Resistive Plate Chambers for Tomography and Radiography

Muon and Neutrino Radiography – Clermont Ferrand, April 2012

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Outlook

- Introduction
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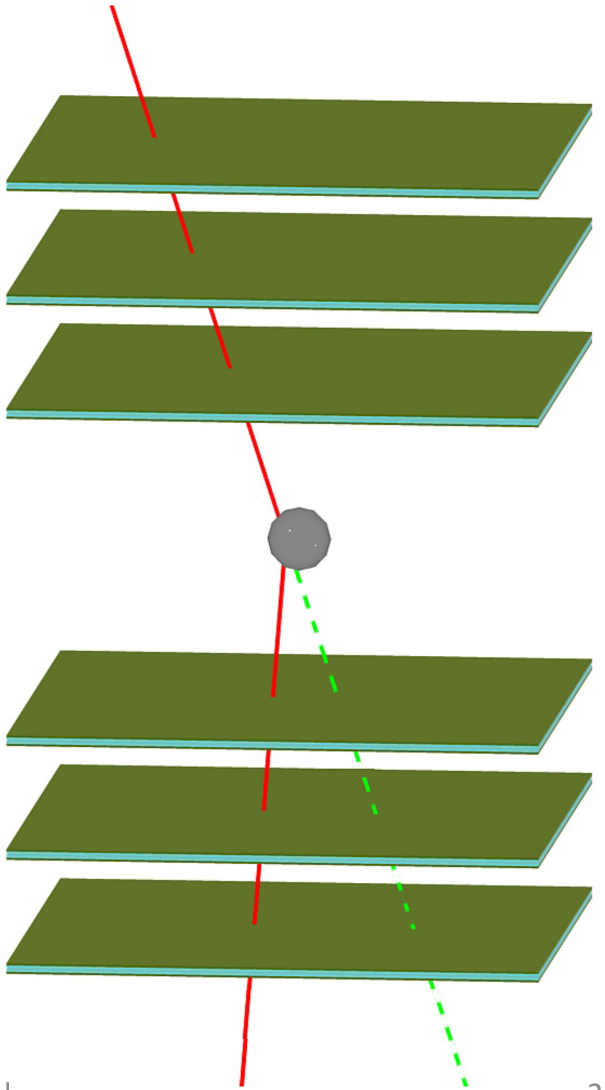
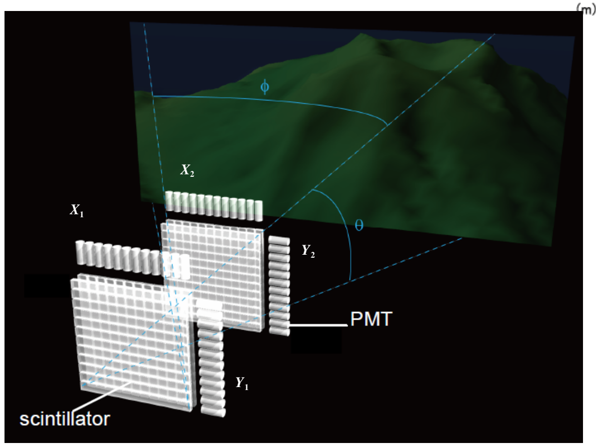
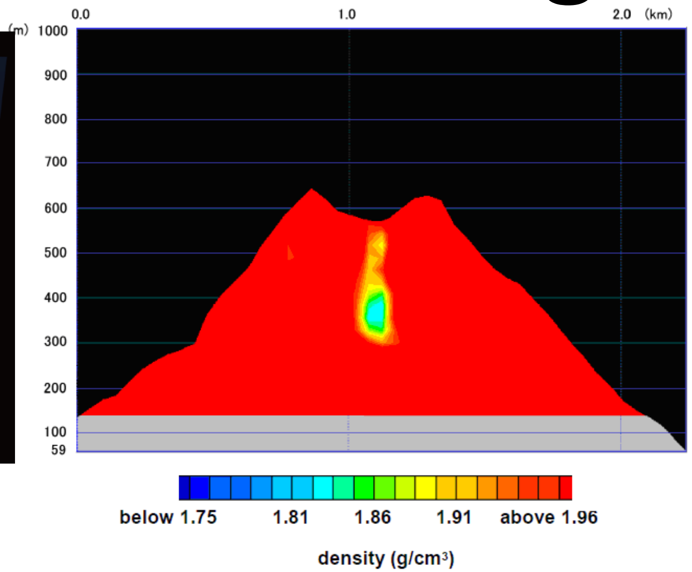
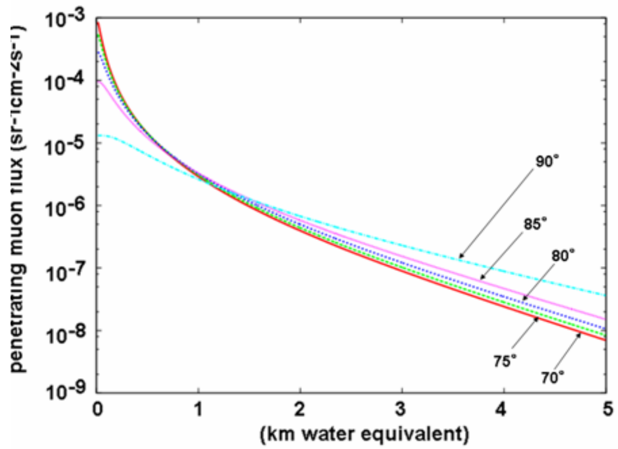
  - Muon scattering tomography
  - Radiography vs. tomography
- RPCs and MST hardware
  - RPCs
  - MST setup
- Data analysis
  - Peak distribution
  - Track fitting
  - Reconstruction
- Current developments
- Summary



Volcano Radiography







From Tanaka *et al*. 2009 [2]

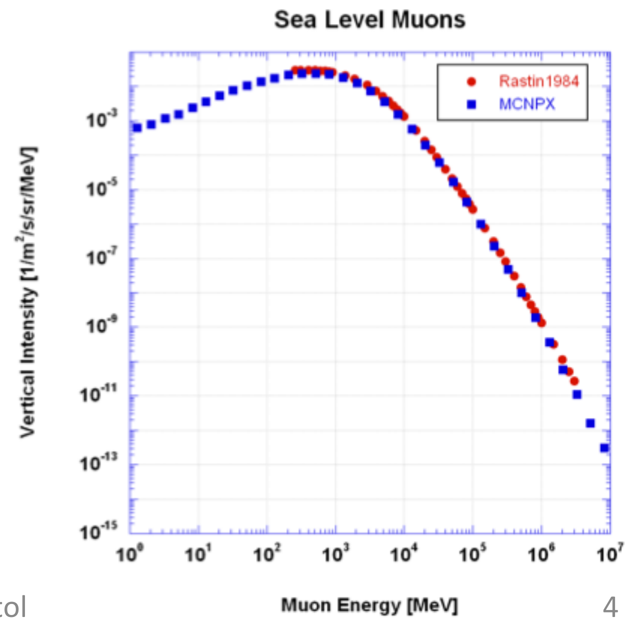
- Obtain information on the density distribution within geological targets.
- Measure cosmic muon flux through target with detector setup.
- Compare measured flux with (known) flux from the incidence direction.
- From muon flux attenuation derive estimate of target density.

Muon Scattering Tomography

- Homeland security a hot topic: need to scan shipping containers for nuclear material to stop potential threats.
- University of Bristol (UoB) and Atomic Weapon Establishment (AWE) partnership to build and study a prototype scanner for Muon Scattering Tomography (MST).
- The prototype is used to scan a target volume in search of high-Z materials.

Why?

- Muons are excellent probes:
  - Readily available, with flux of ~100 Hz/m^2 and energies from 0.1 GeV upwards.
  - Virtually impossible to screen against, since for 1 GeV muons dE/dx ~ 2 MeV·g^{-1}·cm^2.
  - Charged; can be easily detected.
  - No radiation hazard for the scanner operators.
  - MST is undetectable by the object being scanned, since no extra radiation is introduced.

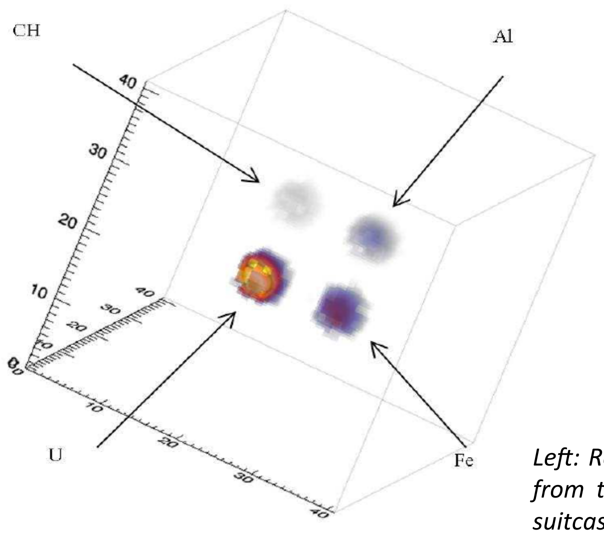


Muon Scattering Tomography

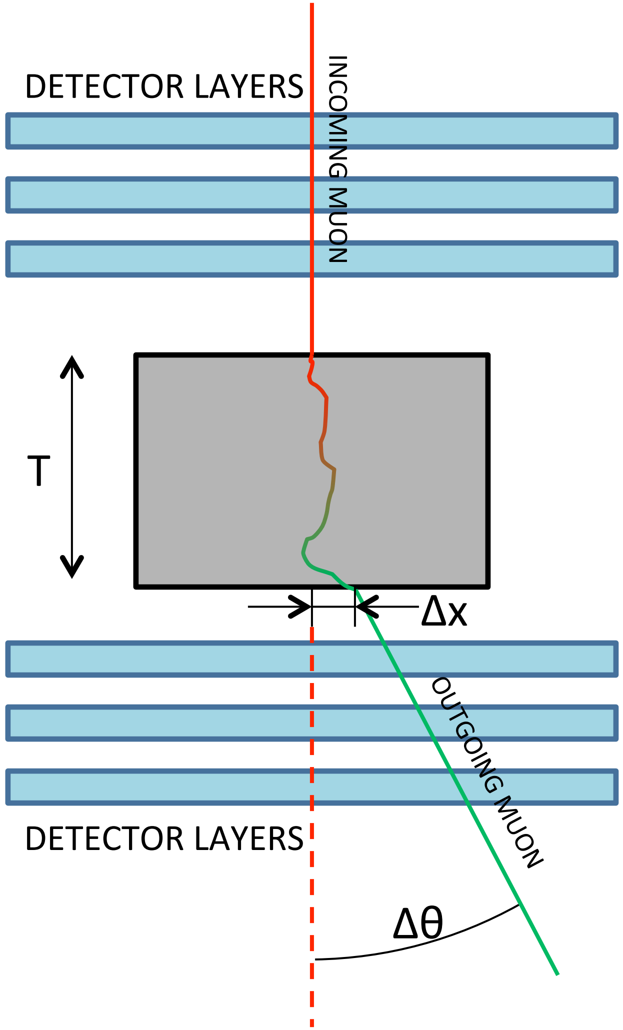
- Muons undergo multiple coulomb scattering within the detector volume.
- The angular distribution is Gaussian, with σ_0 depending on the radiation length X_0 (and ultimately on Z^2).
- Due to the Z^2 the method is very sensitive for high-Z materials.

$$X_0 \approx \frac{A \cdot 716.4 g / cm^2}{\rho \cdot Z \cdot (Z+1) \ln(287/Z)}$$

$$\sigma_0^2 \approx \left(\frac{15 MeV}{pc\beta}\right)^2 \frac{\mathrm{T}}{\mathrm{X}_0}$$



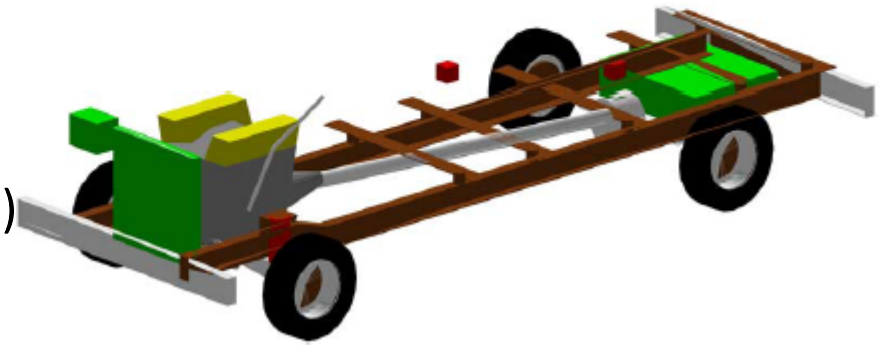
Left: Reconstructed image showing muon scattering from tennis ball of different materials in a typical suitcase volume (courtesy AWE).

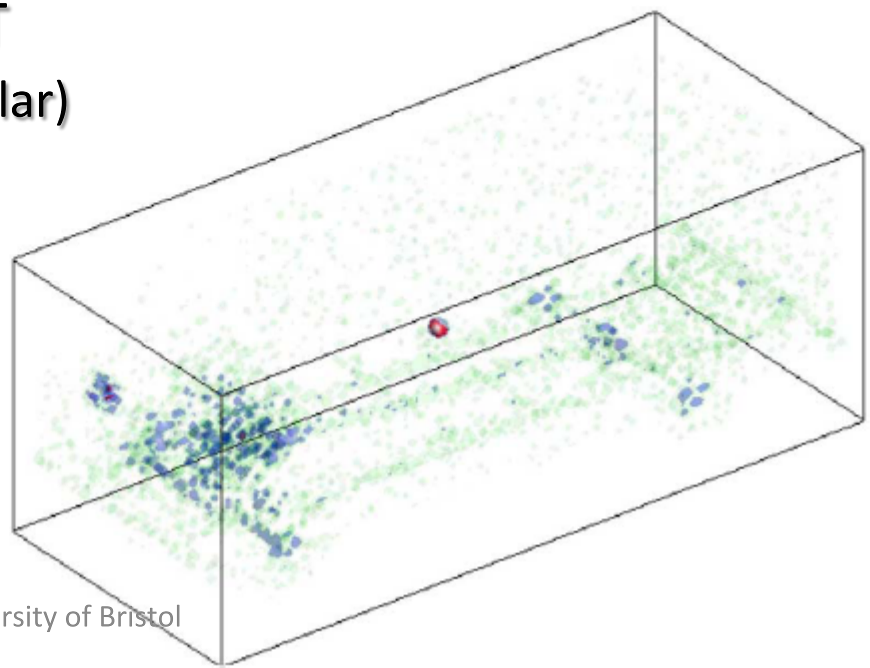


Muon scattering tomography principle.

MST Detector Requirements

- Applying MST to homeland security introduces some additional requirements for the detector:
  - Large area (shipping containers, trucks)
  - Scalability
  - Low cost per unit area
- RPCs are a very good option for MST
  - Good resolution (timing / spatial / angular)
  - Efficient
  - Robust





Top:
Simulation of a passenger van containing a tungsten block (10 cm x 10 cm x 10 cm). [5]
Bottom:
Reconstruction of 1 minute of simulated muon exposure for the van above. The tungsten block is clearly visible. [5]

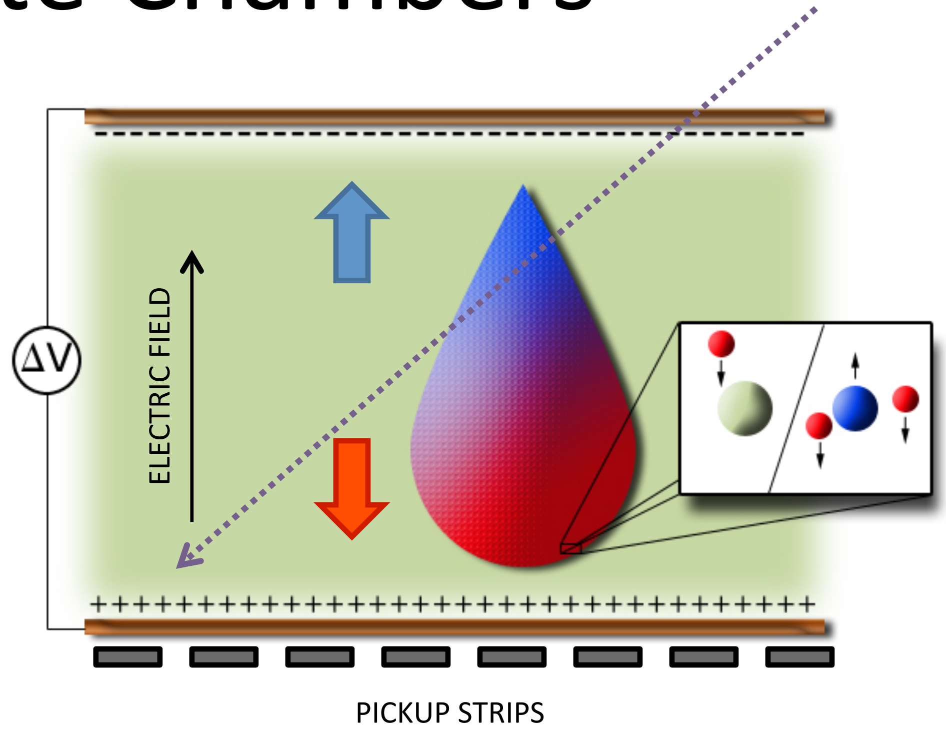
Radiography vs. Tomography

A comparison of the shared requirements of these two methods:

Volcano Radiography		*MS Tomography*
Large distance to target requires good angular resolution	– Angular/spatial resolution	Identify target Z by scattering behaviour
Can identify muon direction (forward/backward) by hit timing	– Time resolution	Need to precisely associate hits to muon tracks
Detectors deployed in non-ideal circumstances	– Robustness	Scanners in freight harbors need to be robust
Set up experiment "out of the box" without requiring particular expertise	– Ease of use	Set up easy-to-use systems in harbors for non-scientific personnel
Large detector area allows for large acceptance	– Scalability to large areas	Standard shipping container roughly 7x4x2 m in size
Detectors can be built larger without significant increase in cost	– Cost efficiency	Wide-range application requires cost-efficient technology

Resistive Plate Chambers

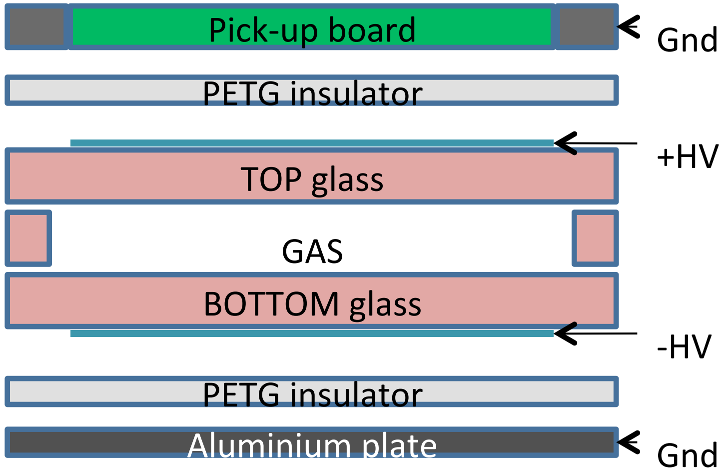
- A gas cavity of 2 mm is filled with gas mixture (typically Argon, Isobutane, Freon or SF6)
- An electric field E_0 is established by means of high voltage (~ 9 kV)
- As the charged particle travels in the gas, it creates free electrons which are accelerated by E_0 and produce more free electron (avalanche effect) [4]
- The avalanche induces a signal on the pickup strips or pads

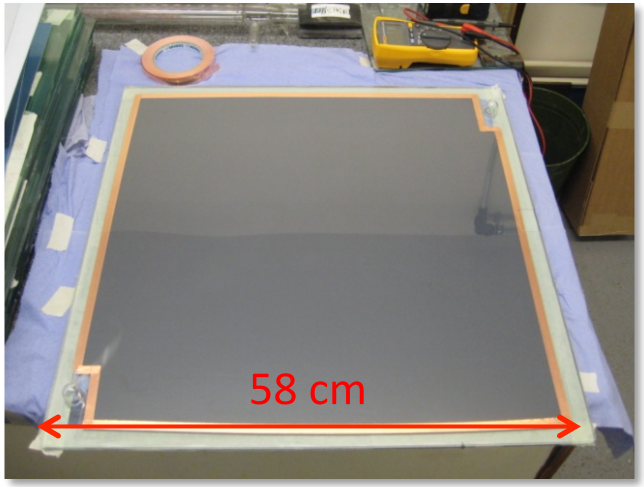


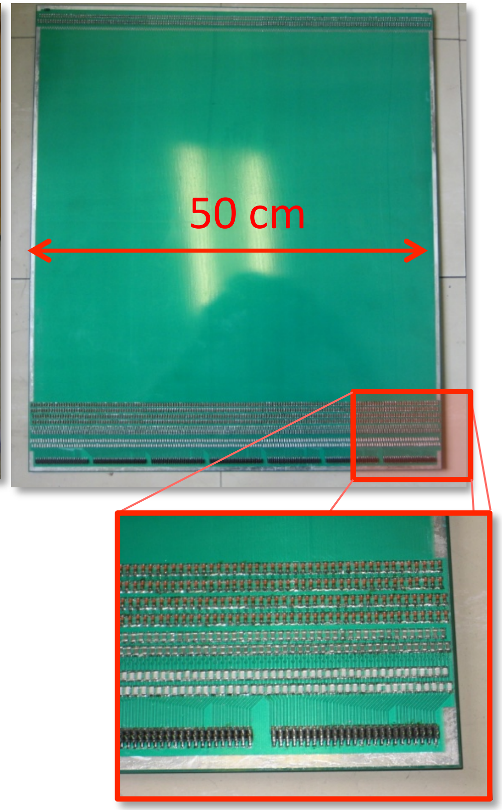
Features of RPCs in general:

- Ruggedness
- Low cost per unit area
- High efficiency: typically above 90%
- Excellent time resolution: ~ 1 ns
- Good space resolution: < 1 mm
- Scalability to large sizes: e.g. muon chambers of CMS@CERN use areas ~10^3 m^2
- Well-established technology

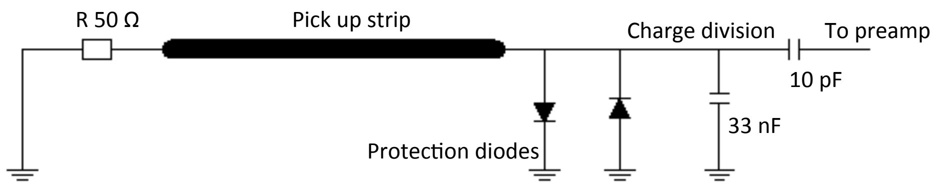
Setup - RPC



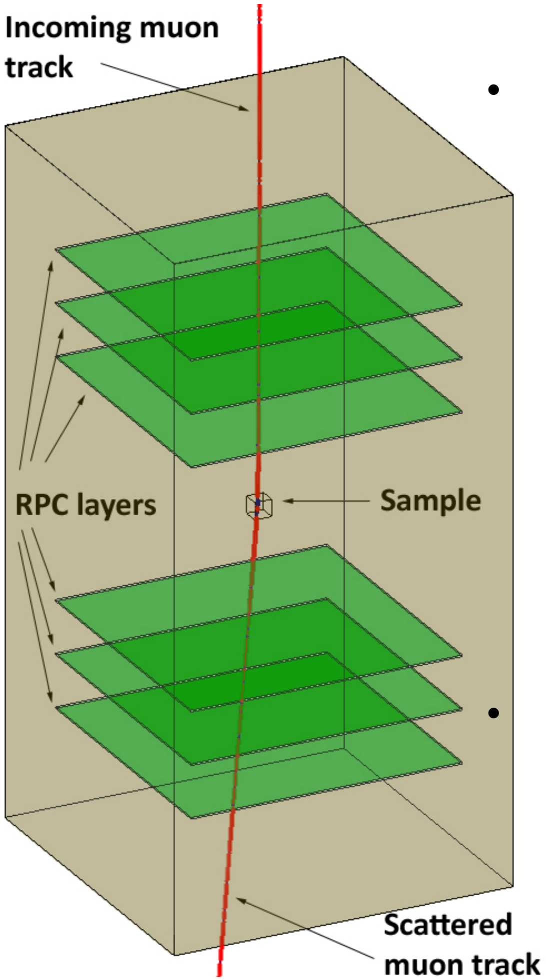




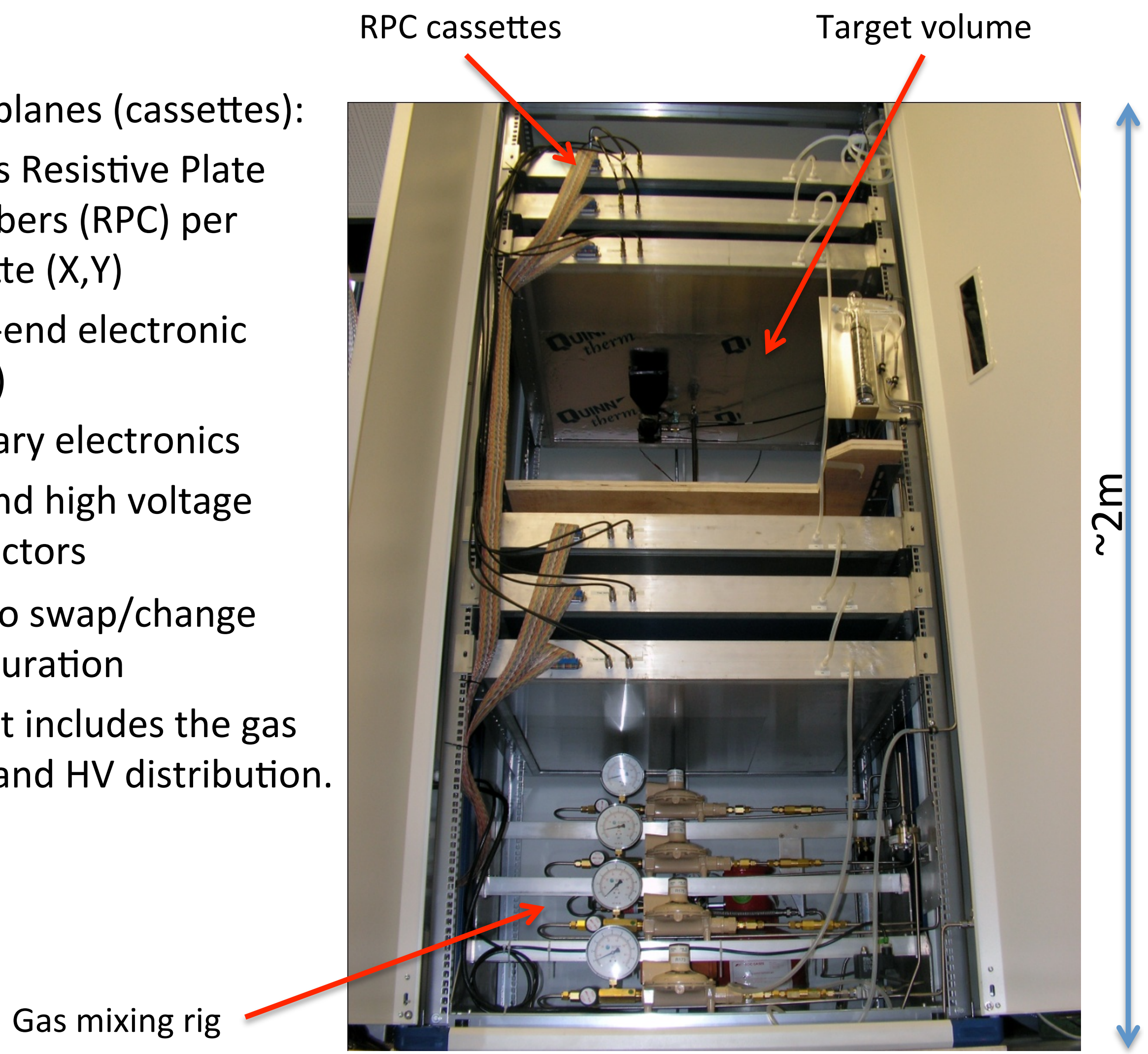
- Glass RPC
- 2 mm gas gap
- Argon, freon, iso-butane, SF_6
- 50 cm x 50 cm active area
- 330 strips per RPC provide 1D readout
- Strip pitch: 1.5 mm



Setup – Hardware Overview



- 6 readout planes (cassettes):
  - 2 glass Resistive Plate Chambers (RPC) per cassette (X,Y)
  - Front-end electronic (Helix)
  - Auxiliary electronics
  - Gas and high voltage connectors
  - Easy to swap/change configuration
- The cabinet includes the gas mixing rig and HV distribution.

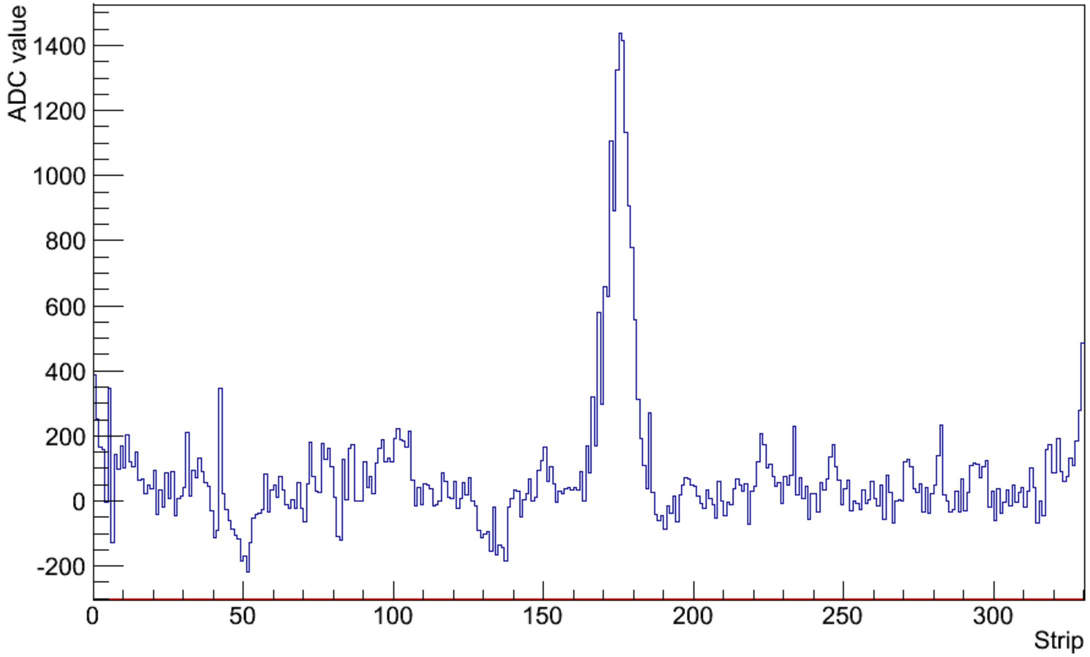


RPC Signals

- A simple centre of gravity algorithm provides the hit position.

- 1000 ADC counts correspond to ~50 pC on the strip.

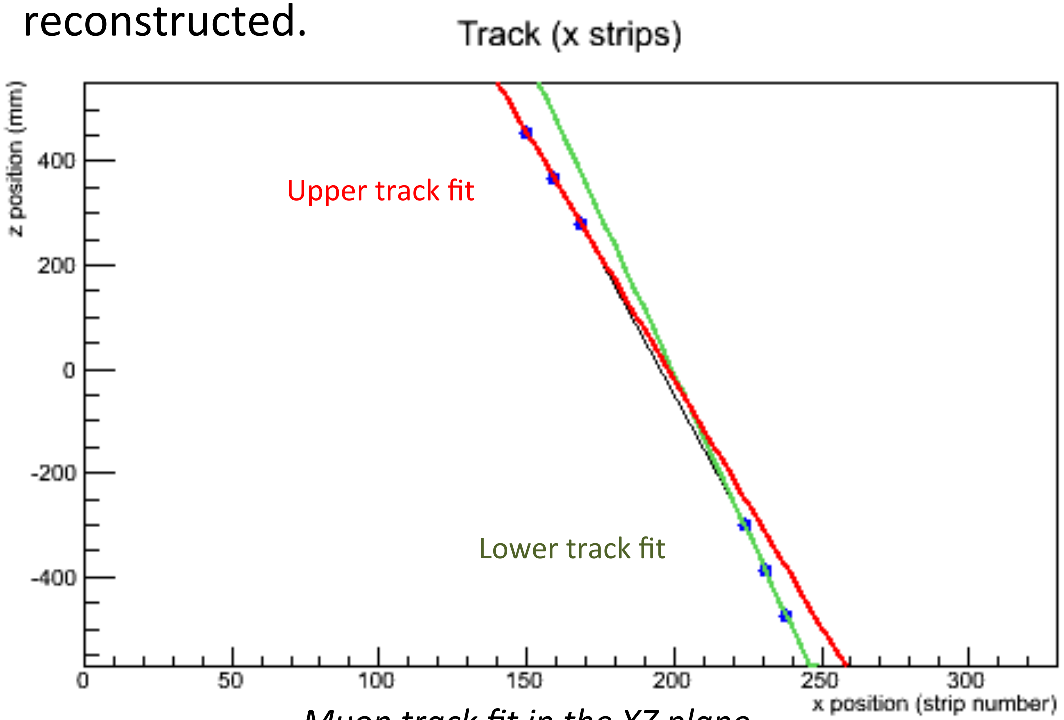
- Signal/noise ratio varies between 25 and 90 among layers:
    - Mainly due to variations in the noise (Complicated common mode).



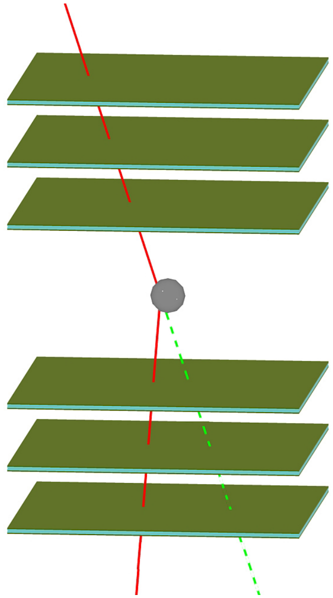
Signal induced on the strips of one RPC by a passing muon. Pedestal subtracted.

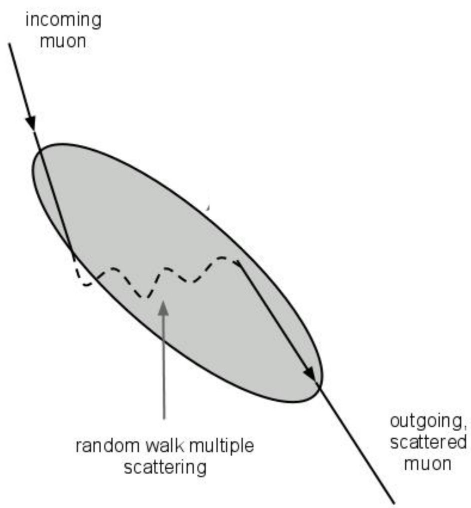
Tracks

- Tracks are fitted in the X and Y components. From a straight-line fit to the upper and lower hits the incoming and outgoing muon tracks are reconstructed.
- Incoming muon undergoes multiple scattering and exits the volume. The amount of scattering and the likely position where the scattering happened (vertex) can then be reconstructed.



Muon track fit in the XZ plane.





Summary of our MST prototype

- Raw spatial resolution varies from channel to channel, but between 0.6mm – 1mm.
- Timing resolution in the order of ns.
- Hit finding efficiency in each layer > 99%.

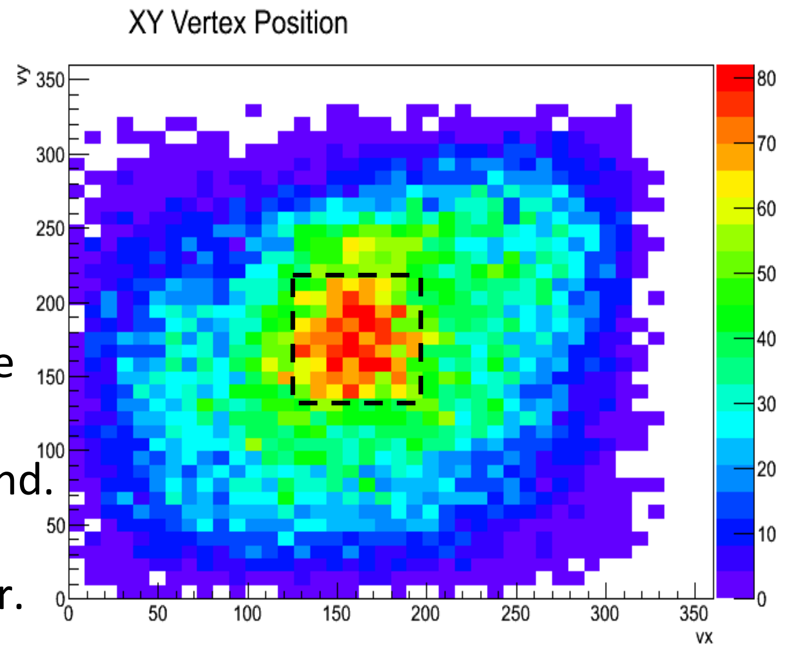
- These parameters are optimized for our project.

Test with lead blocks

- Proof of principle. (Not proper tomography!)

- 10 cm x 10 cm x 15 cm lead block in target volume.
- Combined track and vertex fitting algorithm.
- Cut on χ^2 of the tracks.
- Plot scatter vertex positions with scatter angle above 30 mrad.
- See the lead block clearly above a smooth background.

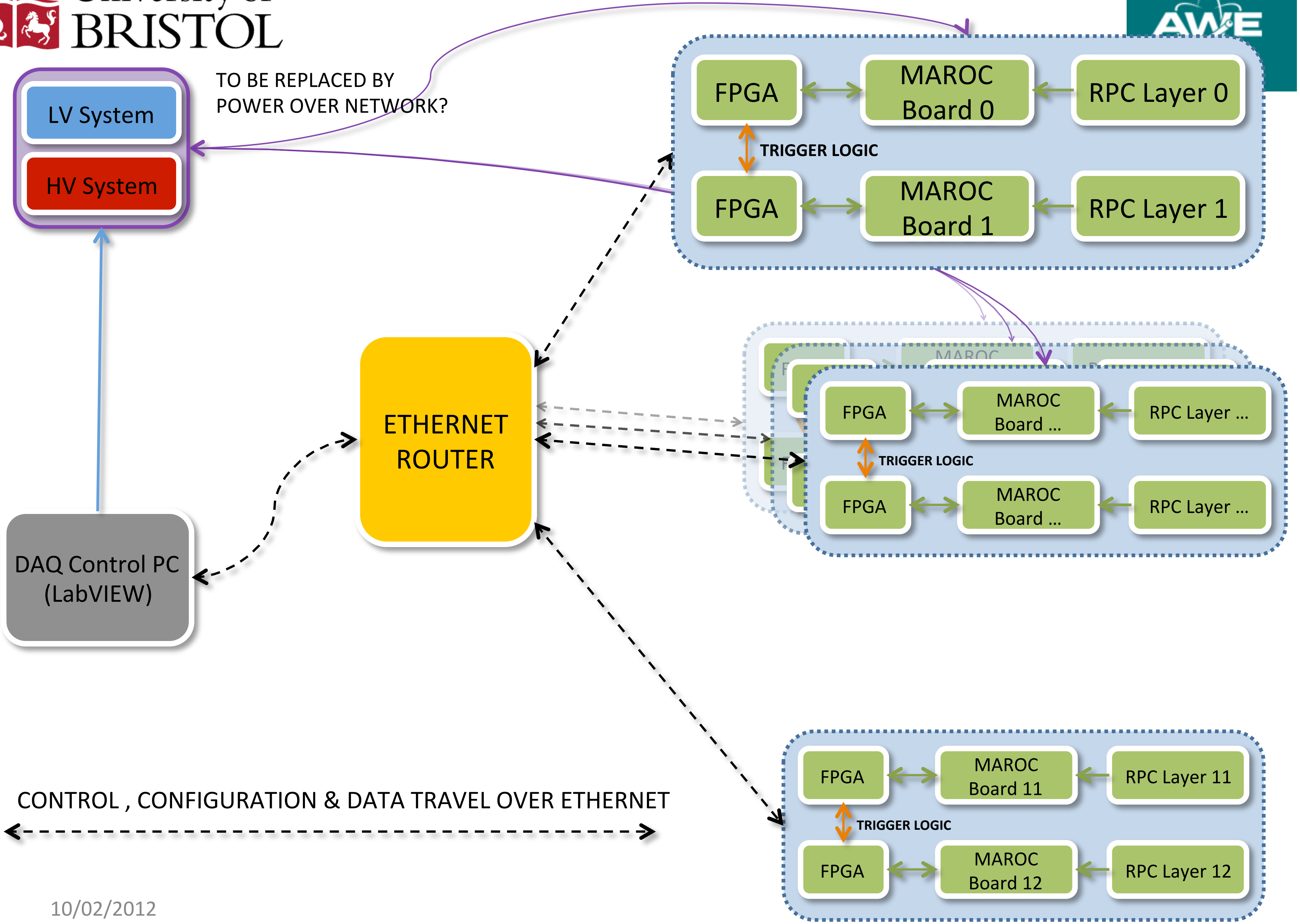
- Simple analysis made in Bristol to check the detector.
- AWE works on algorithms for proper tomography.
- Bristol developing alternative techniques to complement the analysis.



Vertex positions in XY plane with scattering angle > 30 mrad. Units are in strips.

Current Developments

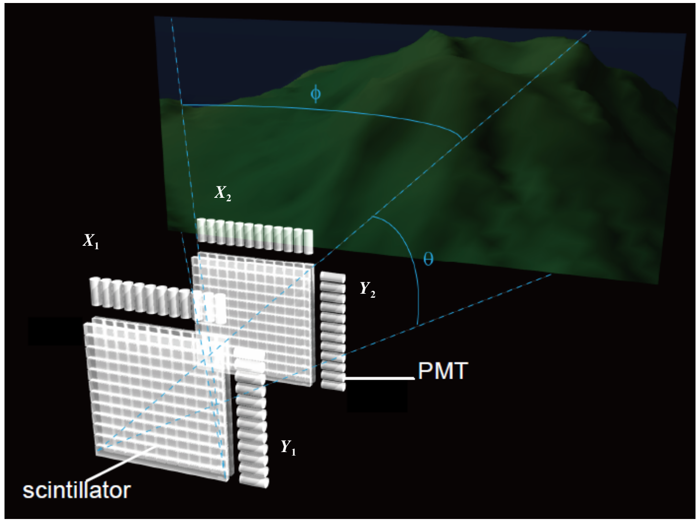
- Replacing the readout chips.
  - Developing new DAQ system at Bristol.
  - Chose the MAROC chips (developed at LAL-France).
- Working towards very large systems.
  - Investigating maximum strip length.
  - Investigating maximum pitch.
- Working on making the system portable.
  - Developing "sealed-for-life" detectors, i.e. no constant gas flushing required.
  - New boards use Ethernet protocols for configuration and readout. Suitable to be used remotely.


TO BE REPLACED BY
POWER OVER NETWORK?
LV System
HV System
DAQ Control PC
(LabVIEW)
ETHERNET
ROUTER
FPGA
MAROC
Board 0
RPC Layer 0
TRIGGER LOGIC
FPGA
MAROC
Board 1
RPC Layer 1
FPGA
MAROC
Board ...
RPC Layer ...
TRIGGER LOGIC
FPGA
MAROC
Board ...
RPC Layer ...
FPGA
MAROC
Board 11
RPC Layer 11
TRIGGER LOGIC
FPGA
MAROC
Board 12
RPC Layer 12
CONTROL , CONFIGURATION & DATA TRAVEL OVER ETHERNET

Volcano Radiography

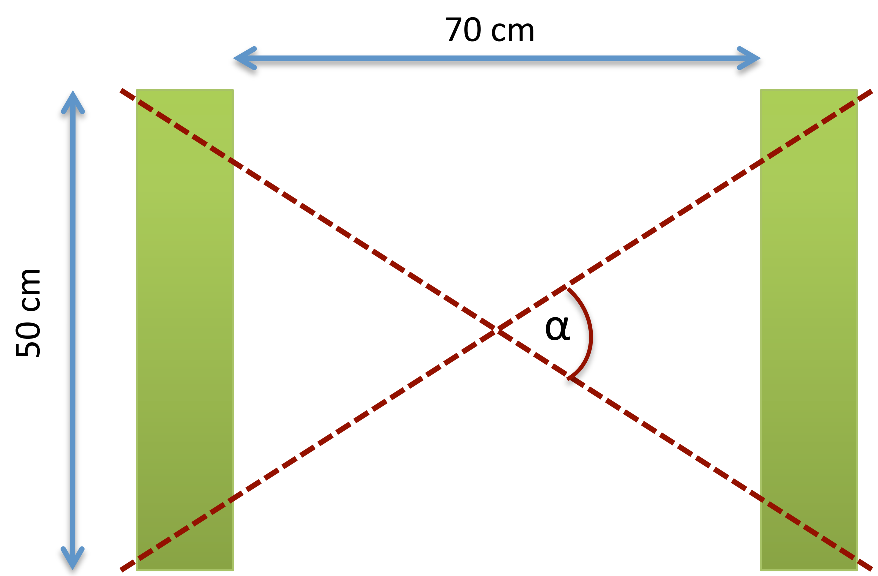
RPCs very applicable:

- Good angular and spatial resolution allows for precise reconstruction of muon tracks
- RPCs relatively cheap per square metre
- RPCs offer very good time resolution
- Single output + self-triggering + precise time stamp -> self-contained detector units
- Sealed-for-life solutions and ethernet readout allow for easy long-term application



Angular Resolution and Acceptance

- Dependent on spatial resolution and detector setup.
- Spacing of 70cm and 1mm resolution yields angular resolution of ~1.4 mrad.
- Timing resolution of ~2ns allows for left/right discrimination.
- Obtain real-time muon energy spectrum from wrong direction muons.



2 detector setup. Dashed lines indicate maximal resolvable angle.

In this setup, α ≈ 71 degrees, so the acceptance would be ~1.4 sr.

Conclusions

- We successfully built and tested a prototype to track muons with fine pitch RPCs.
- The prototype is suitable to perform Muon Scattering Tomography.
- RPCs are a successul, well-established and well-tested technology.
- Similar requirements show that this technology is very applicable for use in geological radiography.
- We are working on further developments to make our RPC systems larger, portable, and more useable out-of-the-box.

We are excited about the prospect of expanding our area of application and are open to collaboration and discussion.

Thank you for your attention!

References

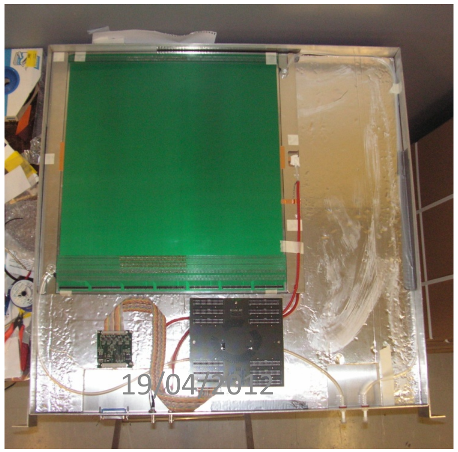
- [1] Cox et al., “*Detector Requirements for a Cosmic Ray Muon Scattering Tomography System*”, Nuclear Science Symposium Conference Record, 2008. NSS '08. IEEE
- [2] Tanaka et al., “*Development of a portable assembly-type cosmic-ray muon module for measuring the density structure of a column of magma”, Earth Planets Space, 62, 119–129, 2010*
- [3] Gibert et al., “Muon tomography: Plans for observations in the Lesser Antilles”, *Earth Planets Space, 62, 153–165, 2010*
- [4] Lippmann, “*Detector physics of resistive plate chambers*”, Nuclear Science Symposium Conference Record, 2002 IEEE
- [5] Schultz et al., *“Statistical Reconstruction for Cosmic Ray Muon Tomography”,* IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 16, NO. 8, AUGUST 2007

Backup slides

Setup - Electronics

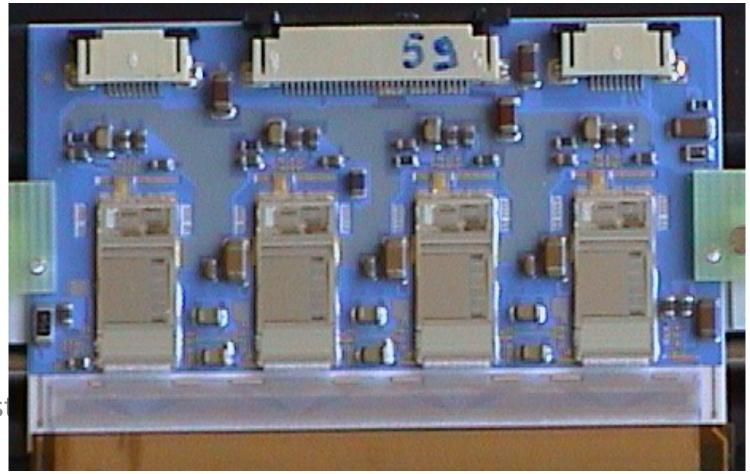
- Front-end: Helix chips.
  - Analog chips, originally developed for silicon microstrip detectors and microstrip gaseous chambers.
  - 128 analog inputs; 1 analog output.
  - Self trigger capability (not in our setup).
  - In our system 4 Helix are daisy-chained (hybrid): the samples from the 512 inputs are sent onto a single analog line.
- The 330 strips from an RPC are fed to one hybrid (some spare inputs).
- Analog data from the Helix chips are fed to CAEN ADC and digitized.

- Problem: no longer available (and not many spares). Need a replacement.

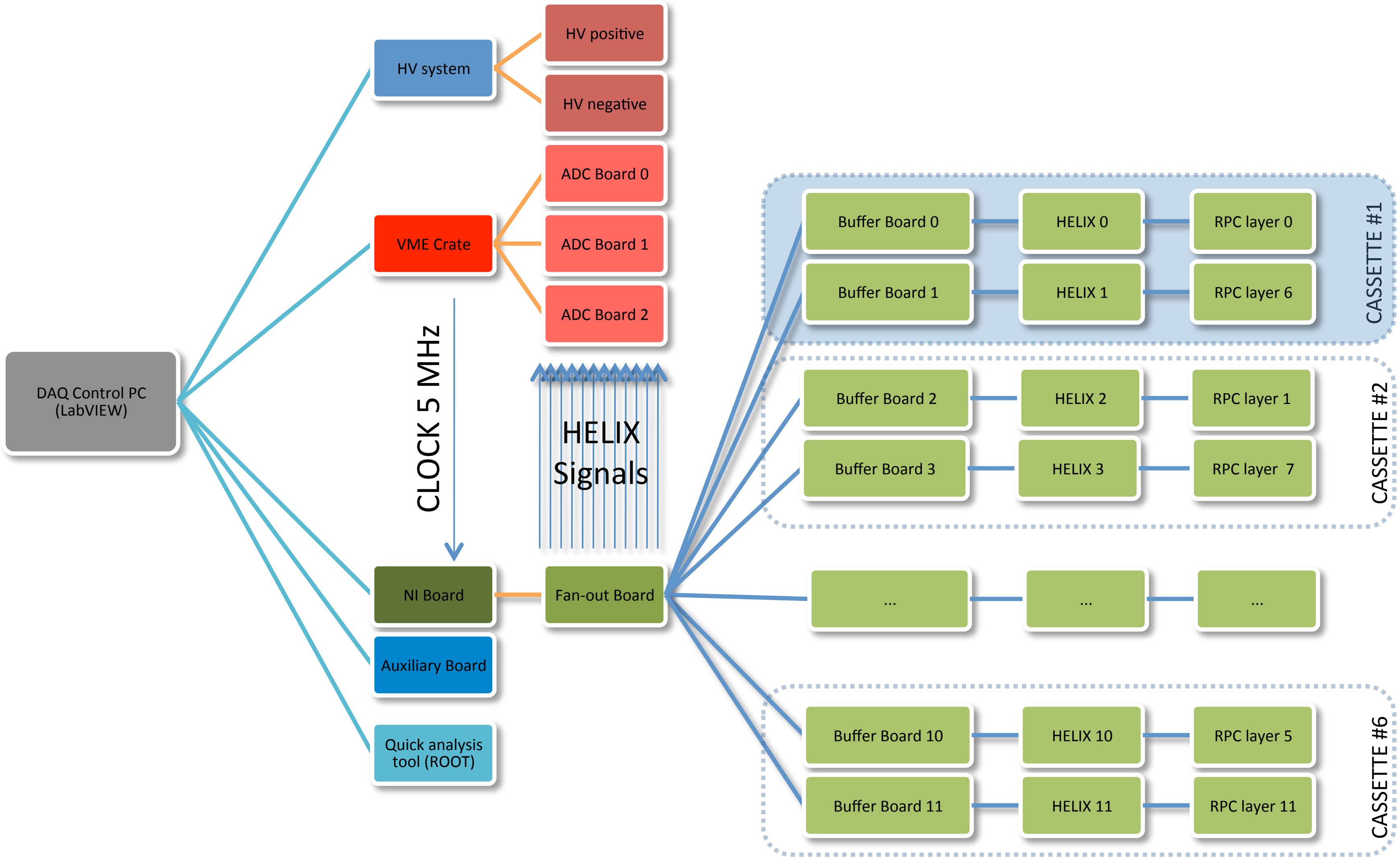


Left: Cassette with one of the two RPC already installed.

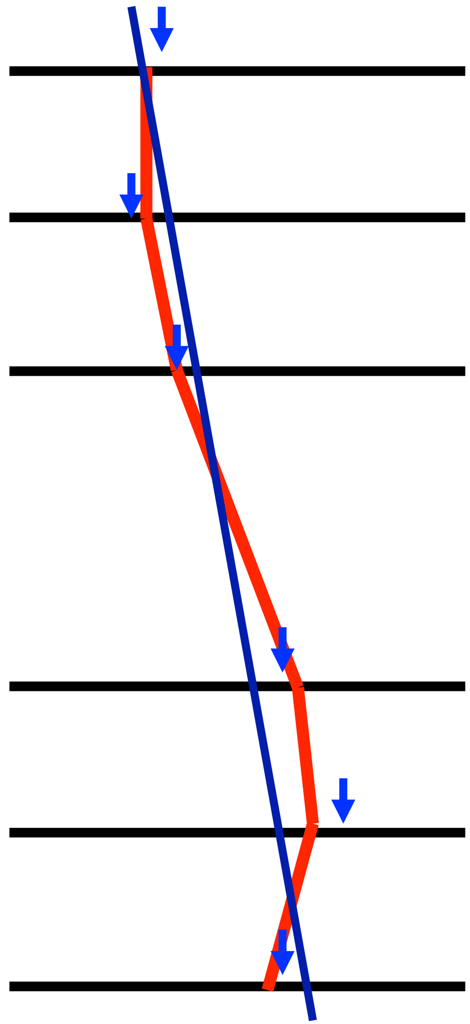
Right: HELIX hybrid.



Setup – DAQ overview (HELIX)



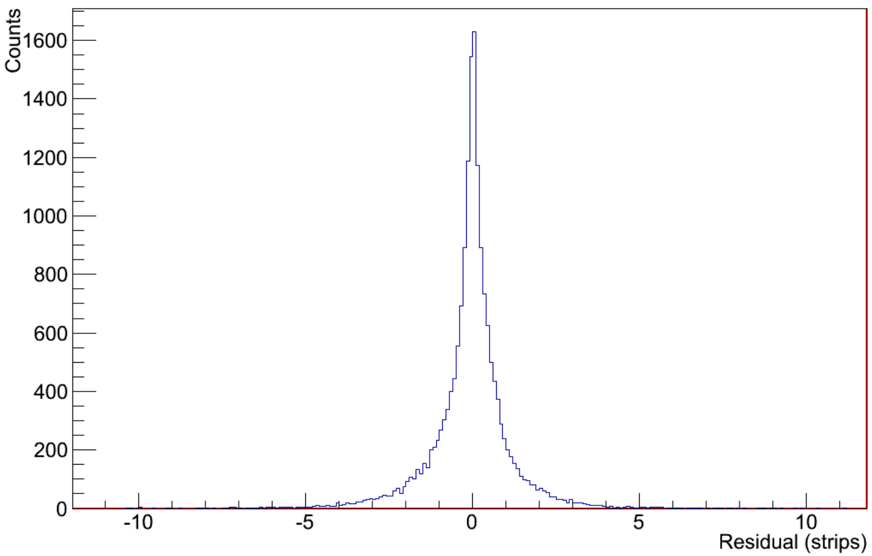
Raw vs. Intrinsic Resolution

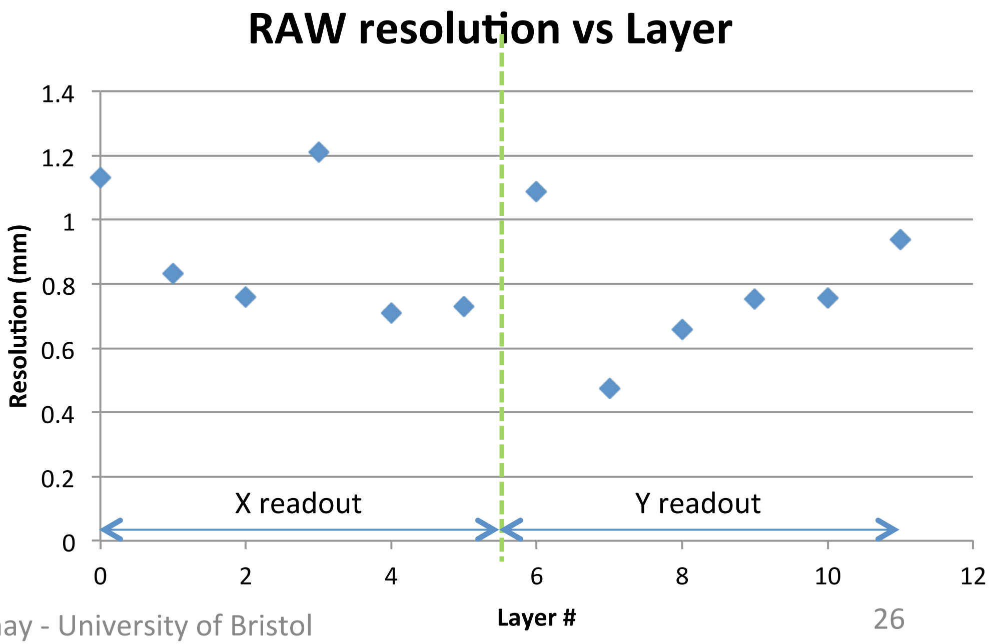


Track Residuals

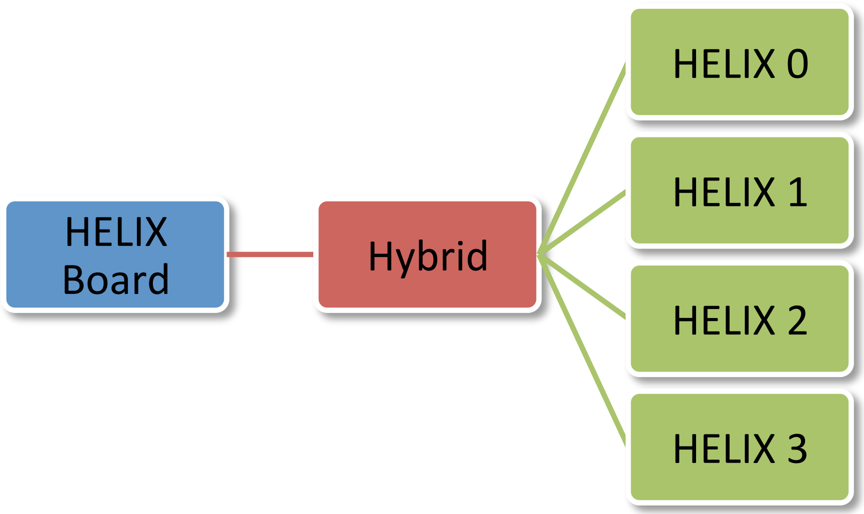
- Raw difference between reconstructed track and hit position for one layer.
- Overall hit finding efficiency> 99%.

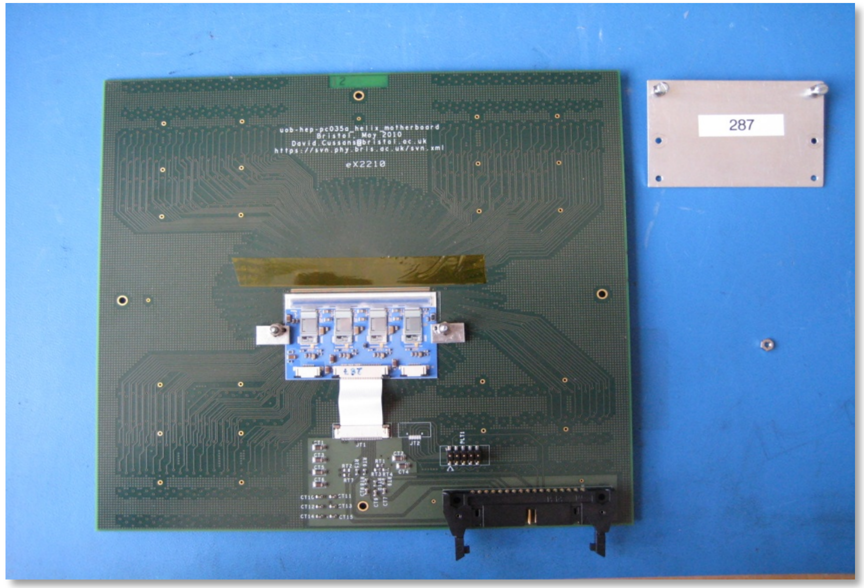
- Contribution of multiple scattering due to the detector material (σ_{scat}) is not taken into account. We are working on a Monte Carlo simulation to properly estimate this contribution.
- Also not accounted for is the extrapolation error due to the position of the layer on the track.





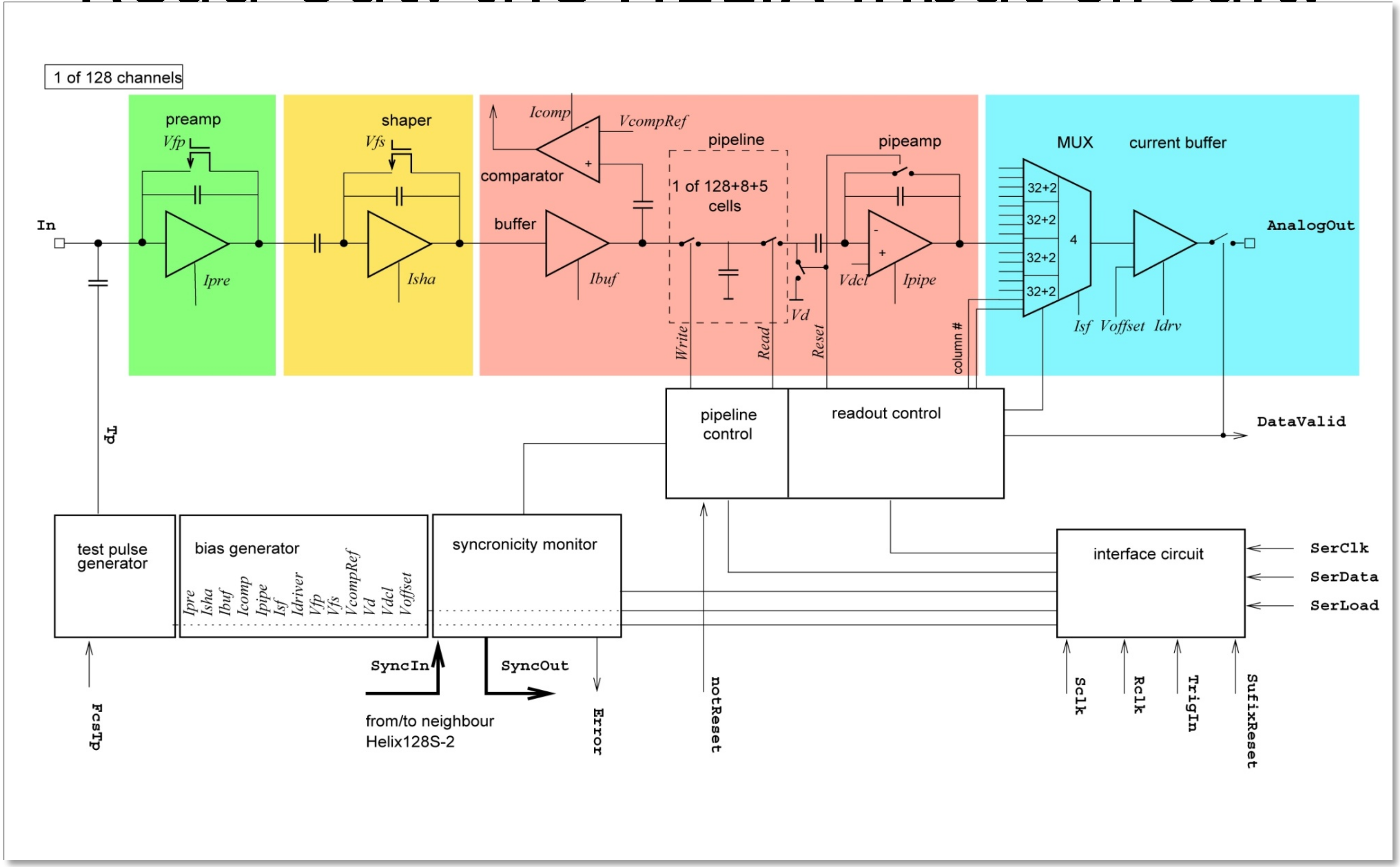
Read-out: HELIX hybrid and mezzanine





- 4 HELIX are daisy-chained and hosted on a hybrid chip: this is our basic front-end unit read-out
- Each hybrid has been wire bonded to a HELIX mezzanine board (designed in Bristol) which acts as an interface between the 100 µm pitch adaptor of the hybrid and the strip board
- Mezzanine:
  - 11 connectors (50-way, 1/10 inch pitch) to plug the strips in
  - Provide power to the HELIX
  - 1mezzanine: 1 RPC
  - Output samples, power and control signals are all transferred through the mezzanine

Read-out: the HELIX input circuit.

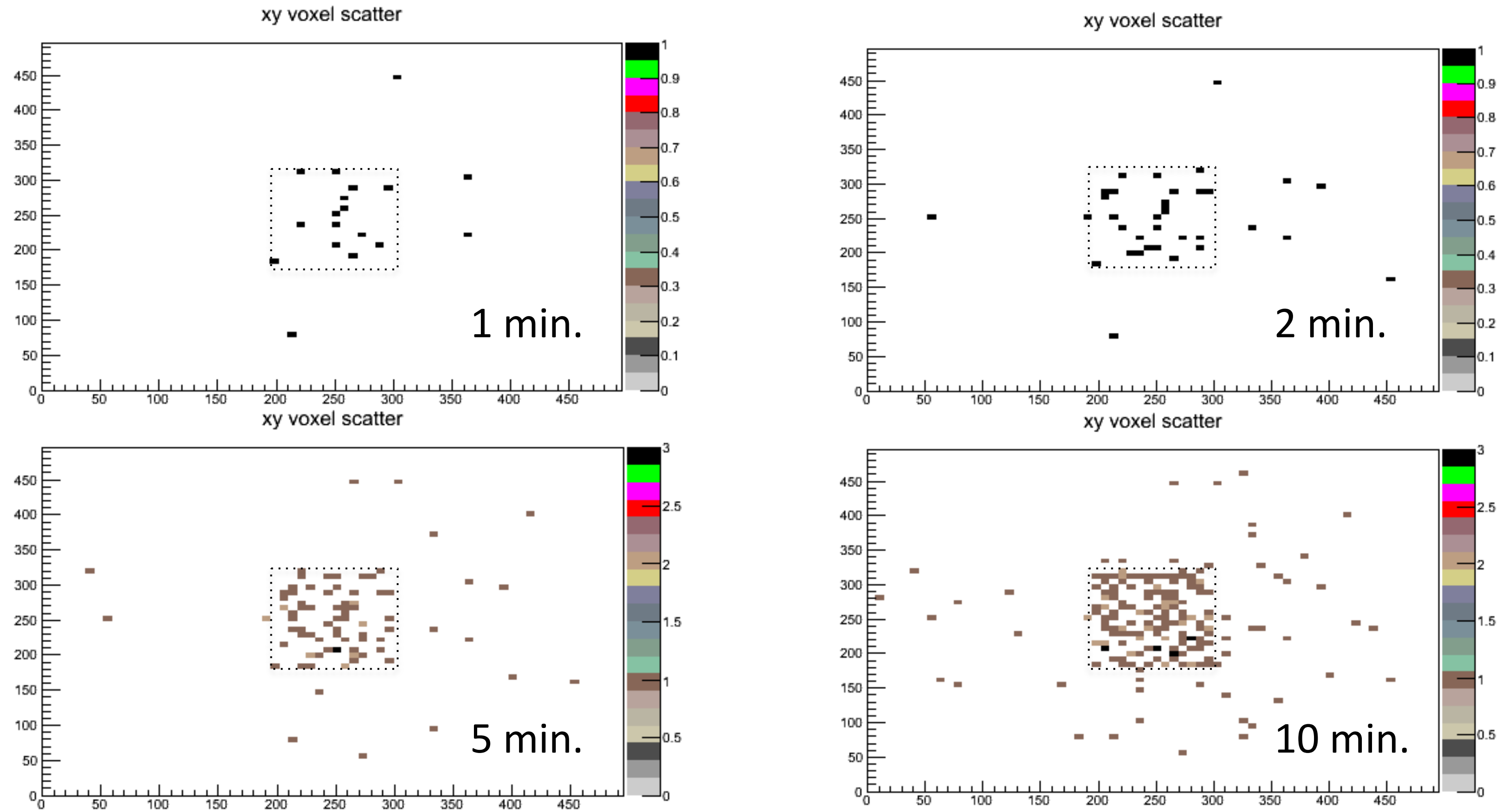


Summary of layer distributions

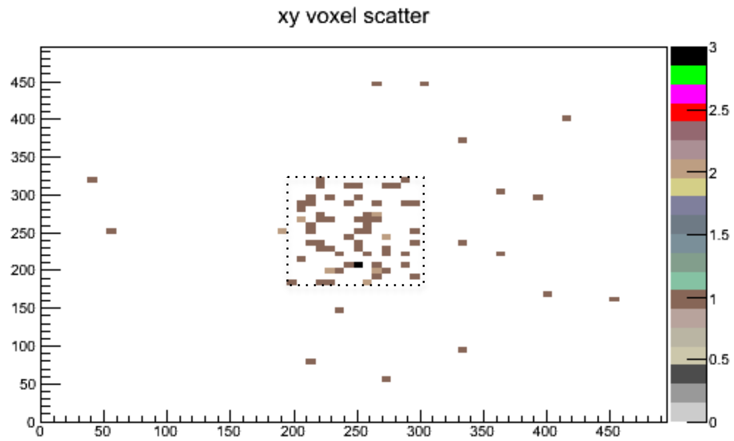
Layer	Peak (MPV)	Cluster (MPV)	Sigma Noise	S/N (averaged)
0	1364	6915	74	93
1	1342	3815	56	68
2	867	3350	58	58
3	1135	4138	60	69
4	1133	3923	90	44
5	889	3326	70	47
6	1151	4482	69	65
7	1144	3679	157	23
8	1058	3087	100	31
9	843	2887	61	47
10	791	3077	64	48
11	988	4007	74	54

Scan Time Estimate – I

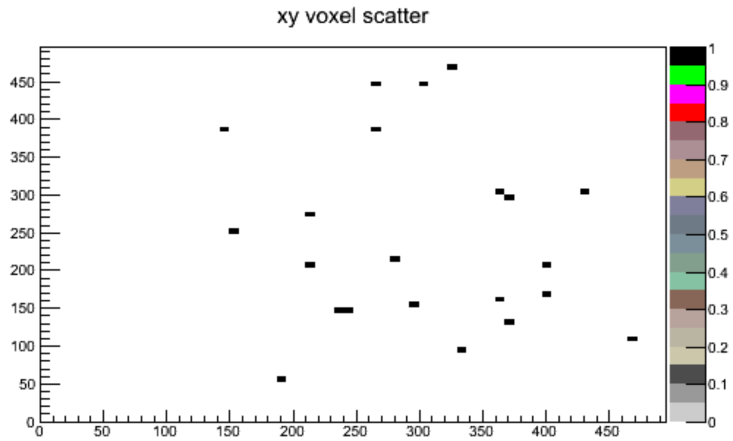
- Want to know how much "real" time it takes us to identify a slab of lead. We use only the POCA algorithms (on simulated data) for this, to form a base line for our future analyses. Time comes from the amount of muons GEANT/CRY produces for a set length of simulation. Plotted are vertex positions with a scatter angle > 30 mrad.



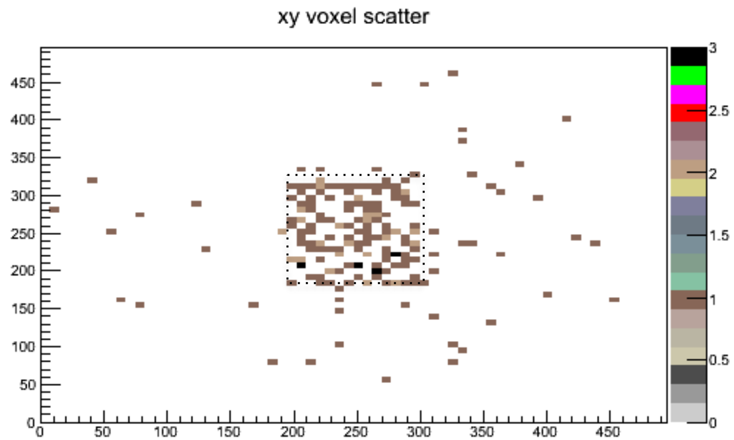
Scan Time Estimate – II



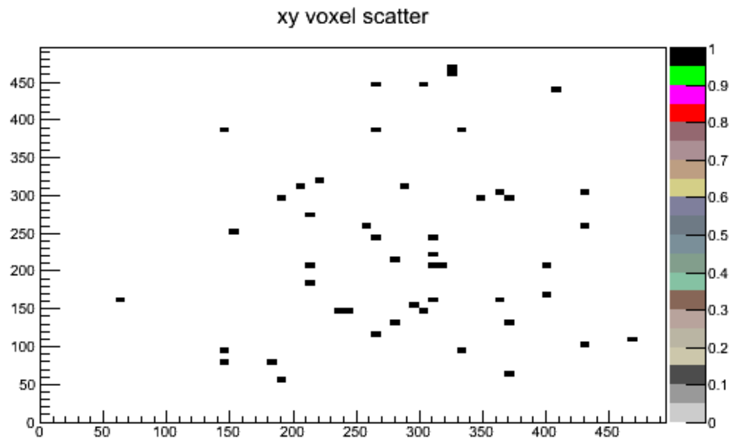
5 min. with lead



5 min. without lead



10 min. with lead



10 min. without lead

Power Consumption

- Dependent on multiplexing: 5-MAROC board draws ca. 1.05A at 5V (70mA per MAROC and 700mA for the board)
- If one 5-MAROC board reads out 5 strips at 1mm pitch and 2m length, readout draws 1.5 W/m^2
- HV consumption in the order of 100 mW/m^2
- So total consumption in the order of 2 W/m^2

- Values come from our current system and are not optimized!