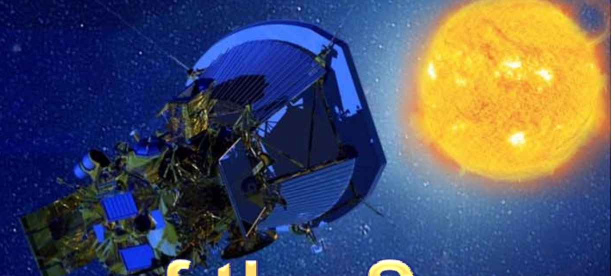
Solar Probe Plus

A NASA Mission to Touch the Sun



Integrated Science Investigation of the Sun Energetic Particles

Preliminary Design Review

05 – 06 NOV 2013

EPI-Hi Sensor Design

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EPI-Hi Lead Co-I (JPL)

Outline

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- Measurement Requirements
- Sensor System Overview
- Low-Energy Telescopes
- High-Energy Telescope
- Solid-State Detectors
- Species, Energy Coverage and Energy Binning
- Element Resolution
- Helium Isotope Identification
- Electron Identification
- Fields of View
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- Measurement Cadences
- Dynamic Range in Particle Intensities
- Redundancies: Design for Graceful Degradation
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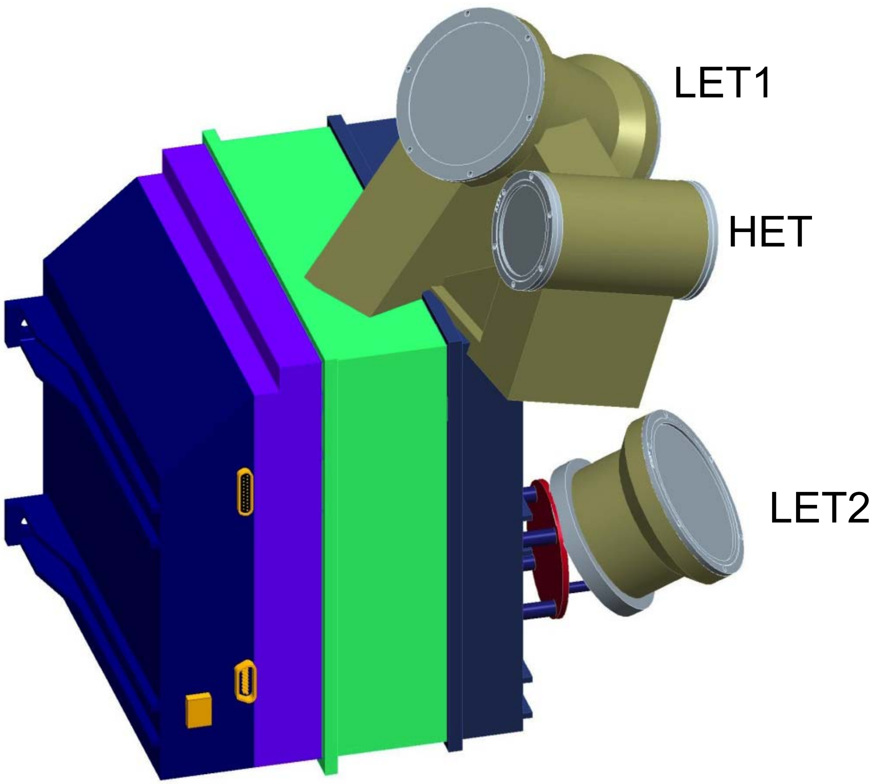
EPI-Hi Measurement Requirements

- Protons and Heavy Ions
  - Energy range: 1 MeV/nuc (TBR) to ≥50 MeV/nuc
  - Energy binning: ≥6 bins per decade
  - Cadence: at least energy bin with time resolution of 5 s or better
  - FoV: ≥π/2 sr in sunward and anti-sunward hemispheres (incl. 10° from S/C-Sun line)
  - Angular sectoring: ≤30° sector width
  - Composition: at least H, He, C, O, Ne, Mg, Si, Fe, ^{3}He
  - Species resolution: FWHM ≤ 0.5 (TBR) × separation from nearest abundant neighbor
  - Max intensity: up to 10% (TBR) of upper limit proton spectrum from EDTRD
- Electrons
  - Energy range: 0.5 MeV (TBR) to ≥3 MeV
  - Energy binning: ≥6 bins per decade
  - Cadence: at least energy bin with time resolution of 1 s or better
  - FoV: ≥π/2 sr in sunward and anti-sunward hemispheres (incl. 10° from S/C-Sun line)
  - Angular sectoring: ≤45° sector width
  - Max intensity: up to 10% (TBR) of upper limit electron spectrum from EDTRD*

*Note: upper limit electron spectrum not yet specified in EDTRD

EPI-Hi Sensor System Overview (1/2)

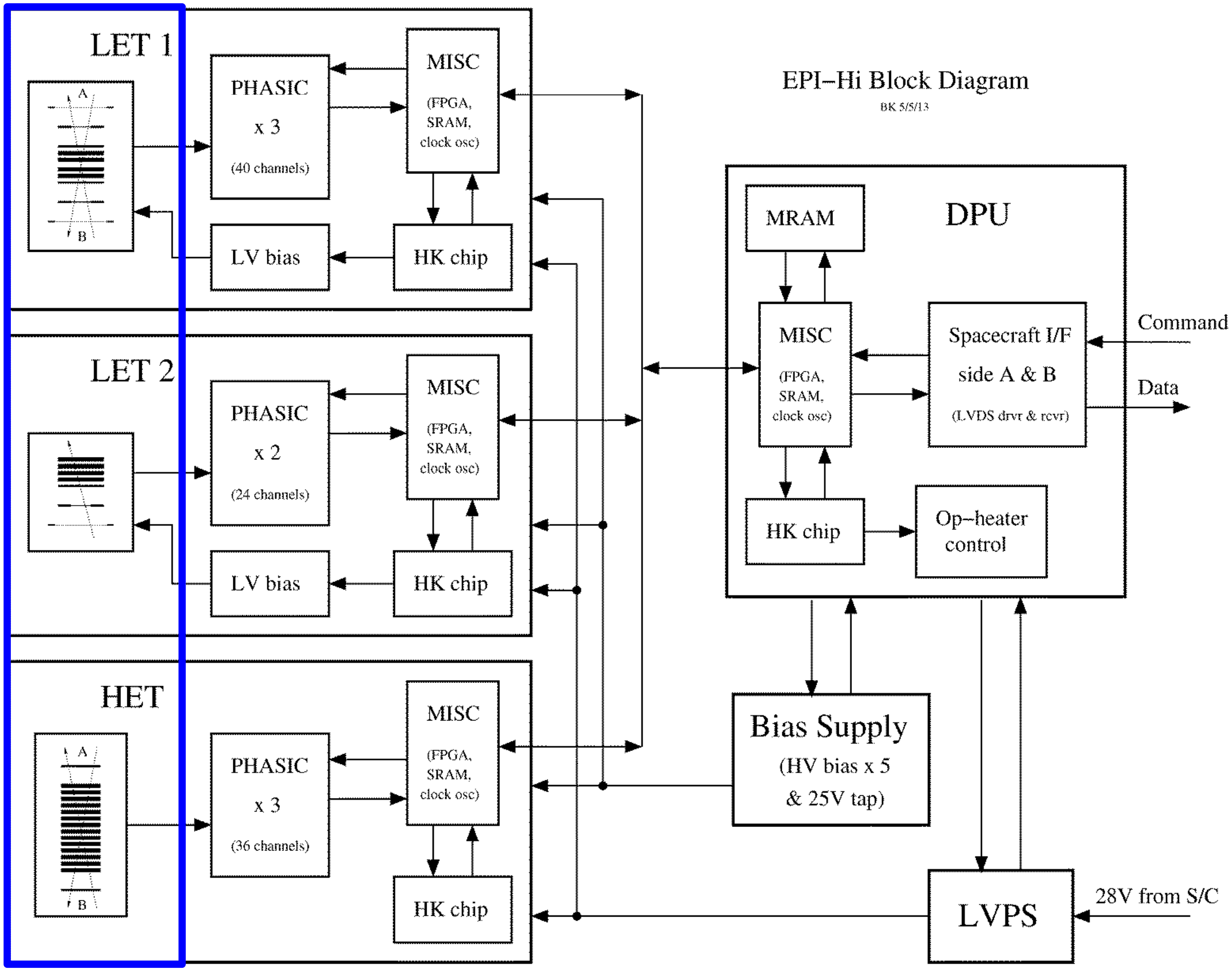
- Sensor Approach
  - All sensor elements are silicon solid-state detectors
  - Multiple detector telescopes to provide large energy range and sky coverage
  - Some telescopes double-ended to increase sky coverage
  - Detector segmentation to provide angular sectoring and adjustable geometrical factor
- Heritage
  - Numerous energetic particle instruments over the past 40 years
  - Direct predecessor: STEREO/LET & HET
- Key Differences
  - Thinner detectors and windows to reduce energy threshold
  - Compact telescope designs to reduce saturation at high particle intensities and backgrounds at low intensities



EPI-Hi Sensor System Overview (2/2)

3 detector telescopes:

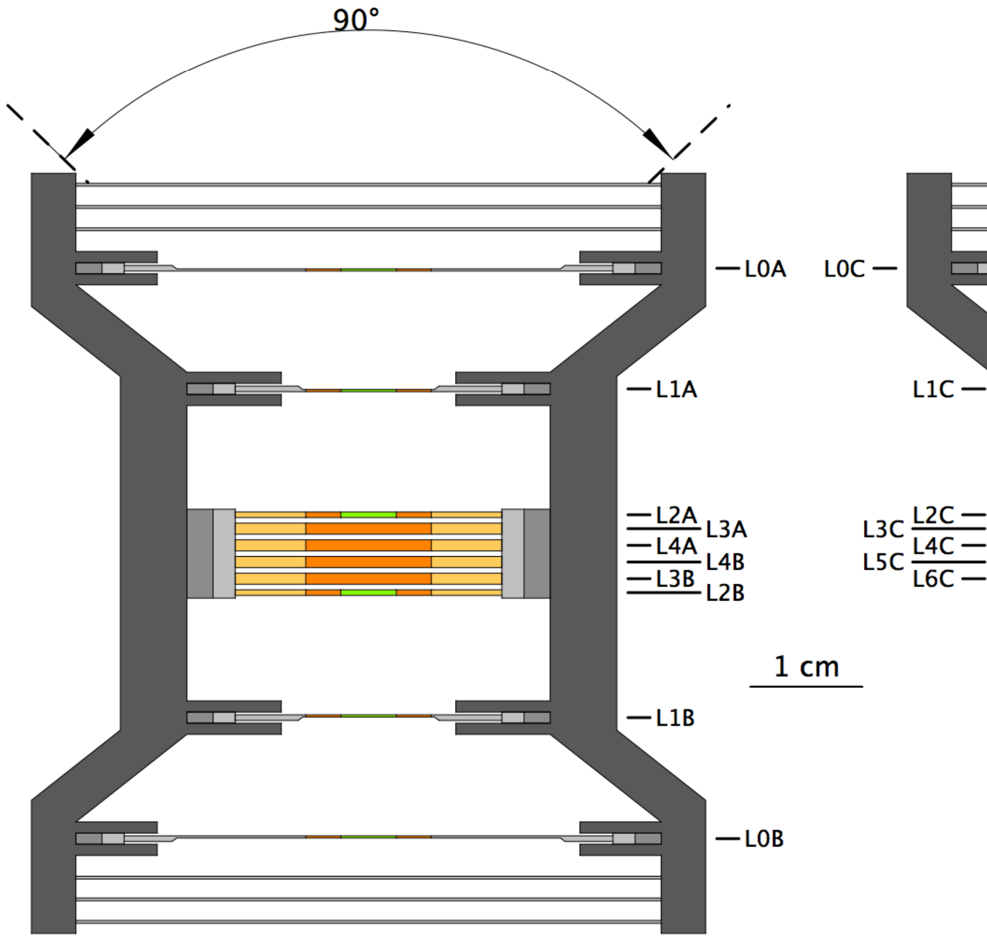
- 1 double-ended low-energy telescope (LET1)
- 1 single-ended low-energy telescope (LET2)
- 1 double-ended high-energy telescope (HET)
- All sensor elements are ion-implanted silicon solid-state detectors
- Signals from each telescope processed by an individual electronics board



Low-Energy Telescopes

LET1 (double-ended)

LET2 (single-ended)



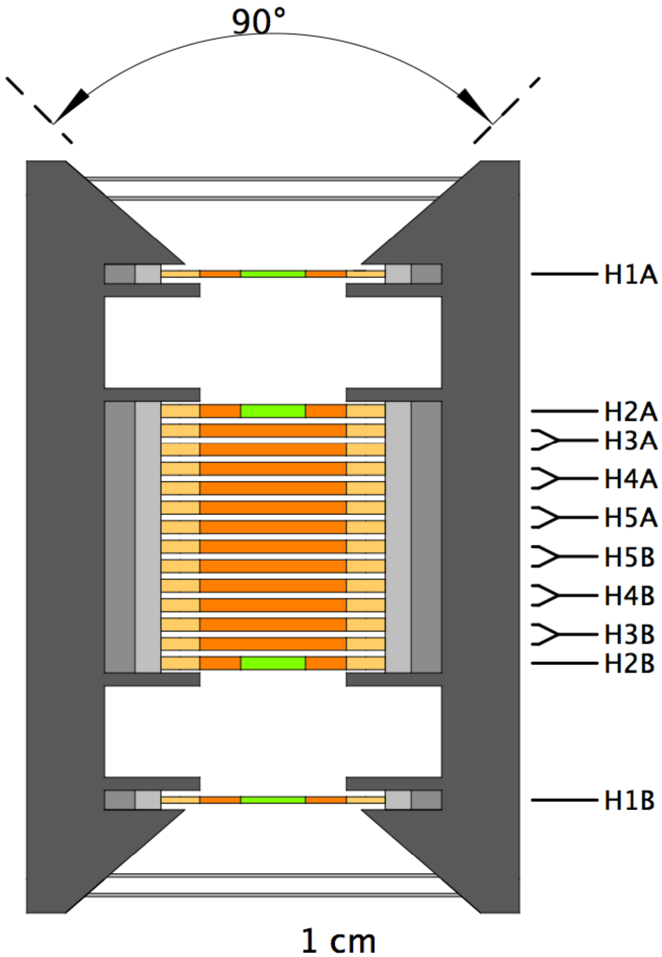
windows (each end):
2 µm, 1 µm, 1 µm Kapton

color: active silicon
grey: inactive material

High-Energy Telescope

Conceptual Cross Section

HET (double-ended)



windows (each end):
2 × 127 μm Kapton

color: active silicon
grey: inactive material

Solid-State Detectors

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EPI-Hi Silicon Solid-State Detector Designs

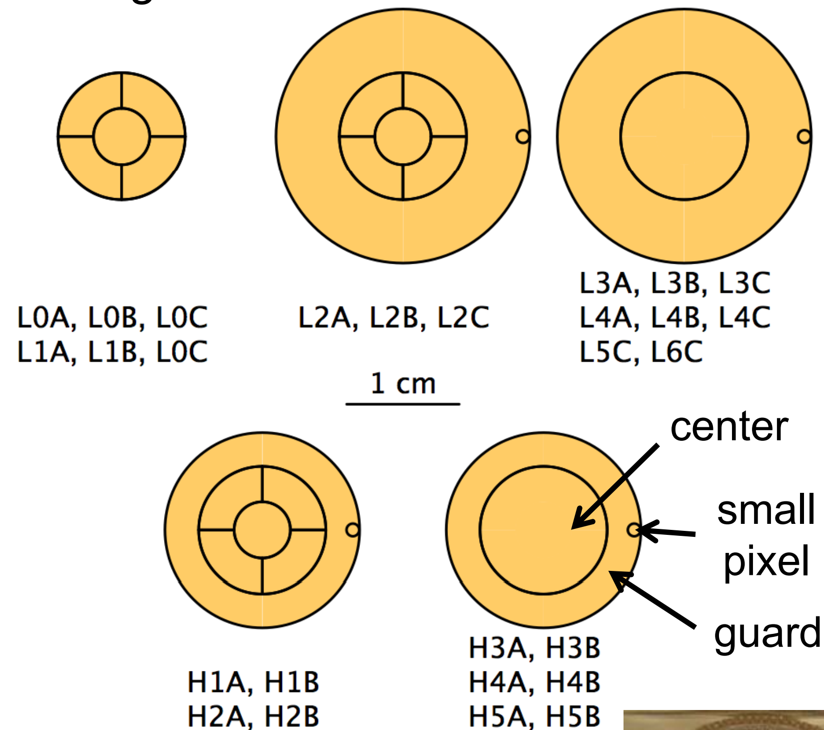
Detector Telescope	Detector Designations	Thickness	Number of Central / Guard / Small Pixel Segments	Central Active Area	Guard Active Area	Notes
LET1	L0A, L0B	12 µm	5 / 0 /0	1.0 cm^2	N/A	[1]
	L1A, L1B	25 µm	5 / 0 / 0	1.0 cm^2	N/A	[1]
	L2A, L2B	500 µm	5 / 1 / 1	1.0 cm^2	3.0 cm^2	[2]
	L3A, L3B	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
	L4A, L4B	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
LET2	L0C	12 µm	5 / 0 / 0	1.0 cm^2	N/A	[1]
	L1C	25 µm	5 / 0 / 0	1.0 cm^2	N/A	[1]
	L2C	500 µm	5 / 1 / 1	1.0 cm^2	3.0 cm^2	[2]
	L3C	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
	L4C	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
	L5C	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
	L6C	1000 µm	2 / 0 / 1	4.0 cm^2	N/A	[2]
HET	H1A, H1B	500 µm	5 / 1 / 1	1.0 cm^2	1.73 cm^2	[2]
	H2A, H2B	1000 µm	5 / 1 / 1	1.0 cm^2	1.73 cm^2	[2]
	H3A, H3B	2 × 1000 µm	1 / 1 / 1	1.0 cm^2	1.73 cm^2	[2]
	H4A, H4B	2 × 1000 µm	1 / 1 / 1	1.0 cm^2	1.73 cm^2	[2]
	H5A, H5B	2 × 1000 µm	1 / 1 / 1	1.0 cm^2	1.73 cm^2	[2]

Notes:

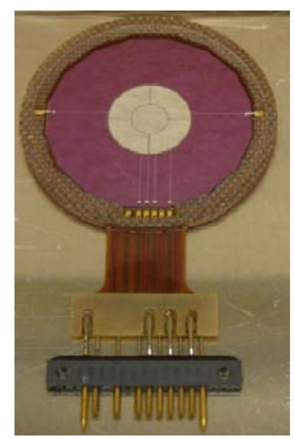
[1] new technology development

[2] small pixel at edge for rate monitoring on some detectors; area: 1 mm^2

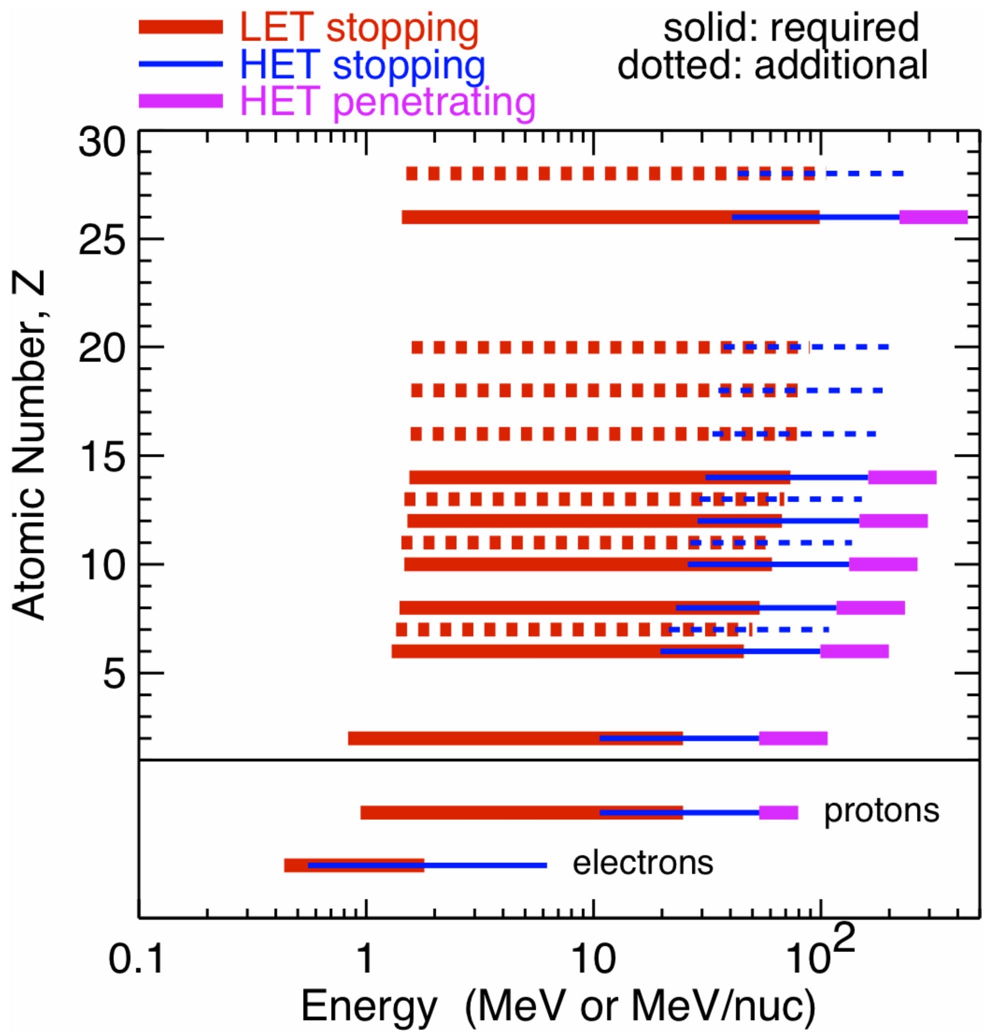
Segmentation of Active Areas:



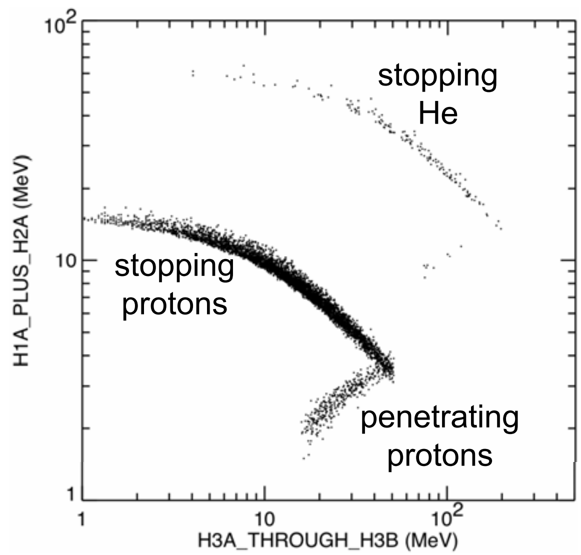
prototype
L1 detector



Species, Energy Coverage and Energy Binning

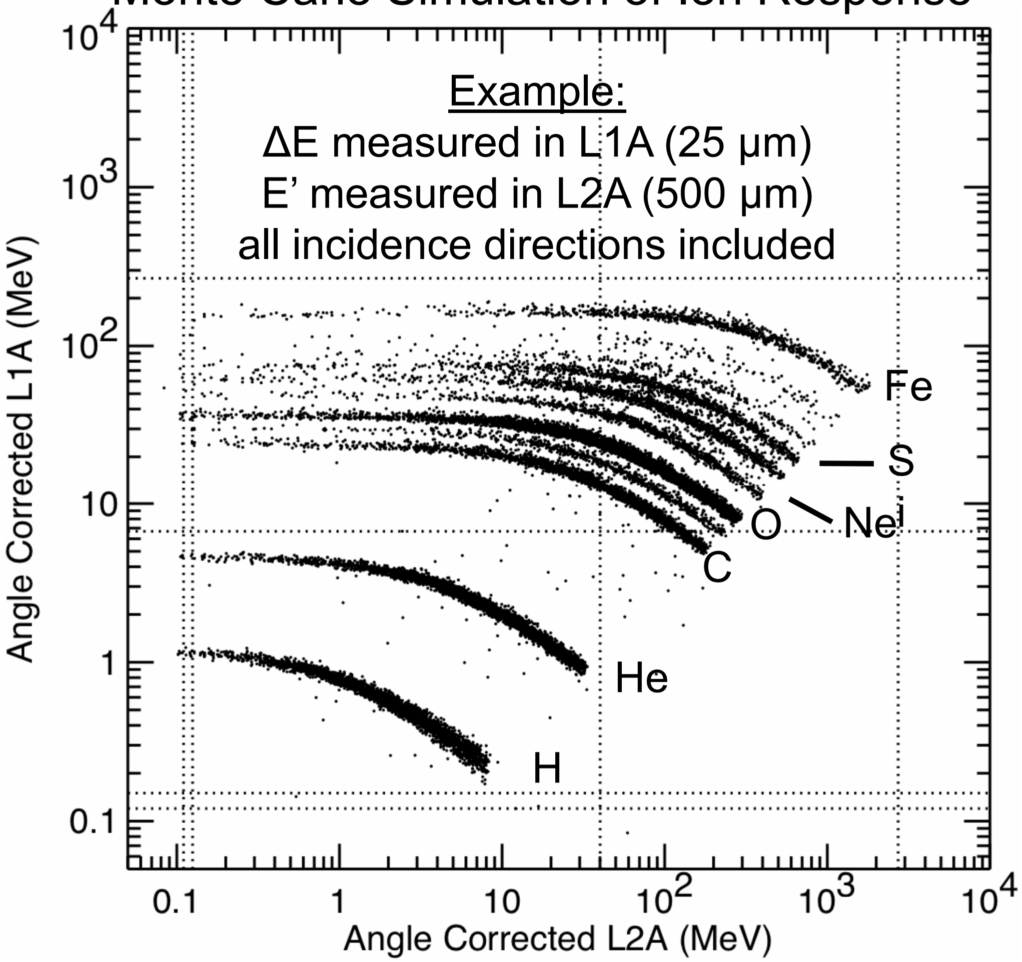


- Rates are accumulated on board in logarithmically spaced energy bins of width of a factor of 2^½ or 2^¼
- Bin width of 2^½ corresponds to ~6.6 bins per decade
- Larger bins are used for some rates accumulated at the highest cadence (1 second) in order to increase statistical accuracy



Element Resolution

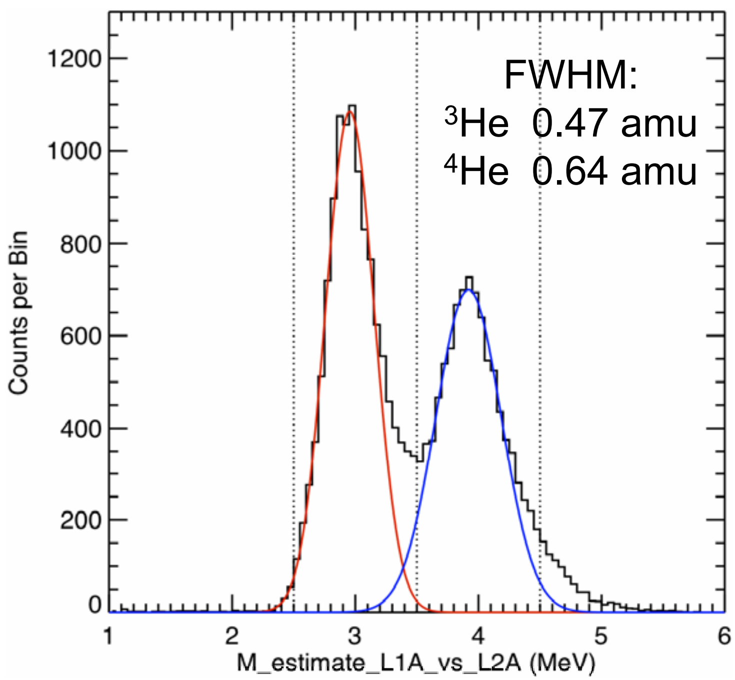
Monte Carlo Simulation of Ion Response



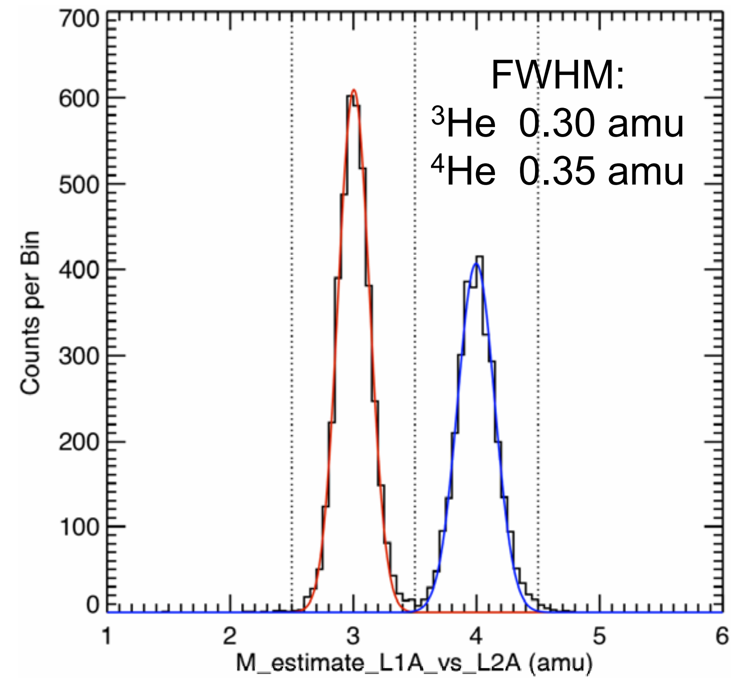
- Energy loss measurements from the detector in which a particle stops (E') and the preceding detector (ΔE) organize the data into distinct tracks for the various elements.
- Sector information is used to obtain mean thickness penetrated in the ΔE detector and make an on-board correction to the measured energies to optimize species resolution.
- Energy assigned on board includes energies measured in overlying detectors and calculated energy loss in windows.

Helium Isotope Identification

Full Geometry Defined by
L1•L2 Coincidence



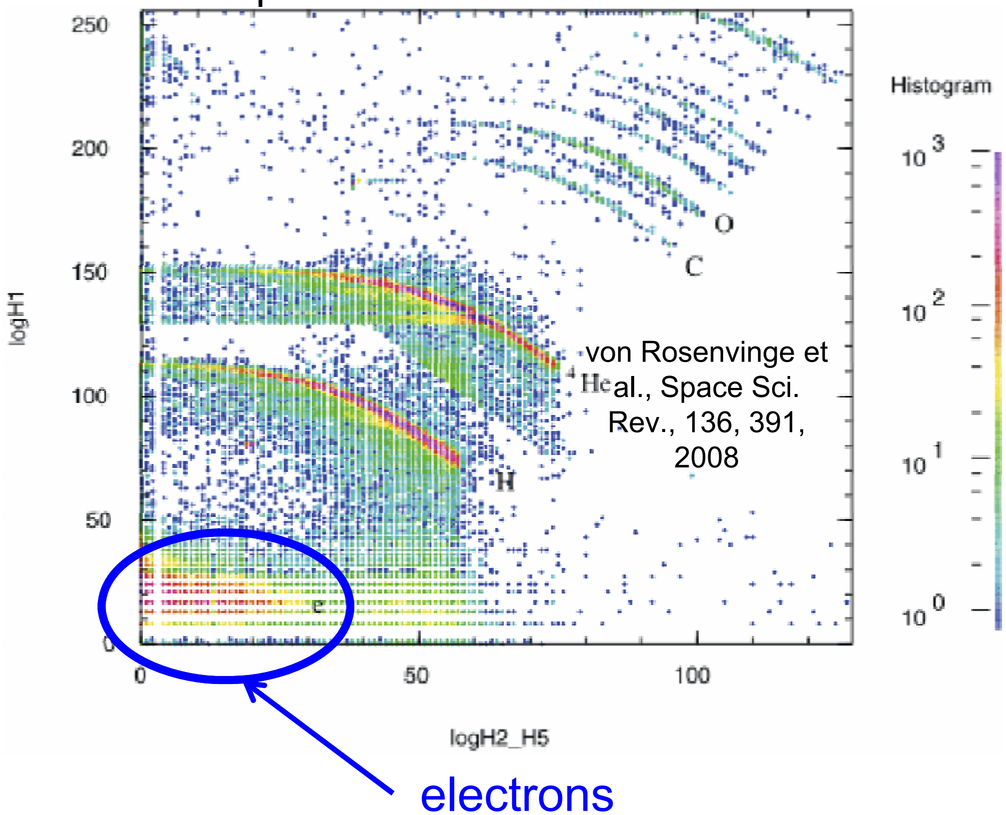
Geometry Defined by
L0•L1•L2 Coincidence
(~1/4 of L1•L2 geometry)



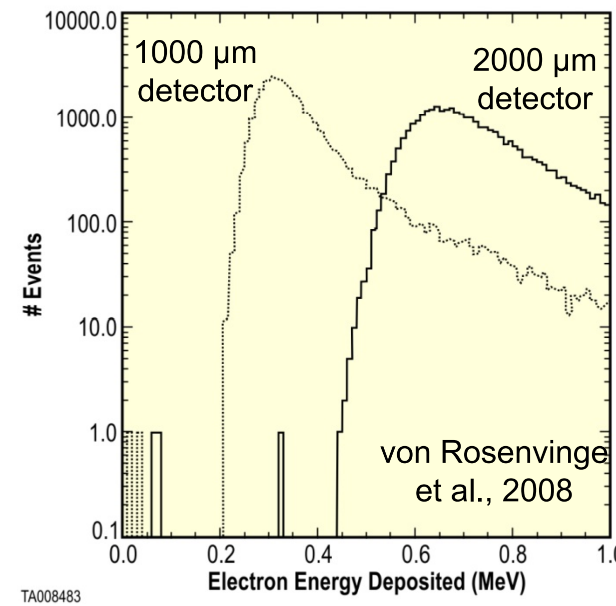
- Monte Carlo simulation of He isotope resolution: example based on L1A vs. L2A
- Resolution dominated by effect of incidence angle uncertainty on ΔE thickness penetrated
- Restricting analysis to narrow-angle sectors gives higher resolution dataset
- Other effects (e.g., channeling) limit measurable $^3He/^4He$ ratio at energies of a few MeV/nuc to >~5%

Electron Identification

Example: measurements from the STEREO/HET telescope in the 13 Dec 2013 SEP event

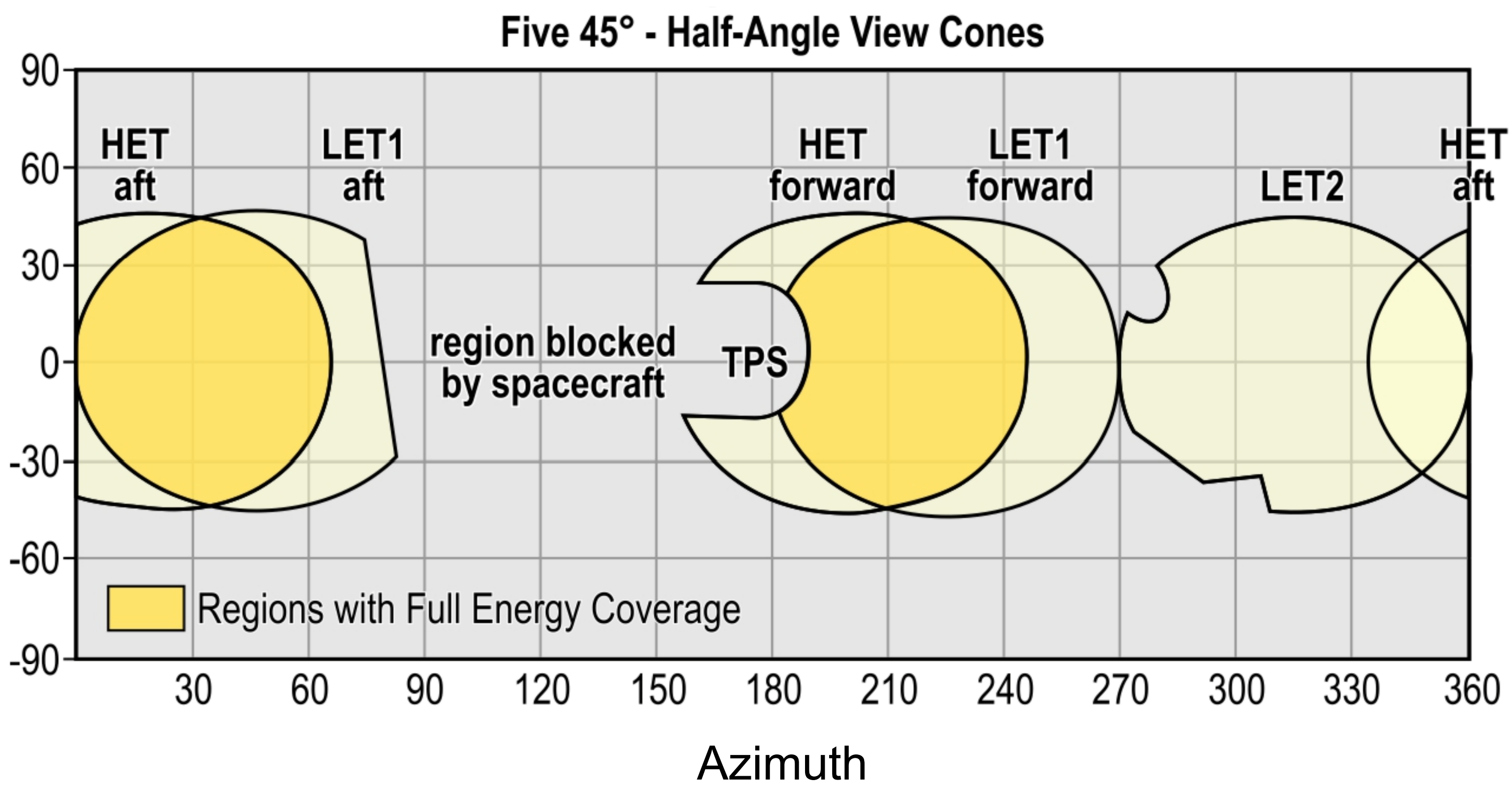


STEREO/HET Electron Threshold: GEANT4



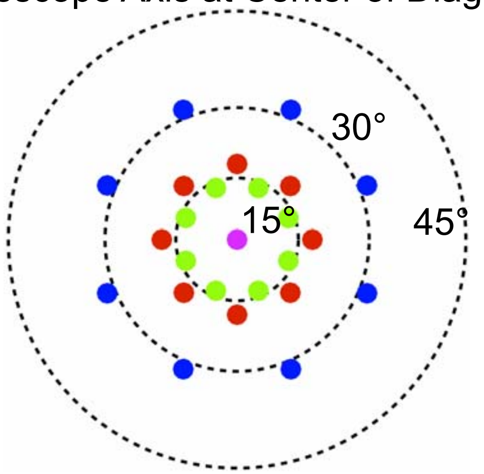
- EPI-Hi HET uses a 500 µm front, detector vs. 1000 µm in STEREO/HET
- High-energy electrons should deposit ~0.17 MeV in H1 and be detectable using the modeled 0.11 MeV threshold
- Once electronic noise level has been measured in a realistic setup, we will assess whether a modest increase in the H1 thickness is desirable

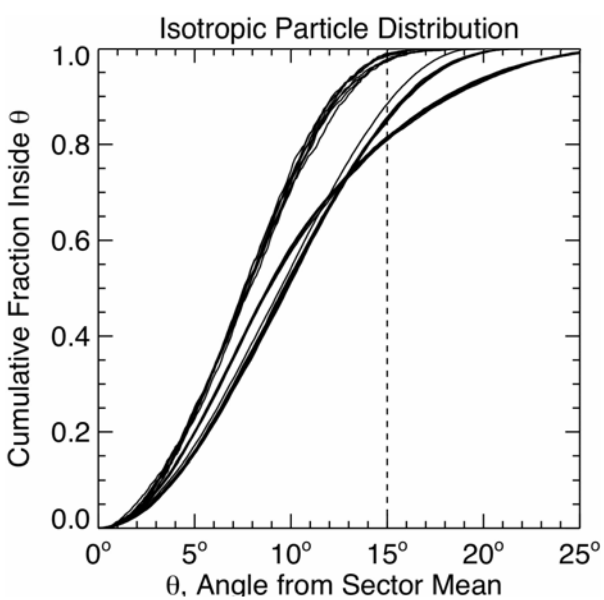
Fields of View



Angular Sectoring

Locations of Centers of Angular Sectors,
Telescope Axis at Center of Diagram





- Particle directions of incidence are determined based on active elements hit in two position-sensitive Si detectors (L0 and L1, L1 and L2, or H1 and H2)
- Each of these detectors has central bull's eye surrounded by 4 quadrants
- Area of each active element is 0.2 cm^2
- Quadrants in the second detector rotated 45° about the telescope axis relative to those in the first detector
- 25 combinations of hit elements in the two detectors are used to assign event to a viewing sector
- For an isotropic distribution of particles, ≥80% of the particles detected in a sector have directions of incidence within 15° of the mean viewing direction of the sector
- Significant overlaps among sectors allow measurements of particle distributions with angular resolution smaller than the size of a sector
- HET provides sectored electron data, LET1 provides only front-back direction information for electrons

Measurement Cadences

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- Highest cadence: 1 second
  - Used for one electron bin below and one above 1 MeV
  - Used for 4 proton bins above 1 MeV
- Intermediate cadence: 10 sec
  - Used for narrow energy bins for e, H, He, ^{3}He
  - Used for intermediate energy resolution bins for element groups CNO, NeMgSi, Fe
- Normal cadence: 60 sec
  - Used for narrow energy bins for ^{3}He, and major elements from C through Ni
  - Used for wide energy bins for groups of ultra-heavy elements
- Low cadence: 300 sec
  - Used for angular distribution of e, p, He, ^{3}He, CNO, NeMgSi, and Fe in intermediate energy bins
- very low cadence: 1 hr
  - All rates accumulated at cadences of 60 sec and 300 sec are also accumulated over 1 hr

Dynamic Range in Particle Intensities (1/2)

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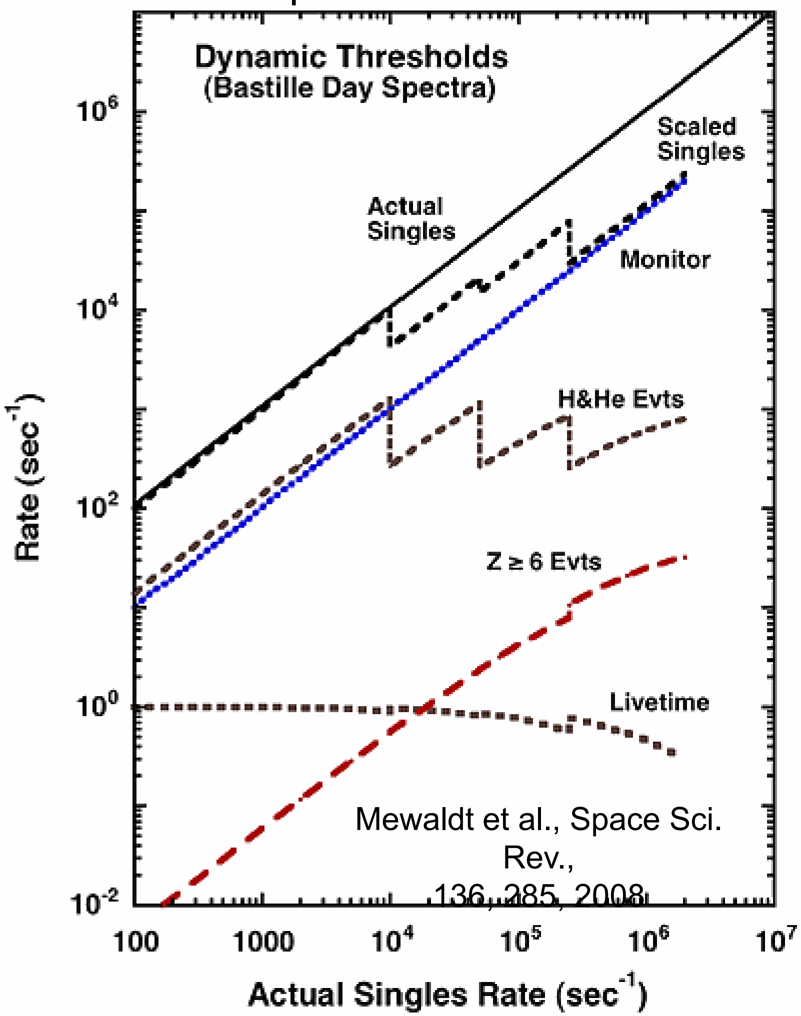
Example from STEREO/LET



Mewaldt et al., Space Sci. Rev., 136, 285, 2008

- Protons and He dominate the EPI-Hi count rates and the associated dead-time
- A "dynamic threshold" system, successfully used in the LET and HET instruments on STEREO, allows the adjustment of the geometrical factor for protons and He while maintaining the full geometrical factor for Z≥6 elements
- In several stages, thresholds are raised on all but one active element in detectors progressively deeper in the stack to suppress protons and He over a portion of the instrument geometrical factor
- A detector element that remains sensitive to protons and He is used to monitor the actual rate so that thresholds can be returned to the lower values (with some hysteresis) when particle intensities have decreased
- Count rates at which thresholds are dynamically raised and lowered are controlled by entries in the command table

Dynamic Range in Particle Intensities (2/2)

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- The SPP Science and Technology Definition Team estimated that measurements of protons above 1 MeV would need to cover an intensity range up to 5×10^5/cm^{2}sr-s
- Recent analysis by the SPP project derived a 95% confidence level worst case proton intensity a factor of 300 greater than this value, 1.5×10^8/cm^{2}sr-s
- Monte Carlo simulations of the HET response to this worst case spectrum (assumed to be isotropic) found an overall count rate ~1.5×10^9/s, including out-of-geometry protons
- In its normal operating mode, EPI-Hi will be able to measure protons up to rates of ~10^4/s with minimal dead-time, corresponding to an integral intensity of ~10^3/cm^{2}sr-s
- Use of dynamic thresholds to reduce the geometrical factor for protons and He by a factor ~25 allows measurements up to intensities of ~2.5×10^4/cm^{2}sr-s with high live-time and up to ~2.5×10^5/cm^{2}sr-s before the live-time fall to ~10%
- To continue operation beyond this point, small (1 mm^2) pixels with areas ~5% of the smallest normal detector elements are used for counting singles rates at a few depths in the instrument
- By setting pixel thresholds just below the energy of a stopping proton, the variation of pixel count rates with depth in the telescope will also provide some rudimentary spectral information
- Present estimates are that these pixels will be useful for measuring proton intensities up to at least ~5×10^6/cm^{2}sr-s, an order of magnitude greater than called for by the STDT but a factor ~30 below the recent estimate from the project, thus the very largest SEP events occurring close to perihelion will saturate the instrument
- Further analysis is needed to refine the above estimates and determine their science impact

Redundancies: Design for Graceful Degradation

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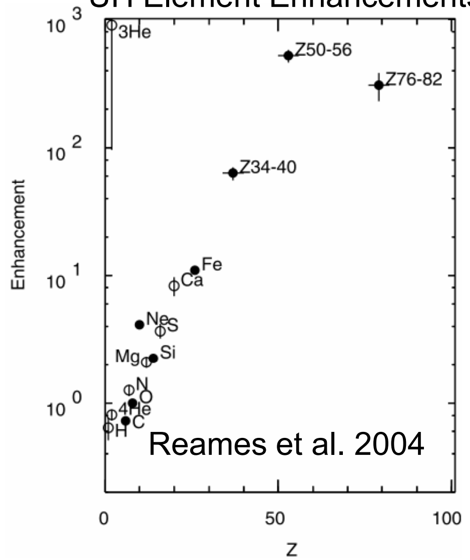
- The radiation and dust environments close to the Sun are poorly known and may be severe.
- The front detectors, particularly in the LETs, have minimal shielding in order to achieve a low energy threshold and are thus particularly vulnerable to damage by radiation and dust.
- The normal instrument coincidence logic defines some categories of events that do not require a signal from an L0 detector, so failure of an L0 detector would increase the LET telescope threshold but otherwise not interfere with instrument operation.
- The coincidence equations can be redefined in order to optimize performance in the event of other detector failures. For example, if an H1 detector were to fail, the HET coincidence could be redefined to define events based on detectors deeper in the stack and allow measurements with poorer angular and energy resolution.
- The double-ended telescopes have separate bias supplies for the two ends to preserve functionality in the event of a bias failure.
- Resistors in series with detectors allow a limited number of shorted detectors without compromising the operation of an entire telescope end.

Additional Capabilities: Bonus Science Opportunities

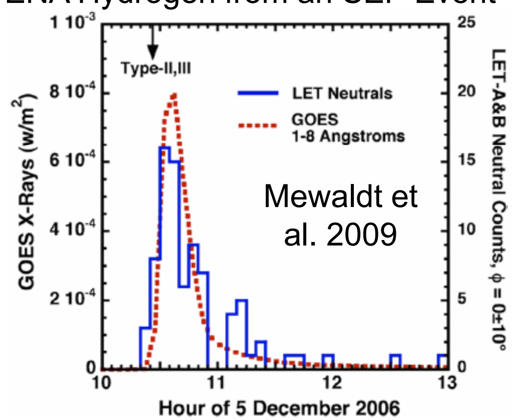
EPI-Hi lends itself to several measurements without requiring modifications of the hardware design:

- Ultra-heavy (UH) elements: PHASIC dynamic range allows measurements of groups of elements with atomic numbers Z≥30. Large enhancements of UH elements are sometimes observed in impulsive SEP events.
- $^{22}Ne/^{20}Ne$ isotope ratio measurements: this isotope ratio has been observed to be enhanced by factors ~5 in some impulsive events.
- Neutral particles including gamma-rays, neutrons, and energetic neutral atoms (ENAs): HET should be capable of measuring gammas and neutrons in some large SEP events. LET should be able to identify ENA hydrogen originating from charge exchange between SEP protons and ambient H atoms in the corona.

UH Element Enhancements



ENA Hydrogen from an SEP Event



Peer Review Results

- A combined peer review of the sensor system and front-end electronics (PHASIC) design was held on 1 March 2013 to address the suitability of this combination for making the required measurements. External (non-EPI-Hi) reviewers: Rick Leske (Caltech), Matt Hill (APL), Mihir Desai (SwRI).
- Significant Issues Raised and Responses or Actions Taken:

1) If the instrument experiences large temperature variations, electronic thresholds, gains, and offsets could change enough to require updating parameters used for the on-board analysis during a solar encounter. Response/Action: The project has been requested to provide estimates of how temperature will vary over an orbit in order to determine whether software will need to have the capability of autonomously updating thresholds, gains, and offsets during the encounters.
2) Large dynamic range could lead to significant cross-talk and possibly retriggering, as experienced on STEREO/LET. Response/Action: PHASIC design has been modified to reduce the amplitude of the second lobe of the shaped pulse, which is what could cause retriggering. New design incorporates a register for recording time dependence of discriminator output so that it can be used to identify retriggering and cross-talk. These new features will require testing.

Summary

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- EPI-Hi builds on heritage from the STEREO/LET and HET instruments to provide a combination of sensor system and electronics capable of meeting the requirements of Solar Probe Plus
- Significant new features include:
  - The development of thin silicon detectors to reduce the EPI-Hi energy threshold and achieve some overlap with EPI-Lo
  - Compact packaging of detector stacks to reduce backgrounds and improve performance under conditions of high particle intensities
  - Addition of small detector segments (“small pixels”) that can be used to provide a measure of proton intensities under extreme conditions
  - Enhancement of capabilities for on-board analysis including He isotope identification and multiple measurement cadences to optimize the use of available telemetry