Full simulation of the LUCID experiment in the LEO radiation environment

T. Whyntie [a,b] & M. A. Harrison [a]

[a]Langton Star Centre, [b]Queen Mary, University of London

iWoRID 2014, Trieste, Italy

Wednesday 25th June 2014

Overview of the talk

- Introduction;
- The Low Earth Orbit radiation environment;
- Simulating the LUCID experiment;
- Results and discussion;
- Conclusions.

A brief history of LUCID

In 2008, the **Simon Langton Grammar School for Boys** entered a satellite experiment design competition run by the British National Space Centre (now the **UK Space Agency**) and **Surrey Satellite Technology Limited** (SSTL).

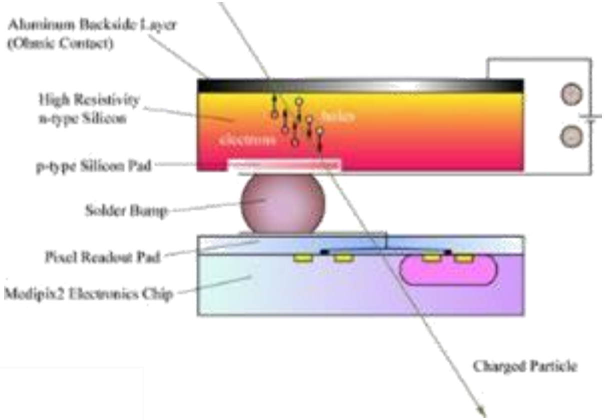
- The **Langton Ultimate Cosmic ray Intensity Detector** (LUCID) will use Timepix detectors, developed by the **Medipix 2 Collaboration**, to measure the space radiation environment in Low Earth Orbit (LEO). It was designed by school students, built by SSTL, and is due to launch in early July 2014.

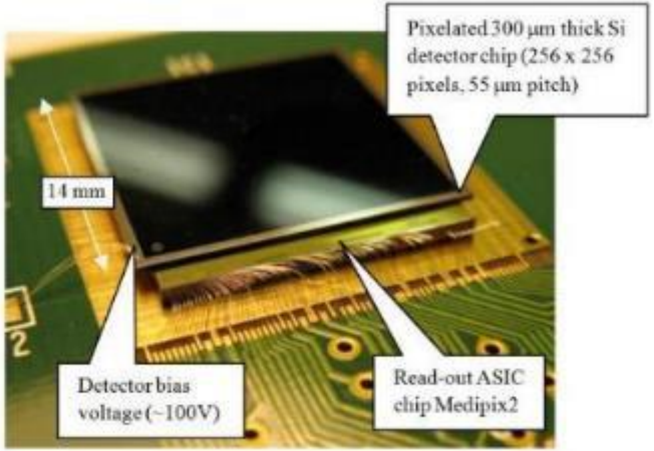
- LUCID is now part of CERN@school, a programme that enables school students perform authentic scientific alongside professional scientists using Medipix technology.

The Timepix detector

The Timepix hybrid silicon pixel detector (Llopart et al. 2007), developed by the Medipix Collaboration, features a 300 μm thick silicon sensor bump-bonded to a Timepix readout chip. 256 × 256 pixels of pitch 55 μm provide 65,536 readout channels from the 1.98cm^2 sensor element.

It can be used to detect and visualise ionising radiation, make energy (LET) measurements (when calibrated) and perform particle identification (to an extent).





The LUCID experiment

The Langton Ultimate Cosmic ray Intensity Detector experiment features five Timepix detectors in an open-faced cube, housed in a ~0.68 mm aluminium “dome” (not pictured), to measure the LEO radiation environment.

Data taking/transmitting capabilities:

- Max. shutter frequency: ~4Hz
- Transmission: 80Mbs^{-1} (20Mbs^{-1});
- Storage: 2GB;
- Operational 2 out of every 8 days.

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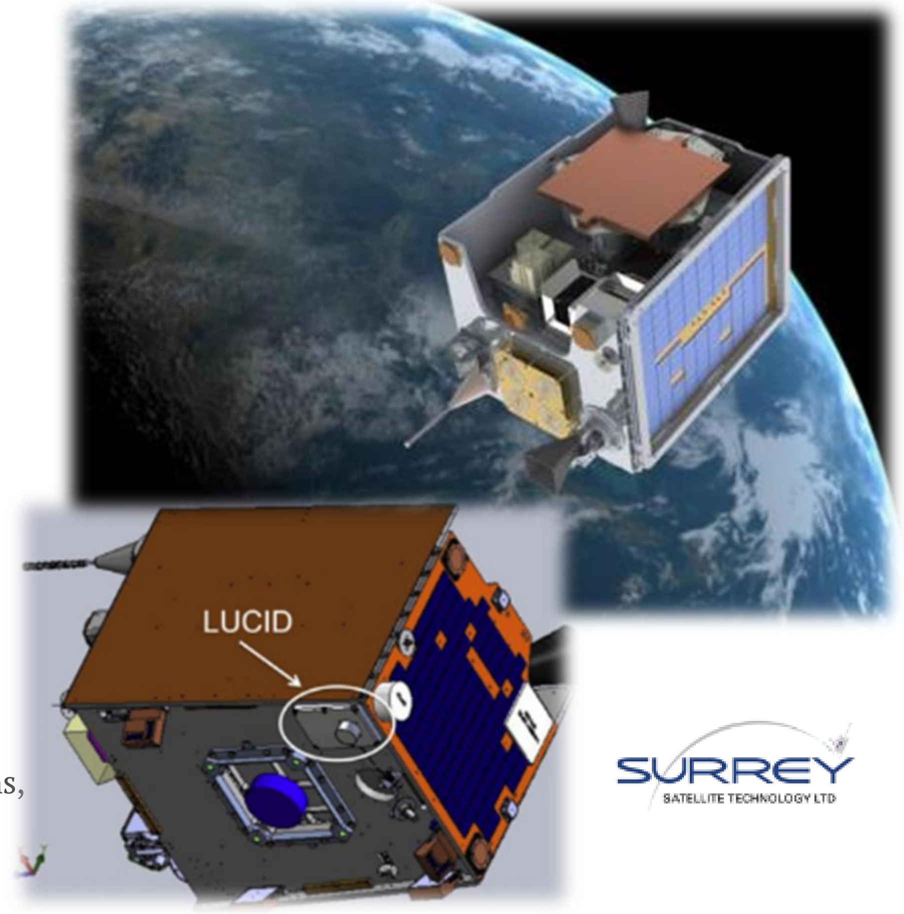
TechDemoSat-1

LUCID will launch aboard **TechDemoSat-1** from Baikonur Cosmodrome aboard a Soyuz 2b launch vehicle in July 2014.

- TechDemoSat-1 is an "in-orbit test facility" from SSTL supported by the UK's Technology Strategy Board;
- Many scientific payloads from UK academic institutions/labs, of which LUCID is one.

Orbit parameters

- *Altitude*: 635km;
- *Orbit*: sun synchronous;
- *Inclination*: 98.4°;
- *LTDN*: starts at 0900, with drift of 40 minutes per 6 months.
- *Dominant radiation sources*: trapped protons and electrons, outer electron belts, South Atlantic Anomaly (SAA).



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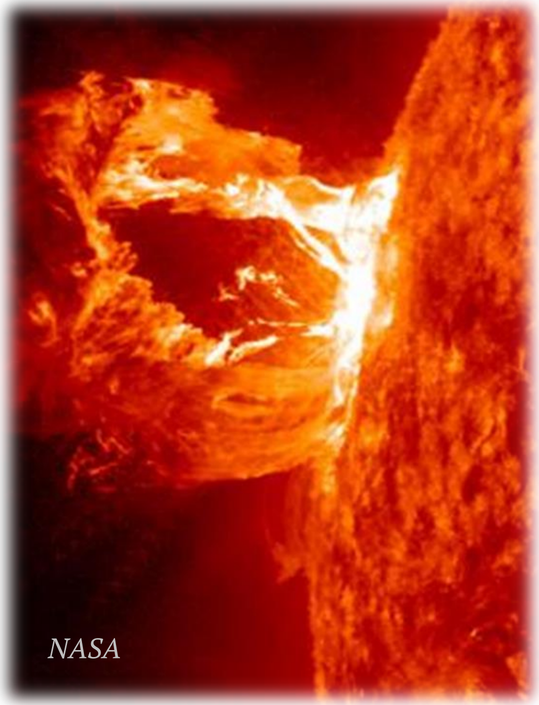
LUCID: scientific aims and objectives

- *Directionality of particles*:
  - Pattern recognition; estimates of angles of incidence; inter-detector track reconstruction.
- *Particle spectra*:
  - Measure particle intensities as a function of space and time;
  - Determine dose (J/kg) and the LET spectrum.
- *Solar flares/SPEs*:
  - Investigate the difference in time between electron and proton surges;
  - Log solar activity for the mission life time (which is more than 50% of the solar cycle);
  - Investigate the Forbrush Decrease.



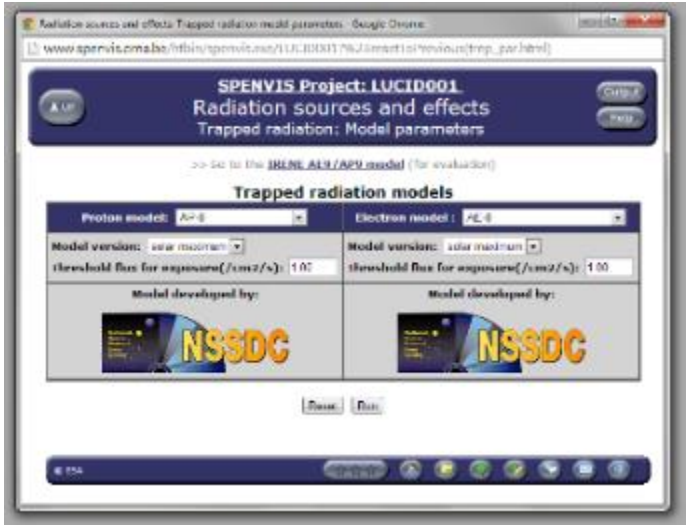
Aims and objectives of this work

- Overall aim - understand the performance of LUCID using Monte Carlo simulations of the detector and its environment:
  - Model differing LEO conditions along the spacecraft trajectory;
  - Full simulation of detector response, from source particle to material interactions, hits in the sensor element to digitisation;
- Other aims:
  - Develop tools and workflows for Monte Carlo sample production;
  - Understand our “background” – trapped protons and electrons – in Low Earth Orbit (c.f. “minimum bias” events at the Large Hadron Collider);
  - Generate “training samples” for the LUCID Collaboration data operations team (until we have real data!).
- Builds on earlier data rate estimate work (CHEP 2013).

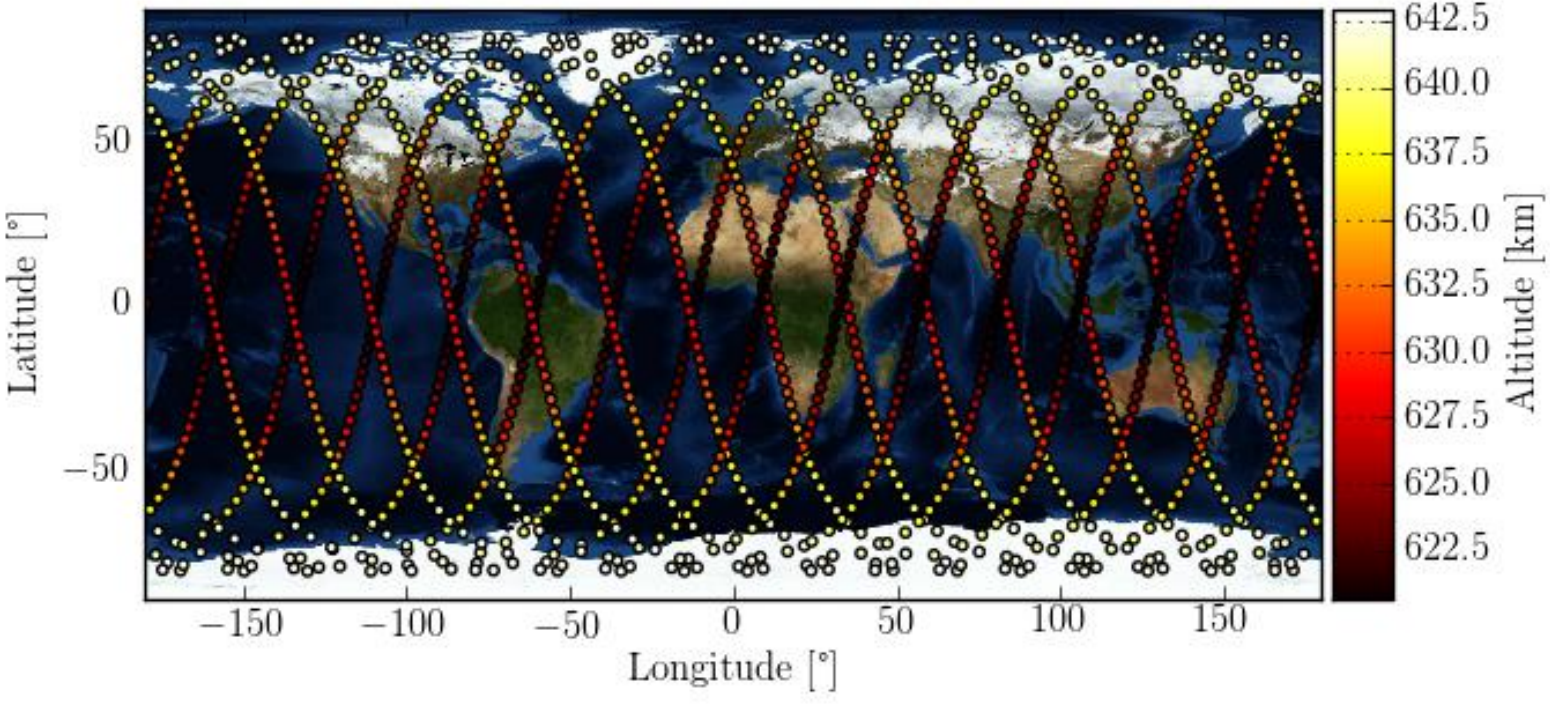
ESA's SPENVIS

ESA's Space Environment Information System, providing a web portal for various space radiation models:

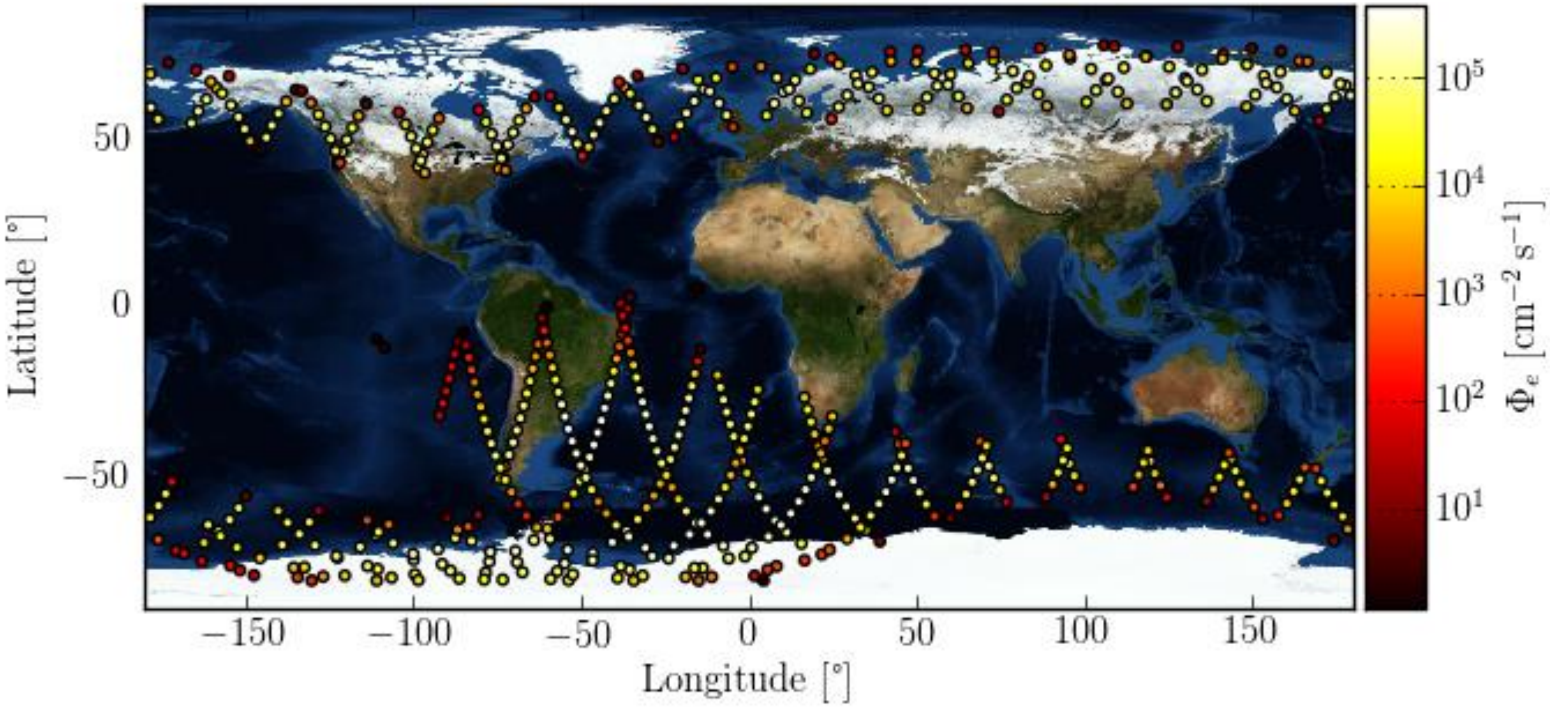
- Spacecraft coordinates can be generated by supplying orbit parameters;
- Various radiation models can then be applied to these coordinates to provide estimates of dose, SEUs, etc.
- We use NSSDC's AP8 (AE8) model for trapped protons (electrons) in TechDemoSat-1's orbit.
- Energy cut-off imposed to reduce number of high-flux, low energy particles: $E_e > 0.4$ MeV, $E_p > 10$ MeV – blocked by Al dome shielding.



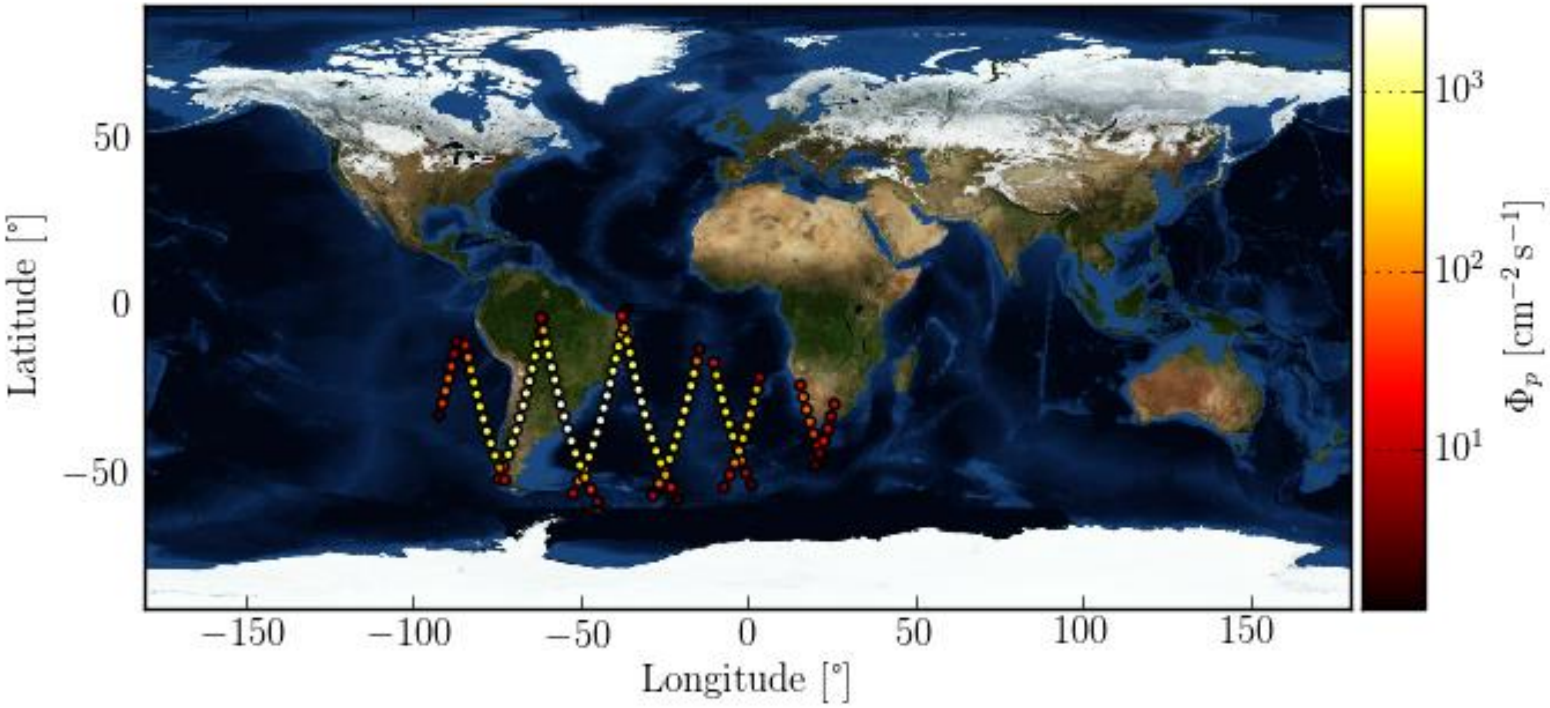
https://www.spenvis.oma.be



TechDemoSat-1's orbit (T ~90 min.)



Integrated electron flux (AE8) E_e > 0.4 MeV along TechDemoSat-1's orbit.

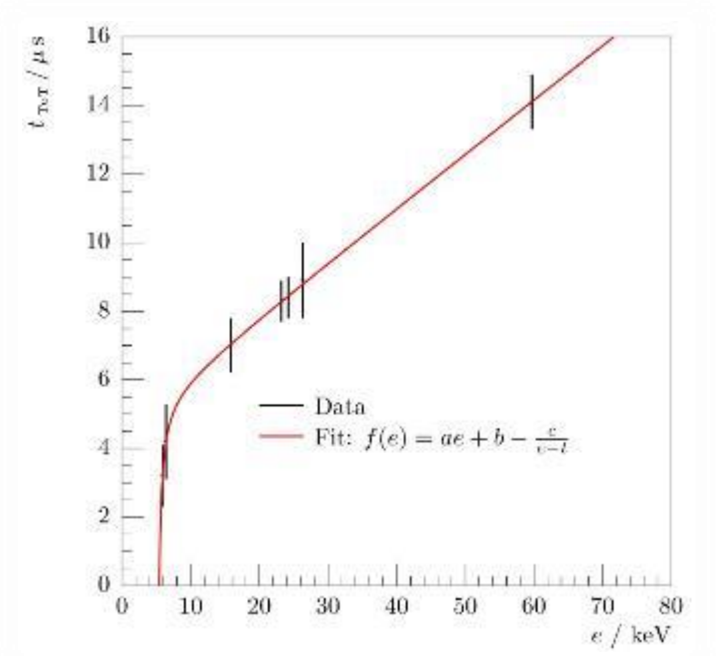


Integrated proton flux (AP8) E_p > 10.0 MeV along TechDemoSat-1's orbit.

Allpix – pixel detectors in GEANT4

Developed by J. Idarraga, M. Benoit et al, Allpix provides a suite of tools to simulate silicon pixel detectors. Customised for LUCID and CERN@school.

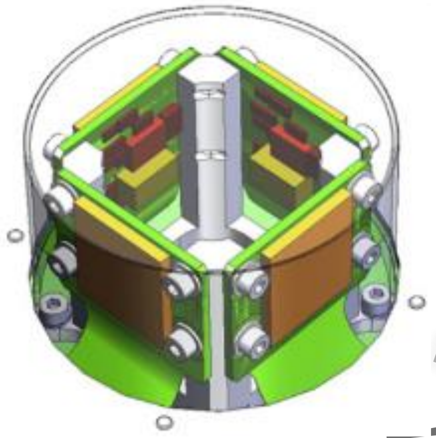
- Timepix digitizer module models charge diffusion and charge sharing in the bulk; known to perform less well for alphas, heavy ions, but e^- and p^+ work well.
- The Time-over-Threshold response is modelled using LUCID's actual calibration parameters (thanks IEAP, CTU Prague).
- Pixel thresholds idealised for simplicity.

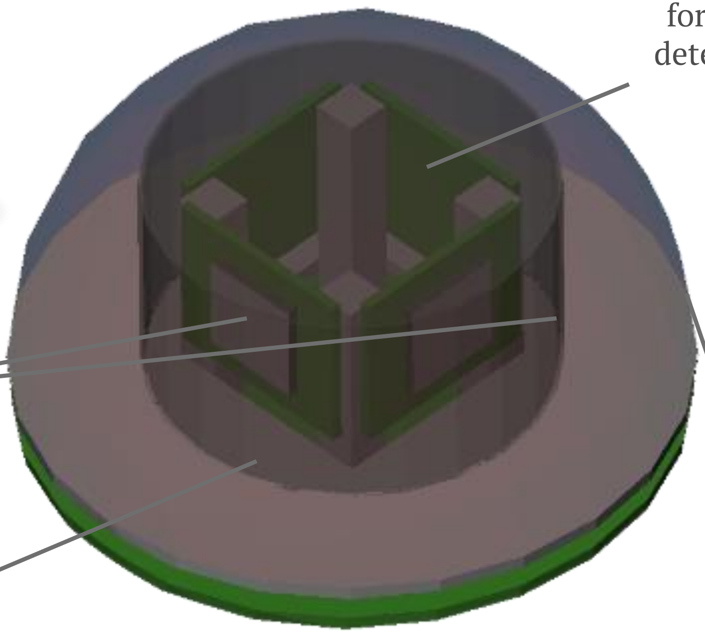


The Timepix energy calibration surrogate function.

The simulation geometry

Support posts





PCB mounts for TPX detectors

Timepix detectors (including TPX0, through gap)

Aluminium “dome” (cylinder with roof), thickness ~0.7mm

50mm radius hemisphere

Particle sources – GEANT4 GPS

The GEANT4 General Particle Source (GPS) allows the user to specify multiple primary particle types, positions, energies, etc.

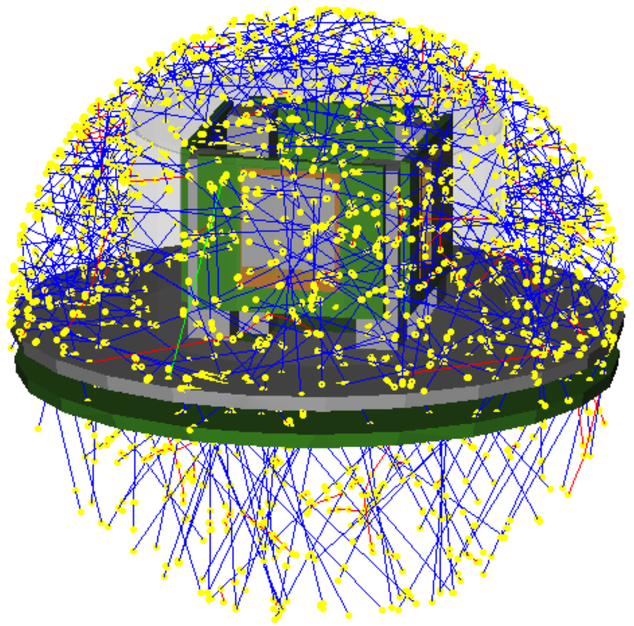
- The SPENVIS differential flux spectra for *e*, *p* at each point in the orbit are used to specify a GPS. Relative intensity set by flux ratio.
- Particles are created on a 5cm radius hemisphere with a cosine distribution (as required for an isotropic environment).
- The number of particles per frame is:

$$\frac{1}{2}\pi R^2 \cdot \Phi_i \cdot \Delta t$$

Integrated flux

Hemisphere radius

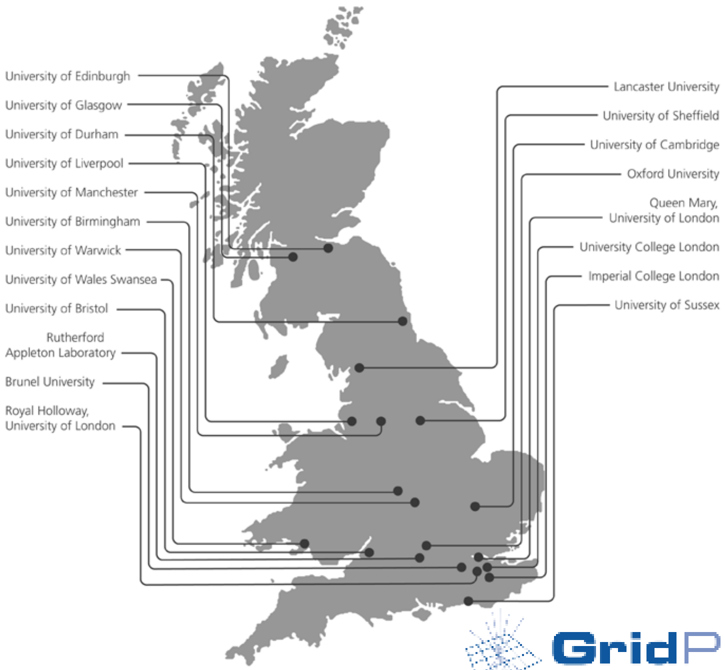
Acquisition time [s] = 0.25 [s]



Monte Carlo production with GridPP

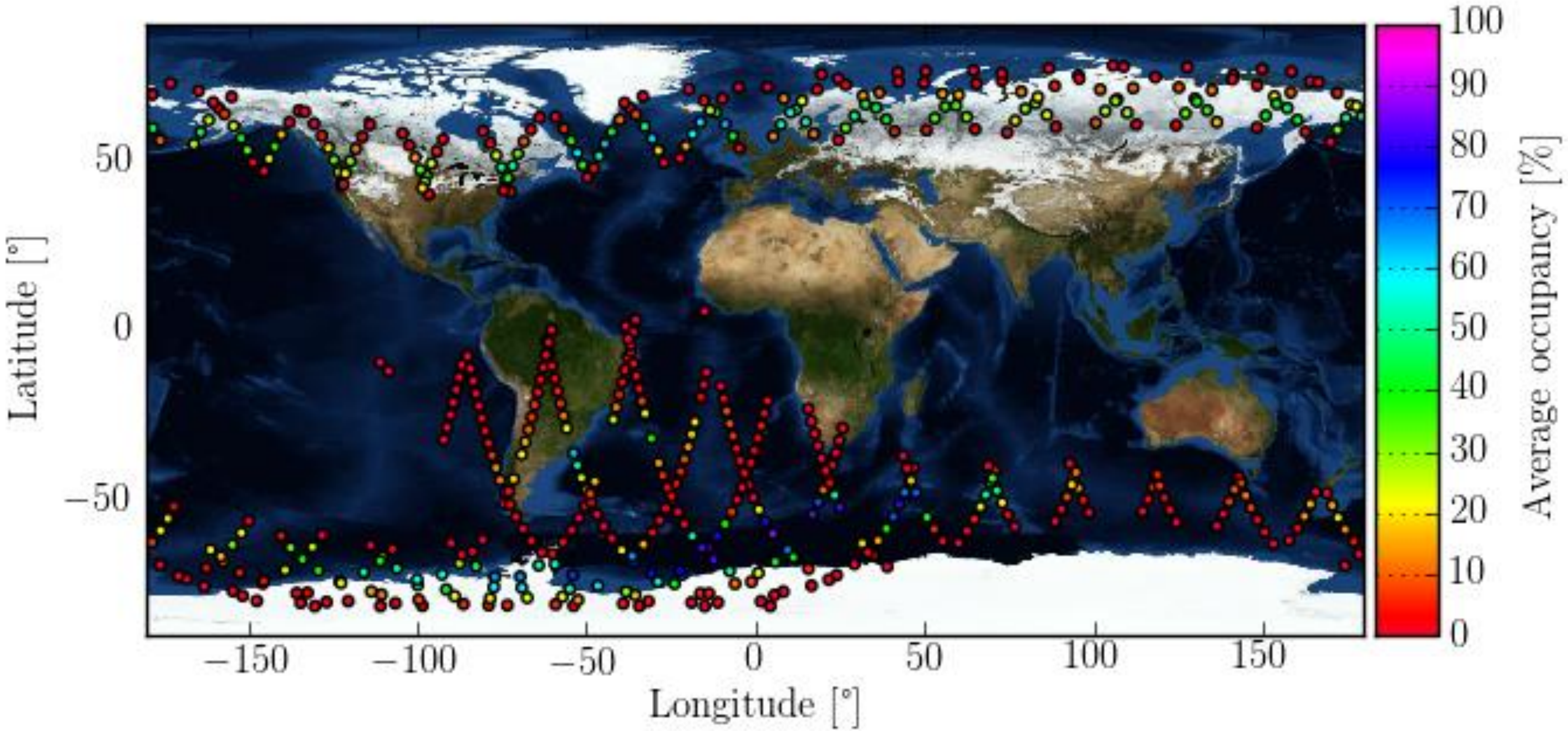
Mass simulation made possible by **GridPP** – the UK's contribution to the Worldwide LHC Computing Grid (WLCG), comprised of 19 institutions. Four sites support the **cernatschool.org** Virtual Organisation (VO).

- Typical production run – +500 points in the orbit with non-zero e- or p+ flux, 5M source particles per Timepix frame.
- Grid tools used: **CVMFS** for Allpix software deployment to grid worker nodes; **DIRAC** (Distributed Infrastructure with Remote Agent Control) for job and storage management.



Simulation results - occupancy

- Key factor in detector performance – we need to be able to resolve individual clusters in order to analyse them. What do the models say about LUCID's performance in the electron belts and SAA?

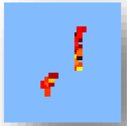


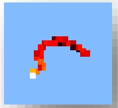
Estimated occupancy (%) in TPX-0 for e, p with an acquisition time of 0.25 [s].

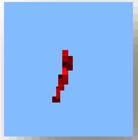
Outer belts – low flux

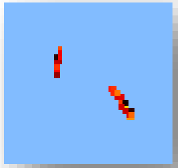
e.g. (53.53°, -4.78°) - over the UK;

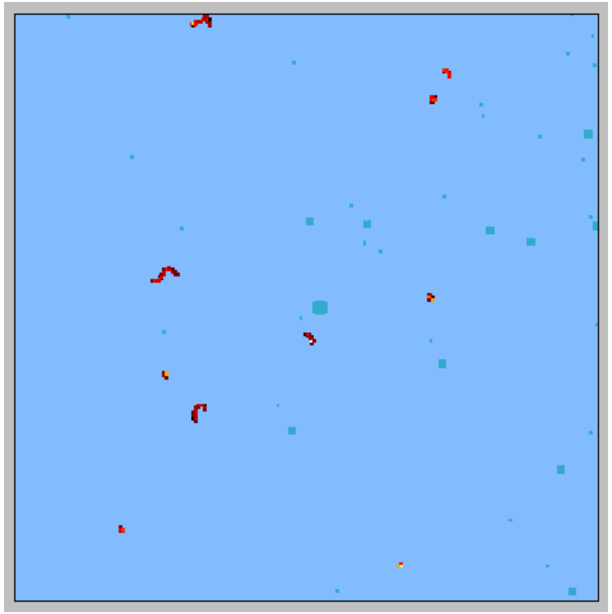
- Low occupancy – O(0.1%)
- Cluster identification possible; particles easily identifiable.
- Low energy electrons can easily be excluded in favour of more "exotic" particles (not simulated).







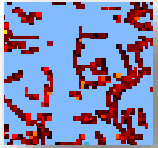


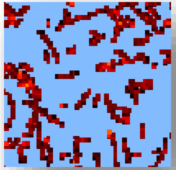


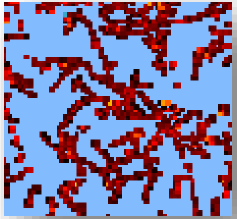
Outer belts – high flux

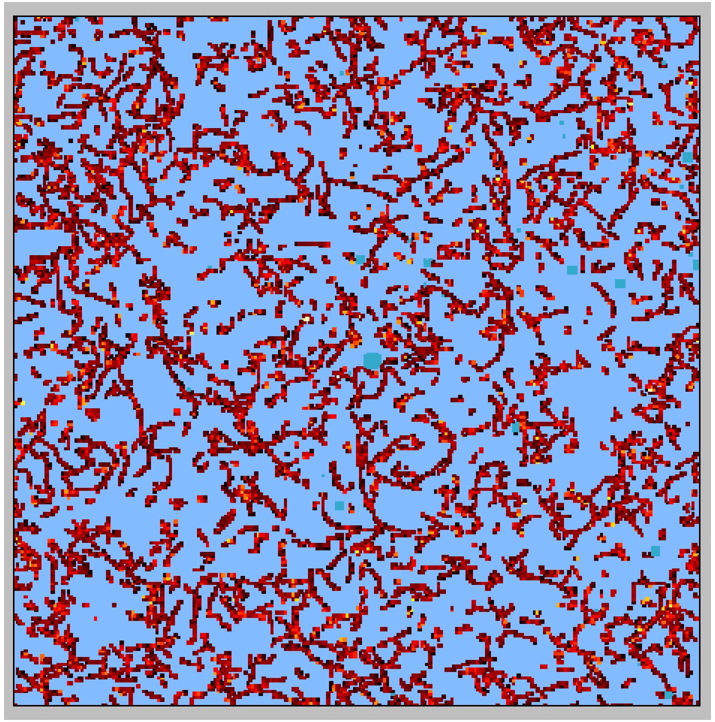
e.g. (46.46°, -123.18°) - over Seattle;

- This frame: $\Delta t = 0.25s$, occupancy is 25%.
- Some particles distinguishable but clustering "tricky"; track structures apparent.
- Generally low energy though (ToT ~100); filtering may be possible.





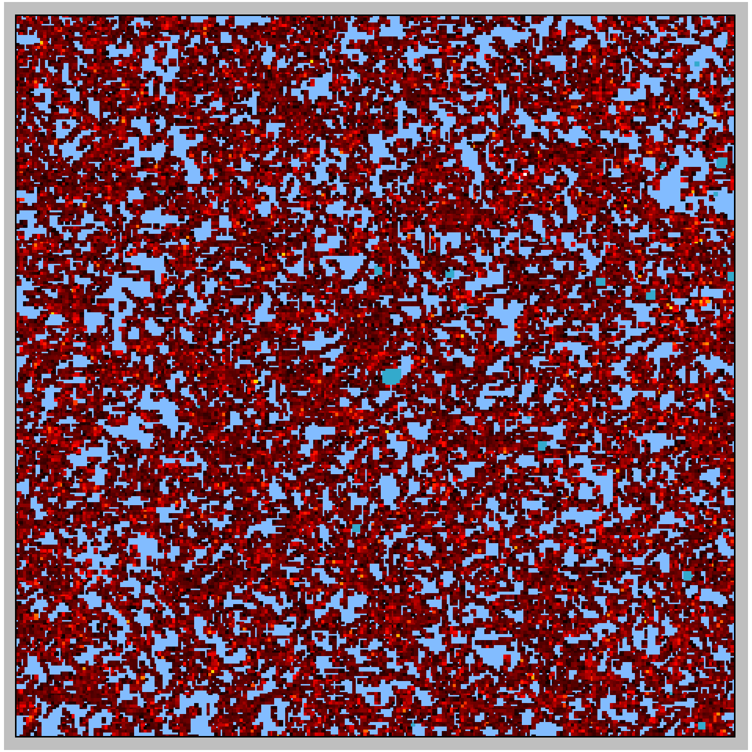




Outer electron belt – high flux

e.g. (-72.26°, -92.68°) – just off Antarctica;

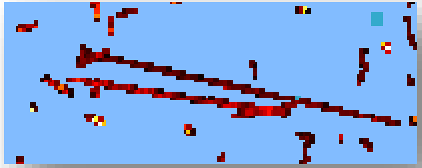
- This frame: $\Delta t = 0.25$s, occupancy is 60%.
- Pretty much unusable; will push limit of data transmission rates from the satellite (see CHEP 2013 paper).
- Some sort of shutter rate adjustment will be required; we can use the results of these simulations to inform our Ops team.

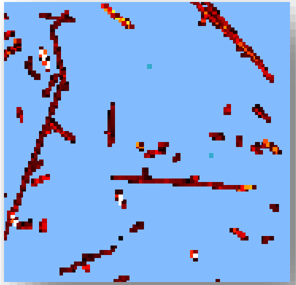


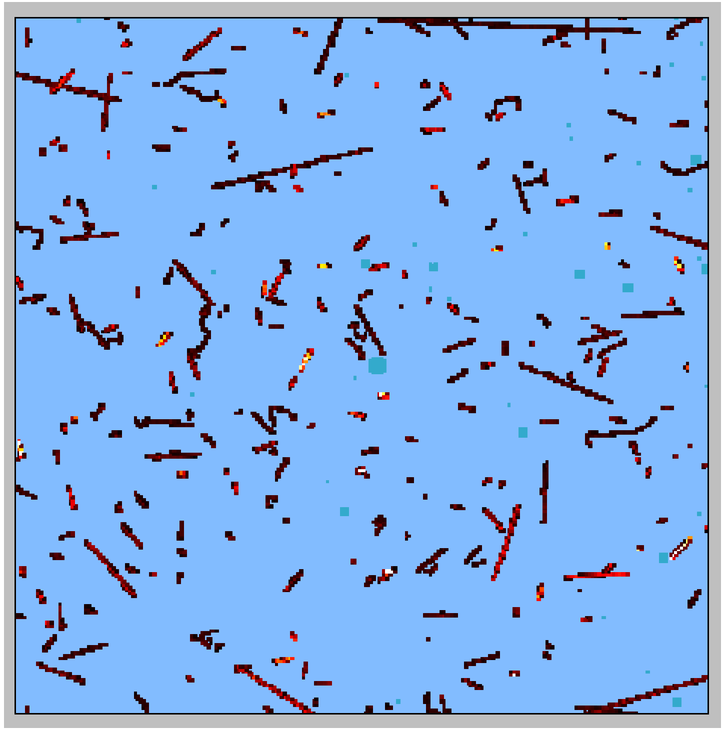
SAA– low flux

e.g. (-19.22°, -40.27°) – over Belo Horizonte;

- This frame: Δt = 0.25s, occupancy is 5%.
- Protons and electrons clearly identifiable.
- High energy tracks ~1000 ToT counts per pixel; electrons much less.



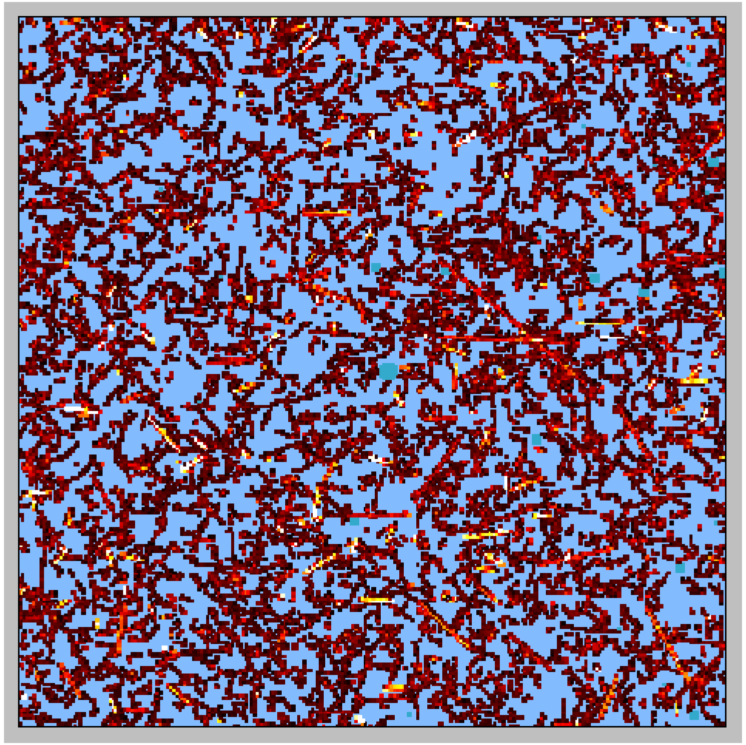


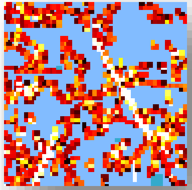


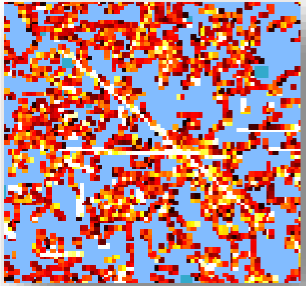
SAA– high flux

e.g. (-32.10°, -30.76°) – over Atlantic ocean;

- This frame: Δt = 0.25s, occupancy is 40%.
- Protonsvisible amongst the electrons (see ToT max =300 images below).
- Again, lower/adaptable frame rate probably necessary.







Discussion and further work

- As suspected, we need to develop high occupancy strategies:
  - Removal of soft electron background;
  - Overlap detection.
- Low occupancy directionality and tracking studies.
- Particle identification (with and without background).
- Data-driven calibration of TPX-4.
- Heavy ion (fragment) simulation – FLUKA? GEANT4Medipix for particles causing large charge diffusion?
- Compare with real data once the satellite launches!
- Compare with data from similar experiments (ISS, SATRAM).

Conclusions

- We have developed a framework for simulating the LUCID experiment in the Low Earth Orbit environment:
  - Particle source modelling provided by SPENVIS;
  - The GEANT4 application "Allpix" performs full-chain modelling of the Timepix detector, the experiment geometry and the LEO environment;
  - Large-scale production runs have been carried out on the grid with GridPP support and easy-to-use distributed computing tools.
- Analysis of frames "collected" in certain regions (i.e. the electron belts, the SAA) indicate that large occupancies may need to be mitigated against.
  - Shorter acquisition times with delays between frames may be necessary;
  - A variable "shutter speed" would be desirable.
- The simulation results and further analysis can be used to further inform experiment operations when the satellite launches in July.

Thanks and acknowledgements

- Prof. L. Pinsky (Uni. Of Houston/NASA);
- Surrey Satellite Technology Limited (SSTL);
- The Medipix 2 Collaboration;
- STFC and GridPP;
- J. Idarraga & M. Benoit (Allpix);
- IEAP, CTU Prague (LUCID calibration).

This work was supported with a Special Award from the Royal Commission for the Exhibition of 1851.

Thank you for listening! Further information:

http://cernatschool.web.cern.ch

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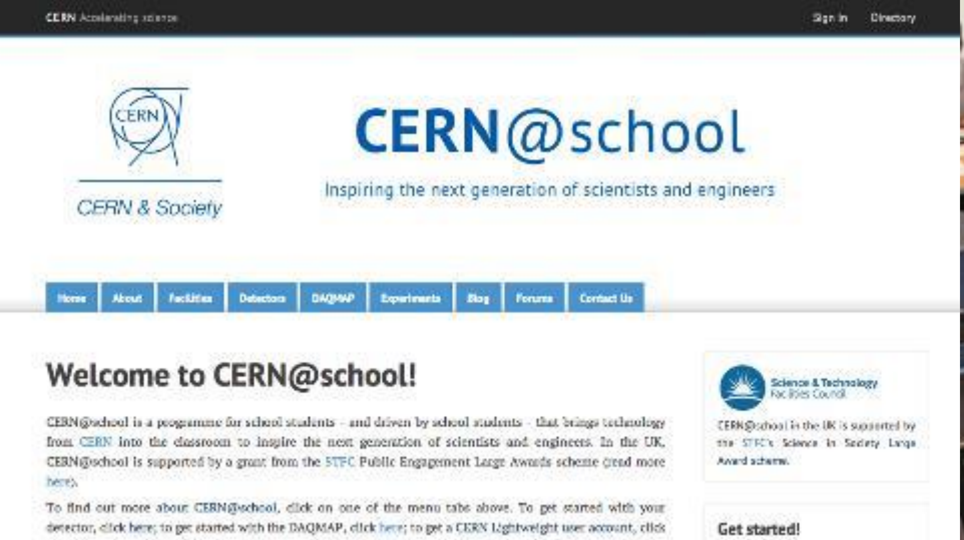
Backup

Mainly on CERN@school…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Bringing CERN into the classroom

- UK activities are supported by STFC, the Royal Commission for the Exhibition of 1851 and GridPP; in-kind support received from the IOP, SEPnet, CERN;
- 25 STFC-funded detector kits are currently in schools around the UK, distributed by the IOP Physics Teacher Network. Many more schools have access to CERN@school data via the web portal (the DAQMAP, see next slide).