

# Performance Characteristics of Frisch-Grid CdZnTe Detectors

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## Talk outline

### Introduction

1. Operating principle of virtual Frisch-grid devices
2. Expected and actually measured device performance
3. Factors responsible for device performance degradation:
  - effect of non-uniform E-field
  - effect shielding inefficiency
  - effect of device thickness

### Conclusion

# CZT Virtual Frisch-Grid (Bar) detectors

## Bar-shaped CZT crystal

3x3x6 mm<sup>3</sup>, 4x4x8 mm<sup>3</sup>, 5x5x10 mm<sup>3</sup>,  
8x8x16 mm<sup>3</sup>

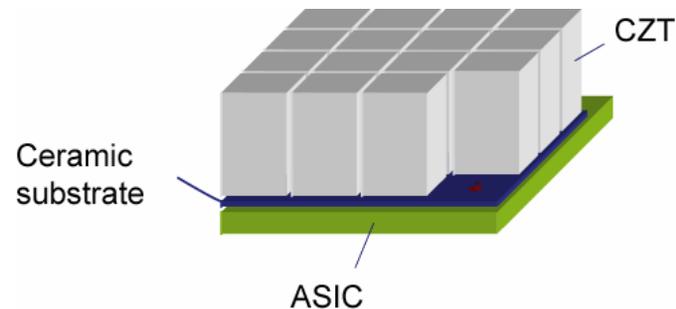


The operating principle of the device was proposed by D. McGregor, KSU and experimentally demonstrated by Montémont et al, LETI, France

**Drawback** of this technique is that it is a kind of substitution of pixel device. Pixel device approach, which takes full advantage of highly expensive CZT material, is the mainstream of CZT detector developments.

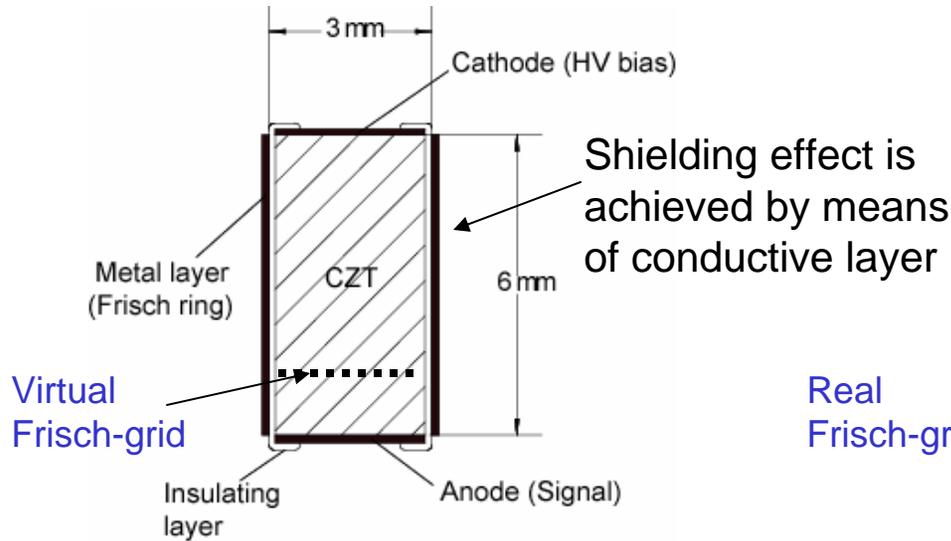
## Advantages of bar-shaped detectors:

- made of easy-to-produce and least expensive CZT crystals;
- provide good energy resolution and high stopping power due to large thickness of CZT crystals;
- can be assembled in large area arrays for imaging and spectroscopy of gamma-radiation.

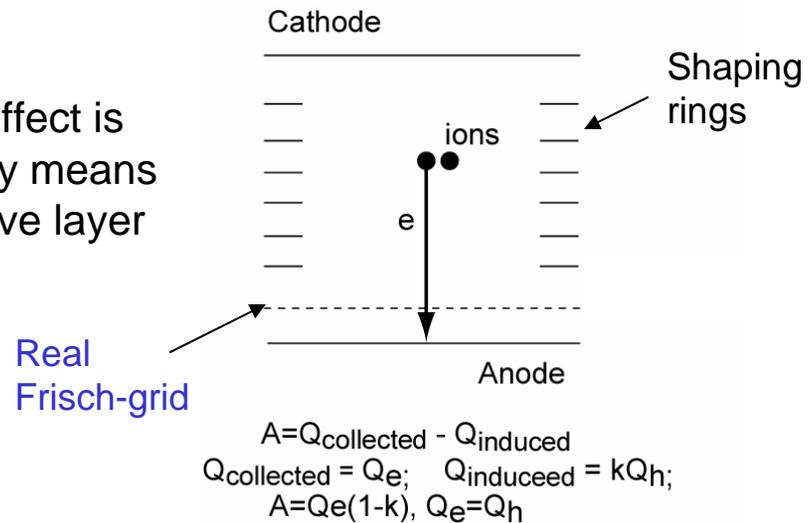


## Schematic of virtual Frisch-grid (bar) detector

Single carrier device



Gas ionization chamber

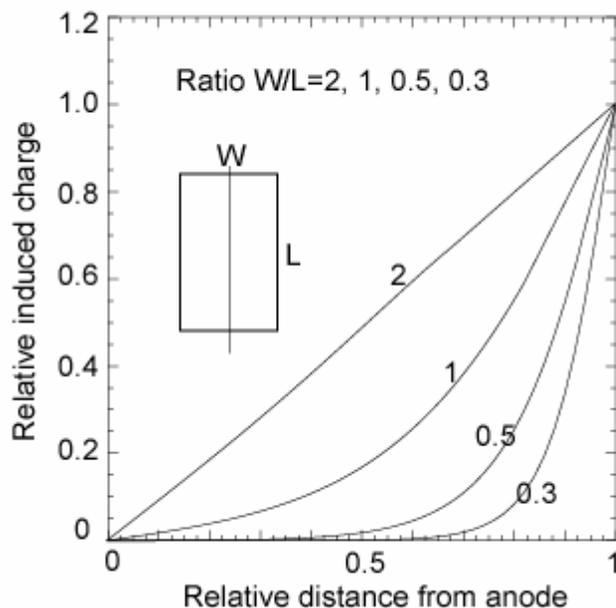


Certain geometrical aspect ratio,  $W/L$ , is required to achieve good shielding efficiency.

The surface conductivity of CZT crystal plays the same role as shaping rings in gas ionization chamber

Surface leakage current provides gradual change of potential on the surface which results in uniform electric field distribution inside the detector.

## Calculated dependence of the induced charge versus distance from anode



We used a standard solution for the electrostatic potential created by a point-like source charge inside the grounded metal box.

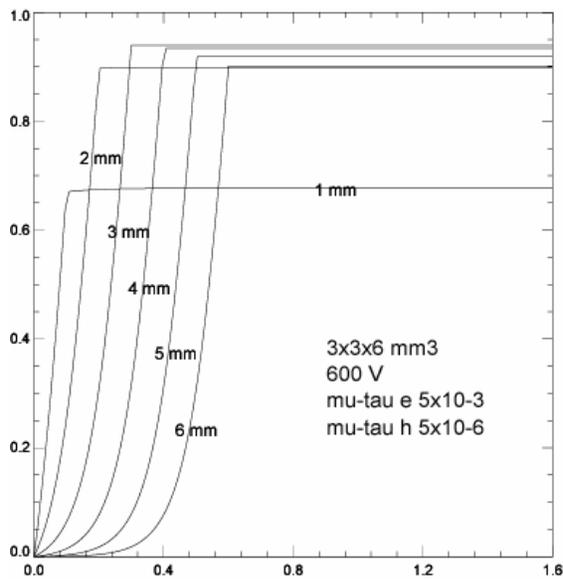
Plots were calculated for the charges located on the central axes of the box and different aspect ratios:  $W/L$ .

At large aspect ratios the dependence is linear => planar detector.

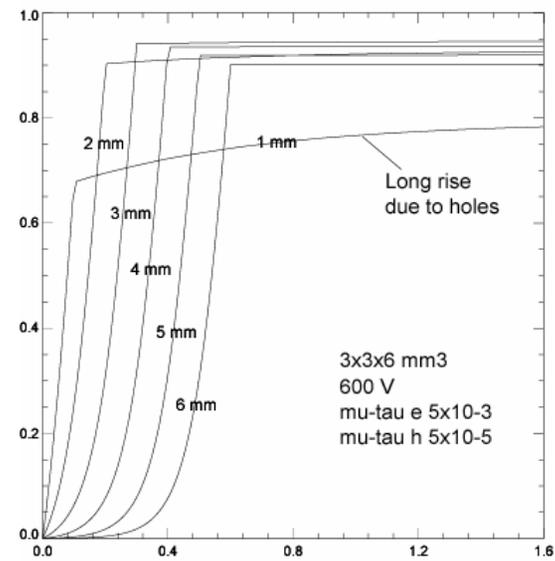
At small aspect ratios the anode charge is induced when the source charge is located close to the anode => indicates formation of virtual Frisch grid.

Calculated dependence of the output waveforms versus point of interaction (distance from the cathode) for 3x3x6 mm<sup>3</sup>

Typical hole mu-tau



Unrealistically high hole mu-tau

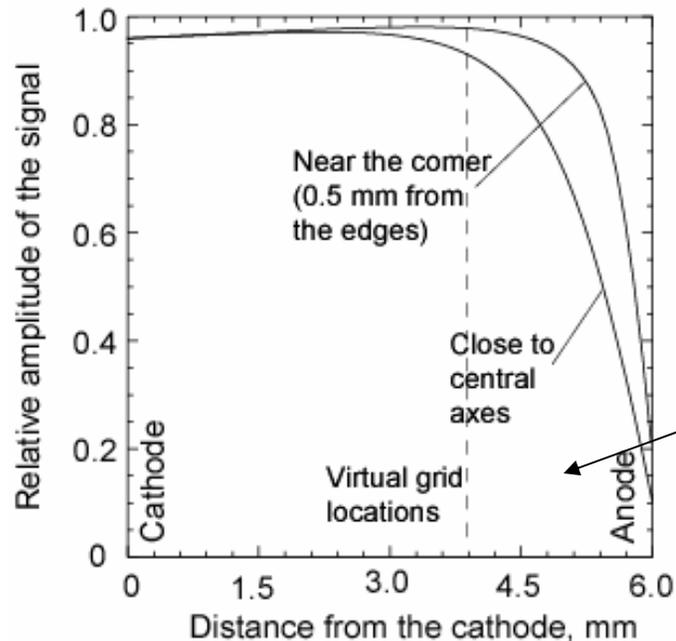


Amplitude of the signals slightly depends on the point of interaction due to shielding inefficiency and charge trapping.

No slow-rising part of waveforms due to hole collection is expected!

## Calculated dependence of the signal amplitude versus point of interaction

3x3x6 mm<sup>3</sup> bar detector



The shape of the curves indicates the compensation effect between the charge loss due to trapping and shielding inefficiency. Also observed for coplanar-grid and pixel detectors.

Used properties of typical of CZT crystal:

electron  $\mu\tau=5\times 10^{-3}$  cm<sup>2</sup>/V

electron  $\mu=1000$  cm<sup>2</sup>/Vs

hole  $\mu\tau=5\times 10^{-6}$  cm<sup>2</sup>/V

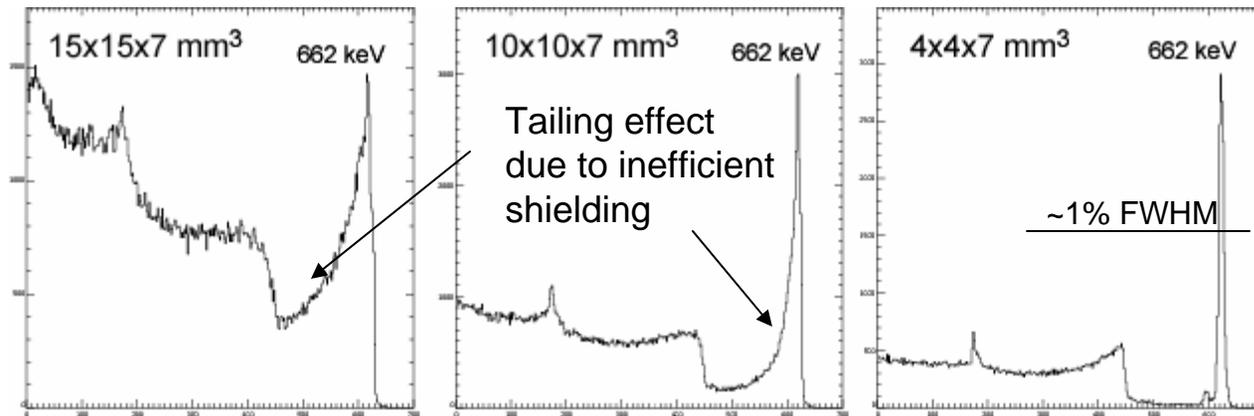
hole  $\mu=50$  cm<sup>2</sup>/Vs.

Cathode bias 1500 V

For the events interacting in this region, output signals depend on point of interaction which causes tailing effect.

To make this region smaller, it is desirable to have a longer detector with smaller aspect ratio. However, there are other factors that limit thickness of the detector, e.g., maximum applied bias, electron trapping, strong electron diffusion. Optimal detector design is a trade off between all these factors.

## Simulated pulse-height spectra for several detector geometries: 15x15x7, 10x10x7, and 4x4x7 mm<sup>3</sup>



### Characteristics of typical CZT crystal:

Electron  $\mu\tau=5\times 10^{-3}$  cm<sup>2</sup>/V

Hole  $\mu\tau=5\times 10^{-6}$  cm<sup>2</sup>/V

Cathode bias 1500 V

Electronic noise 2 keV FWHM

Use Monte-Carlo code to trace photons and exact solution for 3-D weighting potential to calculate charge signals.

We simulated geometry of the real experiment with the uncollimated source located on the cathode

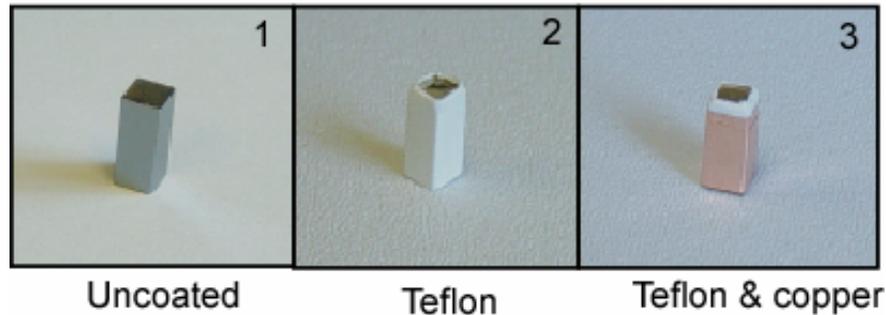
These spectra illustrate improvements in detector response with reduction of the detector width.

For the small detector ~1% energy resolution at 662 keV and high Peak-to-Compton ratio were obtained.

This demonstrates that we can expect an excellent performance from the bar detectors with aspect ratio less than 0.5.

# Detector fabrication and experimental setup

Fabrication steps of CZT bar detectors



CZT crystals are from eV-Products, Saint Gobain, Yinnel Tech., and Freiburg University. Samples were re-shaped into bar detectors with different aspect ratios

Re-fabricate new detectors by using the same CZT crystals.

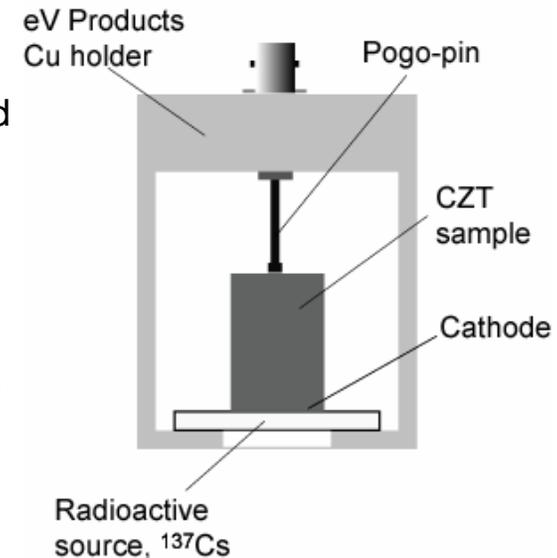
No dependence of shield bias on detector response was observed.  
=> Cathode and Cu shield were connected together.

We used standard spectroscopy electronics to collect pulse-height spectra and a digital oscilloscope to measure waveforms readout from a charge sensitive preamplifier.

In the beginning of the project we observed significant variations in the pulse-height spectra measured with our detectors which can be rated from excellent to very bad. Later we learn how to fabricate good devices with ~100% yield.

## Experimental setup

Bar detector inside eV-Products holder

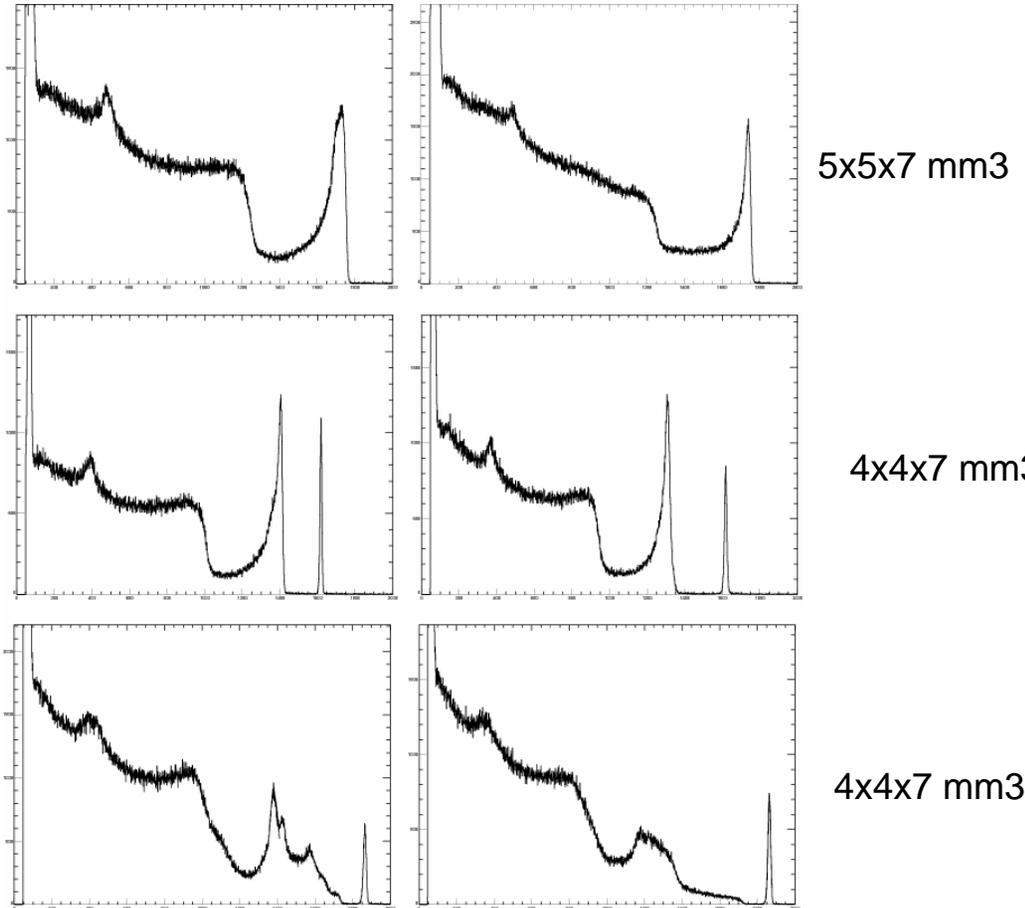


Source located inside the holder to ensure that photons enter detector from cathode side.

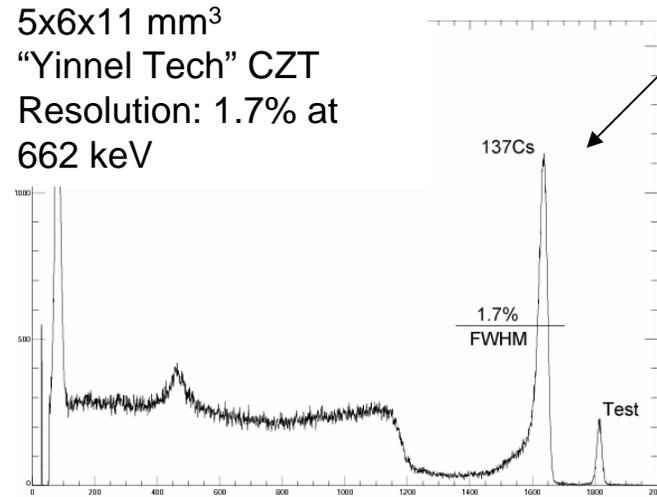
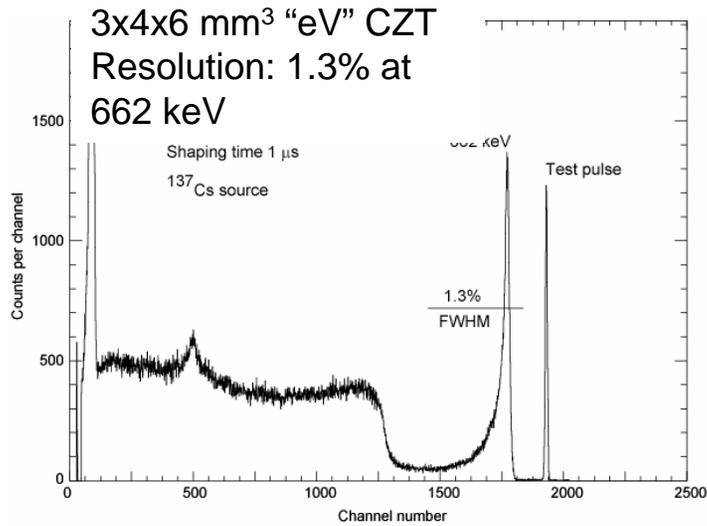
## Examples of pulse-height spectra measured with detectors that had poor performance

Satellite peaks, strong tailing, and low-energy background are very common features in the spectra from the “bad” detectors.

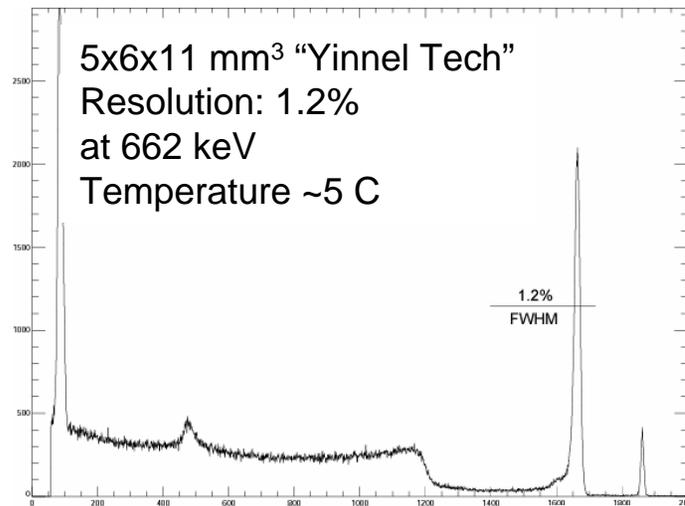
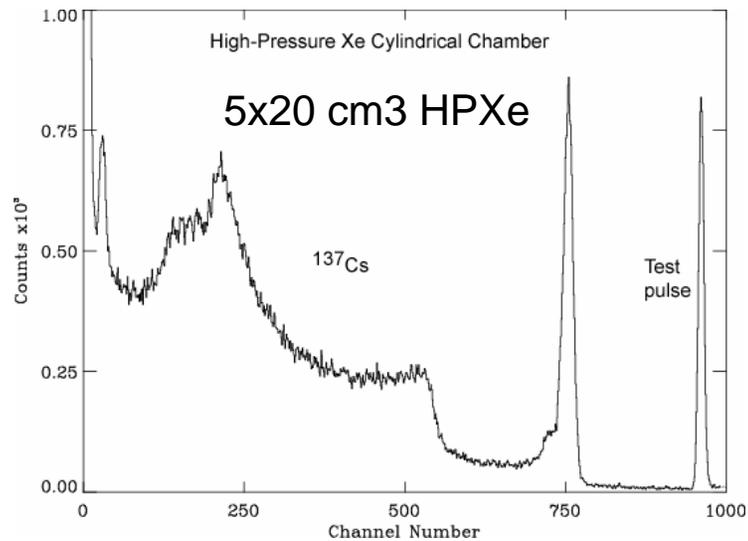
We found, that detectors re-fabricated from the same crystals had different responses. This suggests that internal crystal defects cannot completely explain poor detector responses.



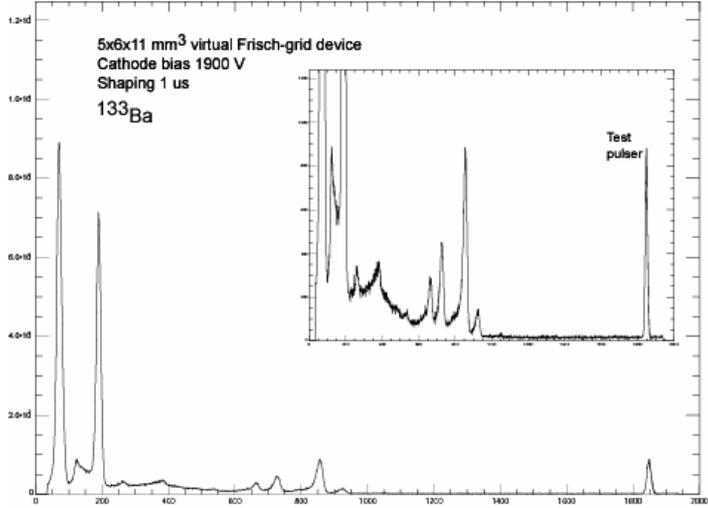
# Pulse-height spectra measured with a “good” detectors



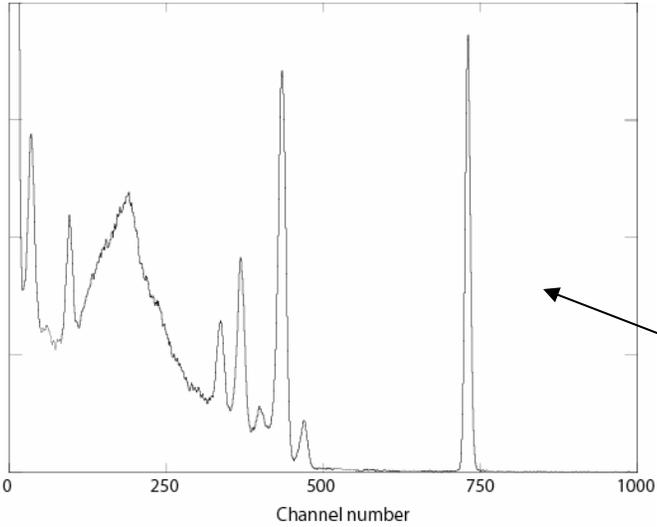
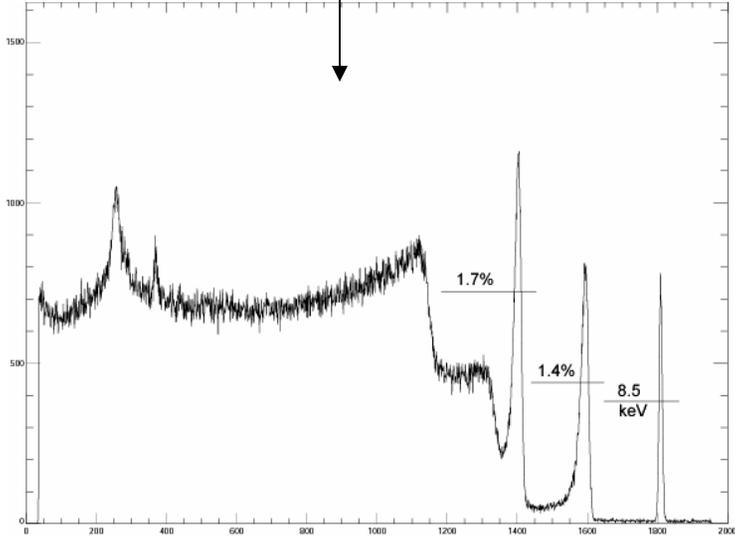
We expected better result



Good 5x6x11 mm<sup>3</sup> detector

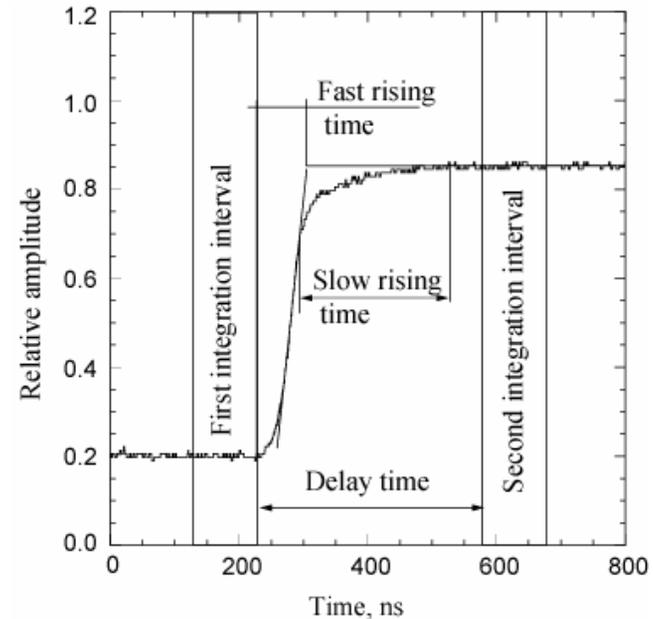
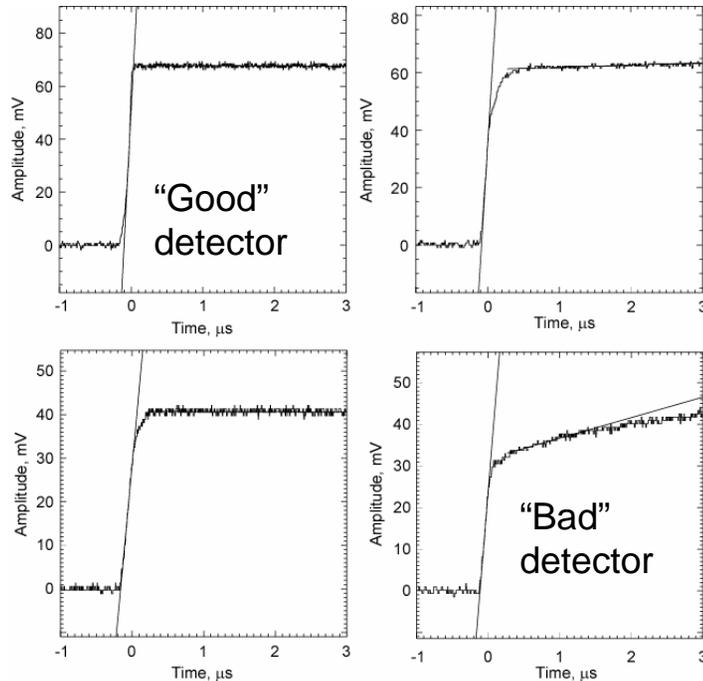


5x6x11 mm<sup>3</sup> “Yinnel Tech  
<sup>60</sup>Co and <sup>133</sup>Ba sources at room  
temperature



5x20 cm<sup>3</sup> HPXe  
<sup>133</sup>Ba sources at room temperature  
Density 0.3 g/cc

## Waveforms analysis

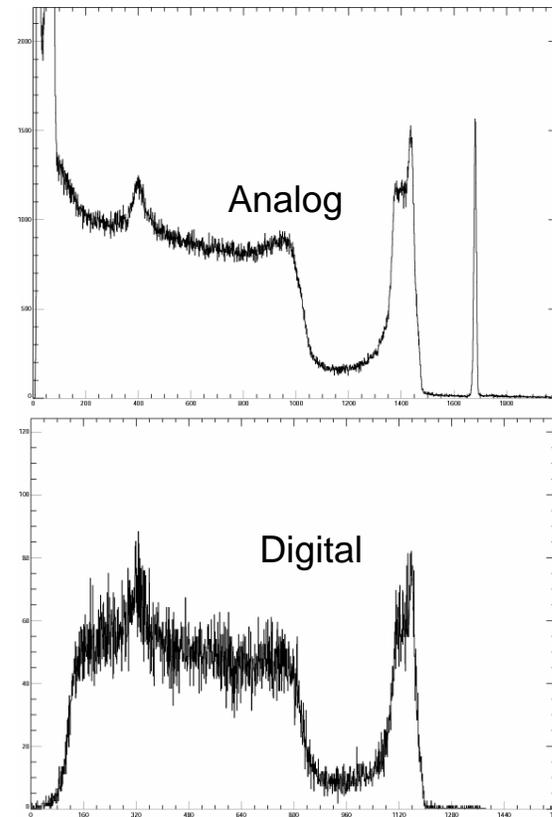
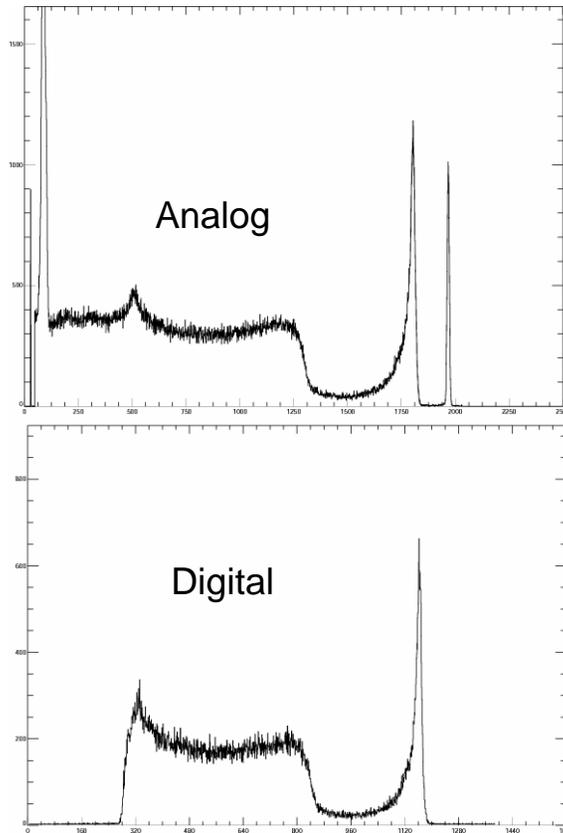


We found that waveforms measured with "good" detectors typically have fast rising edges (small rounding is due to preamp response function and diffusion).

For "bad" detectors, the majority of the events have two rising slopes: fast and slow. The slow rising component is the only difference between "good" and "bad" detectors.

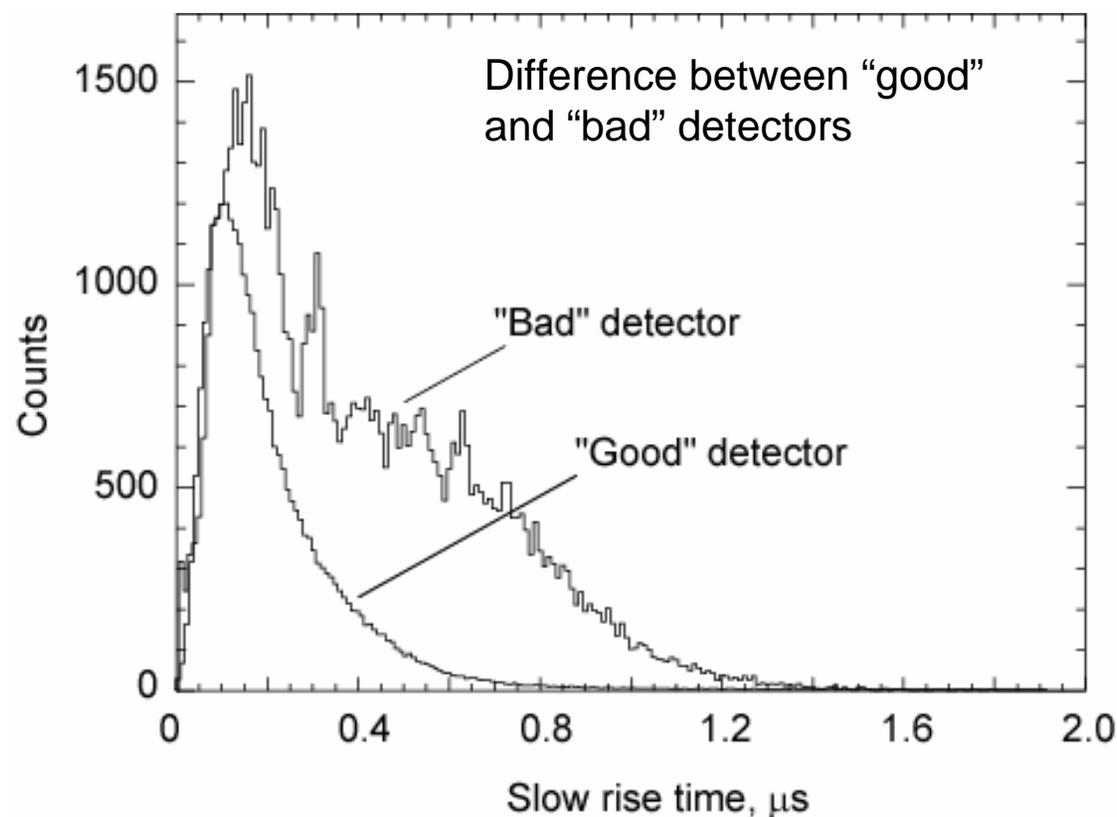
We developed an algorithm that analyze each pulse and evaluates the fast and slow rise times, and amplitude of the signal.

## Comparison of analog and digital pulse processing to check the algorithm



Waveform analysis turned out to be a powerful tool for understanding the processes inside the detectors.

## Slow-rise time distribution evaluated for “bad” and “good” detectors



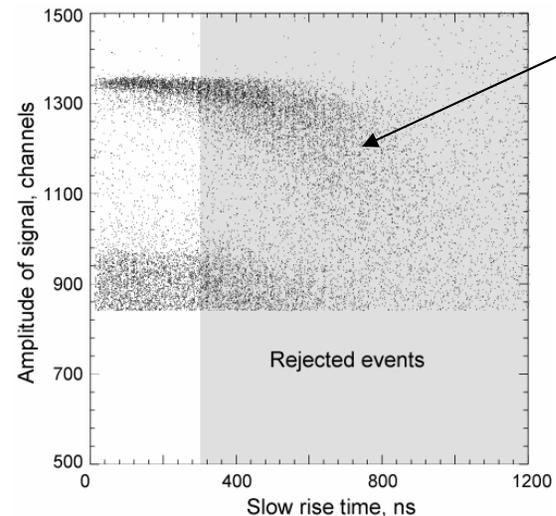
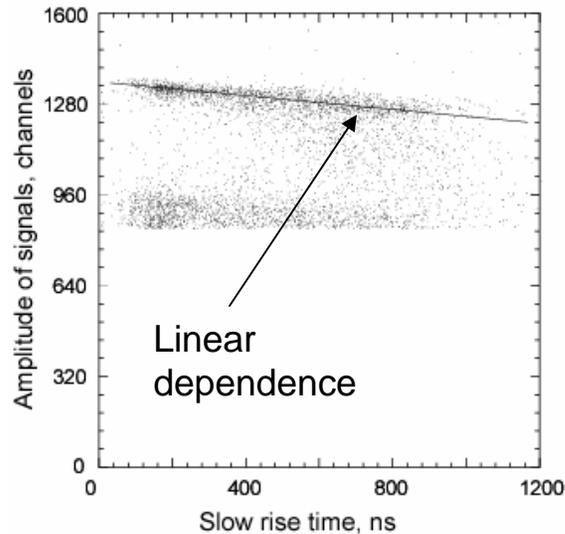
The fraction of slow-rising events in a “good” detector is significantly less than in a “bad” one.

Slow rise time exceeds several  $\mu\text{s}$ .

One of the problems associated with slow-rising events is ballistic deficit due to the limited shaping time of amplifier.

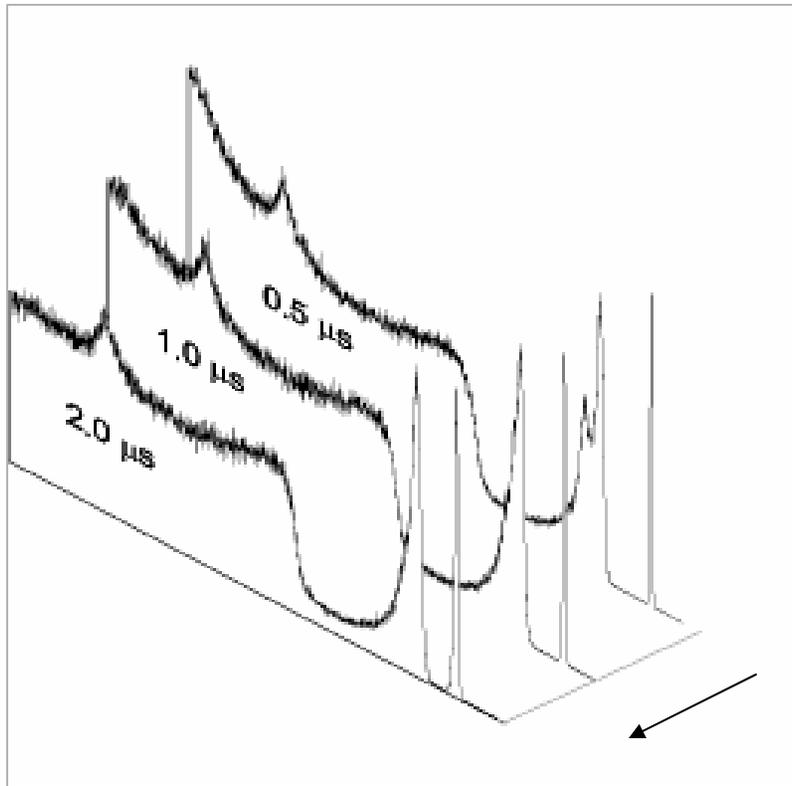
The second problem is charge loss due to trapping.

## Effect of slow-rising events on detector performance (correlation between amplitude of signal and slow-rise-time)



For “bad” detectors, amplitude decreases as liner function of time which could be simply explained by ballistic deficit, but broadening of the dots distribution indicates fluctuations of the charge loss due to the trapping!

## Improvement of “bad” detectors response by using long shaping time

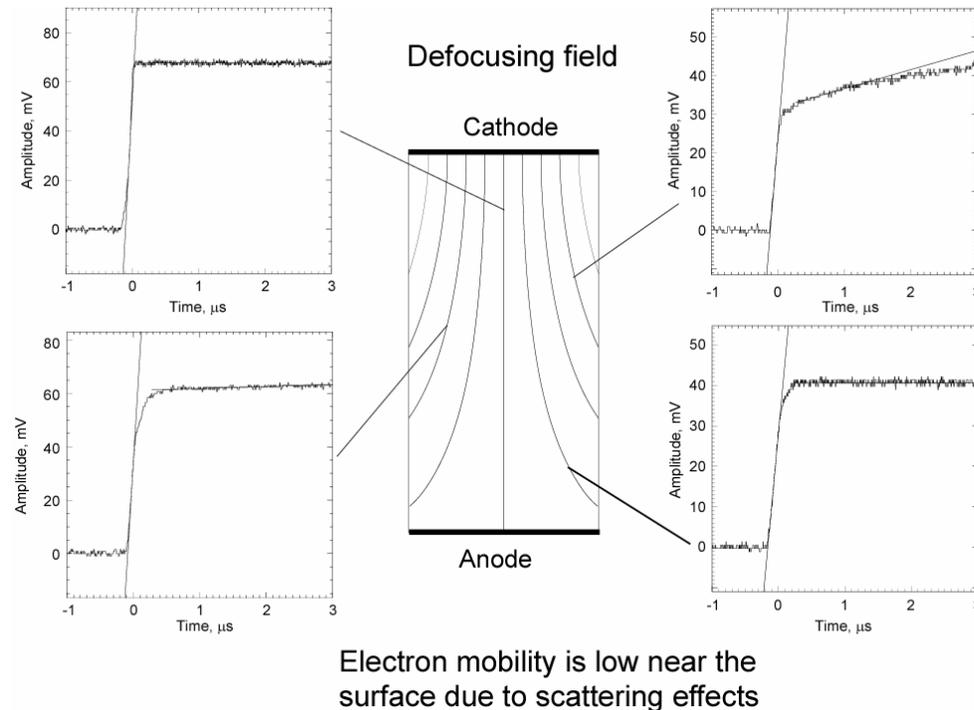


However, longer shaping time did not solve the problem completely. FWHM is still ~3-4%.

In addition, long shaping time results in large electronic noise.

## What is the origin of “slow drift regions”?

We found strong indications that slow rising events are caused by the specific distribution of the electric field inside the detectors (if exclude the material defects)



The field lines distribution is determined by the boundary conditions on side surfaces which depends on surface resistivity.

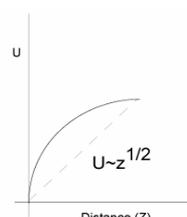
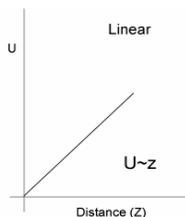
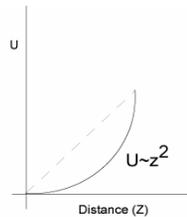
# Calculations predict three possible field distributions inside a bar-shaped detector (focusing/defocusing)

Changes of electrostatic potential along the surface →

Superlinear

Linear

Sublinear

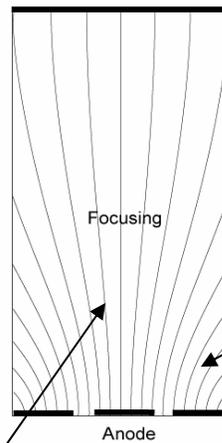
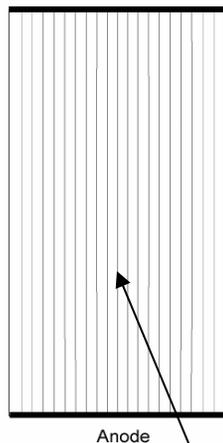
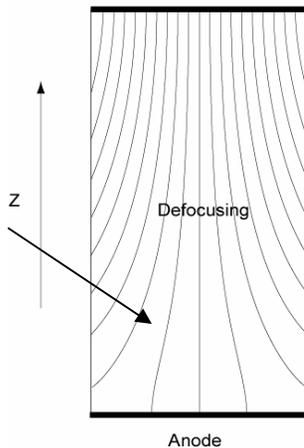


Cathode

Cathode

Cathode

“Bad” detector



“Good” detectors

Focusing field is more preferable because:

electrons will be directed toward the anode and away from side surfaces.

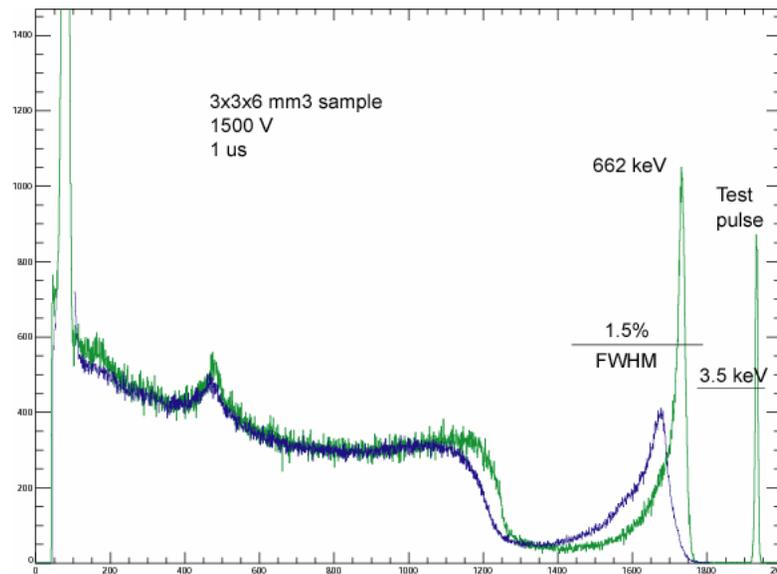
Minimize edge effects

In this case the anode contact can be smaller.

Two experimental facts support this point of view.

# 1) Improvement of detector response after chemical treatment of the side surfaces

The first fact is that detector performance depends on the surface quality and surface passivation.

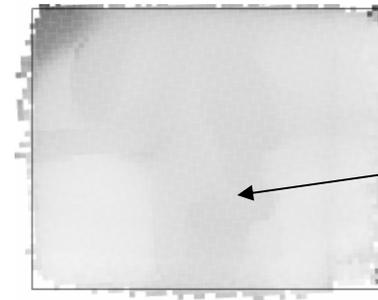
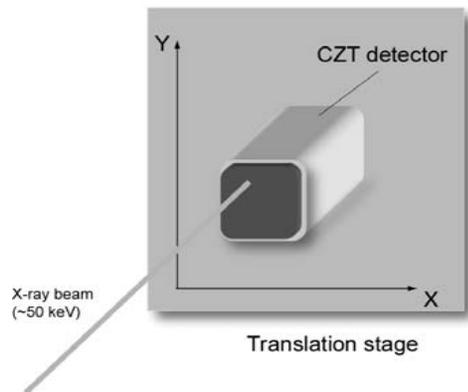


Improvement of the detector response after surface treatment with  $\text{NH}_4\text{F}/\text{H}_2\text{O}_2$  (ammonium fluoride) solution (proposed by G. Wright)

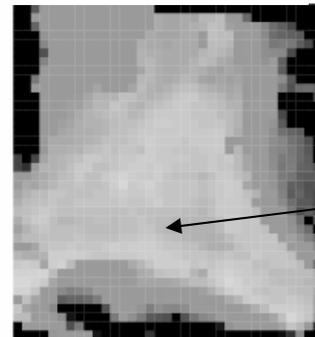
## 2) X-ray scan of virtual Frisch-grid detectors

National Synchrotron Light  
Source at BNL:

X-ray beam characteristics:  
high intensity  
highly collimated  
up to 90 keV  
focused down to 10x10  $\mu\text{m}$



“Good”  
3x4x6 mm<sup>3</sup>  
bar detector



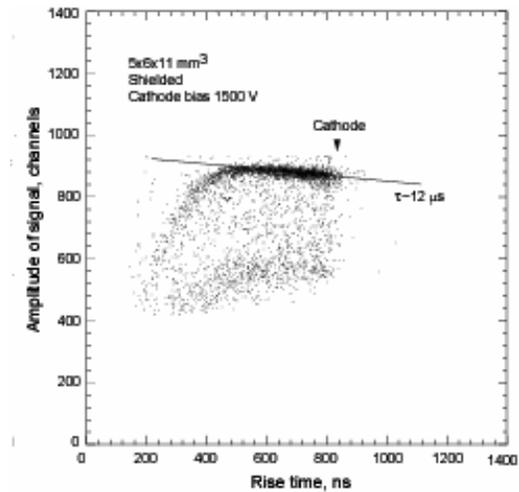
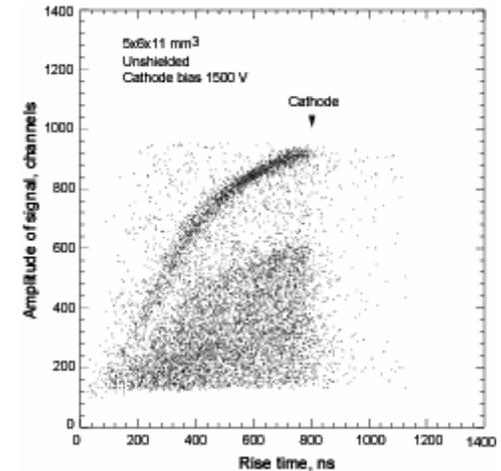
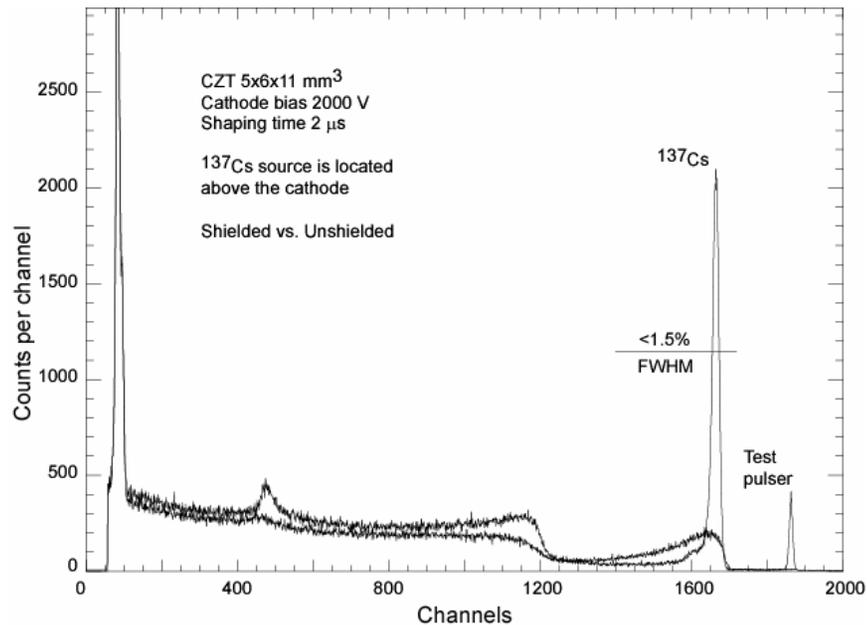
“Bad”  
3x3x6 mm<sup>3</sup>  
bar detector

To conclude this part of the talk: de-focusing field is the main factor that degrades the response of bar detectors. Solution: correct surface preparation and passivation. Unfortunately, there are other effects degrading the device response.

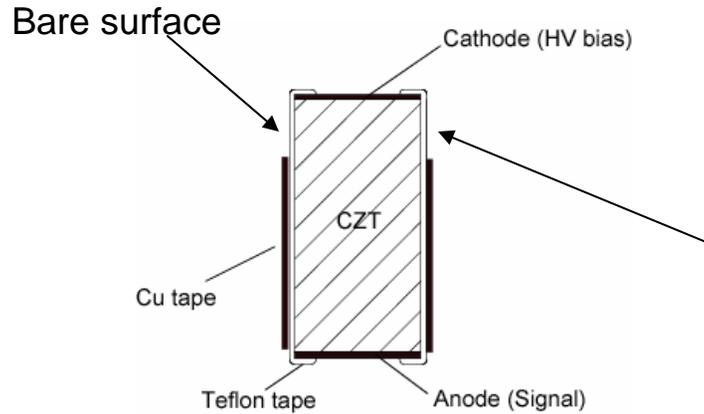
## Second factor: effects of poor shielding (illustrated on several examples)

To achieve good shielding it is important: 1) use very thin insulating layer (place the metal shield as close as possible to the CZT surface); 2) cover an entire area of the surface.

5x6x11 mm<sup>3</sup> bar detector with and without the shield

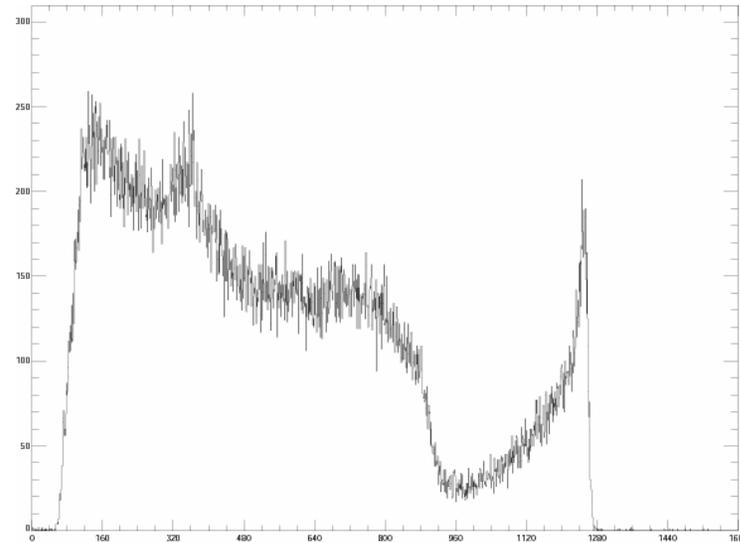
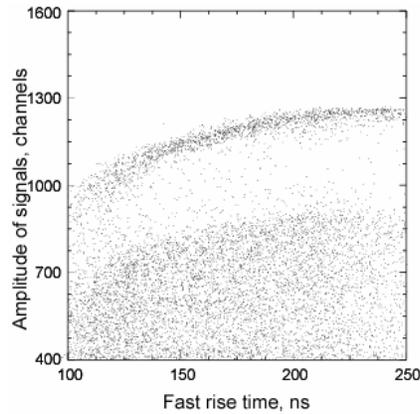


## Shielding efficiency of the virtual Frisch-grid

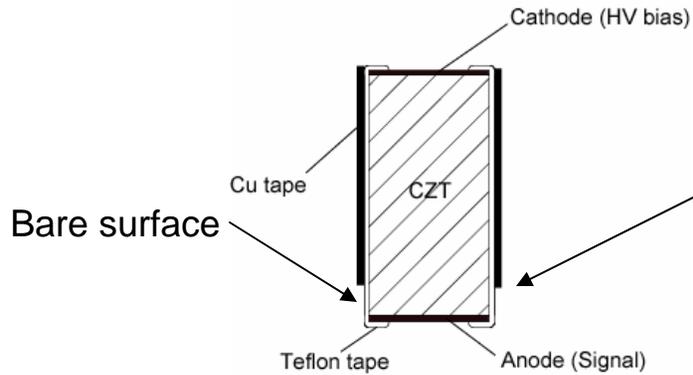


A “good” detector which had a ~1-mm gap of bare CZT surface between the cathode and the Cu shield (6-mm thick device).

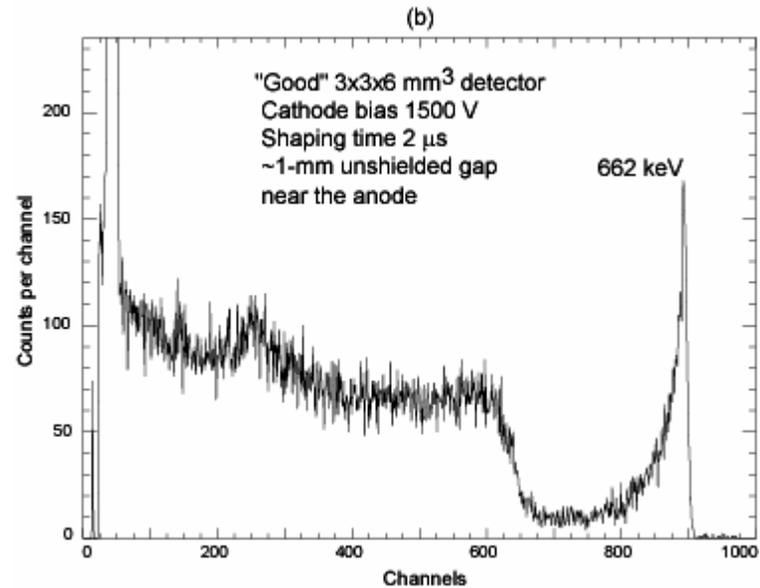
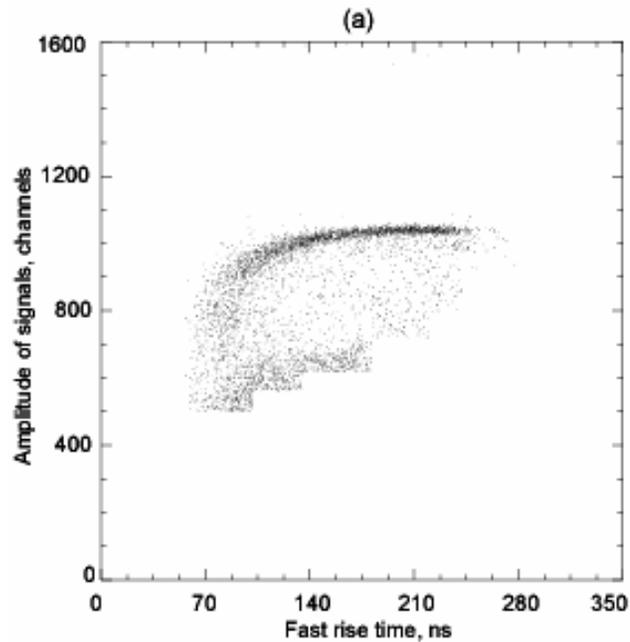
Correlation between amplitude and rise time (interaction depth).



## Effect of poor shielding near the anode

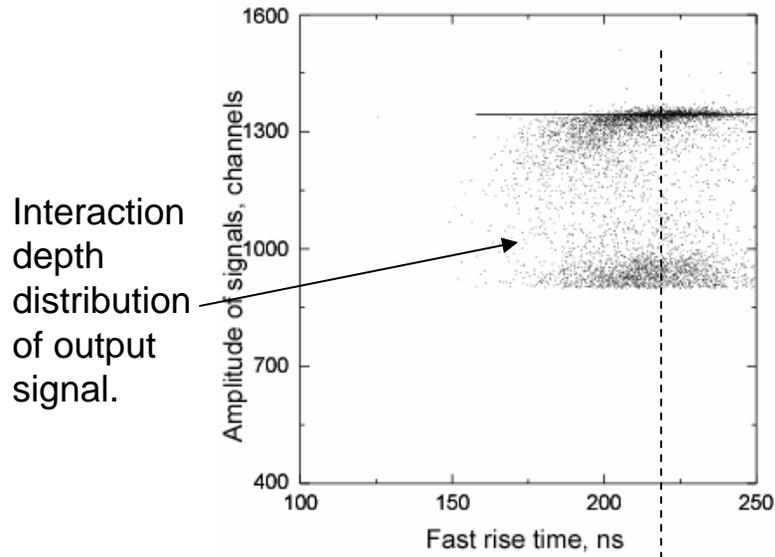


Correlation and pulse-height spectrum measured for the detector which had a ~1-mm gap of bare CZT surface between the anode and the shield



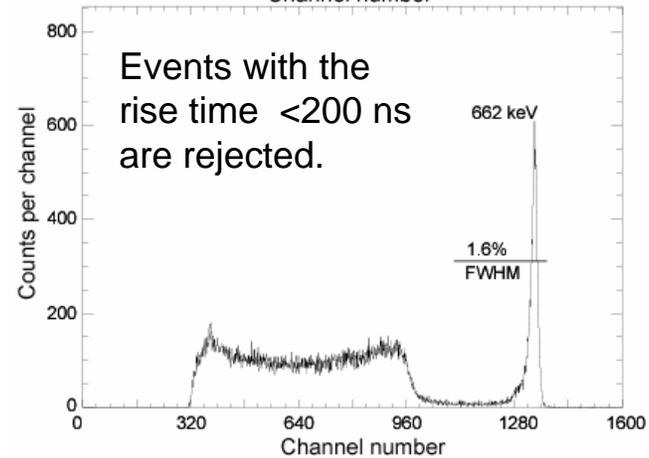
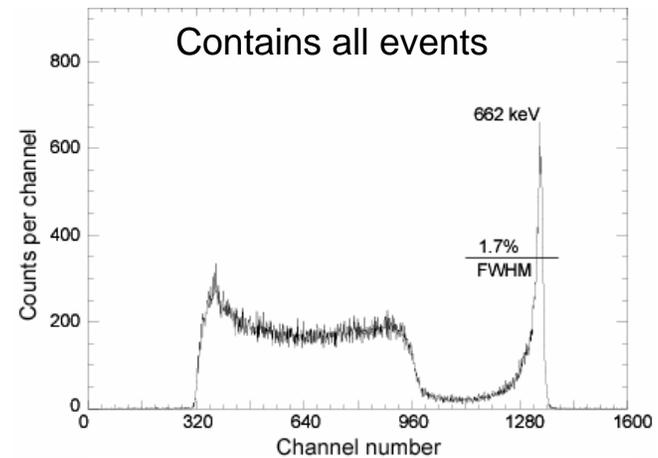
These examples show an importance of shielding entire side surface of CZT!

## Correlation between amplitude of the signal and interaction depth (rise-time)

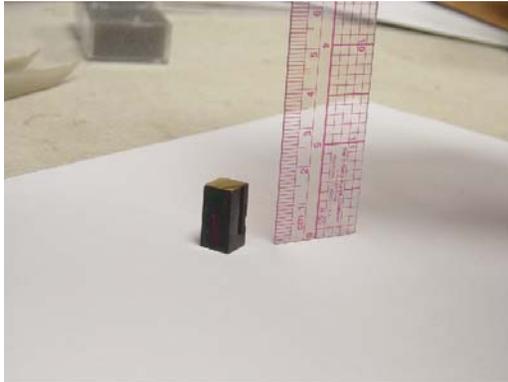


This is a typical distribution used for bi-parametric corrections

Tailing effect is caused by the events interacting close to the anode where shielding efficiency is poor. This is a natural behavior of these type of devices. Fortunately, the fraction of such events is low and they can be rejected.



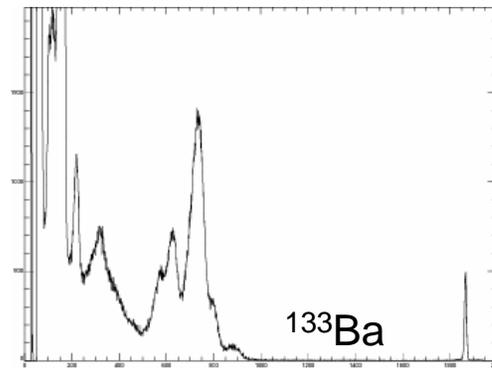
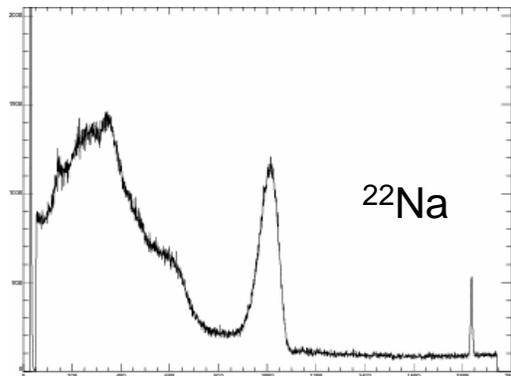
## Third factor: large device thickness. (Result with very long 8x8x17 mm<sup>3</sup> virtual Frisch-grid detectors)



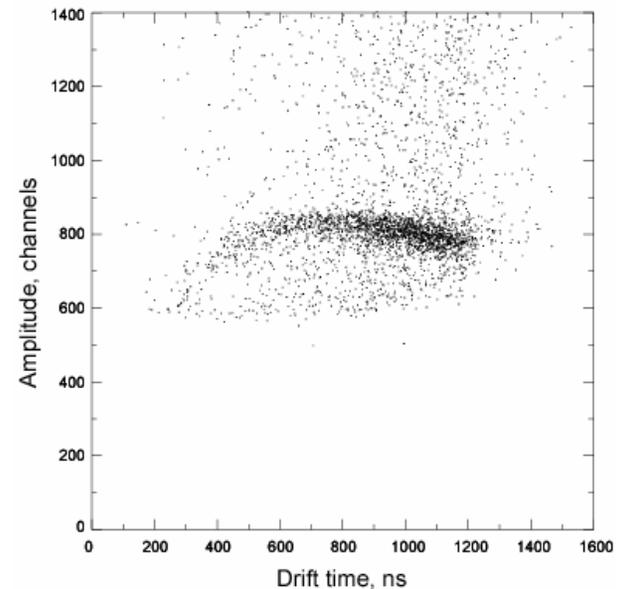
We used the same good CZT material, same technique, same passivation, etc. IR images shows low concentration of precipitates, no crystal defects

The only difference is thickness.

Achieved limit in CZT device thickness?



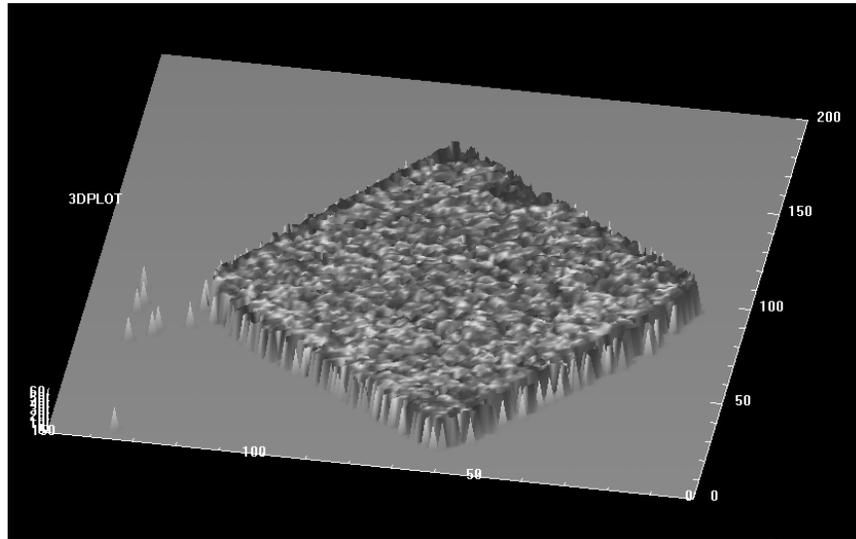
8x8x16 mm<sup>3</sup> CZT crystal  
Cathode bias 2500 V



Such effect cannot be explained by uniformly distributed single traps! We should consider some microscopic defects that accumulate locally high concentration of traps. Precipitates ?

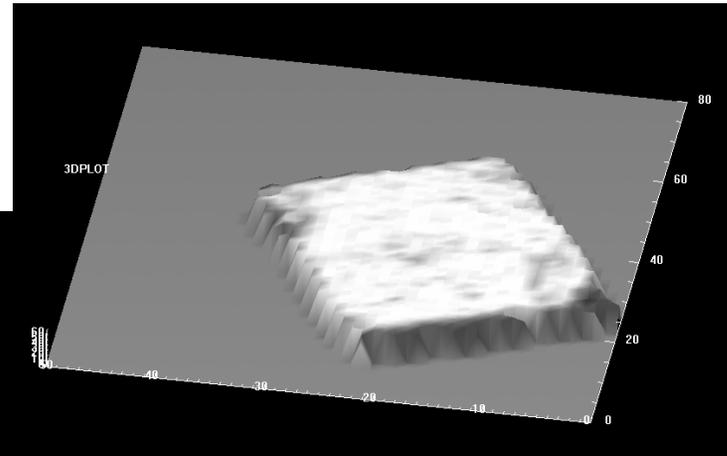
## Result with very long virtual Frisch-grid detectors

Beam energy ~ 80 keV  
Beam size =  $25\mu\text{m} \times 25\mu\text{m}$   
Step size =  $100\mu\text{m}$   
Detector size =  $8 \times 8 \times 17 \text{ mm}^3$   
 $V_B = 3000\text{V}$



Small scale variations  
due to precipitates ?

Detector size =  $5 \times 6 \times 10 \text{ mm}^3$   
Good detector



Effect of  
precipitates?

x-ray scan results by G. A. Carini

## Conclusions

- Virtual Frisch-grid (bar) detectors have many potentials. They provide:
  - good energy resolution,  $<1.5\%$  FWHM at 662 keV and
  - high stopping power
  
- To fabricate “good” virtual Frisch-grid detectors it is important:
  - (1) shield entire area of side surfaces,
  - (2) use thin insulating layer,
  - (3) use CZT crystals with small aspect ratio,  $<0.5$
  - (4) ensure a “focusing” field inside the device