GEANT4-Based Design of a Particle Spectroscope : The Energetic Particle Telescope (EPT)

M. Cyamukungu[1], Gh. Grégoire[1], S. Benck[1] and J. Lemaire[2]

[1]Center for Space Radiations, UCL

[2]Belgian Institute for Space Aeronomy

Acknowledgment: The Belgian Institute for Space Aeronomy has funded the hardware construction of the EPT prototype.

Motivations

Scientific objectives

- Pitch angle distribution of very energetic ions and electrons trapped in the Radiation Belts with an improved angular resolution
- Survey and model the energy spectra of these particles with a time resolution of the order of the spin period of the spacecraft
- Develop a new directional flux model for energetic protons near the inner edge of the radiation belt
- Study (realtime) changes of pitch angle and energy distributions as consequences of the expansion of the upper atmosphere during enhancements of solar and geomagnetic activities or other types of space weather events

Instrumental features

- Angular distribution and energy spectra of charged particles
- High performance of particle discrimination in-flight
- Very low background
- High data acquisition rate
- Optimal Energy range/Cost ratio

Design methodology

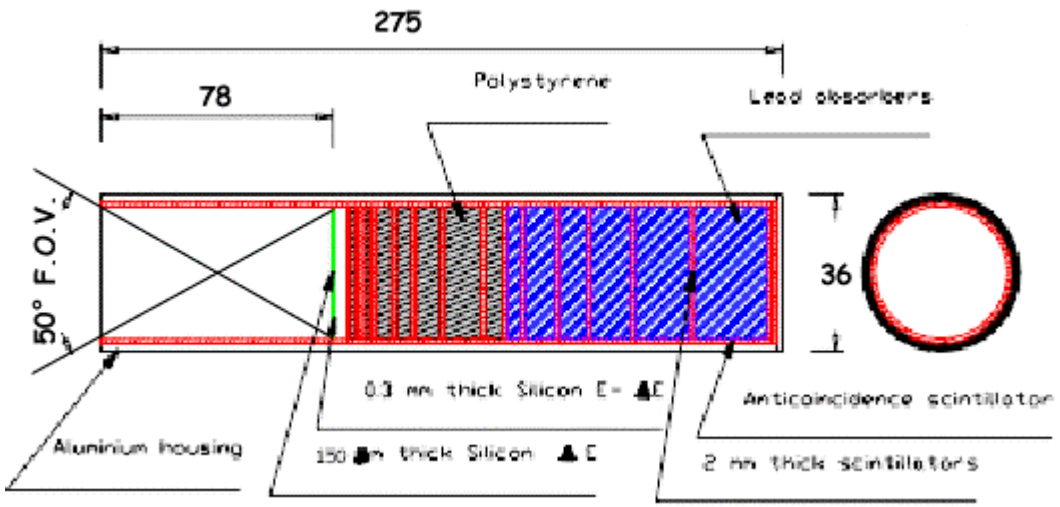
Basic mechanical assembly designed using range and stopping power tables

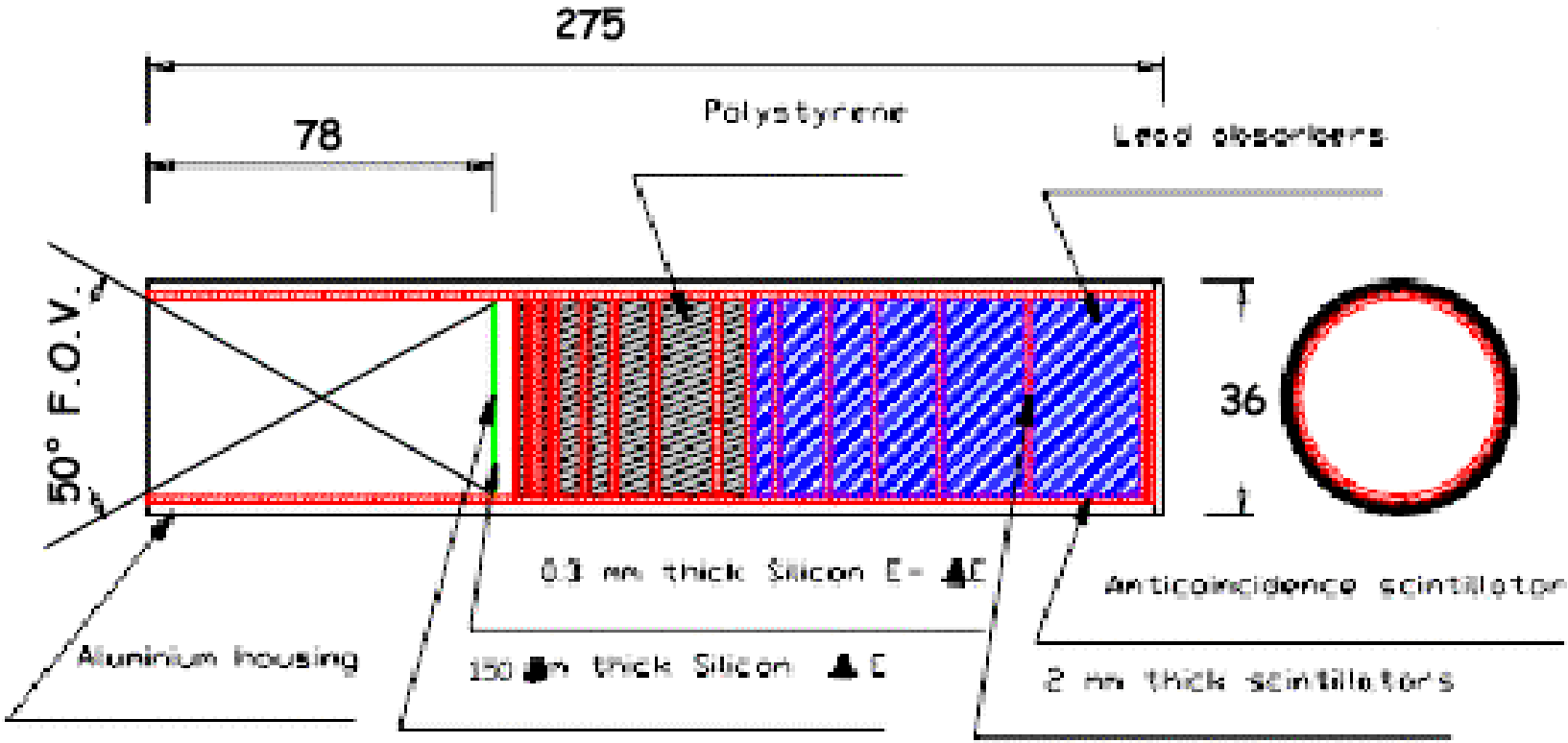
Optimization by extensive use of Monte-Carlo tools (GEANT)

In-beam test of components

Efficiency calculation

Discrimination features

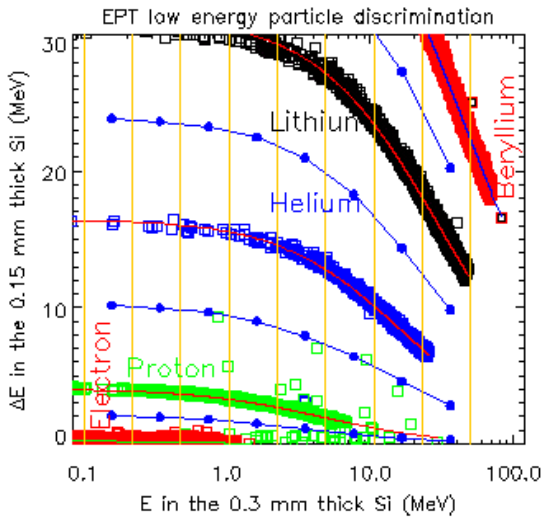


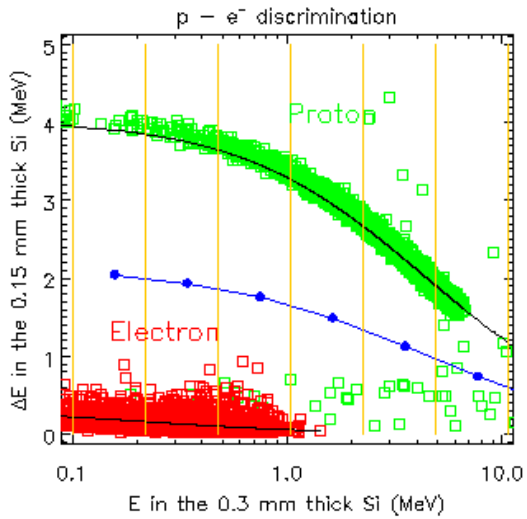

275
78
Polystyrene
Lead absorbers
50° F.O.V.
36
0.3 mm thick Silicon E-ΔE
Anticoincidence scintillator
Aluminium housing
150 μm thick Silicon ΔE
2 mm thick scintillators

Numerical calibration

Procedure: GEANT tracking of isotropic fluxes of electrons (0.1 - 15 MeV), protons (0.2 - 300 MeV), He (2 - 500 MeV) and Li (4 - 500 MeV).

Results: the low energy section

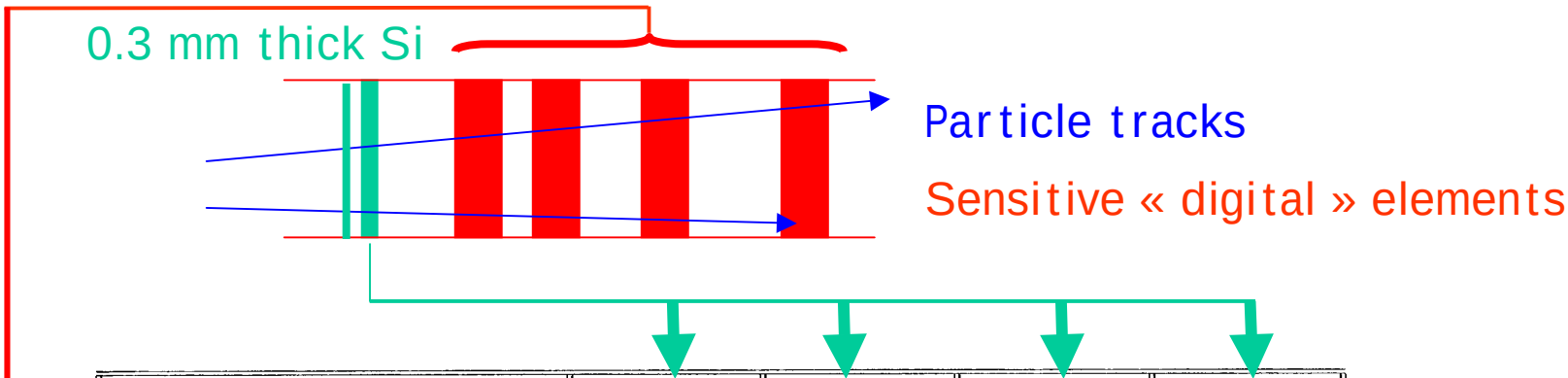




- Particle species are well separated using the energy loss from the 0.15 mm (ΔE) and 0.3 mm (E) thick Si sensitive elements.

- 8 logarithmically spaced energy channels are defined for each particle type.

Results: the high energy section



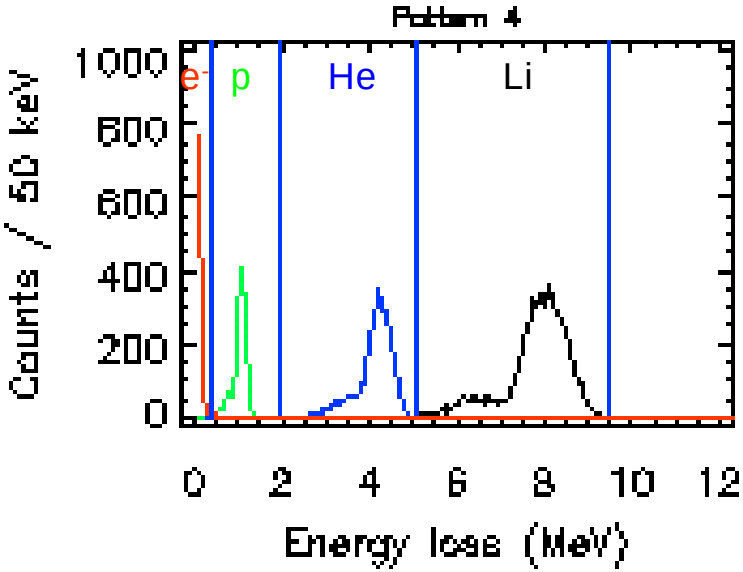
PATTERNS			ELECTRON		PROTON		ALPHA		LITHIUM	
Nr.	Output bits 123456789ABCDEF	Pattern code	Bin nr.	Energy (MeV)	Bin nr.	Energy (MeV)	Bin nr.	Energy (MeV)	Bin nr.	Energy (MeV)
1	1000000000000000	1	9	0.6	33	9	57	37	81	
2	1100000000000000	3	10	1	34	17	58	68	82	120
3	1110000000000000	7	11	2	35	25	59	100	83	190
4	1111000000000000	15	12	3	36	31	60	121	84	230
5	1111100000000000	31	13	4	37	40	61	156	85	300
6	1111110000000000	63	14	7	38	51	62	200	86	380
7	1111111000000000	127	15	8	39	62	63	245	87	450
8	1111111100000000	255	16	10	40	75	64	300	88	
9	1111111110000000	511	17	12	41	86	65	344	89	
10	1111111111000000	1023	18	20	42	100	66	397	90	
11	1111111111100000	2047	19	30	43	130	67		91	
12	1111111111110000	4095	20		44	165	68		92	
13	1111111111111000	8191	21		45	200	69		93	
14	1111111111111100	16383	22		46	245	70		94	
15	1111111111111110	32767	23		47	300	71		95	
16	1111111111111111	65535	24		48		72		96	

Results: the high energy section (channel limits)

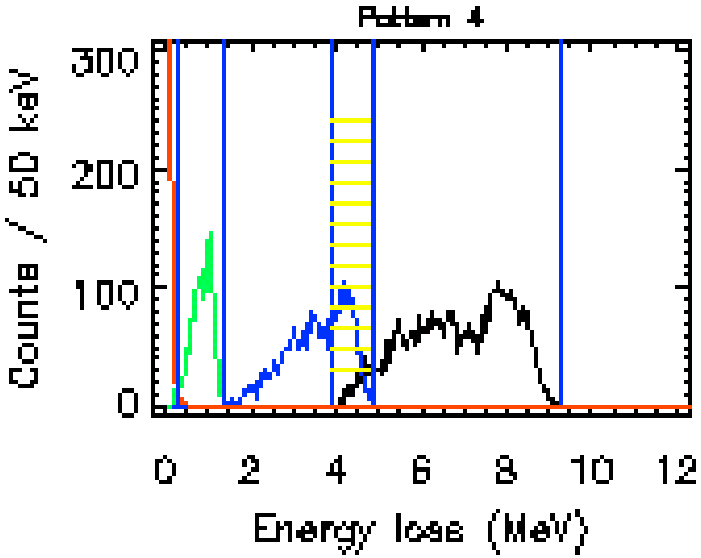
PATTERNS			e^-		p		α		Li	
Nr	Output bits 123456789ABCDEF	Code	Bin Nr.	Energy (MeV)	Bin Nr.	Energy (MeV)	Bin Nr.	Energy (MeV)	Bin Nr.	Energy (MeV)
1	1000000000000000	1	9	0.4-1.8	33	7.8-16	57	46-66	81	
2	1100000000000000	3	10	0.9-2.3	34	16-22	58	66-90	82	130-170
3	1110000000000000	7	11	1.5-3.0	35	22-28	59	90-100	83	170-200
4	1111000000000000	15	12	2.0-3.5	36	28-33	60	100-130	84	200-240
5	1111100000000000	31	13	2.8-5.5	37	33-45	61	130-180	85	240-330
6	1111110000000000	63	14	4.5-7.3	38	45-55	62	180-220	86	330-400
7	1111111000000000	127	15	6.3-9.5	39	55-68	63	220-270	87	400-500
8	1111111100000000	255	16		40	68-83	64	270-320	88	500-600
9	1111111110000000	511	17		41	83-90	65	320-350	89	600-700
10	1111111111000000	1023	18		42	90-110	66	350-430	90	700-800
11	1111111111100000	2047	19		43	110-150	67	430-580	91	800-1100
12	1111111111110000	4095	20		44	150-178	68	580-700	92	1100-1400
13	1111111111111000	8191	21		45	178-220	69	700-860	93	1400-1700
14	1111111111111100	16383	22		46	220-268	70	860-1000	94	1700-2100
15	1111111111111110	32767	23		47	268-298	71	1000-1300	95	2100-2500
16	1111111111111111	65535	24		48	298-	72	1300-	96	2500-

Results: the high energy section (ctd) – particle identification

90% efficiency modules



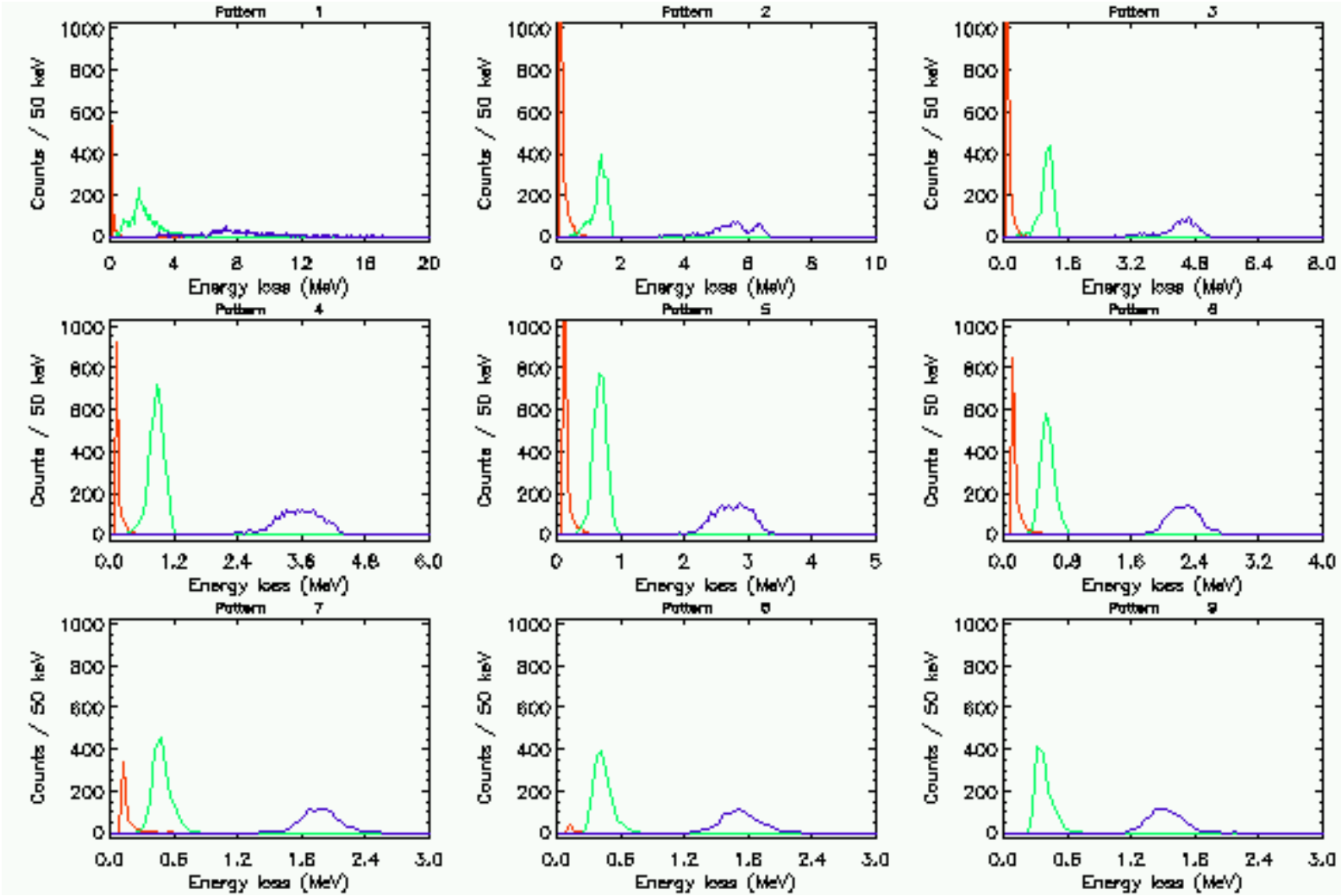
50% efficiency modules

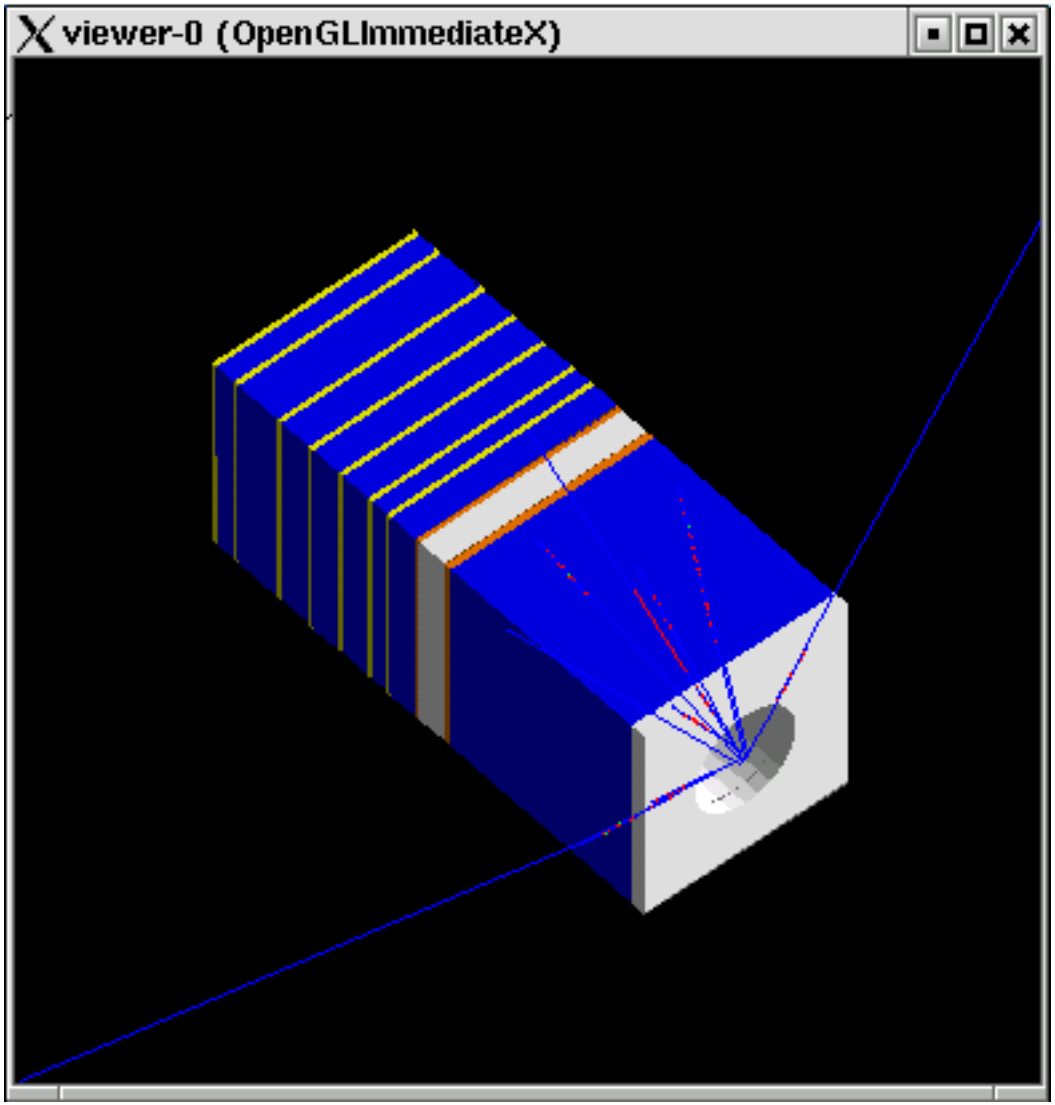


EPT- discriminated particles and channel numbers

Particle	Channels																							
	LOW ENERGY								HIGH ENERGY															
Lithium	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
Helium	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
Proton	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Electron	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

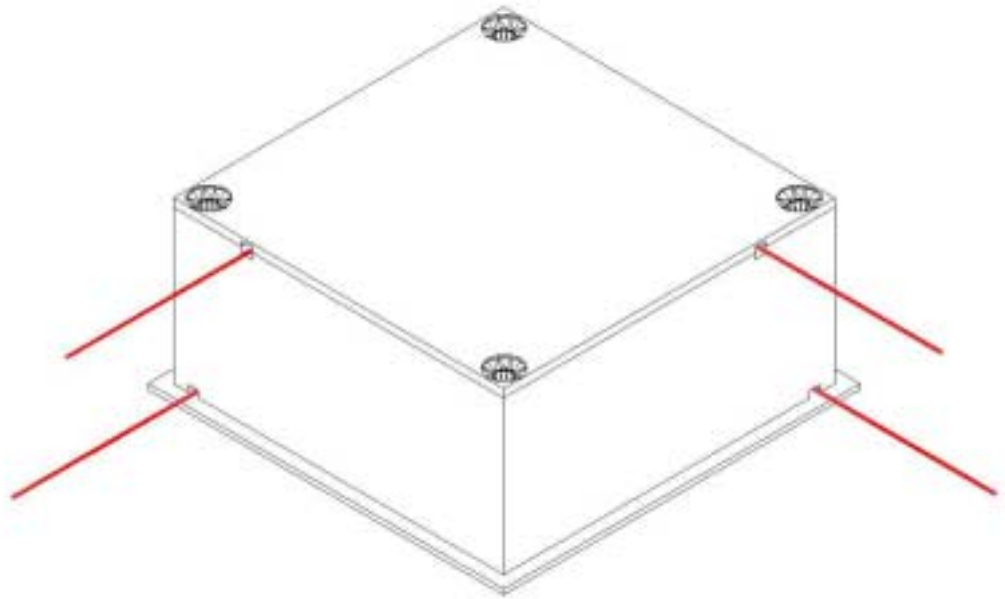
Results: the high energy section (GEANT4 with the final mechanical assembly)

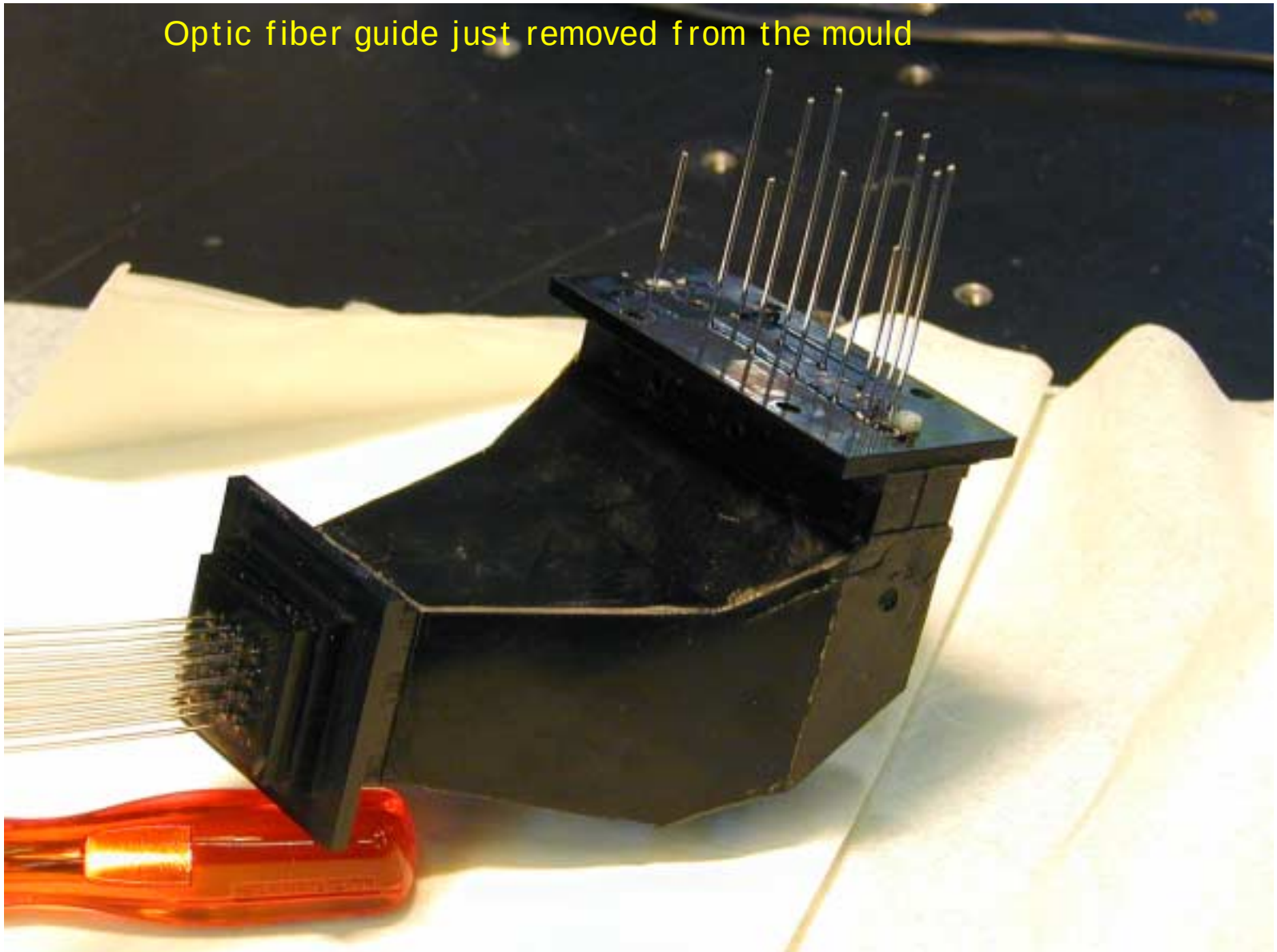


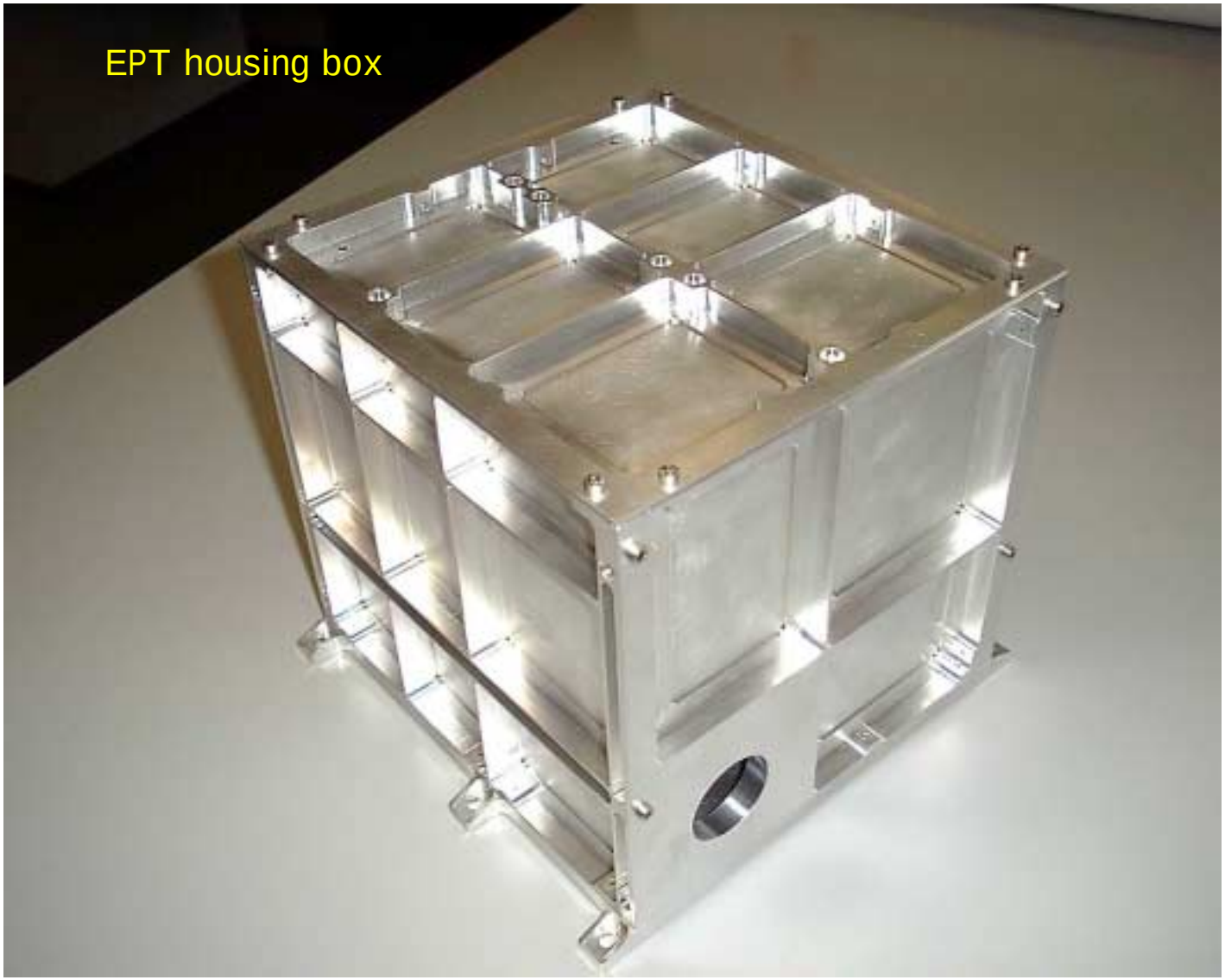


GEANT4 model and incident protons

Single EPT module: redundant optic fiber coupling of the main scintillator and the anticoincidence scintillator.




Optic fiber guide just removed from the mould


EPT housing box

Validation of EPT calibration: efficiency calculation

Calibration:

channel number ⟺ nominal energy interval

efficiency $\varepsilon_i(E)$

$$N_i = G \int_{E^i_{min}}^{E^i_{max}} \varepsilon_i(E)\, J_d(E, par_1, par_2, ..., par_n)\, dE$$

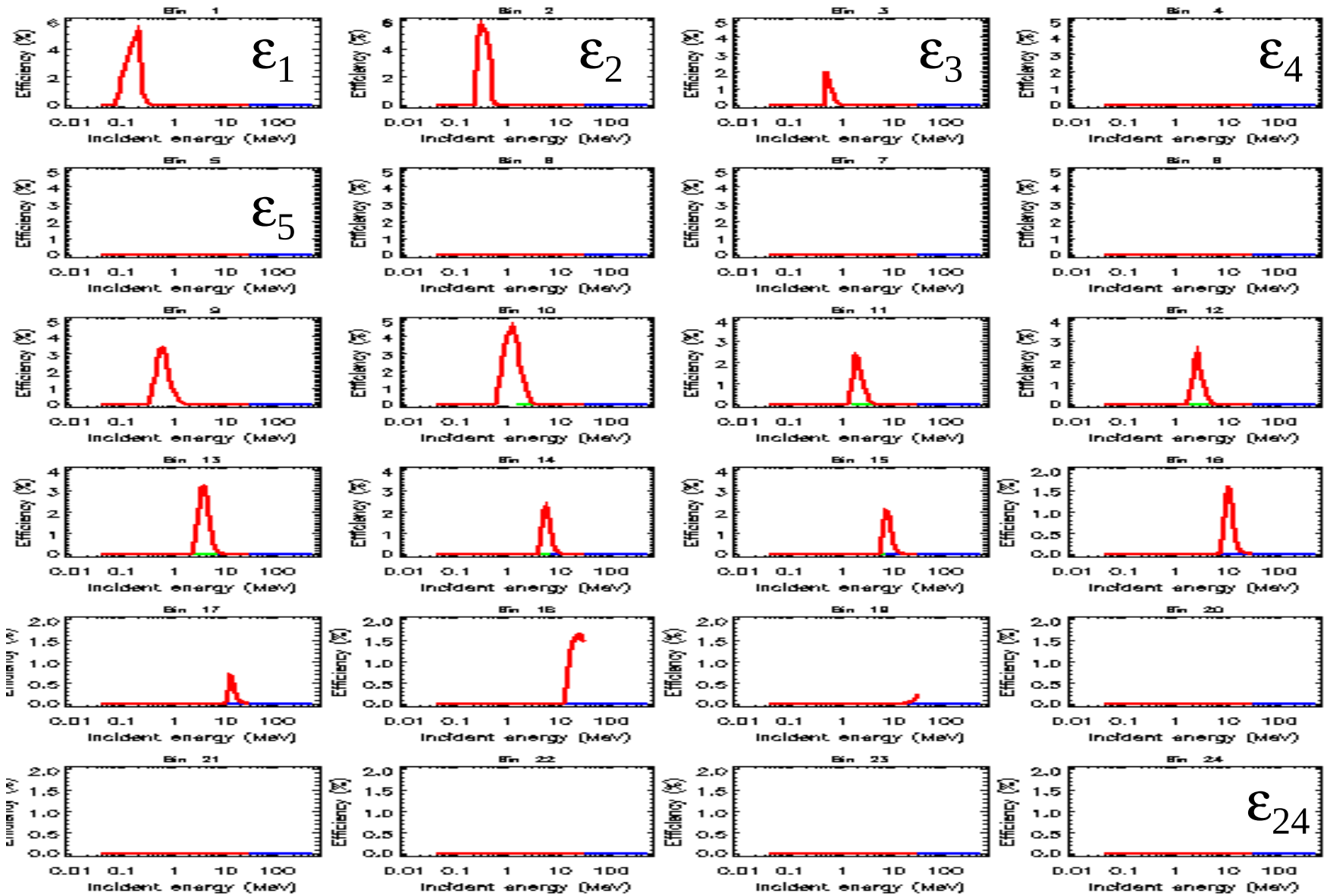
Validation:

check capacity for particle discrimination

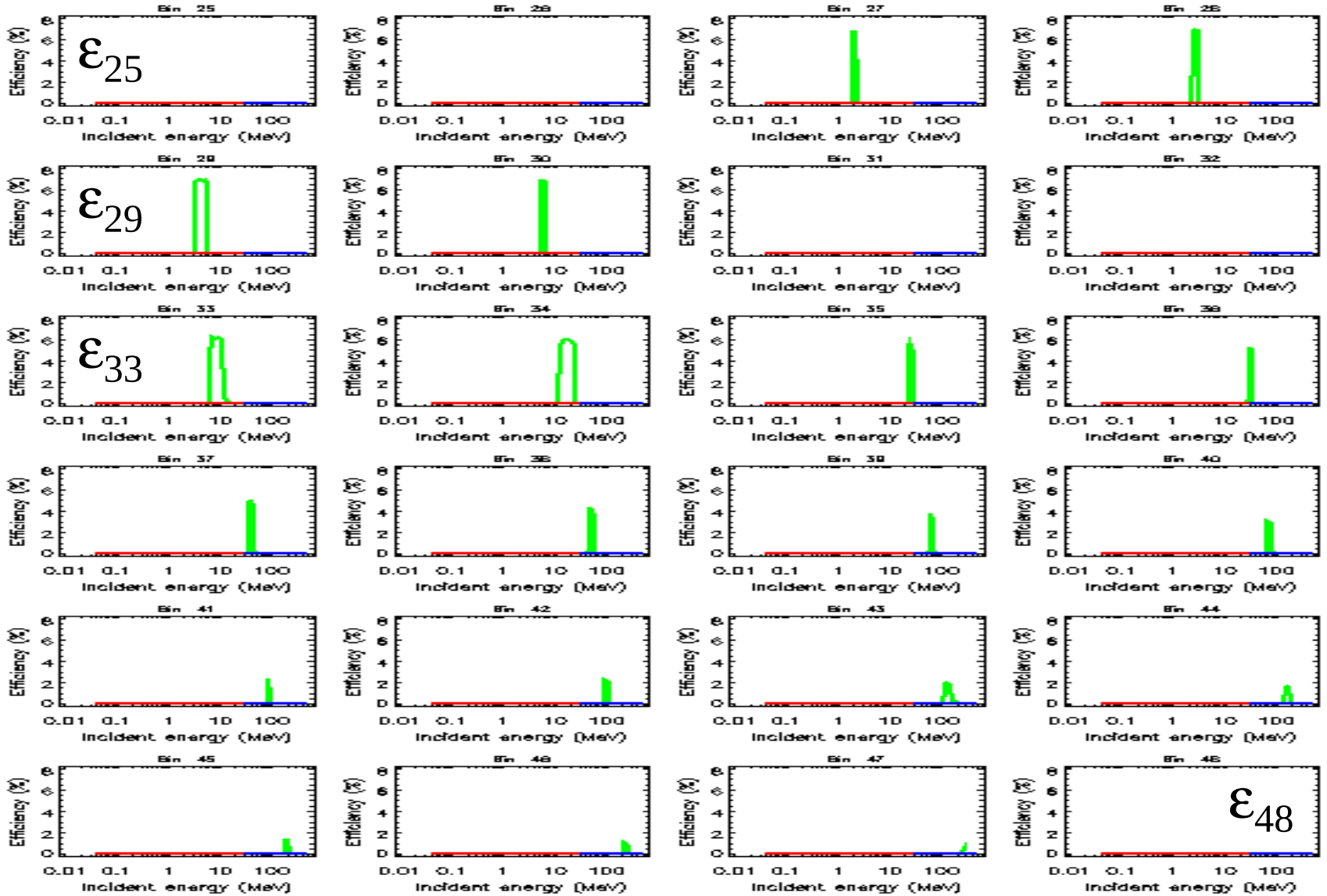
evaluate actual energy interval for each channel

} ⟸ $\varepsilon_i(E)$

Electrons

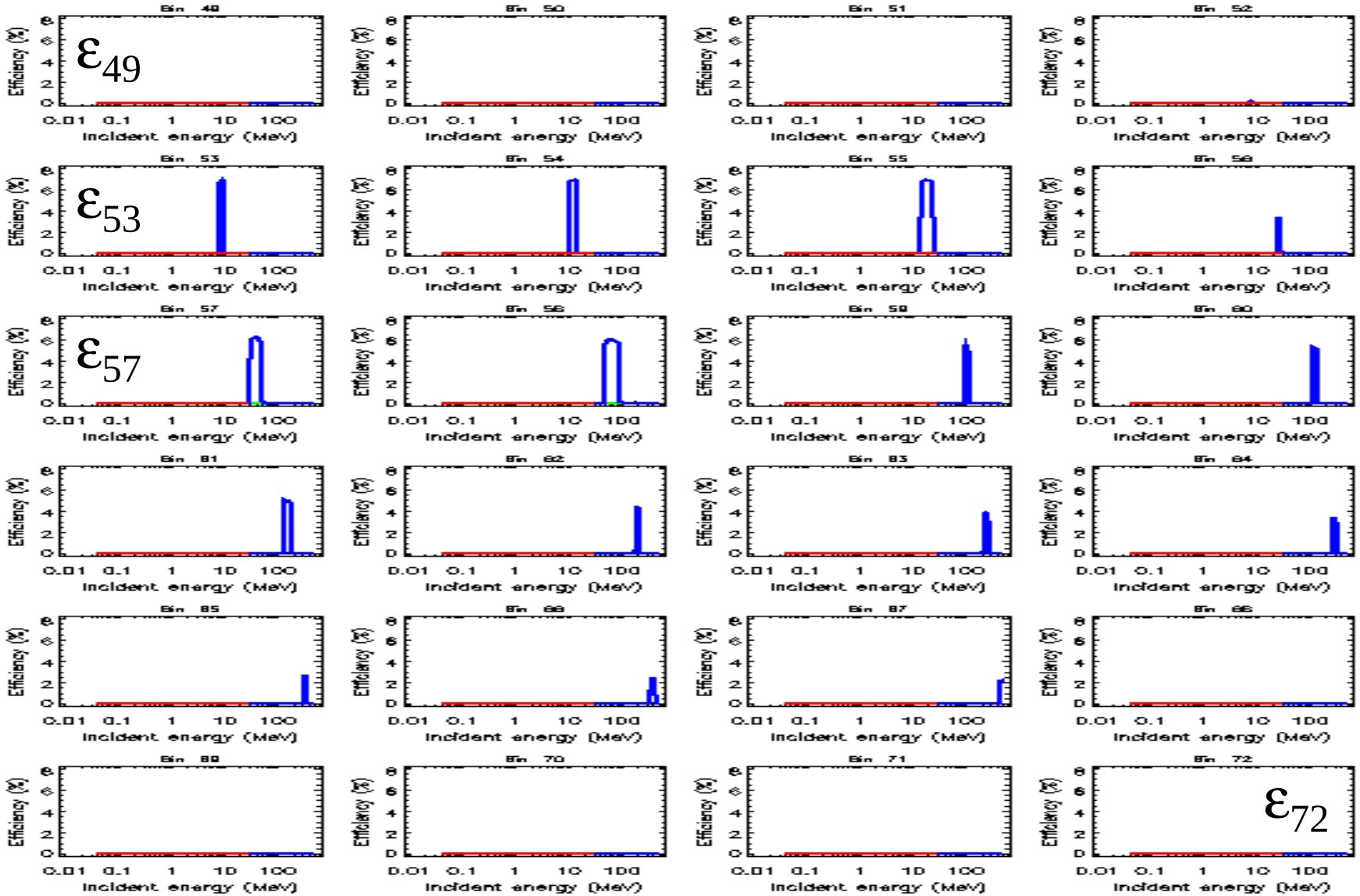

Bin 1
Bin 2
Bin 3
Bin 4
Bin 5
Bin 6
Bin 7
Bin 8
Bin 9
Bin 10
Bin 11
Bin 12
Bin 13
Bin 14
Bin 15
Bin 16
Bin 17
Bin 18
Bin 19
Bin 20
Bin 21
Bin 22
Bin 23
Bin 24
Efficiency (%)
Incident energy (MeV)
0.01 0.1 1 10 100
ε_1
ε_2
ε_3
ε_4
ε_5
ε_{24}

Protons

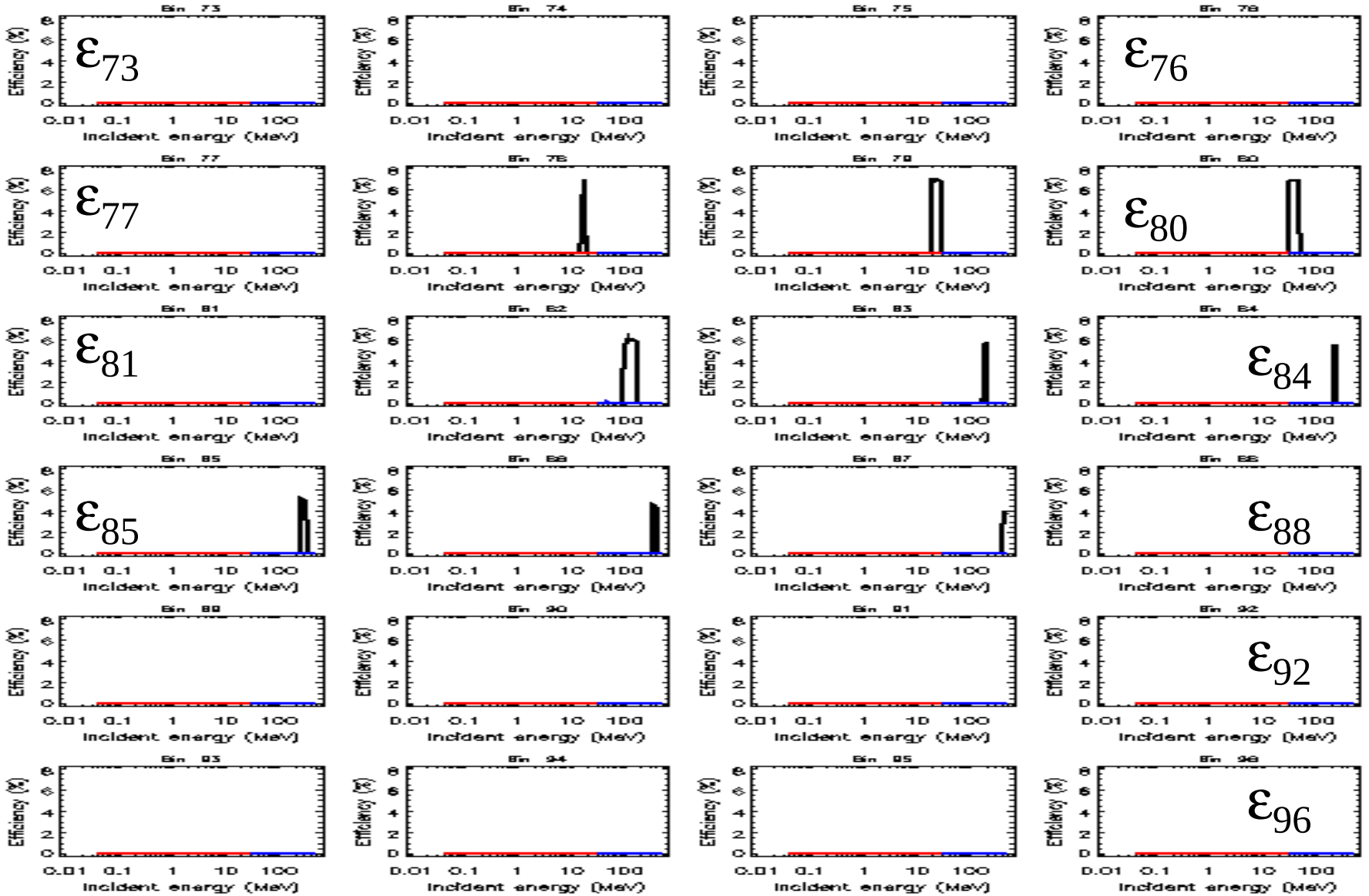


BISA-
IASB

α - particles


Bin 49
Bin 50
Bin 51
Bin 52
Bin 53
Bin 54
Bin 55
Bin 56
Bin 57
Bin 58
Bin 59
Bin 60
Bin 61
Bin 62
Bin 63
Bin 64
Bin 65
Bin 66
Bin 67
Bin 68
Bin 69
Bin 70
Bin 71
Bin 72
Efficiency (%)
Incident energy (MeV)
0.01
0.1
1
10
100
0
2
4
6
8
ε49
ε53
ε57
ε72

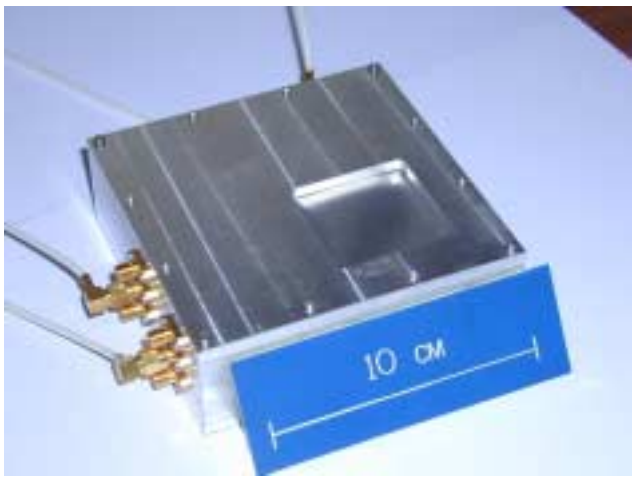
Lithium


ε73
ε76
ε77
ε80
ε81
ε84
ε85
ε88
ε92
ε96
Efficiency (%)
Incident energy (MeV)

EPT design methodology and GEANT4

The outstanding particle discrimination capacity is guaranteed if the « digital » modules are more than 90% efficient.

Silicon detectors could be adequate … as in SAMPEX/PET… but their mechanical strength may be a problem for large sensitive area.



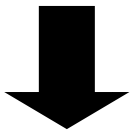
Several other kind of modules were tested before our final selection

However, the EPT is the result of a design methodology extensively based on the GEANT tool and the physics (energy losses, angular distributions, straggling,…) inside it, not only on engineering skills.

The coupling between the scintillator signal and the photonics readout was experimentaly tested. However GEANT4 based simulation may bring some improvment to implement into future models.

Summary

The Energetic Particle Telescope (EPT) was designed and optimized by extensive use of Monte-Carlo simulation tools and in-beam tests of its components



Reported (numerically evaluated) features:

- **outstanding particle discrimination capability**
- **high data acquisition rates due to digital operation mode**
- **almost no background counting**
- **extended energy range covered by a single instrument**

The construction of the EPT is underway.