A MULTI-PURPOSE ACTIVE-TARGET PARTICLE TELESCOPE FOR RADIATION MONITORING

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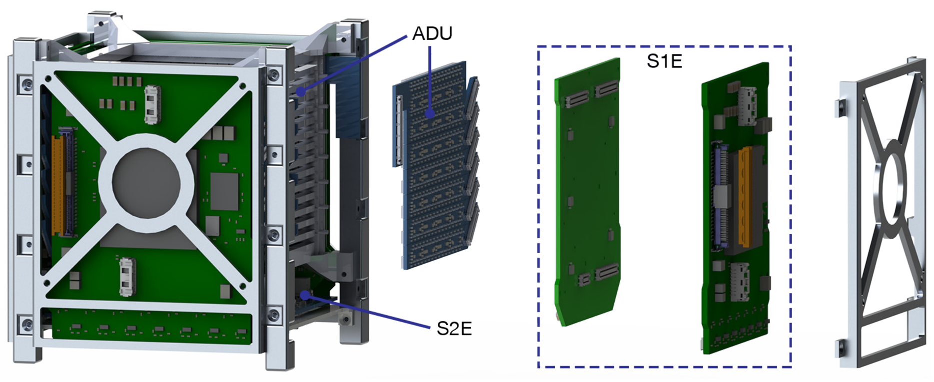
MAPT - THE MULTI-PURPOSE ACTIVE-TARGET PARTICLE TELESCOPE

Continuous monitoring of the radiation background is a key requirement in many applications. Traditional detectors can either measure the total radiation dose omnidirectionally (dosimeters), or determine the incoming particles' charactersitics within a narrow field of view (spectrometers). The Multi-purpose Active-Target Particle Telescope (MAPT) utilizes **Bragg Curve spectroscopy** for particle identification and can **measure fluxes omni-directionally**. We estimated its characteristics using a Monte Carlo simulations.



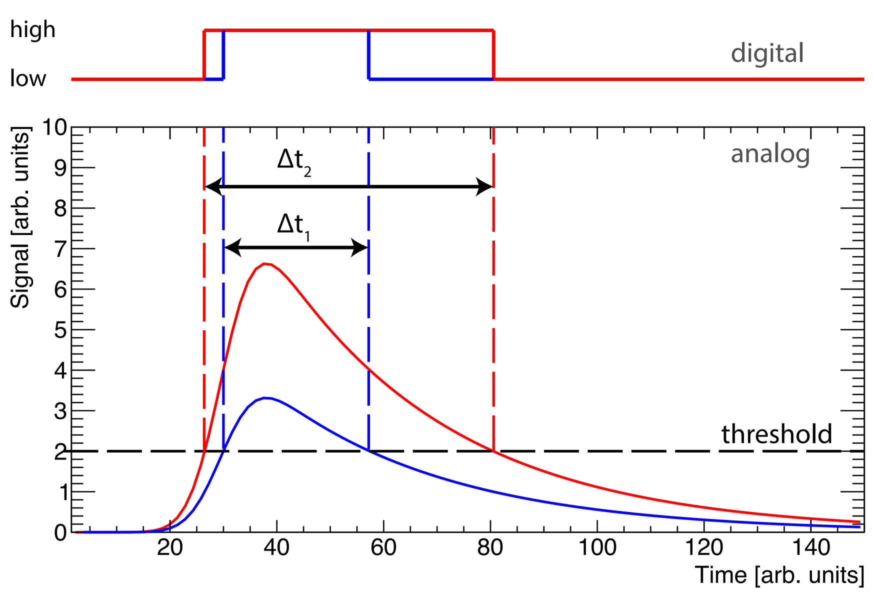
Stuctural layout of MAPT. The ADU made of scintillating fibers and silicon photomultipliers (SiPMs) is symmetrically surrounded by the front-end electronics (S1E and S2E).

Energy range	25 to 1000 MeV/nucleon
Energy resolution	< 1% (25 to 100 MeV for protons)
	< 25% (100 to 1000 MeV for protons)
Opening angle	4π (complete solid angle)
Geom. acceptance[1]	793.10 ± 0.25 cm²sr
Angular resolution	< 6° [(a)]
Mass	< 2.5 kg
Dimensions	11 x 11 x 12 cm³
Power consumption	~ 30 W

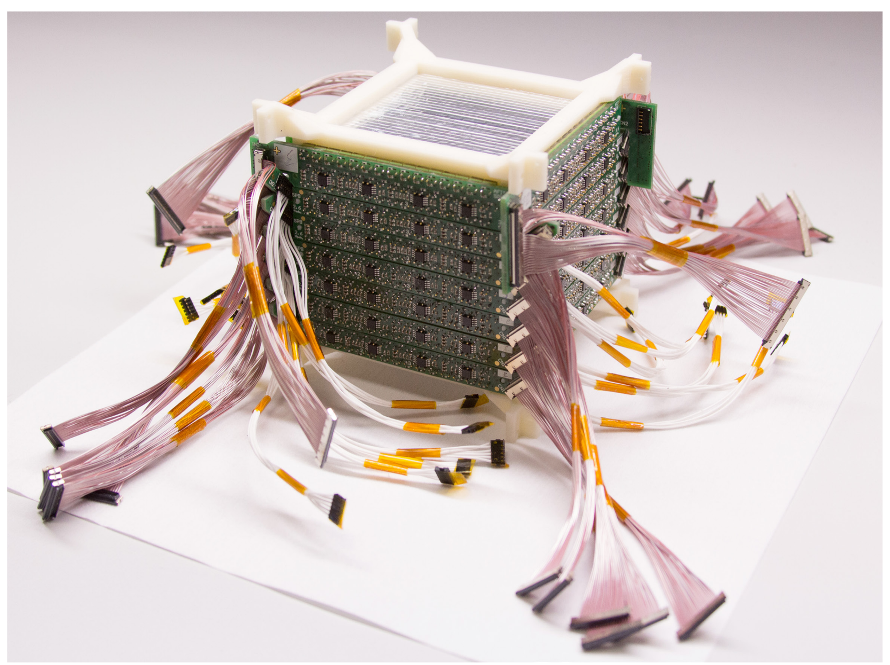
(a) Can be significantly improved by track-fitting algorithms.

ACTIVE DETECTION UNIT (ADU)

- 900-channel active-target particle detector
- **active volume**: scintillating plastic fibers
- silicon photomultipliers (SiPM) for light detection
- allows **3D tracking** of charged particles



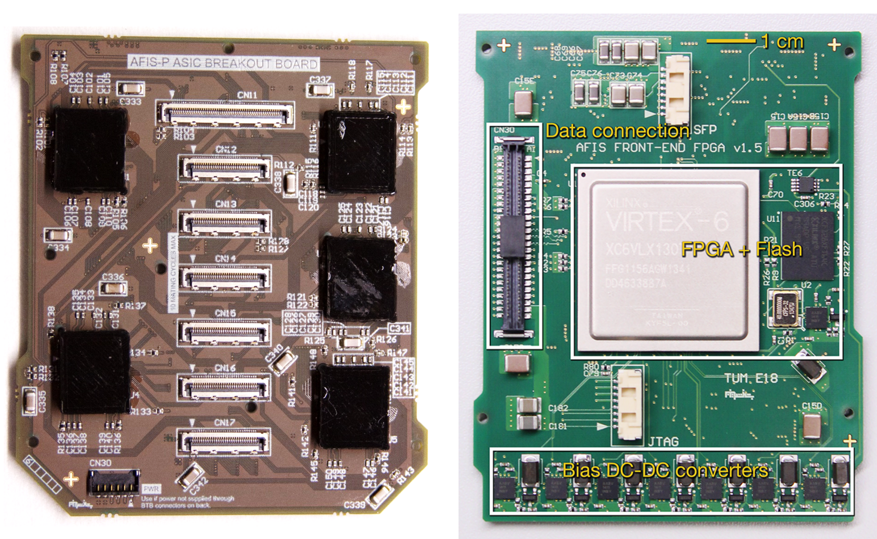
Principle of the time-over-threshold measurement.



A fully functional prototype version of the ADU.

STAGE-1 ELECTRONICS (S1E)

- fully parallel time-over-threshold measurement
- **time-over-treshold ASICs**
- Xilinx Virtex-6 FPGA for TDC
- microcontroller for control & housekeeping
- 250 MHz main oscillator
- SiPM bias voltage generation
- interfaces: 2x SPI, 1x JTAG, 1x SFP
- **time resolution: 350 ps best, 500 ps nominal**



S1E: five time-over-threshold ASICs (left, under black covers) and one Virtex-6 FPGA (right) make up each of the four sections.

STAGE-2 ELECTRONICS (S2E)

- combination of signals and trigger
- **on-line event reconstruction**
- Xilinx Kintex-7 FPGA
- Atmel microcontroller for housekeeping
- Atmel MCU for data processing
- radiation-tolerant MRAM-based program & data storage
- **CsI crystal + SiPM for total dose measurement (TID)**
- interfaces: Ethernet, 802.11, SpaceWire

DIGITIZATION CONCEPT

- parallization for high-rate acceptance
- resolution only limited by number of SERDES bits in FPGA I/O
- acceptance limited by pile-up effects in SiPMs

APPLICATIONS

Radiation Monitoring in Manned and Unmanned Spacecraft

- hadronic component of radiation spectrum (protons, nuclei/ions): measurement of individual particle energies and species
- <10% energy resolution in region most interesting for human radiation monitoring
- total dose measurement (electrons, neutrons, gammas): no limit on particle energy

Astrophysics: Measurement of Trapped Antiprotons in Earth's Radiation Belts

- requires dedicated satellite missions
- data complementary to PAMELA's data

Medical Applications: Radiation Therapy, DAQ for PET, ...

Beam Monitoring in Accelerator Facilities

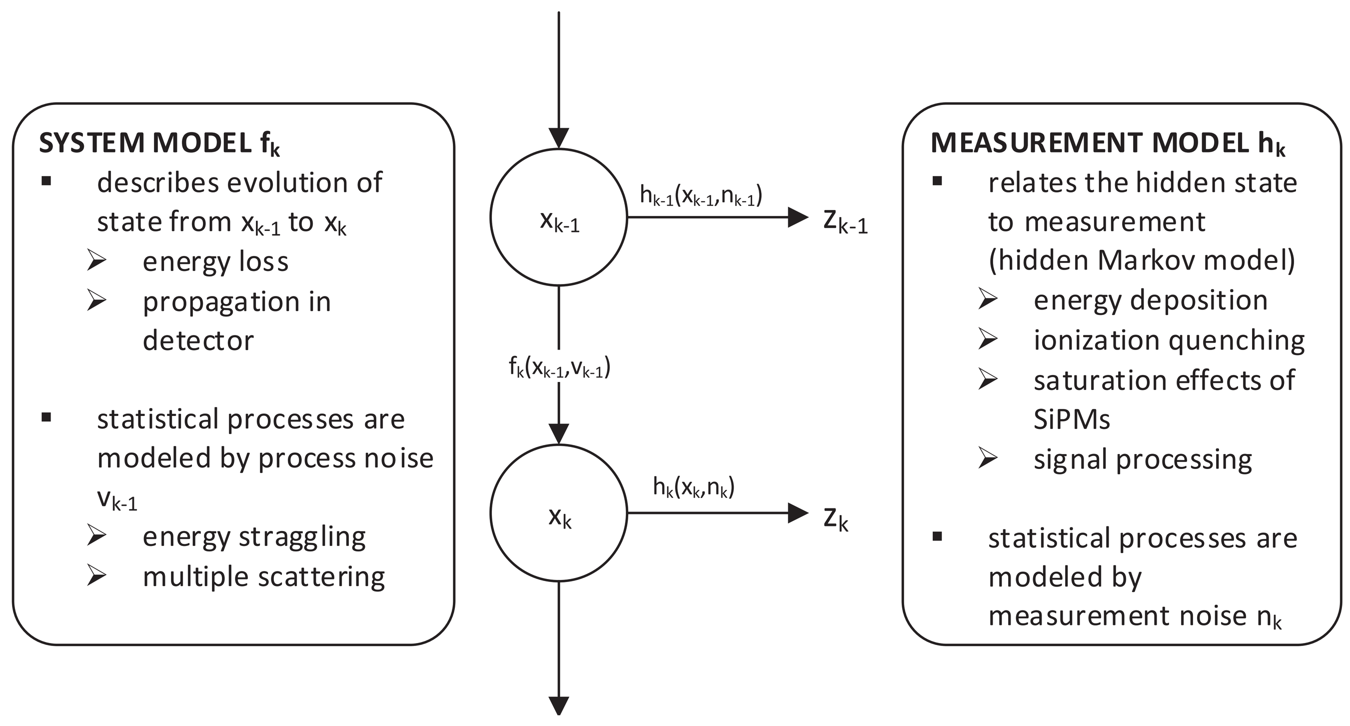
RECONSTRUCTION & ANALYSIS

DYNAMIC STATE SYSTEM

We model the traversing particle and its interaction with the detector as a dynamic state system. We use a sequential Bayesian filtering approach for our analysis.The state vector of our system is given as

$$\vec{x} = (\vec{p}, \theta, \phi, E)^T$$

where $\vec{p}$ is a point on the particles trajectory, θ and ϕ the angles of the track to the surface normal, and E its kinetic energy. The measurements z_k are observed states of the hidden Markov model (HMM). The true state is assumed to be an unobserved Markov process.



OPTIMAL BAYESIAN SOLUTION

The aim of the tracking algorithm is to recursively calculate a certain degree of belief in the state x_k after k measurements. It is required to calculate the PDF $p(x_k|z_{1:k})$ which can be done recursively for every measurement 1 to k. Given the PDF at $k-1$, the propagated state can be predicted using[2]

$$p(x_k|z_{1:k-1}) = \int p(x_k|x_{k-1})p(x_{k-1}|z_{1:k-1})dx_{k-1}$$

where $p(x_k|x_{k-1})$ is defined by the system model. In the next stage we use the measurement k to update our predicted PDF using Bayes' theorem

$$p(x_k|z_{1:k}) = \frac{p(z_k|x_k)p(x_k|z_{1:k-1})}{p(z_k|z_{1:k-1})}$$

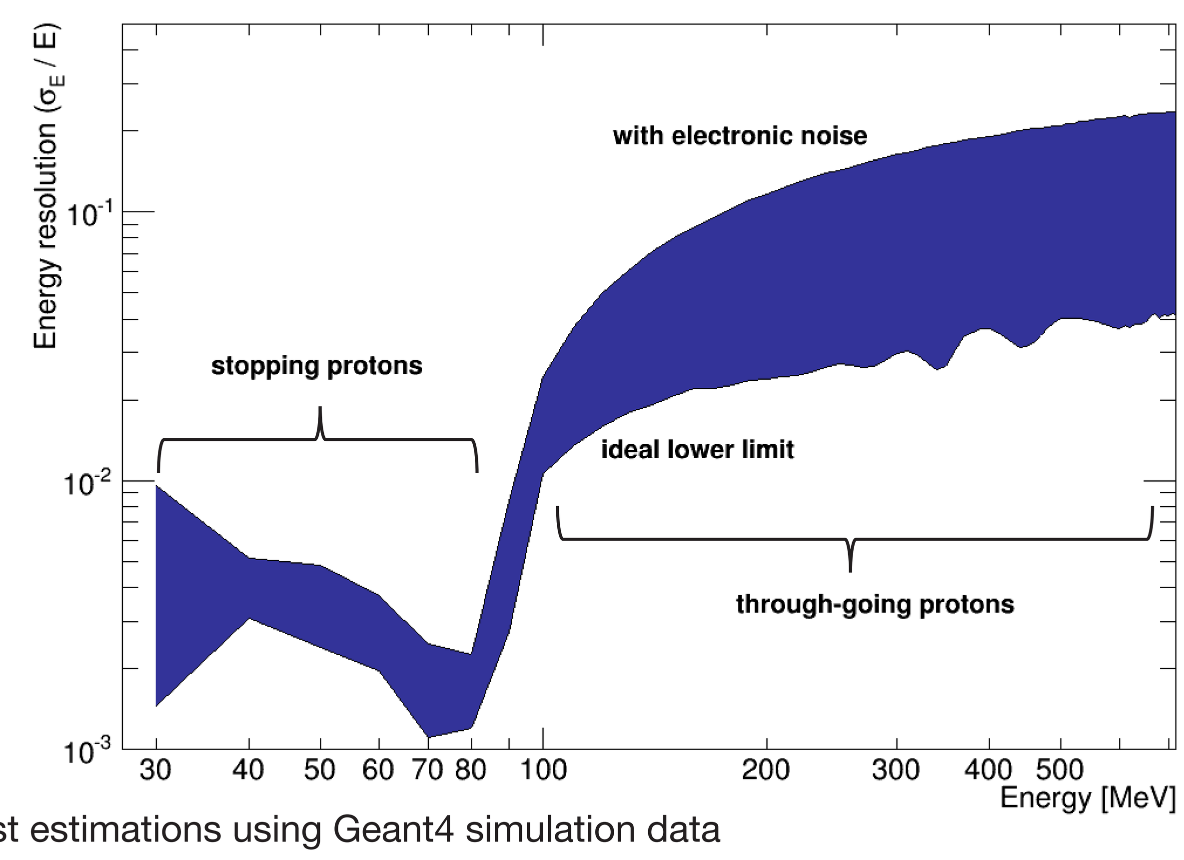
where $p(z_k|x_k)$ is defined by the measurement model.

PARTCILE FILTER IMPLEMENTATION

For a non-linear system model and non-Gaussian process noise, the optimal Bayesian solution cannot be solved analytically. We use a sequential Monte-Carlo (MC) approach known as particle filtering or survival of the fittest[2]. In a sequential MC approach, the PDFs are modeled as a set of random samples with associated weights. This method approaches the optimal solution for a large number of samples.

Using this method, we are able to handle uncertanties in each event individually.

ENERGY RESOLUTION



- first estimations using Geant4 simulation data
- analysis based on Markov Chain Monte Carlo simulations (using the Bayesian Analysis Toolkit)[3]
- resolution <1% for protons with energies lower than 100 MeV
- cross check with experimental data from prototype test at PSI beam facility[4]
- energy resolution at high energies strongly influenced by electronic noise of DAQ

[1] J.D. Sullivan, Geometrical Factor and Directional Response of Single and Multi-Element Particle Telescopes, *NIST* 95 (1971): 5-11.
[2] M.S. Arulampalam et al., A Tutorial on Particle Filters for Online Nonlinear/Non-Gaussian Bayesian Tracking, *IEEE Transactions of Signal Processing* 50 (2002): 174-188.
[3] https://www.mppmu.mpg.de/bat/
[4] M. Losekamm et al., AFIS: A New Instrument for Cosmic Radiation Studies on BEXUS 18 and Future Nanosatellite Missions, *22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research*, 2015.