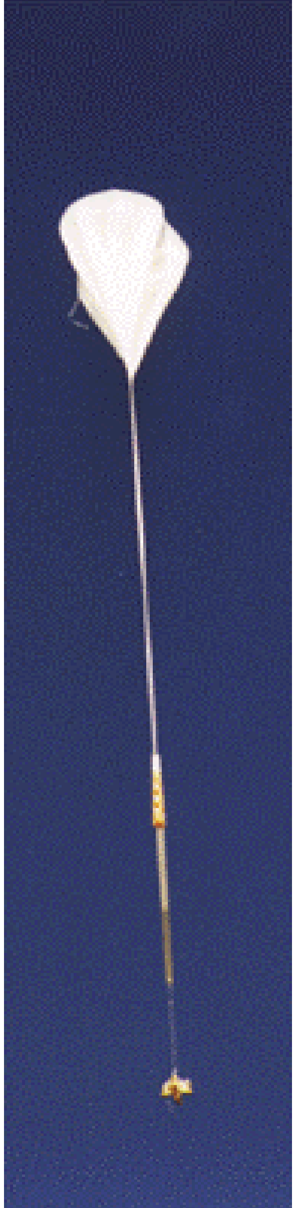
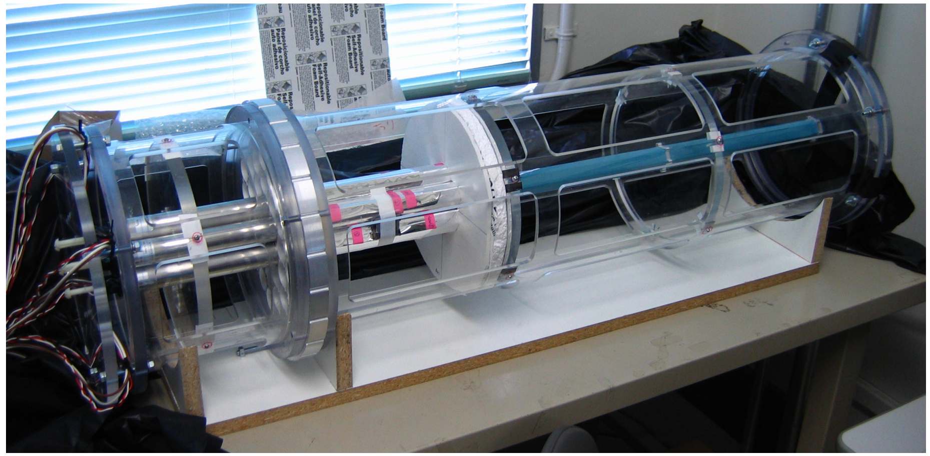


The Polarized Gamma-ray Observer



Mózsi Bank Kiss & Tomi Ylinen

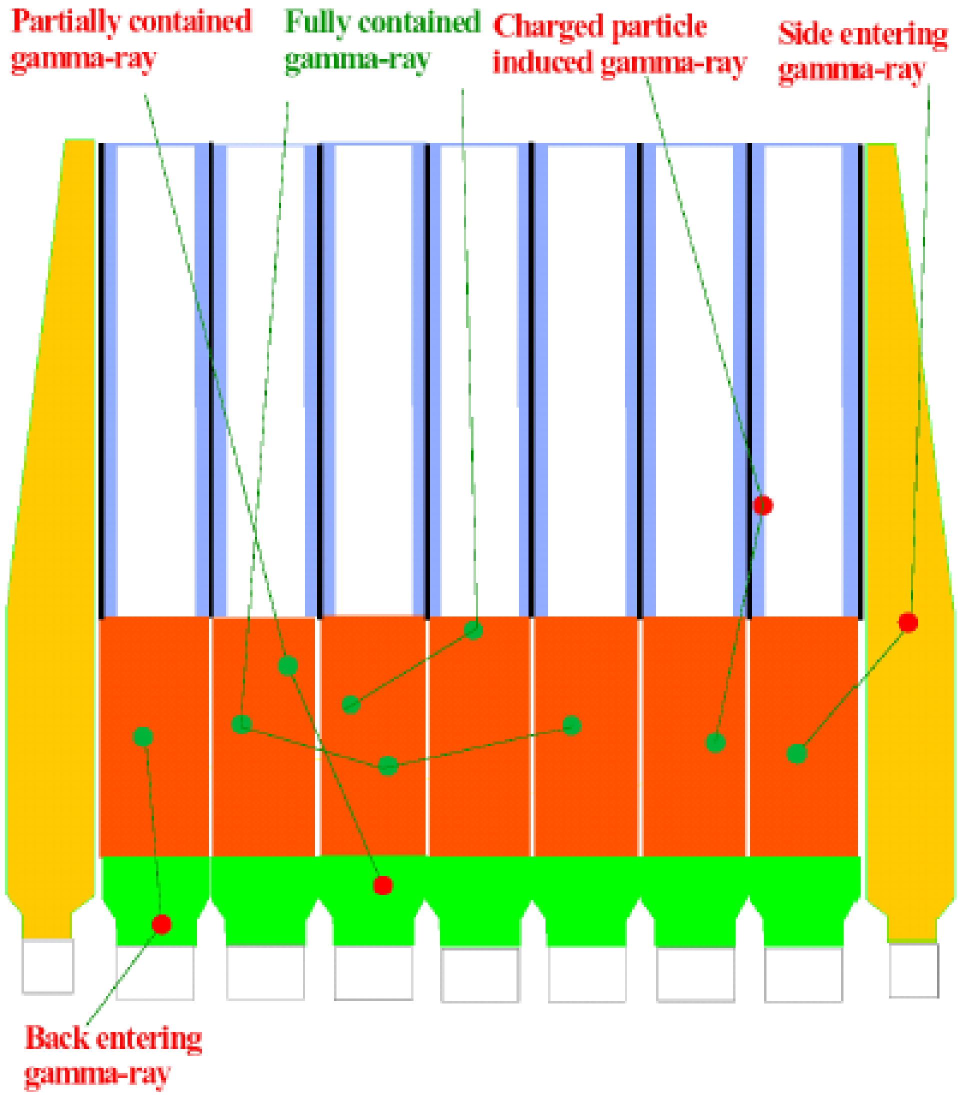
GLAST lunch meeting – February 16, 2006

Contents

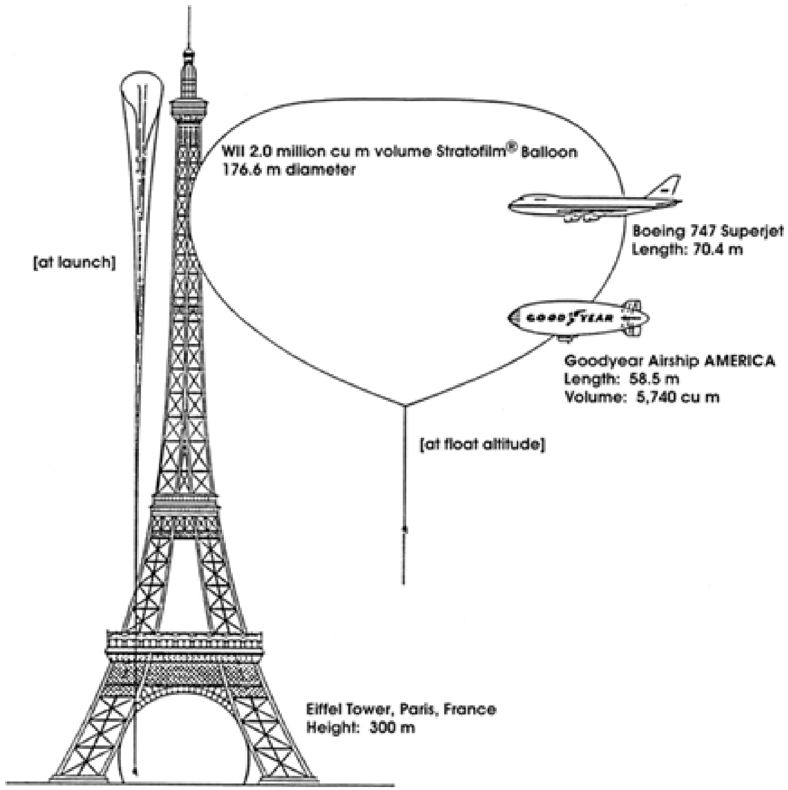
PoGO – The Polarized Gamma-ray Observer (1)

- Balloon-borne experiment – measure polarization from different sources at energies 25-200 keV
- International collaboration between the United States, Japan, Sweden and France
- Consists of 217 well-type phoswich detector cells (PDCs)
- Each PDC consists of a hollow “slow” scintillator (230 ns), a solid “fast” scintillator (1.8 ns) and a BGO crystal (300 ns)
- Side Anti-coincidence Shield made of BGO
- Field of view: 5 deg^2. Effective detector area: 243 cm^2
- Detect 10% polarization from a 100 mCrab source in a 6 h flight

PoGO – The Polarized Gamma-ray Observer (2)



PoGO – The Polarized Gamma-ray Observer (3)



NASA balloon size

- Gondola and flight system already developed for GRIS, InFOCuS and ISOMAX
- Can sustain an instrument mass of 910 kg

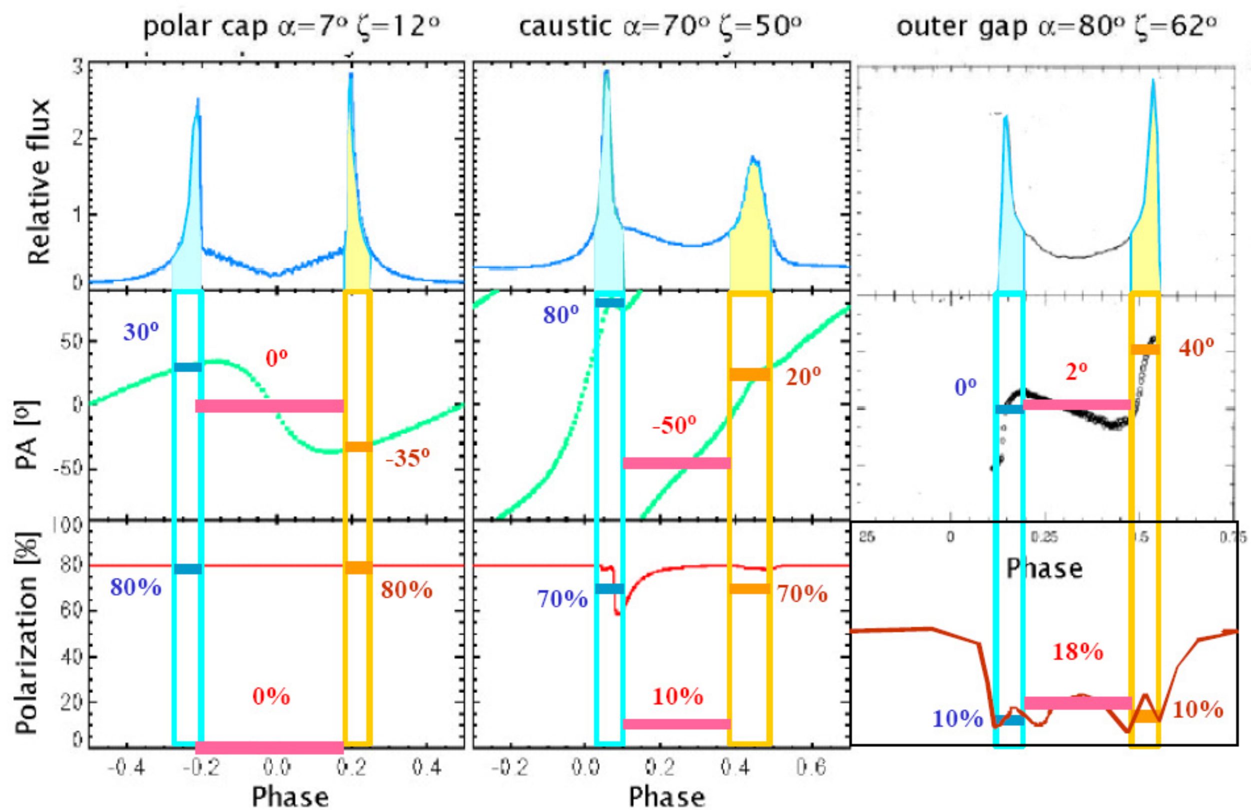
Scientific goals

Polarization is expected from many astrophysical objects.

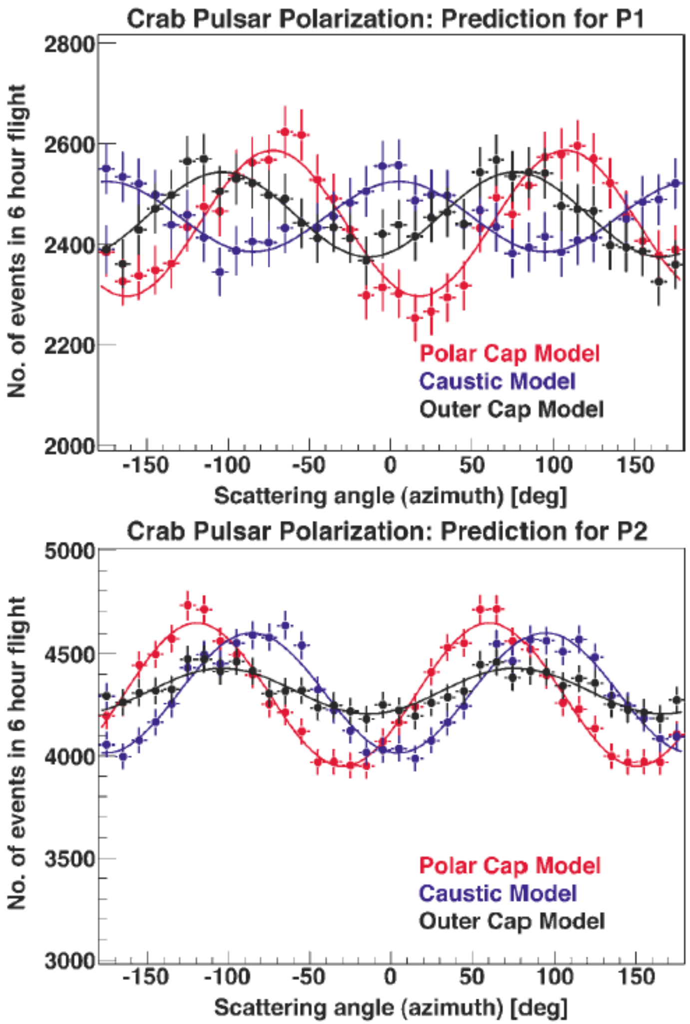
- Isolated pulsars and binary pulsars
- Neutron stars with strong magnetic fields
- Black hole accretion discs
- Jet-dominated active galaxies

Isolated pulsars and binary pulsars (1)

- Three major models: polar cap, caustic and outer gap
- Prime targets: the Crab pulsar, PSR B1509-58



Isolated pulsars and binary pulsars (2)

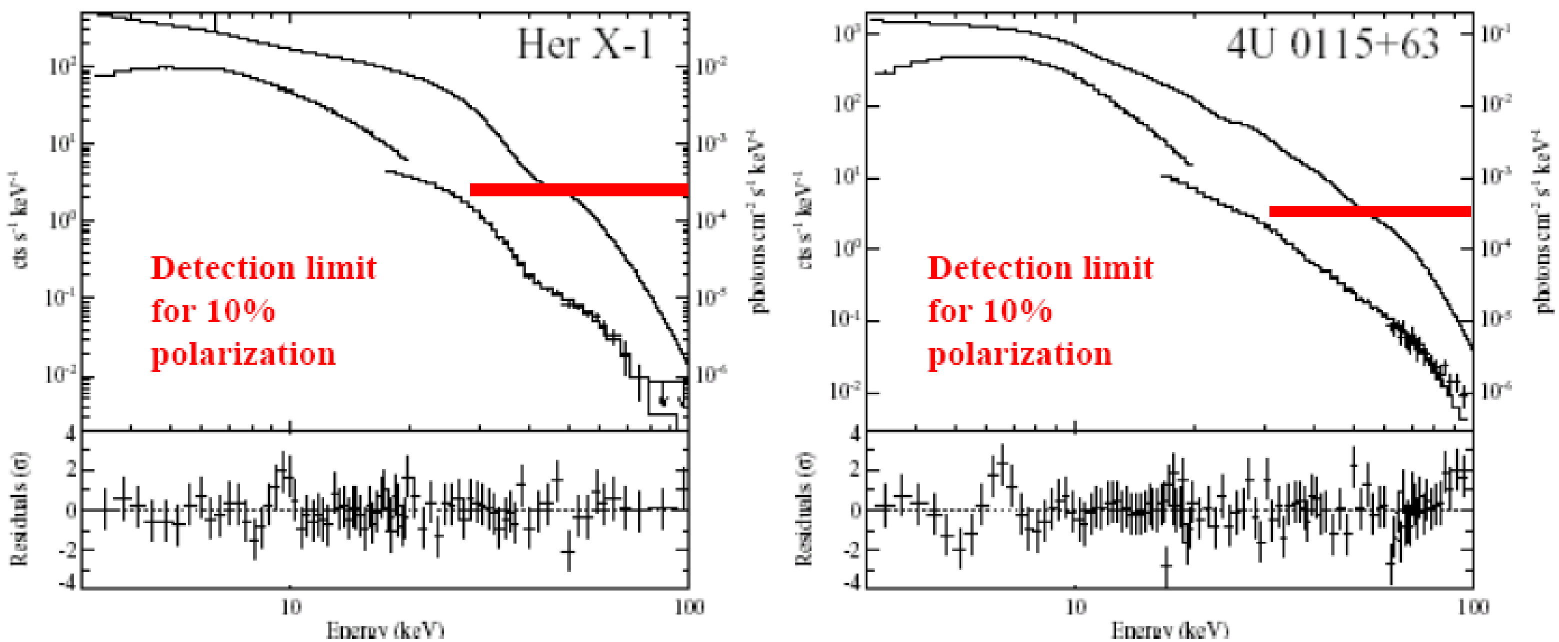


- Measurements of the modulation can distinguish between the different models

simulations

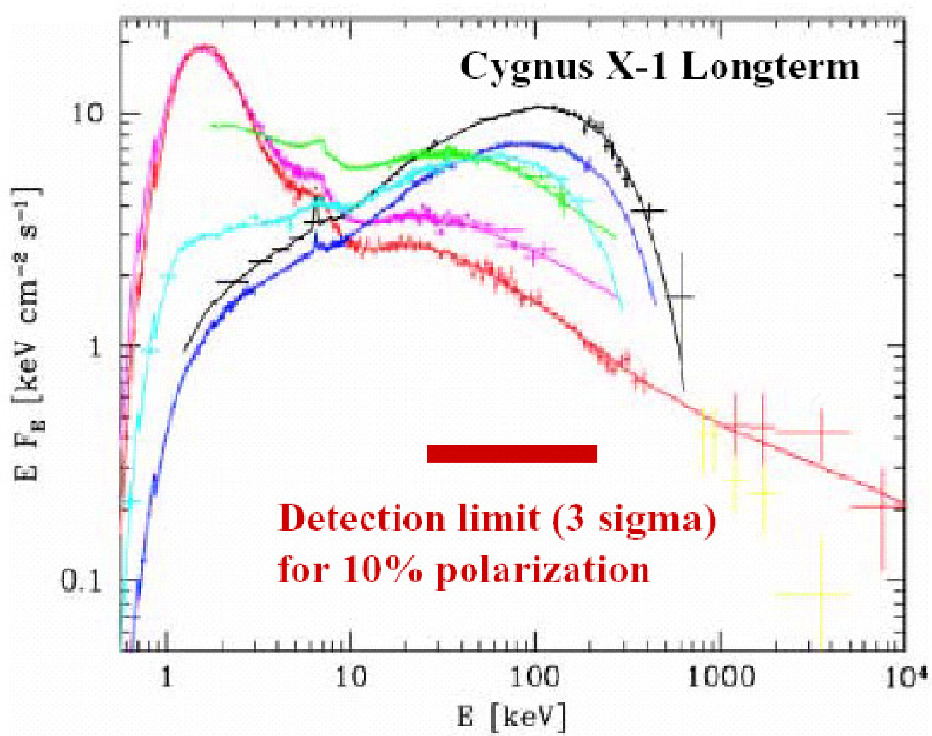
Neutron stars with strong magnetic fields

- Surface magnetic fields of up to 10^{15} G
- Polarization measurements will help to reconstruct the direction of the magnetic field
- Primary targets: Her X-1, 4U 0115+63



Accretion onto black holes

- Primary soft gamma-ray flux from multiple Compton up-scattering
- Compton reflection of primary soft gamma-ray flux expected to be strongly polarized
- Primary target: Cygnus X-1

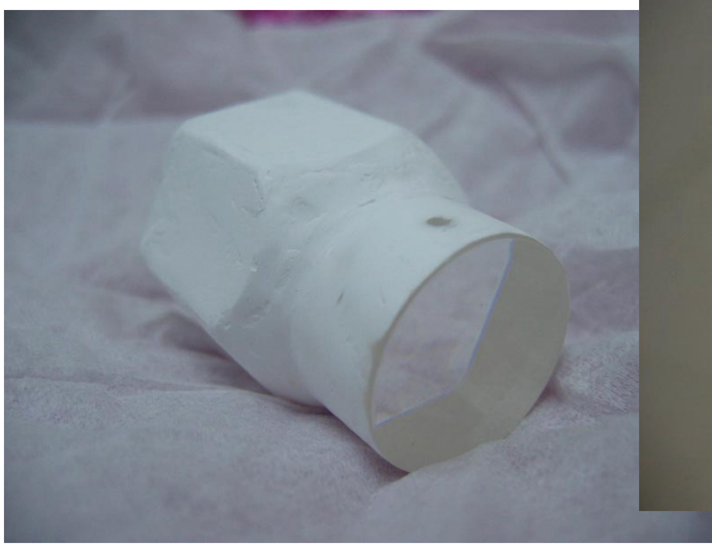


Jet-dominated active galaxies

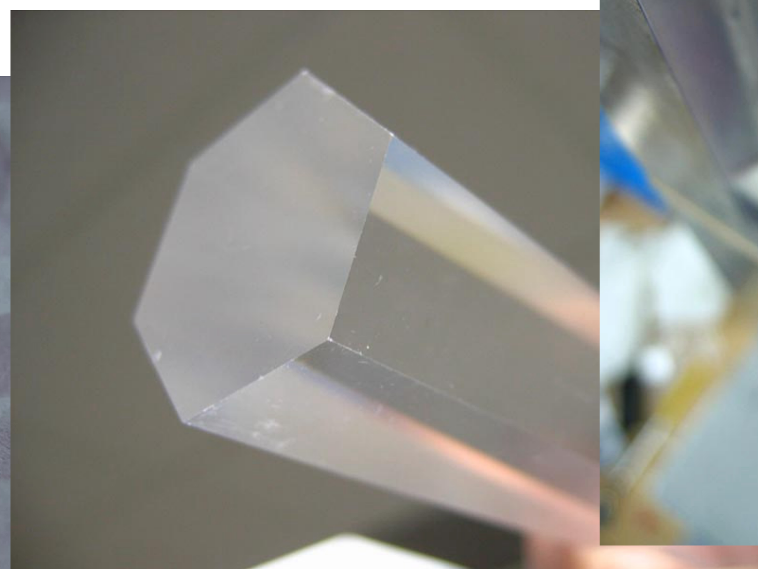
- Powerful gamma-ray emitters, powered by accretion of galactic matter onto black holes
- Spectra contains two humps:
    - one in the radio to soft gamma-ray region (synchrotron processes)
    - one in MeV/GeV band (inverse-Compton processes)
- Polarization observed in radio through UV bands, but nothing is known about the polarization in the X-ray/soft gamma-ray region
- Primary targets: Mkn 501, PKS 2155-304

Gluing (1)

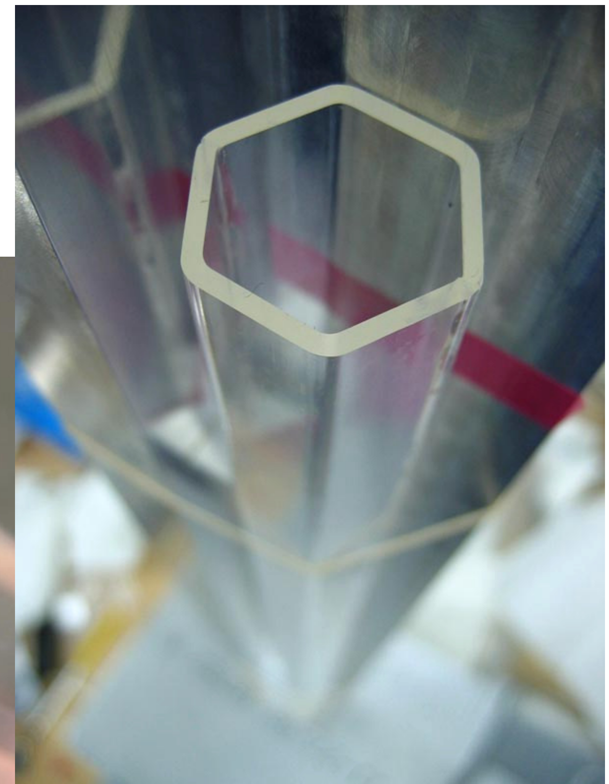
BGO crystal



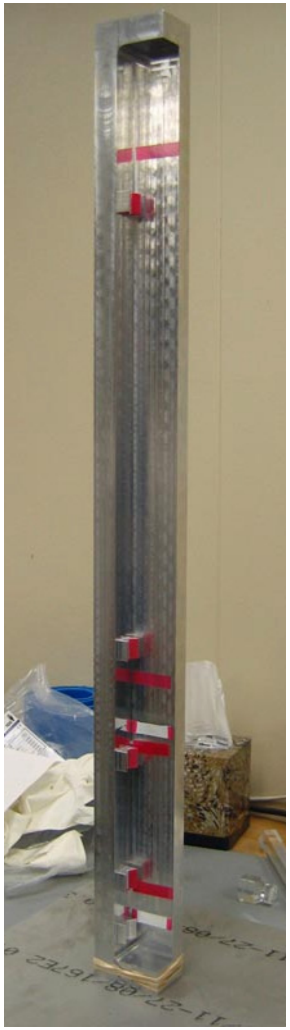
Solid “fast” plastic scintillator

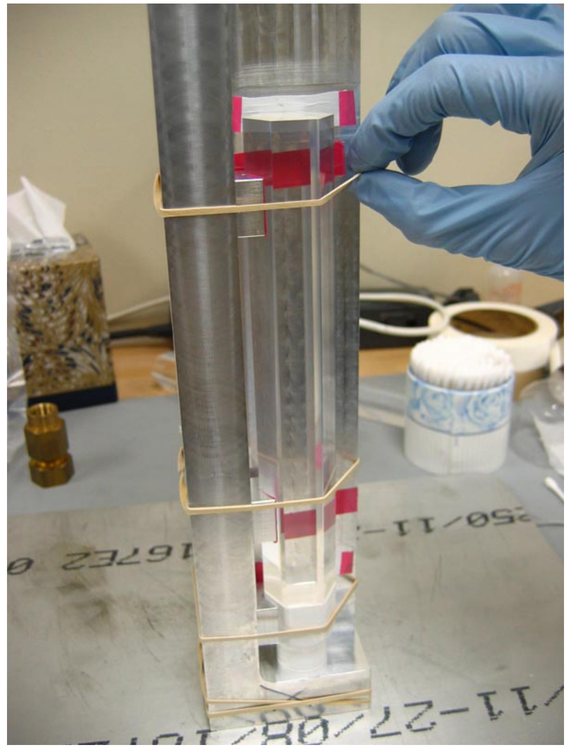


Hollow “slow” plastic scintillator



Gluing (2)



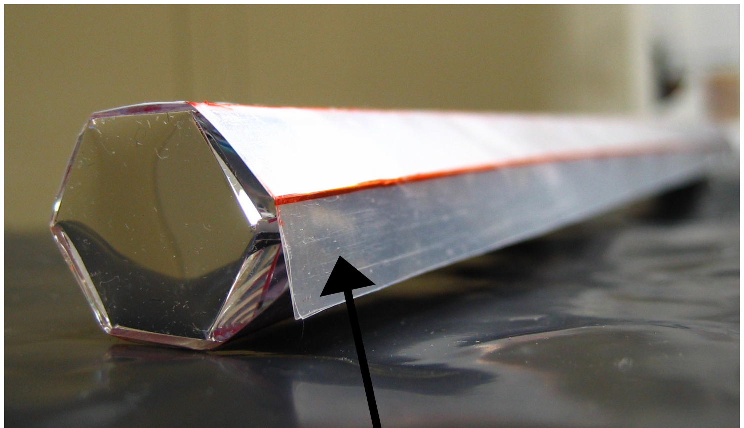


Hollow “slow” plastic scintillator

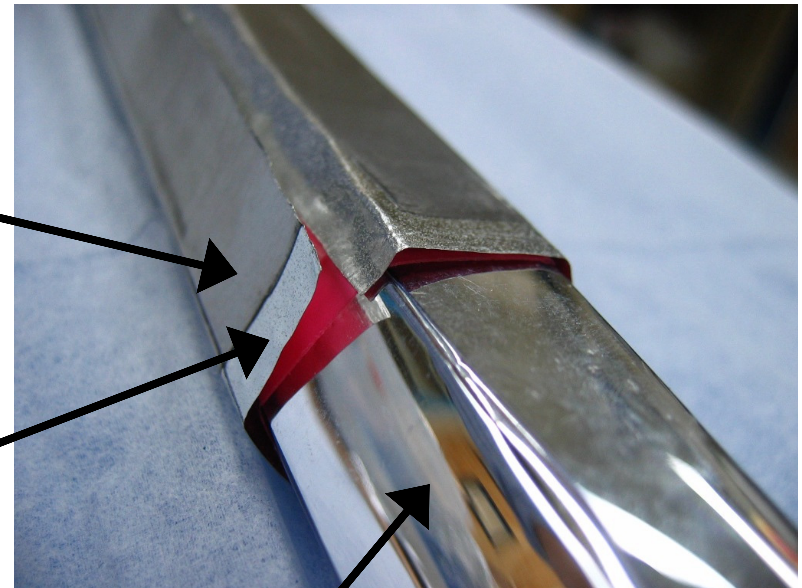
Solid “fast” plastic scintillator

BGO crystal

Covering (1)



VM2000: "multilayer birefringent polymer reflector film"



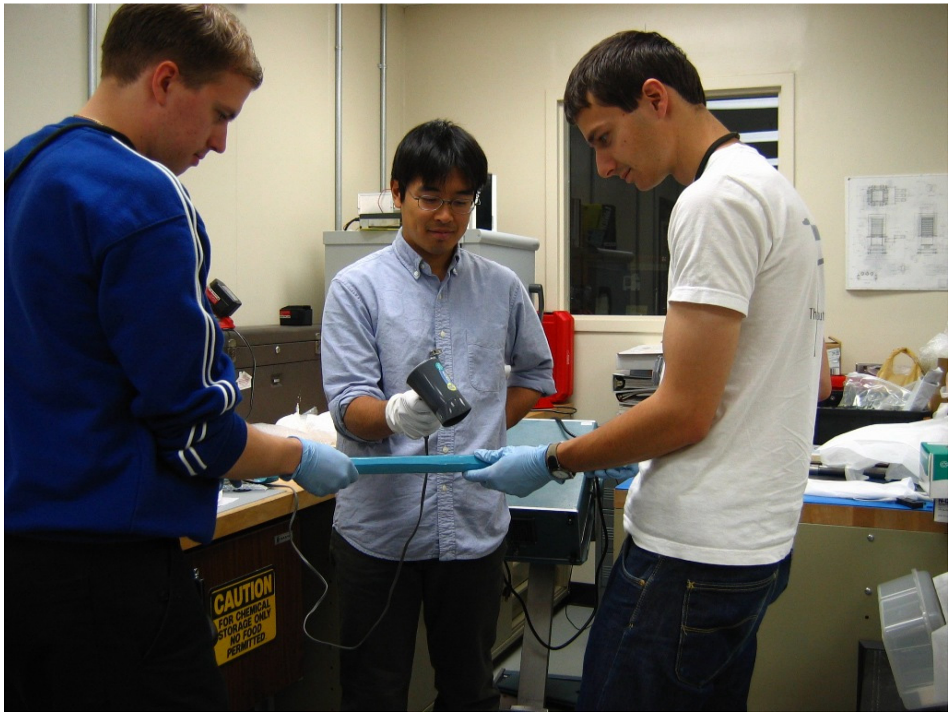
Lead foil

Tin foil

VM2000

- VM2000 keeps scintillation photons inside the tube
- Lead and tin foils keep charged particles and photons out of the tube

Covering (2)

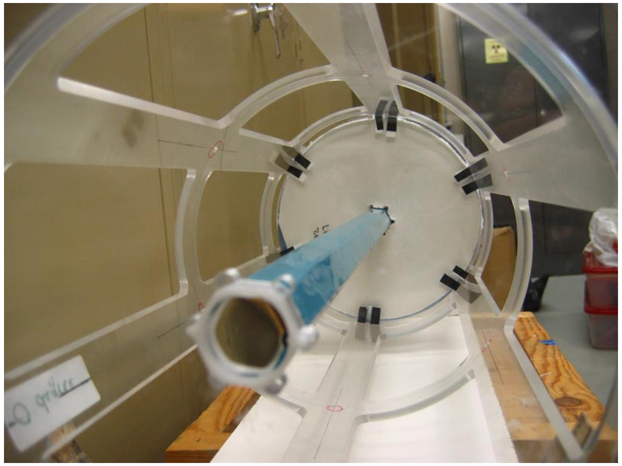


Applying shrink tube...

The final result

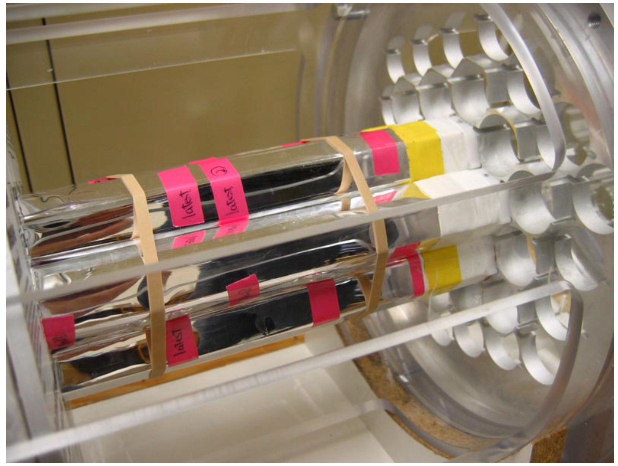
Assembling the prototype (1)

Step 1:



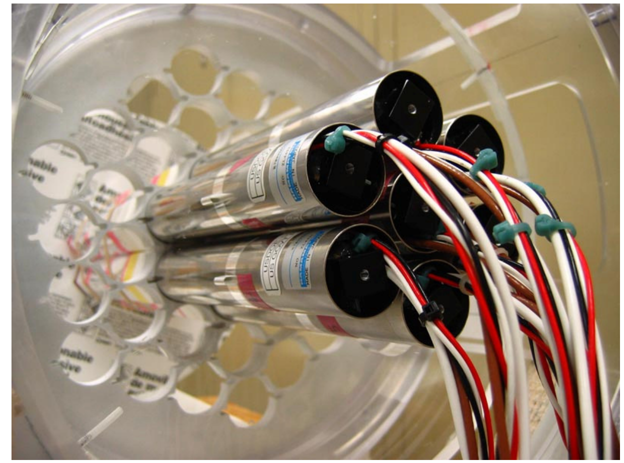
Central unit (full PDC)

Step 2:



Peripheral units (fast scintillator only)

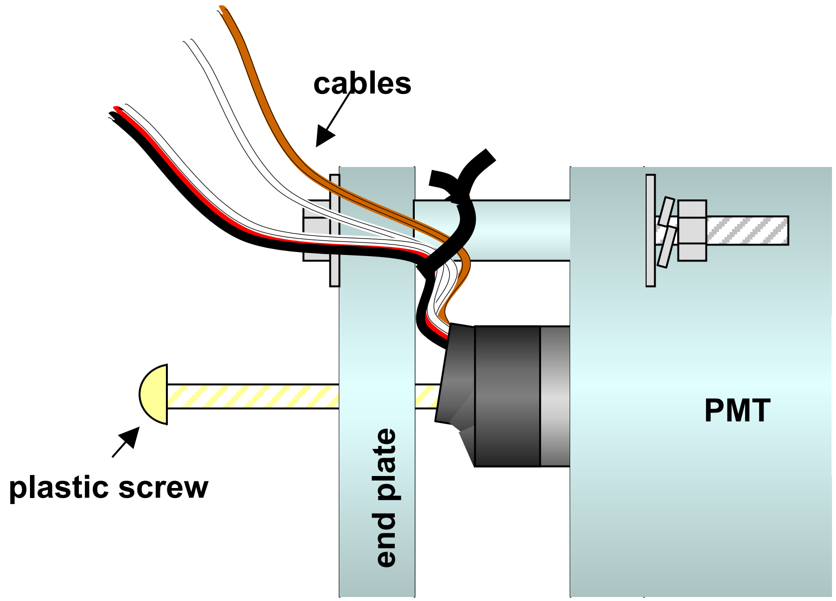
Step 3:



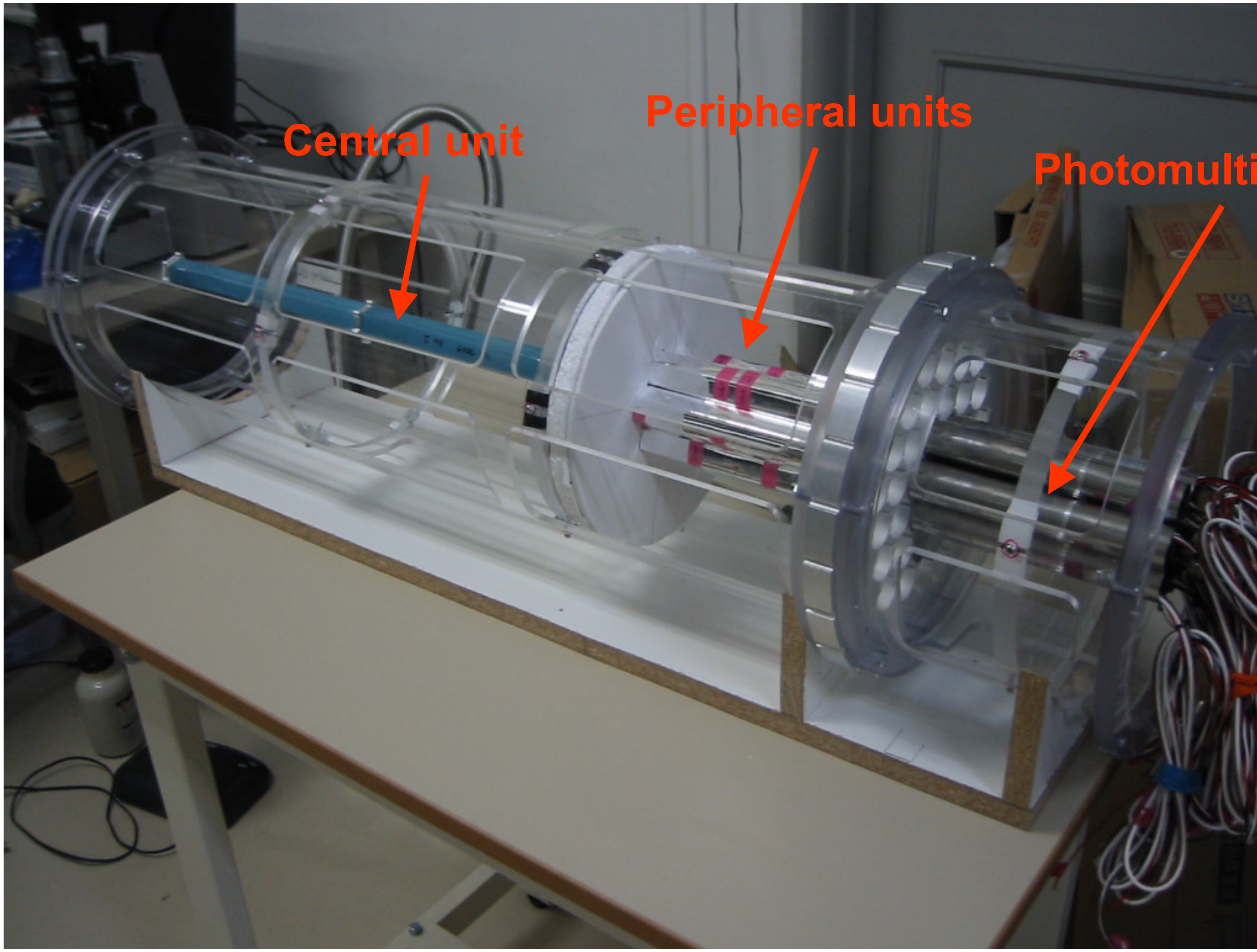
PMTs

Prototype: PMTs supported from the bottom by plastic screws

Flight model: units held together with nylon strings



Assembling the prototype (2)



KEK-PF beam test

KEK Photon Factory, High Energy Accelerator Research Organization

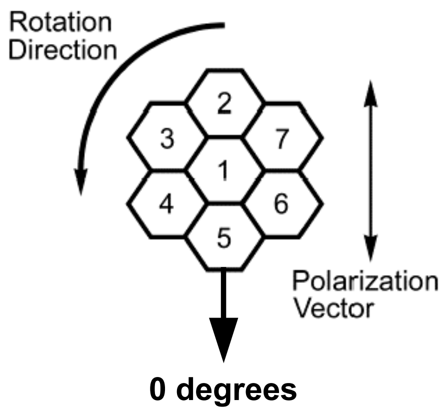
Tsukuba, Japan

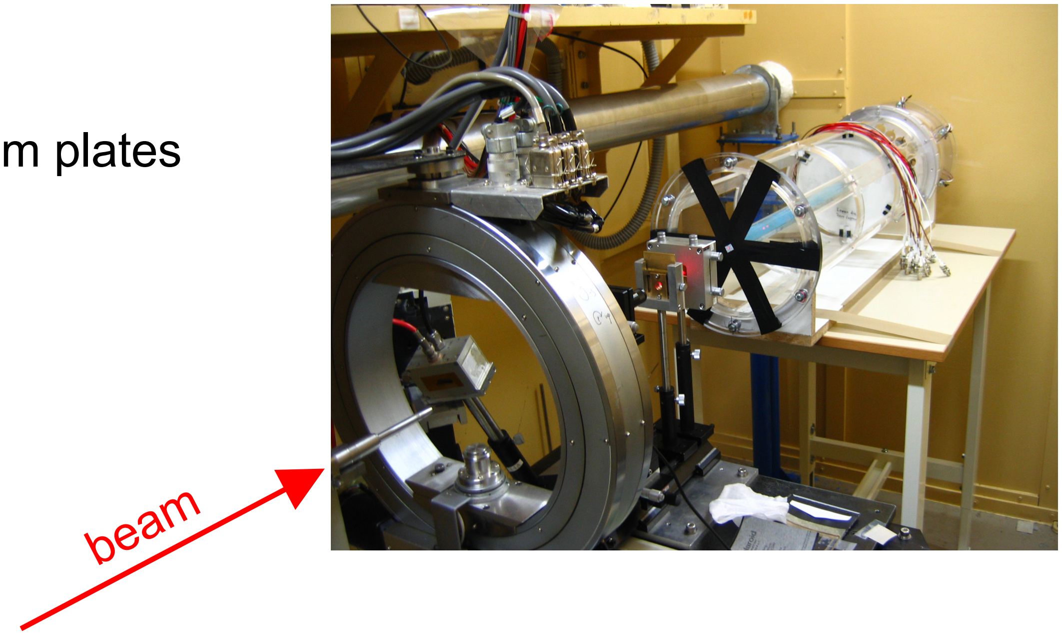
Experimental setup

Vertically plane-polarized beam from two monochromator crystals of ^{533}Si

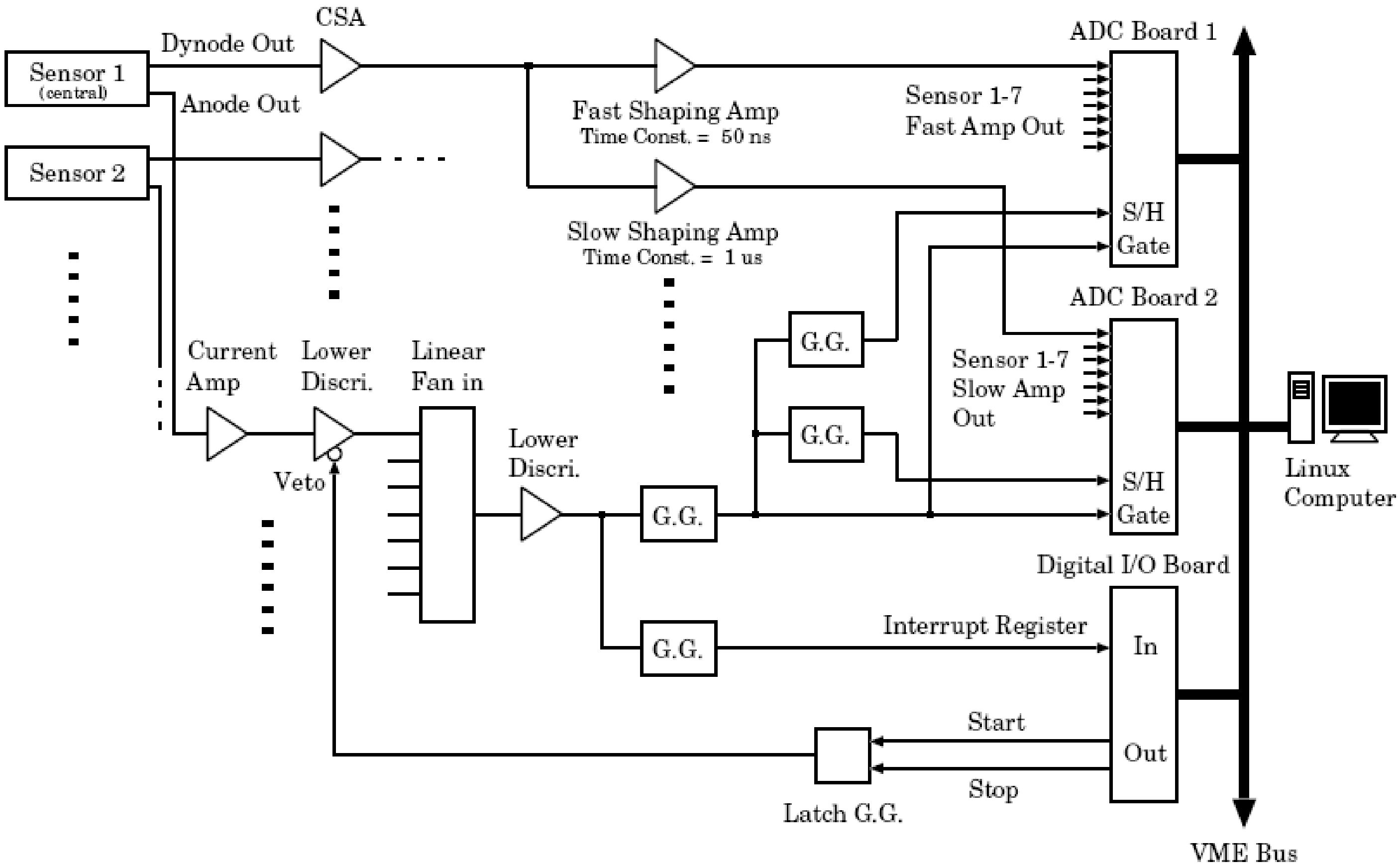
Intensity adjusted with metal attenuator
- Trigger rate: ~1 kHz

Beam collimated with tantalum plates
- Beam size: ~1 mm^2





Electronics



- Dynode output of PMT is used for spectroscopy
- Anode output of PMT is used for discrimination

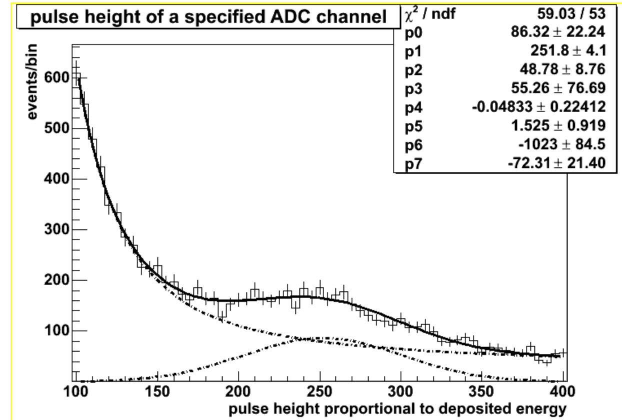
Calibration

The same method as used at SLAC

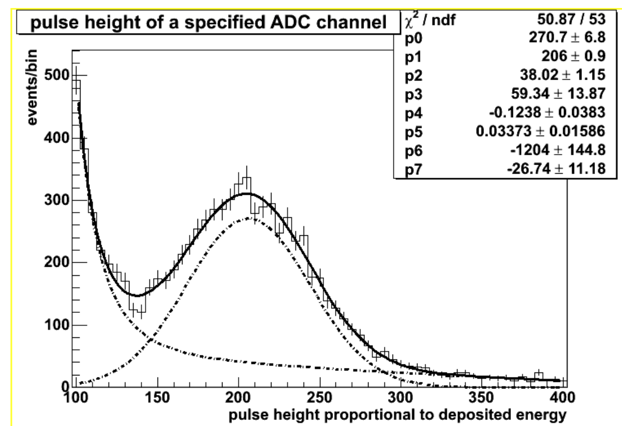
- A radioactive source of ^{241}Am irradiates the scintillators one by one from the side

- The central scintillator is irradiated through the peripheral units

- Peak values are used in analysis as calibration constants



central unit



peripheral unit

Pulse shape discrimination

Decay times	
Fast scintillator	1.8 ns
Slow scintillator	230 ns
BGO	~300 ns

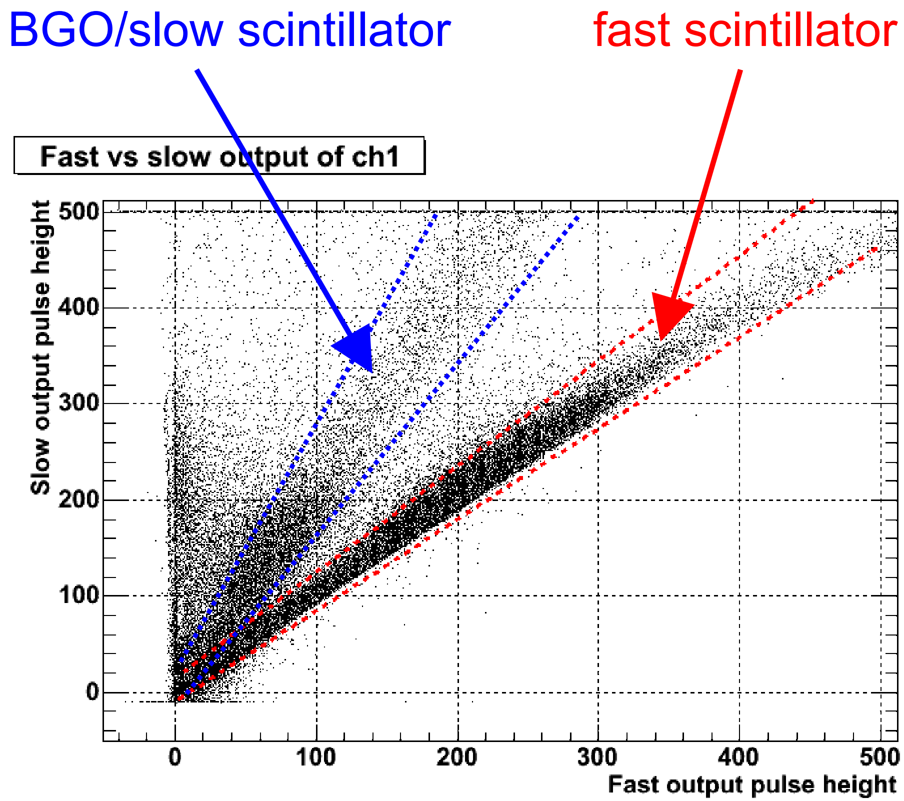
Time constants of shaping amplifiers	
Fast	50 ns
Slow	1 μs

In the fast shaping amplifier the whole signal from the fast scintillator is integrated. Only a small part of the signal from BGO and slow scintillator are integrated

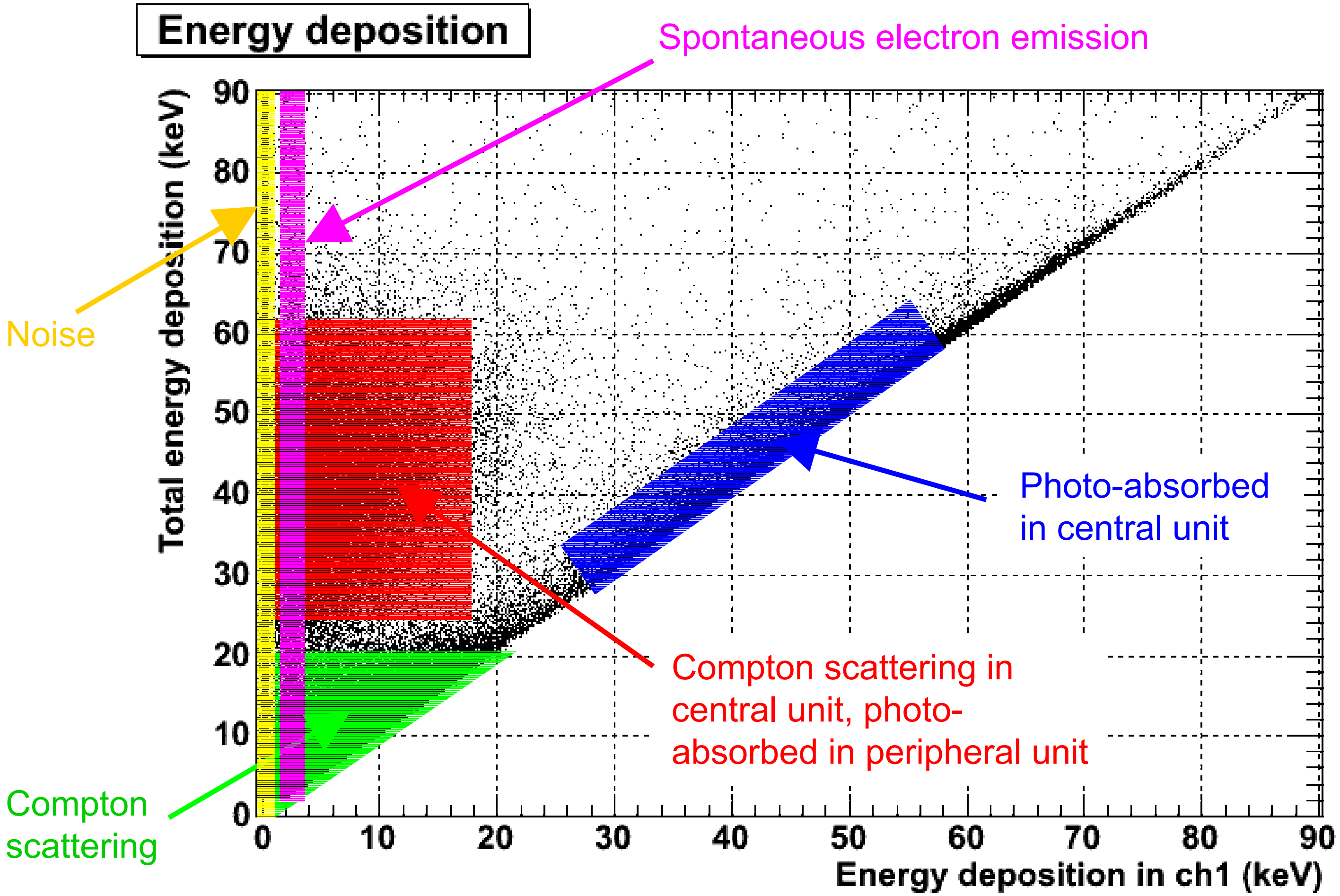
In the slow shaping amplifier the whole signal from all scintillators are integrated, but the total contribution from the fast scintillator is smaller

Fast and slow outputs

- The result is a clear separation of signals from fast scintillator and BGO/slow scintillator
- Fast scintillator branch is chosen for analysis, since the fast scintillator is the detection part and to avoid background and pile-up



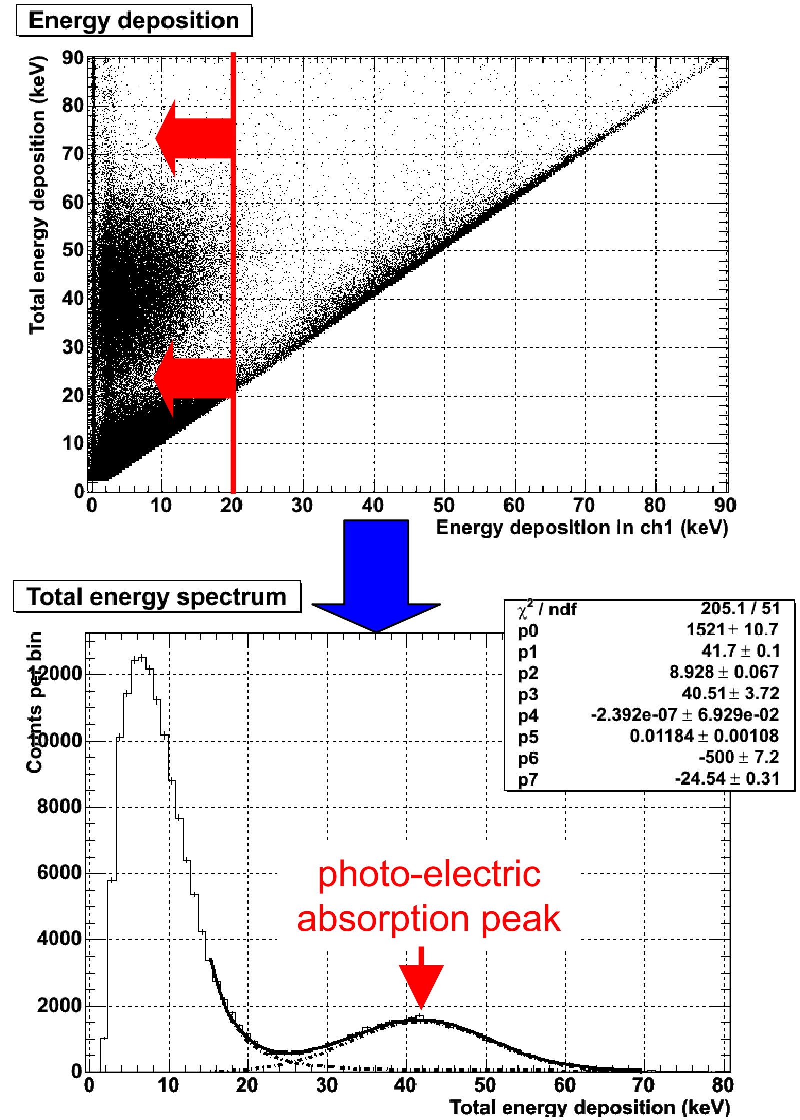
Central vs. Total energy deposition



- Events where one peripheral scintillator is hit are plotted

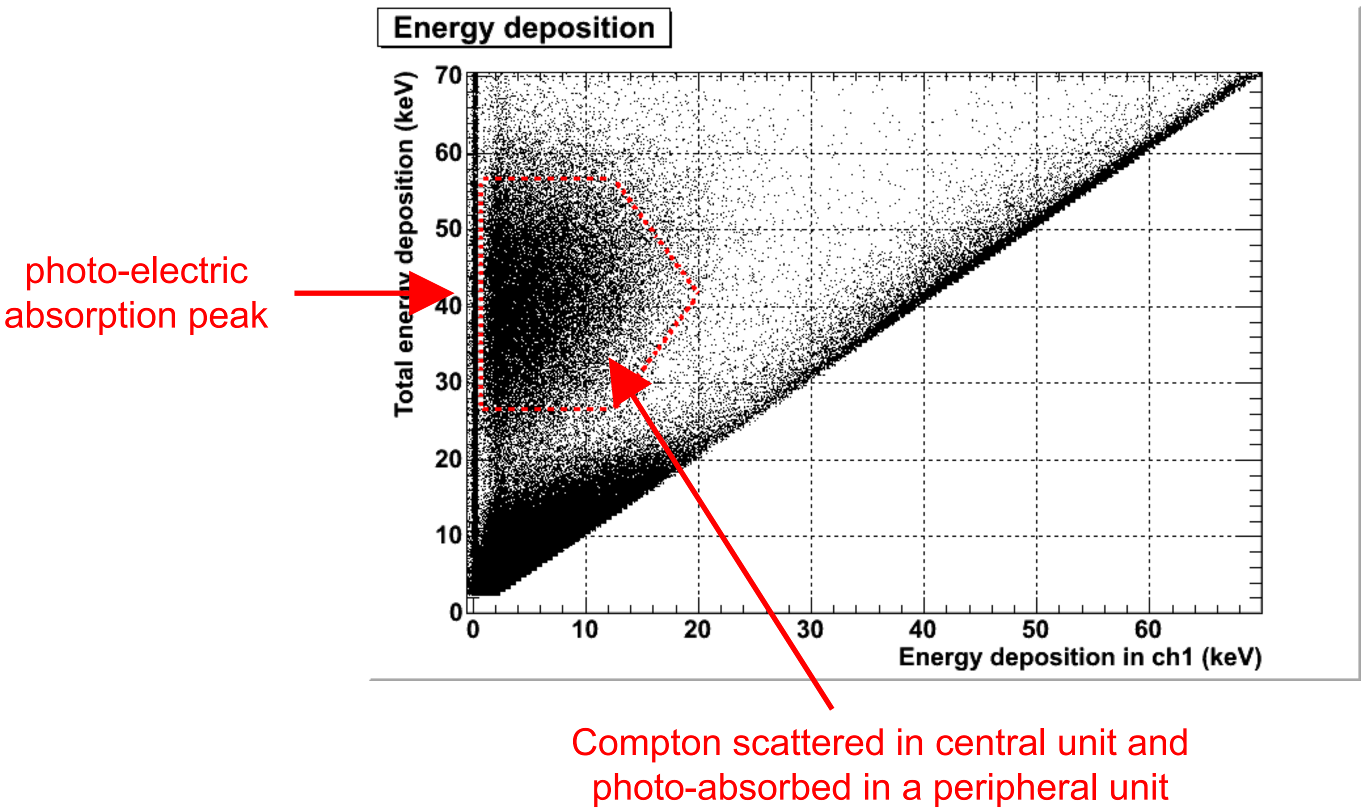
Total energy spectrum

- Events which deposited less than a certain energy in the central unit were projection onto the total energy axis
- Total energy spectrum is fitted with a gaussian and an exponential function
- Peak position is used to choose events from two dimensional plot



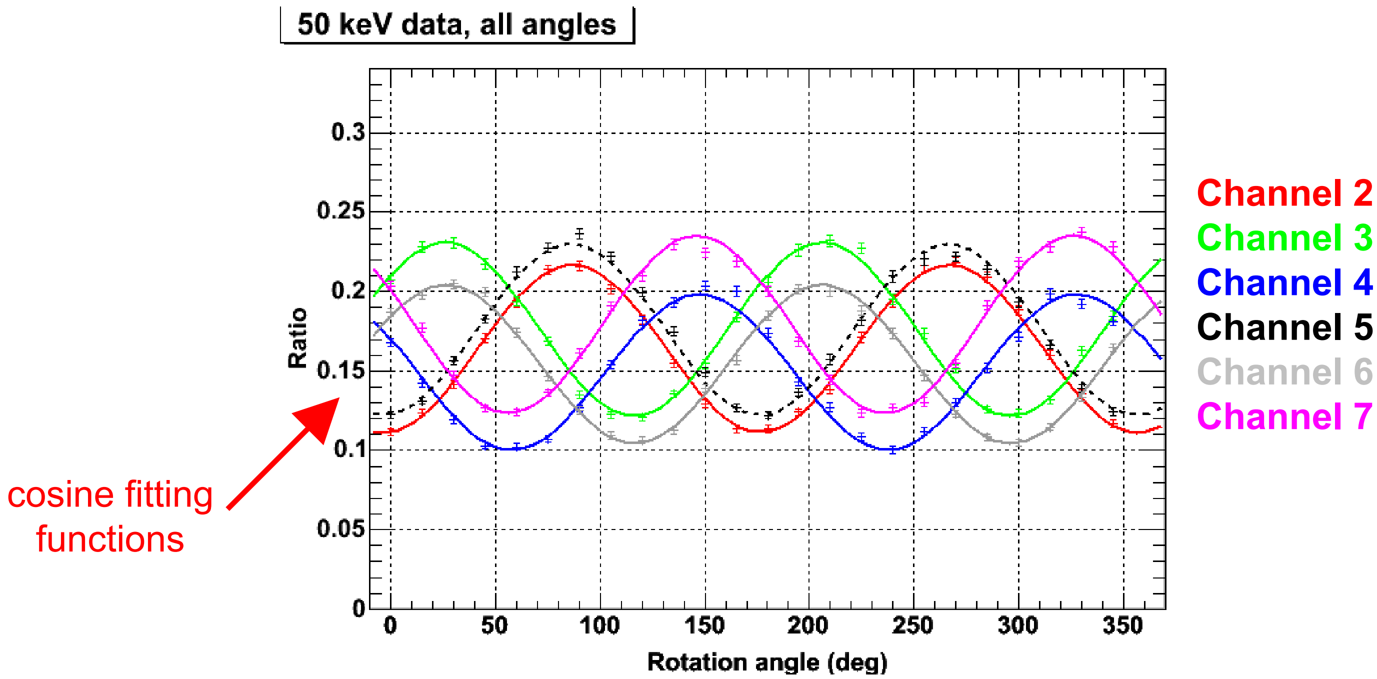
Energy deposition

- Selection of the events which correspond to Compton scattering in the central unit and photo-electric absorption



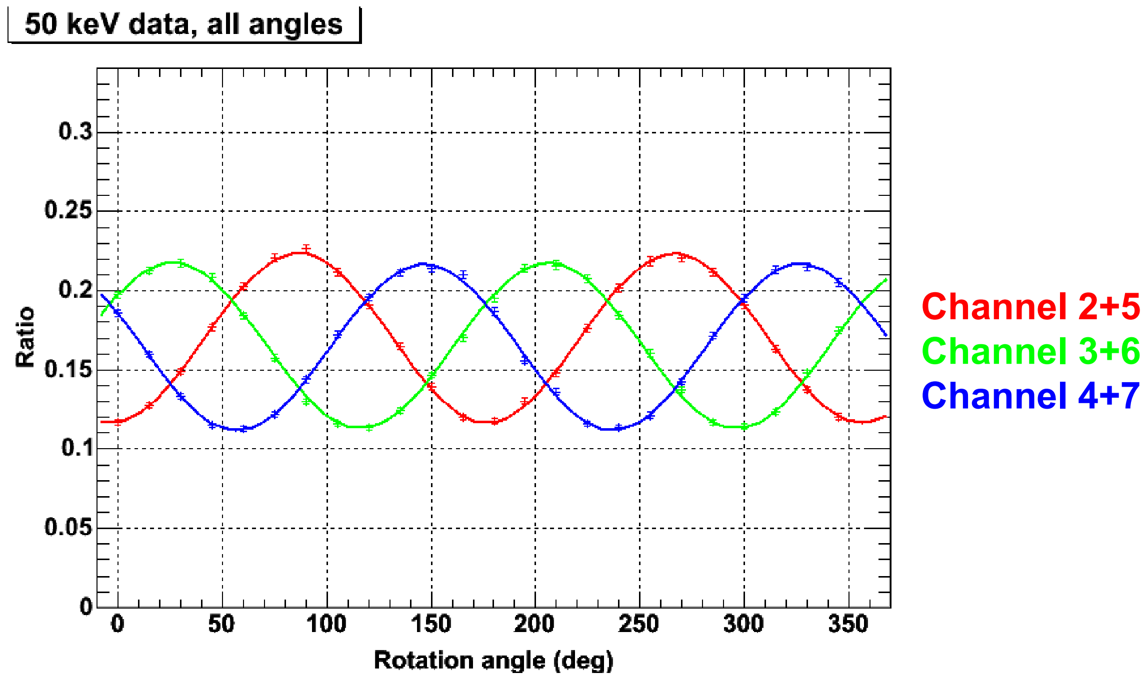
Modulation curves (1)

- The number of events in each scintillator plotted as a function of rotational angle
- Ratio = the number of events in each scintillator divided by the sum of the events in all scintillators



Modulation curves (2)

- The average of the events in two opposing scintillators



Results

- Data was taken at three different energies: 30, 50 and 70 keV
- The modulation factors are corrected for background and dead time
- The modulation factor for 100% polarized photons, M_{100}, can be calculated by dividing with the degree of polarization of the beam
- Simulation was made with Geant4 using a modified code for polarization

Energy	Degree of polarization	M_{100}	Simulated values of M_{100}
30 keV	~0.88	~0.348	0.399 ± 0.003*
50 keV	~0.90	~0.360	0.408 ± 0.004*
70 keV	~0.90	~0.413	0.411 ± 0.006*

*Obtained using slightly different event selection criteria

Improvements to the analysis

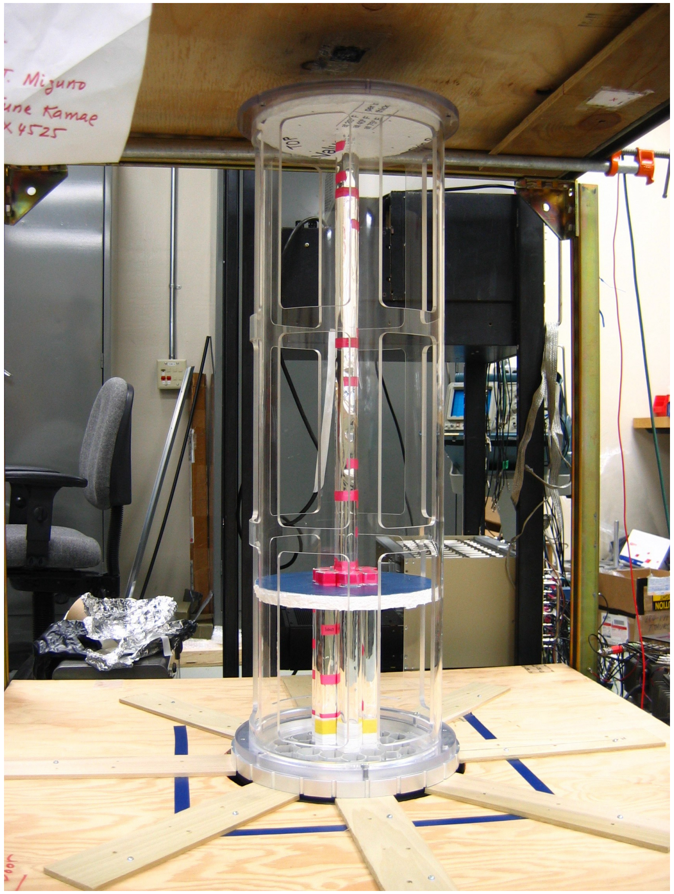
- Consideration of the non-linearity of fast scintillator

If the number of scintillation photons is proportional to the energy deposition. A measurement of the linearity was performed at KEK prior to polarization measurement. Analysis is in progress.

- More frequent calibration

The calibration constants can change during the course of the beam test. An analysis made by Y. Kanai indicates that they do change.

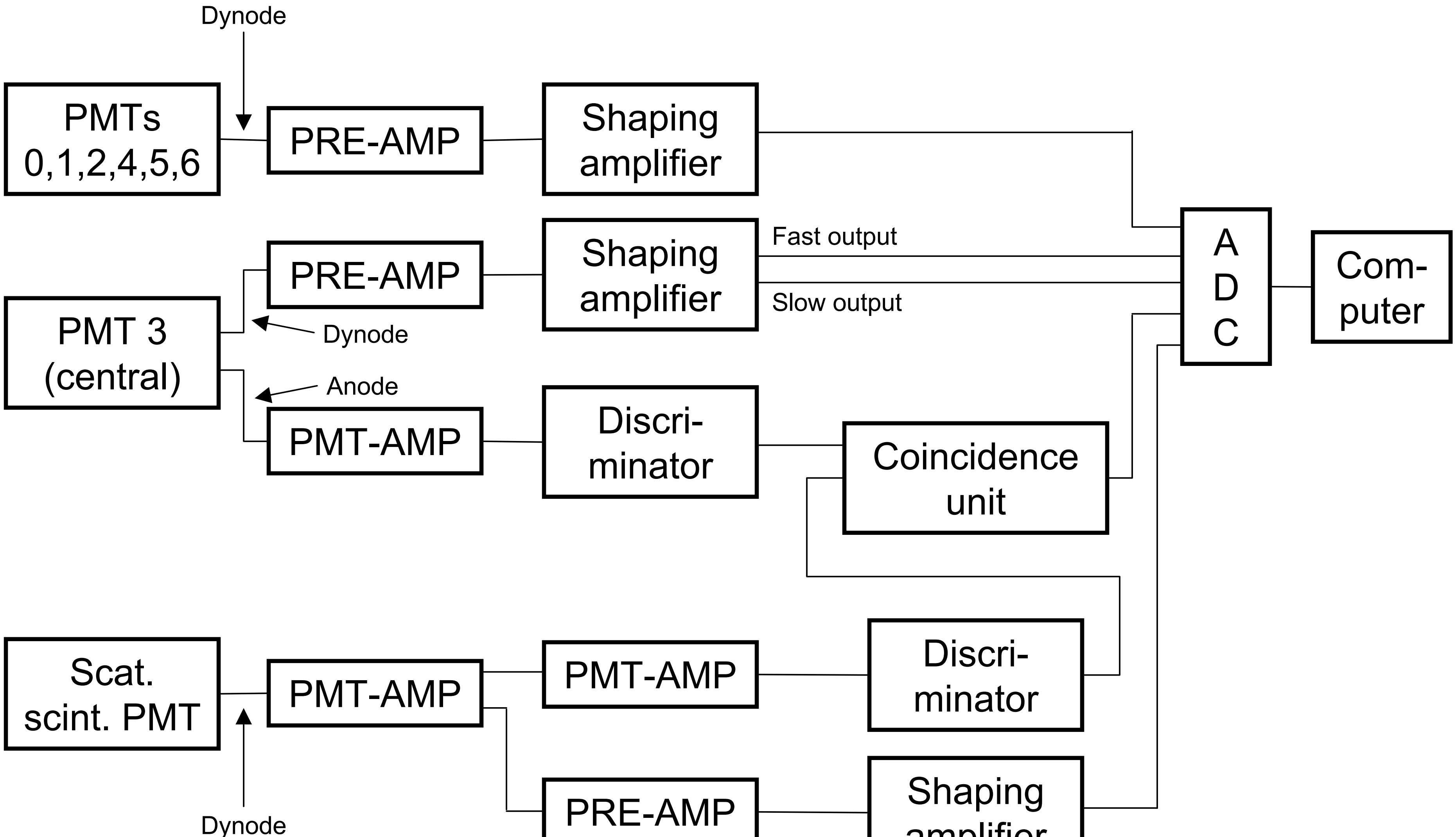
SLAC



Measurements:

- Polarization
- Light yield
- BGO crystal comparison

Electronics (1)

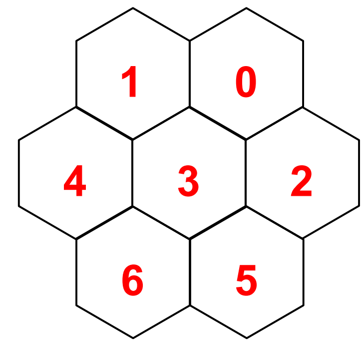


Electronics (2)

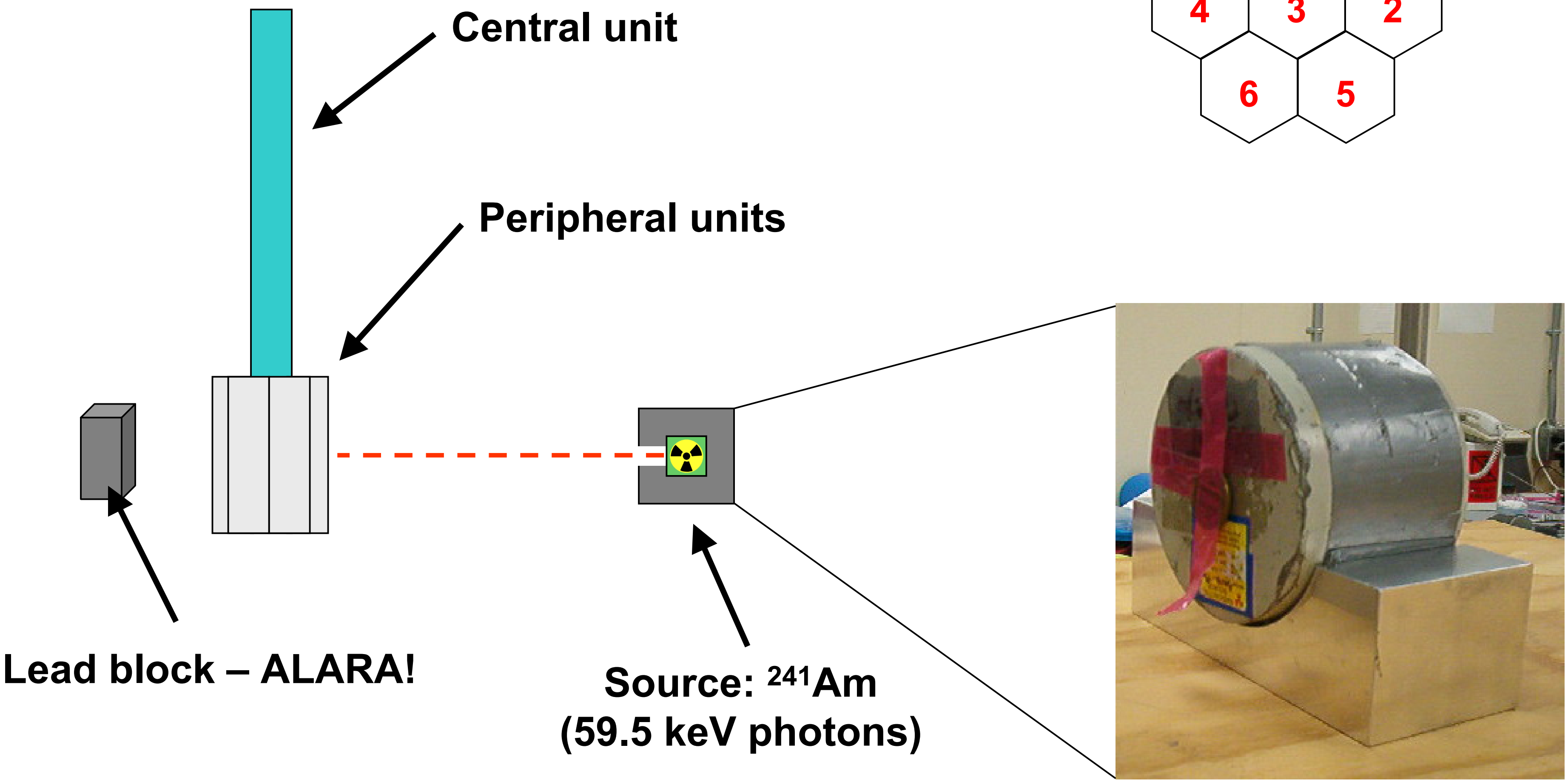
- Coincidence in scattering scintillator and central unit triggers data acquisition of whole detector array
- Pulse height sampled at 20 MHz
  ➔ wave form analysis
- Peak values stored in separate file as well
  ➔ smaller file size for “quick looks”

Calibration (1)

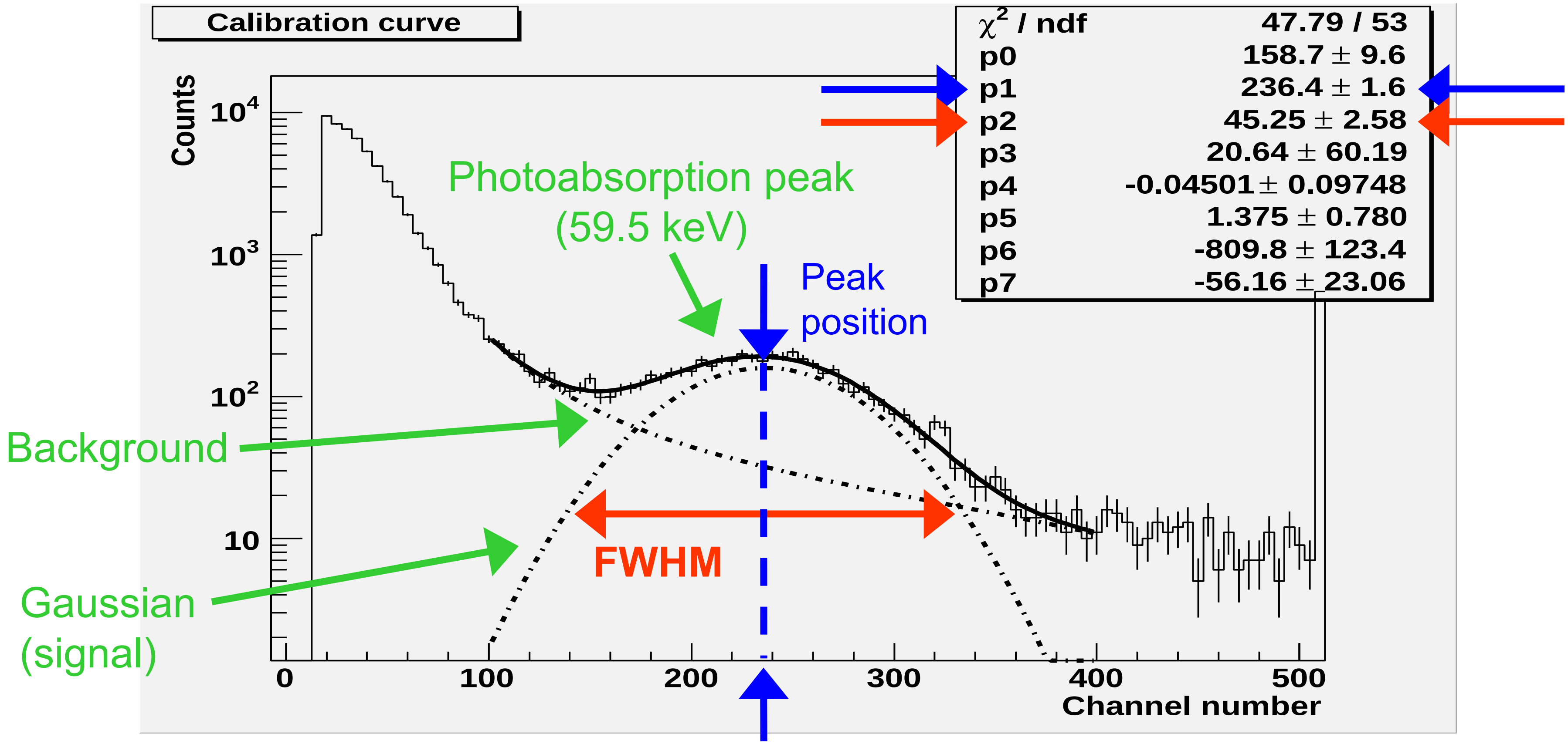
Detector array seen
from the top



Detector array seen
from the side



Calibration (2)

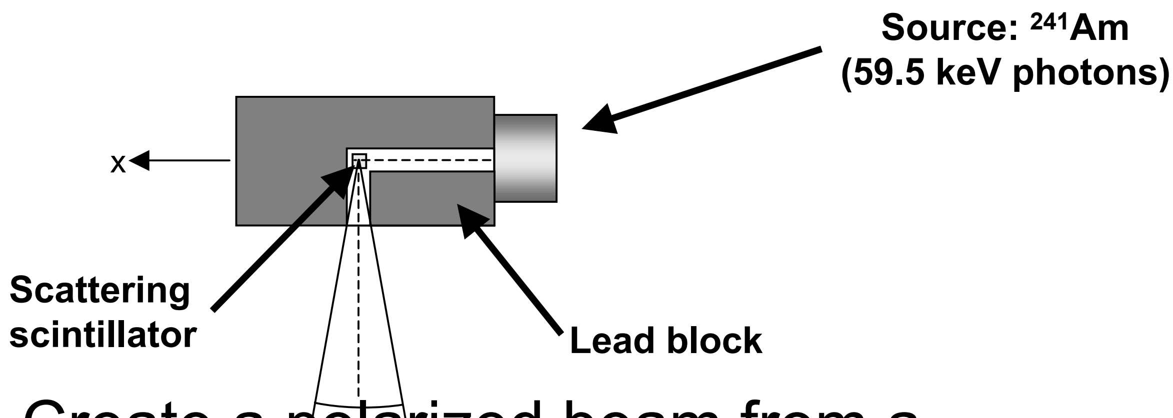


Calibration constant: $\dfrac{\textit{peak energy}}{\textit{peak position}}$

Energy resolution: $\Delta E = \dfrac{\text{FWHM}}{\textit{peak position}} = \dfrac{2.35 p_2}{p_1}$

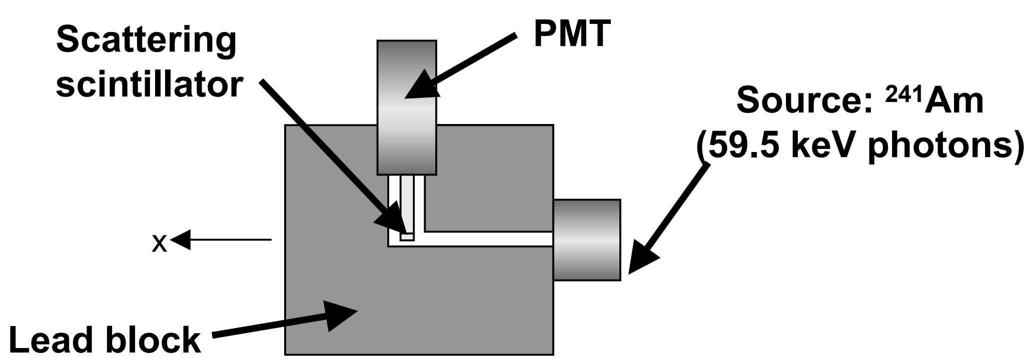
Polarization (1)

Seen from the side



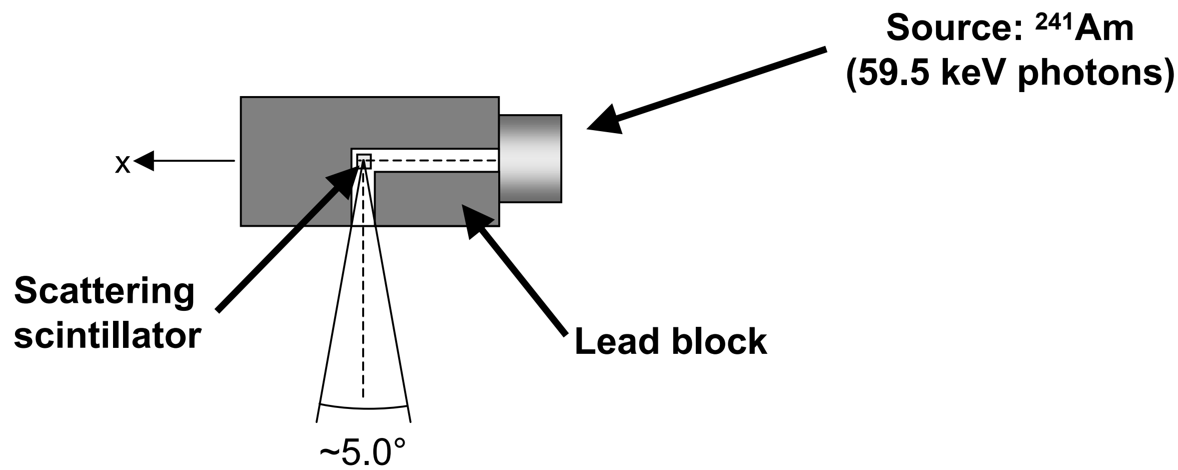
Step 1: Create a polarized beam from a source that emits unpolarized photons…

Seen from above



Polarization (2)

Seen from the side



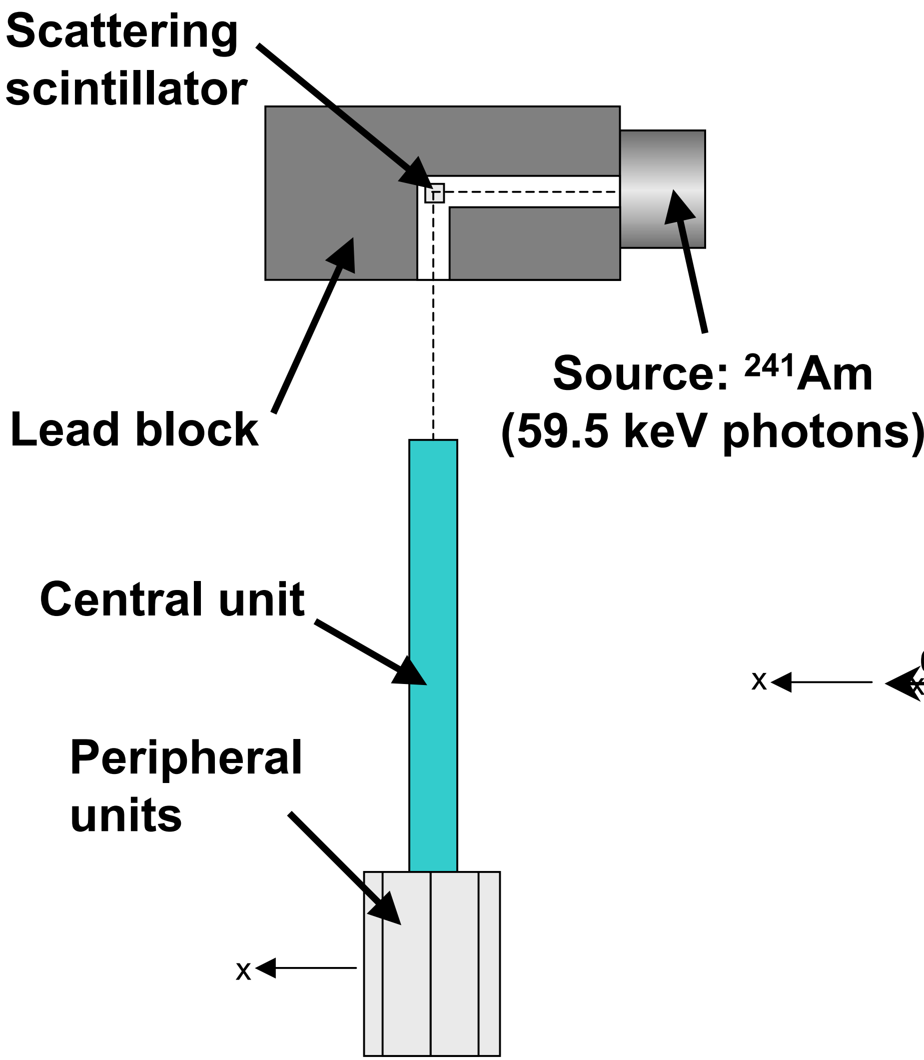
The Klein-Nishina scattering cross-section: $$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{k^2}{k_0^2}\left[\frac{k}{k_0} + \frac{k_0}{k} - 2 + 4\cos^4\Theta\right]$$

➔ Photons more likely to scatter perpendicular to the incident polarization vector.

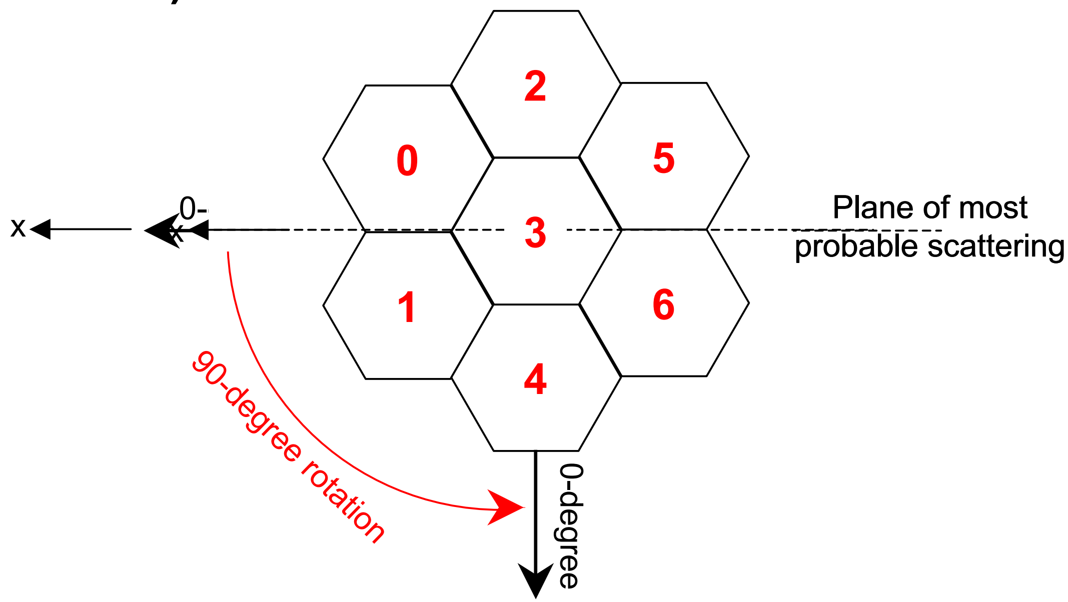
Lead block used to choose only photons scattering at about 90°

➔ polarized beam is obtained!

Polarization (3)



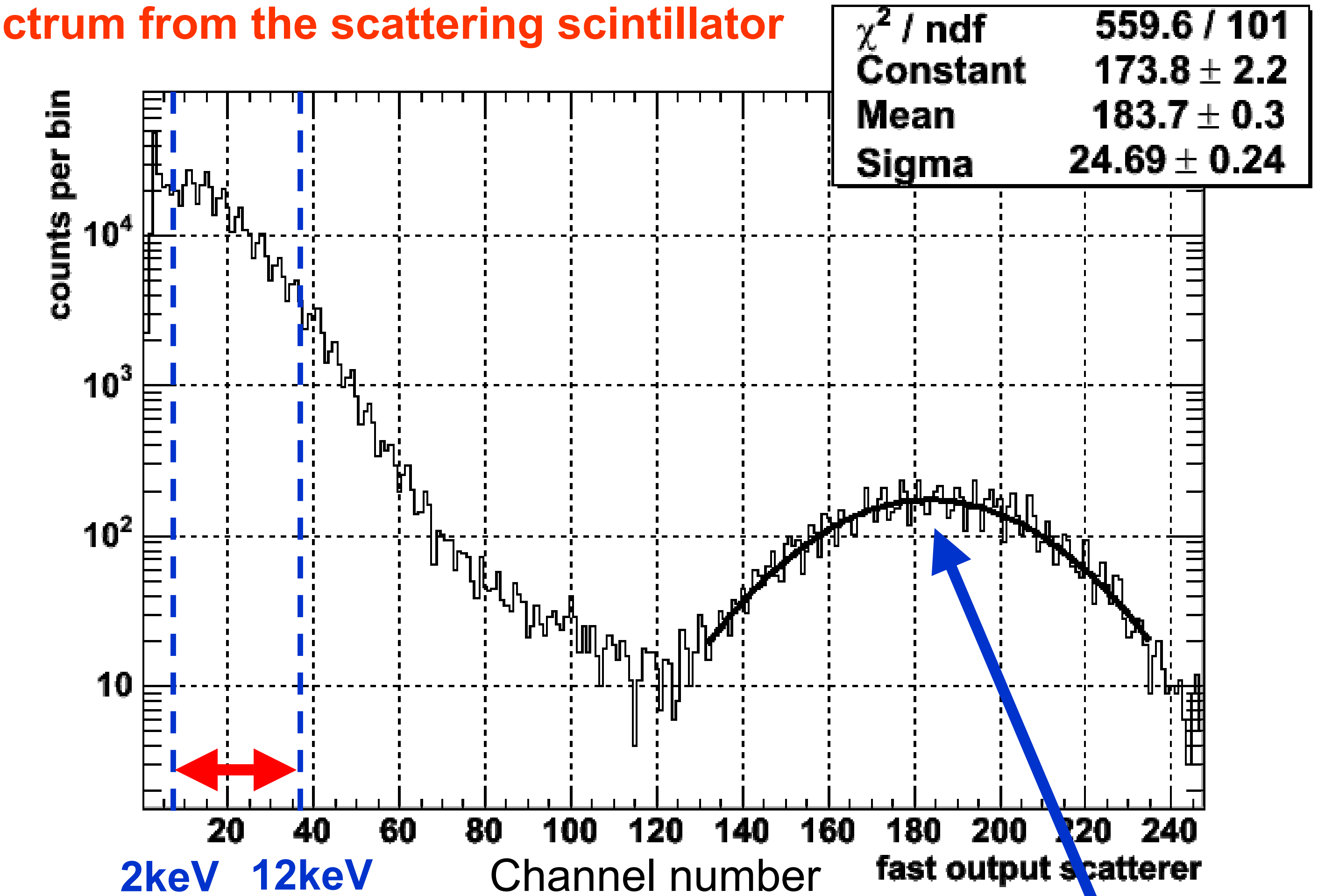
Seen from side



Seen from above

Polarization (4)

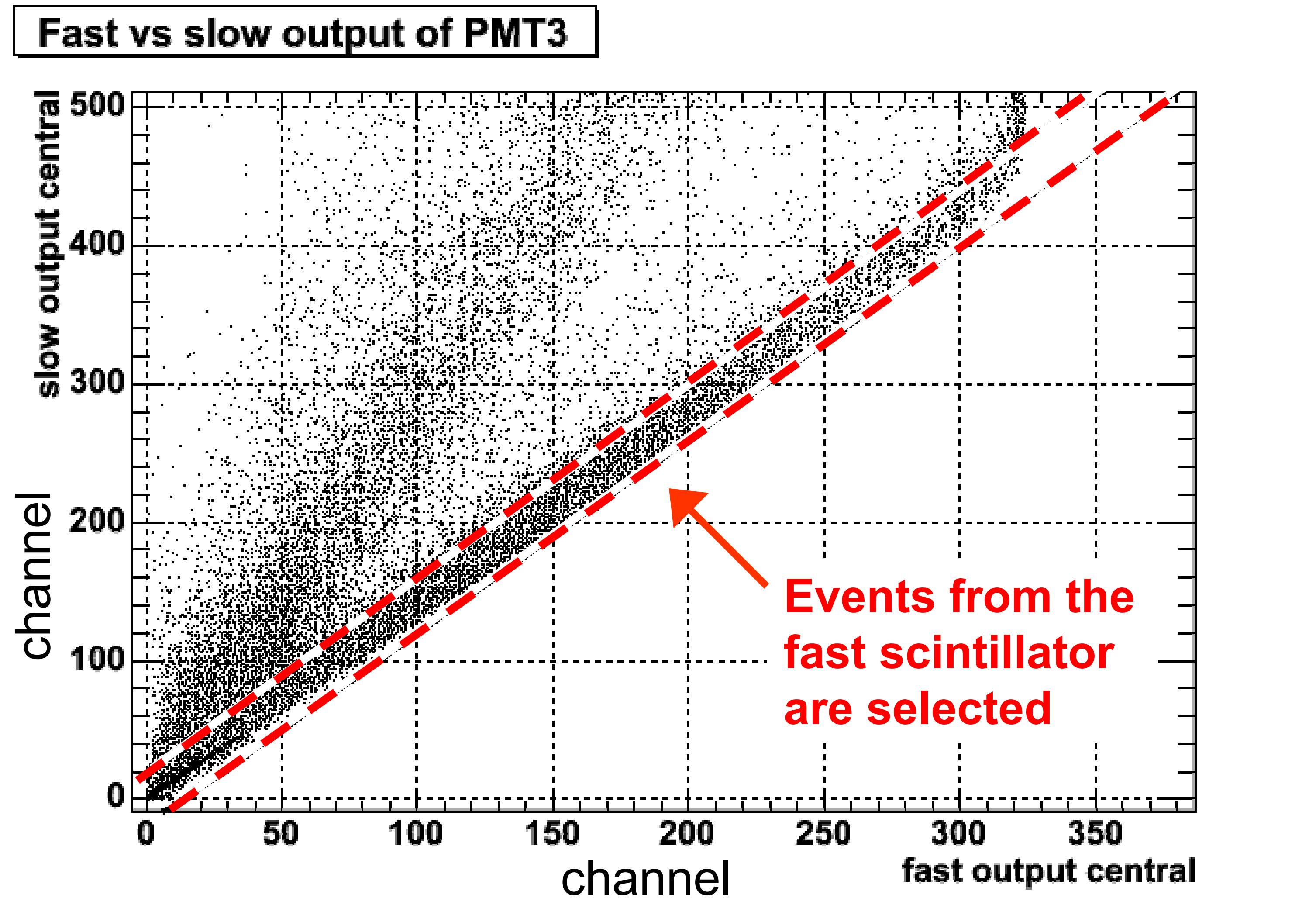
Spectrum from the scattering scintillator



Compton scattering formula ➔ 59.5 keV photons deposit about 6 keV in the scintillator.
Events between 2 keV and 12 keV are selected.
(This corresponds to 90° scattering.)

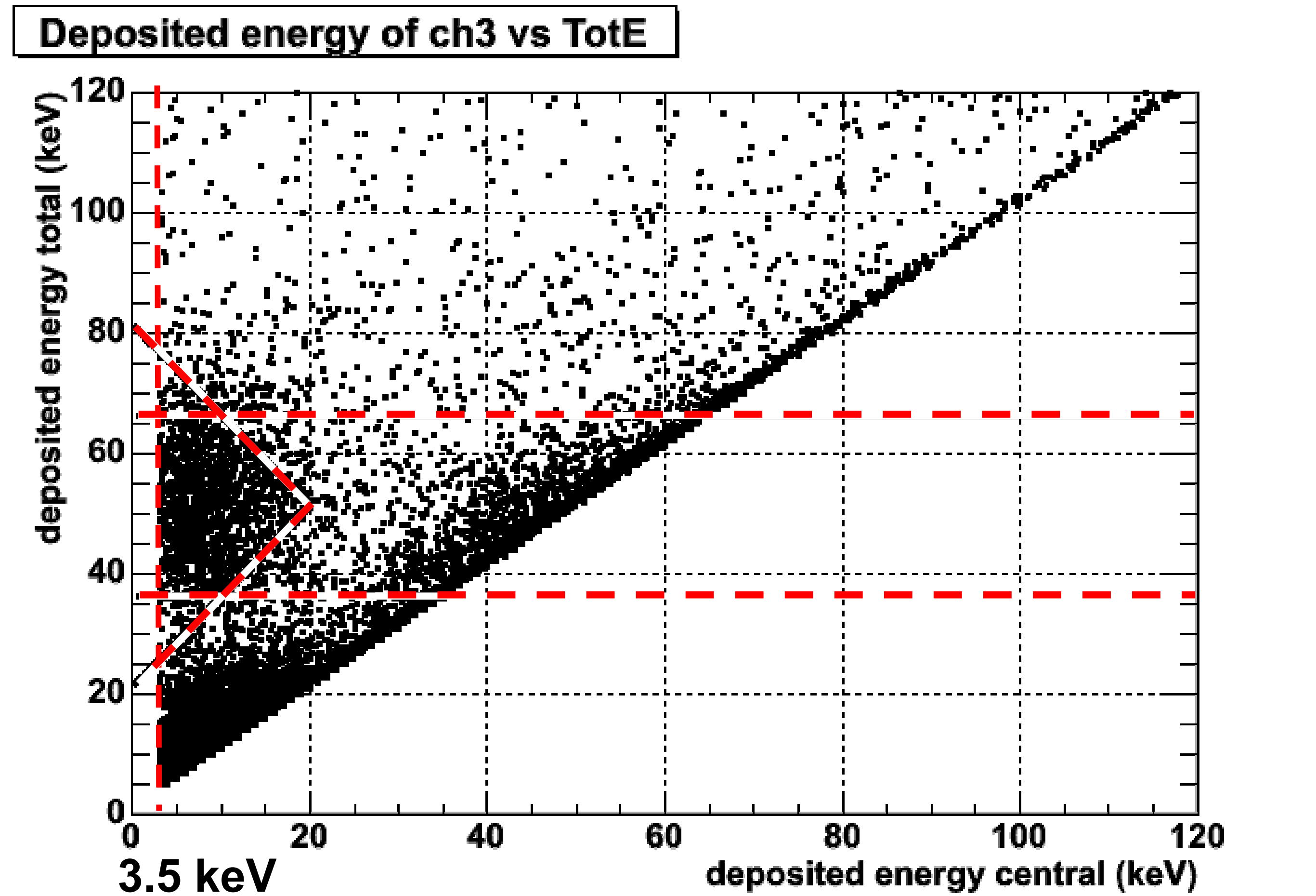
Photo-absorption peak
(59.5 keV)

Polarization (5)



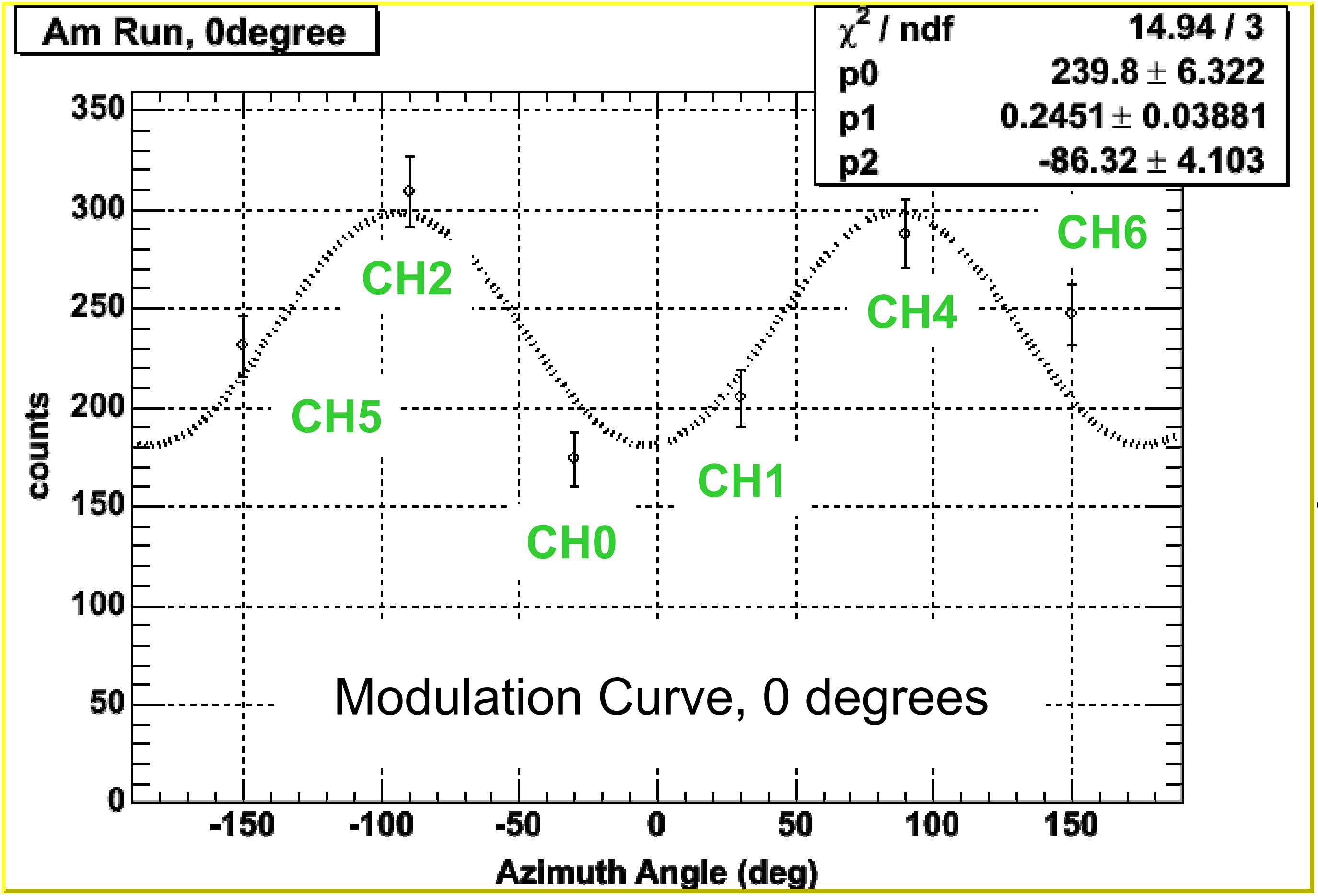
Polarization (6)

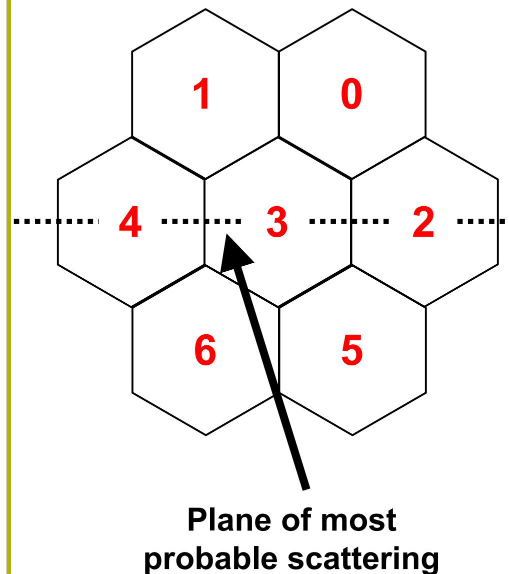
Select events where energy has been deposited in the scattering scintillator, the center scintillator and ONE of the peripheral scintillators.



Events inside the region shown by the red lines are selected for modulation.

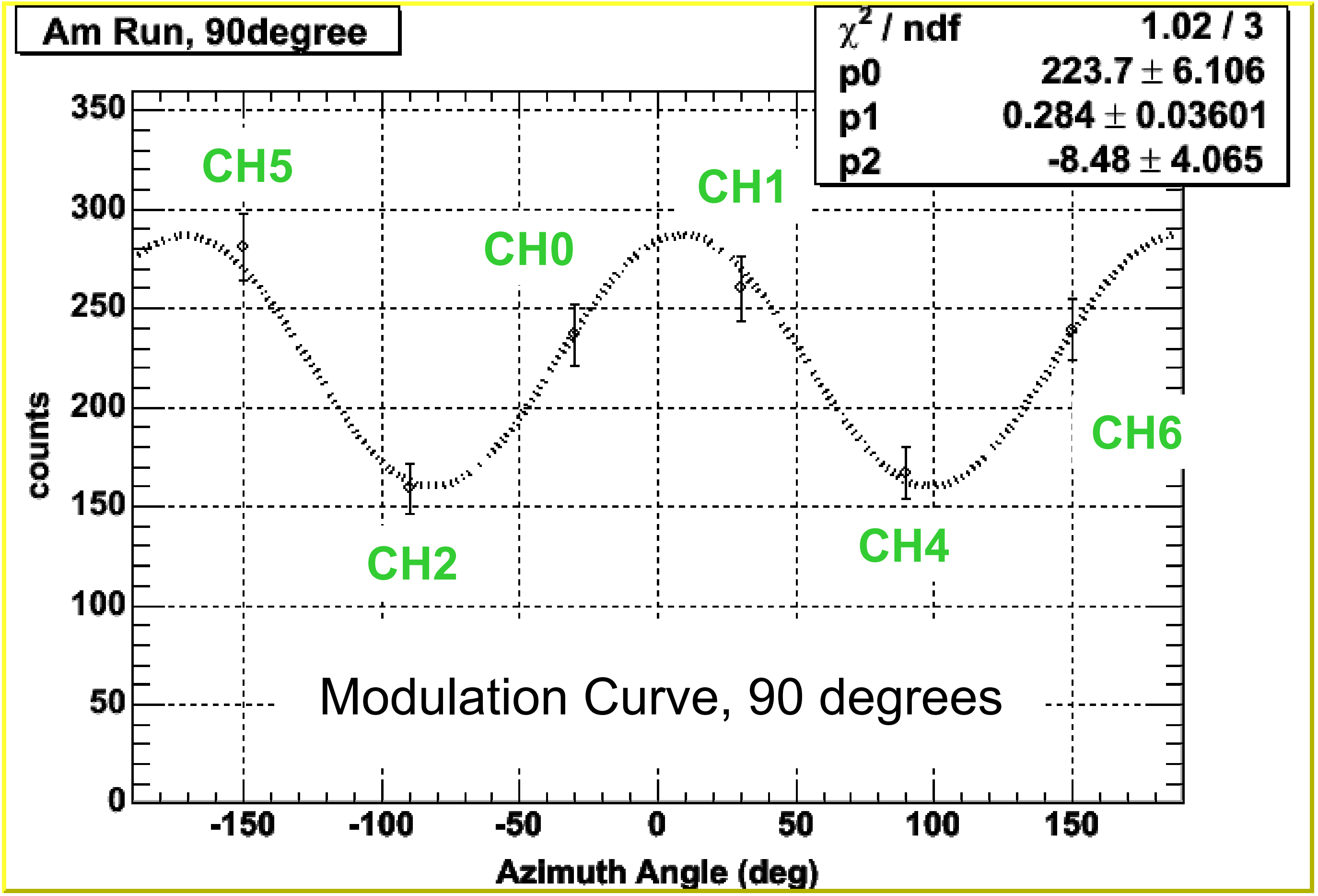
Polarization (7)

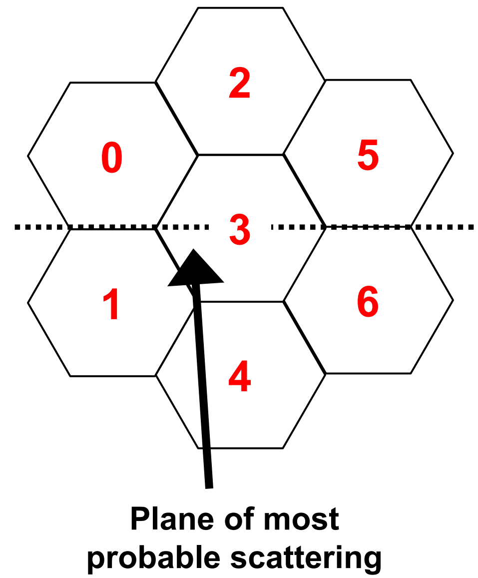




Modulation factor = 24.5% ± 3.9%
Direction of polarization = 3.7° ±4.1°

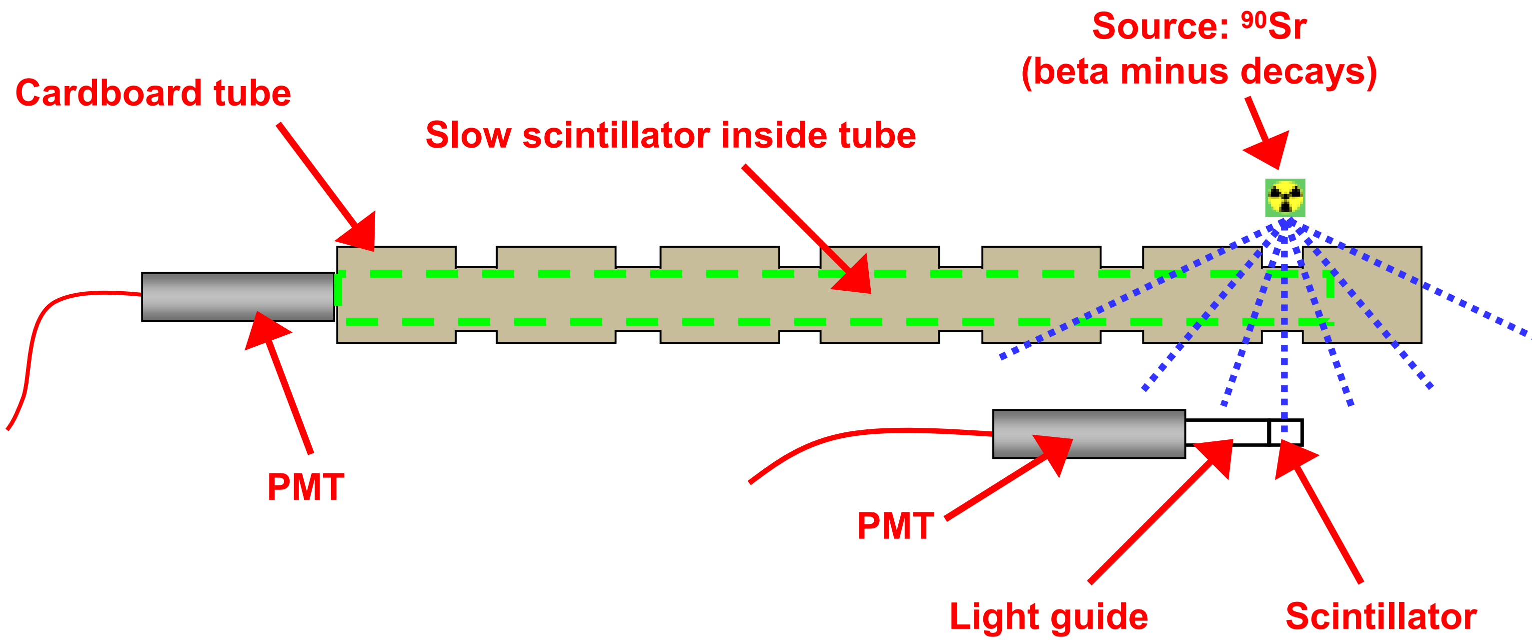
Polarization (7)





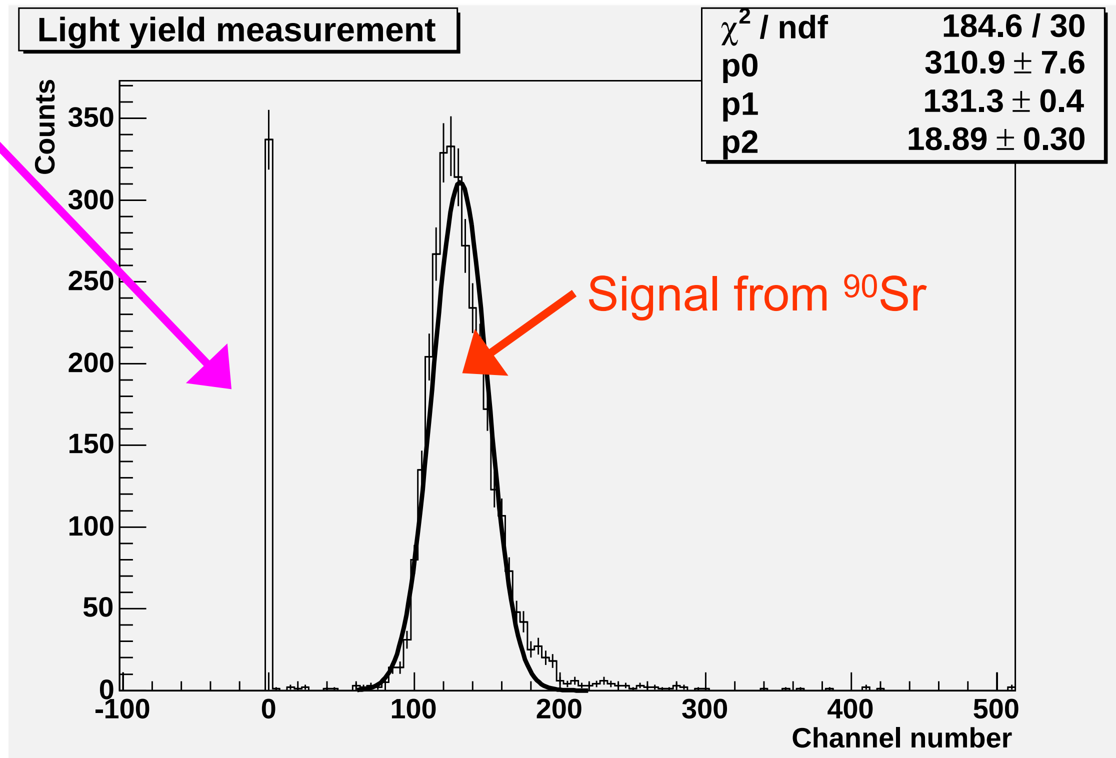
Modulation factor = 28.4% ± 3.6%
Direction of polarization = 81.5° ±4.1°

Light yield (1)



Light yield (2)

Spontaneous electron emission events from PMT and noise from electronics



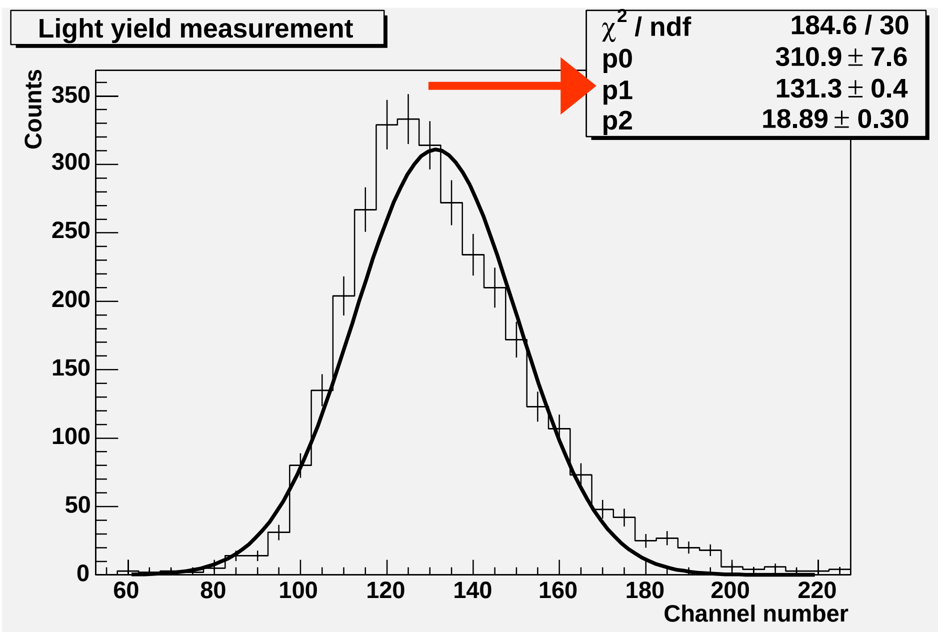
Energy deposition due to the Bethe-Bloch formula: -dE/dx = …

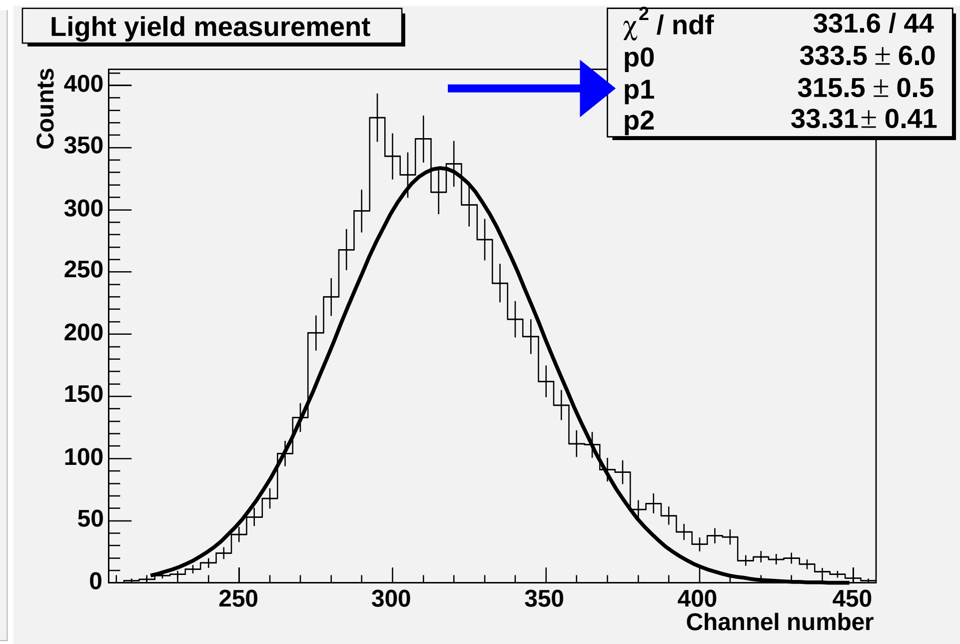
Electrons go through about 4 mm of scintillation material.

Figure of merit: channel number, proportional to the light yield!

Light yield (3)

Without VM2000 inside the slow scintillator





Top of the slow scintillator:

Peak at channel no. 131

Bottom of the slow scintillator:

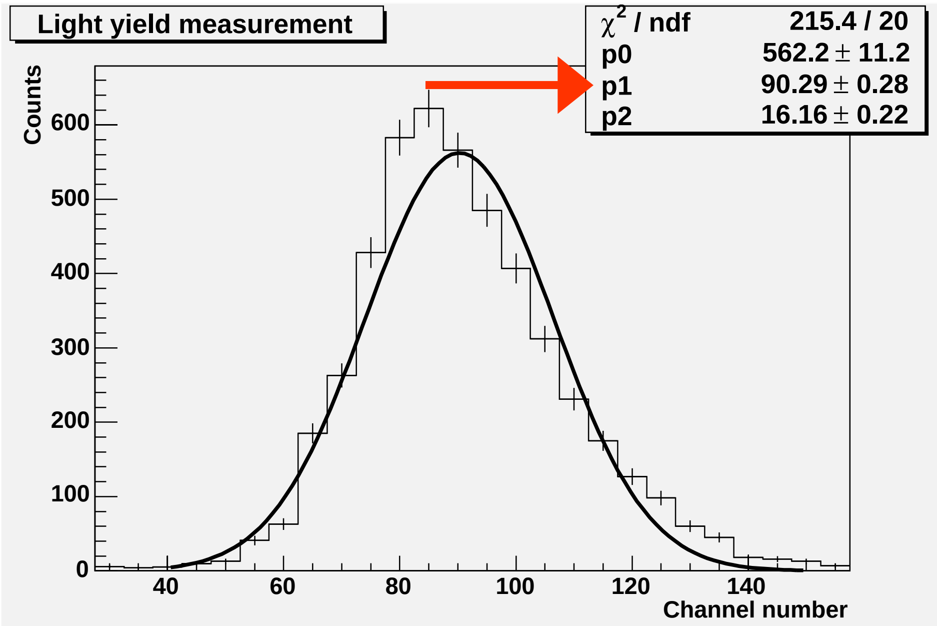
Peak at channel no. 315

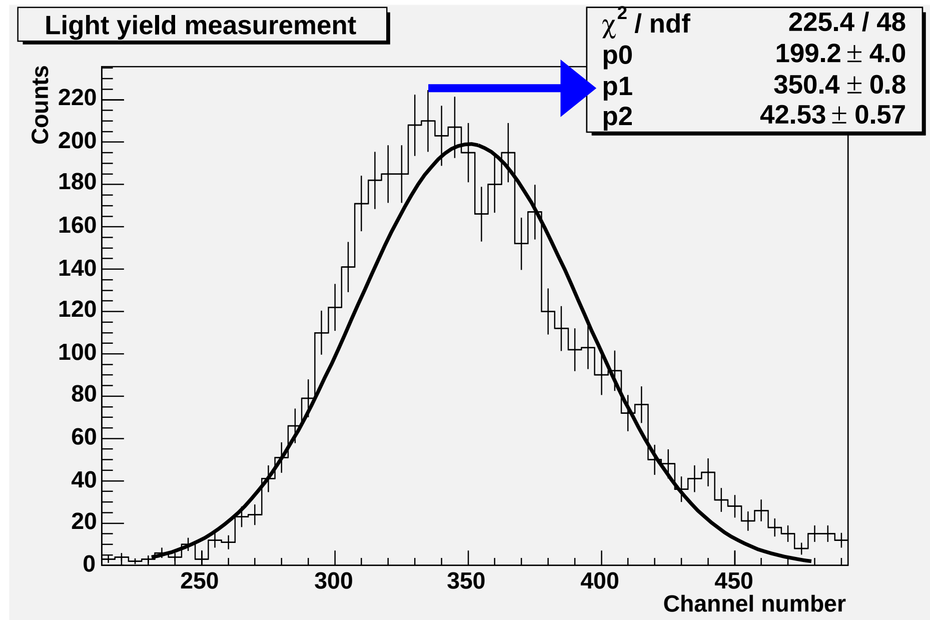
Ratio: 131 / 315 ≈ 0.42 ➔ about 58% of the photons lost

when the inside of the tube is NOT covered with VM2000

Light yield (4)

With VM2000 inside the slow scintillator





Top of the slow scintillator:

Peak at channel no. 90

Bottom of the slow scintillator:

Peak at channel no. 350

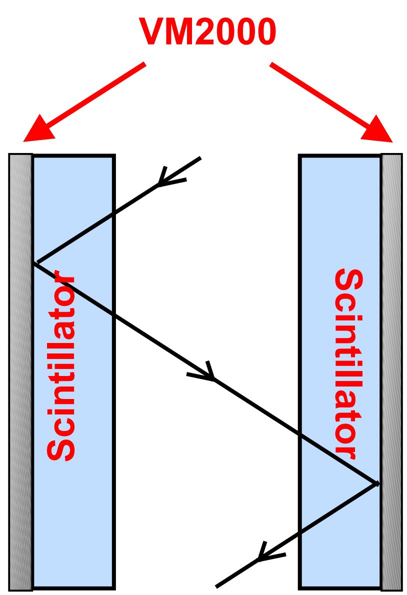
Ratio: 90 / 350 ≈ 0.26 ➔ about 74% of the photons lost

when the inside of the tube IS covered with VM2000

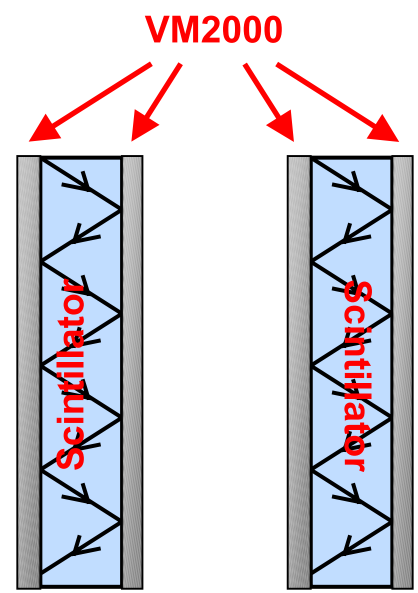
Light yield (5)

Light yield from the top of the slow scintillator lower with VM2000 inside the tube.

This is expected, since light must be reflected more times to reach the PTM.

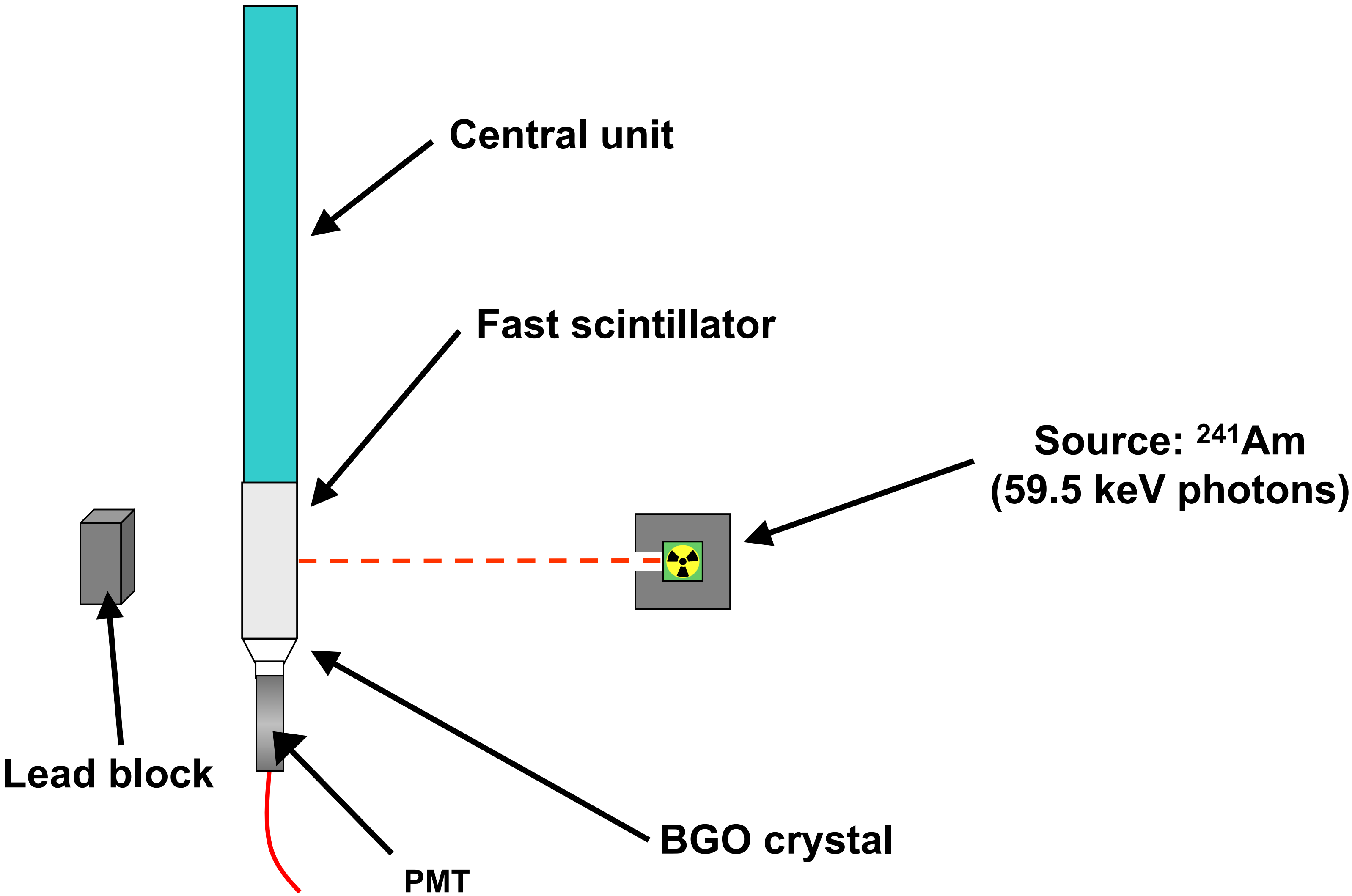


Without VM2000 inside the tube

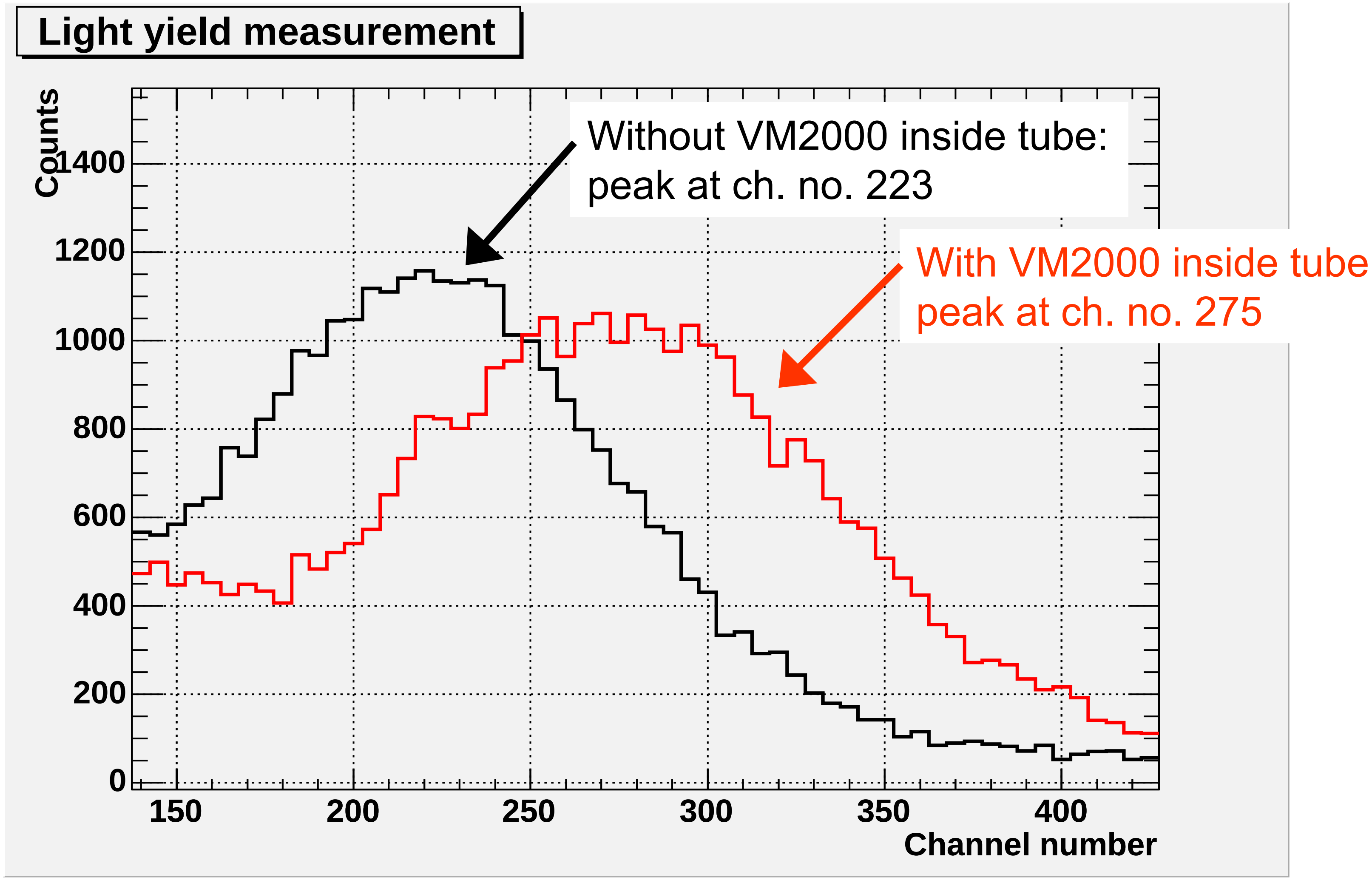


With VM2000 inside the tube

Light yield (6)



Light yield (7)



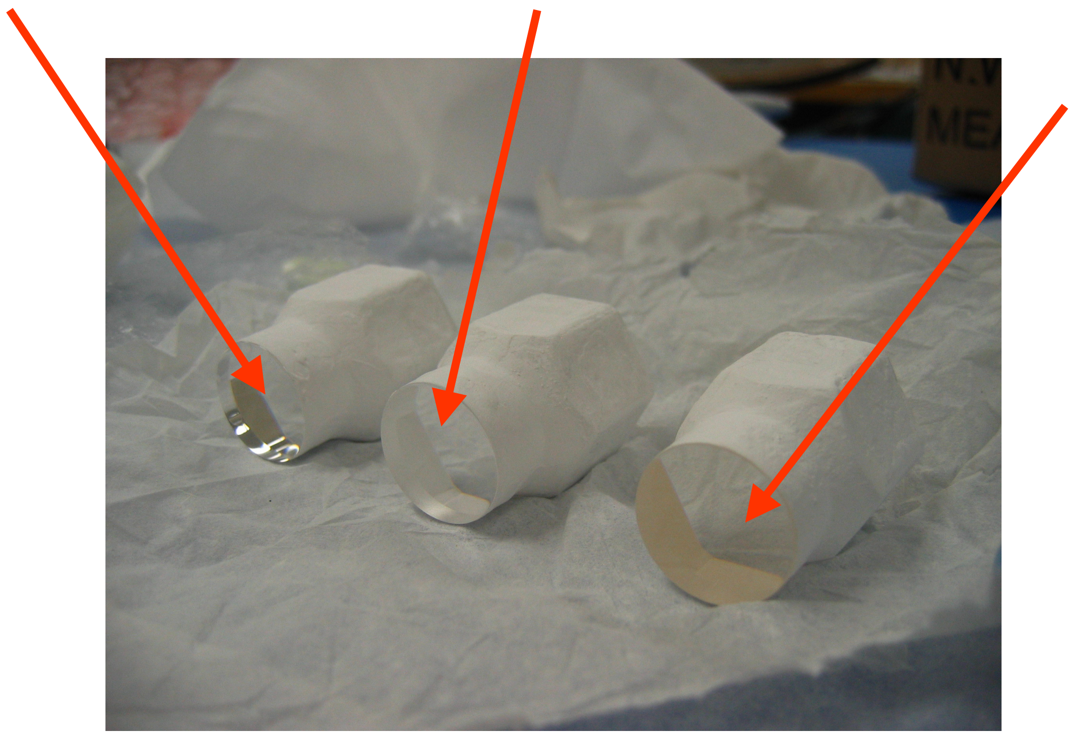
Light yield from fast scintillator increased by about 23% with VM2000 inside the tube

➔ use VM2000 inside the slow scintillator!

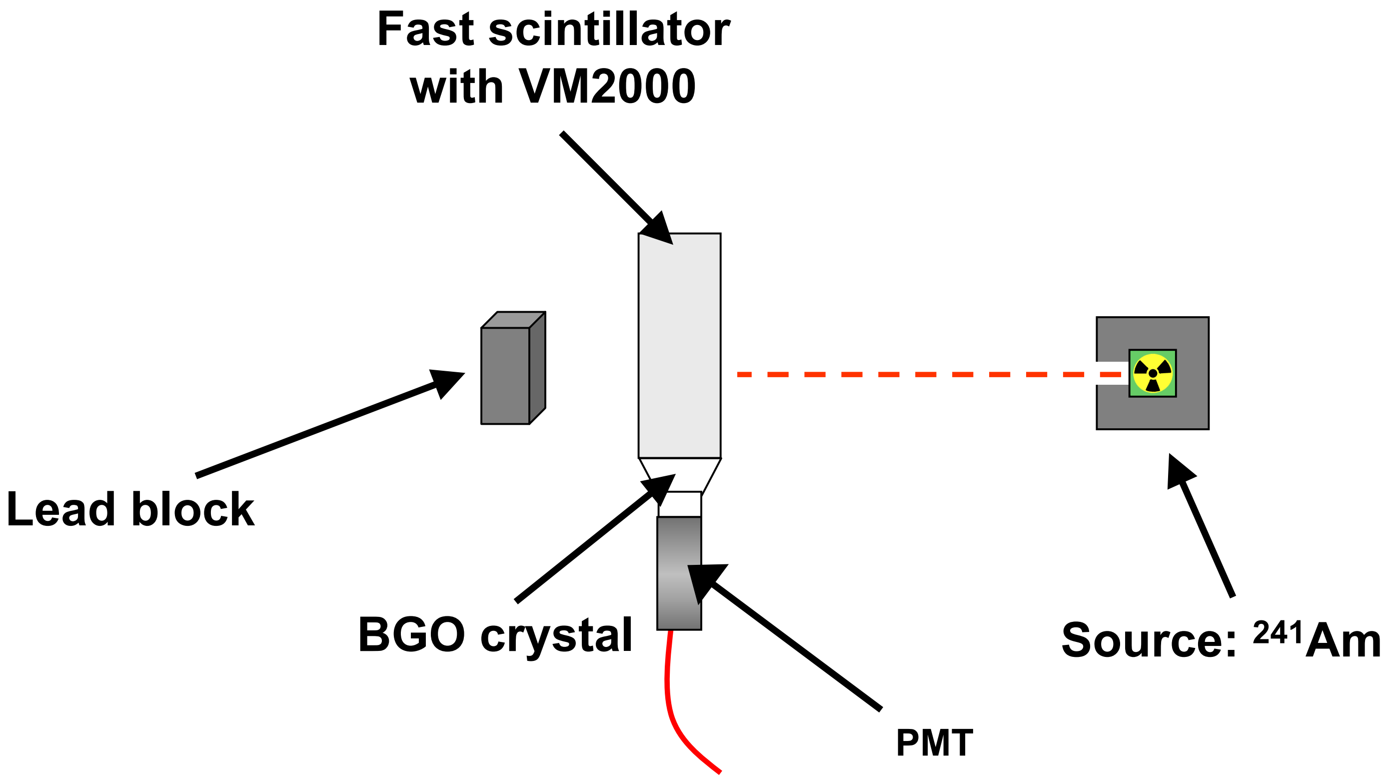
BGO crystal comparison (1)

Three BGO (bismuth germanate) crystals
with differently treated surfaces

Compare light yield from fast scintillator!



BGO crystal comparison (2)

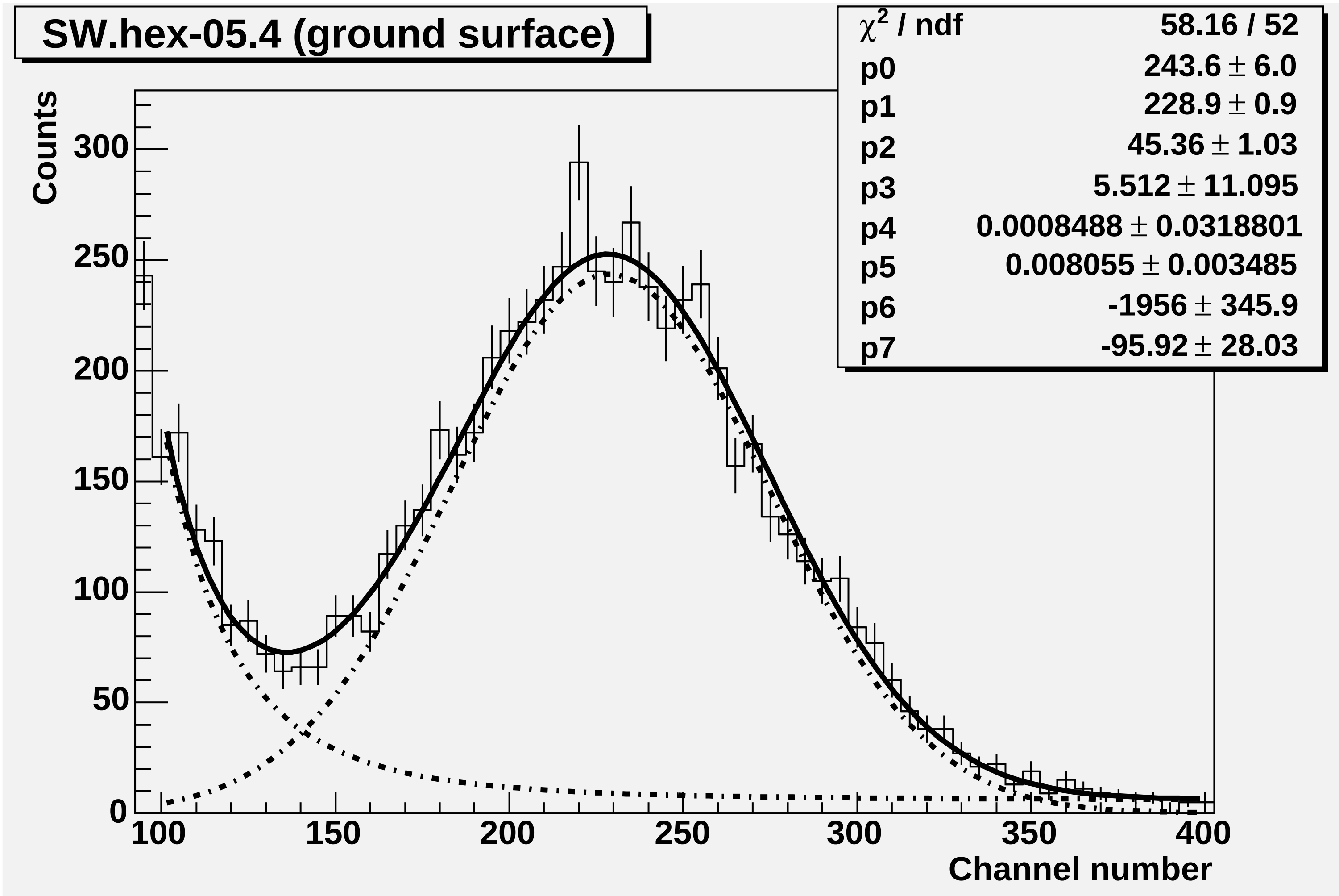


Fast scintillator irradiated with 59.5 keV photons.

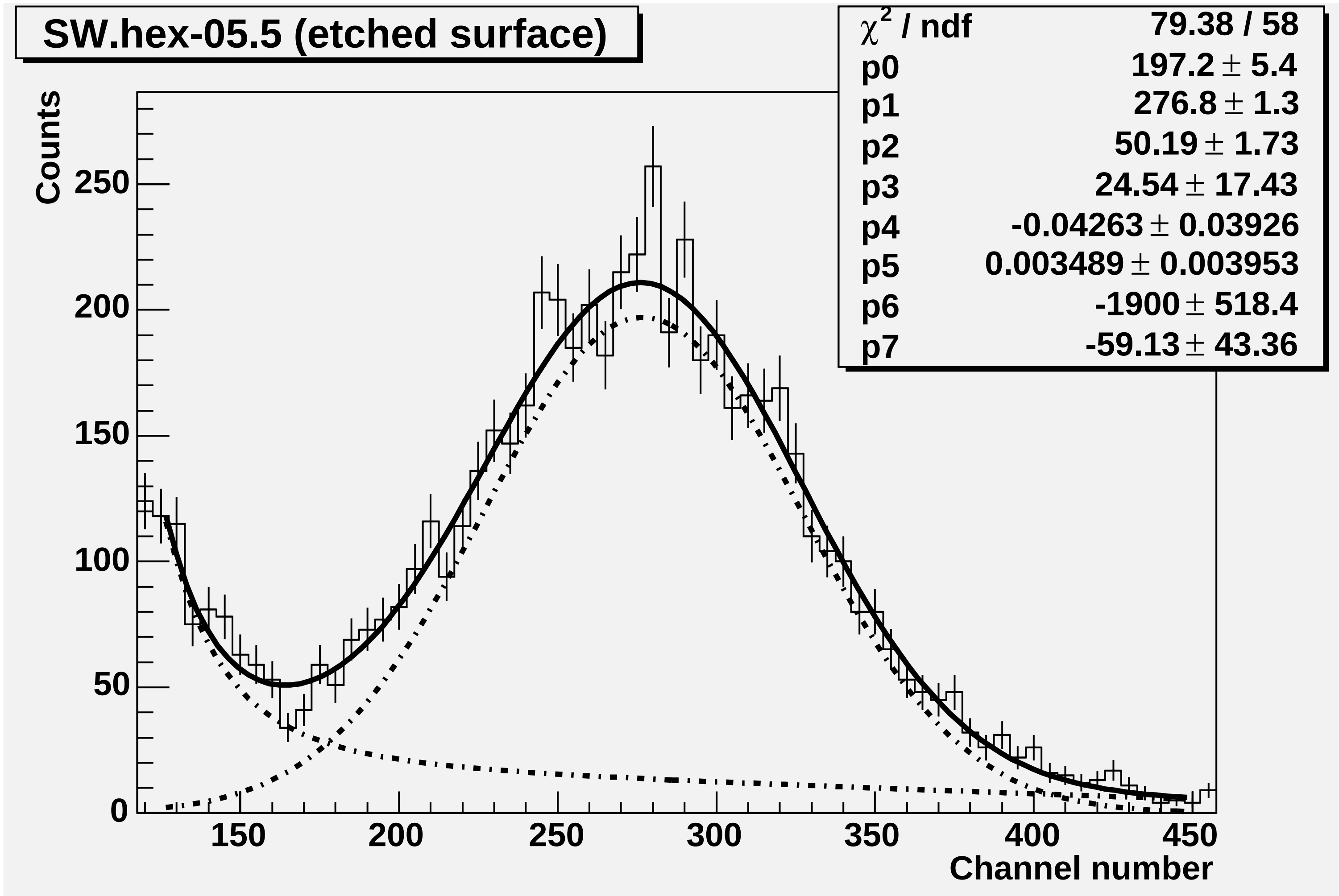
Light yield from the fast scintillator measured with all three BGO crystals.

Figure of merit: channel number, proportional to the light yield!

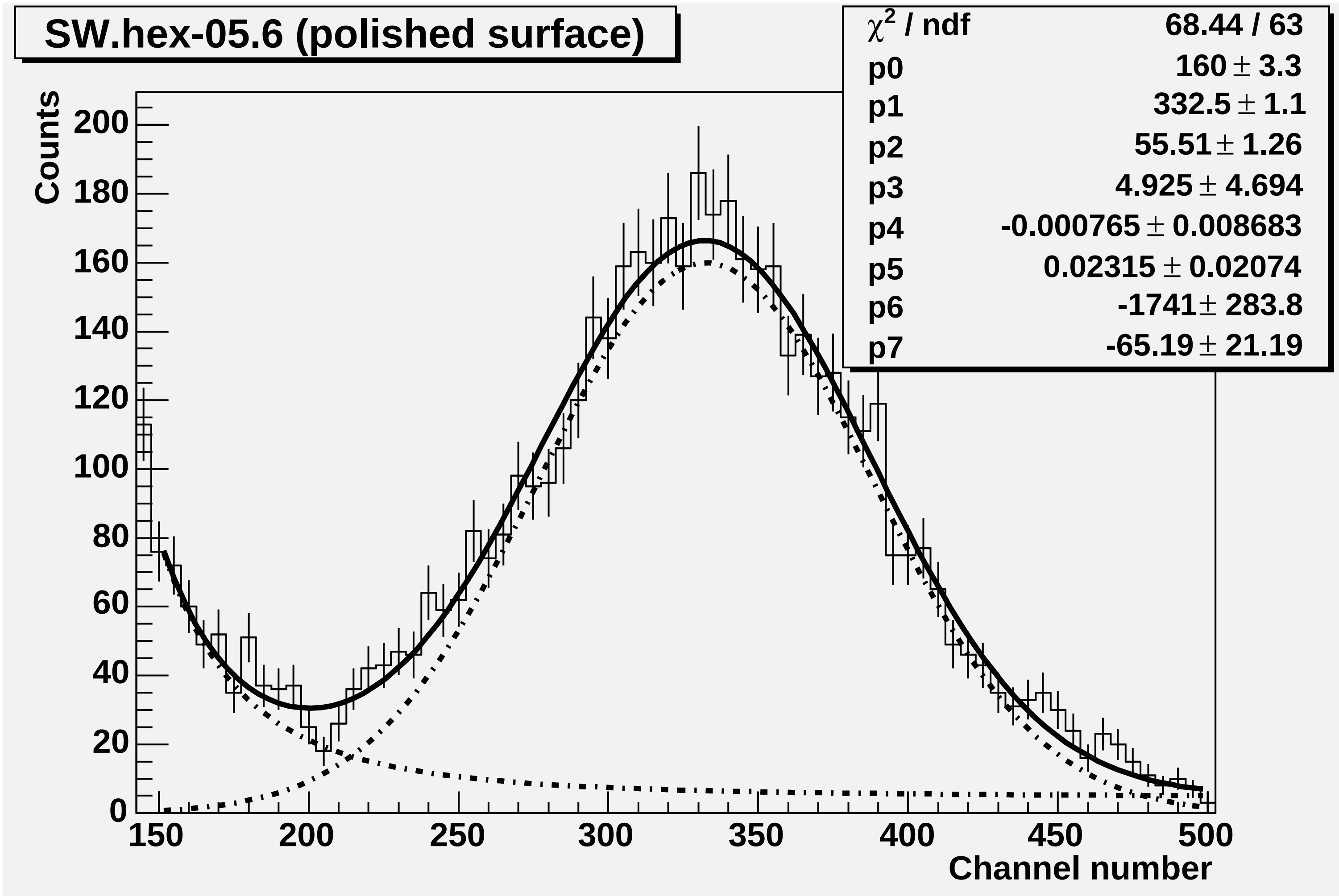
BGO crystal comparison



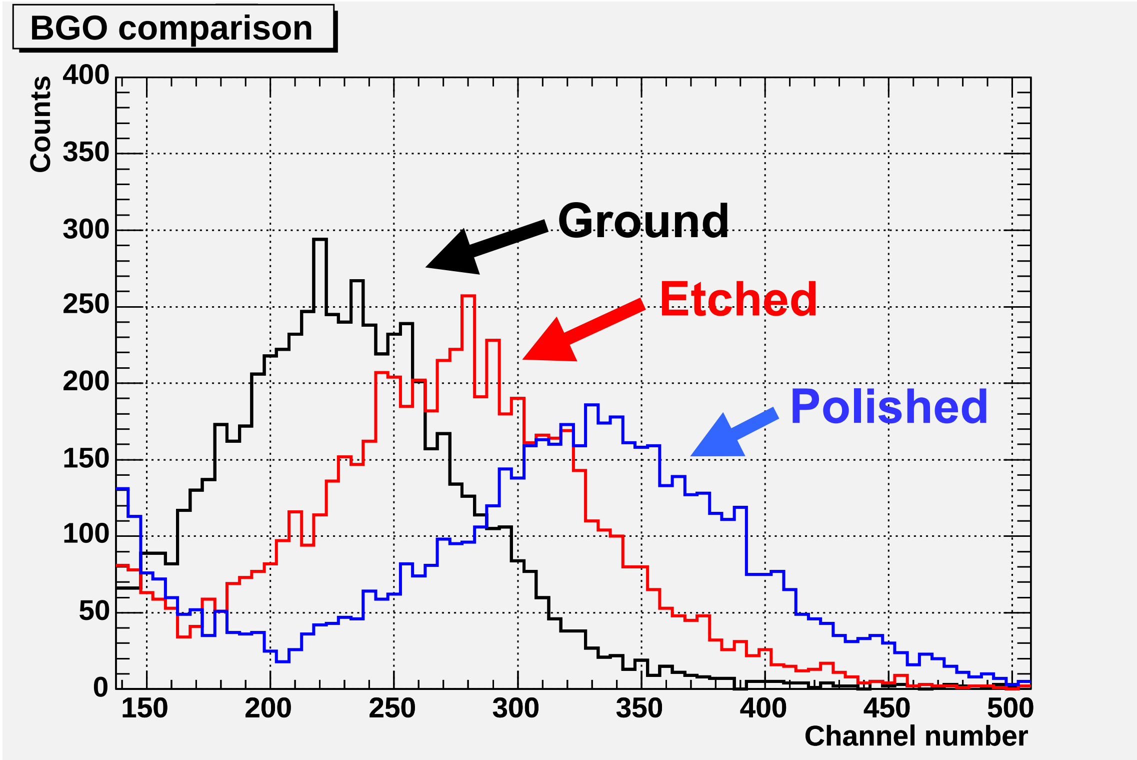
BGO crystal comparison



BGO crystal comparison



BGO crystal comparison (2)



Conclusion: Light yield from fast scintillator maximized with the polished BGO
➔ use polished BGO! (Even if it is a little more expensive…)

Polished	332.5 ± 1.3	45.3%	0.392

The End