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Revision	Effective Date	Description of Changes

Contents

1. Purpose

This document defines the plan and requirements for particle beam tests for the Large Area Telescope (LAT) of the Gamma-ray Large Area Space Telescope (GLAST) Mission.

2. Scope

3. Acronyms and Definitions

3.1. Acronyms

CDR	Critical Design Review
CNO	Carbon, Nitrogen, Oxygen
CU	Calibration Unit
DAQ	Data Acquisition System
EM	Engineering Model
Fe	Iron
GSE	Ground Support Equipment
GSFC	NASA Goddard Space Flight Center, Greenbelt MD
LAT	Large Area Telescope
PDR	Preliminary Design Review
QUAL	Qualifying towers
SLAC	Stanford Linear Accelerator Center

3.2. Definitions

Anomaly: When a hardware item has a significant change in performance but remains within specifications or temporarily exceeds specifications.

Acceptance: The process that demonstrates that hardware is acceptable for flight. It also serves as a quality control screen to detect deficiencies, and normally, to provide the basis for delivery of an item under terms of a contract.

Analysis: A verification method using techniques and tools such as math models, similarity assessments, validation of records, etc., to confirm that verification requirements have been satisfied.

Assembly: A group of components that are not necessarily a functional subdivision, which are mechanically configured together (i.e. a pallet containing two unrelated electronics boxes)

Certification: Those tests and analyses that confirm and formally document that all applicable standards and procedures are adhered to in the production or operation of the item to be certified.

Component: A subdivision of an assembly or subsystem and generally a self-contained combination of items performing a function necessary for the assembly or subsystem's operation.

Demonstration: A method of verification denoting the qualitative determination of properties of an end-item or component by observation. Demonstration is used with or without special test equipment or instrumentation to verify requirements characteristics.

Electromagnetic Compatibility (EMC): The condition that prevails when various electronic devices are performing their functions according to design in a common electromagnetic environment.

Electromagnetic Interference (EMI): Electromagnetic energy, which interrupts, obstructs, or otherwise degrades or limits the effective performance of electrical equipment.

End-to-End Tests: Tests performed on the integrated ground and flight system, including all elements of the instrument, its control, communications and data processing to demonstrate that the entire system is operation in a manner to fulfill all mission requirements and objectives.

Engineering Model (EM): Non-flight hardware that will be used to qualify the design for flight hardware.

Failure (Malfunction): When the performance of a hardware item, or the degradation or change in performance of such an item, prevents the item from meeting its specifications.

Flight Hardware: Hardware intended for flight and tested to flight acceptance levels and durations. Consists of protoflight, follow-on, and spare hardware.

Flight Model (FM): Flight hardware.

Follow-On Hardware: Flight hardware built in accordance with design that has been qualified either as protoflight or prototype hardware. Follow-on hardware is subject to a flight acceptance program.

Functional Test: The operation of a unit in accordance with a defined operational procedure to determine whether performance is within the specified requirements.

Inspection: The process of measuring, examining, gauging, or otherwise comparing an article or service with specified requirements

Performance Verification: Determination by test, analysis, or a combination of the two that the component or instrument can operate as intended in a particular mission; this includes being satisfied that the design of the component or instrument has been qualified and that the particular item has been accepted as true to the design and ready for flight operations.

Protoflight Hardware: Flight hardware of a new design which is qualified to design qualification levels and flight acceptance durations

Prototype Hardware: Non-flight hardware of a new design, which is subject to a design qualification test program.

Qualification: The process of demonstrating that a given design and manufacturing approach will produce hardware that will meet all performance specifications when subjected to defined conditions more severe than expected during its intended use.

Similarity: A procedure of comparing an item to a similar one that has been verified. Configuration, test data, application. and environment should be evaluated. It should be determined that design differences are insignificant, environmental stress will not be greater in the new application and that manufacturer and manufacturing methods are the same.

Spare Hardware: Hardware of a design, which has been proven in a design qualification test program. Spare hardware is subject to a flight acceptance program and is used to replace flight hardware that is no longer acceptable for flight.

Subsystem: A functional subdivision consisting of two or more components or assemblies.

System: A functional subdivision consisting of two or more components, assemblies and/or subsystems

4. Applicable Documents

The applicable documents listed below are relevant for the Beam Test Planning

LAT-PS-00010-A, “LAT Performance Specification ”.

5. Beam Test Program Plan

5.1. Objectives

The objective of this program is to verify that LAT meets some of the requirements imposed upon it. Specifically, the general objectives of this program are to:

a. Verify that the science requirements are met by calibrating the LAT either in a beam of particles or in a cosmic ray test set-up

b. Validate the Monte Carlo simulations for the proposed test matrices and provide sufficient information for extrapolations using simulated events.

c. Demonstrate the LAT capability to handle the data volume in a similar environment to that expected in space.

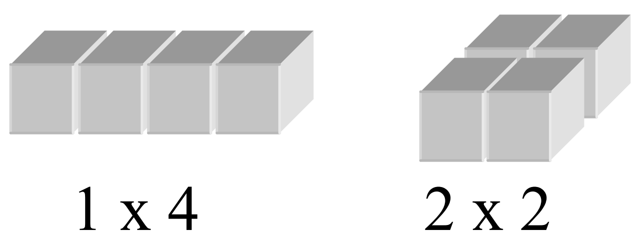
d. Demonstrate systems performance for trigger, data acquisition, event filtering and front-end electronics.

5.2. Test Units

The units used for the tests are defined below

Test Unit	# Of Towers	ACD	1.1.1.1 Tracker	Calorimeter
Engineering Model (EM)	1	13 tiles (3 remain in the EM 10 will be used in the CU)	Non-instrumented trays • Thin 3% (13) • Thick 18% (2) Instrumented trays • Thin 3% (2) • Thick 18% (2)	Fully instrumented?
Qualifying Units (QUAL)	1 or 2	? Tiles	Fully instrumented	Fully instrumented
Calibration Unit (CU)	4	10 tiles	Fully instrumented	Fully instrumented
LAT Flight (LAT)	16	Fully instrumented	Fully instrumented	Fully instrumented

For the calibration unit we envisaged two possible configurations.



6. Verification Program

The verification program consists of two parts, namely science verification and systems integration.

The first part employs beam tests on units assembled with one up to four towers to verify the science requirements and validate Monte Carlo simulations. Since photon events are localized on a scale that is significantly smaller than the full instrument, these tests focus on small sections of the instrument at any one time. The LAT modularity allows a detailed beam test program to be carried out in parallel with the production of the remaining towers without significant impact on the schedule or the schedule risk.

The second part involves cosmic ray tests to study system performance of trigger, data acquisition, event filtering and front-end electronics. This is a step beyond the functionality tests on modules since it addresses the integrated performance in a data taking environment. For that we investigated two possible options: a cosmic ray set-up and the LAT in a high rate beam

The schedule is outlined at the end of this note.

Beam Type				
	Photon	Hadron	Electron	Cosmic Rays
Engineering Model	No	No	No	Yes
Qualifying Unit	Yes	Yes	Yes	Yes
Calibration Unit	Yes	Yes	Yes	Yes
LAT Flight	No	No	No	Yes

The rationale behind this table is the following

- EM – Cannot be used to verify science parameters since it is not fully instrumented. Adequate for environmental and DAQ testing in the cosmic ray set-up.
- CU – The main unit, used for every test.
- LAT – Due to the LAT modular design a beam test with this unit is not needed.

6.1. Science Performance

6.1.1. Photon Beam

The main motivation for the photon beam is to characterize the Point Spread Function (PSF), Effective Area (A) and Field of View (FOV) for off-axis incidence. The energy resolution (E) will also be measured but its main characterization will occur in the positron and proton beams.

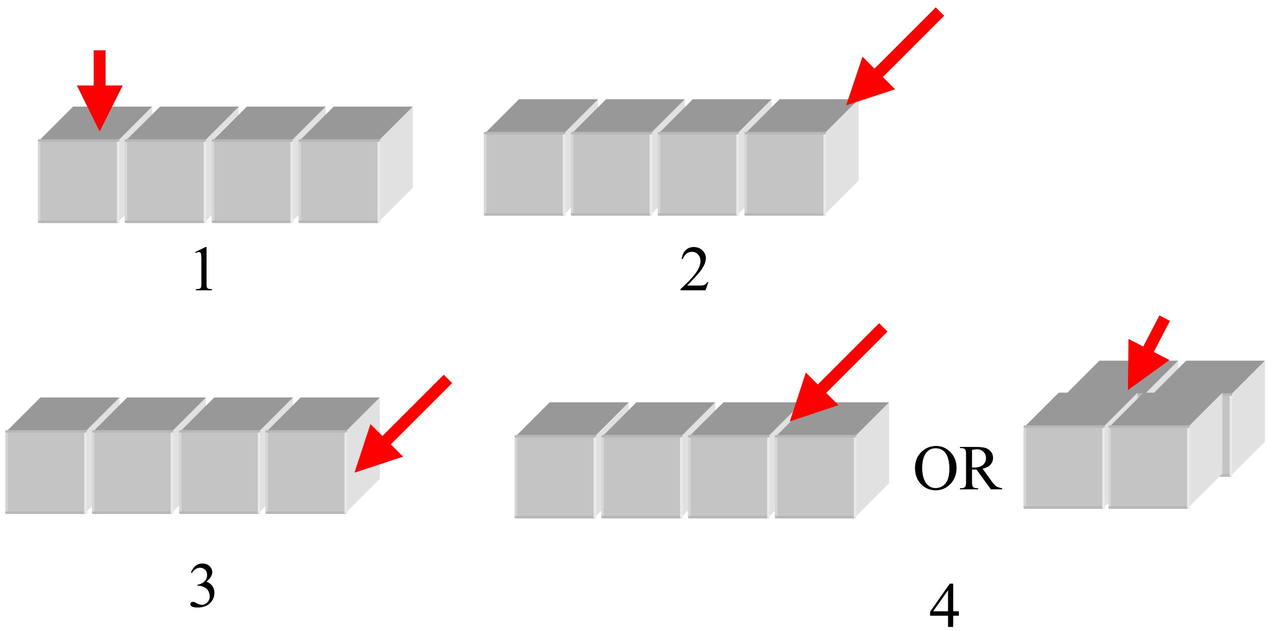
6.1.1.1. High Energy (>100 MeV)

The baseline is taken as the incoherent brehmstrahlung tagged photon beam used for tests at SLAC in 1999/2000. Another possibility is now under investigation for a coherent brehmstrahlung beam.

6.1.1.2. Test Matrix

For every point in the test matrix (energy and polar angle) we require 4000 reconstructed tagged photons (TBR). We estimate the necessary number of photons per energy bin based on the incoherent brehmstrahlung tagged photon beam used for tests at SLAC in 1999/2000. All measurements are to be performed at least one azimuth angle (45 deg) and possibly two (22.5 deg and 45 deg).

	$\phi=0^0$				$\phi=45^0$			
	$\theta=0^0$	$\theta=30^0$	$\theta=55^0$	$\theta=70^0$	$\theta=0^0$	$\theta=30^0$	$\theta=55^0$	$\theta=70^0$
200 MeV								
1 GeV								
10 GeV								



1. 3 energies on-axis incidence, impact point at center of tower 1. High statistics run to characterize the ratio of PSF95/PSF68, nit yet validated in the Monte Carlo.
2. 3 energies and 3 polar angles, impact point with respect to the top corner of the tower at the end of the 1 x 4 stack. Characterize off axis behavior on trays with thin converter.
3. 3 energies and 3 polar angles, impact point 30 cm (TBR) below the top corner of the tower at the end of the 1 x 4 stack. Characterize off axis behavior on trays with thin converter.
4. 3 energies and 3 polar angles, impact point at the center of first two adjacent towers 1 x 4 stack or 2 x 2 stack. Study effects from walls and gap between towers.

Option 4 shows two configurations, the choice will be dictated by how complicated it is to produce a fixture and MC simulations (TBR).

6.1.1.3. Run Time

A detailed description of the estimation of the run time needed is given in Appendix. For every energy setting, these are the main assumptions

- Photon Reconstruction efficiency times photon tagger efficiency > 80% (TBR)
- Beam downtime of 20%
- Additional run of 2h for every energy setting as part of the contingency plan
- A 2.7% radiator Cu foil is used to produce photons out of a positron beam
- 6 additional runs are included per energy bin at 0 degrees polar angle to estimate the corrections on the PSF as explained in Appendix

The allocated time for each configuration shown in Figure is given below

- Configuration 1= **160** hours of beam.
- Configuration 2= **480** hours of beam.
- Configuration 3= **480** hours of beam.
- Configuration 4= **480** hours of beam.

Total of 1600 hours of beam. Assume the beam uptime to be 80%, so we need a total of 1920 hours of beam = 80 days. We add 10 tens for unforeseen problems to **obtain 3 months of run time.** We need an additional month to set up the beam and the instrument (TBR), the set-up time may take longer because we are dealing with Flight Qualified towers.

6.1.1.4. Simulation Results

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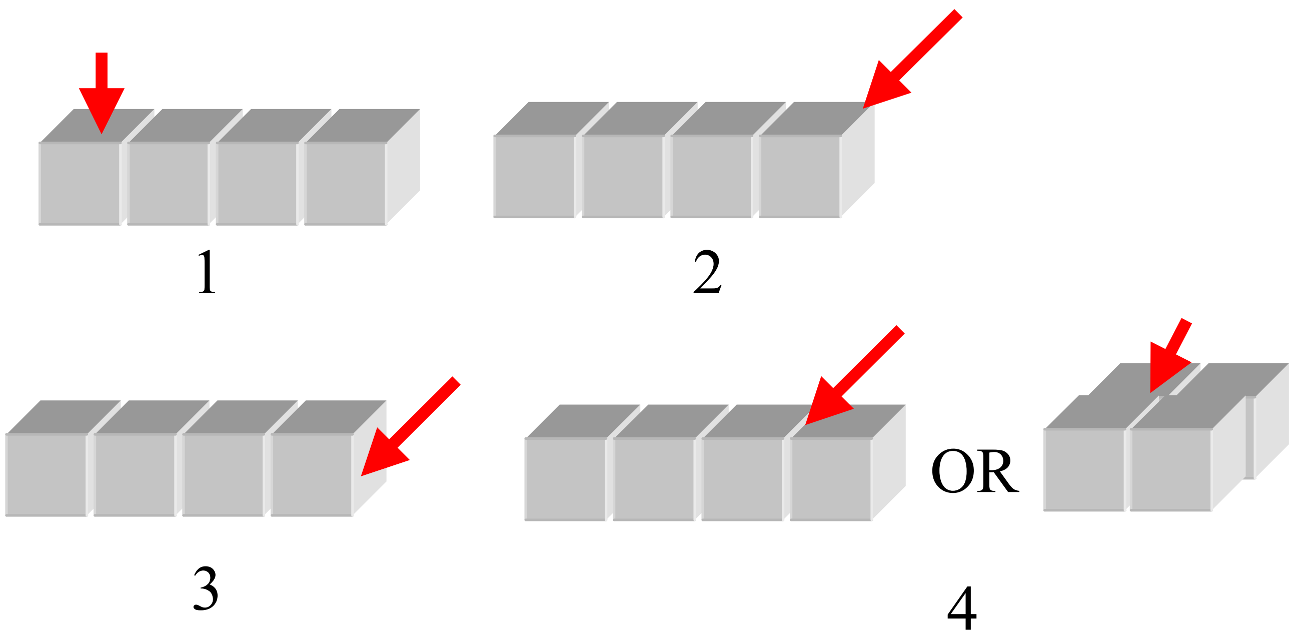
6.1.2. <u>Low Energy (<100 MeV)</u>

This will also be useful for developing algorithms to estimate the energy loss in the tracker (L).

6.1.2.1. Test Matrix

For every point in the test matrix (energy and polar angle) we require 4000 reconstructed tagged photons (TBR). We estimate the necessary number of photons per energy bin based on the incoherent brehmstrahlung tagged photon beam used for tests at SLAC in 1999/2000. That beam was only capable to generate photons up to 50 MeV, so the calculation for the 19.8 MeV may not be accurate and needs revision. All measurements are to be performed at least one azimuth angle (45 deg) and possibly two (22.5 deg and 45 deg). The energy points for this beam depend on the availability of the beam either a Van Der Graaf or a channeling beam.

	$\phi=0^0$				$\phi=45^0$			
	$\theta=0^0$	$\theta=30^0$	$\theta=55^0$	$\theta=70^0$	$\theta=0^0$	$\theta=30^0$	$\theta=55^0$	$\theta=70^0$
19.8 MeV (TBR)								
70 MeV (TBR)								



1. 2 energies on-axis incidence, impact point at center of tower 1. High statistics run to characterize the ratio of PSF95/PSF68, nit yet validated in the Monte Carlo.
2. 2 energies and 3 polar angles, impact point with respect to the top corner of the tower at the end of the 1 x 4 stack. Characterize off axis behavior on trays with thin converter.
3. 2 energies and 3 polar angles, impact point 30 cm (TBR) below the top corner of the tower at the end of the 1 x 4 stack. Characterize off axis behavior on trays with thin converter.
4. 2 energies and 3 polar angles, impact point at the center of first two adjacent towers 1 x 4 stack or 2 x 2 stack. Study effects from walls and gap between towers.

Option 4 shows two configurations, the choice will be dictated by how complicated it is to produce a fixture and MC simulations (TBR).

6.1.2.2. Run Time

A detailed description of the estimation of the run time needed is given in Appendix. For every energy setting, these are the main assumptions

- Photon Reconstruction efficiency times photon tagger efficiency > 80% (TBR)
- Beam downtime of 20%
- Additional run of 2h for every energy setting as part of the contingency plan
- A 2.7% radiator Cu foil is used to produce photons out of a positron beam
- 6 additional runs are included per energy bin at 0 degrees polar angle to estimate the corrections on the PSF as explained in Appendix

- Configuration 1= **80** hours of beam.
- Configuration 2= **240** hours of beam.
- Configuration 3= **240** hours of beam.
- Configuration 4= **240** hours of beam.

Total of 800 hours of beam. Assume the beam uptime to be 80%, so we need a total of 960 hours of beam = 40 days. We add 5 days for unforeseen problems to **obtain 1 1/2 months of run time.** We need an additional month to set up the beam and the instrument (TBR), the set-up time may take longer because we are dealing with Flight Qualified towers.

6.1.2.3. Simulation Results

6.1.3. <u>Positron Beam</u>

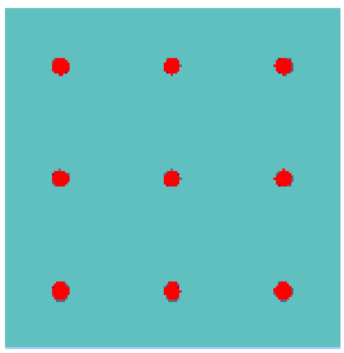
The main motivation for the positron beam is to characterize the shower development between towers and allow their cross calibration. In addition, one will study how to reject the soft electron background. These tests are mostly performed with the Calibration Unit in the 2 x 2 tower configuration.

6.1.3.1. Test Matrix

The test matrix focuses on trajectories that intersect the calorimeter. There are three configurations, characterized by the impact point,

For configuration 1 with the beam entering the front side of the calorimeter

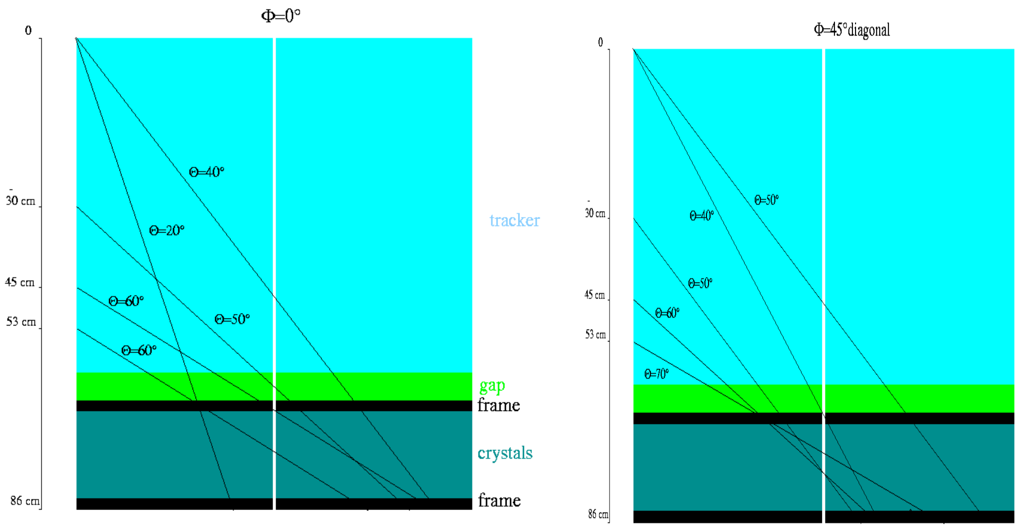
Energy (GeV)	$\theta=0^0$
0.5 (TBR)	4 x 9 = 36
2	4 x 9 = 36
5	4 x 9 = 36
20	4 x 9 = 36



Top View of One face of one calorimeter tower. Dots correspond to beam impact points.

For configuration 2, the beam enters on the side of the towers. The following matrix applies

	$\phi=0^0$	$\phi=22.5^0$		$\phi=45^0$	
	$\theta=0^0$	$\theta=20^0$	$\theta=40^0$	$\theta=20^0$	$\theta=40^0$
500 MeV (TBR)	13	9	5	9	5
2 GeV	13	9	5	9	5
5 GeV	13	9	5	9	5
20 GeV	13	9	5	9	5



Side View of two calorimeter towers

6.1.3.2. Run Time

6.1.3.3. Simulation Results

6.1.4. <u>Proton Beam</u>

The motivation for the proton beam is to study the background rejection, the high energy resolution in the calorimeter and backsplash measurements for the ACD. Backsplash occurs when a primary high energy particles interacts in the calorimeter and emits radiation in the backward direction (same direction as the incident particle). These tests shall emphasize on the backsplash as a function of distance to the ACD tiles. A beam test will only partially validate the background rejection capabilities of the instrument, but a set of proton runs will still be useful to tune the simulation. The most important energy range is from 2 to 50 GeV. We also propose to send protons into a block of material approximating the spacecraft below the towers, since these interactions are our largest residual source of background.

6.1.4.1. High Energy (>20 GeV)

Hadron rejection and high energy resolution in the Calorimeter .

6.1.4.2. Test Matrix

	$\phi=0^0$			$\phi=45^0$		
	$\theta=0^0$	$\theta=45^0$	$\theta=87^0$	$\theta=0^0$	$\theta=45^0$	$\theta=87^0$
50 GeV (TBR)	1	2	3	1	2	3
100 GeV (TBR)	1	2	3	1	2	3
250 GeV (TBR)	1	2	3	1	2	3

6.1.4.3. Run Time

6.1.4.4. Simulation Results

6.1.5. Low Energy (<20 GeV)

The backsplash is more important for energies below 10 GeV, since it can affect the Level 1 trigger efficiency and the bandwidth for downlink the data to ground station. In orbit for energies > 10 GeV all events are collected and can be analyzed offline.

6.1.5.1. Test Matrix

The low energy beam test matrix was chosen to addresses the proton cosmic ray spectrum at three points, namely where the flux rises, at its peak and when it decreases. To exploit the azimuth symmetry the 2 x 2 configuration is used.

	$\phi=0^0$			$\phi=45^0$		
	$\theta=0^0$	$\theta=45^0$	$\theta=87^0$	$\theta=0^0$	$\theta=45^0$	$\theta=87^0$
2 GeV (TBR)	1	2	3	1	2	3
5 GeV (TBR)	1	2	3	1	2	3
13 GeV (TBR)	1	2	3	1	2	3

6.1.5.2. Run Time

6.1.5.3. Simulation Results

6.1.6. Heavy Ion Beam

The main motivation for the heavy ion beam is to simulate cosmic Fe and CNO interactions in the calorimeter. It is desirable to have more than one tower in a beam. However, these tests could be accomplished with the EM or one of the QUAL towers.

6.1.6.1. Test Matrix

6.1.6.2. Run Time

6.1.6.3. Simulation Results

6.1.7. .Neutron Beam

The main motivation for the neutron beam is to study background events. Neutrons can be produced in a proton beam with the presence of a hardener.

6.2. Systems Integration

6.2.1. Cosmic Rays

Muons used during cosmic ray tests are of lower energy so we need a piece of material to act as an absorber to select high energy muons.

6.2.1.1. Alignment

Alignment is crucial for the tracker since it measures the direction of incoming photons. The tracker design allows alignment to better than 50 μm in all three spatial coordinates. Therefore towers are treated as rigid bodies and alignment with cosmic rays will involve

6.2.2. LAT in a beam

6.3. Timeline

Verification will occur on photon, positron and hadron beams and cosmic ray tests. They can occur in different phases namely,

- Before Integration begins (2002)
- During Integration (2003/2004)
- After Integration (2004)
- After Launch (2005)

7. Appendices

7.1. Facilities list

7.1.1. High Energy Photon Beam (<100MeV)

	100 MeV	1 GeV	10 GeV
Dimensions (mm^2 x mm^2)			
Shape			
Energy spread			
Angular spread			
Intensity			
Rate (pps)			
Time structure			
Fraction of pulses with > 1 photon			
Tagged Energy			
Tagged Energy Resolution			

7.1.2. Low Energy Photon Beam (>100MeV)

	24 MeV	70 MeV
Dimensions (mm^2 x mm^2)		
Shape		

Energy spread		
Angular spread		
Intensity		
Rate (pps)		
Time structure		
Fraction of pulses with > 1 photon		
Tagged Energy		
Tagged Energy Resolution		

7.1.3. Positron Beam

	500 MeV	2 GeV	5 GeV	20 GeV
Dimensions (mm^2 x mm^2)	Small to minimize photons			
Shape				
Energy spread				
Angular spread				
Intensity				
Rate (pps)				
Time structure				

7.1.4. High Energy Proton Beam (<20 GeV)

	50 GeV	100 GeV	250 GeV
Dimensions (mm^2 x mm^2)			
Shape			
Energy spread			
Angular spread			

Intensity			
Rate (pps)			
Time structure			

7.1.5. <u>Low Energy Proton Beam (<20 GeV)</u>

	2 GeV	5 GeV	13 GeV
Dimensions (mm^2 x mm^2)			
Shape			
Energy spread			
Angular spread			
Intensity			
Rate (pps)			
Time structure			

7.1.6. <u>Heavy Ion Beam</u>

Dimensions (mm^2 x mm^2)						
Shape						
Energy spread						
Angular spread						
Intensity						
Rate (pps)						
Time structure						

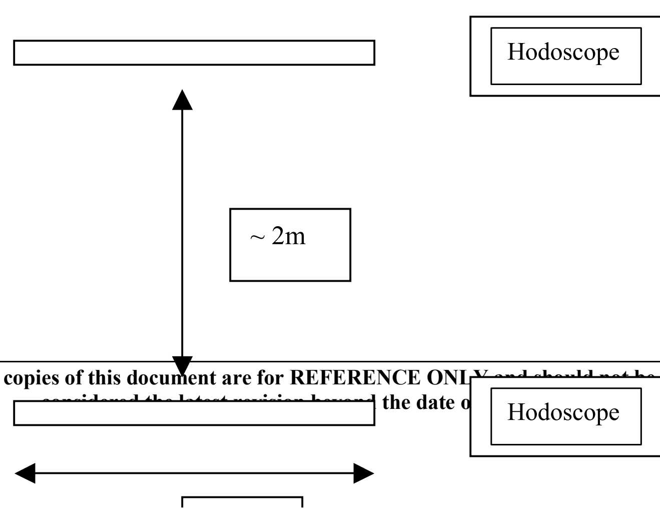
7.1.7. <u>Neutron Beam</u>

Dimensions (mm^2 x mm^2)						
Shape						
Energy spread						
Angular spread						
Intensity						
Rate (pps)						
Time structure						

7.1.8. ***Cosmic ray set-up***

Here is a tentative list of equipment needed

Jaroslav Vavra (SLAC group B) is putting together a large scale Cosmic Muon Telescope in the SLAC research yars. In the following are a few general characteristics:
Location: Bldg 122(?) in the yard, close to Endstation A
Environment: Hall is fairly dirty, but they foresee building a tent for clean operation (for example for the BaBar DIRC and DC upgrades).
Layout: Top and bottom hodoscopes allow to locate the C.R. muon beam to about 1mm location, 1mrad angle.
Clearance: 2m vertical
Active Area (Hodoscope): ~1m x 1m, movable to allow angles
Absorber: ~1m Fe max, crude (20%) measurement of muon momentum
Expected rate: ~10Hz ?



7.2. Run Time Calculation

7.2.1. High Energy Photon Beam (<100MeV)

7.2.2. Low Energy Photon Beam (>100MeV)

7.2.3. Positron Beam

7.2.4. High Energy Proton Beam (<20GeV)

7.2.5. Low Energy Proton Beam (>20GeV)

7.2.6. Heavy Ion Beam

7.2.7. Neutron Beam

7.2.8. Cosmic ray set-up

For perfectly straight trajectories, the tracking resolution is very roughly given by the hit precision/lever arm, and for each event the tower with the smaller track length will dominate the resolution. Assuming at least three XY planes for a track results in a limiting resolution of O(1) mrad. However, multiple scattering is also important. For 2 GeV muons, the characteristic multiple scattering angle after passing through 3 trays in the Front section is 2.6 mrad (5 mrad in the Back). Furthermore since the multiple scattering α 1/E, on a differential muon flux spectrum that falls like $1/E^2$ the mean multiple scattering angle in the sample is more like 8 mrad (for a weighted mean energy of 700 MeV). Thus, for each degree of freedom, a knowledge of better than 0.05 mrad (10 arcsec) will be obtained with a sample of ~25,000 events. To do a two-tower alignment in 6 degrees of freedom implies a sample size of 150,000 events.

Given the above fluxes, the whole instrument will see approximately 400 Hz of muons, or roughly about 25 Hz entering each tower from the top. To do the alignment, we need tracks that cross tower boundaries. On average, tracks at angles of incidence more than ~10°-15° will have a significant enough path length in two towers. Given the $\cos^2$□ dependence, and neglecting track paths through the Back section, we estimate 1 Hz per tower of tracks will satisfy the necessary conditions for a particular tower pair [a more careful calculation is underway]. Since both towers in a pair contribute useful flux by symmetry, the usable rate for a tower pair alignment is 2 Hz. Note that we have neglected muons entering from the sides of the full instrument.

There are different approaches, but a data-hungry, over-constrained approach would be an iterative pair-wise alignment of a tower with all nearest neighbors, resulting in a statistics requirement of 150,000 useful events per tower pair; which, at 2 Hz, can be accumulated in about 21 hours. Note that since the same tower is analyzed by several nearest neighbors, a more system-wide coherent calibration can in principle be done with lower statistics.

7.3. Equipment and Fixtures

7.3.1. Clean Tent

A clean tent (class 10000?) to house the Calibration Unit

7.3.2. Support structure for grid

A crane for mounting towers onto the grid.

7.3.3. Fixture for rotation of towers

A fixture that houses two towers at the time and can be accommodated in both configurations (1x4 or 2x2) as displayed in the drawings above. The fixture shall be easily rotated in controlled steps (TBD).

7.3.4. Spacecraft mechanical simulator

7.3.5. Ground Support Equipment

A transport vehicle to carry the fixture to the beam area. Auxiliary Data Acquisition to merge beam data information with the Calibration Unit Data Acquisition system.

7.3.6. Support Equipment for Cosmic Ray set-up

7.4. Schedule, Resources and Logistics

	$\phi=0^0$	$\phi=22.5^0$		$\phi=45^0$	
	$\theta=0^0$	$\theta=20^0$	$\theta=40^0$	$\theta=20^0$	$\theta=40^0$
500 MeV (TBR)	13	9	5	9	5
2 GeV	13	9	5	9	5
5 GeV	13	9	5	9	5
20 GeV	13	9	5	9	5