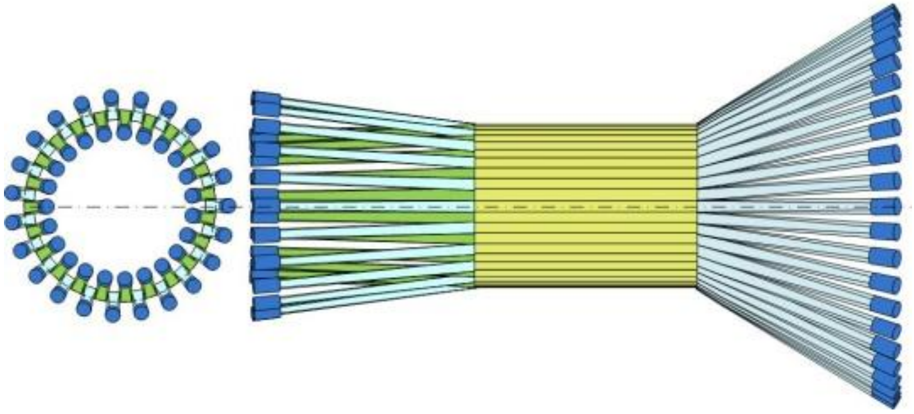
Time-of-flight detectors with plastic scitillators: Selected review, basic principles of operation and calibration.

V. Kuzmetsov
Seminar HEPD@PNPI,
March 10 2020

The GRAAL forward lead-scintillator wall (``Russian Wall”) V.Kouznetsov et al., NIM A 487 (2002) 396.

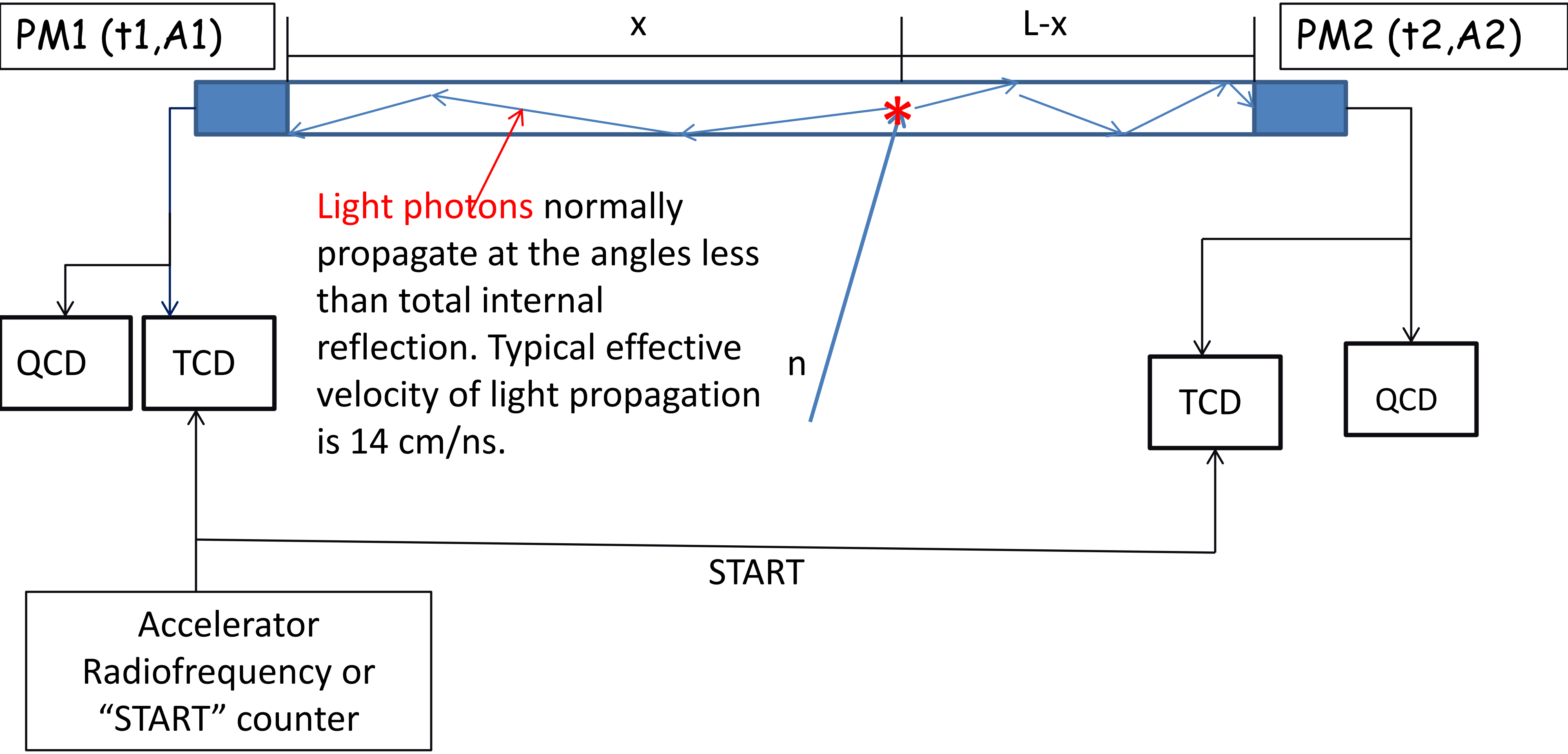
The CLAS12 Central Time-of-flight system,
Time-of-Flight resolution of the CTOF@CLAS12 prototype counter equipped with magnetic-resistant fine-mesh photomultiplier tubes
A. Ni , V. Kuznetsov , S. Chebotarev, H. Dho, A. Kim, W. Kim, E. Milman M. Lee, T. Yang . **JINST 5 (2010) P11001**
DOI: 10.1088/1748-0221/5/11/P11001



- Basics
- Review of selected detectors
- Detectors for neutrons
-Plastic scitintillators
-Time-of-flight resolution and some notes on photodetectors
- Specific features of neutron detection
- Methods to measure TOF resolution
- Calibration procedures: importance and practical examples
- The NeuLand spectrometer at GSI: state-of-art
-The “Russian Wall” at GRAAL – history, design and some photos.

Basic principles of operation

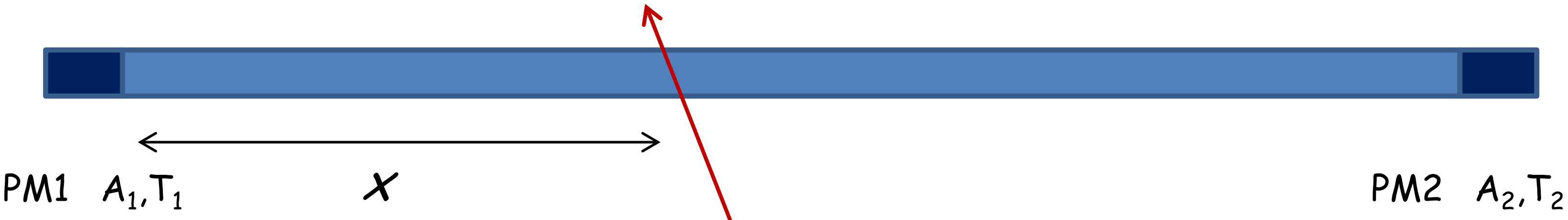
Scintilltor counter is well polished and wrapped round with reflective material. Scintillation light is readout by two phototubes attached to both end by mean of optical grease or optical glue. Pulse heights A1 and A2 are digitized by QDCs, PM arriving times t1 and t2 are measured by TDCs.



Light photons normally propagate at the angles less than total internal reflection. Typical effective velocity of light propagation is 14 cm/ns.

Accelerator Radiofrequency or “START” counter

Basics



$$t_1 = r_1 TDC_1 = TOF + {}^{x}/_{V_{eff}} + Const1$$

$$t_2 = r_2 TDC_2 = TOF + {}^{(L-x)}/_{V_{eff}} + Const2$$

$$x = {}^{(t_1 - t_2}/_{2V_{eff}} + Const3$$

$$TOF = {}^{(t_1 + t_2)}/_{2} + Const4$$

- r1 and r1 are LSB of used TDCs;

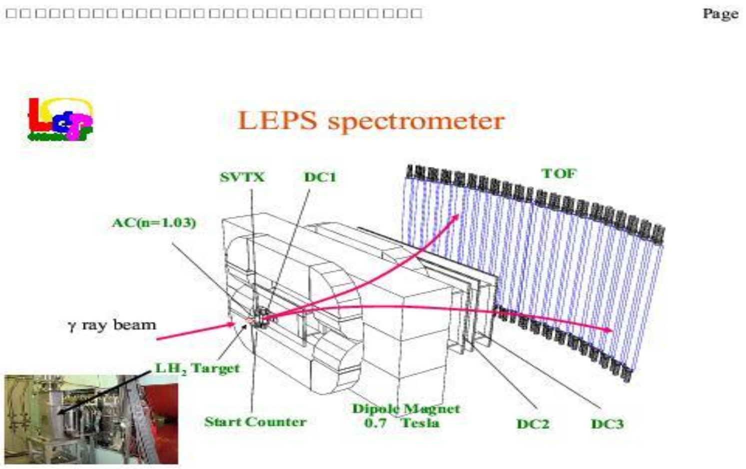
- Veff is the effective speed of light propagation in a scintillator unit;

- Consts are due to cable, electronic and other delays;

Const1,2,3,4 are determined in the caliration procedure

Time-Of-Flight Detectors

Measurement of time-of-flight (TOF) provides the possibility to determine the particle hit position and kinetic energy -> to reconstruct the momentum.



Typical design is an array of long scintillator counters viewed from both sides by photomultipliers through (not mandatory) light guides.

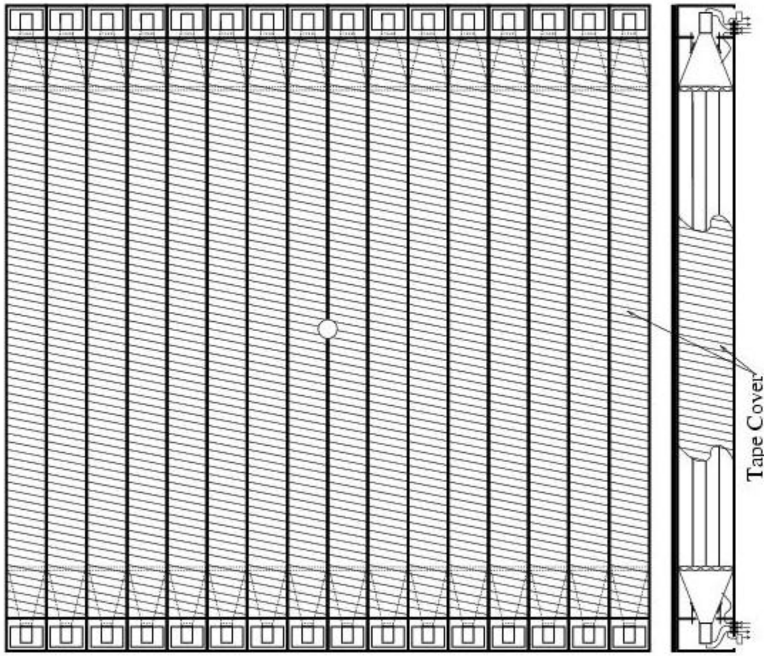
Tens of such detectors were and are in operation

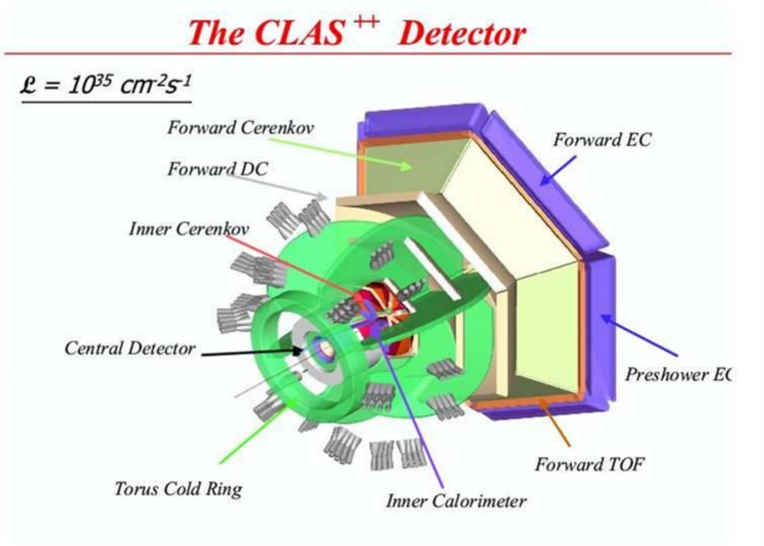
CLAS, GRAAL, CLAS12 (CTOF and FTOF), PANDA ….

Time-of-flight detectors with the option of neutron detection

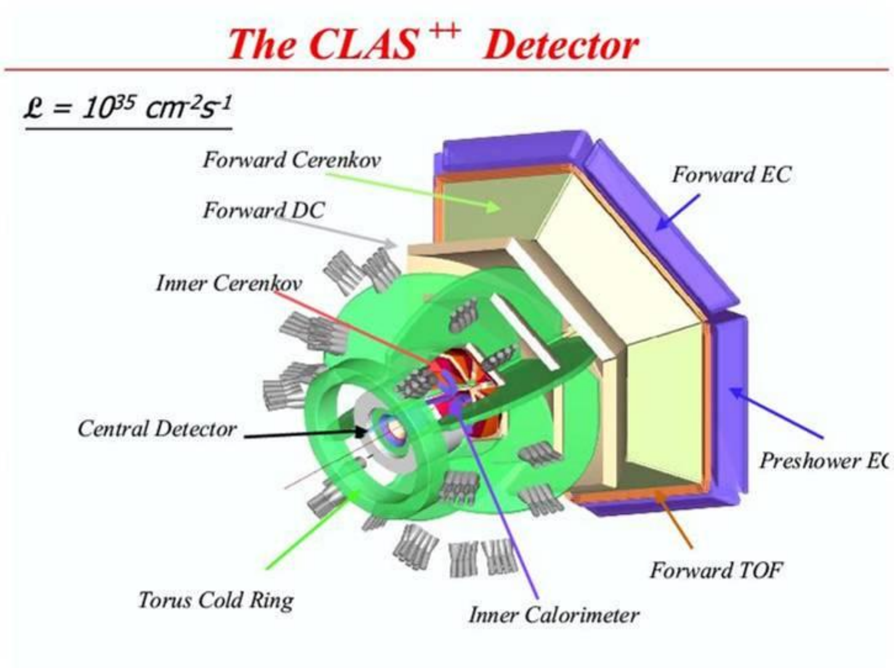
Sandwich lead-scintillator detectors (CLAS, GRAAL, CLAS12)

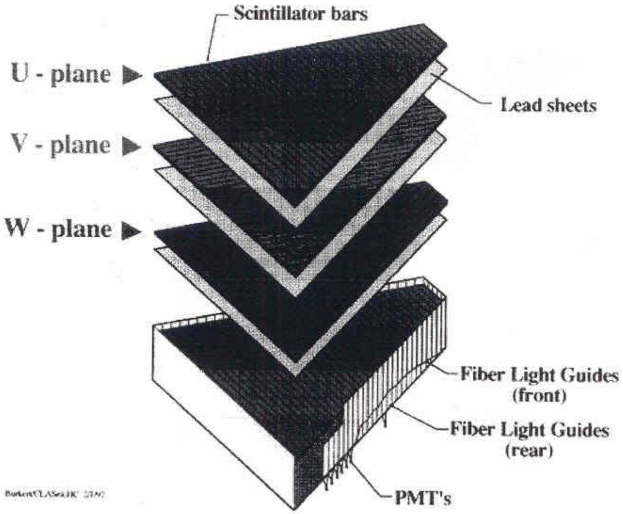
- **Option of a neutron and photon detection**
- Combination of several layers of scintillator with lead plates between them adds the option of photon detection and increases an efficiency of neutron detection.
- A thin scintllator veto-counter and wire chambers at the front of the detector serve to discriminate between charged and neutral particles.
- Main function: detection and identification both charged particles of photons and neutrons.





Hall B (Jlab, USA) Electromagnetic Calorimeter

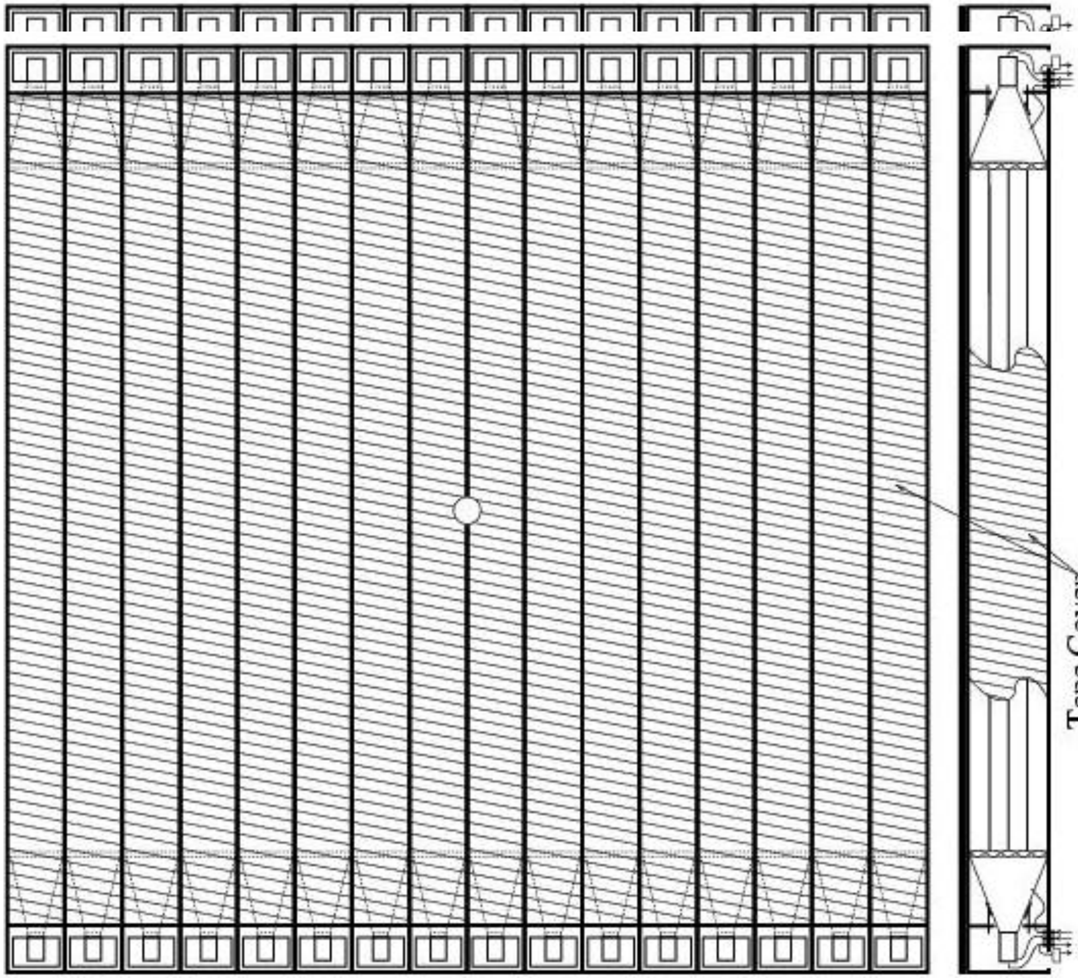




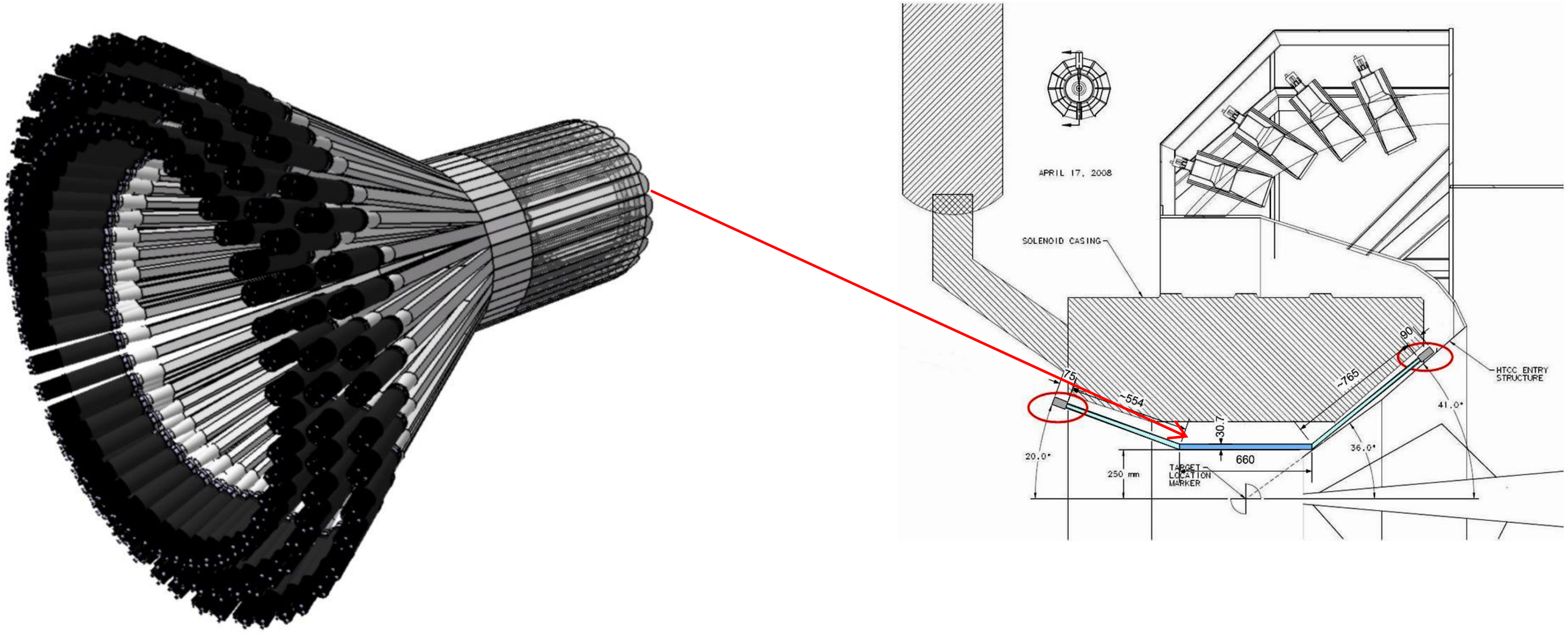
GRAAL forward lead-scintillator wall (``Russian Wall”)

V.Kouznetsov et al., NIM A 487 (2002) 396.

An assembly of 16 modules. Each module is a sandwich of four 3000x40 mm2 bars with 3 mm thick lead plates between them. A 25 mm thick steel plate at the front of the module acts as a main converter and as a module support.



CLAS12
Central Neutron Detector

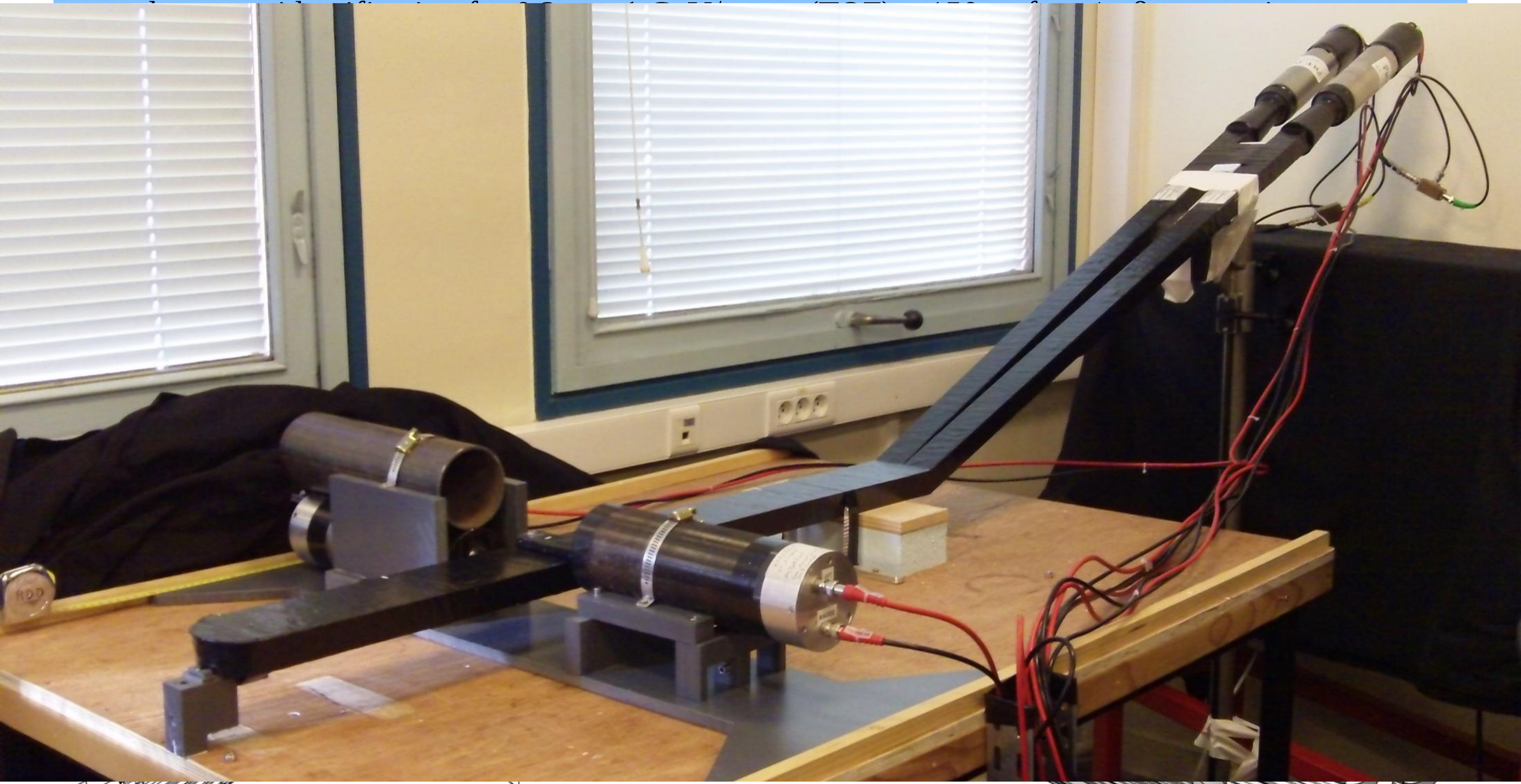


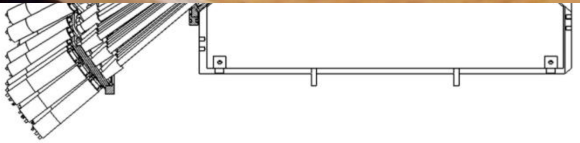
Silvia Niccolai, IPN Orsay
CLAS Collaboration Meeting, JLab, 6-22-2011

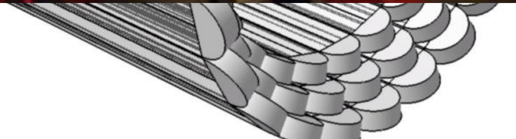
Motivation, constraints and design

Motivation: detect recoil neutrons of **nDVCS** **(80% go in CD)**

The CND must ensure:







Plastic Scintillators

A plastic scintillator consists of a solid solution of organic scintillating molecules in a polymerized solvent with scintillation advent. The ease with which they can be shaped and fabricated makes plastic scintillators an extremely useful form of organic scintillator. Our plastic scintillators are produced in a wide variety of shapes and sizes.

Two main types of a polymerized solvent:

-Polyviniltolyene (поливинилтолуол)
- Polysterene (полистирол)

Platic Scintillators on the base of polyviniltolyene

France
Saint-Gobain Cristaux
Z. I . Mayencin
2, rue des Essarts
38610 Gières
France
sales.europe.SGCD@saint-gobain.com
customer.service.SGCD@saint-gobain.co

USA
ELJEN TECHNOLOGY
1300 W. Broadway
Sweetwater, Texas 79556, United States
Toll Free (USA and Canada): (888) 800-8771
Tel: (325) 235-4276
Fax: (325) 235-0701
Email: eljen@eljentechnology.com

BC-400,BC-404,BC-408,BC-412,BC-416

Premium Plastic Scintillators

The premium plastic scintillators described in this data sheet include those with the highest light output, as well as the most economical (BC-416). The chart below will direct you to the scintillator suitable for your energy application.

	BC-400	BC-404	BC-408	BC-412	BC-416
Radiation Detected					
<100keV X-rays			X		
100keV to 5MeV gamma rays				X	
>5MeV gamma rays	X				
Fast neutrons				X	X
Alphas, betas	X	X	X		
Charged particles,cosmic rays, muons, protons, etc.			X	X	X
Principal Uses/Applications	general purpose	fast counting	TOF large area	large area	large area economy
Scintillation Properties					
Light Output, %Anthracene	65	68	64	60	38
Rise Time, ns	0.9	0.7	0.9	1.0	–
Decay Time (ns)	2.4	1.8	2.1	3.3	4.0
Pulse Width, FWHM, ns	2.7	2.2	~2.5	4.2	5.3
Wavelength of Max. Emission, nm	423	408	425	434	434
Light Attenuation Length, cm*	160	140	210	210	210
Bulk Light Attenuation Length, cm	250	160	380	400	400
Atomic Composition					
No. H Atoms per cc ($x10^{22}$)	5.23	5.21	5.23	5.23	5.25
No. C Atoms per cc ($x10^{22}$)	4.74	4.74	4.74	4.74	4.73
Ratio H:C Atoms	1.103	1.100	1.104	1.104	1.110
No. of Electrons per cc ($x10^{23}$)	3.37	3.37	3.37	3.37	3.37

*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

General Technical Data –

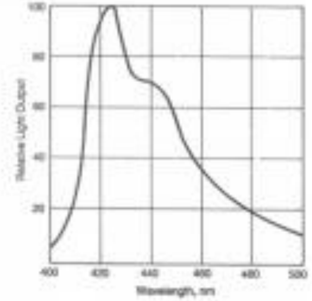
Base	Polyvinyltoluene
Density [g/cc]	1.023
Expansion Coefficient (per°C,<67°C)	$7.8X10^{-5}$
Refractive Index	1.58
Softening Point	70°C
Vapor Pressure	May be used in vacuum
Solubility	Soluble in aromatic solvents, chlorinated solvents, acetone, etc. Unaffected by water, dilute acids, lower alcohols, alkalis and pure silicone fluids or grease.
Light Output	At +60°C = 95% of that at+20°C. Independent of temperature from -60°C to +20°C

BC-400,BC-404,BC-408,BC-412,BC-416

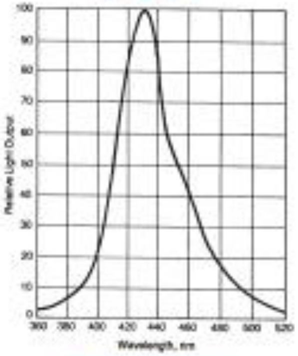
Premium Plastic Scintillators

Emission Spectra

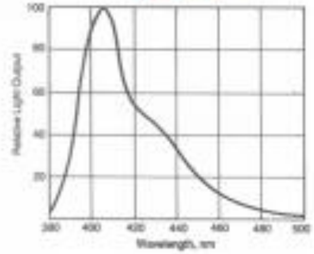
BC-400



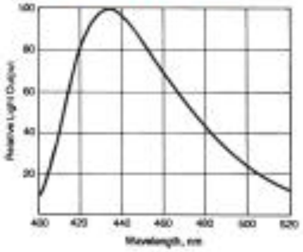
BC-408



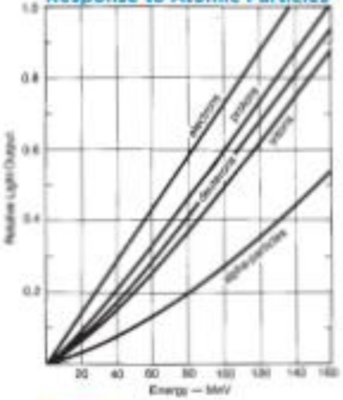
BC-404



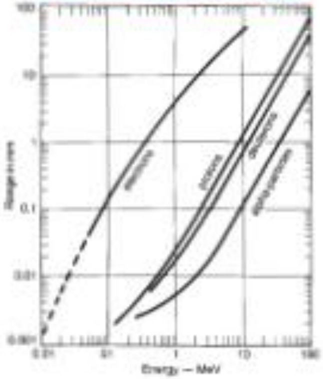
BC-412 & BC-416



Premium Plastic Scintillator Response to Atomic Particles



Range of Atomic Particles in Premium Plastic Scintillator



SAINT-GOBAIN

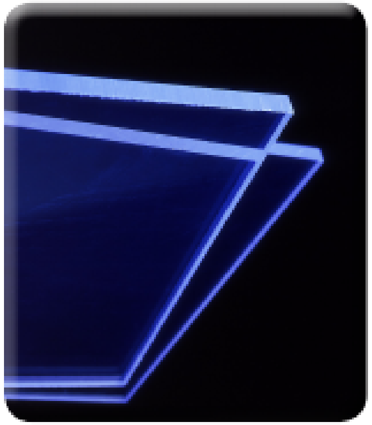
BC-418, BC-420, BC-422
Premium Plastic Scintillators

The premium plastic scintillators described in this data sheet are intended for use in ultra-fast timing and ultra-fast counting applications. BC-418 and BC-422 are recommended for use in small sizes, i.e. when any dimension is less than 4" (100mm). BC-420 is substantially less expensive than BC-418.

	BC-418	BC-420	BC-422
Scintillation Properties			
Light Output, %Anthracene	67	64	55
Rise Time, ns	0.5	0.5	0.35
Decay Time (ns)	1.4	1.5	1.6
Pulse Width, FWHM, ns	1.2	1.3	1.3
Wavelength of Max. Emission, nm	391	391	370
Light Attenuation Length, cm*	NA**	140	NA**
Bulk Light Attenuation Length, cm	100	110	8
Atomic Composition			
No. H Atoms per cc ($x10^{22}$)	5.21	5.21	5.19
No. C Atoms per cc ($x10^{22}$)	4.74	4.74	4.71
Ratio H:C Atoms	1.100	1.100	1.102
No. of Electrons per cc ($x10^{23}$)	3.37	3.37	3.34

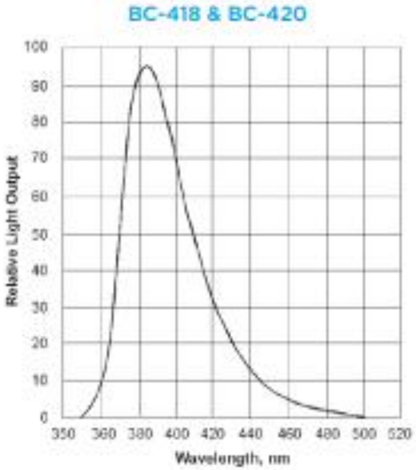
*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

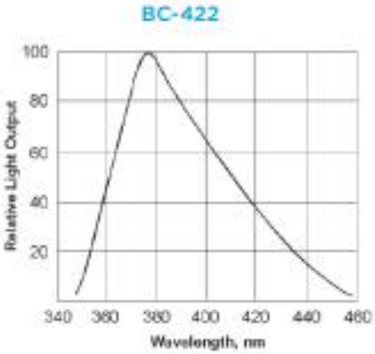
** Scintillator recommended for use in small sizes; therefore, the 1/e attenuation length values are not applicable.



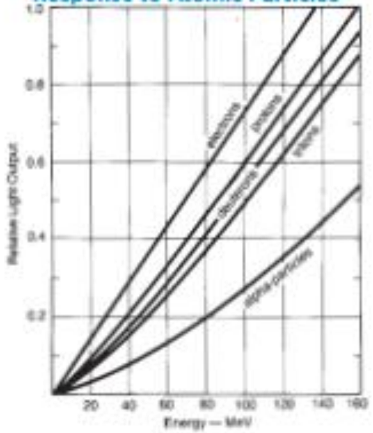
General Technical Data –

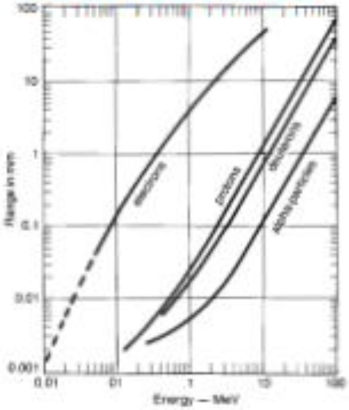
Base	Polyvinyltoluene
Density [g/cc]	1.032
Expansion Coefficient (per°C,<67°C)	$7.8X10^{-5}$
Refractive index	1.58
Softening Point	70°C
Vapor Pressure	May be used in vacuum
Solubility	Soluble in aromatic solvents, chlorinated solvents, acetone, etc. Unaffected by water, dilute acids, lower alcohols, alkalis and pure silicone fluids or grease.
Light Output	At +60°C = 95% of that at+20°C. Independent of temperature from -60°C to +20°C


BC-418 & BC-420

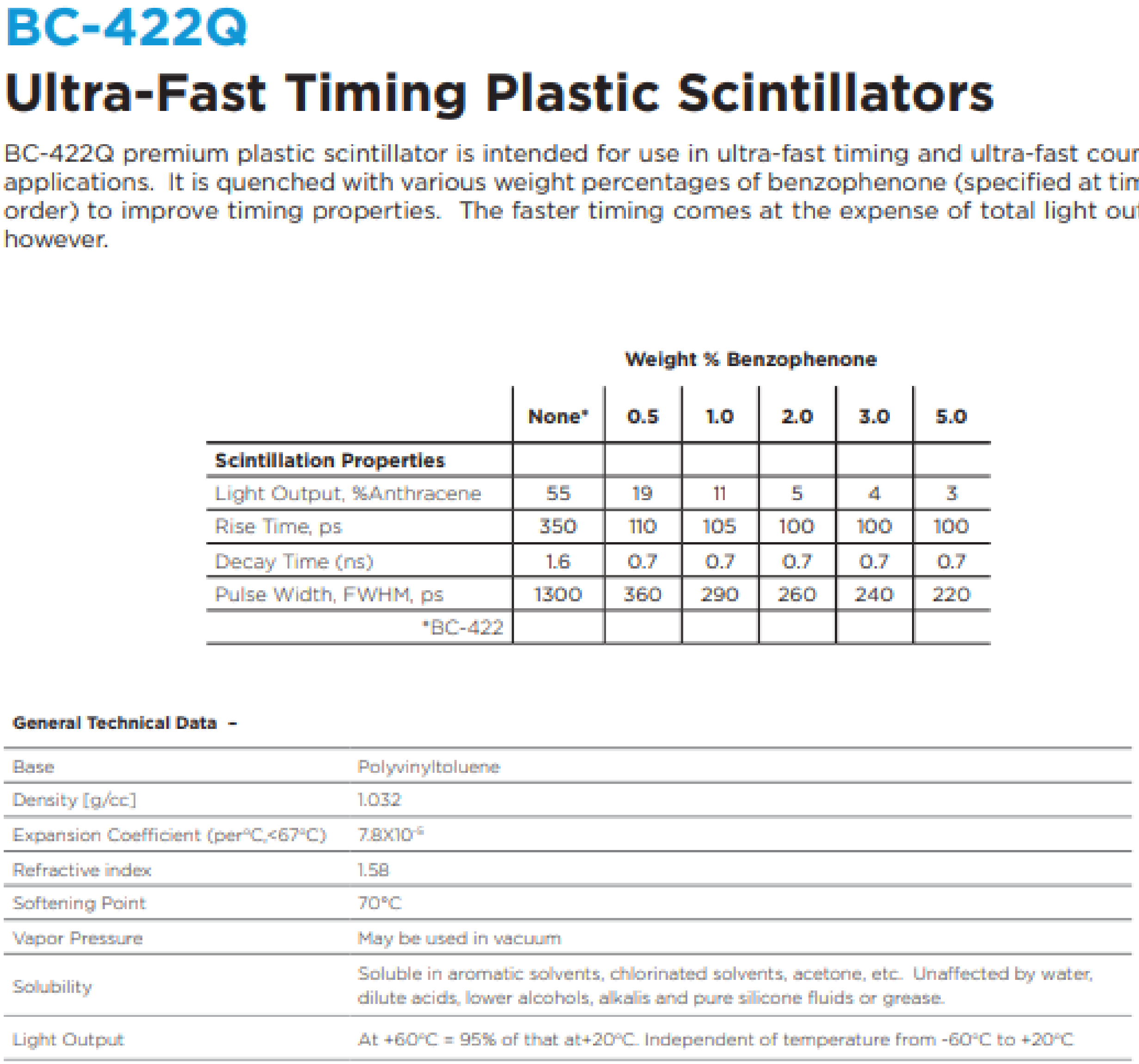

BC-422

Atomic Particles Response


Premium Plastic Scintillator Response to Atomic Particles


Range of Atomic Particles in Premium Plastic Scintillator

SAINT-GOBAIN



BC-422Q

Ultra-Fast Timing Plastic Scintillators

BC-422Q premium plastic scintillator is intended for use in ultra-fast timing and ultra-fast counting applications. It is quenched with various weight percentages of benzophenone (specified at time of order) to improve timing properties. The faster timing comes at the expense of total light output, however.

	Weight % Benzophenone					
	None*	0.5	1.0	2.0	3.0	5.0
Scintillation Properties						
Light Output, %Anthracene	55	19	11	5	4	3
Rise Time, ps	350	110	105	100	100	100
Decay Time (ns)	1.6	0.7	0.7	0.7	0.7	0.7
Pulse Width, FWHM, ps	1300	360	290	260	240	220
*BC-422						

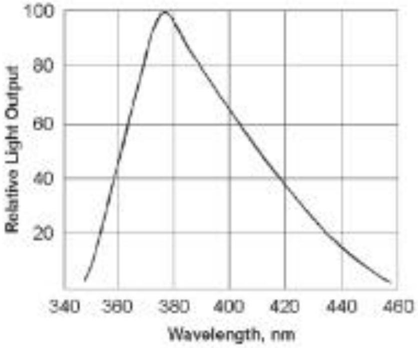
General Technical Data -

Base	Polyvinyltoluene
Density [g/cc]	1.032
Expansion Coefficient (per°C,<67°C)	7.8X10^{-5}
Refractive index	1.58
Softening Point	70°C
Vapor Pressure	May be used in vacuum
Solubility	Soluble in aromatic solvents, chlorinated solvents, acetone, etc. Unaffected by water, dilute acids, lower alcohols, alkalis and pure silicone fluids or grease.
Light Output	At +60°C = 95% of that at+20°C. Independent of temperature from -60°C to +20°C

Bulk attenuation length ~ 10 cm?

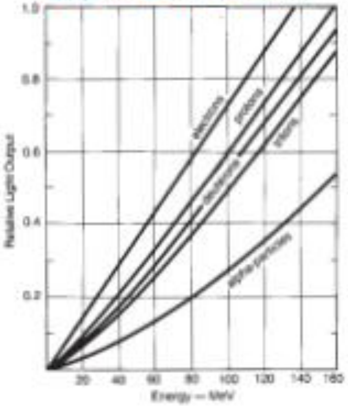
BC-422Q
Ultra-Fast Timing Plastic Scintillators

Emission Spectra

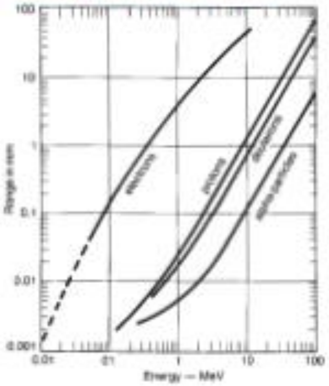


Atomic Particles Response

Premium Plastic Scintillator Response to Atomic Particles



Range of Atomic Particles in Premium Plastic Scintillator



Saint-Gobain Crystals

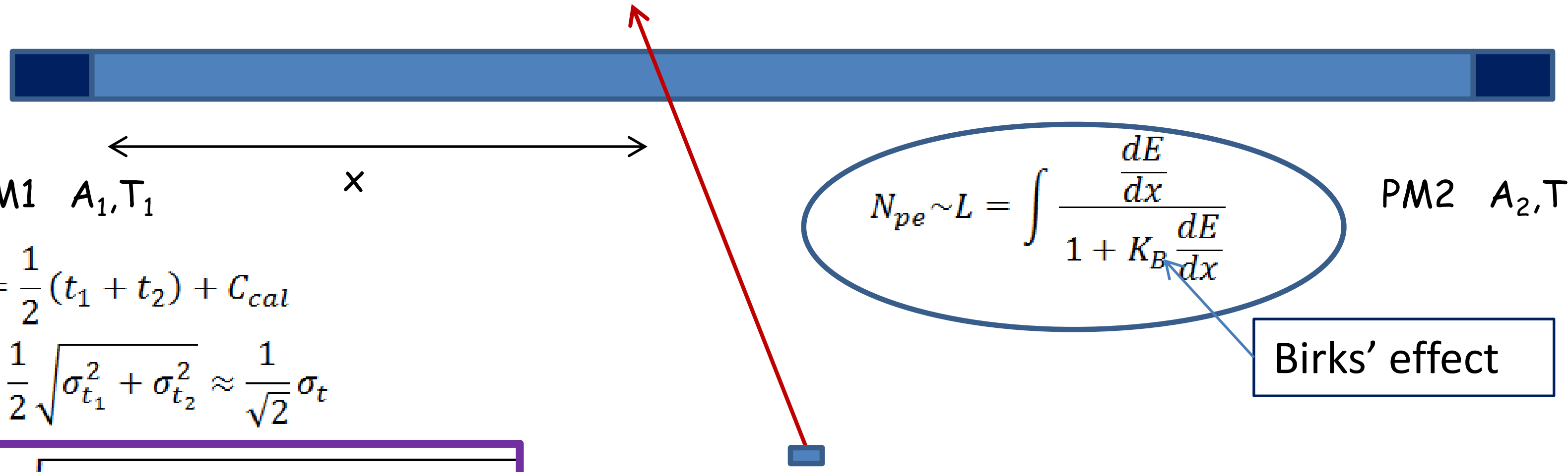
Polysterene scintillators

- Kharkov Institute for Single Crystals;
-Protvino;
- Dubna;

?

Time-of-Flight resolution and some notes on Photodetectors

Some basics for TOF detectors



$$TOF = \frac{1}{2}(t_1 + t_2) + C_{cal}$$

$$\sigma_{TOF} = \frac{1}{2}\sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2} \approx \frac{1}{\sqrt{2}}\sigma_t$$

$$\boxed{\sigma_t = \sqrt{\frac{\sigma_{sc}^2 + \sigma_{LT}^2 + \sigma_{PM}^2}{N_{pe}} + \sigma_{el}^2}}$$

$$N_{pe} \sim L = \int \frac{\frac{dE}{dx}}{1 + K_B \frac{dE}{dx}}$$

Birks' effect

The number of photoelectrons is defined by:
- deposited energy
- **quality of scintillator material** (light production, transparency);
- quality of polishing and wrapping;
- light collection by light guides and PMs

- light decay constant σ_{sc} for BC408 is 2.1 ns;
- light transportation uncertainty σ_{LT} is ~1.8ns $\sqrt{x}$
- transit time spread σ_{PM} (TTS) depends on phototubes and varies from 0,1 to 3 ns

Birks effect

Plastic scintillator does not respond linearly to the ionization density. This non-linear response of
scintillator called Birks' effect . The semi-empirical Birks' formula is

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_b \frac{dE}{dx}} ,$$

where *L is the scintillation light production, L0 is the specific light production at low ionization* densities (i.e. the light produced by a relativistic minimum-ionizing particle per a unit of deposited energy), *x is a coordinate along the particle track inside a scintillator volume, and kb is Birks' con*stant, which depends on scintillation material and can be determined empirically1 . For minimum ionizing particles (MIPs) *dE dx is constant. The light output generated by MIPs is proportional to*
the energy deposited in a scintillation bar *ΔE. Due to Birks' effect, slow protons which stop* inside a detector, produce less light per unit of deposited energy than relativistic minimum-ionizing particles. The dependence of the light output on the deposited energy is non-linear.

Birks effect

- Conversion of energy deposited in scintillator volume into scintillation light, depends on the mass, charge, and kinetic energy of a detected particle (J.P.Birks, ``The Theory and Practice of Scintillation Counting”, MacMillan Pub. New York, 1964). The relative light production is essentially smaller for non-relativistic particles. Shown on the plot are calculations of the Novosibirsk group (G.Kezerashwilli et al.).

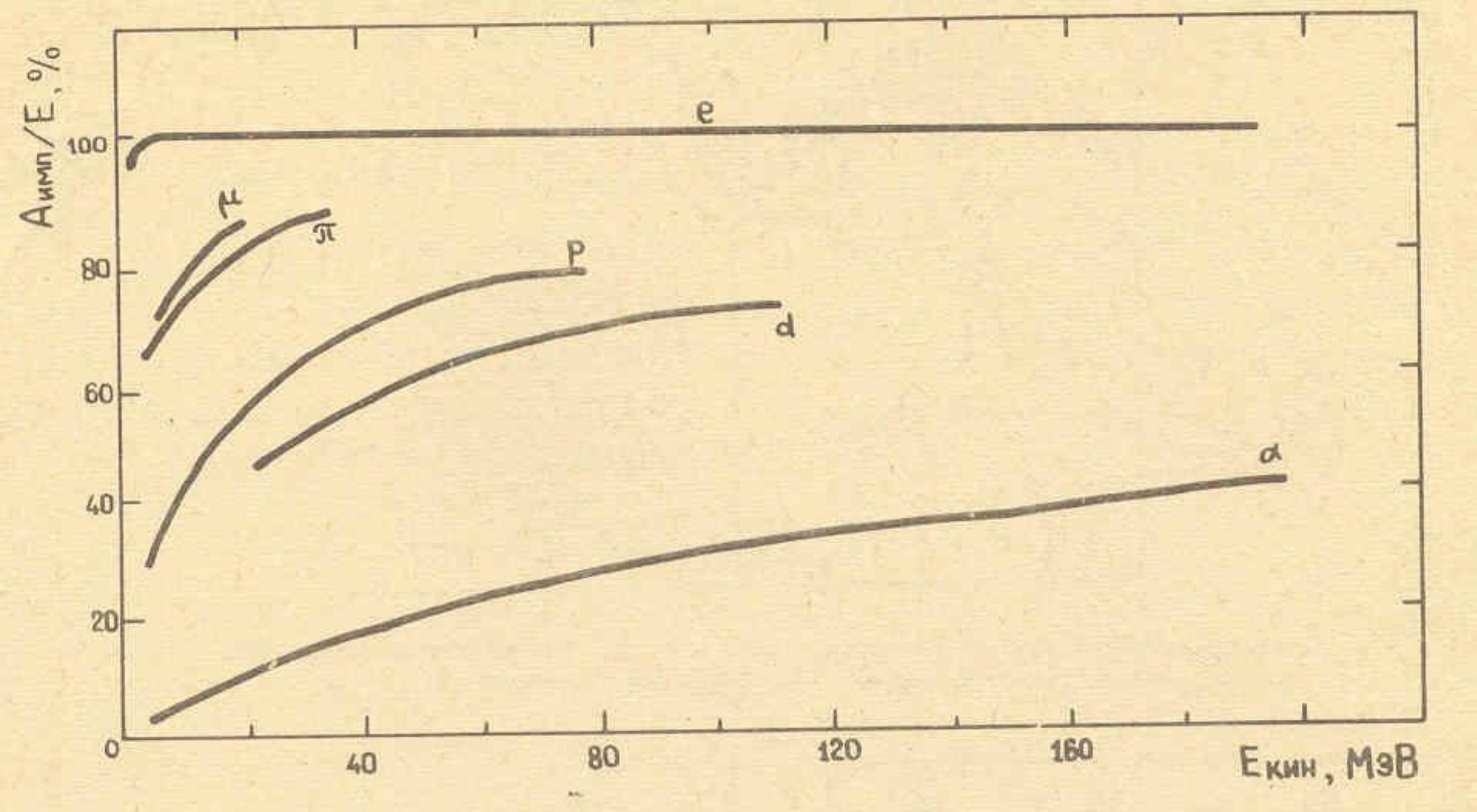


Рис. 7 Относительная конверсионная эффективность пластика.

Key Features for the TOF resolution

Long scnitillator bars

- Light Collection (!) -- Transparency, surface reflection, quality of wrapper;

No need in superfast photodetectors!

Some exmples:

Superfast HP R4998 TTS 0.17 ns, price ~3000 USD

Standard HP R8619 TTS 1.2 ns, price ~ 500 USD

MELZ FEU 115 MKZ TTS 1.2 ns? Price ~200 USD

Two latter ones are/were considered for Neuland/

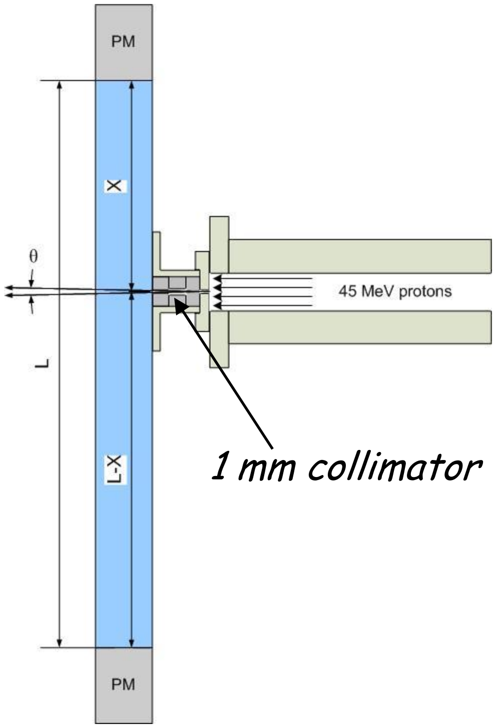
- Small “START” counters – properties of scintillator material and photoderectors.

Measurement of TOF resolution

Measured PM times are defined by the following relations

$$t1=TOF+x/v+Const\ ; \quad t2=TOF+(L-x)/v+Const;$$

Where TOF is time-of-flight of protons from a certain point (target), x is a hit position along the counter axis, L is the counter length, v is the efficient speed of light propagation inside the counter, Constants originate from cable and electronic delays.



$$TOF=(t1+t2)/2+Const;\ x/v=(t1-t2)/2+Const;$$

TOF resolution $\sigma_{TOF} = \sigma((t1+t2)/2)=$

$$sqrt(\sigma^2_{t1}+\sigma^2_{t2})/2;$$

Variation of (t1-t2)/2

$$\sigma((t1-t2)/2)\approx (\sigma^2_{TOF}+(\Delta x/v)^2)^{1/2}$$

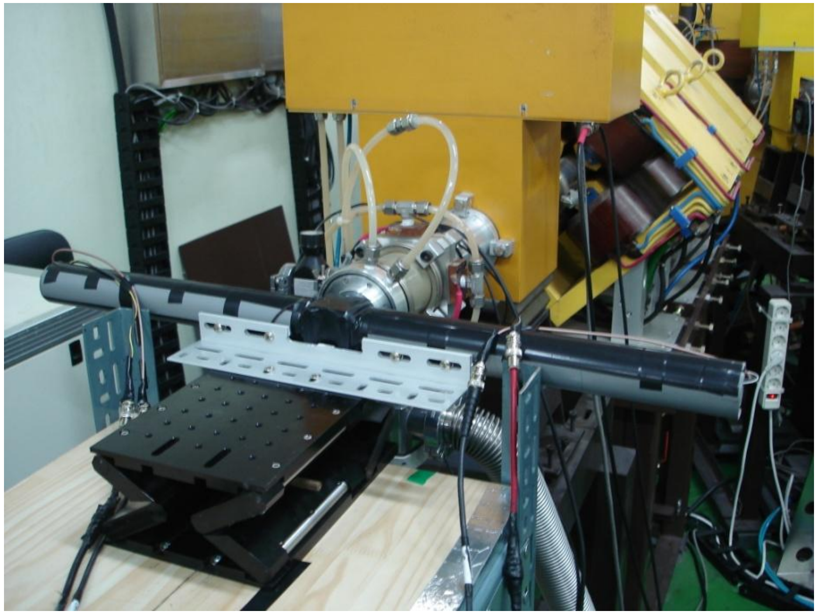
where Δx is the size of the beam spot.

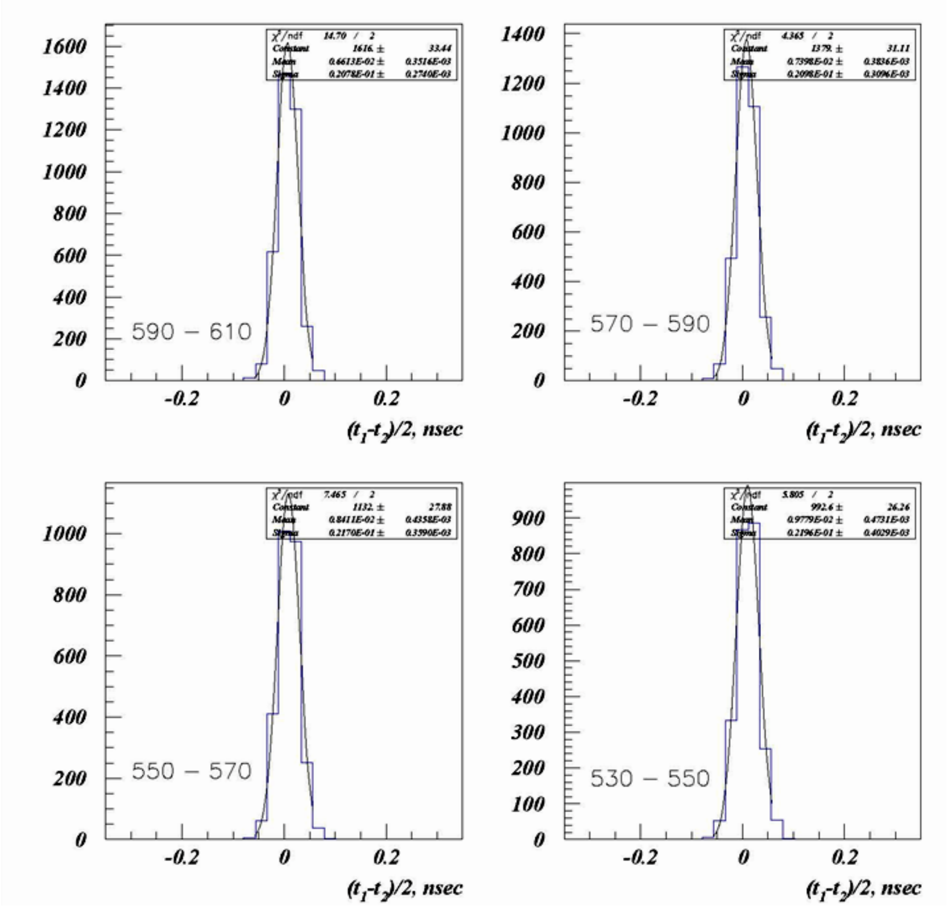
For a point-like beam (Δx~0)

$$\sigma((t1-t2)/2) \approx \sigma_{TOF}$$

TOF resolution of a scintillator counter can be directly extracted from measured spectra of (t1-t2)/2

V.Kuznetsov et al, CTOF review, Jlab, November 21, 2009

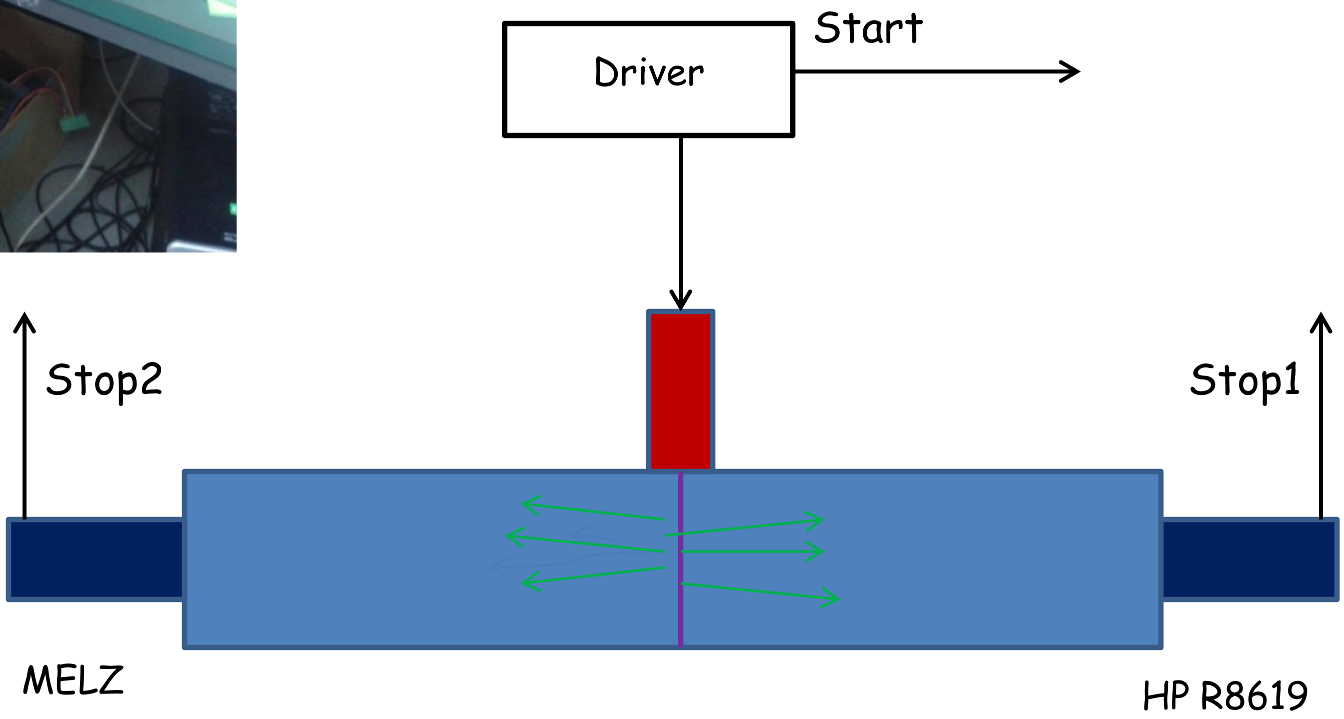




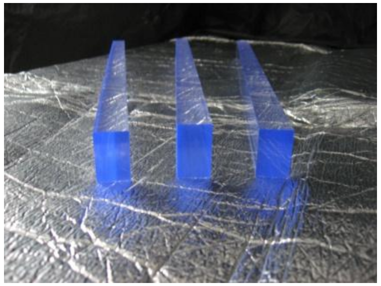
χ²/ndf 14.70 / 2
Constant 1616. ± 33.44
Mean 0.6613E-02 ± 0.3516E-03
Sigma 0.2078E-01 ± 0.2740E-03
1600
1400
1200
1000
800
600
400
200
0
590 – 610
-0.2
0
0.2
(t1-t2)/2, nsec
χ²/ndf 4.365 / 2
Constant 1379. ± 31.11
Mean 0.7398E-02 ± 0.3836E-03
Sigma 0.2098E-01 ± 0.3096E-03
1400
1200
1000
800
600
400
200
0
570 – 590
-0.2
0
0.2
(t1-t2)/2, nsec
χ²/ndf 7.465 / 2
Constant 1132. ± 27.88
Mean 0.8411E-02 ± 0.4358E-03
Sigma 0.2170E-01 ± 0.3590E-03
1000
800
600
400
200
0
550 – 570
-0.2
0
0.2
(t1-t2)/2, nsec
χ²/ndf 5.805 / 2
Constant 992.6 ± 26.26
Mean 0.9779E-02 ± 0.4731E-03
Sigma 0.2196E-01 ± 0.4029E-03
900
800
700
600
500
400
300
200
100
0
530 – 550
-0.2
0
0.2
(t1-t2)/2, nsec

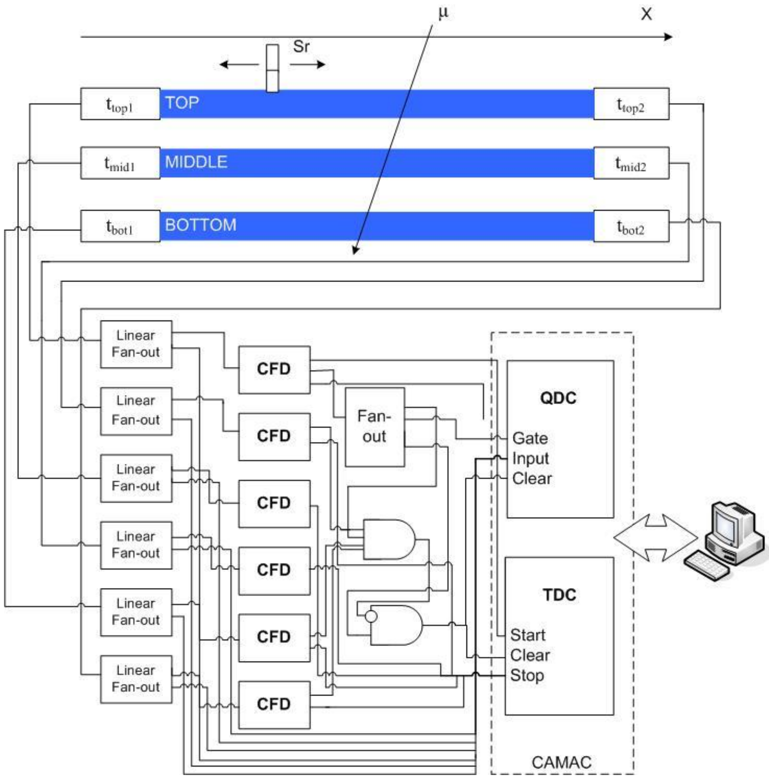
Tests at GSI

Laser driver:
PicoQuant PDL 800-B
Laser head LDH-P-C-375B
370 nm, 100ps pulse duration



Previous measurements using cosmic-ray muons





Schematic view of experimental setup

Cosmic-ray muons were detected in three 30x20x500mm stacked parallel equidistant scintillators made of Bicron 408 and equipped with 6 PMs

PMs signals were digitized by LeCroy 2249A QDCs and their arriving times were measured by LeCroy 2228A TDCs.

Basic Idea.

Cosmic ray tracking

- We make use of three counters equipped with six identical PMTs. The counters are aligned horizontally and are stacked parallel at equal distance each from the other. The times of scintillations caused by a cosmic-ray muon crossing all three counters (top, middle, and bottom respectively), are defined as:

$$t_{top} = (t_{top1} + t_{top2})/2 + C_1$$

$$t_{middle} = (t_{mid1} + t_{mid2})/2 + C_2$$

$$t_{bottom} = (t_{bot1} + t_{bot2})/2 + C_3$$

- Where $\boldsymbol{t_{top1} \dots t_{bot2}}$ are the corresponding TDCs readout values, $\boldsymbol{C_1 \dots C_6}$ are the calibration constants. The muon looses a small part of its energy/momentum inside the counters. Its velocity remains nearly constant. Therefore

$$t_{middle} = (t_{top} + t_{bottom})/2 + C$$

or

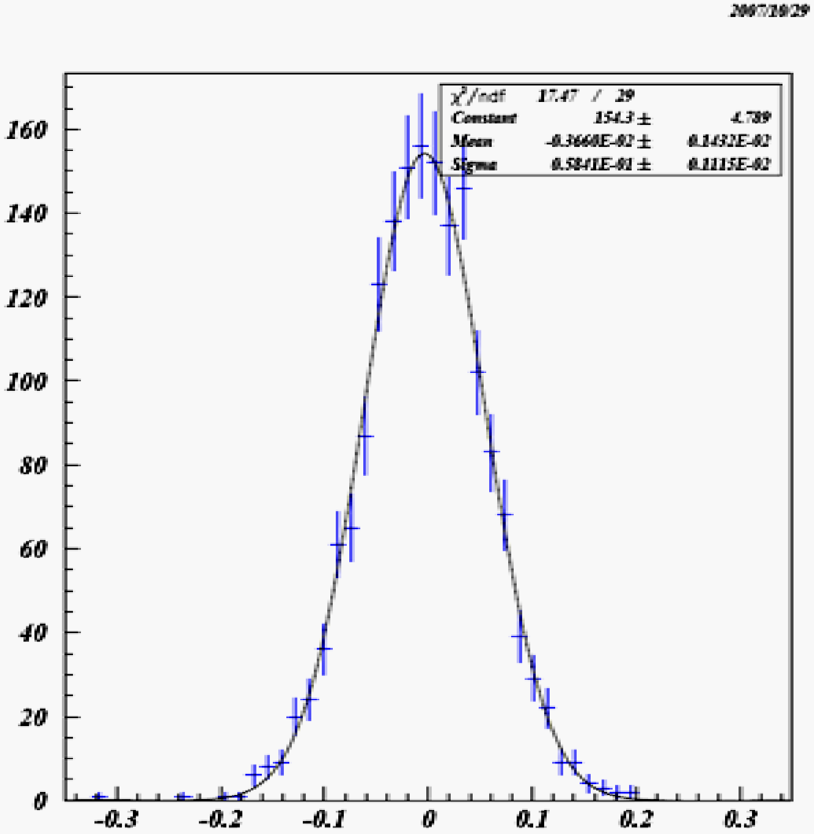
$$\tau = t_{middle} - (t_{top} + t_{bottom})/2 = (t_3 + t_4)/2 - (t_1 + t_2)/4 - (t_5 + t_6)/4 = C$$

- However, since $\boldsymbol{t_1 \dots t_6}$ are smeared by the PMT resolutions, **τ** is distributed around some constant value ***C***. Using the variance of **τ** , one may deduce the average PMT resolution

$$\boxed{\sigma_{PMT} = \frac{2}{\sqrt{3}}\sqrt{\mathrm{var}(\tau)} = \frac{2}{\sqrt{3}}\sigma_\tau}$$

- In practice, the PMT resolution is derived fro k in the measured spectrum of **τ**.

Triplet with 6 R7761-70 PMs



σ_{PMT} = 58 ps

This number might be better in future!

We still observe time walks and work to reduce them.

Calibration

- By using cosmic rays (CLS, NeuLand)
-By using experimental data (the Russian Wall at GRAAL)

Some remarks: the overall TOF resolution of the EC@CLAS calorimeter is ~1 ns, the TOF resolution of the Russian Wall@GRAAL is 250 ps.

Calibration Uncertainty

In reality

$$TOF = \frac{1}{2}(t_1 + t_2) + C_{real} + \Delta C_{cal}$$

where ΔC_{cal} *is the error of calibration*

If a detector consists of many counters, Δc_{cali} *varies from counter to counter.*

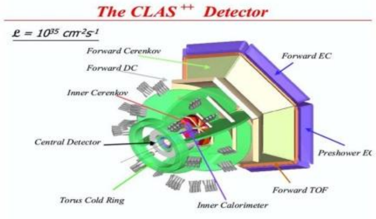
$$\sigma_{tof\_det} \sim \sqrt{\frac{\sigma_{sc}^2 + \sigma_{LT}^2 + \sigma_{PM}^2}{N_{pe}} + \sigma_{el}^2 + \boxed{\sigma_{cal}^2}}$$

Russian Wall at GRAAL

σ_{cal} ~10- 20 ps

Ecal at CLAS@JLAV

σ_{cal} ~200- 500 ps



Calibration and performance

- Main readout: charge (ODC1&QDC2 channels) and timing (TDC1&TDC2 channels) from both ends of a scintillator bar (module).

- **Coordinate and time-of-flight calibration**

- TDC start is given by the tagging system, stop is the signal from the module.

$$r1*TDC1=tof + (L/2-y)/Veff + d1$$

$$r2*TDC2=tof + (L/2+y)/Veff + d2,$$

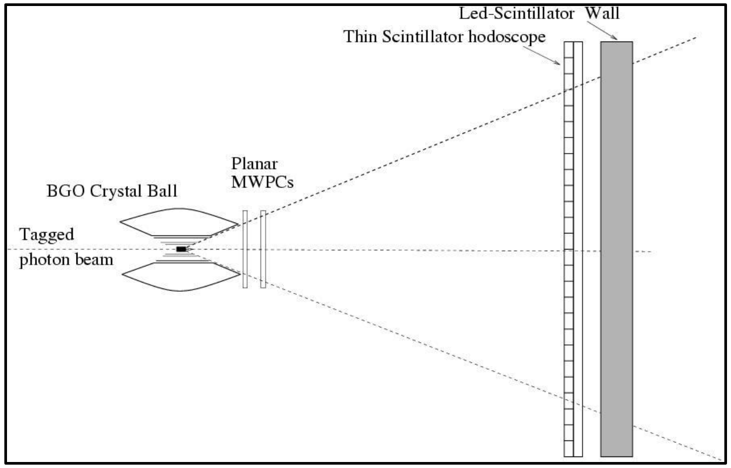
where r1 and r2 denote TDC scales (ps/channels) which can be measured, L is the length of a scintllator bar, y is the hit coordinate along the bar axis, Veff is the effective light propagation velocity, d1 and d2 are cable and electronic delays.

$$y=a * (r1*TDC1-r2*TDC1) + b.$$

$$tof=0.5*(r1*TDC1+r2*TDC2) + c$$

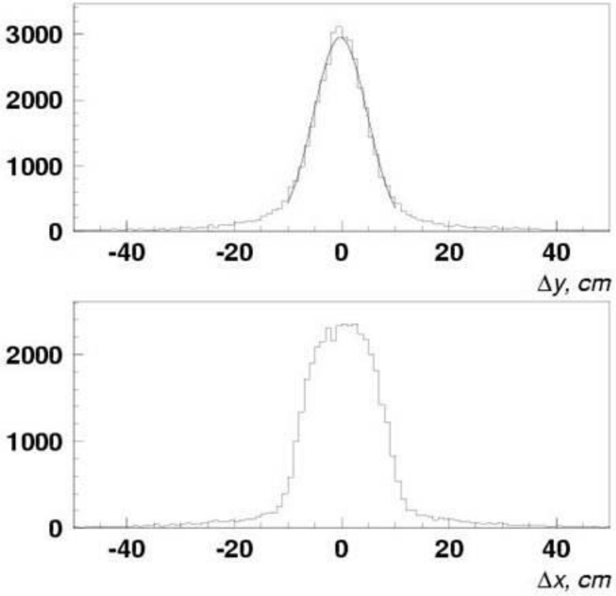
- a,b,c are the calibration coefficients to be determined.

Coordinate calibration



- \- Selection of charged hits which are in coincidence with preceding planar chambers and a thin hodoscope;
- \- Track reconstruction in planar chambers;
- \- Determination of the calibration coefficients a and b from minimization of the difference (Ych-a*(r1*TDC1-r2*TDC2)-b)

Note: a=Veff/2 (can be fixed once)

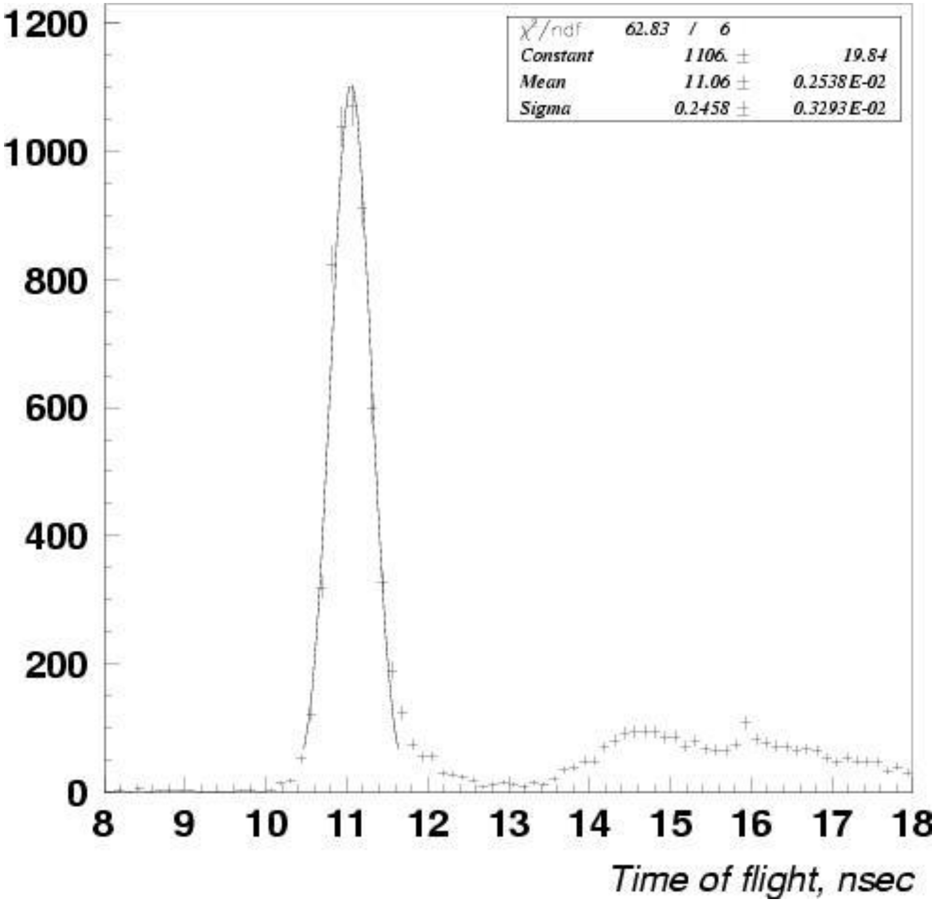


Time-of-flight Calibration

- \- Selection of neutral hits using anticoincidence with preceding wire chambers and a thin scintillator hodoscope
- \- Determination of the calibration coefficient C by positioning a photon peak in the spectrum of
- (0.5*(r1*TDC1+r2*TDC2)+c)*cosθ

to its expected value (11.06 ns).

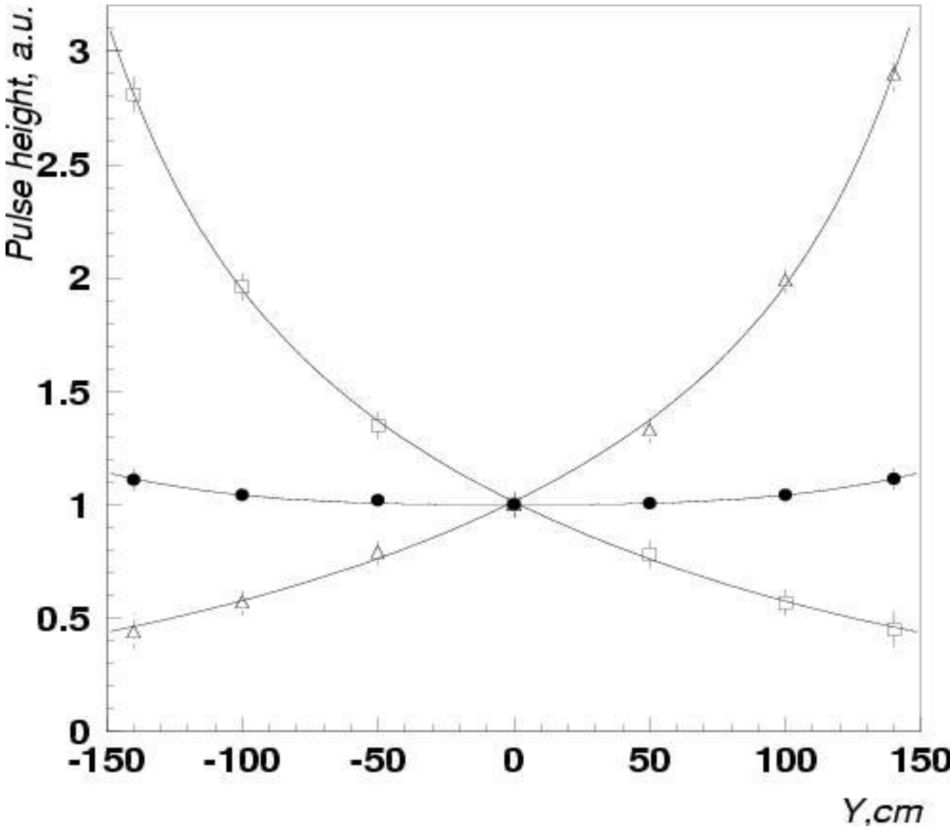
- Θ is a Lab angle of a photon track derived from the hit position.



Light attenuation and dE calibration

- Light attenuation in a long scintillator bar is described as
- A=Const*(c1*exp(-y/c2)+exp(-y/c3).
- Typical values:
- c3=2-4 m – the light attenuation length, which characterizes the quality of a scintillator material;
- C1 and C2 mostly depend on the light collection system; C2 is usually about 30-50 cm; C1 is about 0.05-0.3;

- The quantity
- L~ sqrt(A1*A2)=sqrt(QDC1*QDC2)
- Is almost independent on the hit position and can act (after small correction) as a measure of produced scintillation light.
- Another approach:
- L~QDC1/f1(y)+ODC2/f2(y)
- The light output is calibrated by comparing it with the signal corresponding to the minimum-ionizing energy deposited by fast charged particles crossing the detector in the perpendicular direction.

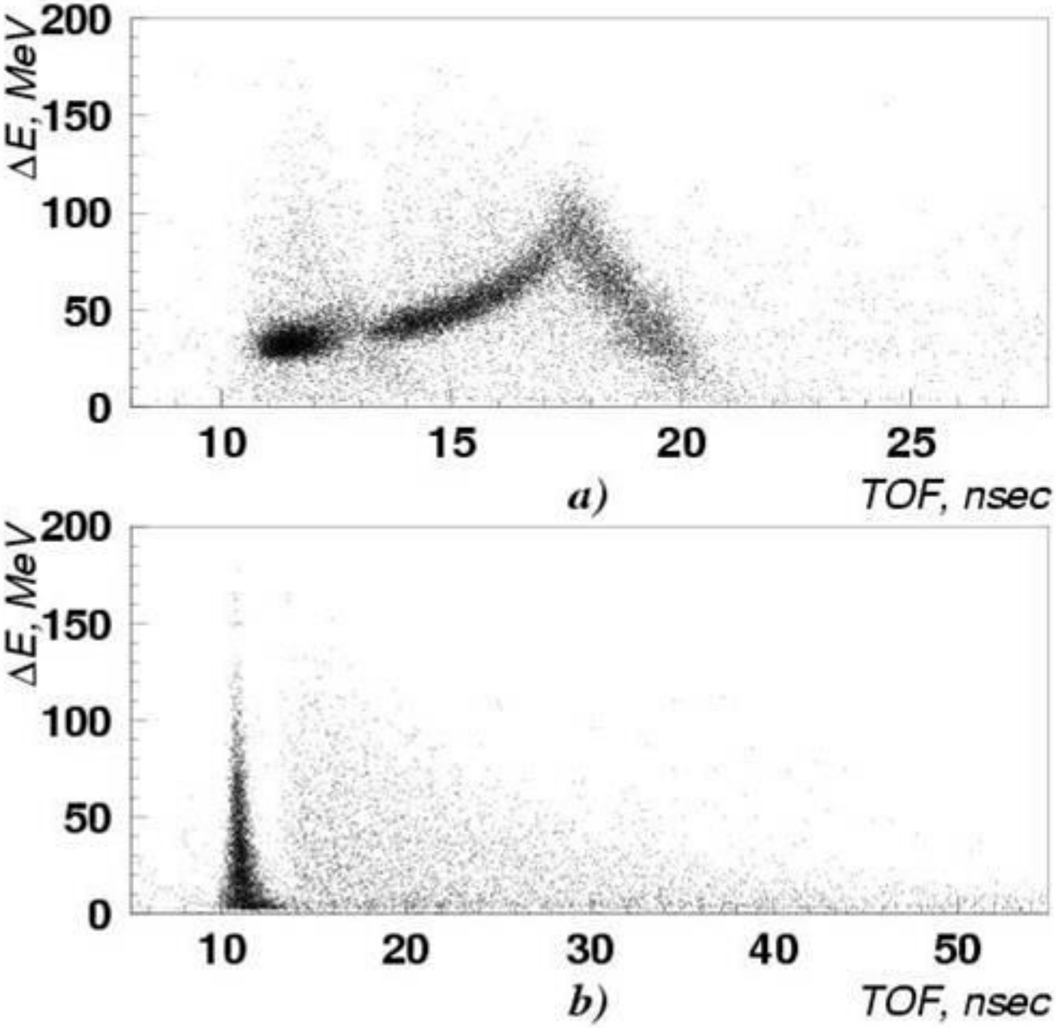


Particle identification and performance

- Typical performance of TOF detectors:

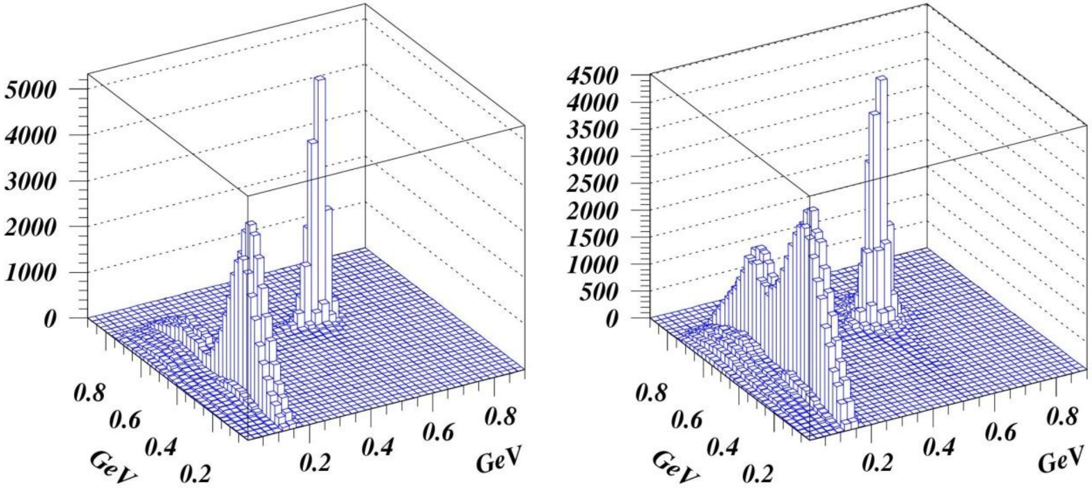
- TOF resolution 0.4-0.8 ns (FWHM);
- Coordinate resolution 5-15 cm (FWHM).

- Performance of the Russian Wall at GRAAL:
- TOF resolution – 0.6 ns
- Angular resolution – 2-3 deg
- Photon efficiency – 95%
- Neutron efficiency – 22%

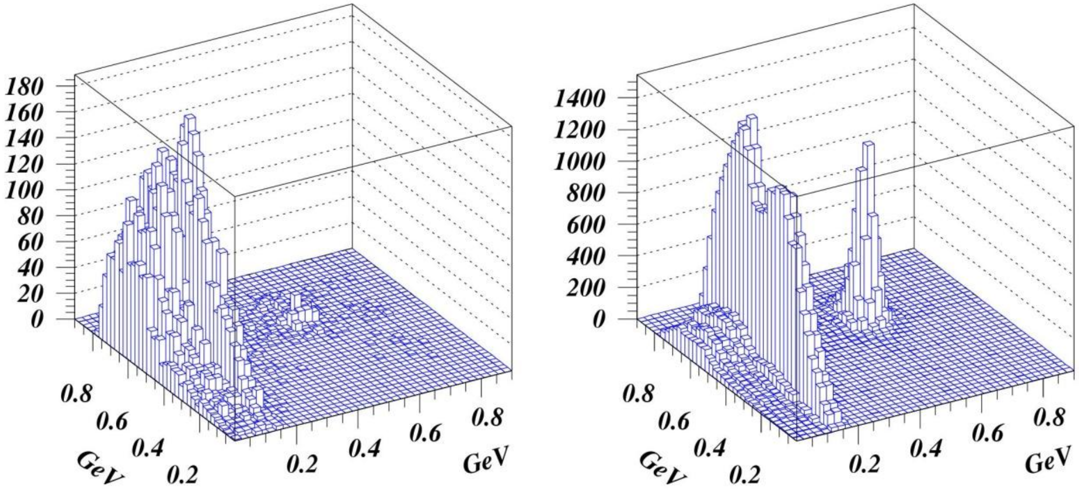


γn→ηp and γp→ηp reactions
on the quasi-free neutron and proton bound in the deuteron target.

Shown on the plot is the invariant mass of two photons from η→2γ decays versus the missing mass calculated from momenta of recoil nucleons.



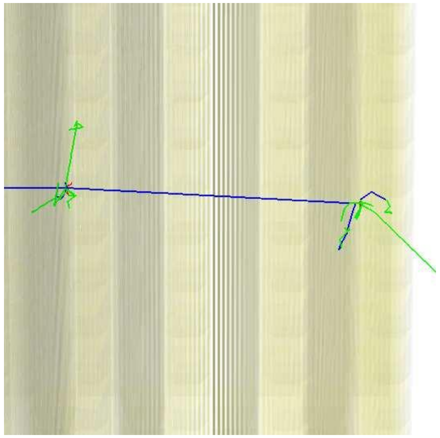
Recoil proton, proton target ***Recoil proton, deuteron target***



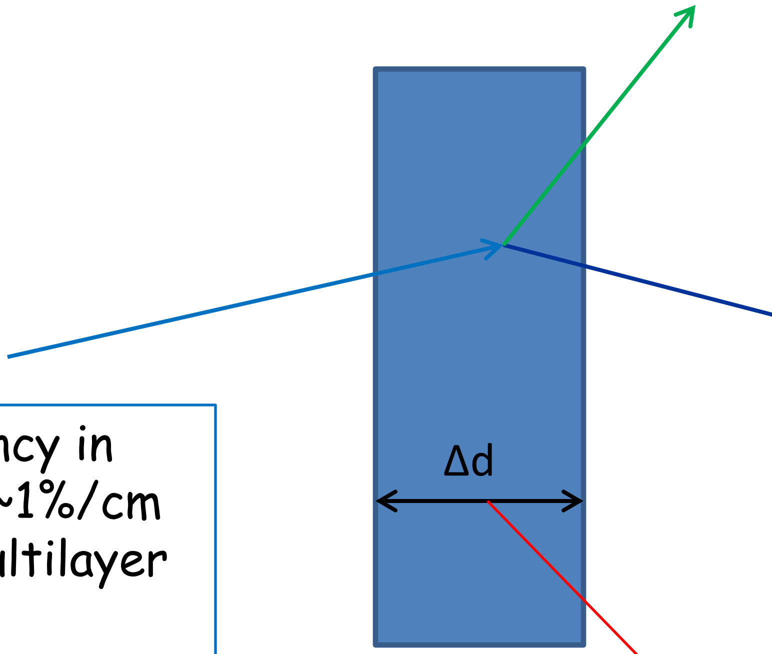
Recoil neutron, proton target ***Recoil neutron, deuteron target***

Neutron detection

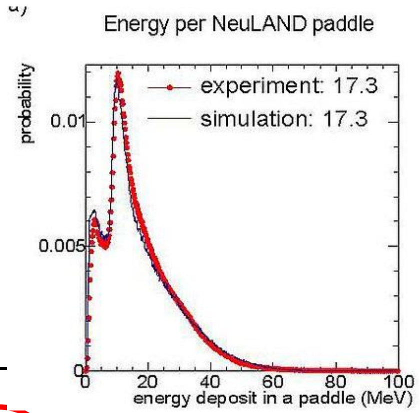
Neutron detection: Specific features



Neutrons interact inside detector volume mostly through knock out of recoil protons.



Detection efficiency in scintillator bars is ~1%/cm -> Need for thick multilayer detector



$$\sigma_{tof\_det} \sim \sqrt{\frac{\sigma_{sc}^2+\sigma_{LT}^2+\sigma_{PM}^2}{N_{pe}} + \sigma_{el}^2 + \sigma_{cal}^2 + \boxed{\sigma_{neut}^2}}$$

Wide range of deposited energy -> Need for low threshold to increase efficiency

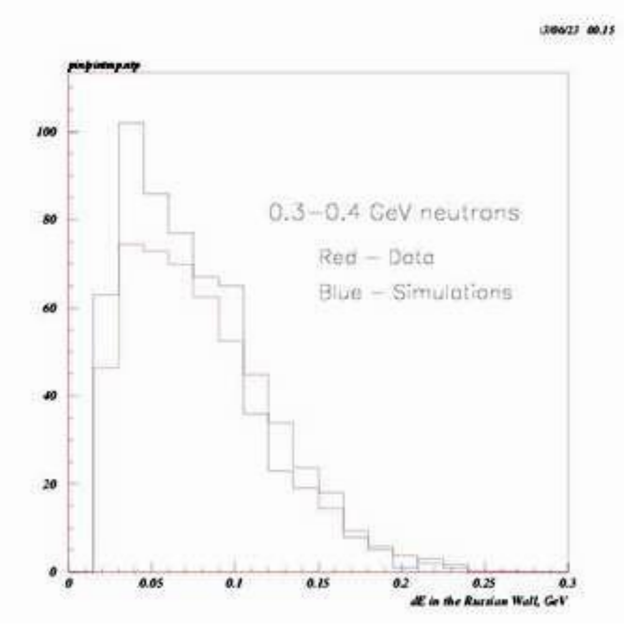
Specific requirements for neutron detectors

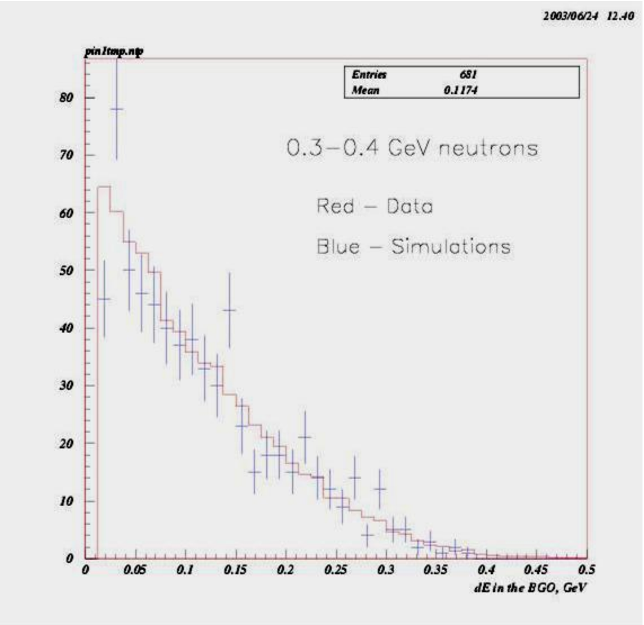
- Enough thickness to provide required detection efficiency;
- High granularity;
- Extended range of pulse heights and low threshold;
- Less requirements to phototubes:
- Accounting for the Birks' effect.

Light response to neutrons: Geant simulations and real data

- Neutrons are mostly detected through the knock-out of protons.
- The energy spectrum of recoil protons is rather soft.
- Birks effect is poorly studied and not included in Geant.
- This leads to an overestimation of neutron efficiency in simulations.
- Neutron efficiency in the Russian Wall: simulations ~ 30%, experimental value ~ 22%.

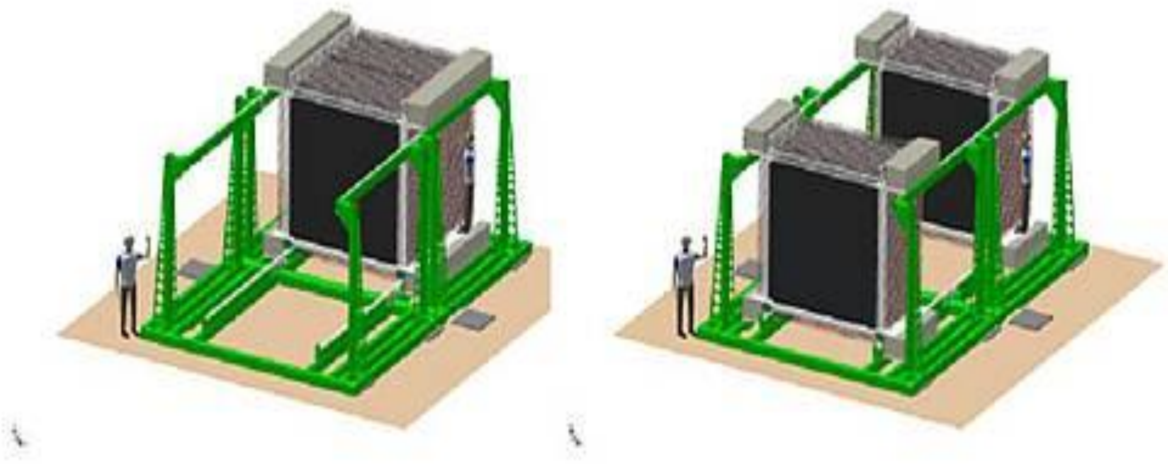
- Shown on plots are the light response (real data and simulations) of the Russian Wall and the BGO ball to 0.3-0.4 GeV neutrons from γp→π+n reaction.



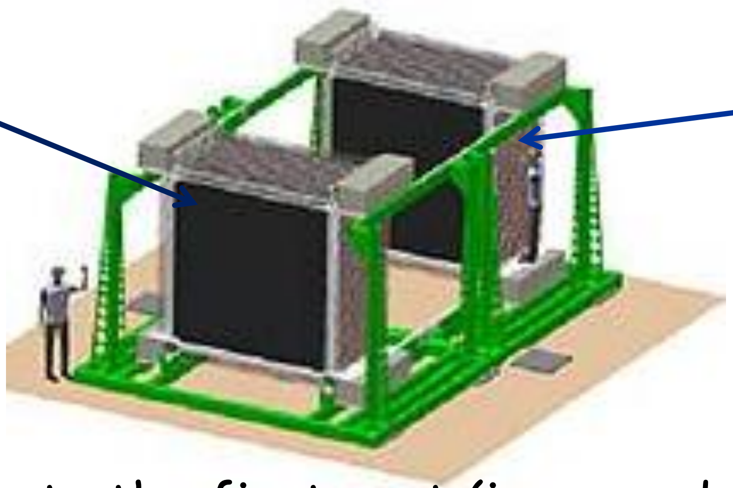


NeuLand Detector

NeuLand will consist of 3000 individual submodules with a size of 5x5x250 cm3, arranged in 30 double planes with 100 submodules providing an active face size of 250x250 cm2 and a total depth of 3 m. NeuLAND can be divided into two detectors for special applications and will be placed at different distances from the target, in order to meet specific experimental demands. A momentum resolution of $\Delta p/p$ of 10-3 similar to that for is desired, resulting in resolution requirements for the time of flight of $\sigma(t) < 150$ ps and a position resolution of $\sigma(x,y,z) \approx 1.5$ cm for given flight paths in the range from 10 to 35 m. Apart from the excellent energy resolution of NeuLAND, the enhanced multi-neutron recognition capability with an efficiency of up to ~50% for a reconstructed five-neutron event at 1 GeV will constitute a major step forward.



Detector Construction



First part
1500 counters
2018 - 2019

Second part
1500 counters
~2022

Russian Contribution to the first part (in accordance with previous agreement) – 700 scintillator bars

Our suggestion: 700 scintillator counters (bars + PMs)

Current situation: deliverance of two prototype counters to GSI by the fall of 2015, discussion of a large contract in the first half of 2016.

Scintillator counters

Cost-effective solution for PMs:

Hammamatsu Photonics R8619

- Rise time - 2.5 ns
- Transition time spread - 1.2 ns
- HV at anode sensitivuty 100 A/Lm - ~1000 V
- Expected operating HV 700 – 900 V

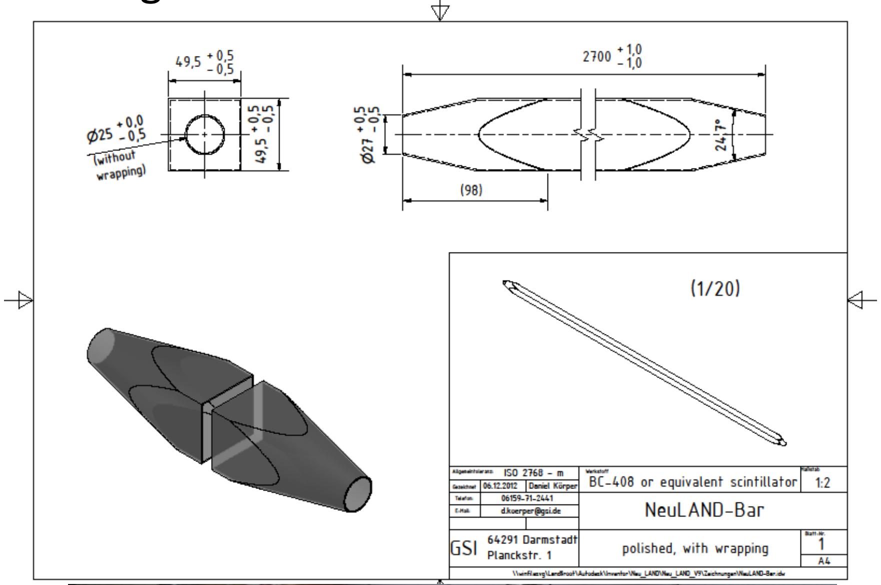
Requirements for PMs from the HV system HV <1500V.

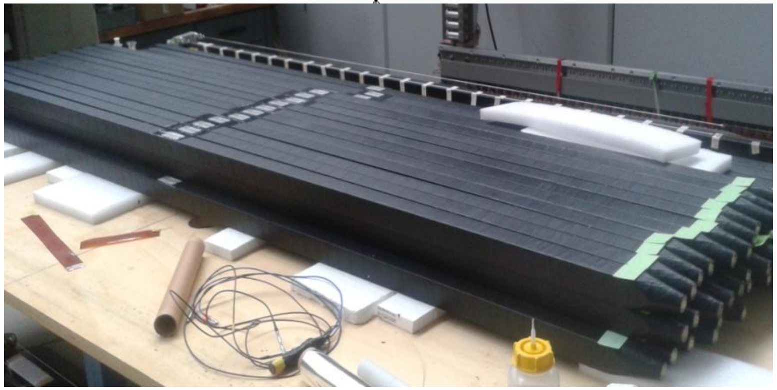
BC408 scintillator bars

Light decay – 2.1 ns

Light output – 60% relative to antracene

Bulk light attenuation ~ 4 m



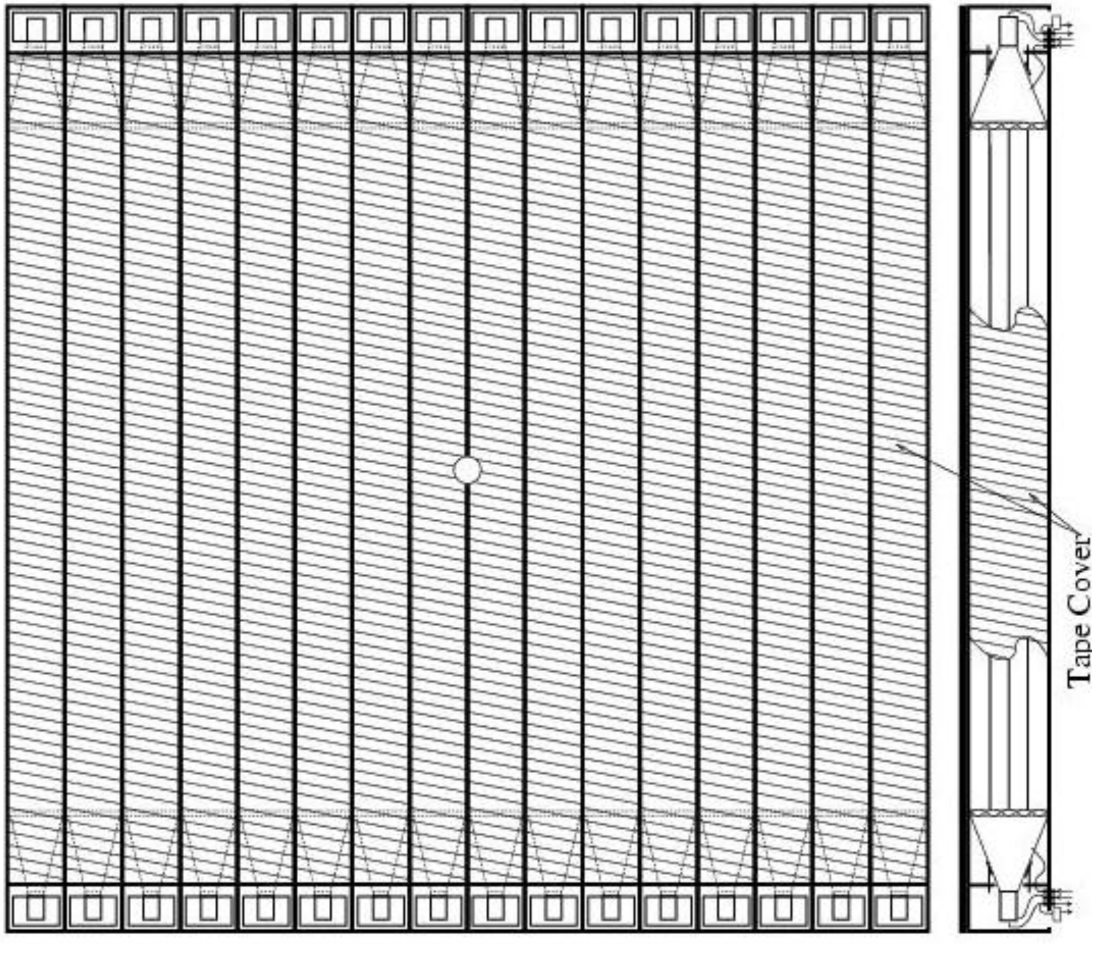


Scintillator Bars at PNPI

two roughly-cut BC-408 bulks from Saint-Gobaine have been purchased, machined and polished at the PNPI workshop

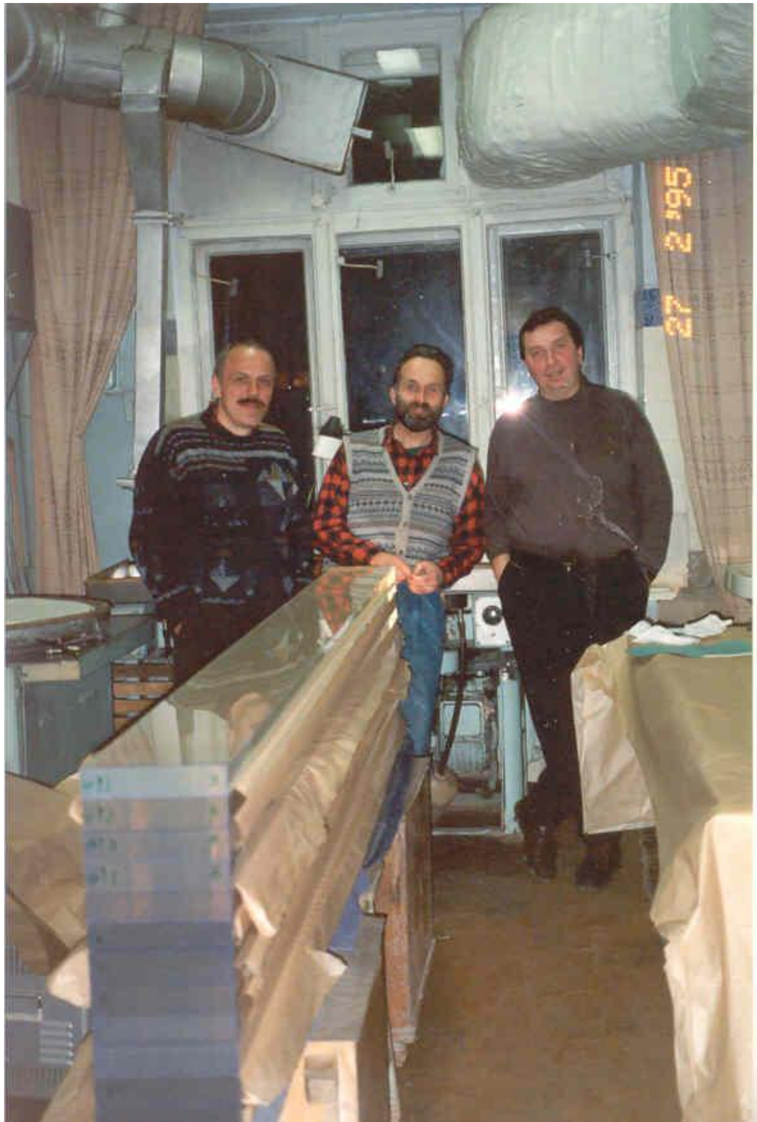
Two bars are ready and now to be examined, wrapped and tested.

Constuction of the Russian Wall at GRAAL:
Some Photos.



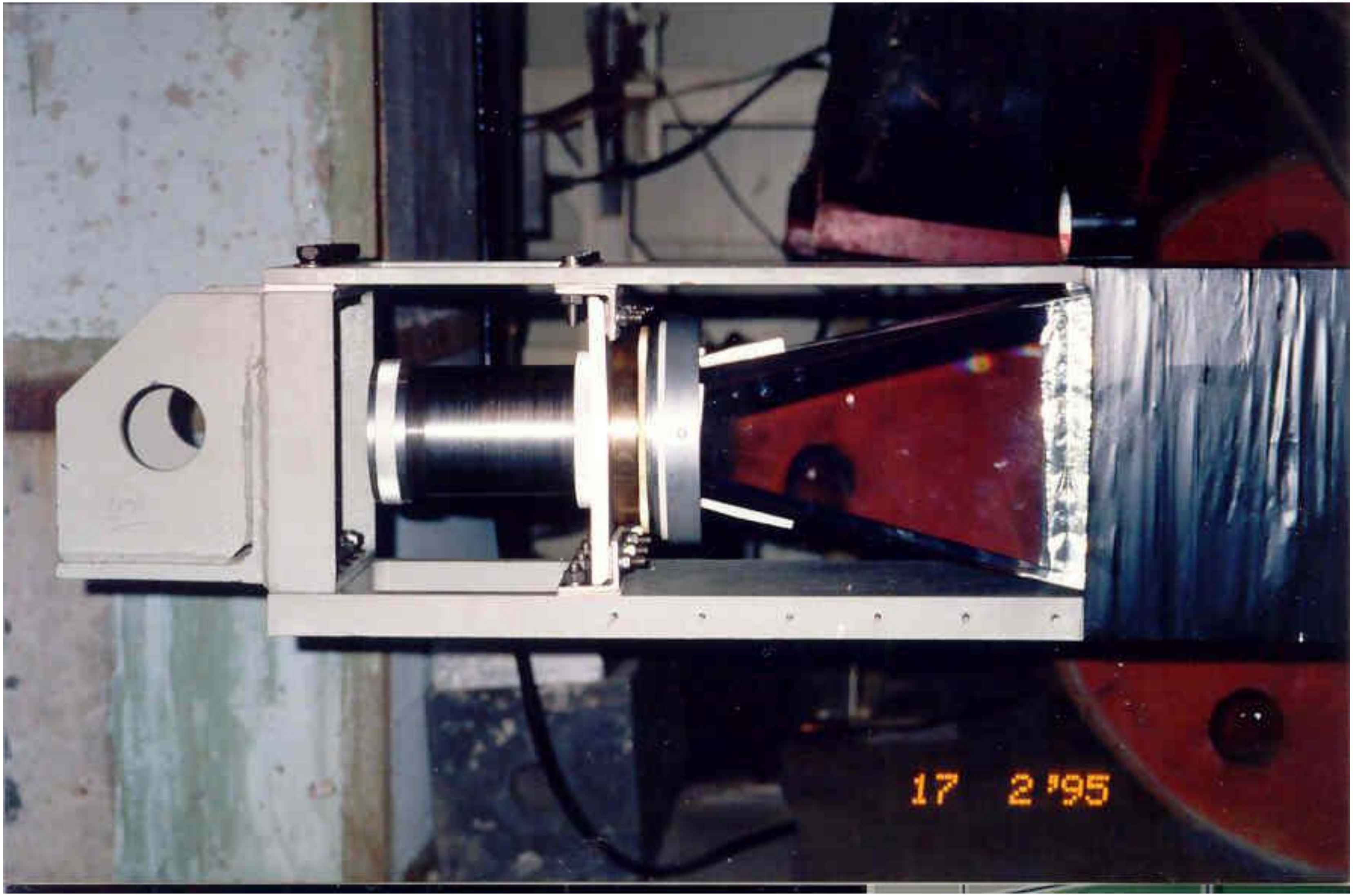
Scintillator strips have been manufactured in the Institute for Single Crystals, Kharkov, Ukraine

Material: polysterene + scintillatining impurities



Optical contact between the light guide and strips is critical.

We use a sandwich of two types of optical grease and optical rubber.

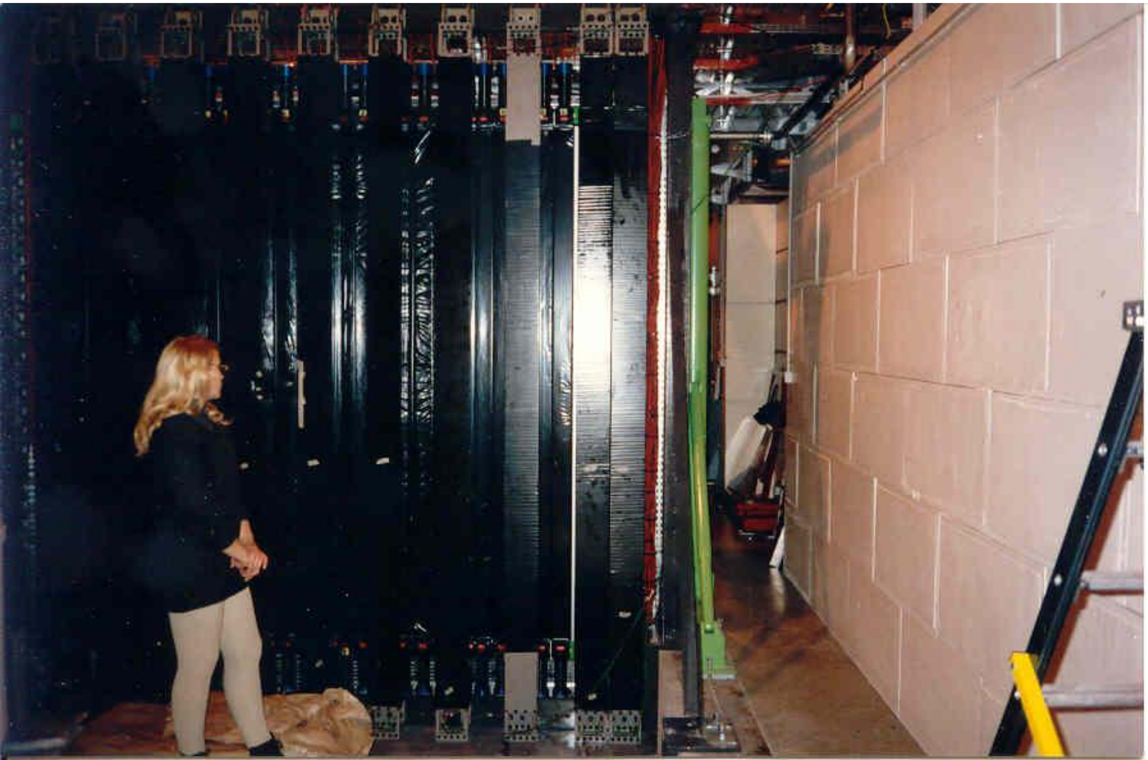


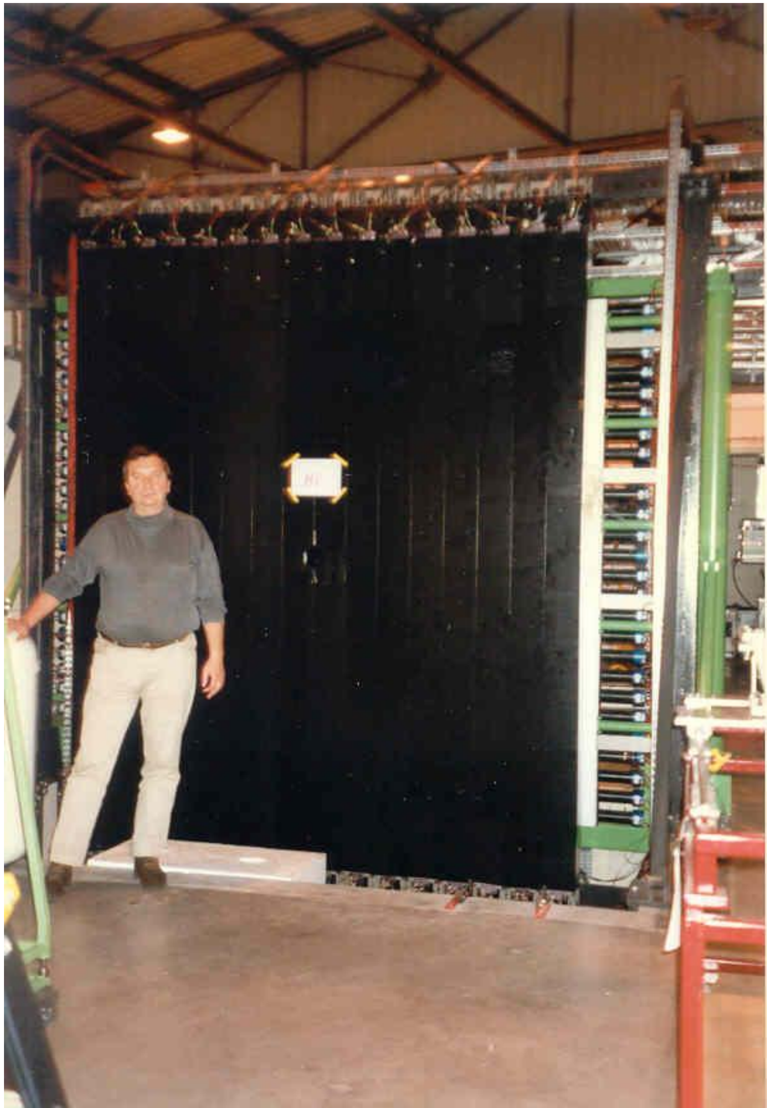
The most delicate operation is lifting up the module

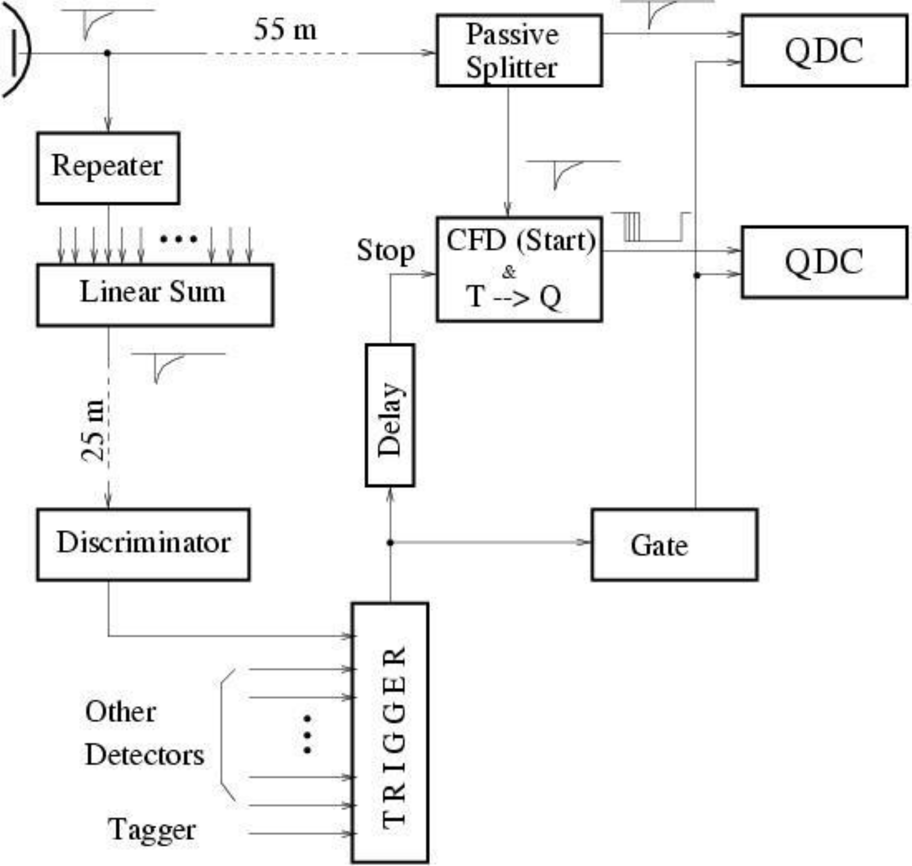
17 2 '95

… and completed

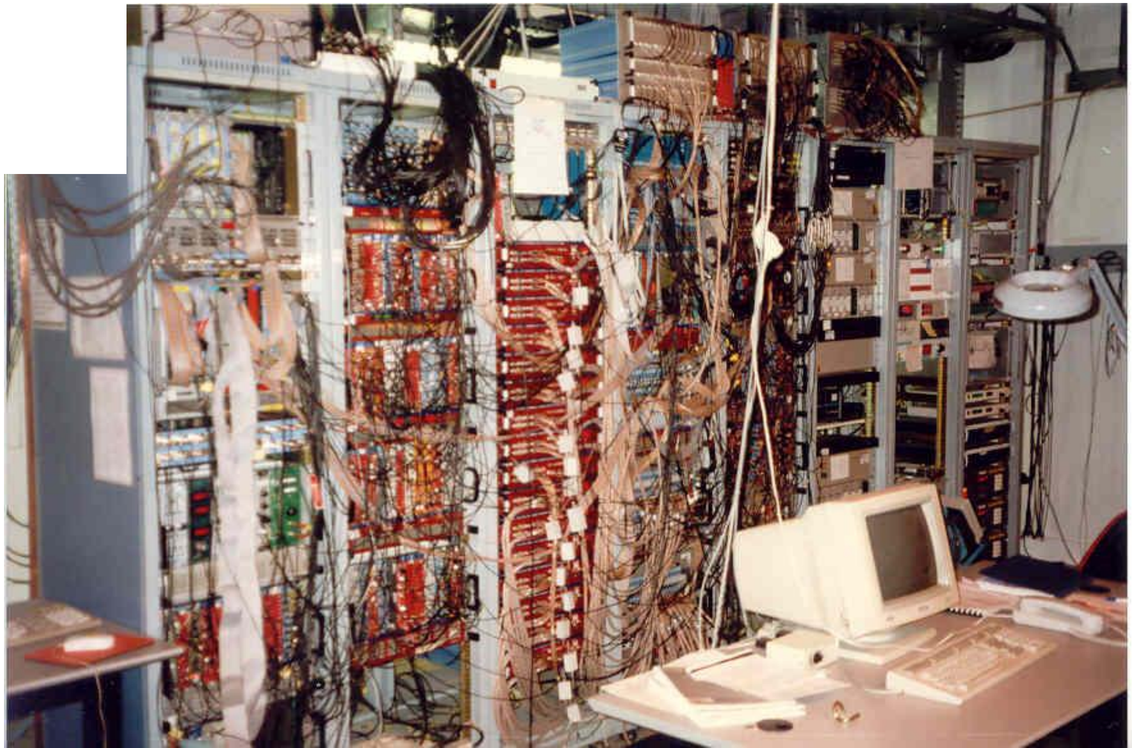
Almost installed …..







Electronics



Many Thanks!