The Silicon Strip Tracker of the Fermi Large Area Telescope

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on behalf of the Fermi LAT collaboration

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The Fermi-LAT Collaboration

United States
- Stanford University (SLAC and HEPL/Physics)
- Goddard Space Flight Center
- Naval Research Laboratory
- Ohio State University
- California State University at Sonoma
- University of California at Santa Cruz
- University of Washington

PI: Peter Michelson (Stanford & SLAC)
- ~ 390 Members (including ~ 95 Affiliated Scientists, plus 68 Postdocs, and 105 Graduate Students)
- Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden
- Managed at Stanford Linear Accelerator Center (SLAC)

Sweden
- Royal Institute of Technology
- Stockholm University

Japan
- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Tech.

France
- IN2P3
- CEA/Saclay

Italy
- INFN
- INAF
- ASI
The Fermi observatory

Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV→ 300 GeV
- Large field of view (≈ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours.
- Long observation time: 5 years minimum lifetime, 10 years planned, 85% duty cycle.

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.
The Large Area Telescope

- Overall modular design.
- \(4 \times 4\) array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by an Anti-Coincidence Detector (ACD)

Tracker
- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 73 m\(^2\) of silicon active area, 1M readout channels.
- High-precision tracking, short instrumental dead time.

Anti-Coincidence Detector
- Segmented (89 tiles) to minimize self-veto at high energy.
- 0.9997 average efficiency (8 fiber ribbons covering gaps between tiles).

Calorimeter
- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.
Basic tracker design

- 19 tray structures
  - Basic mechanical framework
- 18 x-y detection planes
  - Single sided SSDs, below the W foils
- Front: 12 planes with 0.03 $X_0$ converter
  - Best angular resolution
- Back: 4 planes with 0.18 $X_0$ converters
  - Increase the conversion efficiency
- Bottom: 2 planes with no converter
  - Tracker trigger needs at least 3 x-y layers
- Total depth: 1.5 $X_0$ on axis
Tracker design: mechanics

- Less than 2 mm spacing between silicon layers
- Readout electronics on the tray sides: 90° pitch adapters, read out via flat cables
- 2 mm inter-tower separation to minimize dead area
18 flight towers integrated and tested in 9 months
  ▶ Flight Module A suffering from some processing issues during the set up of the assembly chain
The Tracker electronics system

**Basic design**

- 24 front-end chips and 2 controllers handle one Si layer
- Data can shift left/right to either of the controllers (can bypass a dead chip)
- Zero suppression takes place in the controllers (hit strips + layer OR TOT in the data stream)
- Two flat cables complete the redundancy

**Key features**

- Low power consumption ($\approx 200 \, \mu W/\text{channel}$)
- Low noise occupancy ($\approx 1$ noise hit per event in the full LAT)
- Self-triggering (three $x$-$y$ planes in a row, i.e. sixfold coincidence)
- Redundancy, Si planes may be read out from the right or from the left controller chip
- On board zero suppression
The launch

Just turned three years in orbit

Launch

- Launched on June 11, 2008 from the Kennedy Space Center.
- Launch vehicle: Delta 7290H-10.
- Circular orbit, 565 km altitude, 25.6° inclination.
- Some of the milestones: ≈ 190 billion triggers ≈ 35 billion events downlinked to ground, ≈ 610 million photon candidates released to the community, > 99% uptime.
Some Fermi Science Highlights!

- **Diffuse $\gamma$-ray emission**
  - no features in the ExtraGalactic Background spectrum

- **Dark Matter WIMP annihilation**
  - constraints are close to thermal cross-section below $\sim 10$ GeV

- **Cosmic-ray Electrons and positrons**
  - spectrum measured from 7 GeV up to 1 TeV
  - rising positron fraction up to 100 GeV

- **Gamma-ray Bursts**
  - high energy emission
  - testing Lorentz Invariance Violation

- **Pulsars**
  - 88 pulsars now known: radio loud, gamma-ray selected, millisecond pulsars

- **Active Galactic Nuclei, pulsar wind nebulae, novae, solar flare, moon emission. . .**
All the relevant tracker quantities are monitored on a run by run basis:

- noise occupancy;
- hit and trigger efficiency;
- Time over Threshold distributions;
- alignment.

Run selection for this summary:

- roughly all the runs taken in the nominal data taking configuration;
- more than 1500 s long, most of them are ~5000 s long and contain ~2M events;
- not including the early phase of the L&EO.

⇒ numerology: ≈ 17000 runs, from September 2008 to June 2011.
Hit efficiency

Average hit efficiency: 99.96 ± 0.01 %

Slope = (+0.0006 ± 0.0006) % year⁻¹

Tower 15

Average hit efficiency: 98.46 ± 0.03 %

Slope = (-0.0449 ± 0.0030) % year⁻¹

Johan Bregeon (INFN)
- Long term trending of the position of the MIP peak in the Tracker
  - Time Over Threshold (averaged over the LAT)
- The two noticeable discontinuities are due to hardware/software changes
  - Analog signal remarkably stable (within much less than 1%) since the last of the two changes.
Long term trending of the noise occupancy for a typical silicon layer

- Measured accumulating counts on the silicon layers far from triggering towers (and cross-checked with dedicated periodic triggers)

Noise occupancy at the level of $4 \times 10^{-3}$ for a layer (1536 strips)

- Translating into $2-3 \times 10^{-6}$ at the single strip level (dominated by accidental coincidences)

- ... or 2–3 noise hits per event in the full LAT
Some 200 noisy strip masked prior to launch (0.02%)

213 additional noisy strips masked over the first three years of mission, for a total of 416 (0.05%)

Two major contributors

- Tower 0 (Flight Module A): the first one being assembled, suffering from some processing issues—showed some evolution throughout the first year
- Tower 3 (Flight Module 15): noise issue in one ladder—more on that later
A MINOR HARDWARE ISSUE

- Noise in one silicon ladder steadily increasing since January 2010
  - Really only one of the 2304 silicon ladders in the LAT
A minor hardware issue
To be debugged in space

One power supply per tower
- We only monitor the currents at the tower level (i.e. each HV line is biasing $36 \times 4 = 144$ silicon ladders)
- Not trivial to measure a relative increase in the leakage current at the level of a single ladder

Test runs with reduced bias HV (40, 60, 80 V vs. nominal 105 V)
- Normal data taking, charge injection calibration

No obvious root cause identified
- Even if we lose the entire ladder it’s less than 0.05% of the tracker
- No evidence of similar phenomena in any other part of the LAT
Conclusions

- The LAT tracker is the largest solid-state tracker ever built for a space application
  - 73 m$^2$ of single-sided silicon strip detectors
  - Almost 900,000 independent electronics channels
- All design goals met with large margins
  - Single-plane hit efficiency $> 99\%$
  - Noise occupancy at the level of $10^{-6}$
  - 160 W of power consumption
- Major science results obtained during the first three years
  - Fermi 2-year point source catalog
    - 1873 sources, including 12 extended!
    - http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog
- No noticeable degradation of the performances observed
  - Fermi is a 5 to 10 years mission!
The South Atlantic Anomaly is a region with a high density of trapped particles (mostly low-energy protons).

We do not take physics data in the SAA (ACD HV is lowered) but we do record the trigger rate from CAL and TKR.

The mapping of the SAA was one of the goals of the commissioning phase, now routinely monitored.
Hardware trigger at the single tower level

- All subsystems contribute
- TKR: three consecutive xy planes in a row hit
- CAL_LO: single CAL log with more than 100 MeV (adjustable)
- CAL_HI: single CAL log with more than 1 GeV (adjustable)
- ROI: MIP signal in one of the ACD tiles close to the triggering TKR tower
- CNO: heavy ion signal in one of the ACD tiles

Event readout

- Each particular combination of trigger primitives is mapped into a so-called trigger engine (determines hardware prescale factors, and readout mode)
- Upon a valid L1 trigger the entire detector is read out
Filter basics
- Need software onboard filtering to fit the data volume into the allocated bandwidth
- Full instrument information available to the onboard processor
- Flexible, fully configurable (the following reflects the nominal science data taking setting)

Nominal implementation
- Each event is presented to up to 4 (adjustable) different filters
- GAMMA: rough photon selection (main source of science data)
- HIP: heavy ions (continuously collected for calibration purposes)
- MIP: used in calibration runs
- DGN: configured to provide a prescaled ($\times 250$) unbiased sample of all trigger types
- Final gamma selection performed on ground (see the following)
Instrument design drivers

- **Science design drivers**
  - Effective area and angular resolution: design of the tracker converter
  - Energy range and resolution: thickness and design of the calorimeter
  - Charged particle background rejection: mainly driving the ACD design, but also impacts the tracker and calorimeter design, along with the trigger and data flow

- **Mission design drivers**
  - Launcher vehicle: instrument footprint (1.8 × 1.8 m²)
  - Mass budget (3000 kg): maximum depth of the calorimeter
  - Power budget (650 W overall): maximum number of electronics channels in the tracker—i.e. strip pitch and number of layers
  - Launch and operation in space: sustain the vibrational loads during the launch, sustain thermal gradients, operate in vacuum
Tracker reconstruction: low energy

Simulated 80 MeV gamma-ray

- Angular resolution dominated by multiple scattering
  - Call for thin converters...
  - ...but need material to convert the gamma-rays!
Tracker reconstruction: high energy
Simulated 150 GeV gamma-ray

- Angular resolution determined by hit resolution and lever arm
  - Call for fine SSD pitch, but power consumption is a strong constraint
  - Backsplash from the calorimeter also a potential issue