Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 17

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What is this lecture about?

- Scintillators
  - Basic principles
  - Important materials in current use
  - Light detection
  - Low energy applications (gamma spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Key points from previous lecture

- Calorimeters work on the principle of generating an electromagnetic or a hadronic shower of particles in an active (or a layered active/passive) medium.
- Using the scaling variables X_0 and λ for EM and hadrons respectively one can design a “physicist” calorimeter. Knowing values for these scaling variables you can chose the optical materials for a given mechanical size.
- Showers spread out laterally as the longitudinal distance into the material increases.
- Hadron calorimeters will have intrinsically poorer energy resolution, compared to EM, as the pion production threshold is much higher than the critical energy (EM) in most materials.

Time-of-Flight (ToF)

A particle with mass m and momentum p has velocity

$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

For a path length L the time of flight is inversely proportional to its velocity β:

$$T = \frac{L}{c \cdot \beta}$$

Thus, two particles with the same momentum but different masses have different time of flight

$$T_1 - T_2 = \frac{L}{c}\left(\sqrt{1 + \frac{m_1^2}{p^2}} - \sqrt{1 + \frac{m_2^2}{p^2}}\right)$$

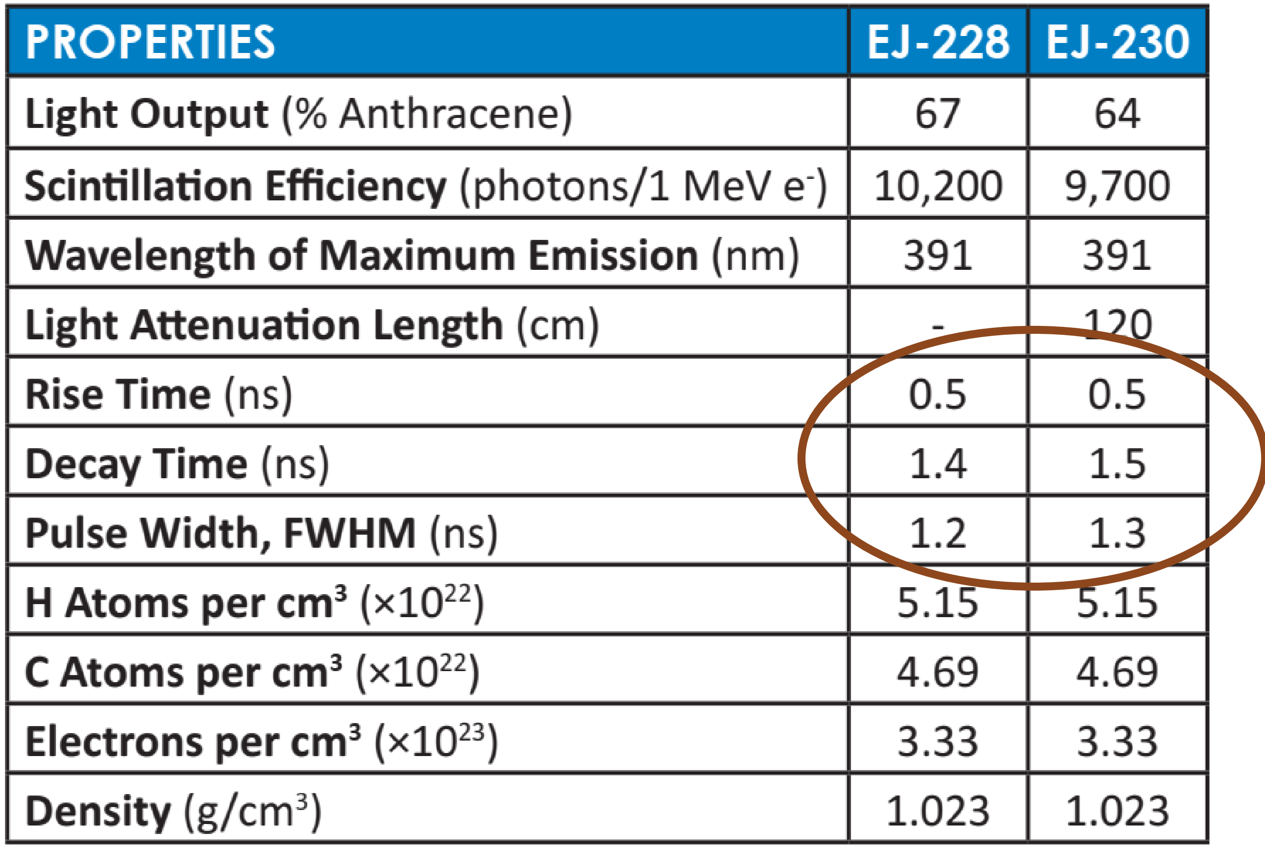
TOF requirements

- Very fast scintillator (strictly fast rise time is the most critical)
- Very fast photodetector – optimised PMT or SiPM
- Minimal timing jitter in the “discriminator” that produces a fixed amplitude digital pulse from the analogue input signal whose pulse height will vary event to event.

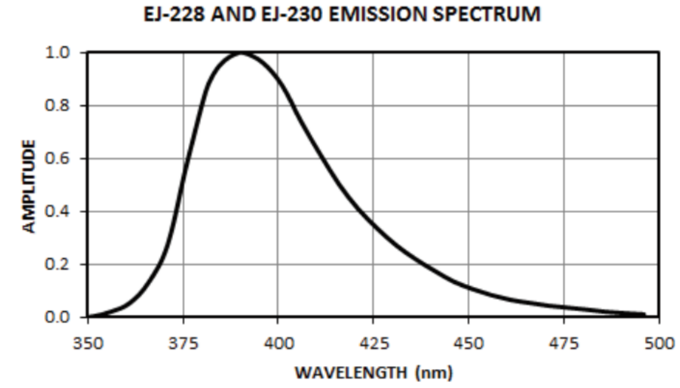
Fast plastic scintillator

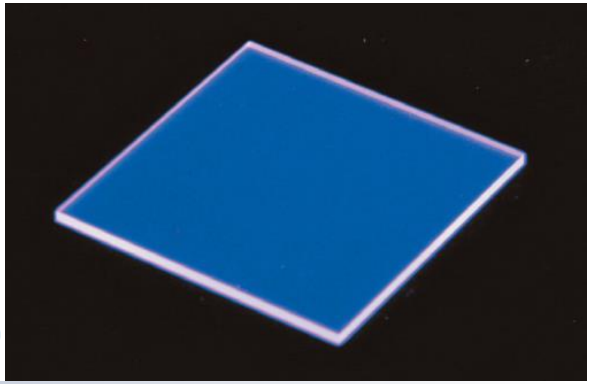
- Most plastic scintillators, based on fluorescent aromatic molecules, are fast and have a reasonable light output (~ 10000 photons per MeV deposited energy)
- Light produced in the violet/blue region of the spectrum – a reasonable match to PMT as well as SiPM.
- Here is an example from Eljen Technology, Sweetwater, TX, USA

https://eljentechnology.com/

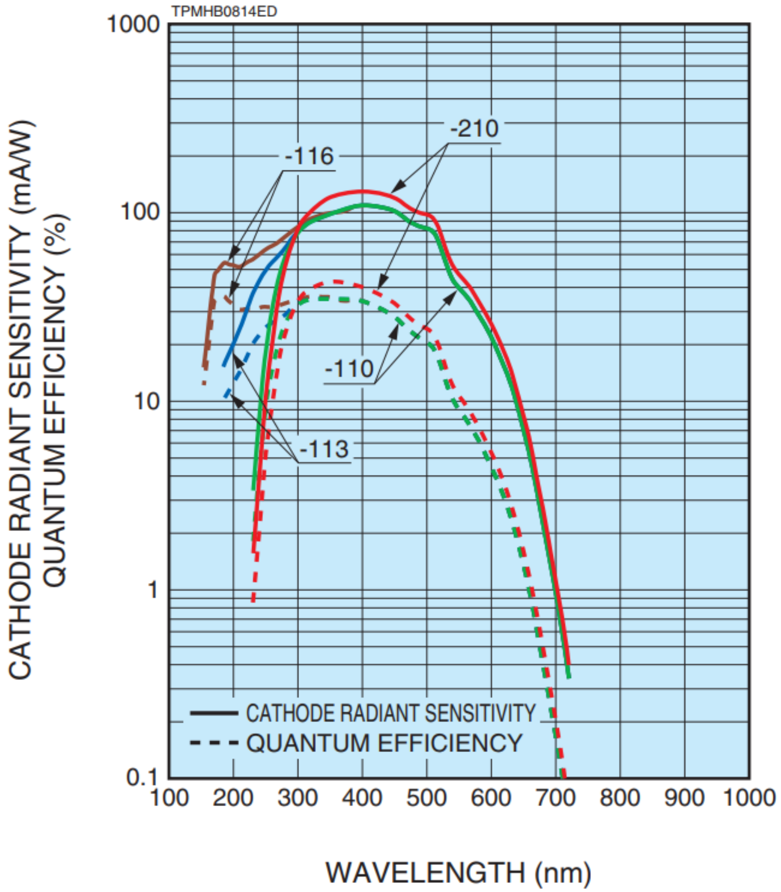


PROPERTIES	EJ-228	EJ-230
Light Output (% Anthracene)	67	64
Scintillation Efficiency (photons/1 MeV e$^-$)	10,200	9,700
Wavelength of Maximum Emission (nm)	391	391
Light Attenuation Length (cm)	-	120
Rise Time (ns)	0.5	0.5
Decay Time (ns)	1.4	1.5
Pulse Width, FWHM (ns)	1.2	1.3
H Atoms per cm^3 ($\times 10^{22}$)	5.15	5.15
C Atoms per cm^3 ($\times 10^{22}$)	4.69	4.69
Electrons per cm^3 ($\times 10^{23}$)	3.33	3.33
Density (g/cm^3)	1.023	1.023





Fast PMT



- Hamamatsu R9880U series PMT
- Active diameter 8 mm
- 2×10^6 gain at 1000V
- Rise time 0.6 ns
- Timing jitter 200 ps

Hamamatstu Photonics KK http://www.hamamatsu.com

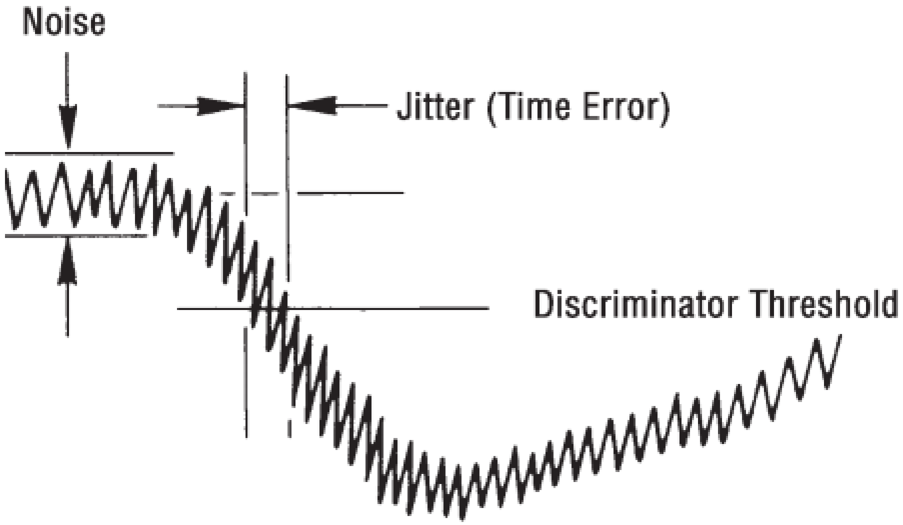
What limits the timing?

- Jitter – due to noise (inevitable)
- Walk (1) – peak amplitude variation (for other wise identically fast pulses)
- Walk (2) – rise time variation (for other wise identical peak amplitude pulses)
- Drift – slow changes due to changes in temperature, ageing etc.

Lets look at Jitter and Walk neglecting the less fundamental aspects of drift.

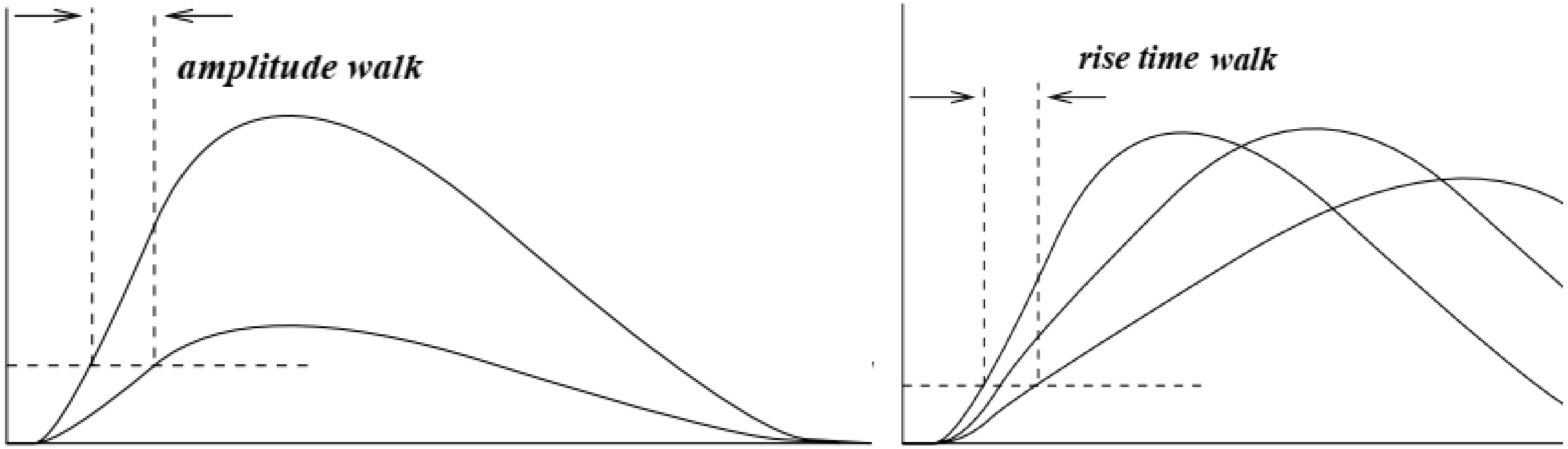
Jitter

- Assuming a fixed voltage level at which a timing discriminator fires then added, random, noise will cause a timing error.
- This can be minimised (not eliminated) by setting the threshold at the point of maximum d*V*/d*t* of the analogue signal (as shown in the figure).



Walk

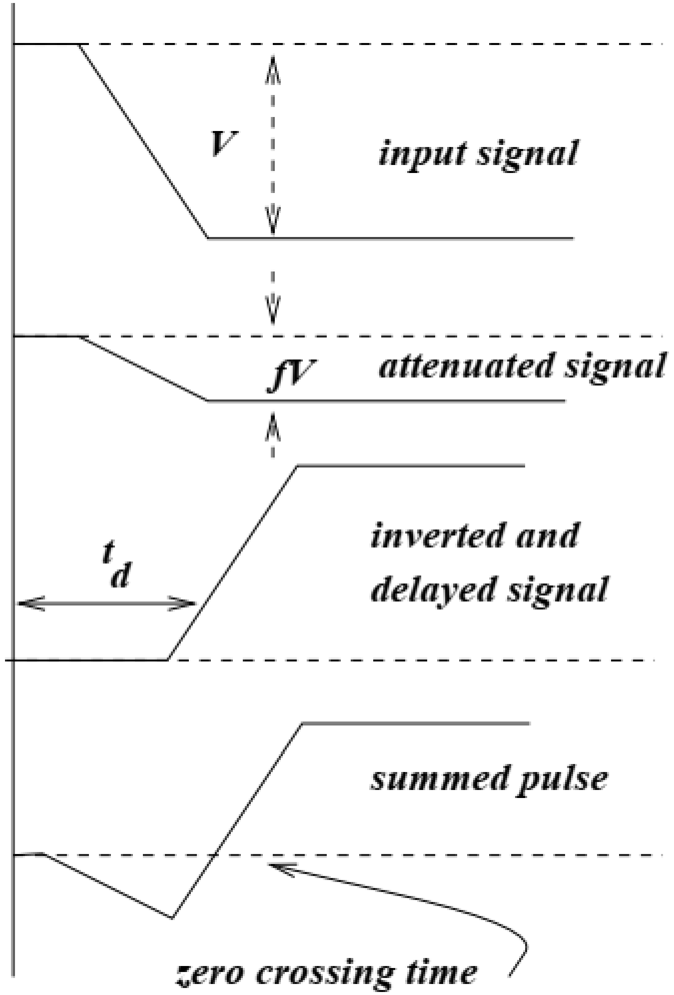
- Both the pulses in the figure below (left) have the same rise time (to peak) but different amplitudes.
- Two of the pulses in the figure below (right) have the same amplitude (to peak) but different rise time
- Even in the complete absence of any added noise, this will lead to timing errors.
- There are a number of electronic methods which can significantly reduce this effect.



Constant Fraction Discriminator (CFD)

- Select a constant fraction (~ 25%) of the input signal.
- Delay and invert the input signal.
- Add the two together.
- Trigger on the *zero-crossing* of the resultant.
- Major reduction in timing variation compared to a fixed threshold discriminator.
- For a helpful technical discussion on setting one up optimally (for enthusiasts only!) have a look at the RoentDek CFD manual

http://www.roentdek.de/manuals/CFD%20Manual.pdf



An example from Space Science

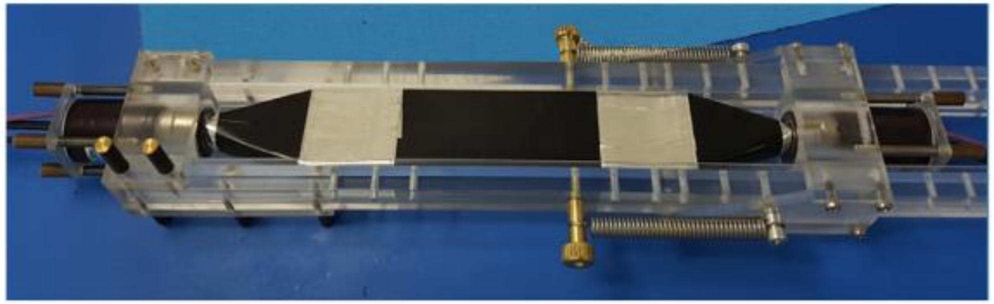
“A compact Time-Of-Flight detector for space applications: The LIDAL System” A Rizzo et al, *Nuclear Inst. and Methods in Physics Research, A* **898** (2018) 98–104

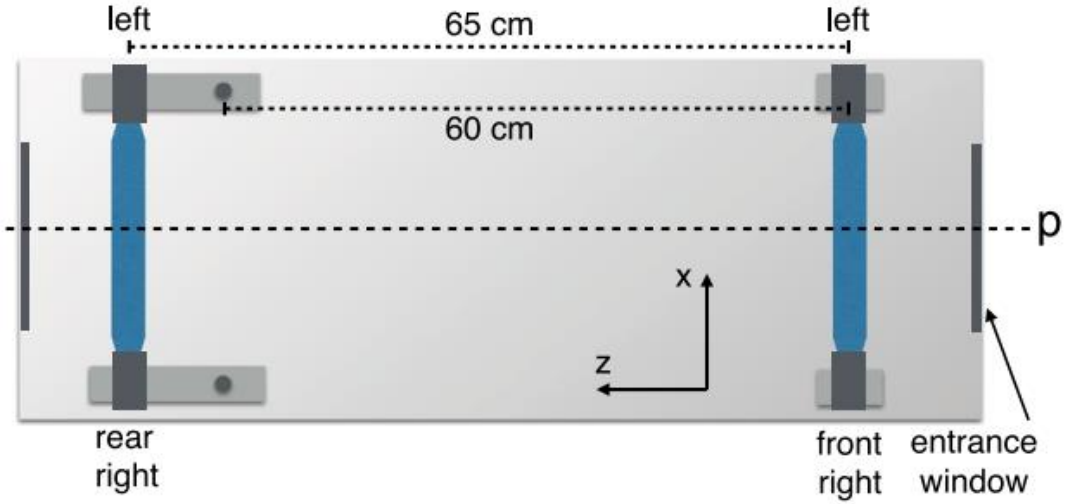
Part of the paper abstract:

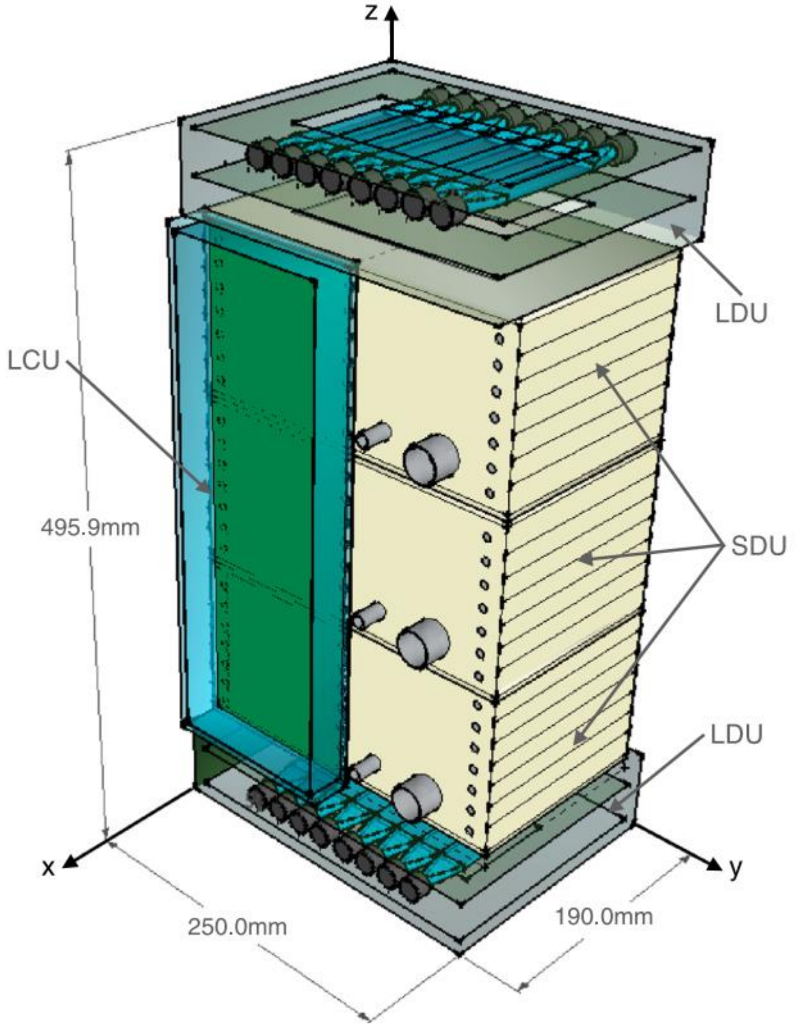
LIDAL (Light Ion Detector for ALTEA system) is a compact detector designed to upgrade ALTEA (Anomalous Long Term Effects on Astronauts) silicon detector apparatus, in order to study in detail the low-Z part of ions spectrum inside the International Space Station (ISS) and to enhance the Particle Identification (PID) capability of the system.

The new detector is designed to trigger ALTEA and to perform Time-Of-Flight measurements. It is based on plastic scintillators for fast timing applications read by Photo-Multiplier-Tubes (PMTs). A custom Front End Electronics (FEE) has been designed to reach time resolutions less than 100 ps (σ) for protons.

An example from Space Science







SDU is a particle telescope with six stripped silicon planes (380 µm thick, 8 × 16 cm2 active area) stacked in a tower configuration, able to measure the energy loss and to reconstruct the track of a particle passing through.

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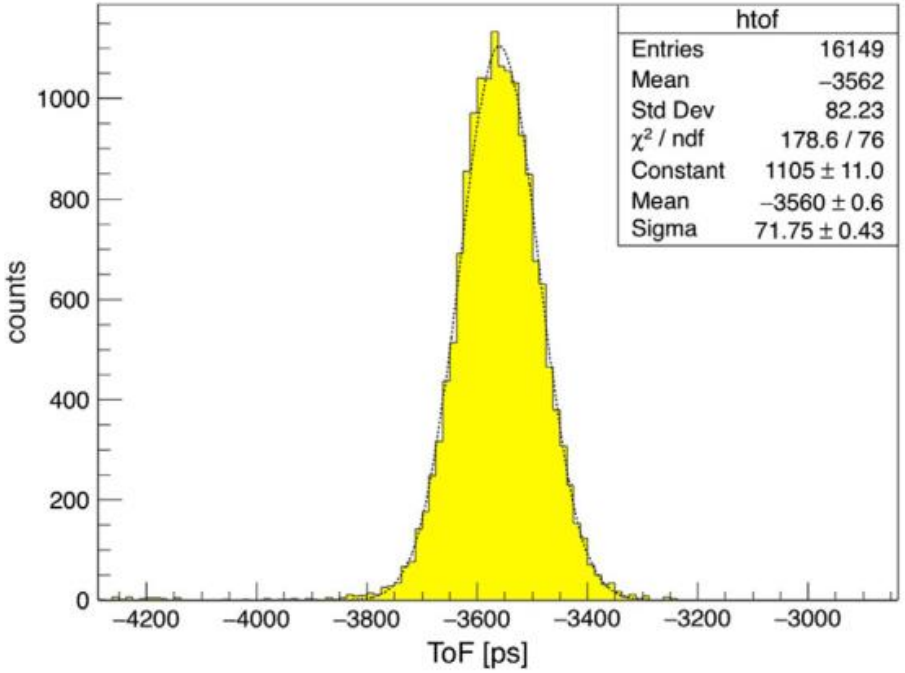
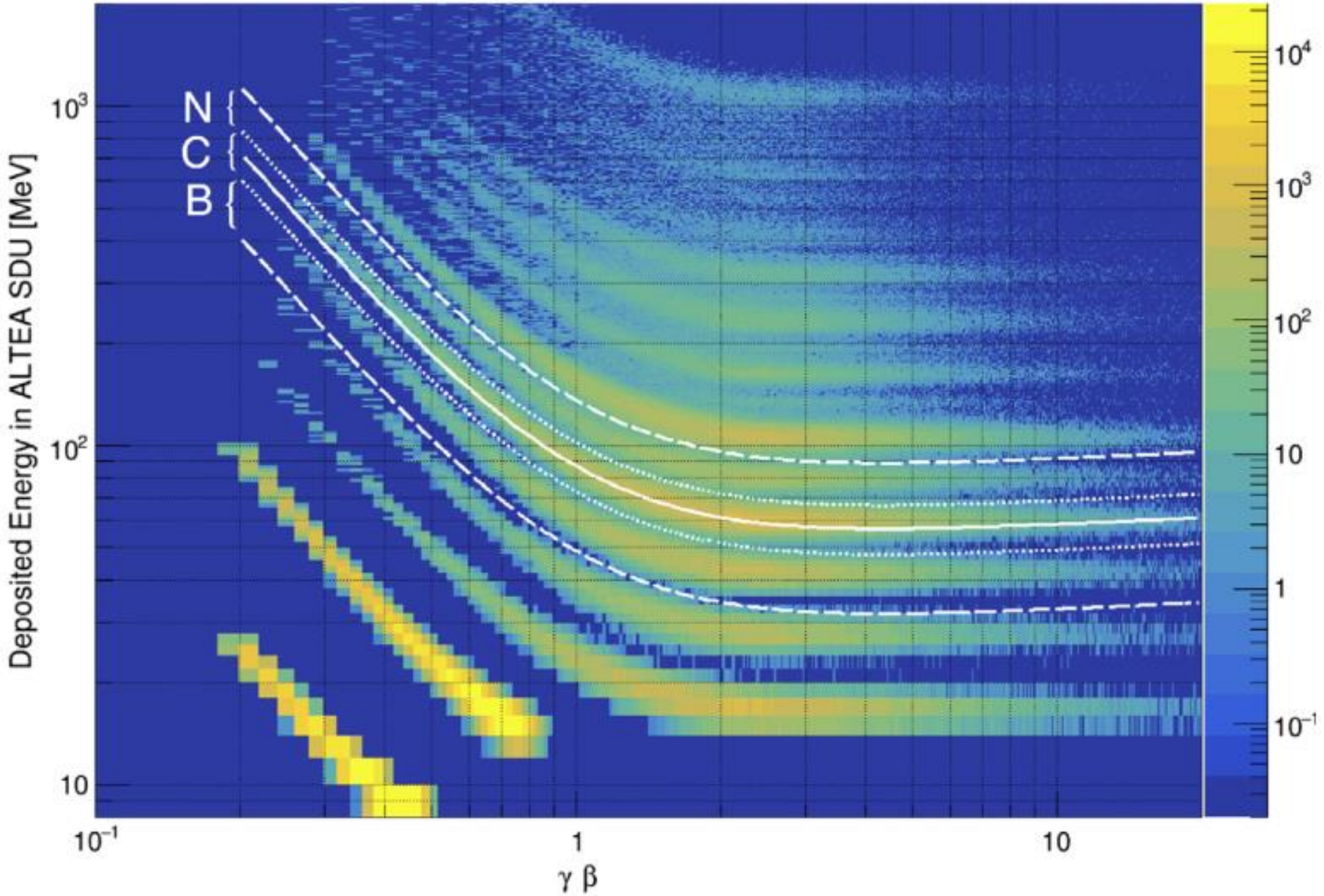


TOF distribution for 228 MeV protons



Simulated data using the measured performance of the TOF and the dE/dx system (SDU)