POLAR-2: Development of a Large Scale Gamma-ray Polarimeter

IAU Symposium 360 - ASTROPOL 2020 Hiroshima

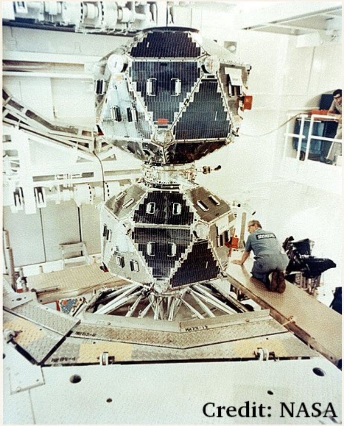
Nicolas De Angelis[1] on behalf of the POLAR-2 collaboration[2]

DPNC, University of Geneva, Switzerland

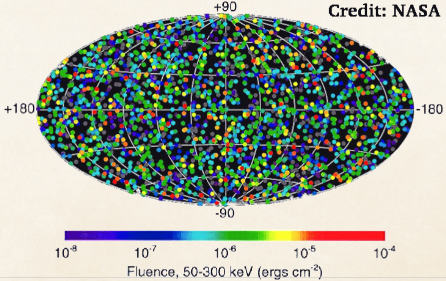
March 22nd, 2021

[1]E-mail: nicolas.deangelis@unige.ch
[2]`https://www.unige.ch/dpnc/polar-2`

GRB history

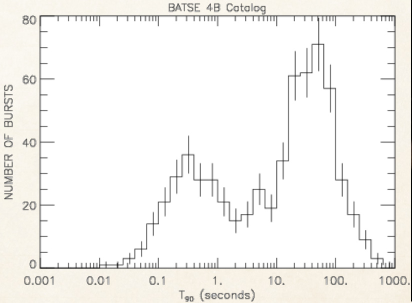


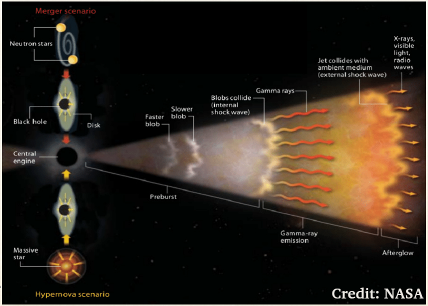
- Bright and short burst of X/γ-ray
- First discovered in 1967 by Vela US military satellite monitoring USSR nuclear weapon tests
- First breakthrough in early 90s, Burst and Transient Source Experiment (BATSE) measured position of thousands of GRBs, uniformly distributed in the sky
  $\Longrightarrow$ extragalactic sources
- Dedicated GRB polarimeter such as GAP and POLAR in the last decade



Gamma-Ray Bursts paradigm

- Extragalactic transient sources, lasting from milliseconds to minutes
- Two categories of GRBs:
  - Short bursts (T_{90}<2s) $\leftrightarrow$ neutron star mergers, detected in coincidence with GW
  - Long bursts (T_{90}>2s) $\leftrightarrow$ thought to originate from hypernovae
- Gamma prompt emission followed by an afterglow (in all wavelengths) from synchrotron process
- Polarization measurements can disentangle between different predicted emission models, allowing a better understanding of the jet and magnetic field structures





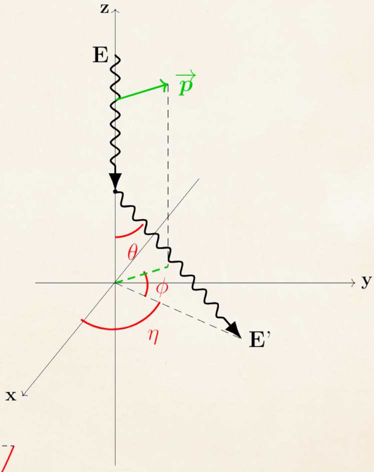
Polarimetry with the Compton scattering

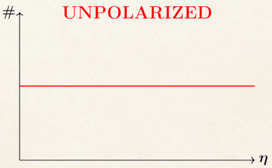
Compton scattering can be used to determine the polarization of a source:

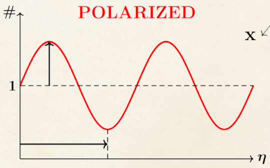
- Azimuthal scattering angle distribution provides information on polarization degree and angle
- So called modulation curved, parametrized by the Klein-Nishina cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA







Polarimetry with the Compton scattering

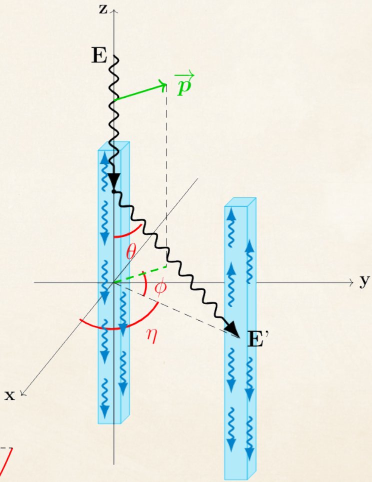
UNIVERSITÉ DE GENÈVE

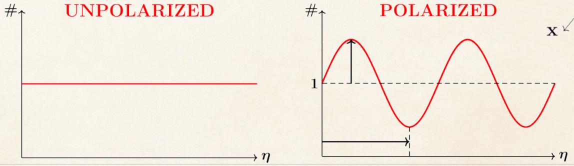
Compton scattering can be used to determine the polarization of a source:

- Azimuthal scattering angle distribution provides information on polarization degree and angle
- So called modulation curved, parametrized by the Klein-Nishina cross-section:

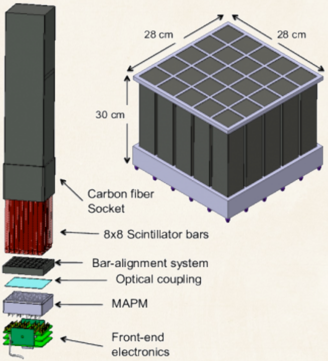
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

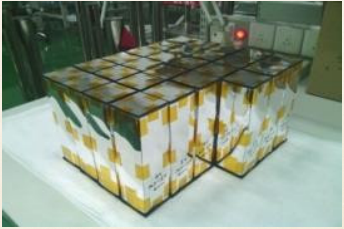
- Relative amplitude $\leftrightarrow$ PD, phase $\leftrightarrow$ PA
- **A segmented array of scintillators can be used to measure the scattering angle distribution**





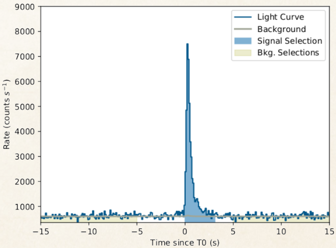
- POLAR was a dedicated gamma polarimeter composed of a 40$\times$40 scintillator array
- Divided in 5$\times$5 modules each made of 64 plastic scintillator bars (176$\times$5.8$\times$5.8mm, EJ-248M), each module being readout by Multi-Anode PMTs
- Optimized for Compton scattering in the 50-500keV range thanks to its low-Z scintillators
- 30kg instrument, half-sky FoV, $\sim 300 cm^2$ effective area at 400keV
- Design described in arXiv:1709.07191
- Launched in Sept 2016 on the Tiangong-2 Chinese space lab for 6 months of operation

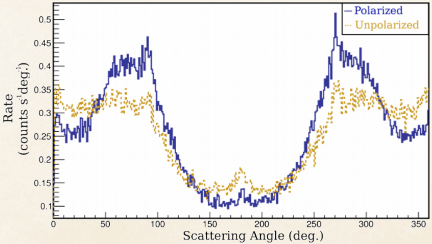




What we learned from POLAR

- Typical measured light and modulation curves shown below, complex modulation curve structure due to instrumental/geometrical effects
- POLAR detected 55 GRBs in 6 months of operation, 14 of which had enough statistics to be analyzed → joint spectral/polarization analysis with Fermi-GBM or Swift-BAT data using 3ML spectral fitting framework (github.com/threeML)



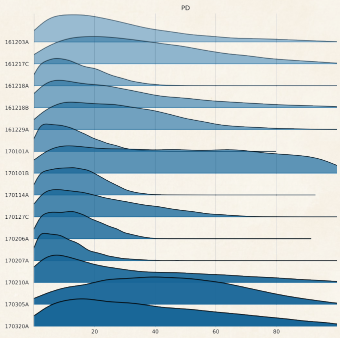


A&A 644, A124 (2020)

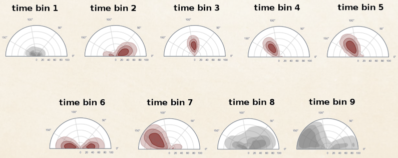
What we learned from POLAR

UNIVERSITÉ DE GENÈVE

- Catalog of 14 GRBs analysed, results show a low or null polarization degree (excluding synchrotron emission models from ordered magnetic field, compatible with photospheric emission model)
- High quality analysis of 5 GRBs published in Nat Astron 3, 258–264 (2019)
- Time resolved analysis show a hint of quickly evolving polarization angle that washes out polarization degree on time integrated analysis $\Longrightarrow$ need more statistics to make proper time resolved analysis
- We need more statistics in order to perform temporal and energy resolved analysis, with lowered energy threshold to probe emission models, and with bigger effective area and longer mission operation to get a larger catalog $\rightarrow$ **the POLAR-2 mission**



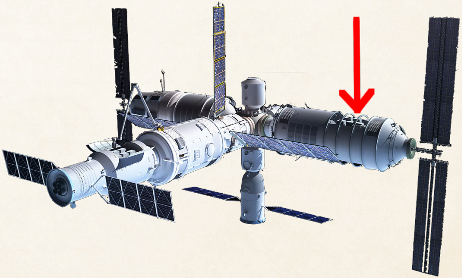
A&A 644, A124 (2020)

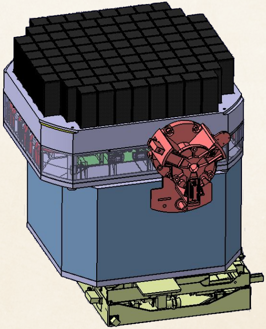


A&A, Volume 627, July 2019

The POLAR-2 mission

- Large scale GRB polarimeter based on POLAR legacy
- 4 times bigger than POLAR (from 25 to 100 polarimeter modules), 10 times more efficient (thanks to an improved design of the polarimeter modules)
- Lowered energy threshold to a few keV
- Equipped with spectrometer modules (CeBr3 or LaBr3) for source localization, allowing to perform autonomous joint spectral and polarization analysis
- Launch on China Space Station early 2024



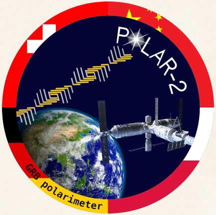


The POLAR-2 collaboration

About 20 people working on POLAR-2 from 4 countries:

- UniGe (DPNC), Switzerland: Management, polarimeter modules, instrument thermal and mechanical integration
- UniGe (DA), Switzerland: Communication system
- NCBJ, Poland: Back-End Electronics, Power Supply
- IHEP, China: Flight Model Acceptance, Spectrometers
- MPE, Germany: Qualification & Verification, Spectrometers

More info on `https://www.unige.ch/dpnc/polar-2`.



UNIVERSITÉ DE GENÈVE

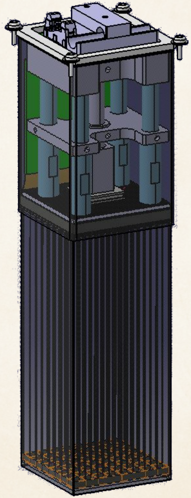
Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

MPE
Max-Planck-Institut für extraterrestrische Physik

Polarimeter module design

- 8×8 array of plastic scintillator bars (5.9×5.9×125mm) wrapped with highly reflective foils
- Readout with SiPM arrays from Hamamatsu (S13361-6075NE-04)
- 3D printed plastic alignment grid for scintillators
- Carbon fiber housing socket, Sorbothane pad at the top
- Back part of the module composed of FEE (using CITIROC ASICs) and cooling system (based on Peltier element and heat pipe, still under design)



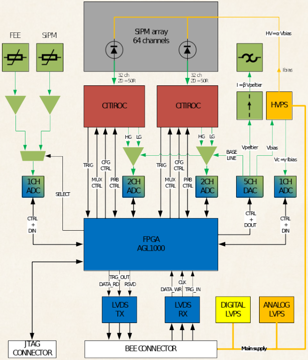
Improvements compared to POLAR:

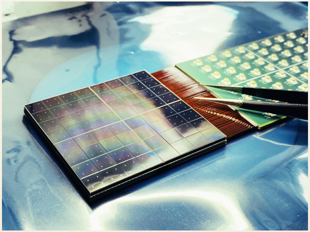
- Multi Anode PMTs are replaced by SiPM arrays $\Longrightarrow$ higher PDE (from 0.2 to 0.5)
- Shorter ($\Longrightarrow$ better SNR) and wider ($\Longrightarrow$ less dead volume between channels) scintillator bars
- Non-truncated scintillators $\Longrightarrow$ bigger readout surface $\Longrightarrow$ better light yield $\Longrightarrow$ lower energy threshold
- Reduced crosstalk by about an order of magnitude

Polarimeter module development

UNIVERSITÉ DE GENÈVE

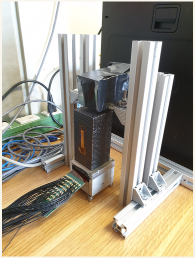
- I-V characteristics of all SiPM array channels are measured to extract the breakdown thermal dependency (important for breakdown non-uniformity and temperature corrections)
- Measurement of transmittance and reflectance spectra of wrapping foils used for scintillators
- Component qualification: irradiation of FPGA, DC/DC converter, Peltier, ADCs etc. with a PuBe neutron source
- SiPM irradiation with neutrons/protons: important to understand the increase of DCR and energy resolution with exposition dose
- Cooling system of the polarimeter modules is currently being tested. Heat extracted from the back of the sensors using Peltier element and heat pipe

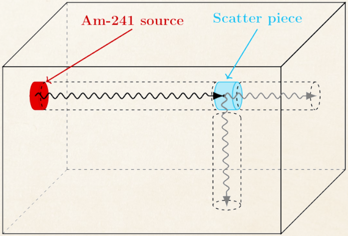


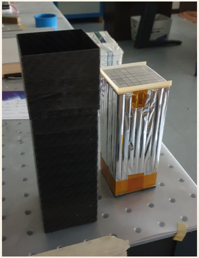


UNIVERSITÉ DE GENÈVE

- Module calibration setup at CERN (Geneva) based on FEE used in a neutrino experiment (also using CITIROC ASIC), our own FEE is expected in a month
- 365MBq Am-241 source (59.5keV photopeak) + 3.37MBq Cs-137 source (470keV Compton edge)
- Lead shielding with integrated scatter piece designed in order to get polarized photons from the Am-241 source

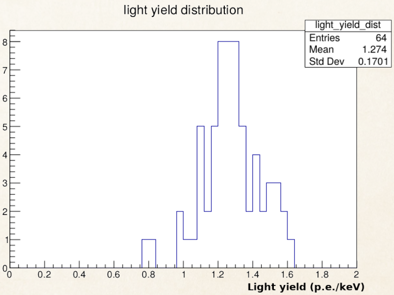


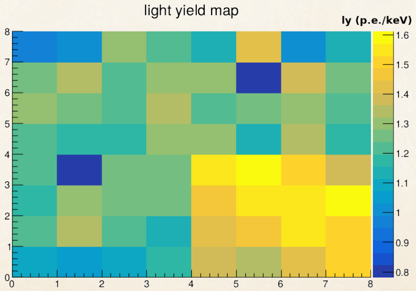




UNIVERSITÉ DE GENÈVE

- POLAR had a light yield of 0.3 p.e./keV
- POLAR-2 is able to reach 1.6 p.e./keV, thanks to a larger contact surface between scintillators and light sensors and higher PDE
- Energy threshold can therefore go down to a few keV ($\sim$50 keV for POLAR)
- Optical crosstalk has also been improved by an order of magnitude compared to POLAR

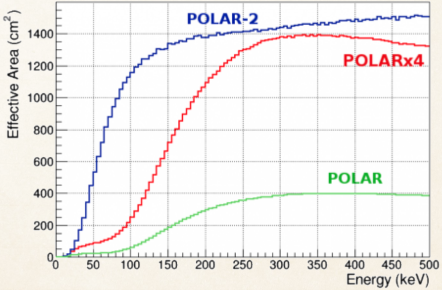


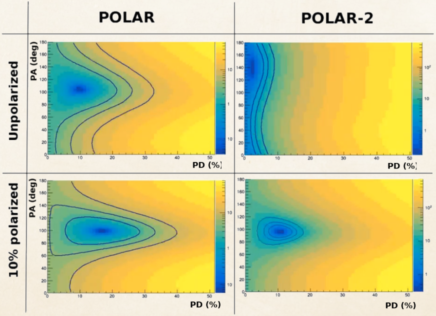


Anticipated Scientific Performance

UNIVERSITÉ DE GENÈVE

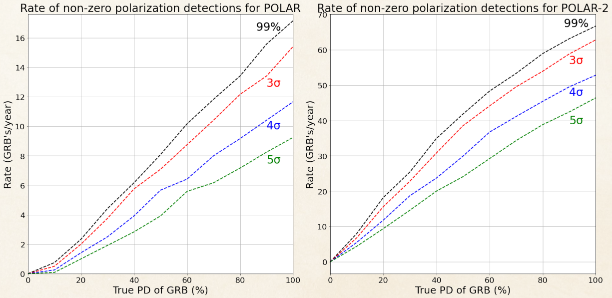
- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV)
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarised and a 10% polarised GRB with 99% CL (here shown for GRB170206A, 19.5° off-axis for POLAR)





Anticipated Scientific Performance

- POLAR-2 effective area will be better than 4 times POLAR due to technological improvements (e.g. for GRB170114A, 26.4° off-axis in POLAR FoV)
- Likelihood for POLAR and POLAR-2 in PA/PD phase space show that POLAR-2 will be able to distinguish an unpolarised and a 10% polarised GRB with 99% CL (here shown for GRB170206A, 19.5° off-axis for POLAR)
- About 50 GRBs/year with quality equal or higher than the best POLAR measurements (fluence $\geq 2\mu$erg/cm^2)



Thank you!

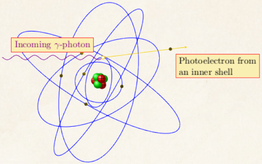
Summary

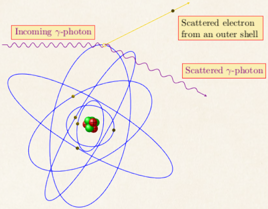
UNIVERSITÉ DE GENÈVE

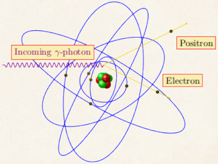
- GRBs are among the brightest and more powerful astronomical events, originated from neutron star merger and hypernovae
- Measuring the polarization of these extragalactic transient events can provide information on physical emission processes at play in this sources
- POLAR detected 55 GRBs, 14 of which where analyzed. Globally low polarization degree, time resolved analyses show a hint of polarization angle evolution in time that washes out the polarization. More statistics are needed.
- POLAR-2 successor mission of POLAR, 4 times bigger and 10 times more efficient (100 improved polarimeter modules), spectrometer modules for localization/joint spectral analysis, launch early 2024 to CSS
- POLAR-2 modules are based on the POLAR legacy with some improvements: MAPMTs upgraded to SiPMs (higher PDE and light yield, lower energy threshold), shorter and wider scintillators (improved SNR and dead volume)
- Polarimeter module design almost fixed (still a bit of work on the cooling system and SiPM-scintillator optical coupling), we will start to build FM-like modules soon. Light yield and crosstalk considerably improved compared to POLAR (from 0.3 to 1.6p.e./keV and from 15-20% to 1.5%)

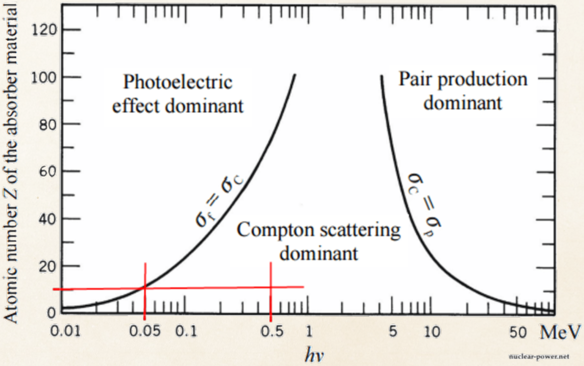
Low-Z scintillators for an optimized Compton cross-section

UNIVERSITÉ DE GENÈVE



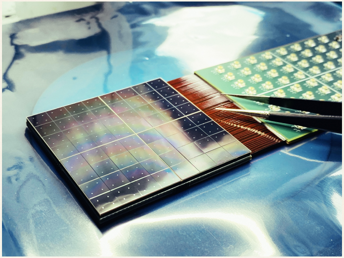


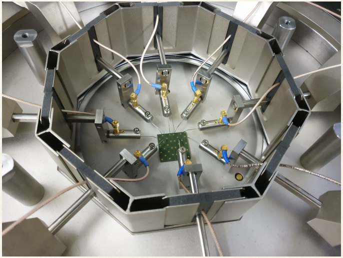


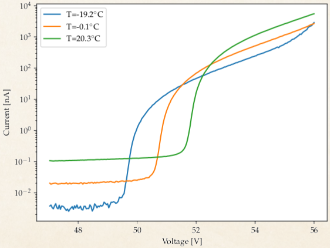


Polarimeter module development SiPM I-V characterization

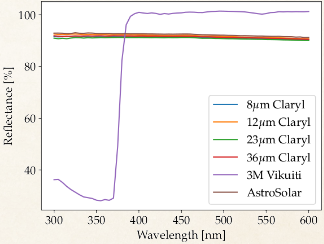
- I-V characterization of every SiPM array with semi-automatic probe station (CascadeMicrotech300)
- Measurement of breakdown vs temperature
- Breakdown non-uniformity correction at the ASIC level (with an integrated DAC) and temperature loop correction in the FEE

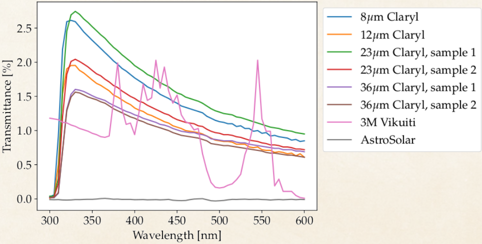




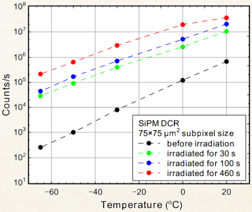


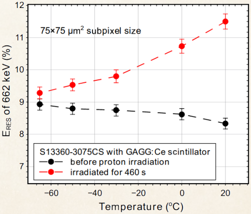
- Transmittance and reflectance measurement of several wrapping foils candidate at CERN (PerkinElmer LAMBDA 650 Spectrometer)
- Scintillators will be first wrapped with Vikuiti from 3M (reflectance of about 99%), and with Claryl from Toray afterward (reflectance of about 90%)



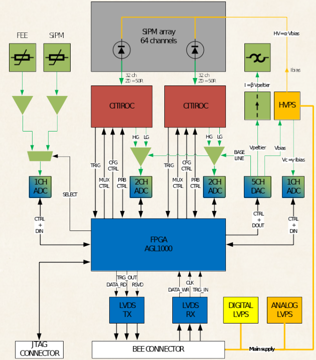


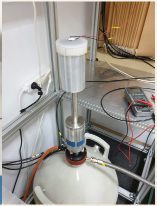
- Front-end component irradiation for space qualification: GoWiN FPGA, DC/DC converter for sensor bias from LT, Peltier element activation, ADCs...
- SiPM irradiation to study the increase of dark current after several years of exposure in space





S. Mianowski et al 2020 JINST 15 P03002

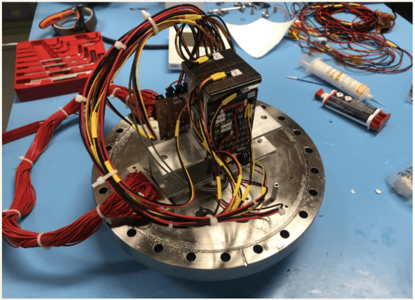


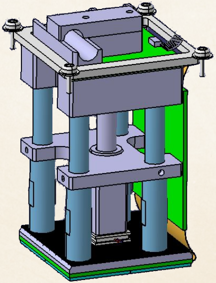


UNIVERSITÉ DE GENÈVE

Polarimeter module development Cooling system

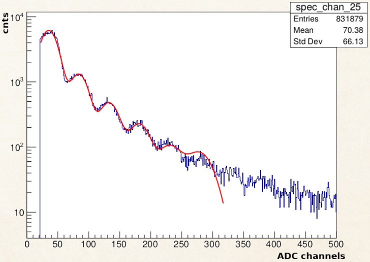
- Cooling system of the polarimeter modules is currently under design and several options are being tested
- Based on Peltier element on the back of the SiPM to reduce dark noise and heat pipes to extract heat from the module
- Overall instrument thermal simulations are also ongoing in order to optimize outer radiator system
- Power budget of 200W for the polarimeter (2W per module) + 100W for the BEE and spectrometer modules

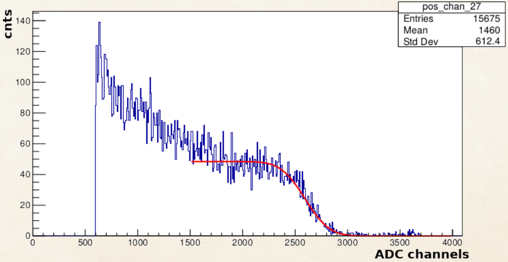




UNIVERSITÉ DE GENÈVE

- Fitting HG finger plot to get the distance between photoelectrons $\Longrightarrow$ gain in ADC/p.e.
- Fitting HG Am241 photopeak (59.5keV) and LG Cs137 Compton edge (470keV) to get the HG-LG ADC conversion (to get a more precise light yield value)
- Dividing the ADC/keV of the cesium CE by the gain leads to the light yield in p.e./keV





Preliminary module performances Crosstalk

- Optical crosstalk between scintillator bars was about 15-20% for POLAR
- This goes down to 1.5-2.5% thanks to an improved scintillator wrapping method and the suppression of a thick optical coupling layer (0.7mm)
- The optical coupling between SiPM and scintillator bars is still under investigation, so the final crosstalk could be a bit worst
- Current crosstalk compatible with transmittance/reflectance measurements: wrapping foil have a transmittance of about 1% and 3m height plastic grid used to assemble the scintillators is 60% transparent $\rightarrow$(122mm/125mm)*1%+(3mm/125mm)*60%=2.416%