x10cm^3



- Compare the individual muon scattering tracks for two materials using a Fisher discriminant.
  - Variables: scattering angle, offset, χ^2 of the fit
- Calculate the mean Fisher output for 1hour of data
- The ROC curve shows that we can discriminate very well.

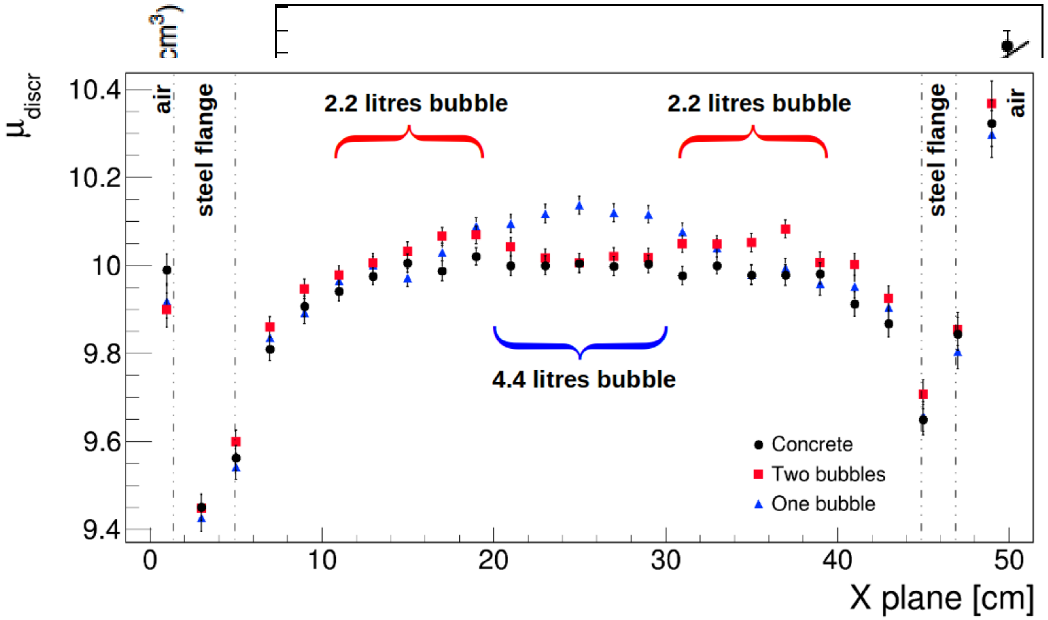
Material identification

- Separation U and Pb almost perfect for 10x10x10cm^3 after 1 hour.
- It takes longer for smaller blocks.
- Still, it works down to 2x2x2cm^3.
- Separation U and W almost perfect for 10x10x10cm^3 after 1 hour.
- It takes longer for smaller blocks.
- Still, again it works down to 2x2x2cm^3.
- Can even discriminate U and Pu for 3x3x3cm^3 blocks



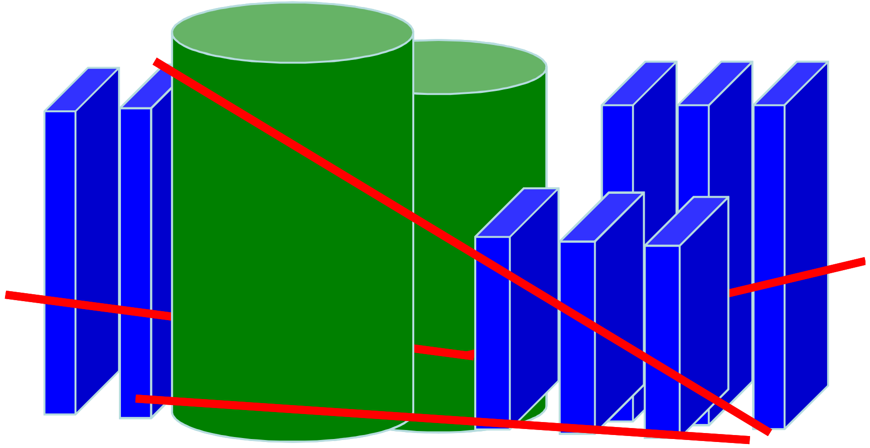
Air bubbles

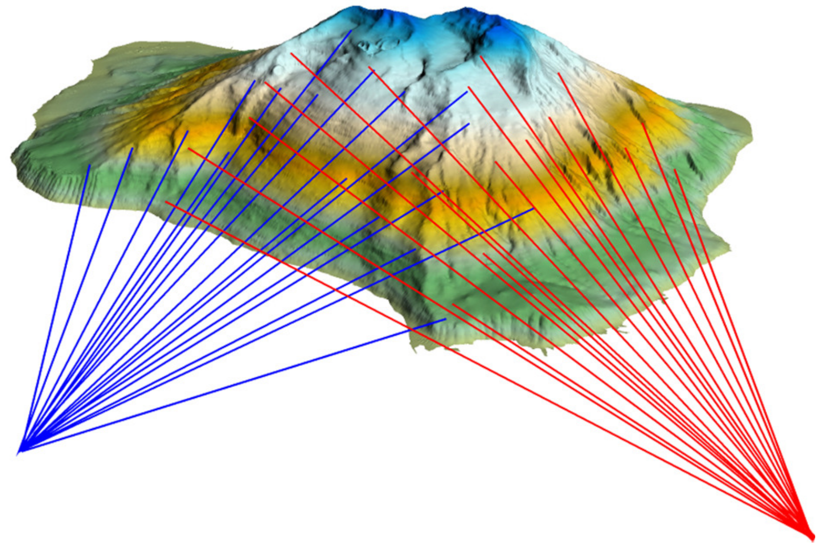
- We follow the same procedure:
  - divide the drum into voxels
  - calculate the discriminator for each voxel
  - study the mean as a function of the amount of hydrogen inside the concrete
- Mean clearly good indicator for the size of the bubbles.
- Can measure the size of the bubbles with ~10% resolution.
- Can distinguish single bubble from more smaller ones.



Large(r) objects

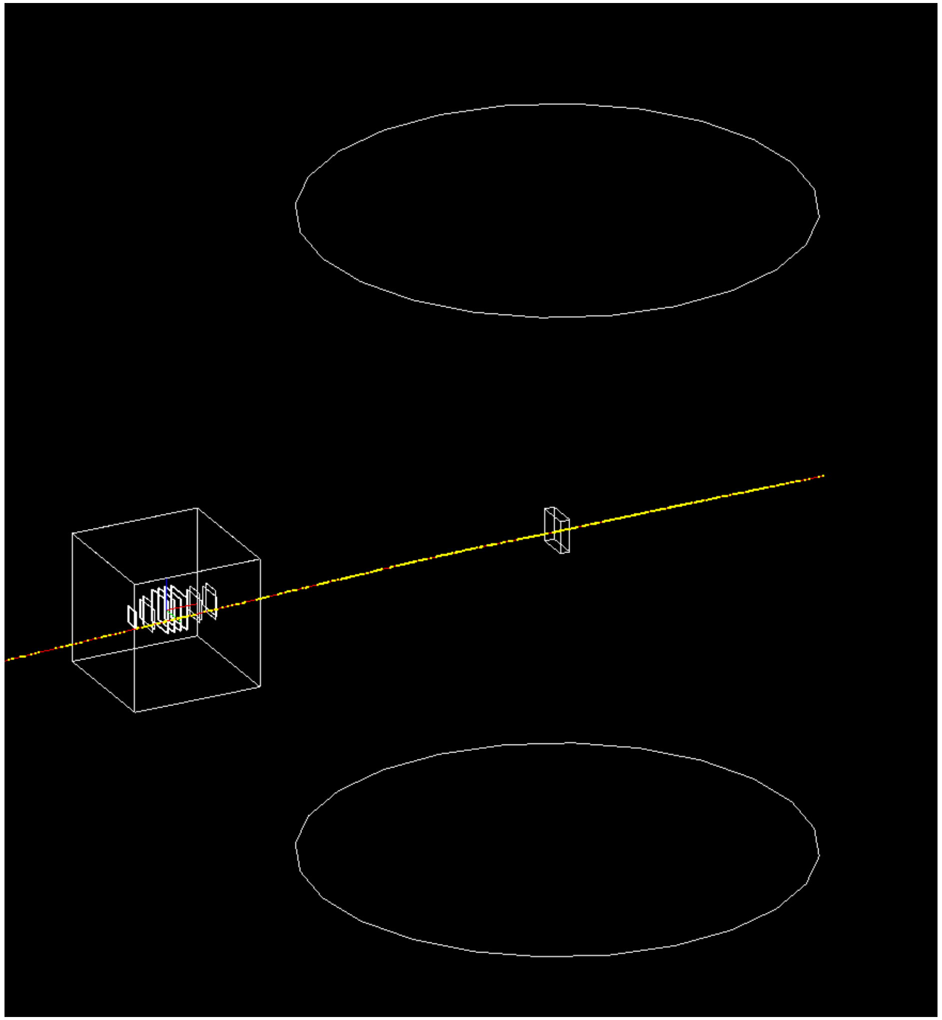
- Tomography needs incoming and outgoing track. Only sensitive in overlap region.
- For large objects this is too expensive and cumbersome. Solution: radiography.
- In radiography, measure absorption along line of muon track and use two detector stations.





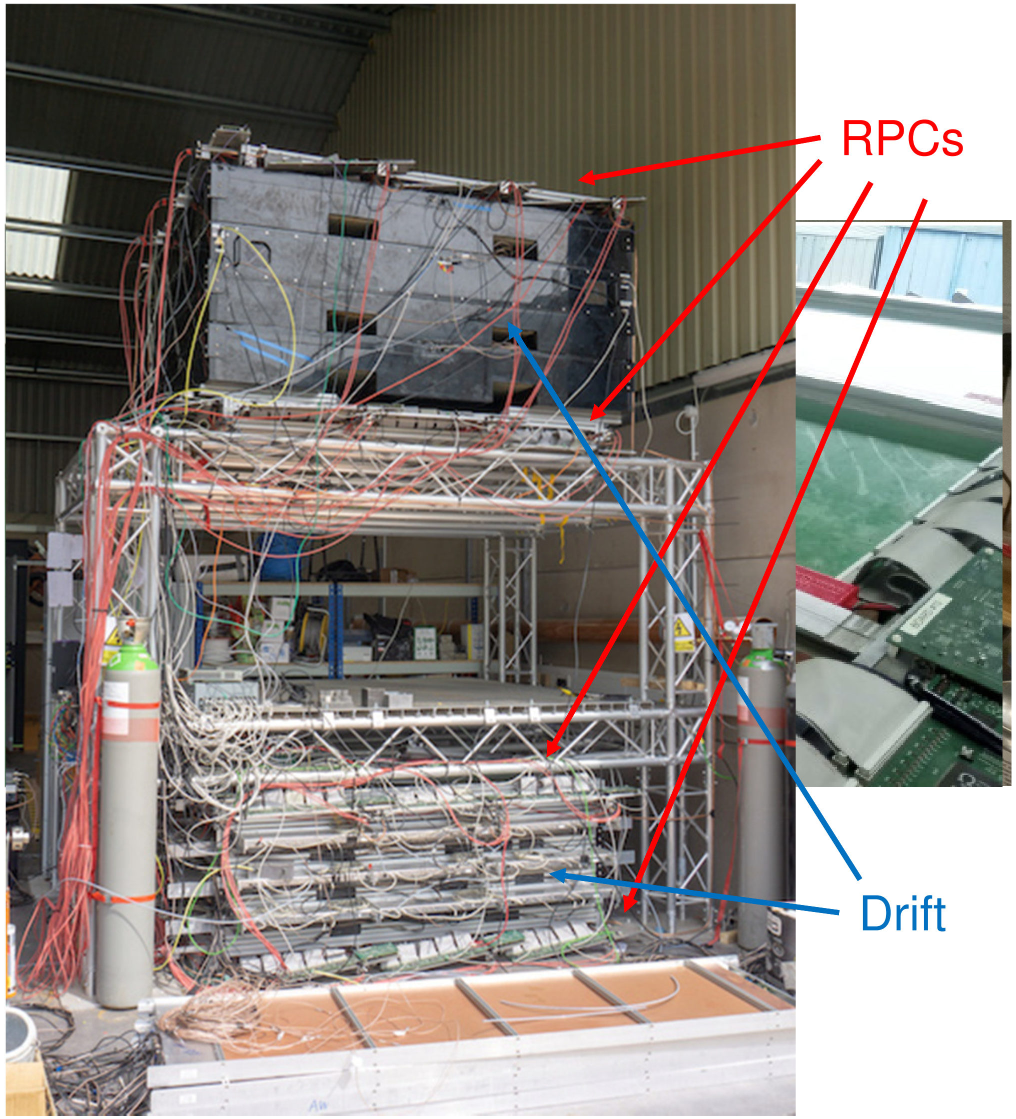
Silo radiography

- A simple MC.
- Around 75^o zenith angle peak momentum at 12 GeV. Fill 15m silo with concrete and insert sheet of U. Expect transmission fraction of
  - 88% for no U
  - 85% for 2 cm U
  - 84% for 5 cm U
  - 79% for 10 cm U
  - 70% for 20 cm U
- To measure with 2% accuracy need ~300 muons. Investigate 5x5 cm sections. Operate on 10^o slope. Takes ~2-3 months in 1D.
- You have thicker material ☺



Detectors for CRT

- Need large detector systems (~ m²)
- Need an angular resolution of ~ 1mrad
- Essential detector properties
  - Timing resolution better than 1 ms
  - Efficiency larger than 90%
- Also important:
  - Cost per unit area
  - Cost of DAQ and processing
  - Robustness
- Produced large system with RPCs
  - area for objects ~2x2m

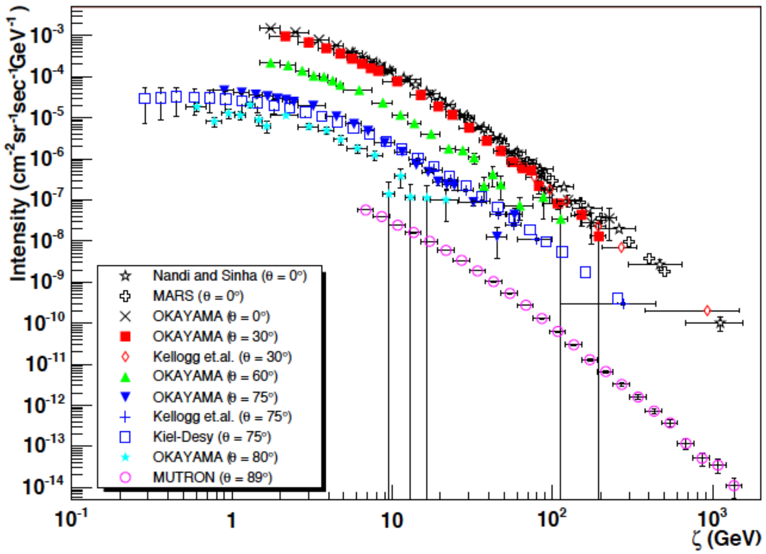


Thoughts on Paldiski

- Muon tomography only feasible technology to scan through so much concrete.
- Many university groups are working on it
  - Many different detector types
  - Many different algorithms
- Only very few companies; all early stage companies
  - To best of my knowledge no company (or university) has delivered successfully a project like yours.

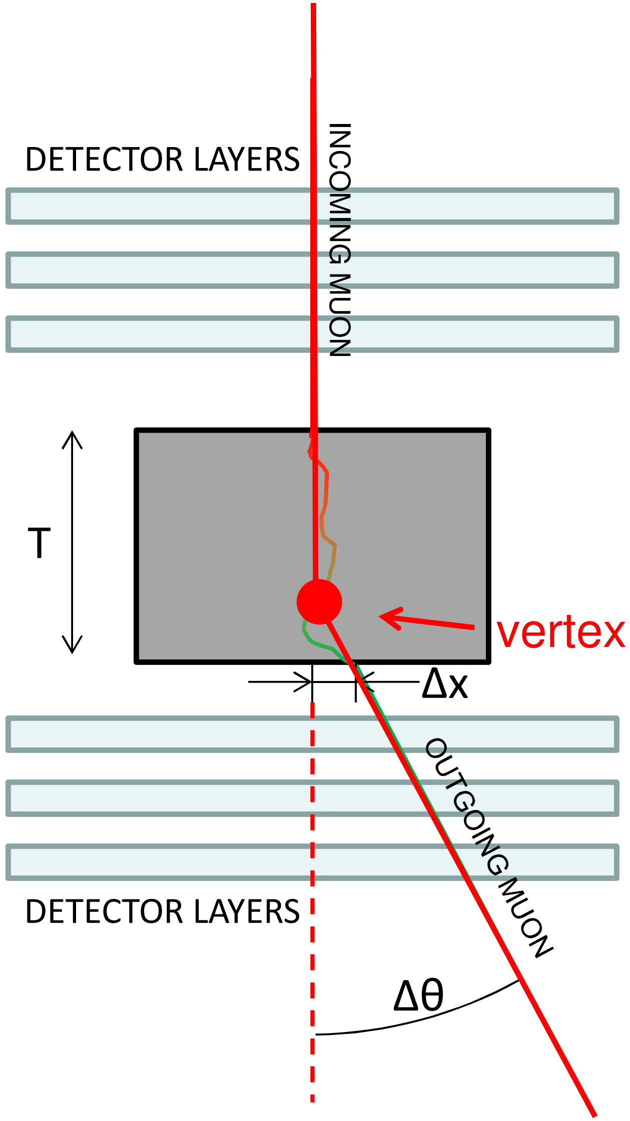
Possible deployment at Paldiski

- The good news: can get underneath and on top.
  - Maximises flux
  - Precision in x,y very good but in z bit worse



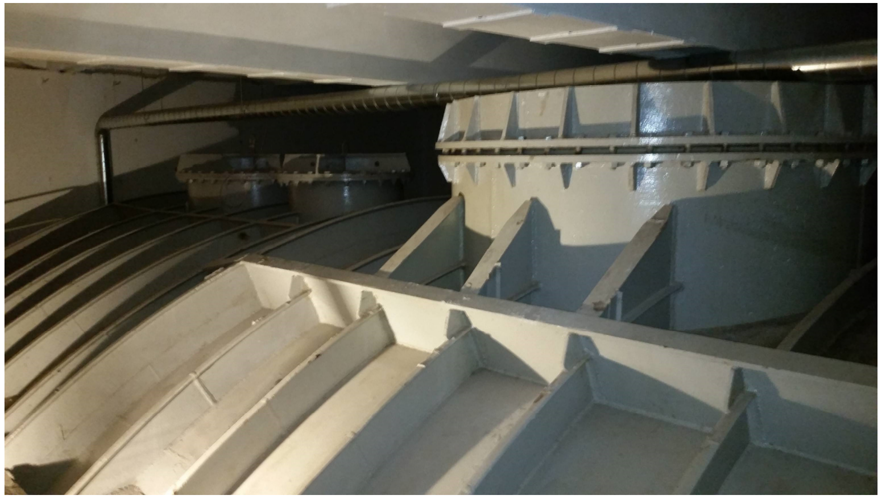
Possible deployment at Paldiski

- The good news: can get underneath and on top.
  - Maximises flux
  - Precision in x,y very good but in z poor
- The "interesting" news: tomography algorithms all rely on measurement of the scattering angle.
  - Need multiple layers
  - Several detector types cannot deal with background radiation.
- Need large detector area or move detectors around.
  - Our detectors cost around £5k/m^2 for one module.
  - At least 12 layers (3x & 3y above and below).



Possible deployment at Paldiski

- The not-so-nice news: can get underneath and on top.
  - Not much space underneath (and on top). The further apart the layers, the more precise the muon direction.
    - On top, can go on roof of sarcophagi

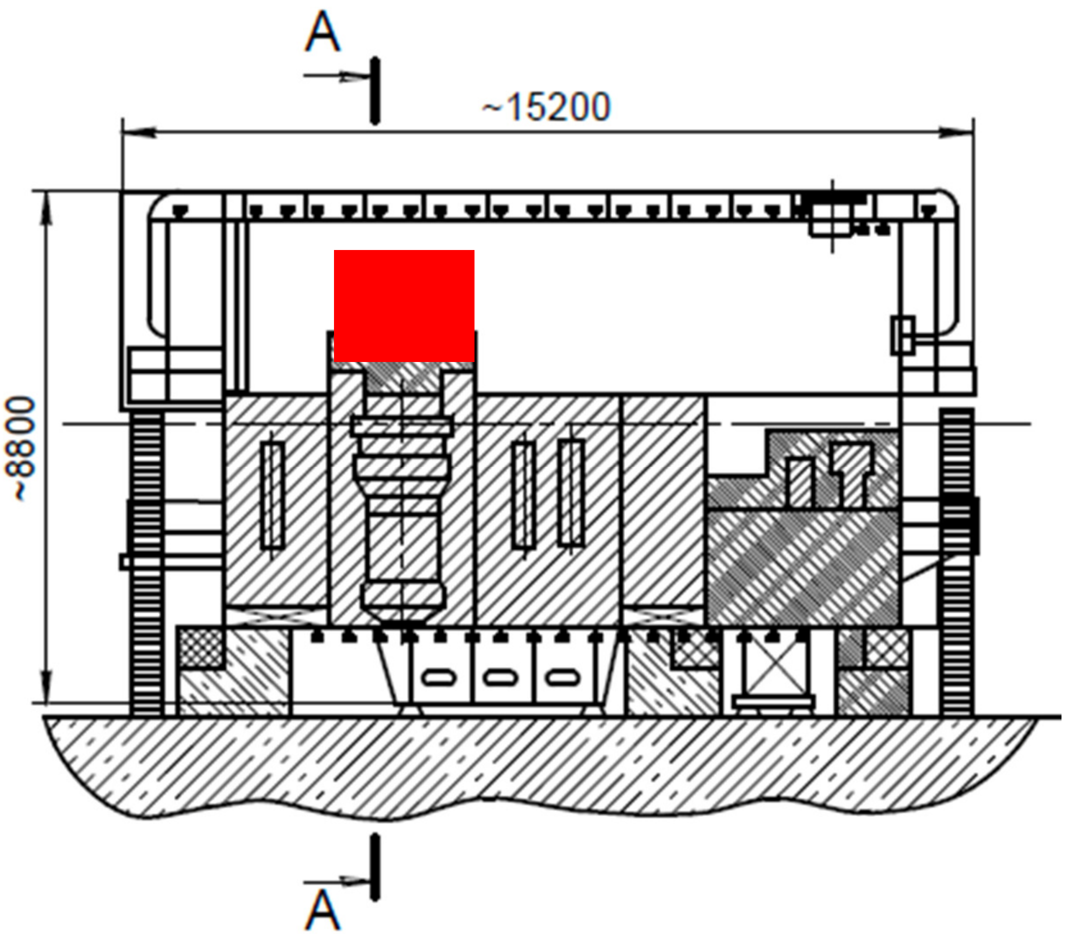


Possible deployment at Paldiski

- Alternatively, mount detector systems outside and measure horizontal.
  - Less flux but can still find the objects.
  - Can live with smaller detectors if one uses radiography

Possible deployment at Paldiski

- The great news: almost all sources in 3 large boxes:
  - paraffin, 400kg (75x75x75 cm)
  - steel/lead 1200 kg (48x48x48 cm)
  - metallic 350kg (35x35x35 cm)
- Rest are unknown wooden and plastic boxes but activity is small (~10^5 Bq)
- According to Valery, everything is in red area.
  - Simple to show the absence of large boxes in the rest.
  - Simple to extract location of boxes.



Structure project and cost indication

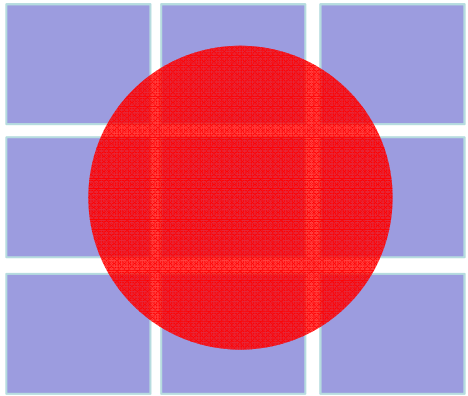
- Would start with MC study (~3 months)
- Suggest 2x6m system with 4 layers either side
- Build detector system (~6 months)
  - actual work ~2 months
  - cost indication (16x12x5k=960k)
- Install on site (~2 months)
- Measure 1 month per location: max 6 months per reactor
    - takes day or two to move detectors
    - this requires 1 person 1 day per week to check data quality
- Total final analysis ~4 months

- Minimum total effort needed:
  - 1 year FTE but not continuous (£150k)
  - technical support (£30k)
  - total cost £1.2M (+/-20% and ideal case)

Just an indication, not an offer!

Budget deployment at Paldiski

- Cheapest way:
  - Confirm boxes in red area.
  - Confirm no boxes next to red area.
- Start with MC study (~3 months)
- Suggest 2x2m^2 system with 4 layers
- Measure 9 areas (3x3 grid) 2 weeks per area
  - Takes day or two to move detectors
- Build detector system (~6 months)
  - actual work ~2 months
    - cost indication (16x4x5k=320k)
    - this requires 1 person 1 day per week to check data quality
- Total final analysis ~4 months
- Minimum total effort needed:
  - 1 year FTE but not continuous (£150k)
  - technical support (£30k)
  - total cost £0.5M (+/-20% and ideal case)



Summary

- A muon tomography campaign is definitely possible and will tell you where the three big boxes are in not too much time.
  - Can find wooden boxes as well, but Pu and Sr filling might make it difficult.
- Need large detector and install above and below the Units.
  - Can try radiography as well.
- Can provide simulated data to qualify the imaging contractor.