Studies on BGO crystals

Roma1 EMC Group

Intro

Because of the large background we already know we'll have to reduce the integration time on the FEE on the barrel EMC;

In order to evaluate the impact of a shorter integration time on the energy resolution we made a simple exercise;

The signal of a PMT reading a BGO crystal (we haven't found a CsI one) was sent into an Ortec pre-amplifier with a variable integration time and registered with a digital oscilloscope;

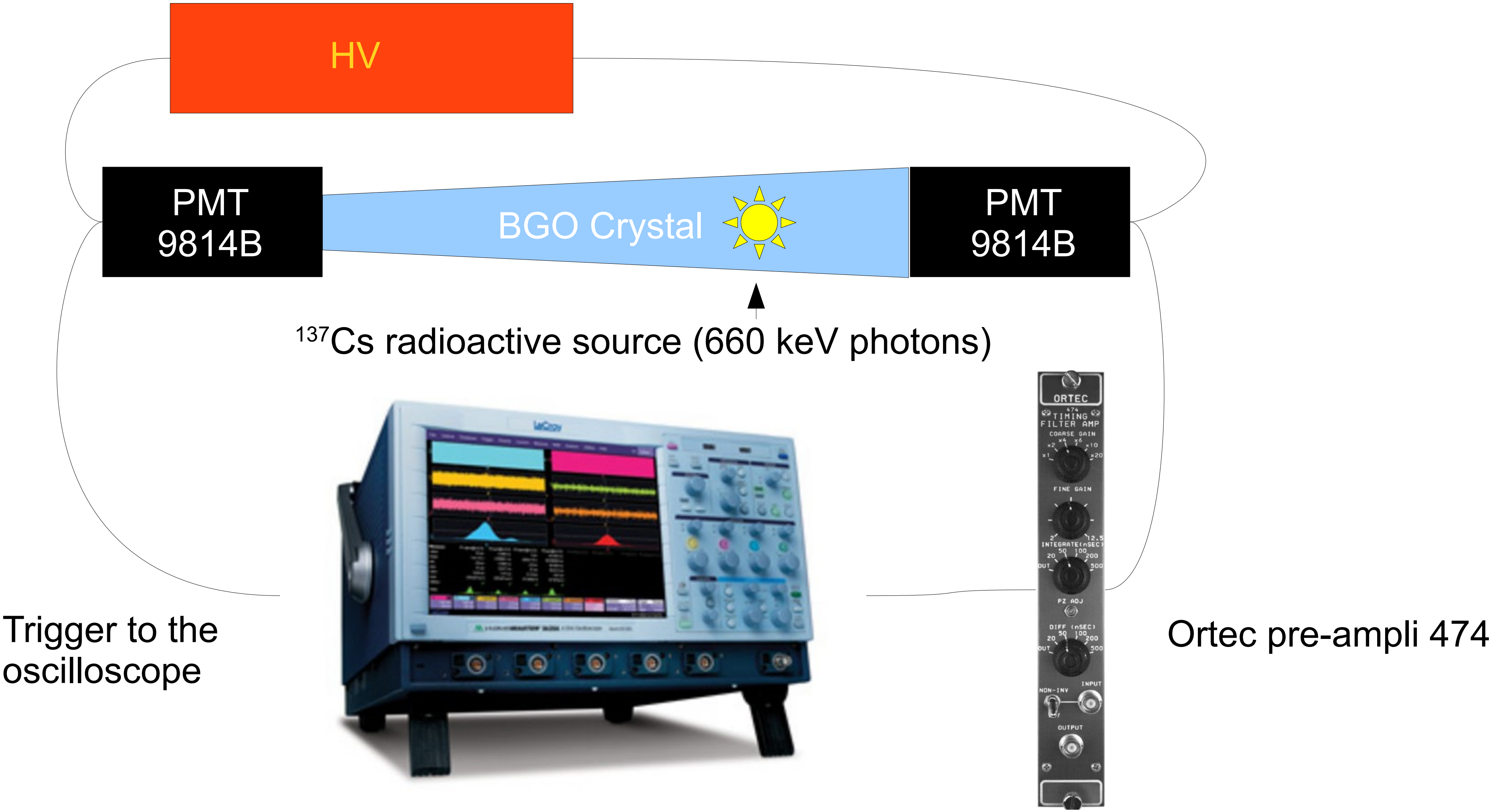
The crystal was irradiated with a ^{137}Cs source;

In an off-line analysis, event by event, we evaluated:

- The total charge as the integral of waveform;
- The signal amplitude, to emulate the response of a shaper placed downstream of the pre-amplifier;

A shorter integration time can be a solution also in case of a non-fully Lyso based forward calorimeter;

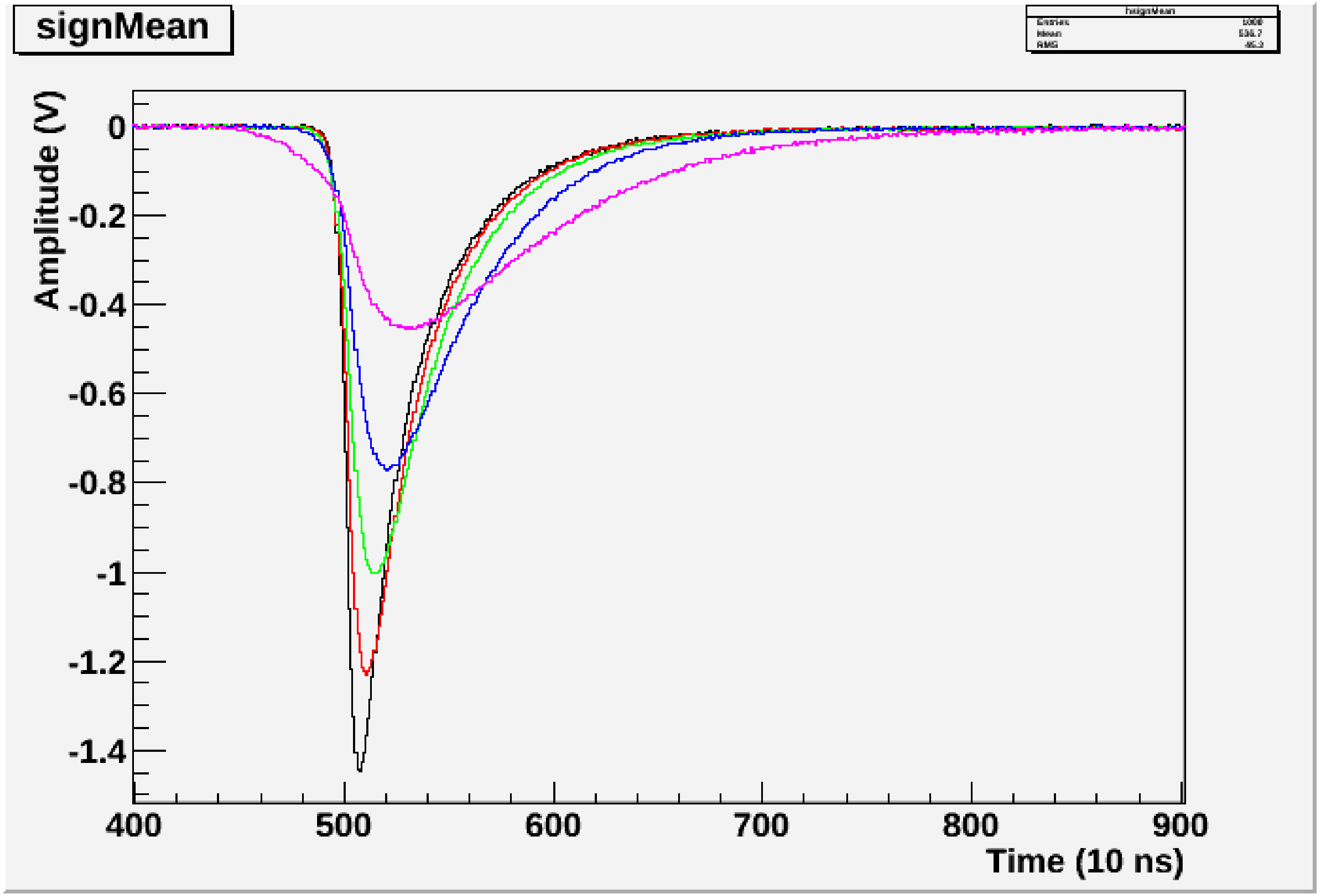
Measurement Set-up



Measurements were taken both with and without the radioactive source, without the Ortec and for integration times of 4ns, 20ns, 100ns, 200ns and 500ns.
No data were taken with random trigger → Pedestal evaluation not easy and not properly done.

Average signals

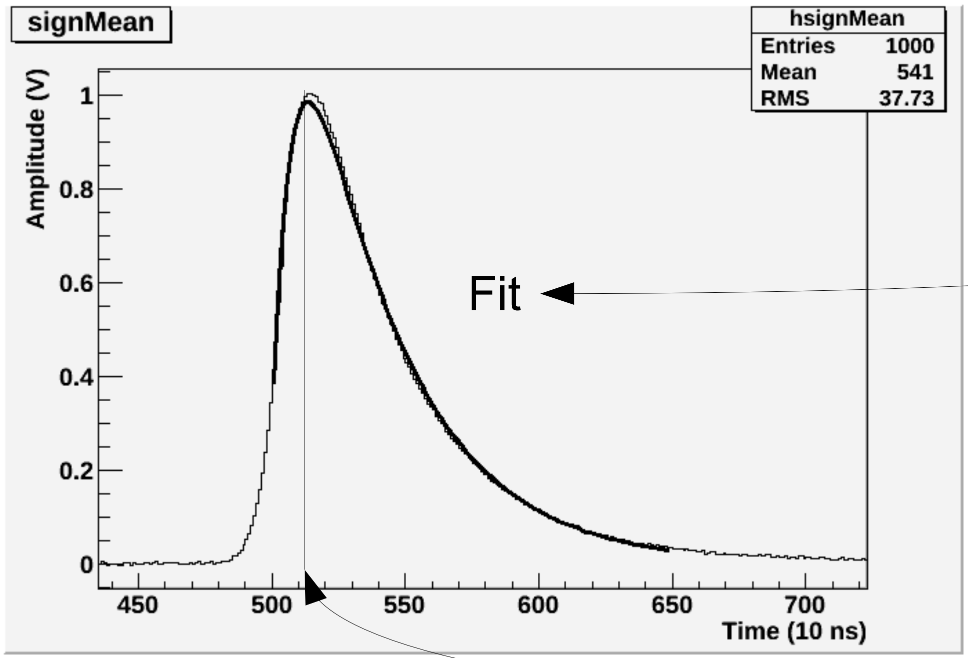
For every integration time we acquired about 10k events and we evaluated the average signal waveforms.



Circuit model

A simple mathematical model of the integrating circuit was developed.

The output signal has a waveform:



$$V_{out}(t) = R_{in}Q\frac{\left(e^{-t/\tau} - e^{-t/RC}\right)}{\tau - RC}$$

The maximum is reached at

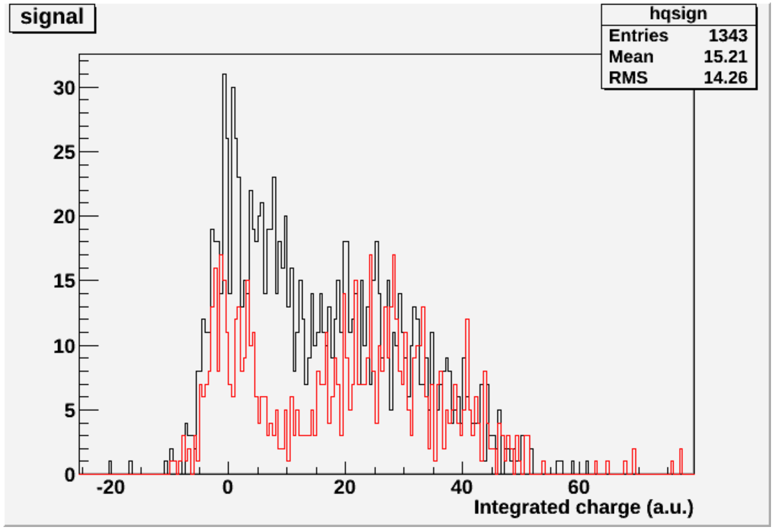
$$t_{max} = \frac{RC\tau}{\tau - RC} ln\left(\frac{\tau}{RC}\right)$$

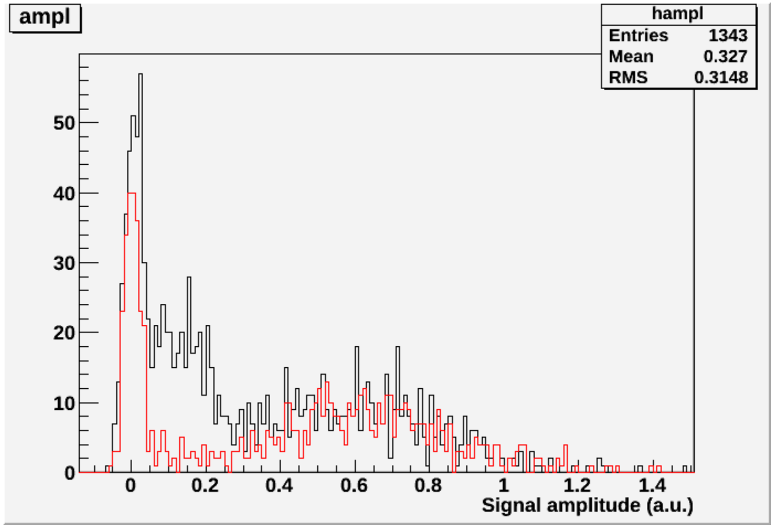
We calculated the fraction *f* of integrated charge after a time t that is:

RC	4 ns	20 ns	100 ns	200 ns	500 ns
$f(t_{max})$	28.3%	35.4%	48.0%	60.1%	77.1%

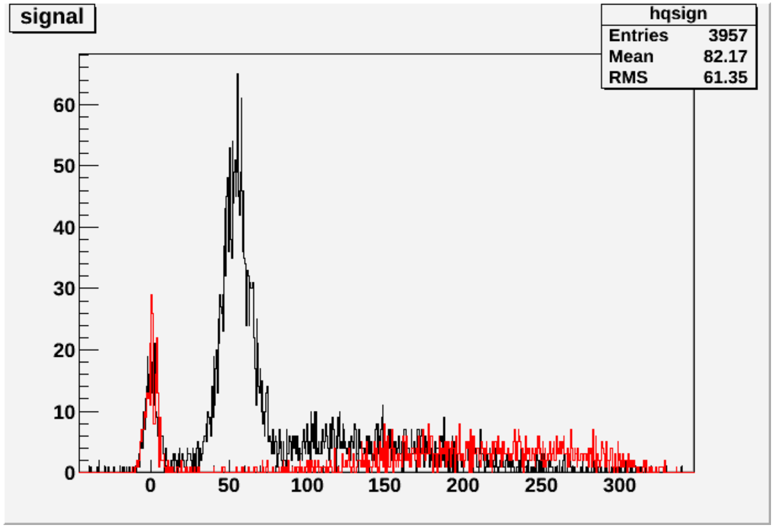
Spectra

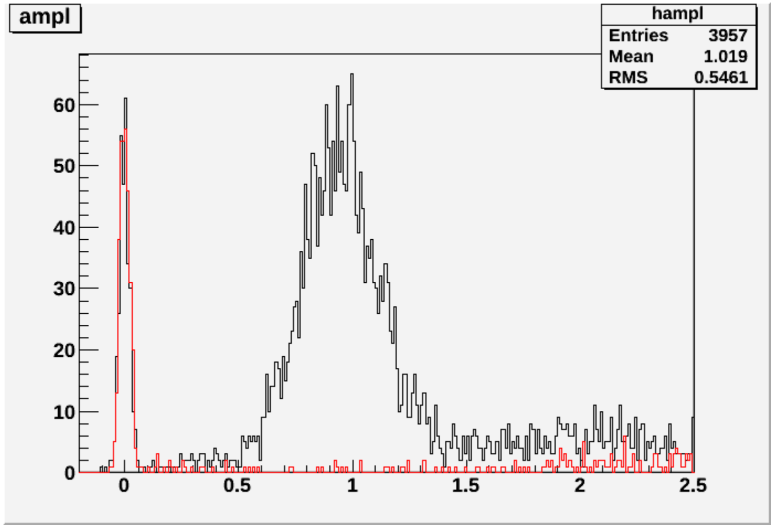
For each integration time we evaluated the spectra of the total integrated charge and the maximum amplitude of the signals;





Without pre-amplifier





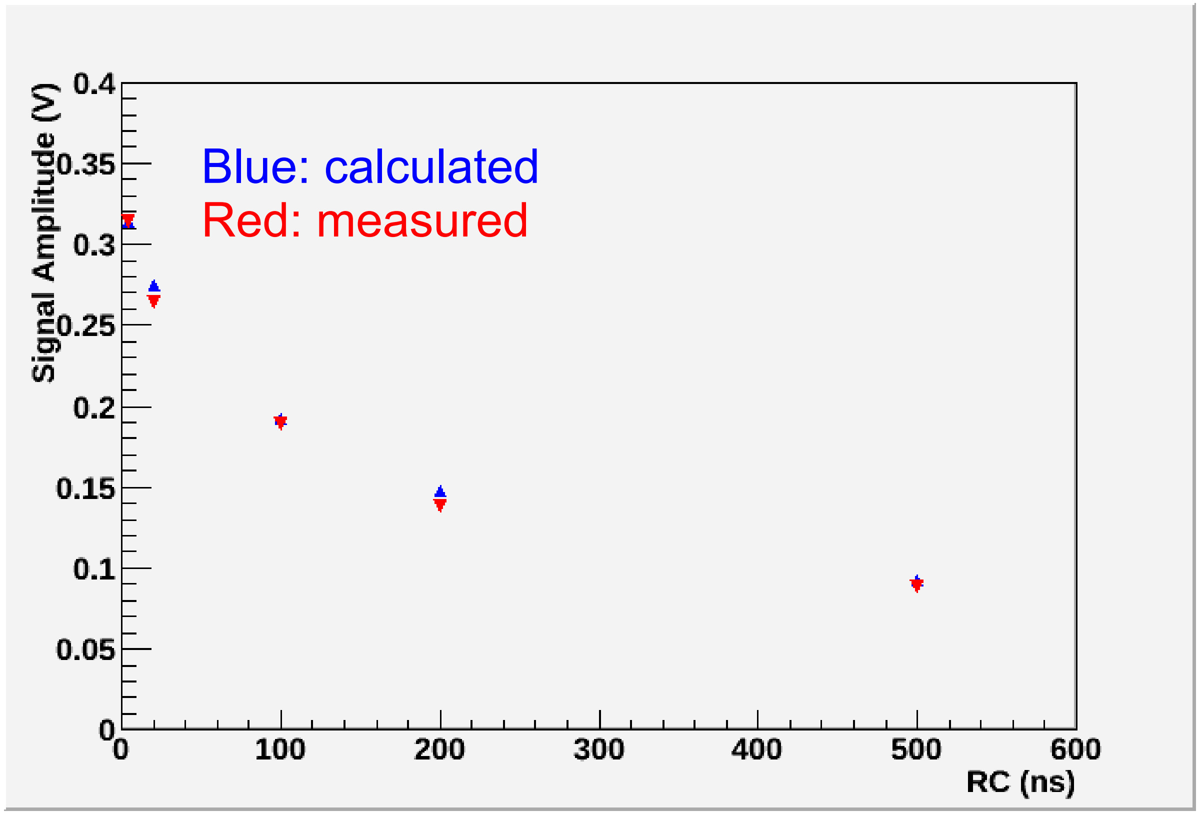
Pre-amplifier with a gain of 8 and an integration time of 100 ns.

Black: Source IN

Red: Source OUT

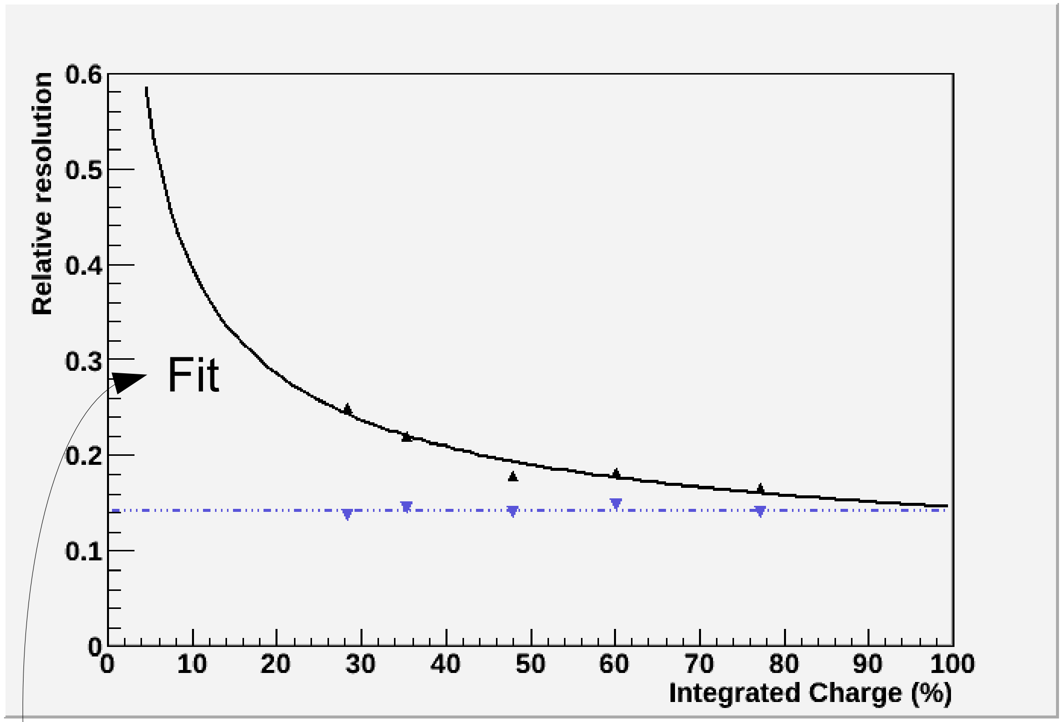
Peak amplitude vs RC

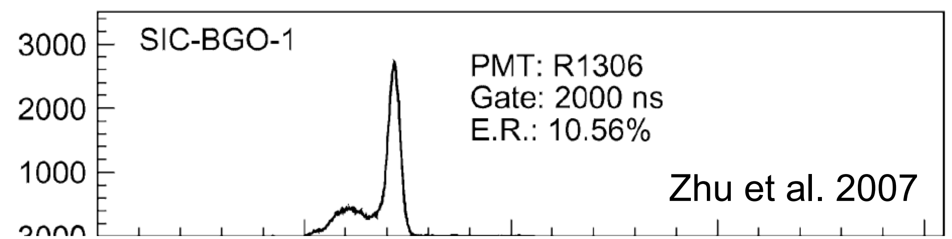
By means of the model we calculated the expected amplitudes and the expected peak times as a function of the integration time.



A very good agreement was found for the amplitude behavior.

Resolution vs RC





With the same source, for a small crystal readout by a PMT, a resolution of 10% was published (→ 100 p.e.).

The resolution obtained by integrating the whole charge provided by the PMT is independent of the RC and is about 14%.

Thus, at least 50 p.e. are produced, that is 75 p.e./MeV.

Taking into account that it is an L3 crystal readout by a 20 years old PMT this number seems reasonable.

The resolution obtained by looking at the peak amplitude improves with the square root of the fraction of the integrated charge *f* :

$$\frac{\sigma_A}{A} = 8\% \oplus \frac{12.6\%}{\sqrt{f}}$$

For $f \rightarrow 100\%$ the $\sigma_A/A \rightarrow \sigma_Q/Q$ as expected

First conclusion and future steps

The energy resolution of a BGO crystal was measured with a ^{137}Cs radioactive source.

From the resolution a light yield of at least 75 p.e./MeV was evaluated, i.e. a statistical contribution of 1.6% on the energy resolution at 50 MeV.

The behavior of the energy resolution with a preamplifier+shaper FEE was studied and it was found that the resolution essentially depends on the square root of the integrated charge.

Future steps:

1. Perform the same studies with a CsI crystal;

2. Acquire cosmic rays (released energy about 30 MeV);

2. Try a realistic FEE with tunable RC;

The BGO re-solution

Because of its large light yield (26% of the Lyso, 13% of the CsI(Tl)), BGO resulted as an interesting crystal also in the low energy region;

With an integration time of 100 ns, about 50% of p.e. are collected, i.e. at least 37p.e./MeV from our PMT measurements → 2.3% of statistical term at 50 MeV.

Measurements performed with APD showed a factor 4 larger light yields:

TABLE III
RESULT OF LIGHT RESPONSE UNIFORMITY WITH APD READOUT

Zhu et al. 2007

Sample	A end coupled to APDs		B end coupled to APDs	
ID	LO_{mid} (p.e./MeV)	δ (%)	LO_{mid} (p.e./MeV)	δ (%)
SIC-BGO	420	0 ± 2	430	1 ± 2
CTI-LSO	1,580	3 ± 2	1,610	-7 ± 2
CPI-LYSO	1,310	3 ± 2	1,320	-10 ± 2
SG-LYSO	1,610	5 ± 2	1,680	-4 ± 2

By using the APD values from this table the statistical term goes down to 1.0%

A more detailed measurement of the energy resolution with a pseudo-final readout should be performed.

Evaluation of the rad-Bhabha background

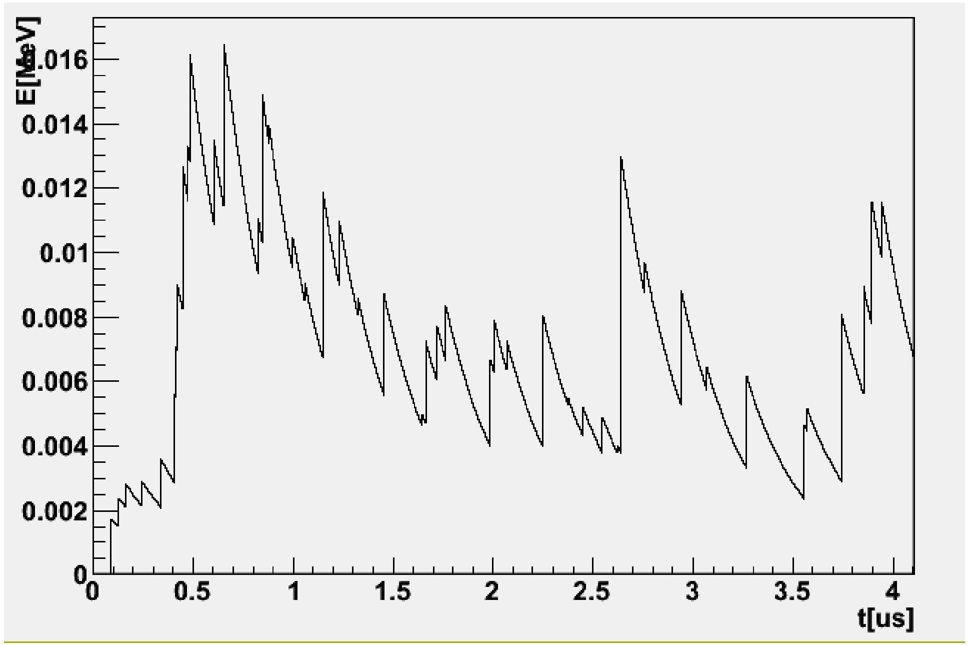
The effect of the noise on the energy has been simulated with a toy MC that:

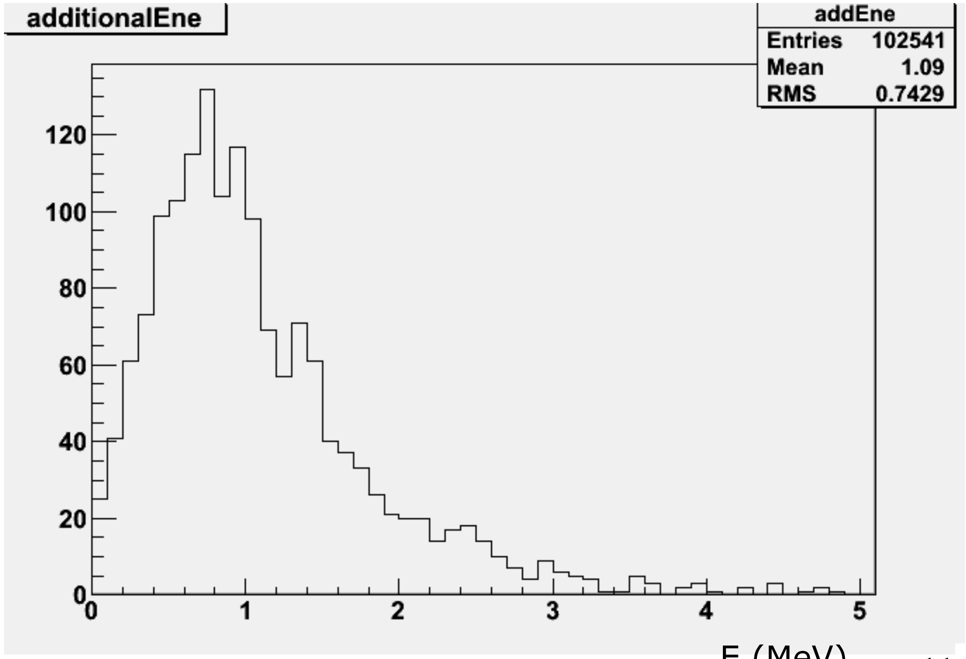
(1) produces, in 1ns bins, the expected release of energy as a function of time for each Xtal, using the suitable light decay time (T_{dec}) for each material;

(2) the integral is imposed to be E;

(3) in each time spectrum MC extracts windows as large as the shaper time and computes the energy in the window;

(4) the RMS of the energy deposition is quoted.





The EMC Rad-Bhabha background

With the latest results on the expected background at SuperB, we evaluated the effect of soft photons (rad-Bhabha) on the energy resolution.

The crystal density has an important impact on the calculated rates;

The total charge collected in 5x5 crystal matrices was evaluated for several “gates”:

RMS(MeV)	$T_{dec}=T_{shaper}$ =50ns	T_{dec}=300ns T_{shaper}=100	$T_{dec}=T_{shaper}$ =300ns	T_{dec}=1300ns T_{shaper}=600ns	$T_{dec}=T_{shaper}$ =1300 ns
central barrel (CsI geom)	N/A	N/A	N/A	0.5	1.0
worst barrel (CsI geom)	N/A	N/A	N/A	2.7	4.9
external FWD (LYSO geom)	0.1 (no bias) 0.2 (CsI)	0.2 (no bias)	0.3	N/A	N/A
internal FWD (LYSO geom)	0.7 (no bias) 1.4 (CsI)	0.7	1.2	N/A	N/A

The situation in the barrel is quite worst than in the FWD, also for a BGO solution with a shaping time of 300 ns.

BGO radiation hardness

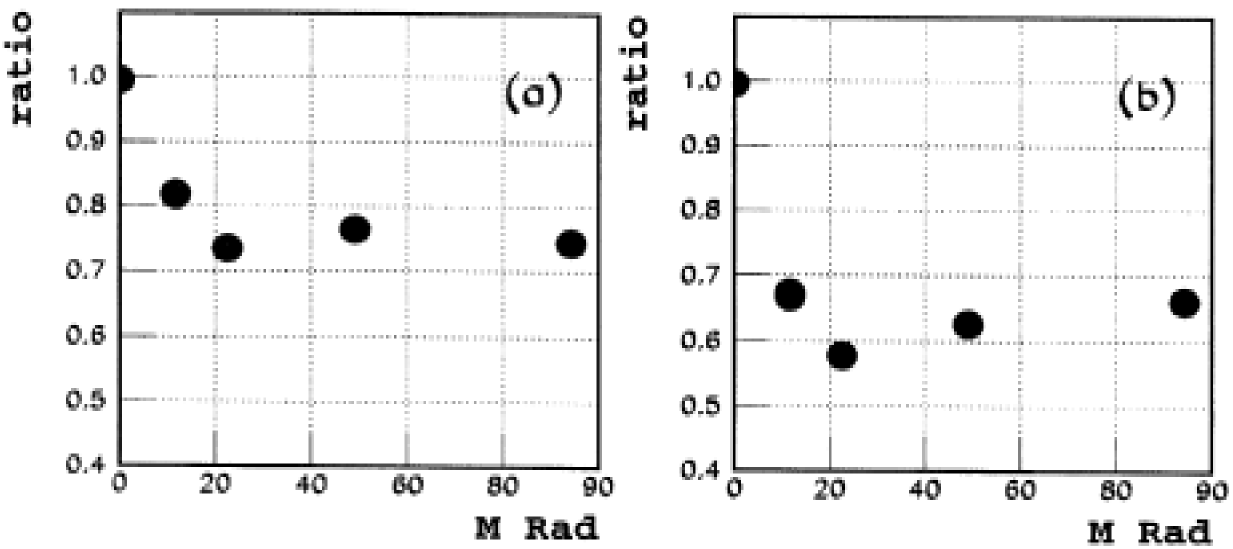
Babar accumulated 750-1200 Rad with a light yield loss between 10% and 15%;

According to the latest simulation, a dose of 1600/2500 Rad/year is expected in the barrel/FWD;

BGO rad-hardness was tested up to 90 MRad.

After a drop of 20%-30% for a dose of 10-20 Mrad, the light yield is stable up to 90 Mrad.

Belle decided to pre-irradiate all crystals.



Lyso and pure CsI showed good behavior after 20 kRad;

Some more aging tests on crystal samples can be carried out at the ENEA-Casaccia Calliope irradiation facility (800 TBq ^{60}Co source);

Readout

Pure CsI must be operated with photo-triode or photo-pentode whose price may be non-negligible;

BGO, Lyso and CsI (Tl) can all be operated with APD or PD:

	av. QE - PMT	av. QE - APD/PD
BGO	8.0 ± 0.4 %	82 ± 4 %
LYSO	13.6 ± 0.7 %	75 ± 4 %
CsI (Tl)	5.0 ± 0.2 %	84 ± 4 %

Costs

The cost of BGO is about 9$/cm^3 while Lyso is about 30 and pure CsI about 4.

Because of the difference in X_0, effective cost of pure CsI is about 70% of the BGO one and 22% of the Lyso;
We are also studying the possibility of re-use L3 crystals;

Mechanical refactoring (cleaning and cutting) would cost about 150$/piece → about 1.5 $/cm^3;

Availability of L3 crystal is under investigation.

Summary

- From the point of view of the radiation hardness and energy resolution+background effect, Lyso, BGO and pure CsI (operated with pentodes or triodes) seem to be all viable solutions.
- Let's suppose to equip all the 9 rings;
- Because BGO and Lyso have a mass density double of the CsI, in all cases we can think to save the mechanical structure by putting 4 crystals per cell;

Material	# of Xtals	Valume (cm^3)	Cost/cm^3	Cost*	Read-Out
Pure CsI	900	800	4$	3 M$	PP-PT ?
LYSO	3600	120	30$	13 M$	APD/PD
BGO	3600	120	9$	4 M$	APD/PD
BGO-L3	3600	120	150$/Xtal	0.5 M$	APD/PD

* The cost doesn't include the readout.

Conclusion

Measurements showed that working with an integration time shorter than the crystal proper time is feasible and that the resolution follows the poissonian fluctuation of the number of collected photoelectrons;

This may help in reducing the very large effect of background in the barrel.

BGO has interesting properties:

- High light yield also in the low energy region;
- Scintillation time compatible with the expected photon background;
- Good radiation hardness to operate in SuperB;
- A good price.

It's thus worth going on with studies on BGO as a real possible, less expensive alternative to the Lyso. Proposal for further studies:

- Ageing test (at Casaccia);
- Try a realistic FEE with tunable RC;
- Measurement of performance with test-beam;

A 100 xtal matrix (currently instrumented with PMTs) is available in Roma.

Back-up

Main characteristics of crystals

Table 28.4: Properties of several inorganic crystal scintillators. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	$\tau_{\rm decay}$	$\lambda_{\rm max}$	$n^\natural$	Relative output†	Hygro- scopic?	d(LY)/dT
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	83	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

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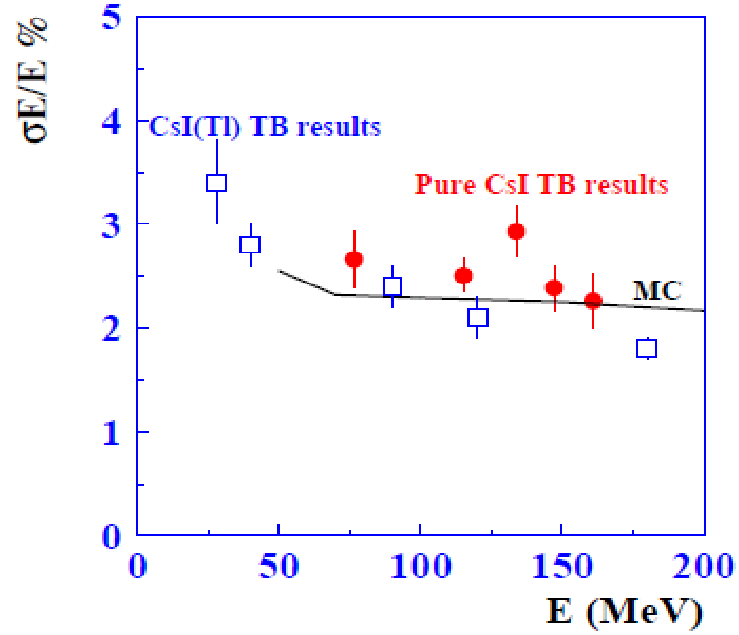
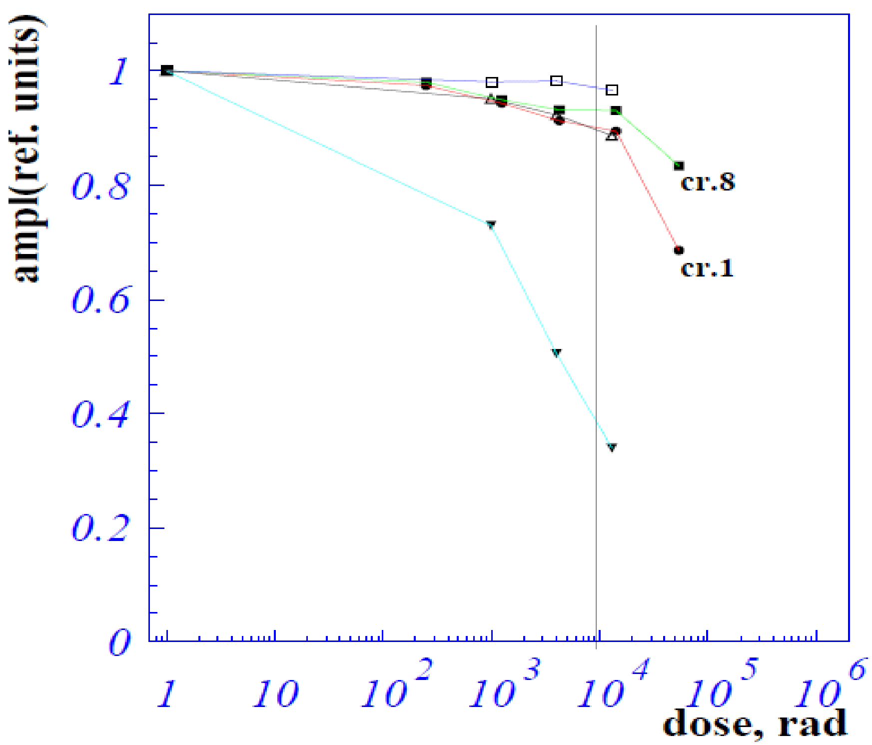
Pure CsI performance



Resolution of pure CsI with PP readout seems compatible with the one obtained with CsI (Tl)

Belle people has measured the radiation hardnes of the pure CsI up to a total dose 10^5 Rad.

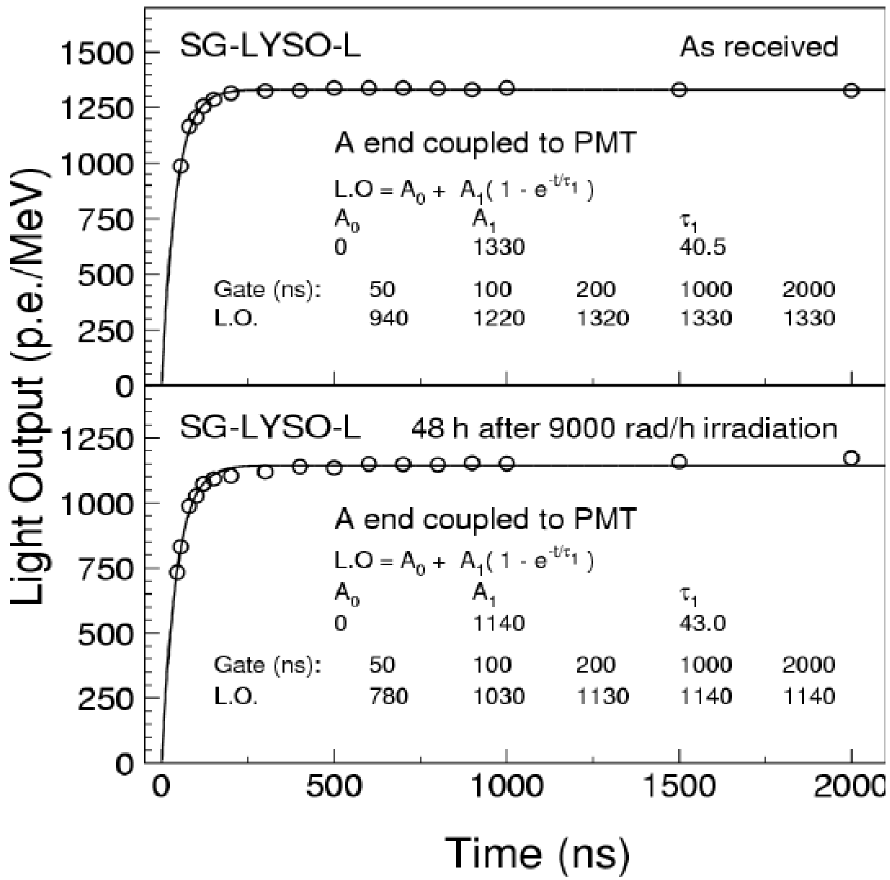


Except for a very strange crystal, light output losses of about 10% after 10 kRad.

New tests are foreseen to understand the differences.

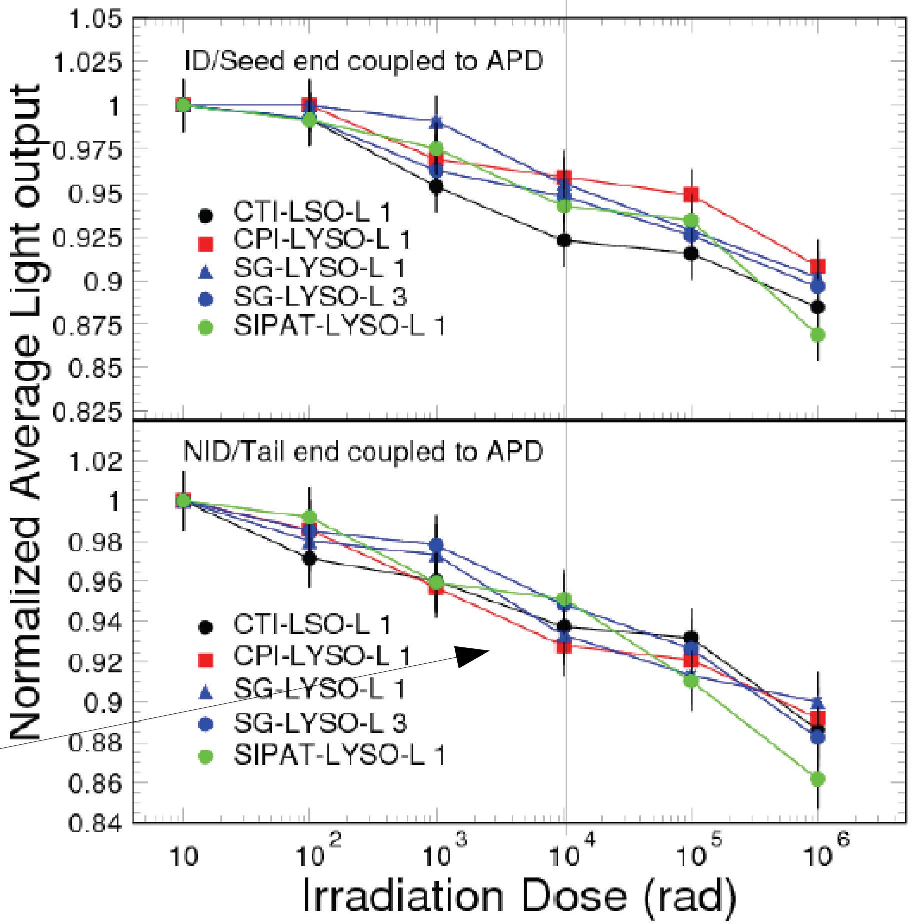
Lyso radiation hardness

Radiation hardness measurements performed by Ren-yuan:



After an irradiation of 9 krad/h x 22h = 0.2 Mrad 86% of light yield (with PMT).

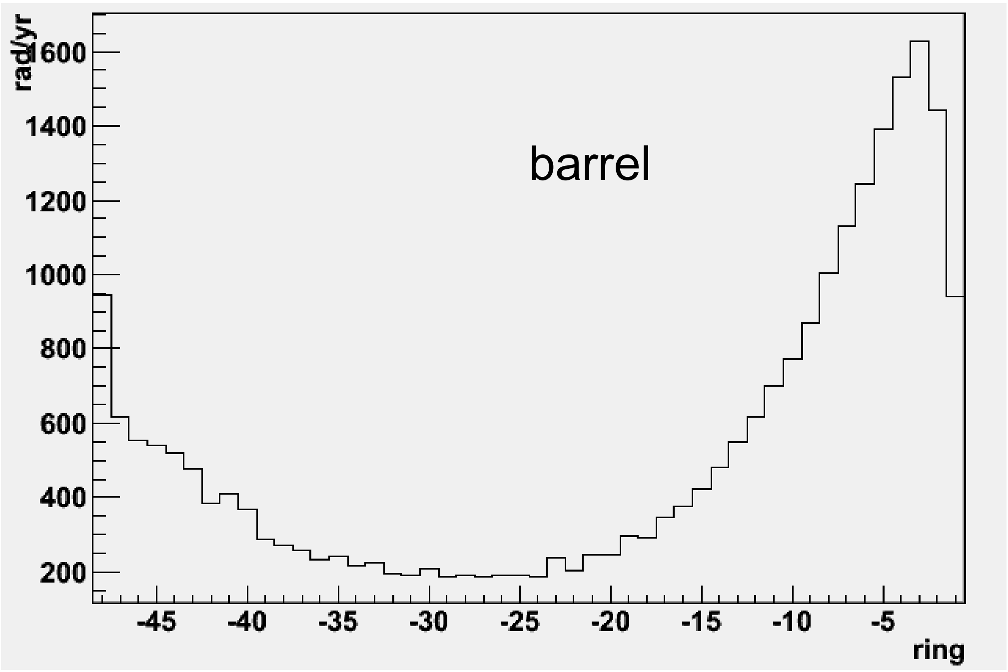
9% - 14% loss by APD

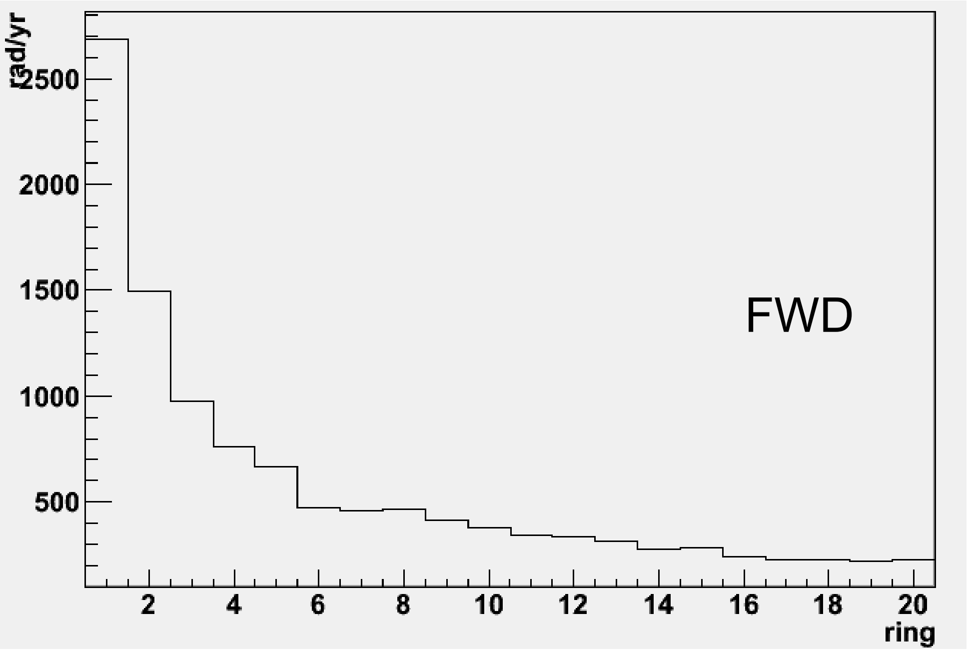


Results confirmed by more detailed tests performed up to 1 Mrad: 10%-15% loss

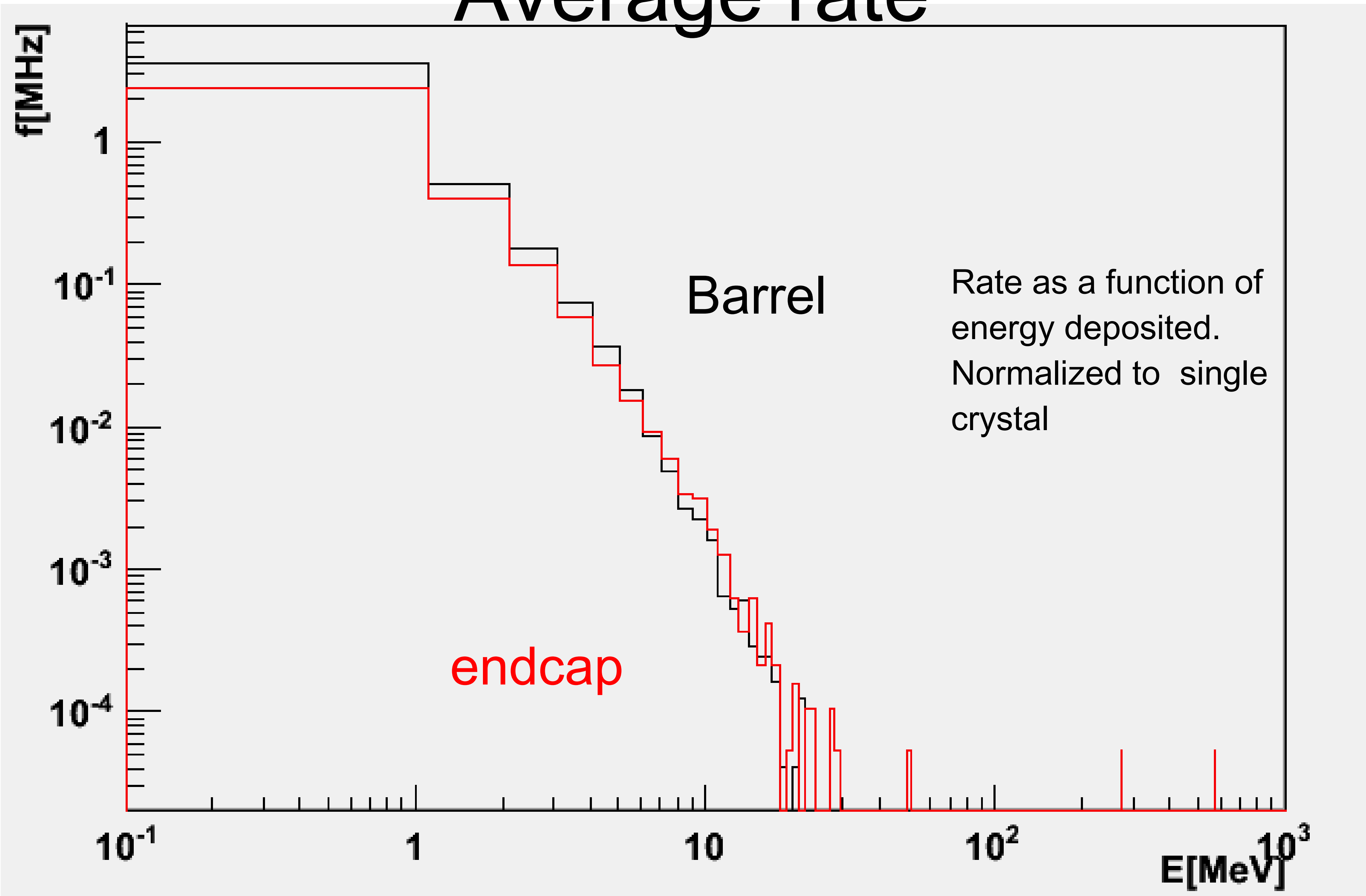
5% - 10% after 10 kRad

Expected dose

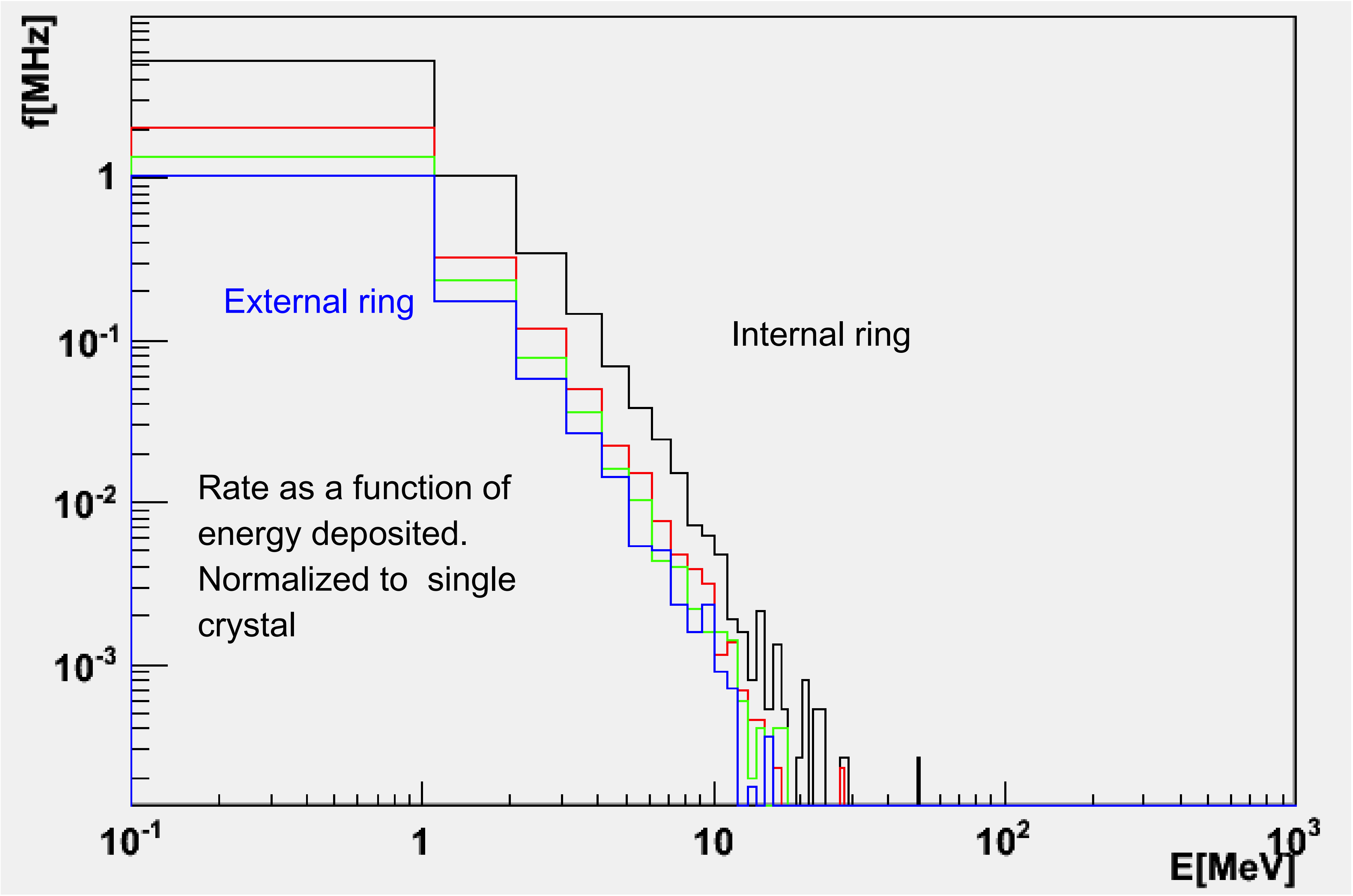




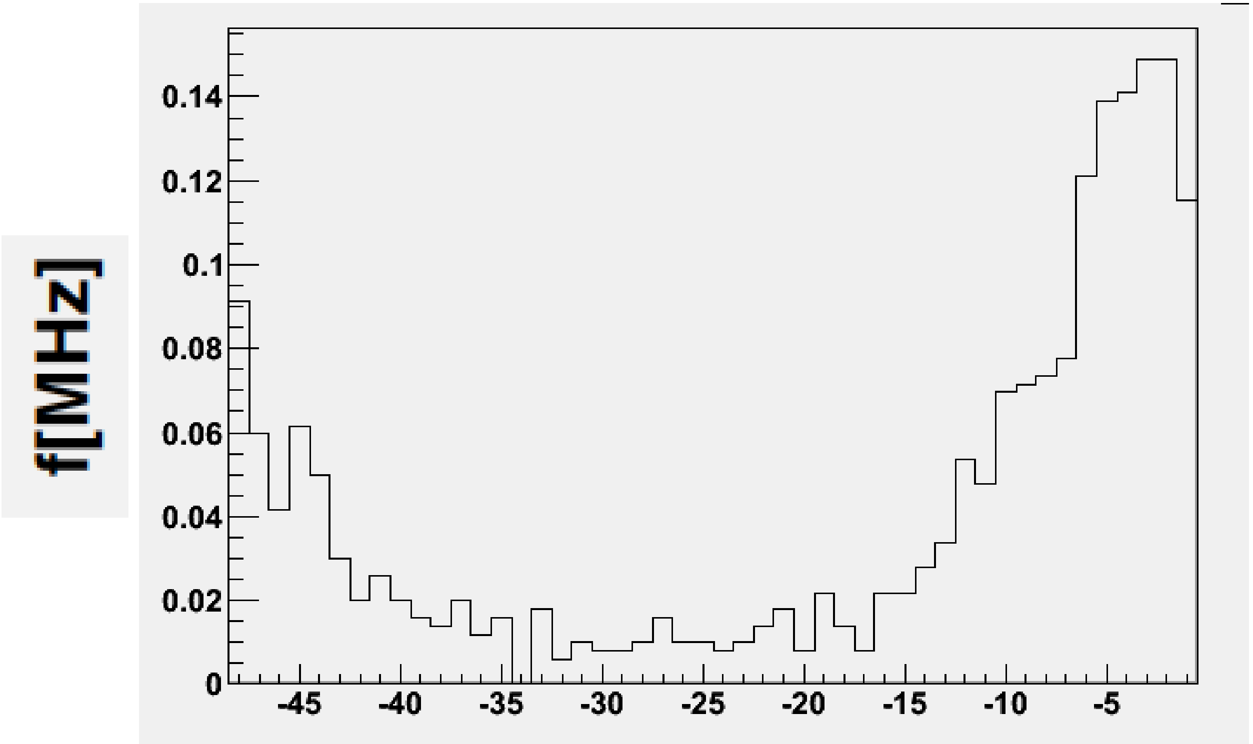
Average rate



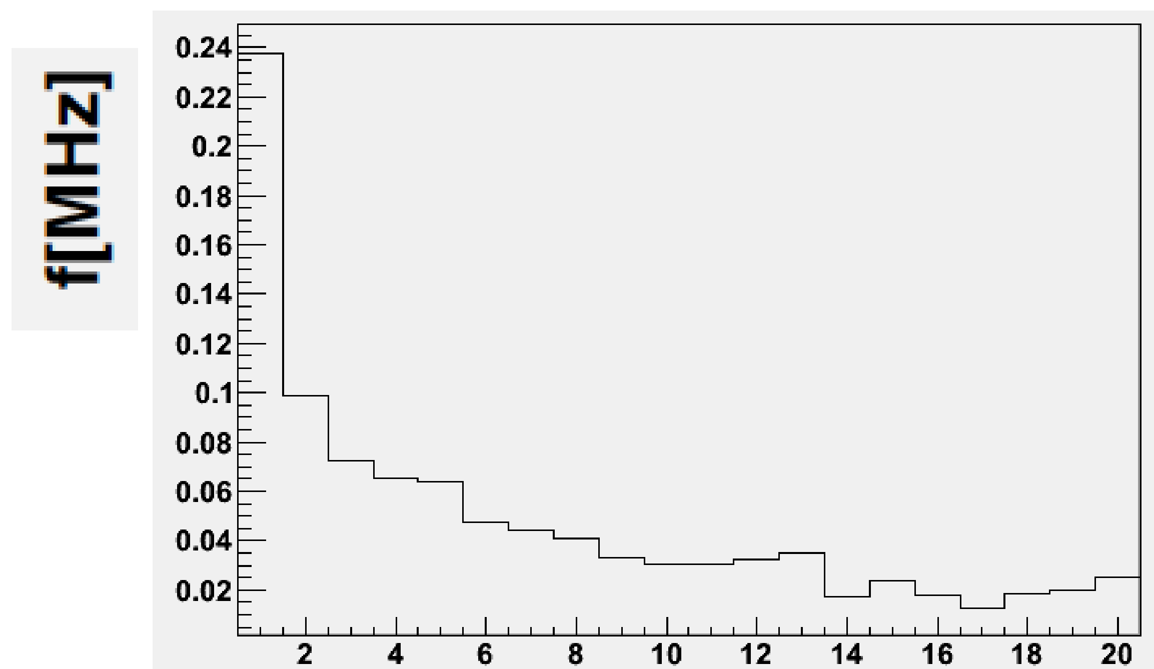
Rates in forward



Ring by Ring Requiring E>5MeV



Ring



Rate as a function of energy deposited. Normalized to single crystal