Pulse Shape Analysis

With the

AGATA DEMONSTRATOR

Bart Bruyneel - CEA Saclay
For the AGATA collaboration
Egan workshop, Padua June 2011

New Facilities, New challenges

FAIR

SPIRAL2 - HIE-ISOLDE - EURISOL - ECOS

Relativistic exotic beams …

- Low beam intensity
- High backgrounds
- Large Doppler broadening
- High γ-ray multiplicities
- High counting rates

…Need :

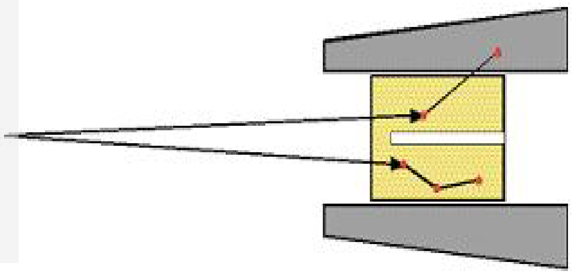
- High efficiency
- High sensitivity
- High position resolution
- High Peak/Total
- High throughput

The idea of γ-ray tracking

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100

Ω ~ 40%
θ ~ 8°



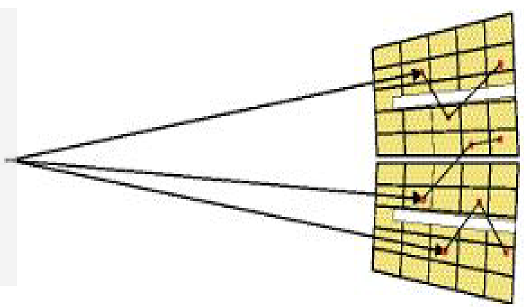
large opening angle means poor energy resolution at high recoil velocity.

Previously scattered gammas were wasted.
Technology is available now to track them.

Ge Tracking Array

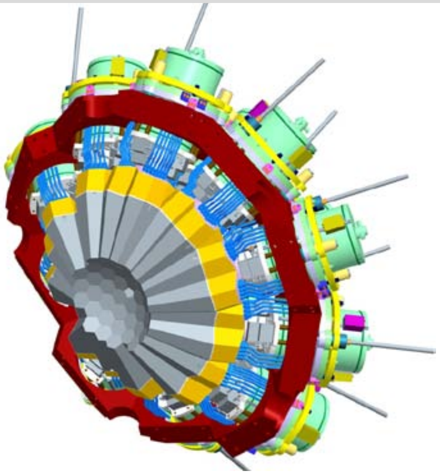
ε_{ph} ~ 50%
N_{det} ~ 100

Ω ~ 80%
θ ~ 1°



Combination of:

- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays

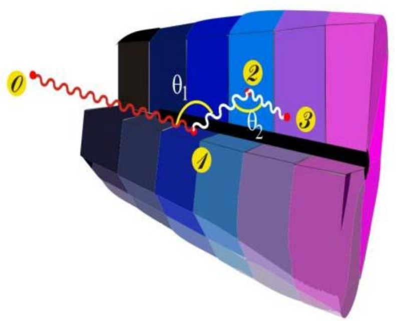


AGATA / GRETA

Ingredients of Gamma-Ray Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

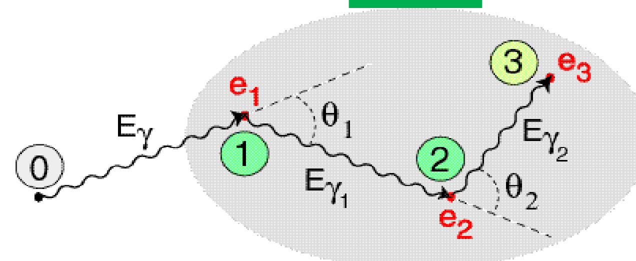
3

Pulse Shape Analysis to decompose recorded waves

Identified interaction points $(x,y,z,E,t)_i$

4

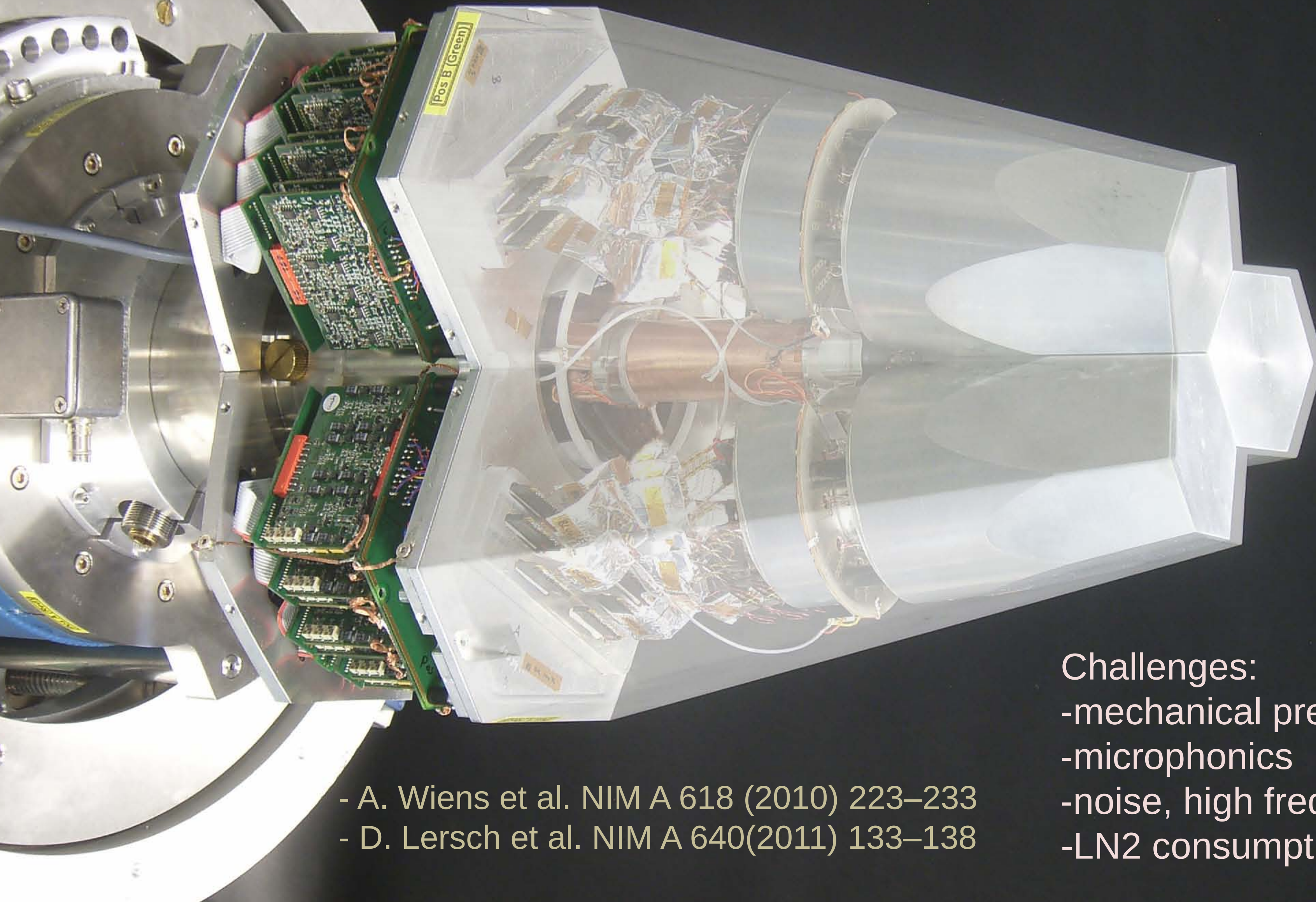
Reconstruction of tracks evaluating permutations of interaction points



Reconstructed gamma-rays

Asymmetric AGATA Tripel Cryostat

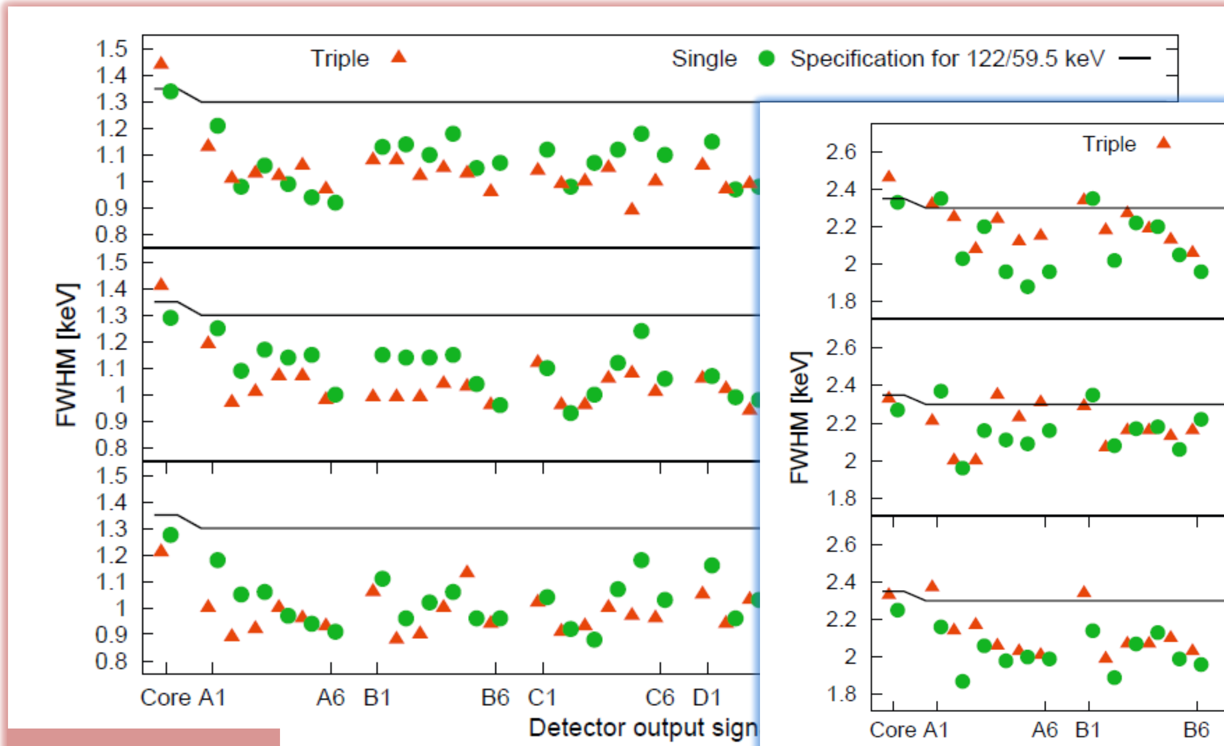
-integration of 111 high resolution spectroscopy channels
-cold FET technology for all signals



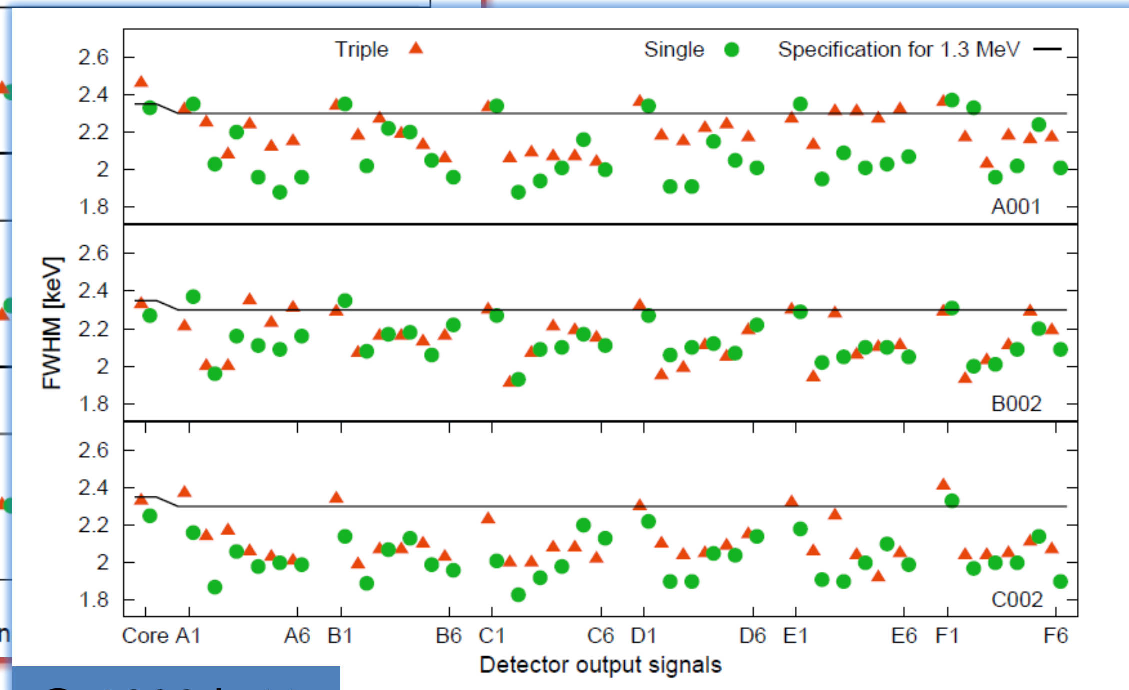
Challenges:
-mechanical precision
-microphonics
-noise, high frequencies
-LN2 consumption

- A. Wiens et al. NIM A 618 (2010) 223–233
- D. Lersch et al. NIM A 640(2011) 133–138

Performance: Energy resolution



@ 60 keV



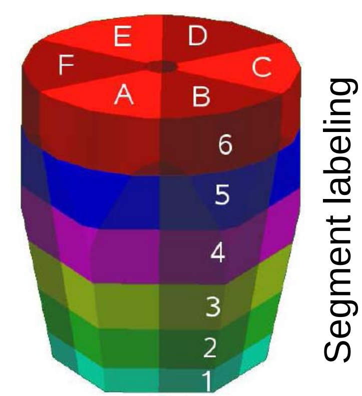
@ 1333 keV

Averages of the segment resolutions
@ 60 keV :

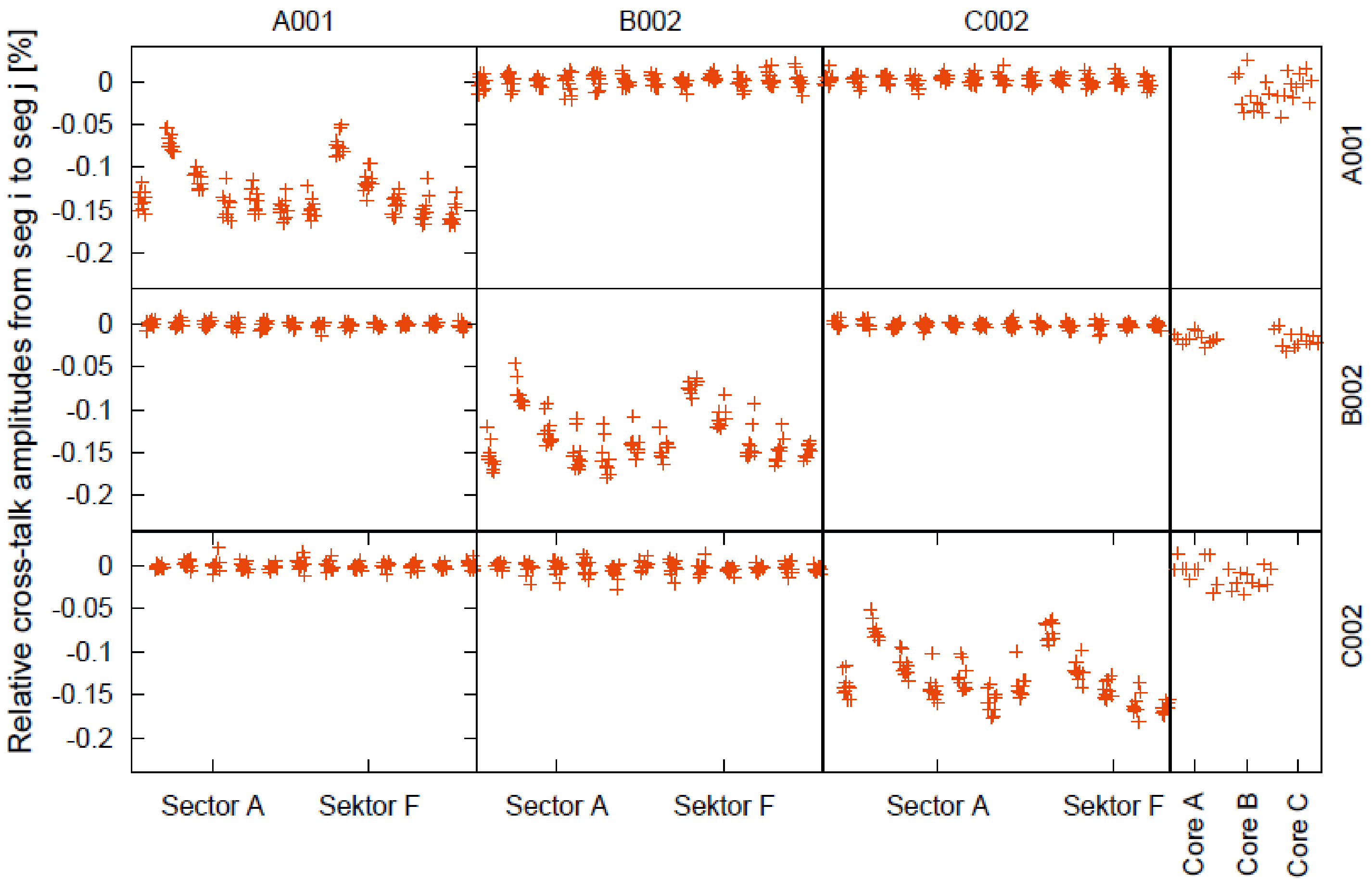
A001:	1011 +/- 53 eV
B002:	1039 +/- 70 eV
C002:	965 +/- 63 eV

Averages of the segment resolutions
Measured in Köln and Legnaro
@ 1333 keV :

	IKP	/	Legnaro
A001:	2,19 keV	/	2,00 keV
B002:	2,09 keV	/	1,98 keV
C002:	2,1 keV	/	1,94 keV



Performance: Crosstalk



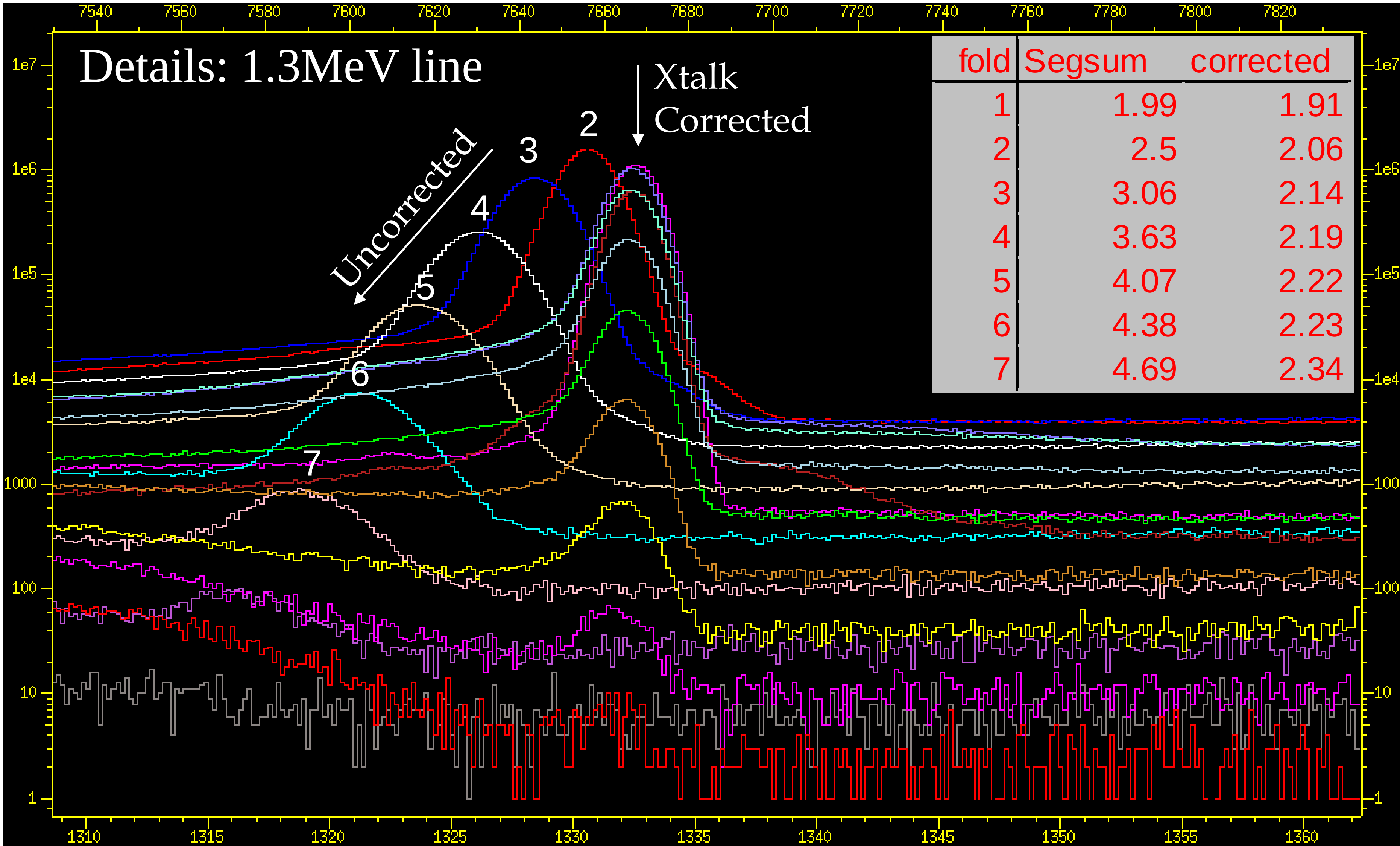
- No crosstalk observed between detectors
- Within one detector, the theoretical crosstalk limit is reached
- Online cross talk correction implemented

B. Bruyneel et al., NIM A 599 (2009) 196

On line Cross Talk Correction

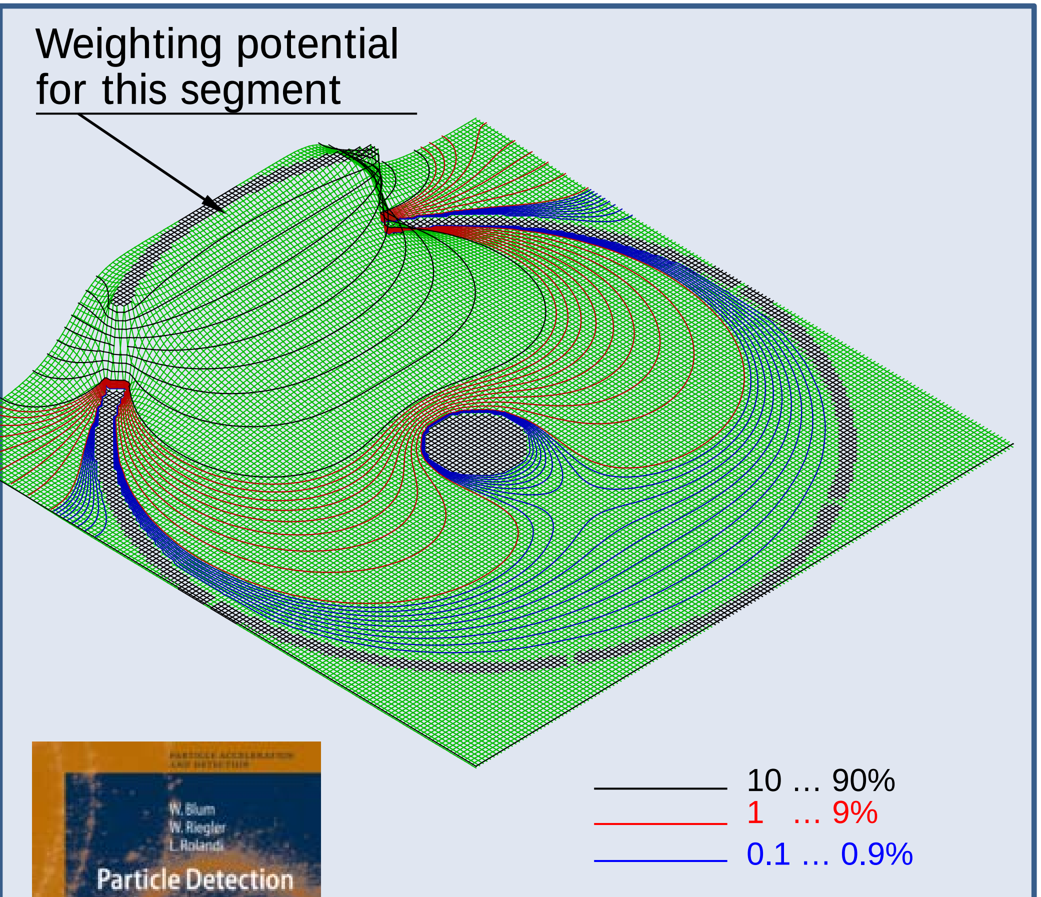
B. Bruyneel et al., NIM A 608, (2009) 99

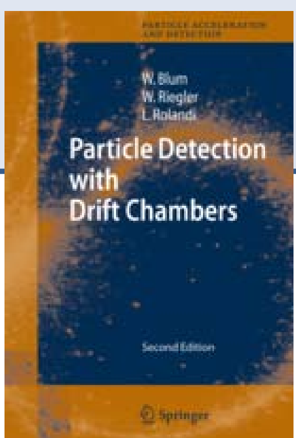
FWHM 60keV: 1.20 → 1.02 !



fold	Segsum	corrected
1	1.99	1.91
2	2.5	2.06
3	3.06	2.14
4	3.63	2.19
5	4.07	2.22
6	4.38	2.23
7	4.69	2.34

How to simulate HPGe detector signals





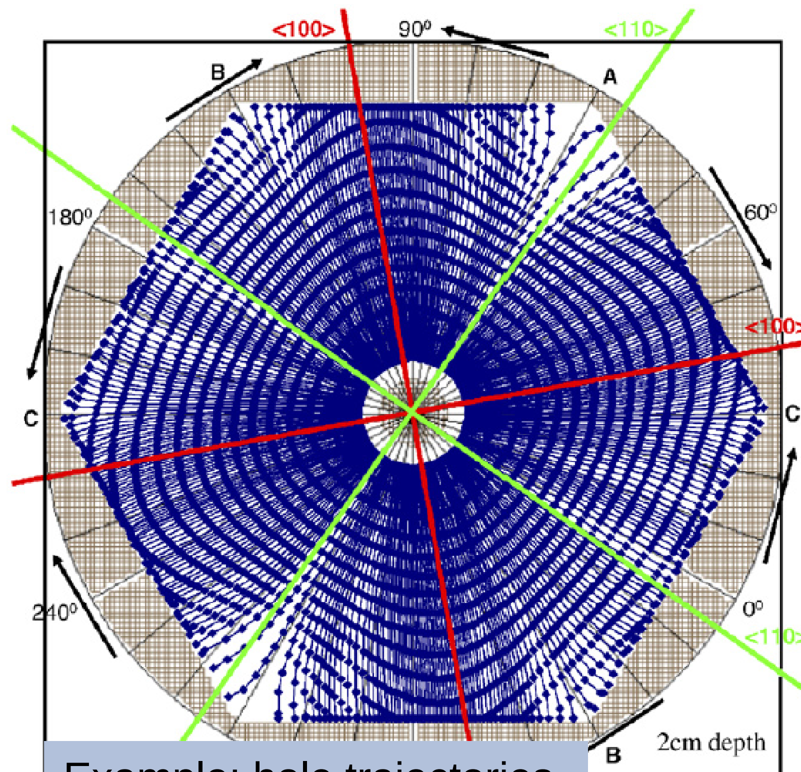
Good book on
(extended) Shockley-Ramo Theorem

B. Bruyneel NIMA 569 (2006) 764-773

B. Bruyneel NIMA 569 (2006) 774-789

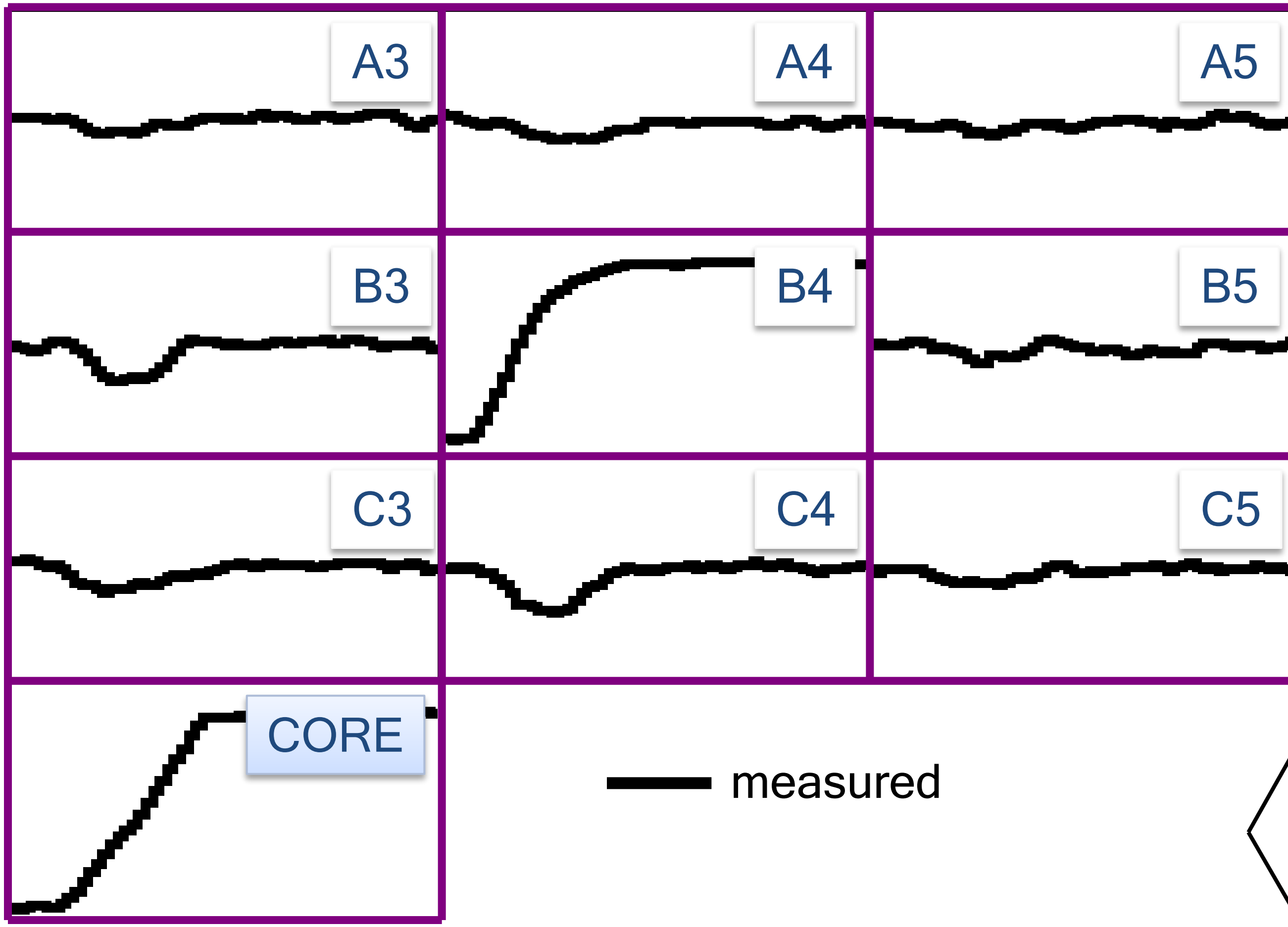
Requirements:

- Weighting potentials
- Electrical field ↔ space charge
- Anisotropic Mobility
- Response of electronics



Example: hole trajectories

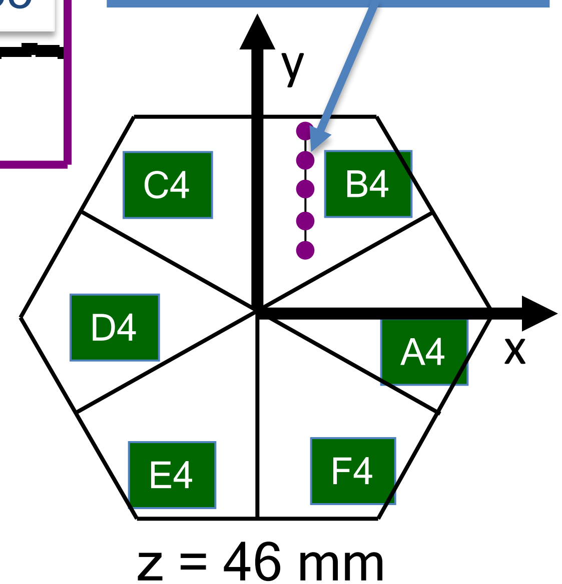
Pulse Shape Analysis Concept



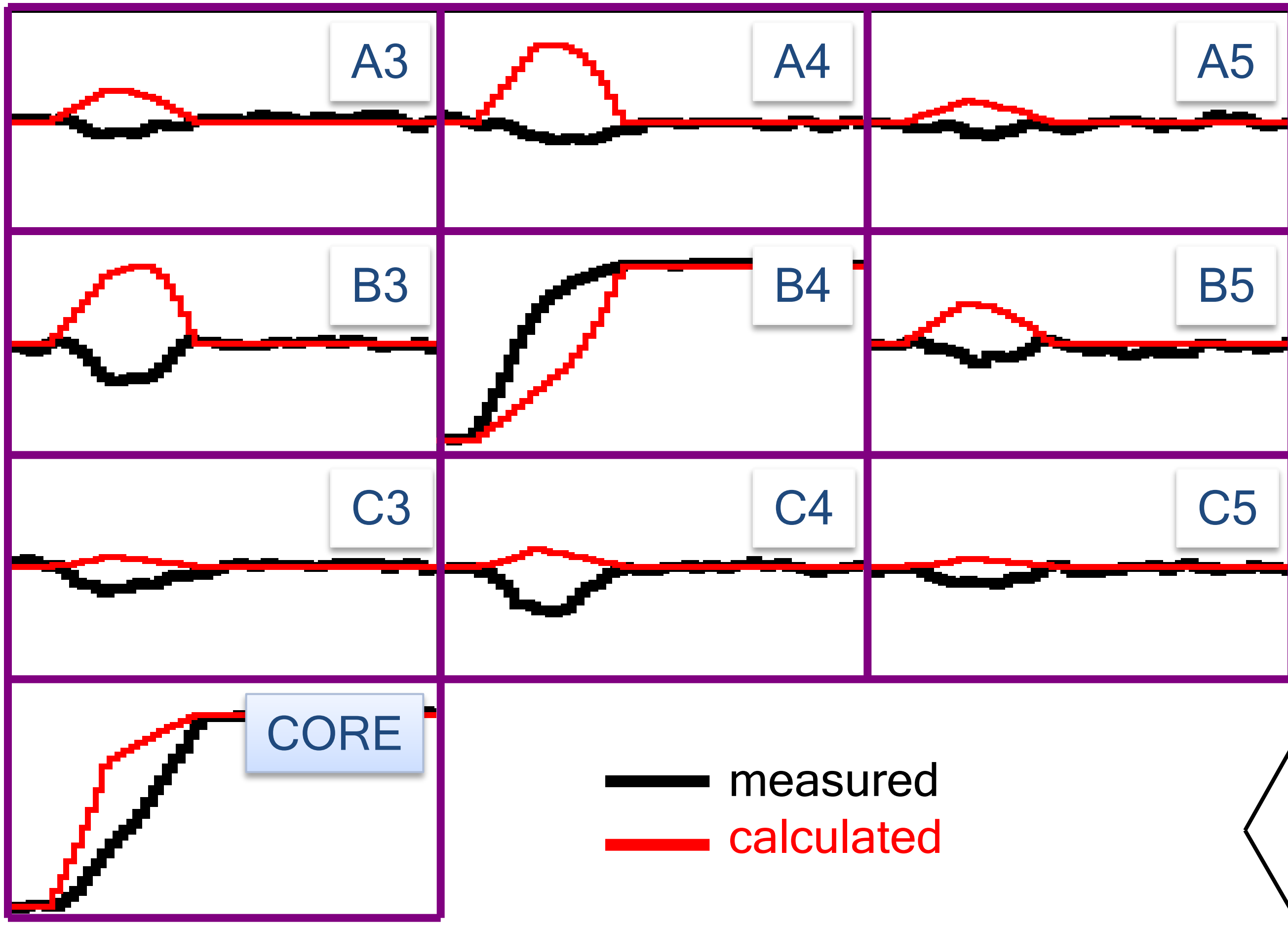
791 keV deposited in segment B4

Library generation

Different codes
ADL (C)
JASS (Java)
MGS (Mathlab)

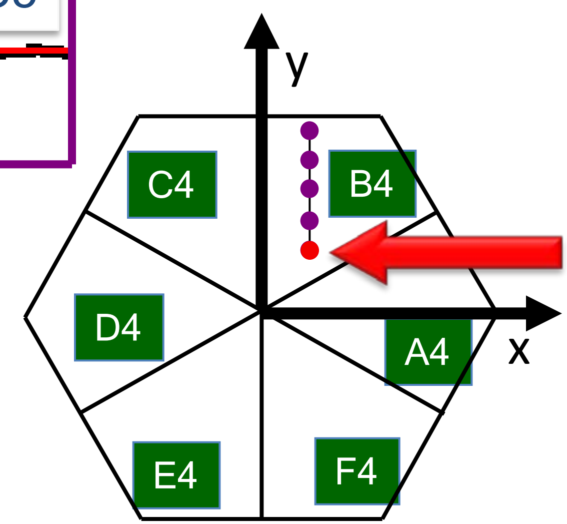


Pulse Shape Analysis Concept

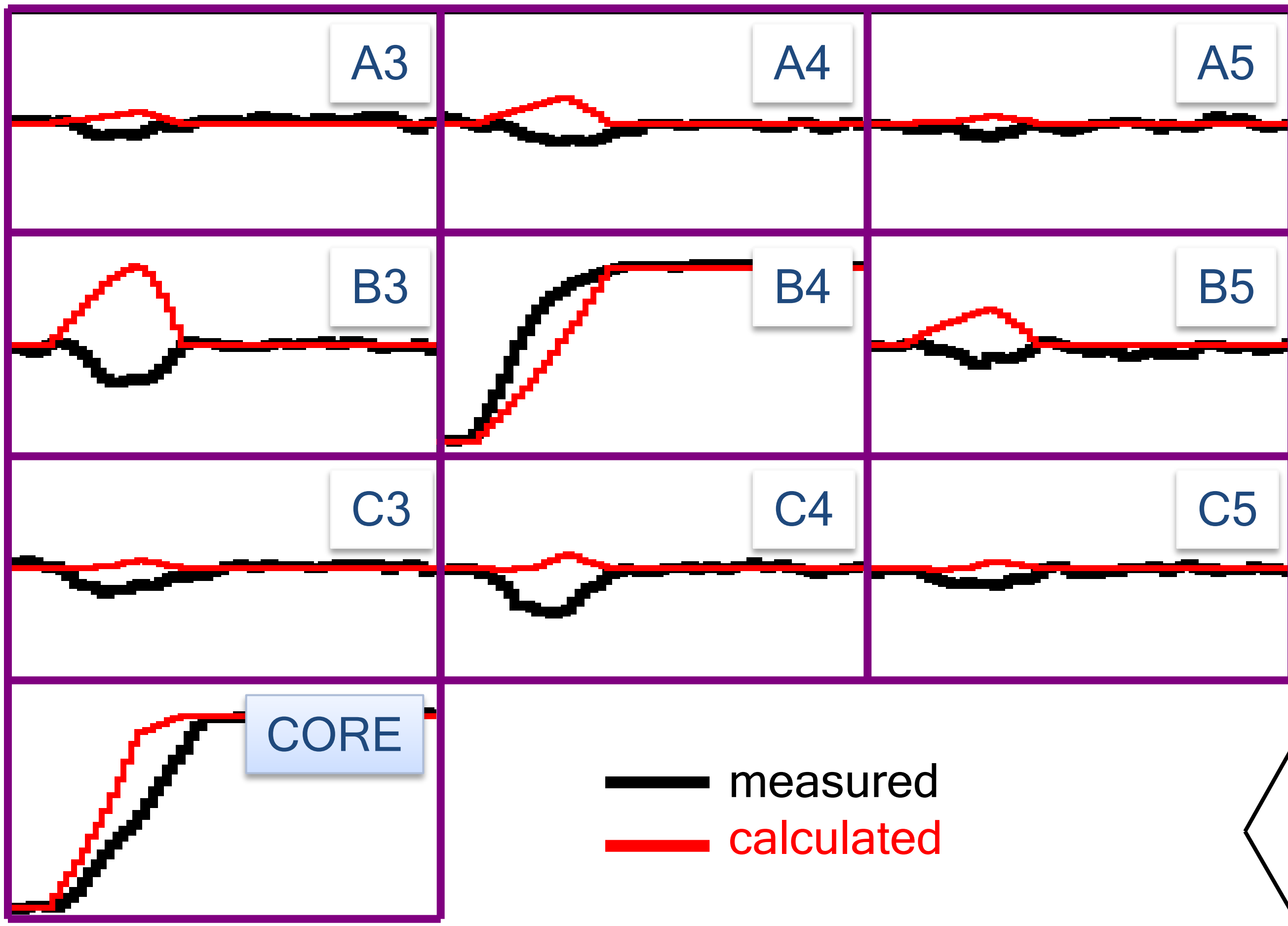


791 keV deposited in segment B4

(10,10,46)



Pulse Shape Analysis Concept



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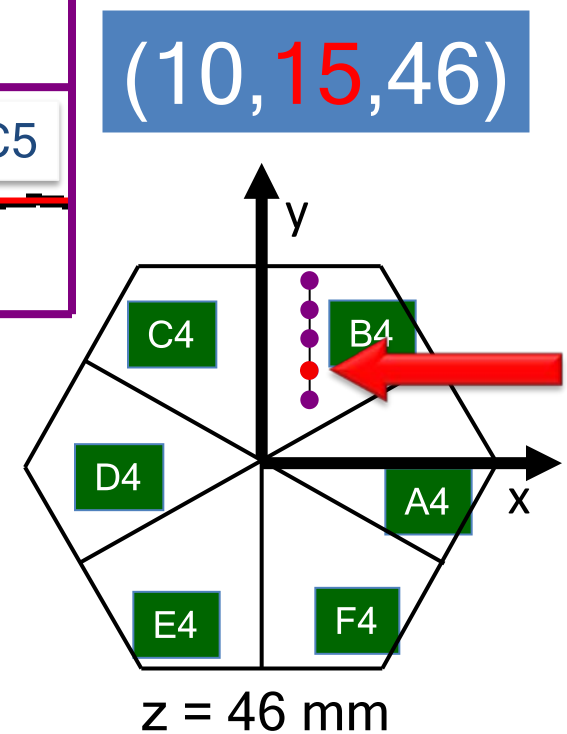
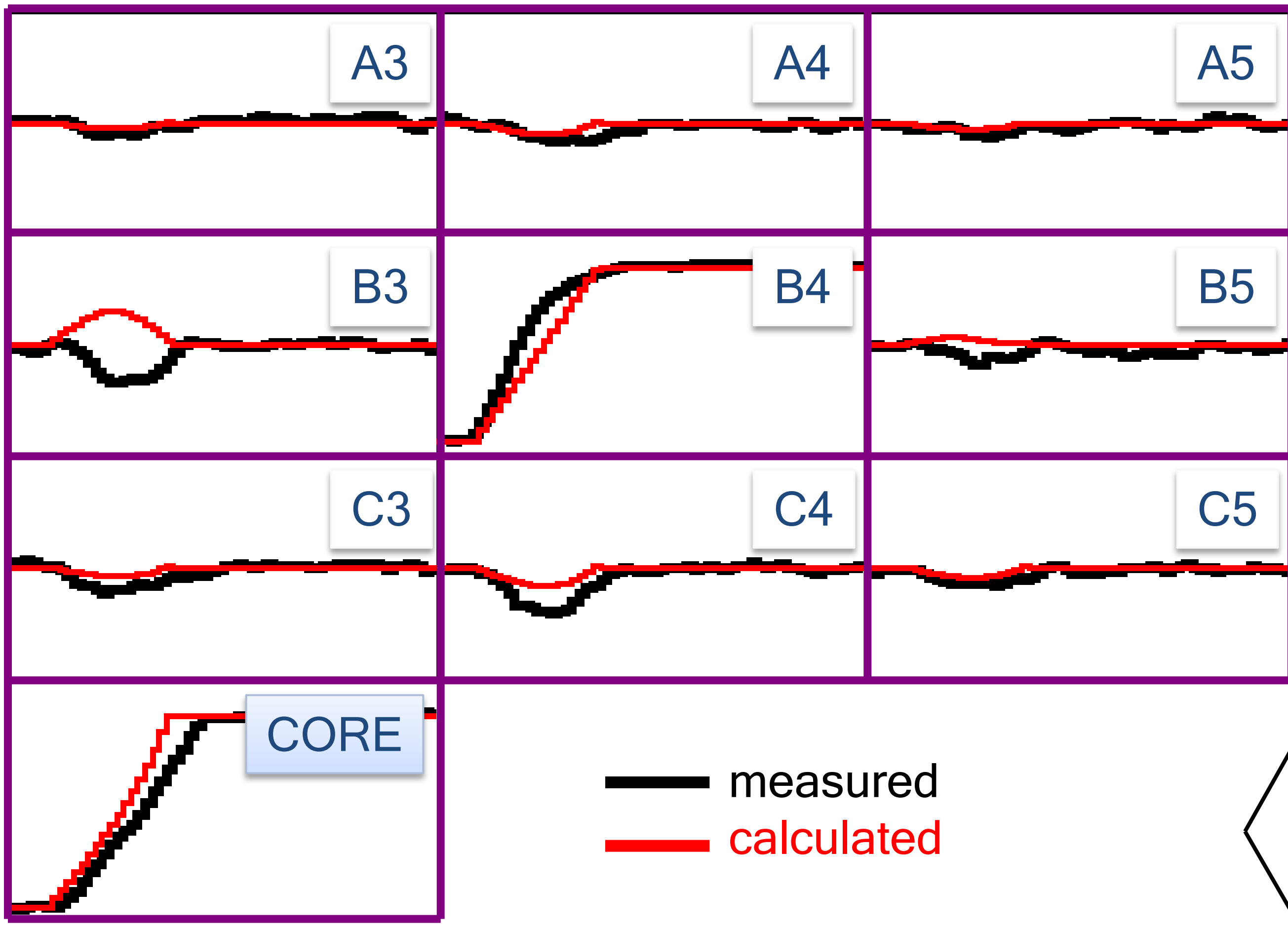


Pulse Shape Analysis Concept



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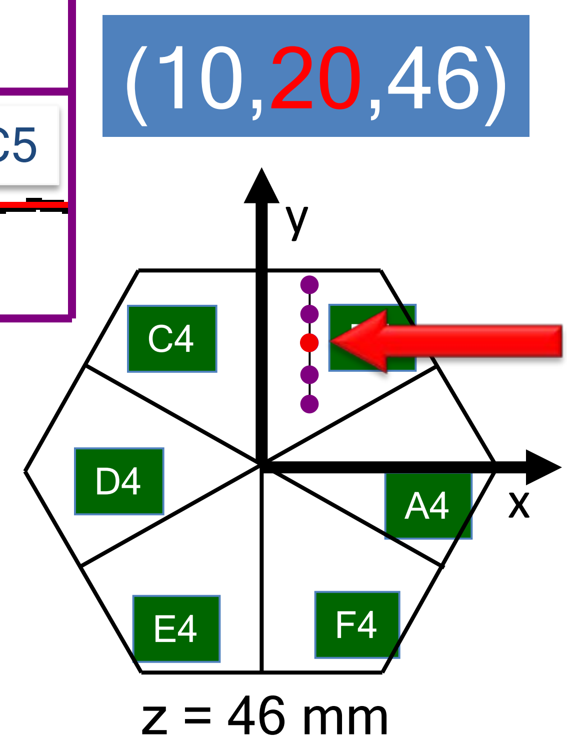
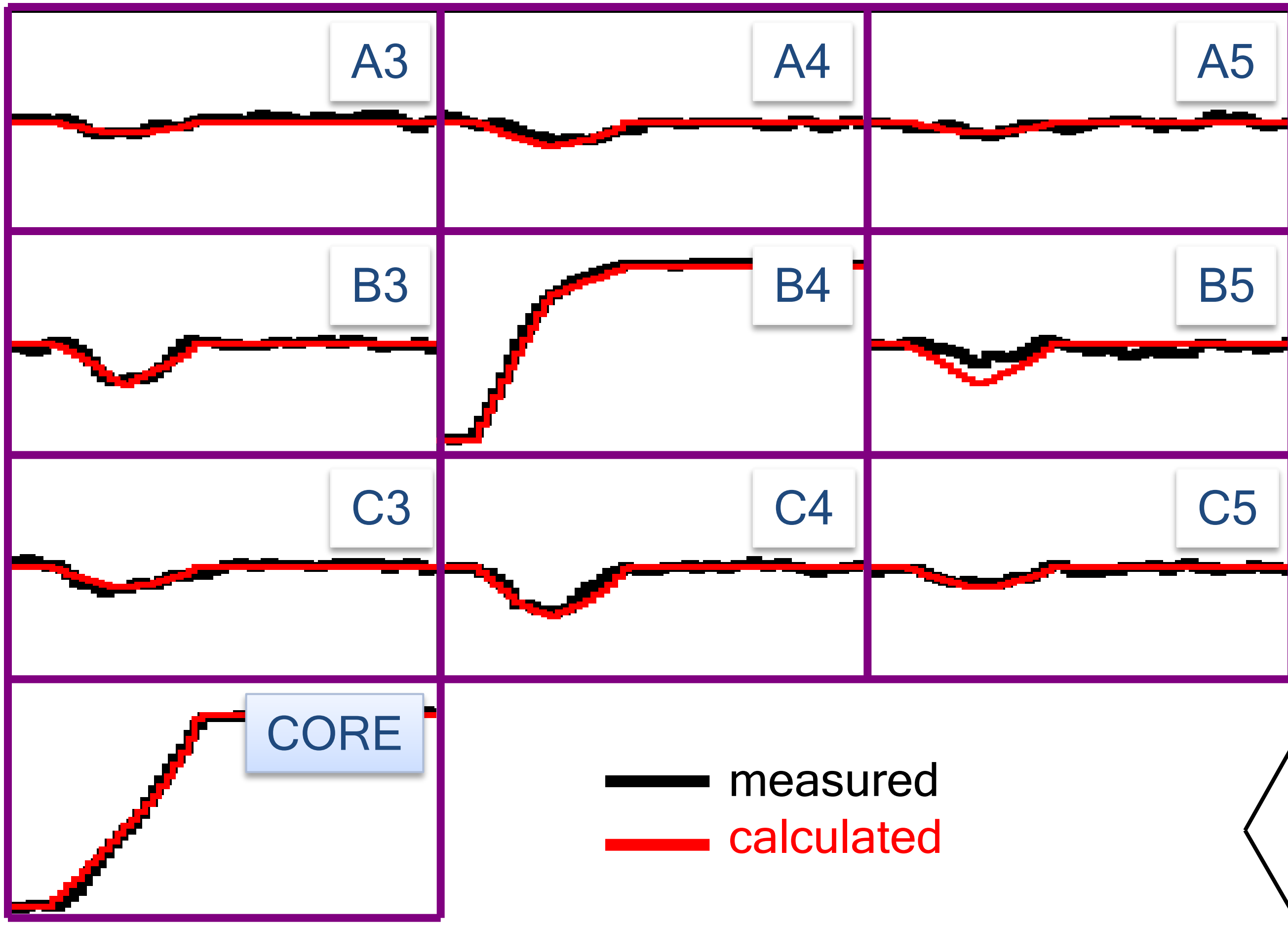
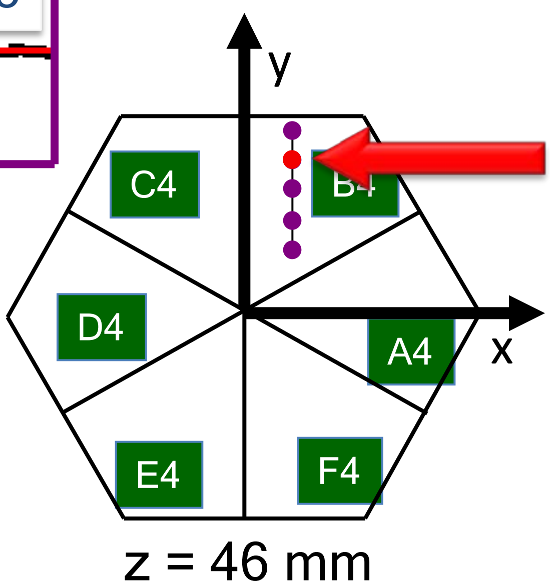


Pulse Shape Analysis Concept

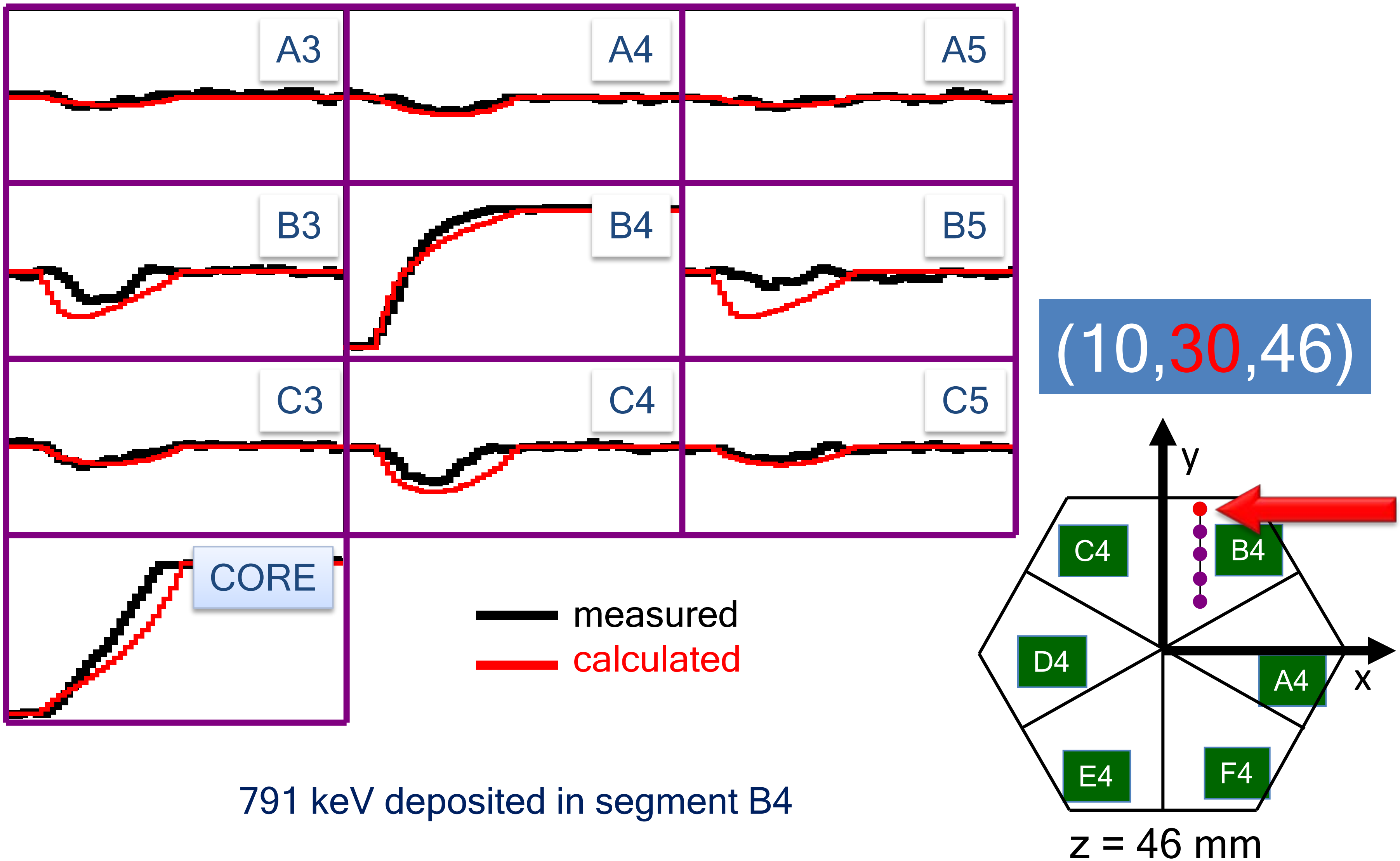


(10,25,46)



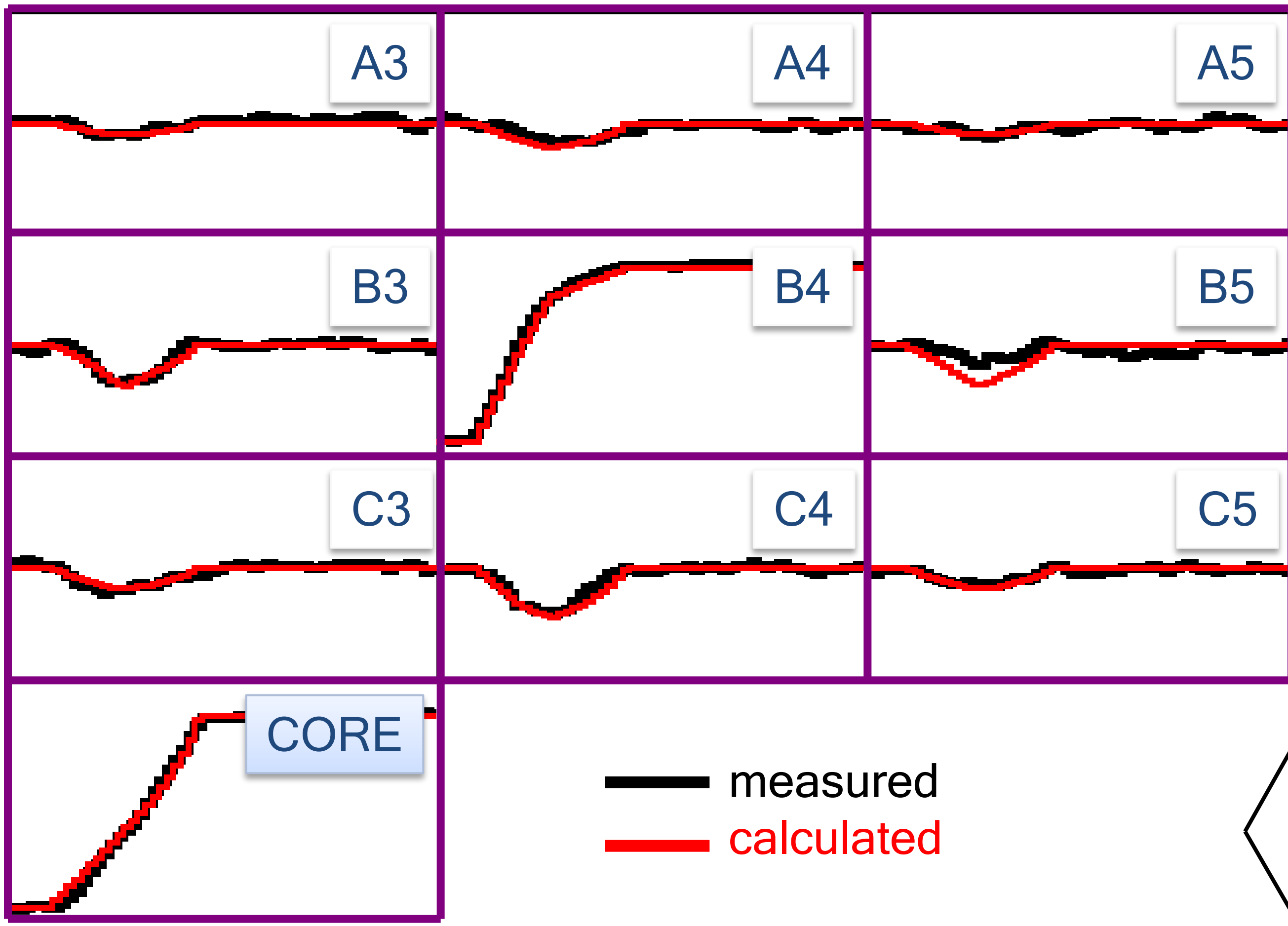
791 keV deposited in segment B4

Pulse Shape Analysis Concept



791 keV deposited in segment B4

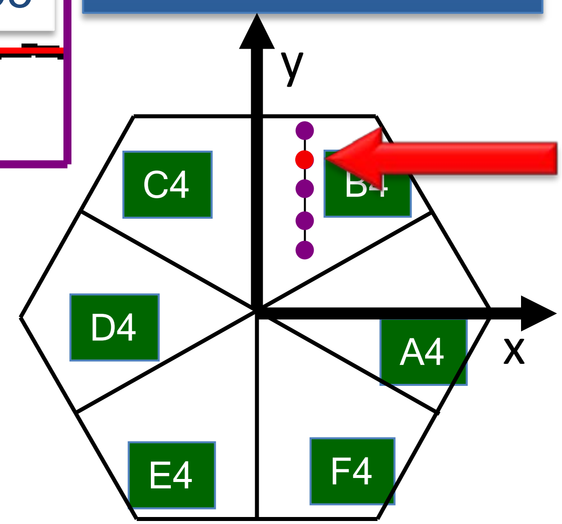
Pulse Shape Analysis Concept



Result of *Grid Search* algorithm

R. Venturelli

(10,25,46)



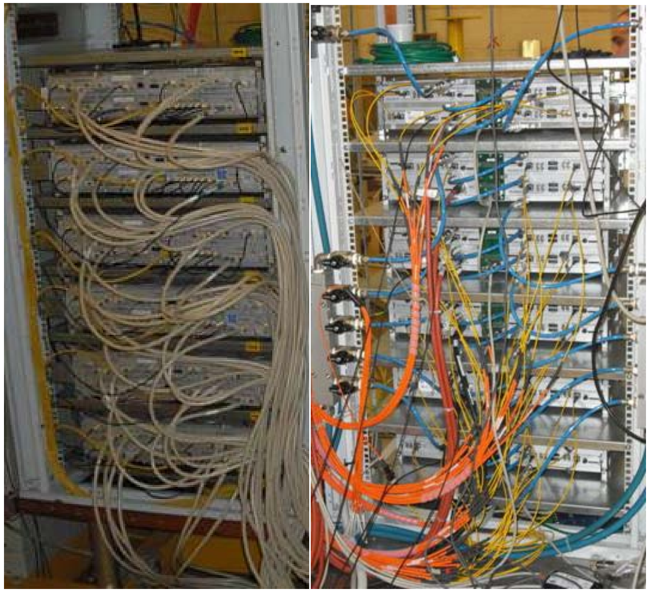
z = 46 mm

791 keV deposited in segment B4

AGATA: Digital Electronics

Digitisers
in the experimental hall

10 m long MDR cables

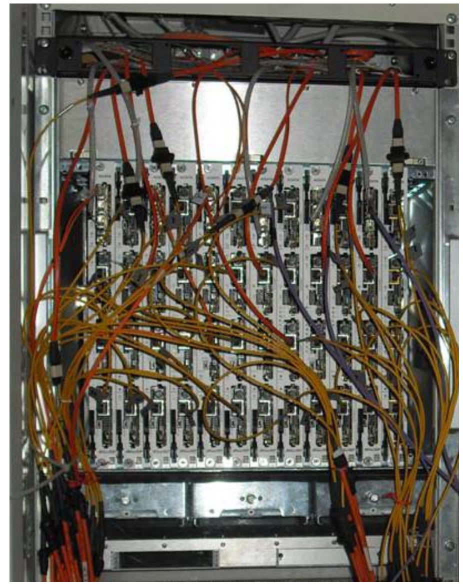


100Mhz, 14 bit
Synchronous &
continuous

80 m long optical fibers

(7.6GB/s/crystal)

Digital proc. electronics
in the users area

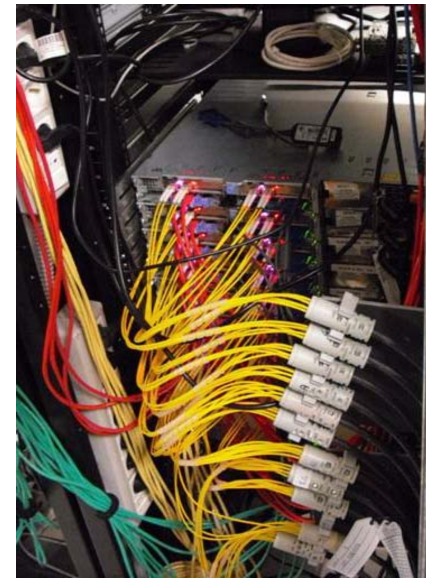


Triggering
Energy
Trace capture

20 m long optical fibers

(10 kB/evt/crystal)

Computer farm
in the computing room



LAN to the disk servers

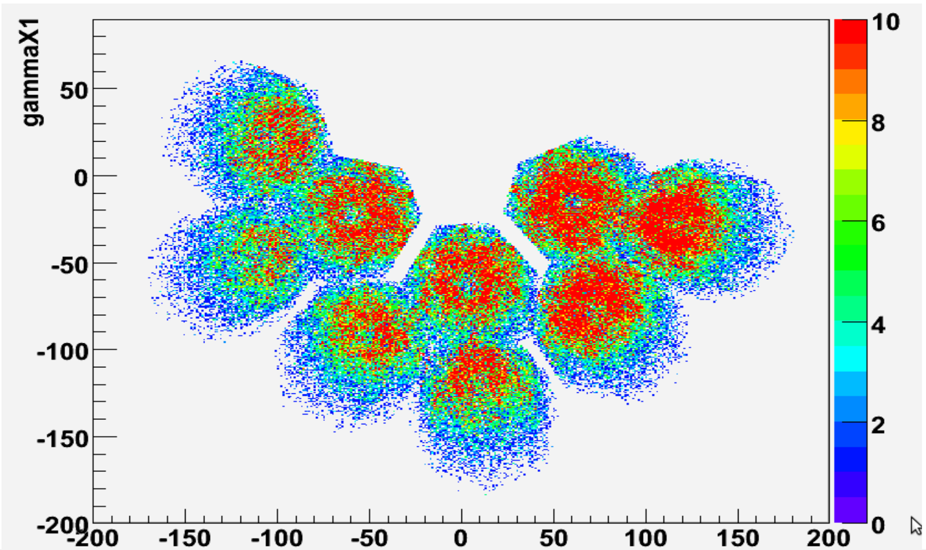
Preprocessing
PSA
Tracking

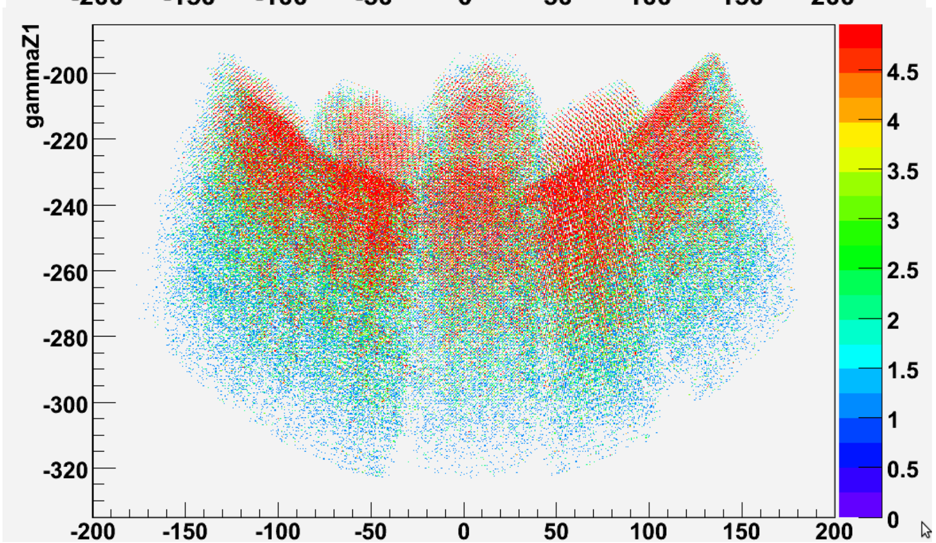
Global
Triggering
System

GTS

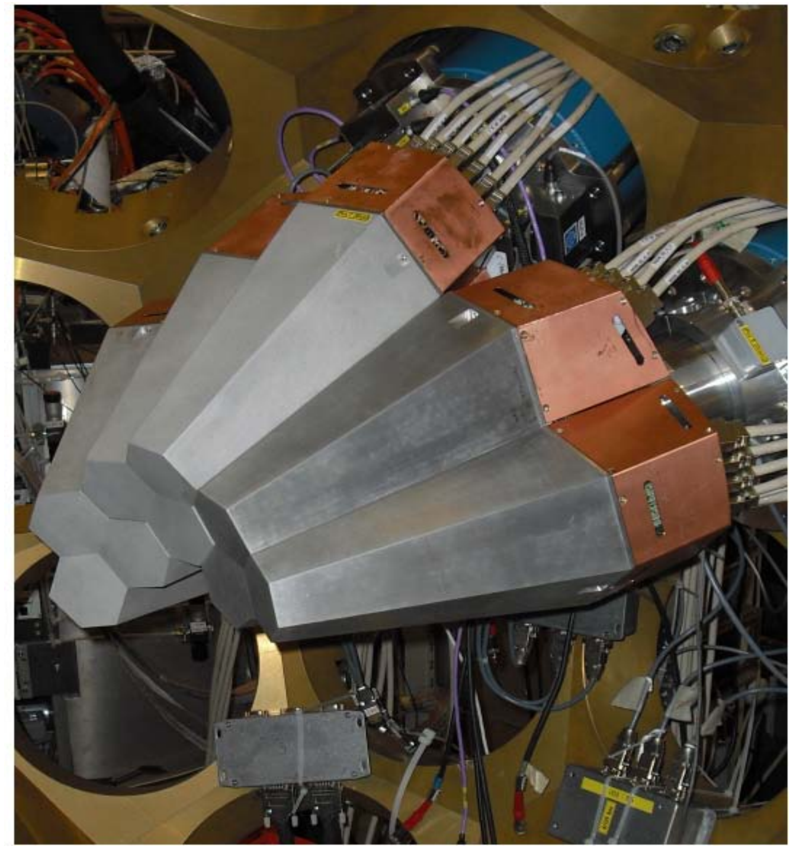
Clock &
Trigger validation

AGATA online



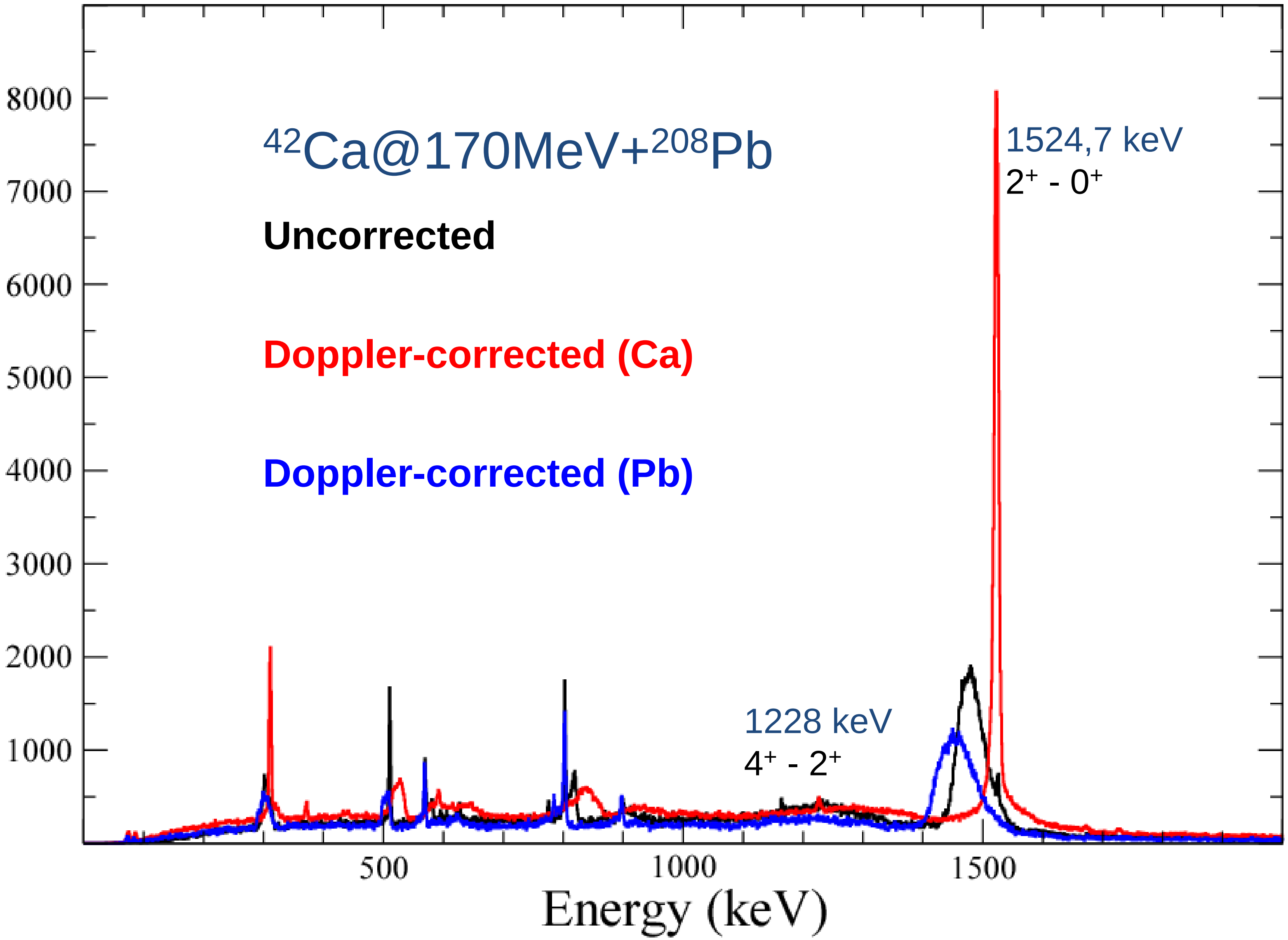


1st experiment with AGATA (18/02/10)



- < 5mm FWHM resolution obtained
- psa online at rates > 5kHz per crystal

AGATA online result



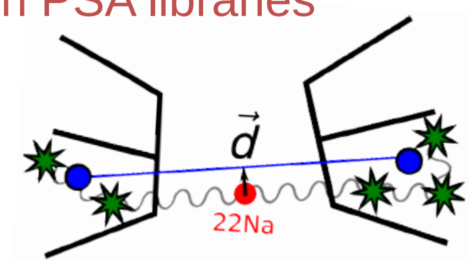
Position Resolution of AGATA

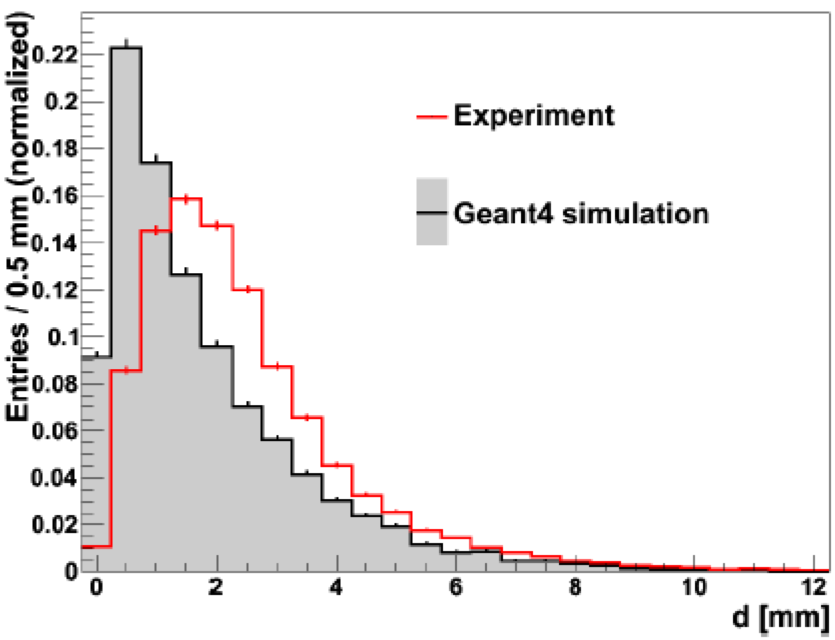
time ↓

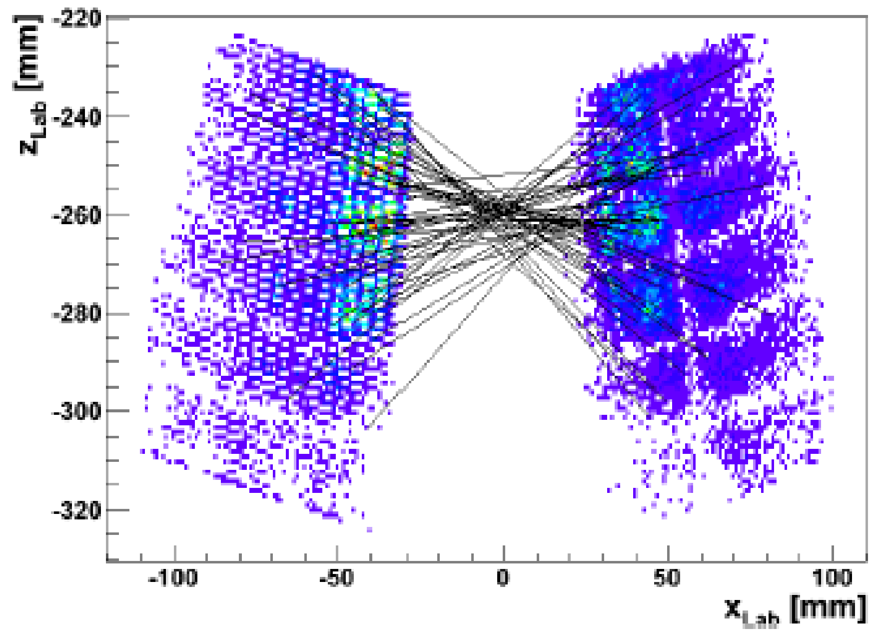
FWHM	Method	Reference
5.2mm	Doppler correction meas.	F. Recchia et al. NIM A (2009)
4.0mm	Doppler correction meas	P.-A. Söderström et al. NIM A (2011)
3.5mm	511keV source meas.	S. Klupp, M.Schlarb, R. Gernhauser, (in prep.)

Resolutions improve over time by improvement on PSA libraries

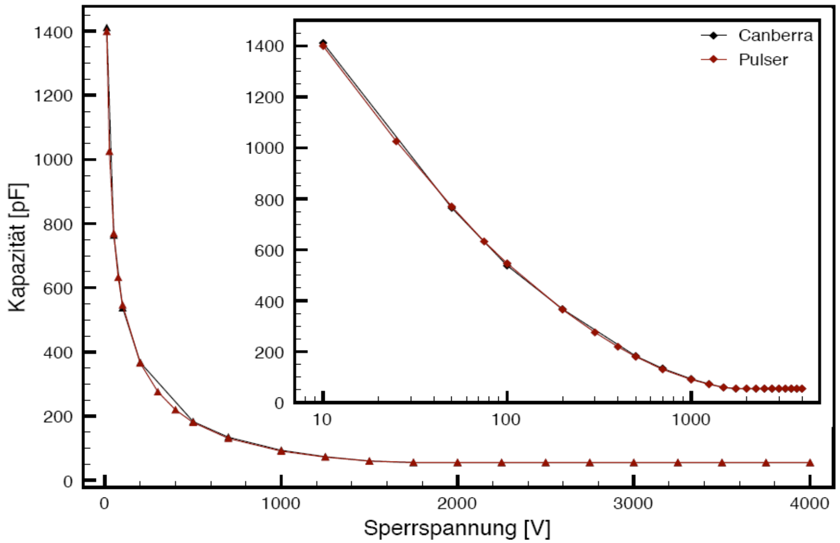
PSA calibration using 511keV source:



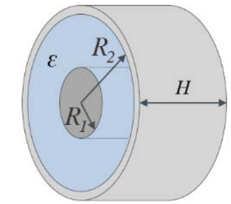




Impurity from C-V measurements



How it works (e.g. cylindrical geometry):

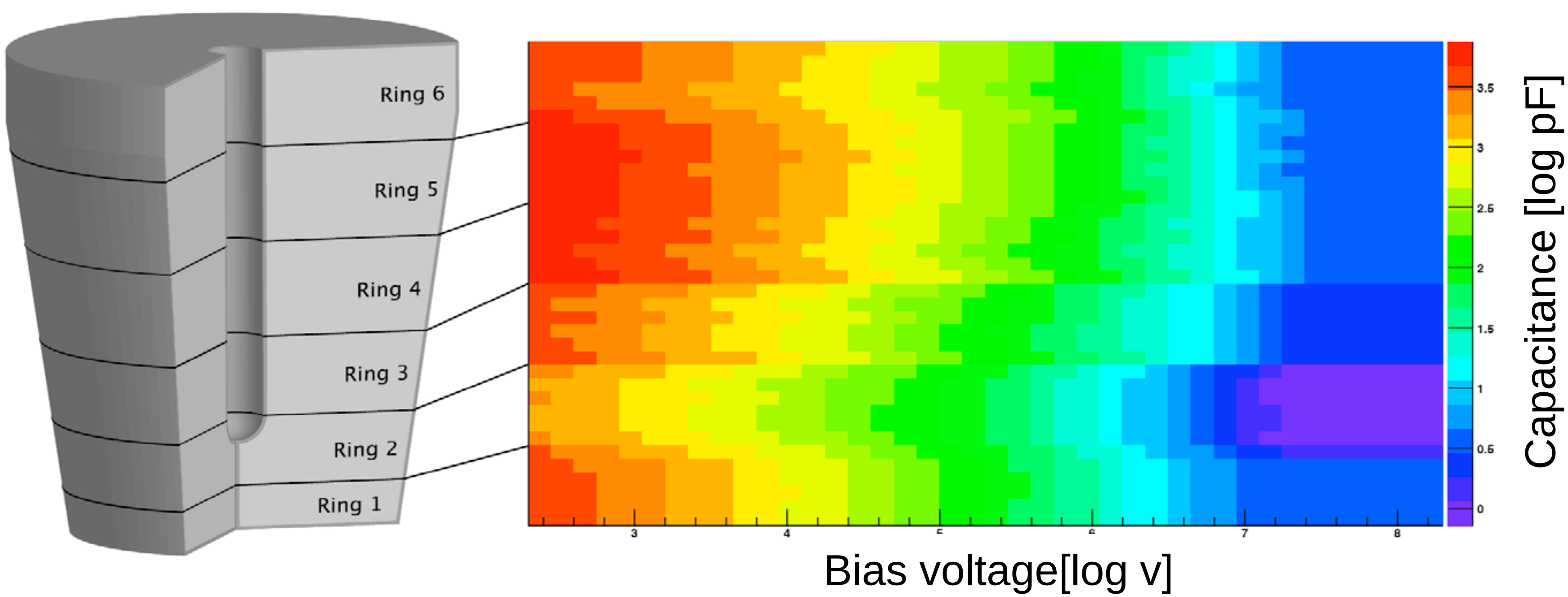


• *C(V)* gives depletion boundary R_1:

$$C = \frac{2\pi\epsilon H}{\ln\frac{R_2}{R_1}}$$

• *C(V), dC/dV* give impurity concentration at R_1

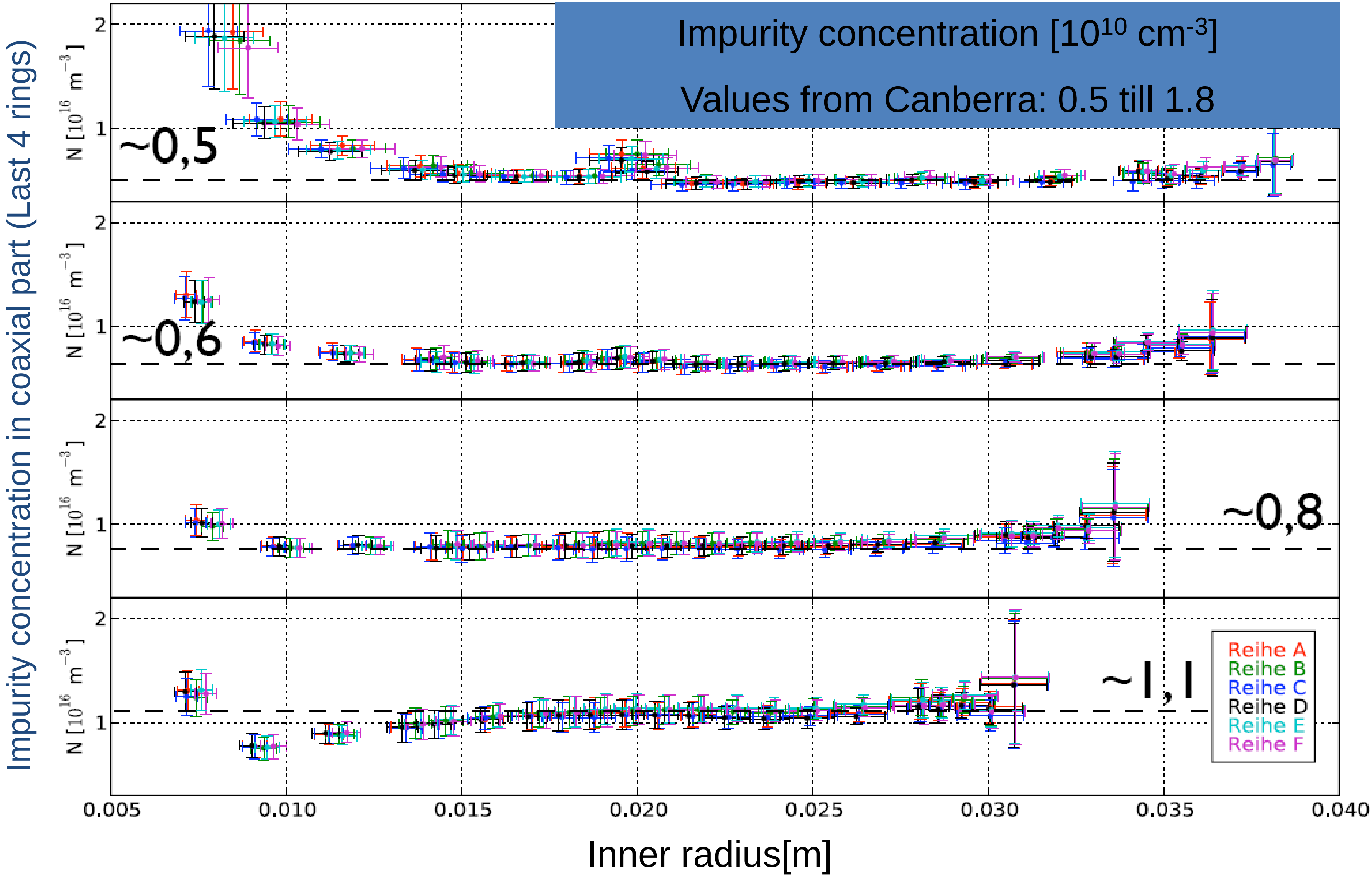
$$N_D(R_1) = -\frac{C^3 e^{\frac{4\pi\epsilon H}{C}}}{4e\pi^2 H^2 \epsilon R_2^2 \frac{dC}{dV}}$$



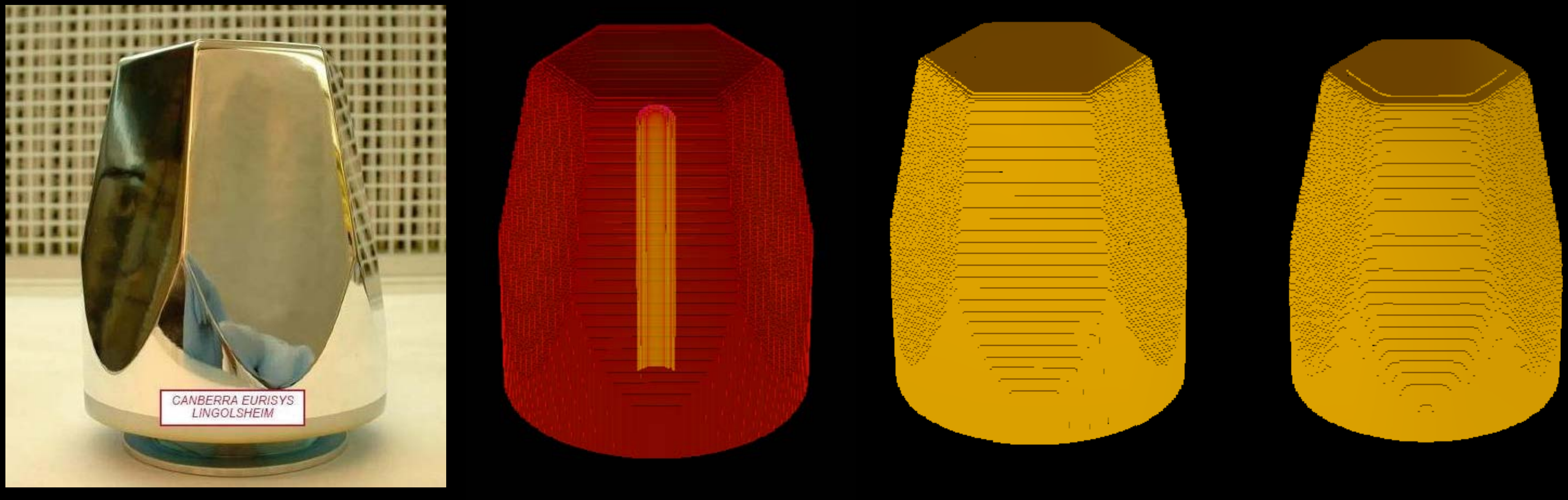
Results with the cylindrical approximation

Impurity concentration [10^{10} cm^{-3}]

Values from Canberra: 0.5 till 1.8



Birkenbach et al. NIM A 640 (2011) 176-184



A | B | C: HV = 10V | D: HV = 100V

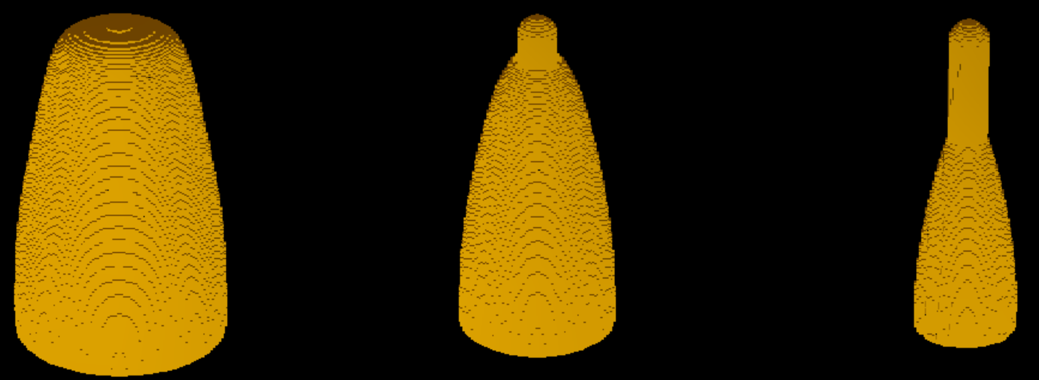
Depletion of a HPGe detector
Using ADL 3.0

A: Bare HPGe germanium crystal
symmetric AGATA detector

B: Geometry in simulation
The HV contact is colored yellow

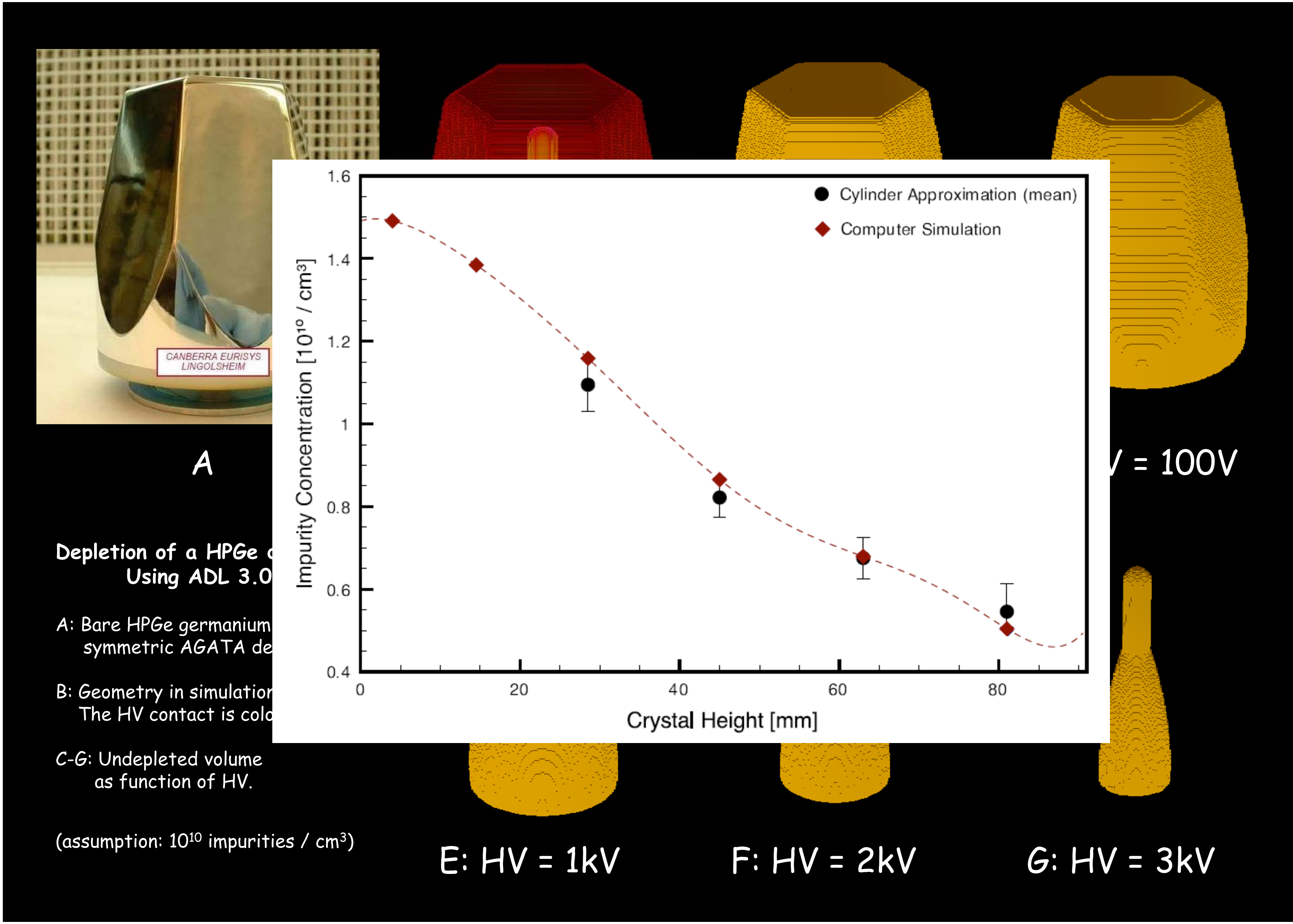
C-G: Undepleted volume
as function of HV.

(assumption: 10^{10} impurities / cm^3)



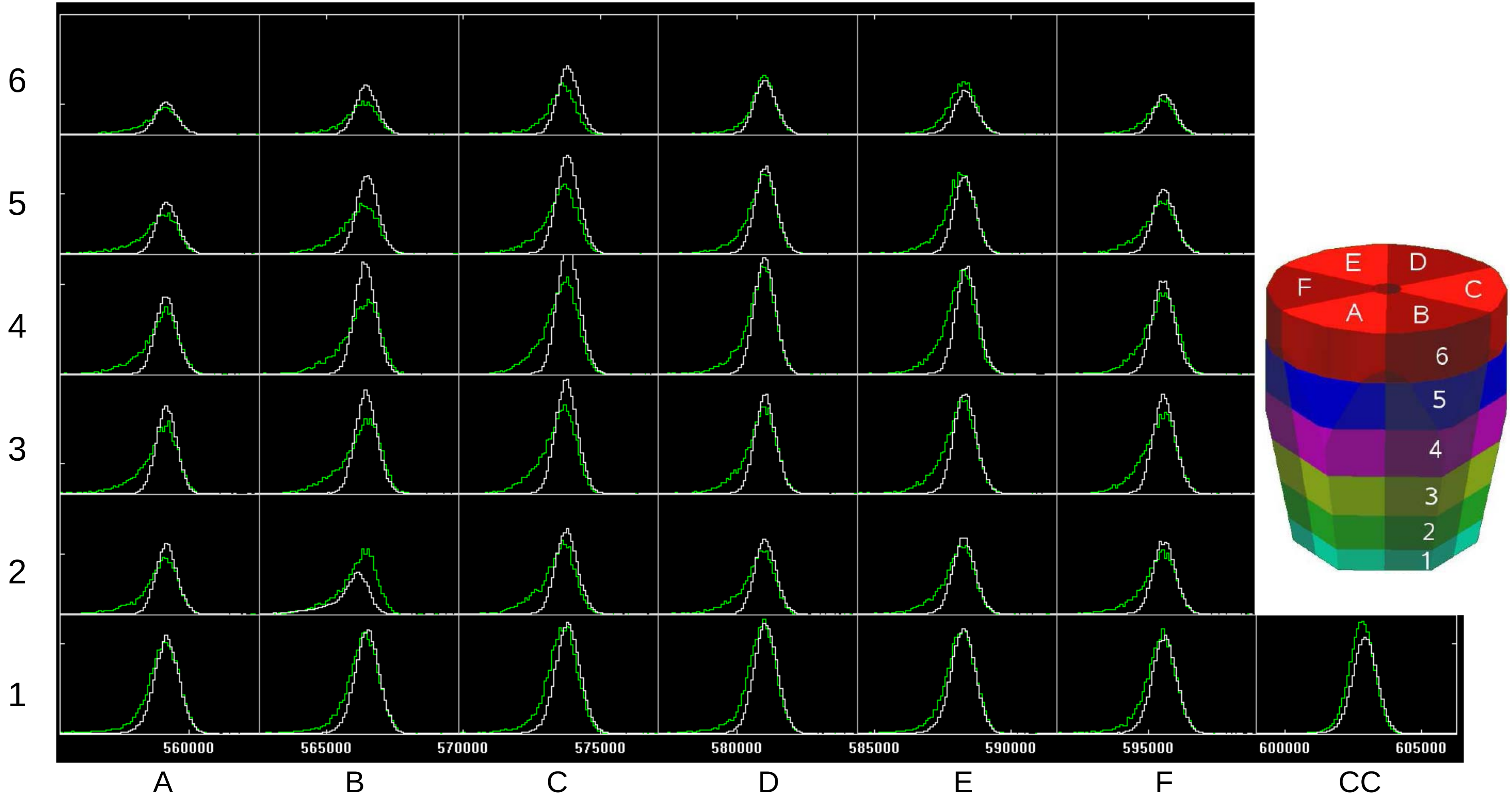
E: HV = 1kV | F: HV = 2kV | G: HV = 3kV

Bruyneel et al. NIM A 641 (2011) 92–100



Bruyneel et al. NIM A 641 (2011) 92–100

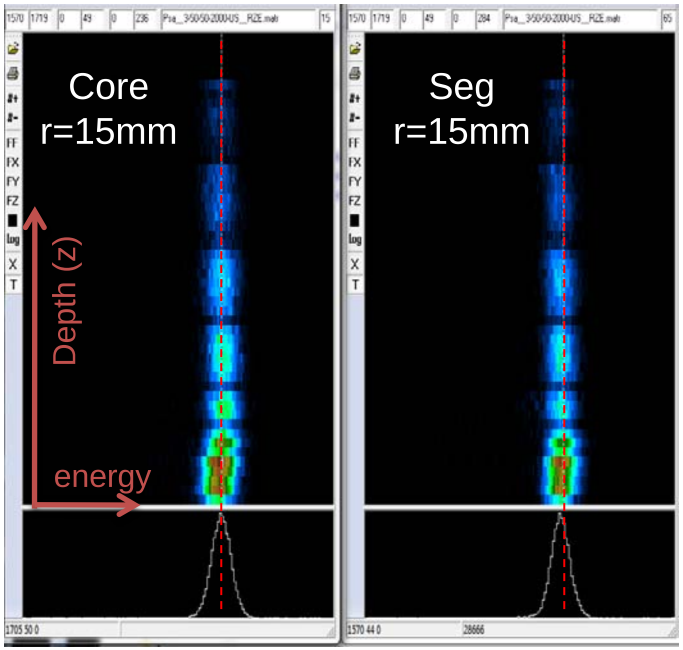
Det. 1B - Shape of the 1332 keV line



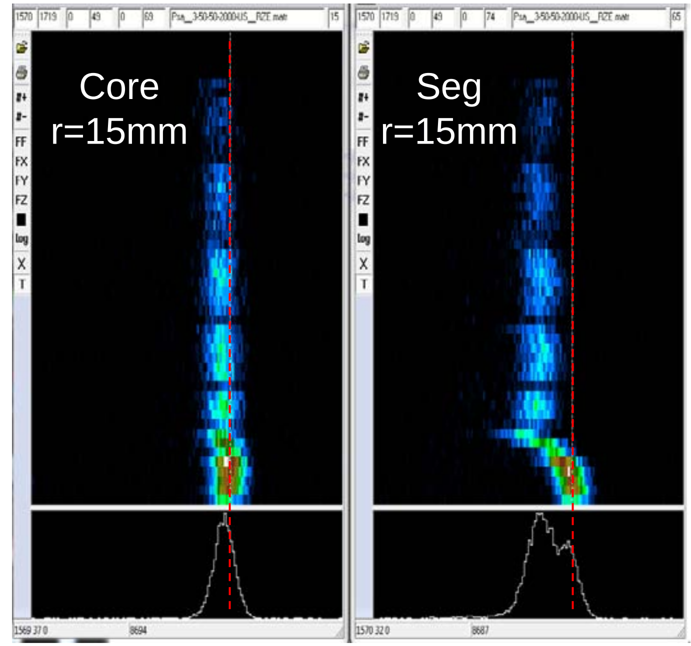
White: April 2010 → FWHM(core) ~ **2.3 keV** FWHM(segments) ~**2.0 keV**
Green: July 2010 → FWHM(core) ~**2.4 keV** FWHM(segments) ~**2.8 keV**
Damage after 3 high-rate experiments (3 weeks of beam at 30-80 kHz singles)

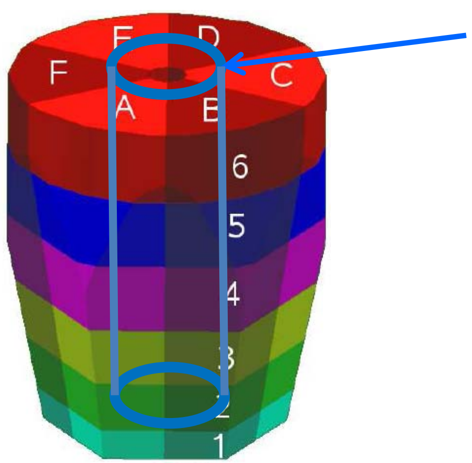
Crystal 1B (C002)

April 2010



July 2010



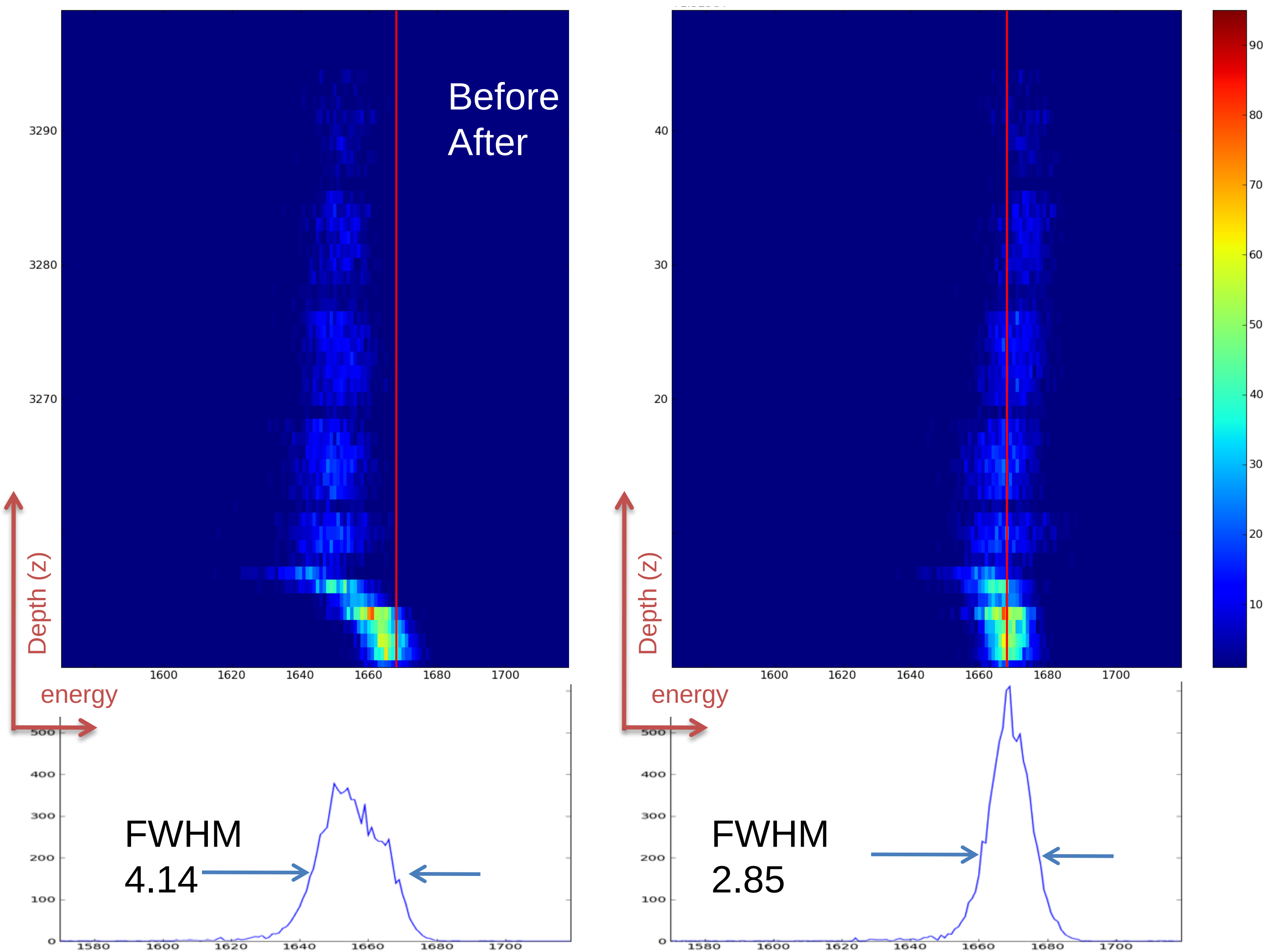


The 1332 keV peak as a function of crystal depth (z) for interactions at r = 15mm

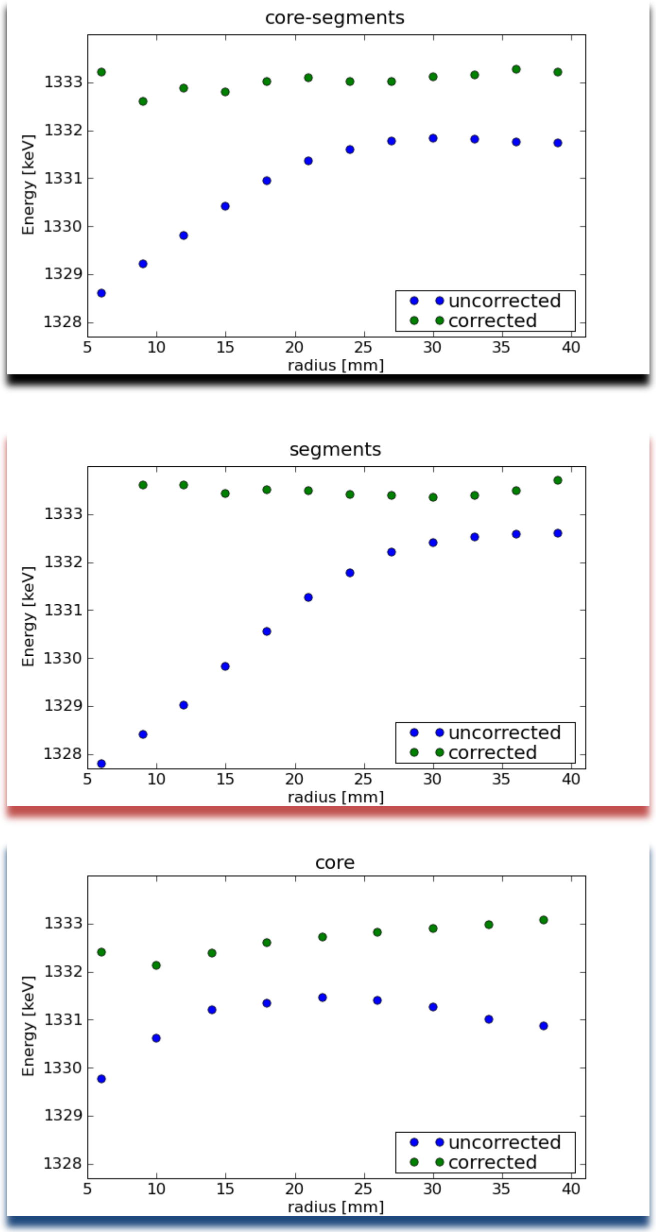
The charge loss due to neutron damage is proportional to the path length to the electrodes. This is provided by the PSA, which is barely affected by the amplitude loss.

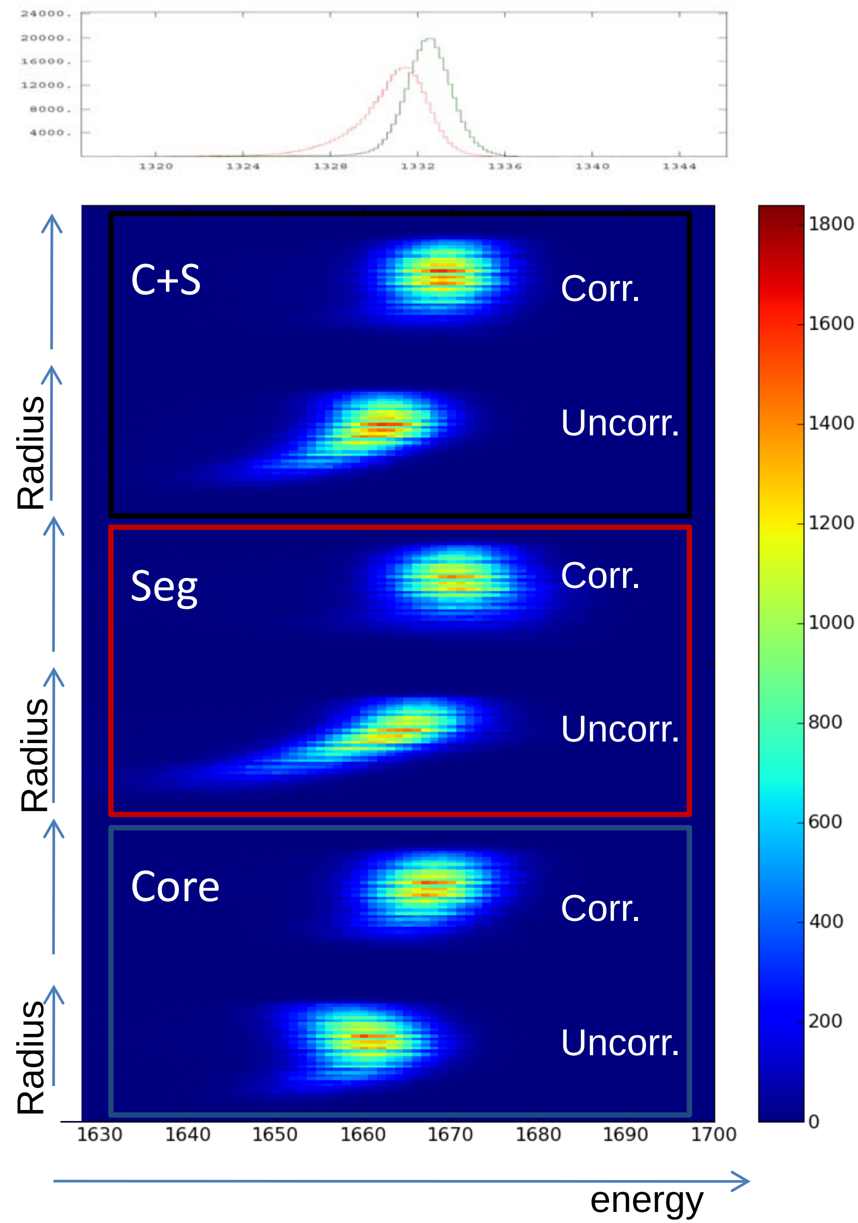
Knowing the interaction position,
the charge trapping **can be calculated and corrected away**

The 1332 keV peak as a function of crystal depth (z) for interactions at r = 15mm (worst case !)



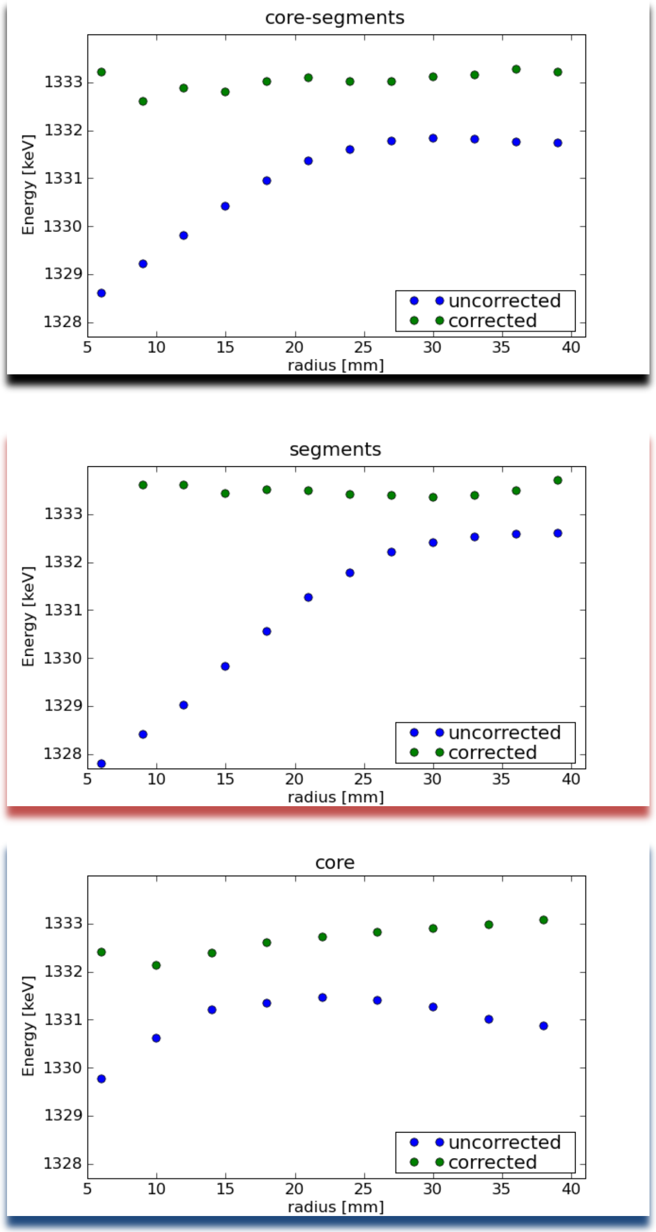
Correction of neutron damage

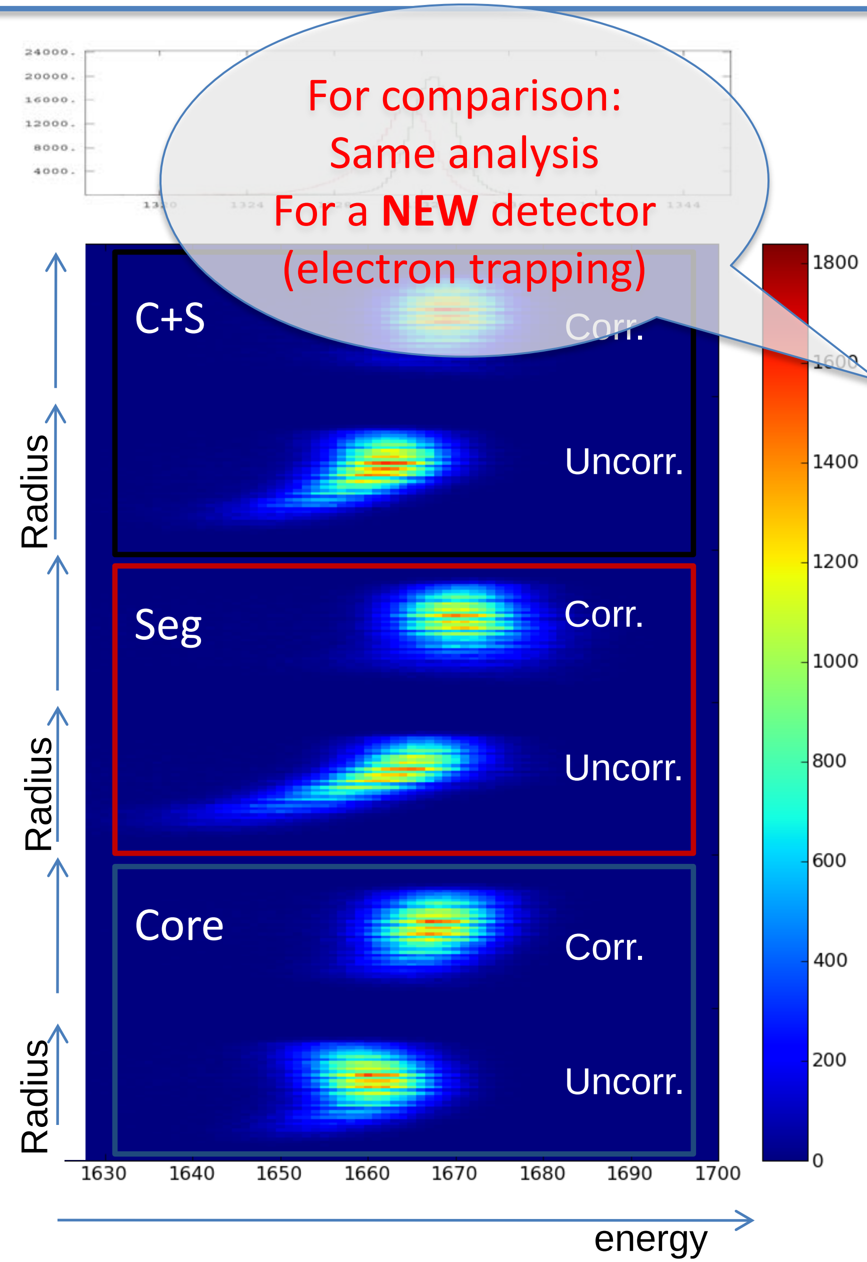




FWHM 1.3MeV	FWTM / FWHM
2.06	1.91
2.44	1.83
2.51	1.83
2.88	2.34
2.30	1.83
2.34	1.83

Correction of neutron damage





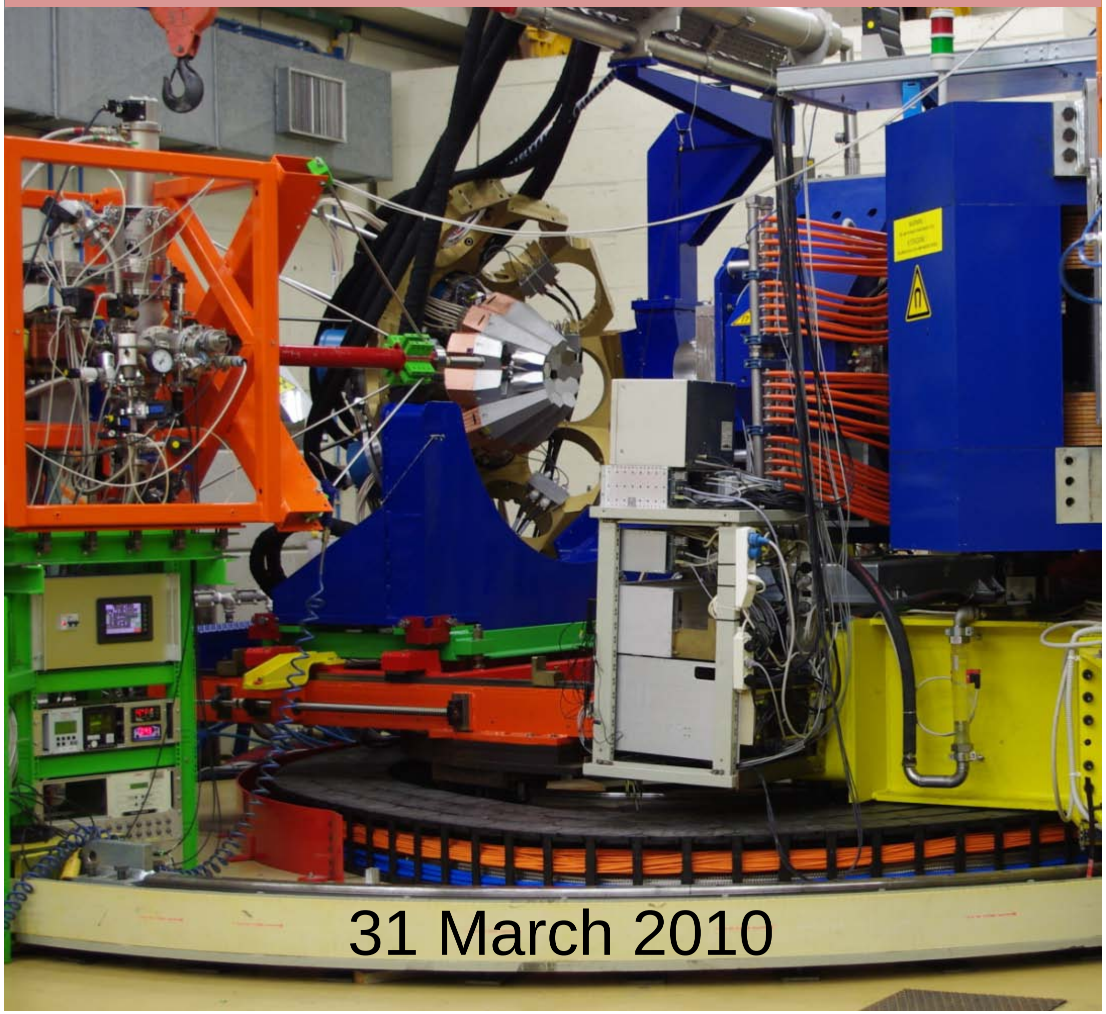
FWHM 1.3MeV	FWTM / FWHM
2.06	1.91
1.80	1.85
2.44	1.83
1.87	1.85
2.51	1.83
1.93	1.86
2.88	2.34
1.98	1.83
2.30	1.83
2.12	1.81
2.34	1.83
2.25	1.83

Conclusion

AGATA Demonstrator + PRISMA

(Legnaro National Lab, Italy)

installation started mid 2008, completed mid 2009



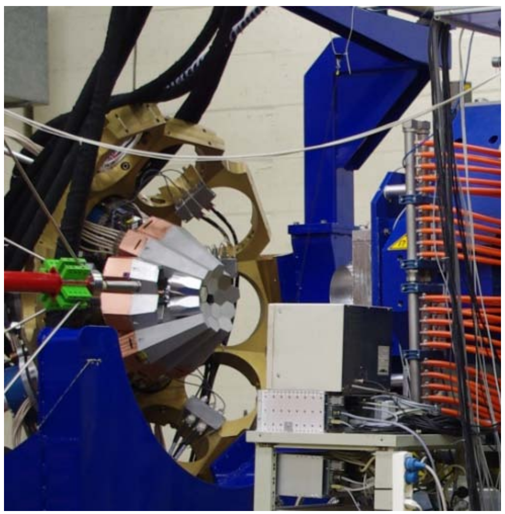
- Detectors brought to optimal performance using digital electronics
- PSA resolution alows tracking, and still improves in time
- Demonstrator = 5ATCs in operation at LNL
- First experiments performed succesfully: ➔ see thursday

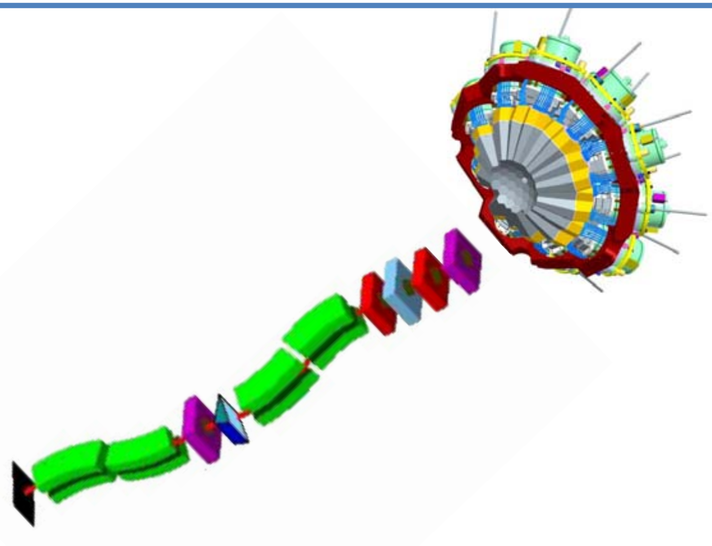
OUTLOOK: Plans for the next few years

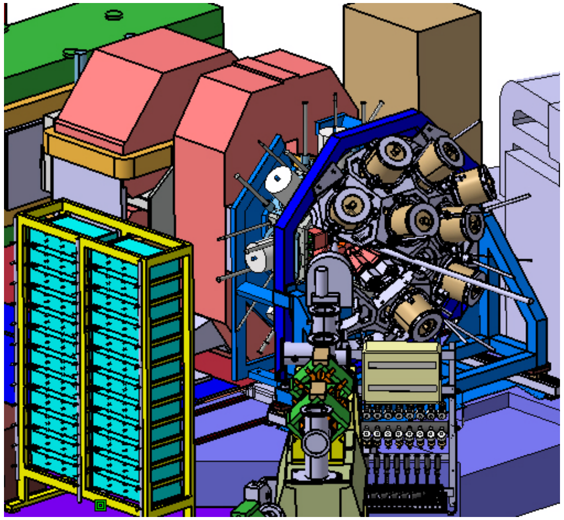
LNL: 2010-2011
5 TC
Total Eff. ~6%

GSI: 2012-2013
≥ 8 TC
Total Eff. > 10%

GANIL: 2014-2015
15 TC
Total Eff. > 20%







AGATA D. + PRISMA

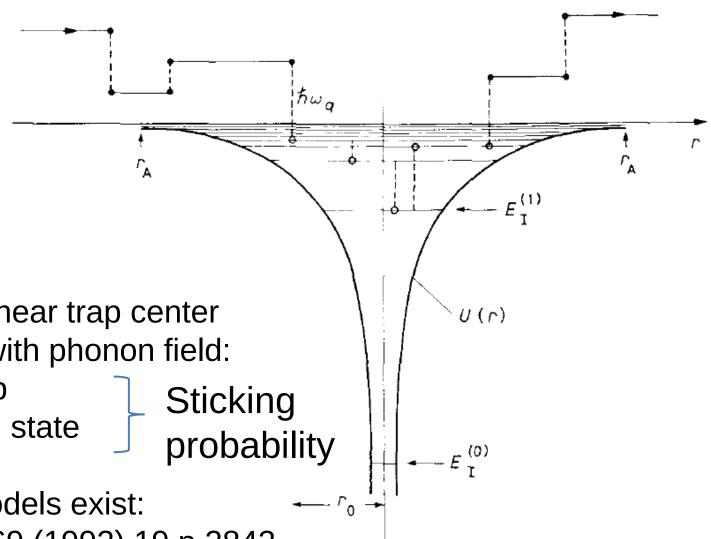
AGATA + FRS

AGATA + VAMOS

Trapping cross sections

L. Reggiani – Rev. del Nuovo Cimento 12 nr 11 (1989)

Most popular is model by Lax:
Cross sections are **velocity** dependent



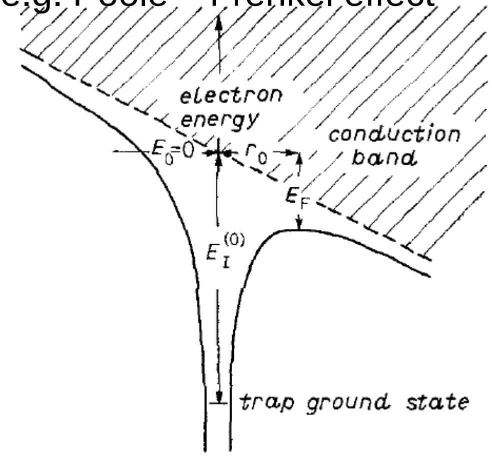
<u>Lax: cascade model</u>

1) electron emits phonon near trap center
2) electron in interaction with phonon field:
   or: struggles out of trap
   or: collapses to ground state

} Sticking probability

But also other (recent) models exist:
e.g. L. S. Darken – PRL 69 (1992) 19 p 2842

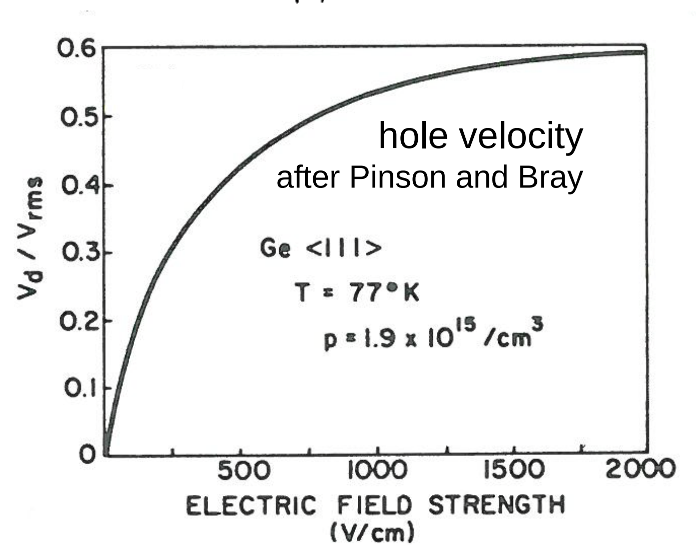
Cross sections are **field dependent** -
e.g. Poole – Frenkel effect



$$< \sigma v > \propto E^x < v^y >$$

- data on $<v^y>$ basically not existing
- difficult to know which model to use

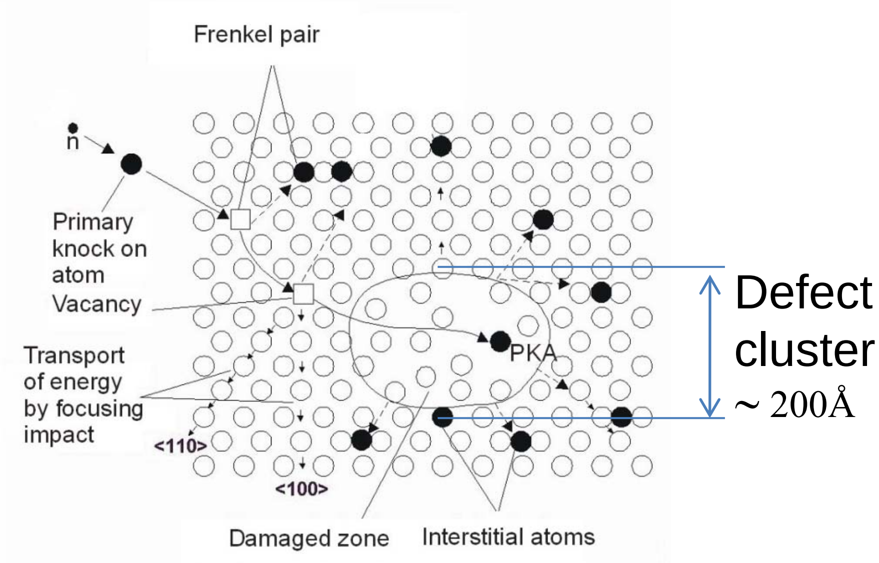
only data



Trapping cross section: neutron damage specific

L. S. Darken et al. NIM 171 (1980)

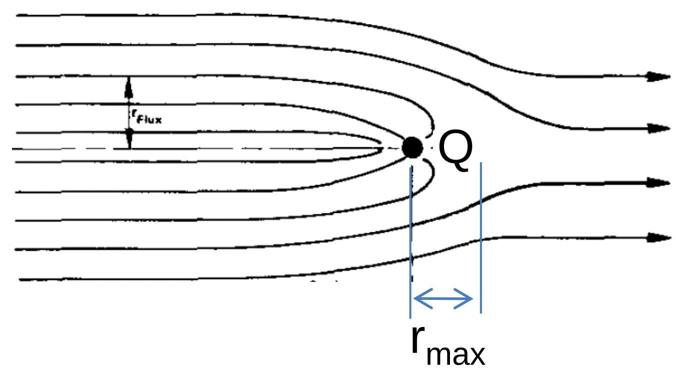
Specific model for fast neutron induced



Cross section from field line disturbance:

Balance between E field and Coulomb force:

$$qE = \frac{Qq}{4\pi\varepsilon r_{max}^2} \quad \Leftrightarrow \quad \sigma \propto 4\pi r_{max}^2 = \frac{Q}{\varepsilon E}$$



Assumptions:

- Trapping only by disordered regions
- Macroscopic model: drift velocity!

Q ~ 100e equilibrium charge state

r_{max} ~ 2 μm cross section (E=2kV/cm)

l_e ~ 0.2 μm dist. betw. optical phonon emission

used: $< \sigma \, v > \propto \frac{v_d}{E}$

Some theory: collection efficiency

- Trapping rate of electrons / holes "q":

$$\frac{dq}{dt} = -<\sigma\, v> N_t q \quad \Leftrightarrow \quad q(t) = q_0 \cdot e^{-\int_0^t <\sigma v> N_t dt'}$$

σ : trapping cross section
v : microscopic velocity
<.>: average over ensemble
N_t : density of trapping centers

- Collection efficiency (position dependent) of electrons / holes for electrode "i":

$$\eta^i_{e,h}(\vec{x}_0) = -\int_0^{t_e} \left(\vec{\nabla}\phi_i \cdot \vec{v}_{e,h}\right) \cdot \frac{q(t)}{q_0} dt$$

= Integral [current to seg i per unit charge]
= total recorded charge by e/h after collection

x_0 : interaction position in detector
ϕ_i : weighting potential of segment i
$v_{e,h}$: drift velocity of electrons / holes
t_e : collection time

- Total collection efficiency for electrode "i" at position x_0 :

$$\eta^i_{tot}(\vec{x}_0) = \eta^i_e(\vec{x}_0) + \eta^i_h(\vec{x}_0)$$

$$\simeq \phi_i(\vec{x}_0) + [1 - \phi_i(\vec{x}_0)] \cong 1$$

Partial collection efficiencies mainly report on weighting potential

Trapping sensitivity*

(*personal definition – don't google!)

•DEFINITION: electron / hole sensitivity of electrode i to trapping

$$s^i_{e,h} = \frac{d\eta^i_{e,h}}{dN_t}\Big|_{N_t=0}$$

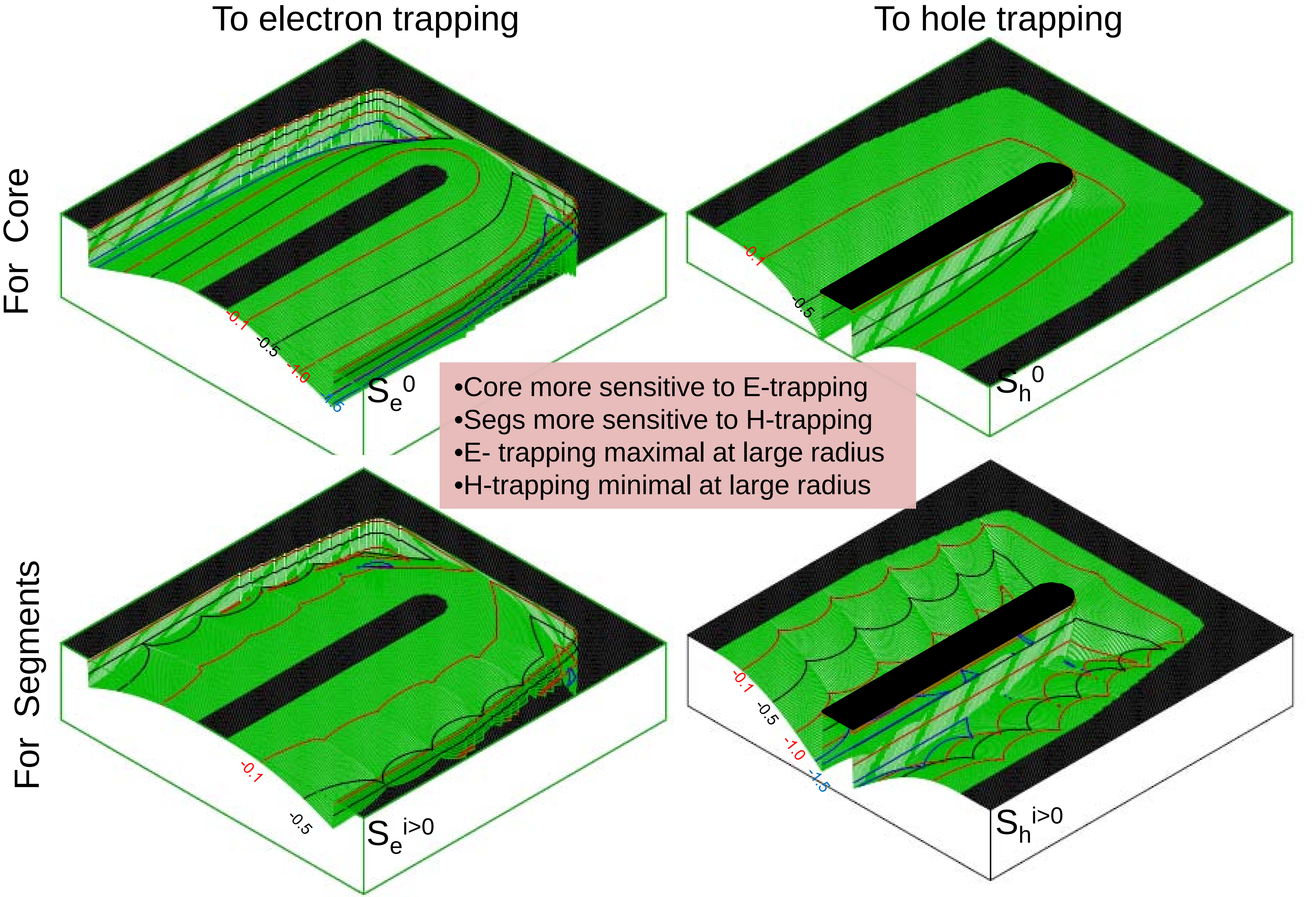
= fraction missing due to trapping
+ induced charge due to trail of trapped charges

•Relation to total collection efficiency:

$$\eta^i_{tot}(\vec{x}_0) = 1 + \left[N_e s^i_e(\vec{x}_0) + N_h s^i_h(\vec{x}_0)\right] + O(2)$$

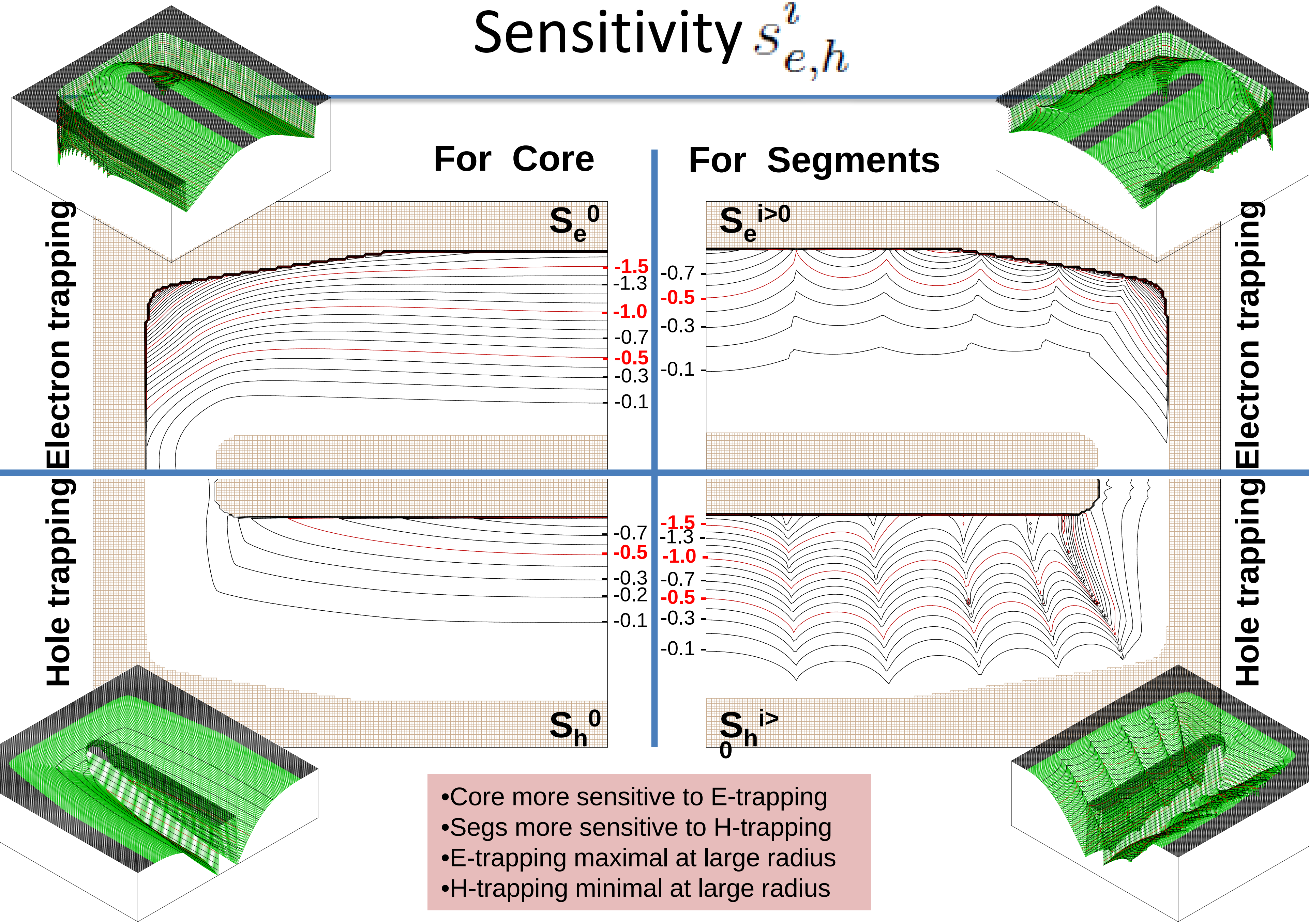
•Ne : density of electron traps, Nh: density of hole traps
•O(2) – higher order terms in taylor expansion - negligible
•sensitivities can be calculated in advance
•Ne, Nh are fit parameters

Sensitivity $s^{i}_{e,h}$



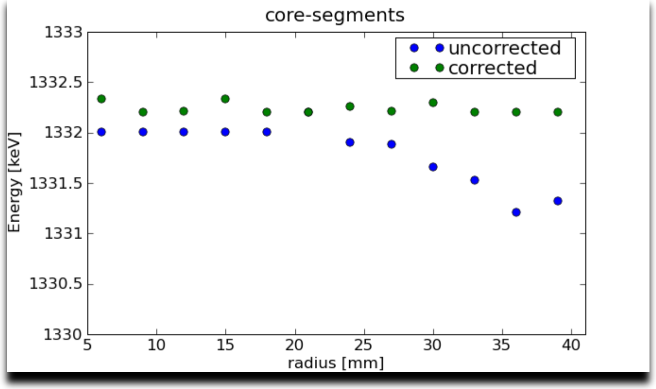
- Core more sensitive to E-trapping
- Segs more sensitive to H-trapping
- E- trapping maximal at large radius
- H-trapping minimal at large radius

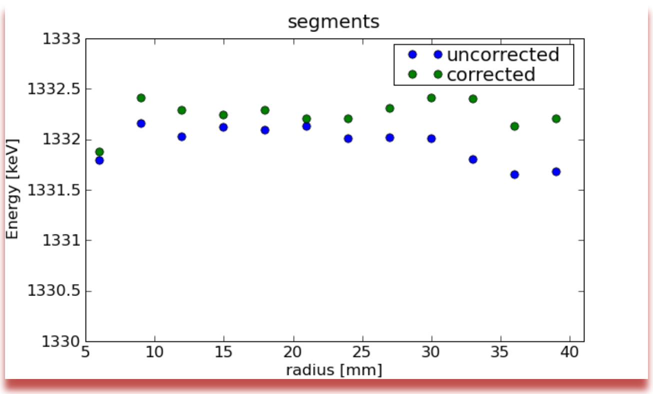
Sensitivity $s^{i}_{e,h}$

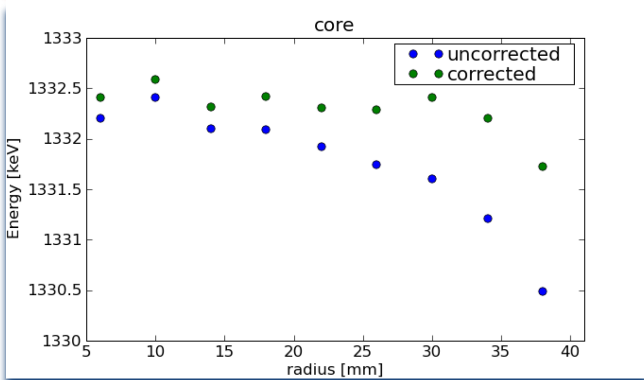


- Core more sensitive to E-trapping
- Segs more sensitive to H-trapping
- E-trapping maximal at large radius
- H-trapping minimal at large radius

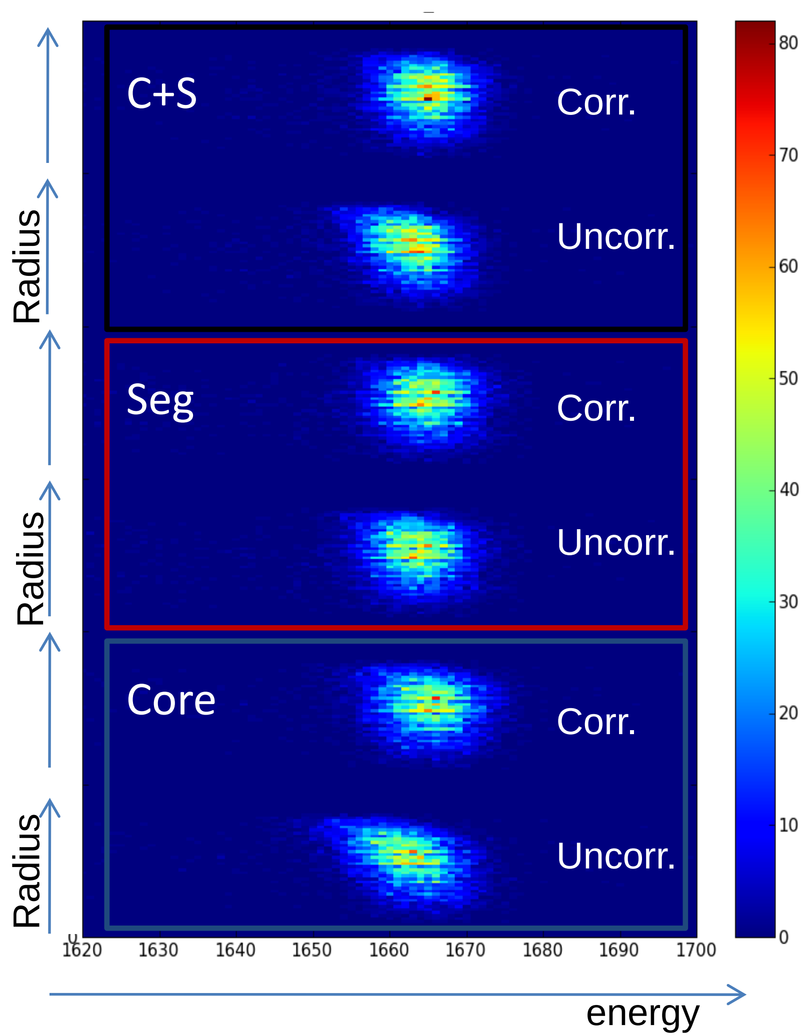
Trapping in new detectors







- Electron trapping present in any detector
- Source of scattering on Fano factors

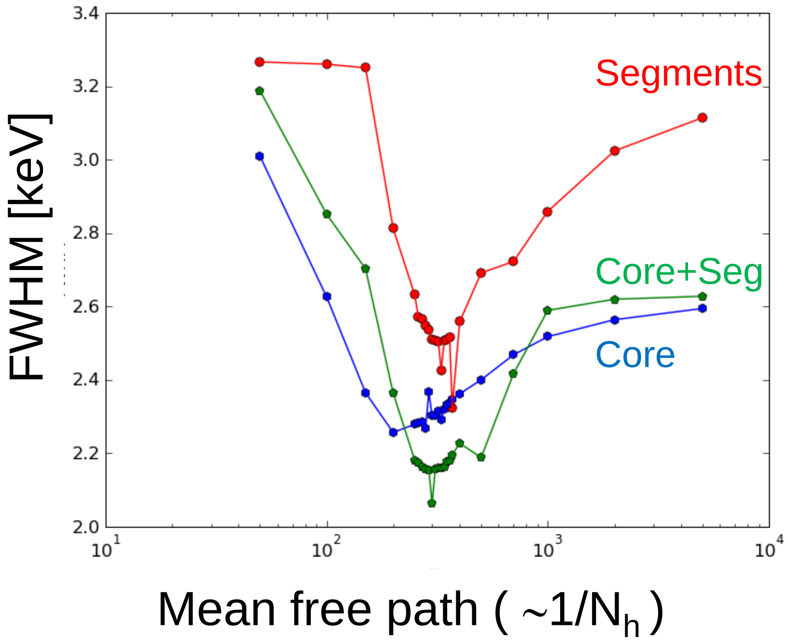


FWHM 1.3MeV	FWTM FWHM
1.80	1.85
1.87	1.85
1.93	1.86
1.98	1.83
2.12	1.81
2.25	1.83

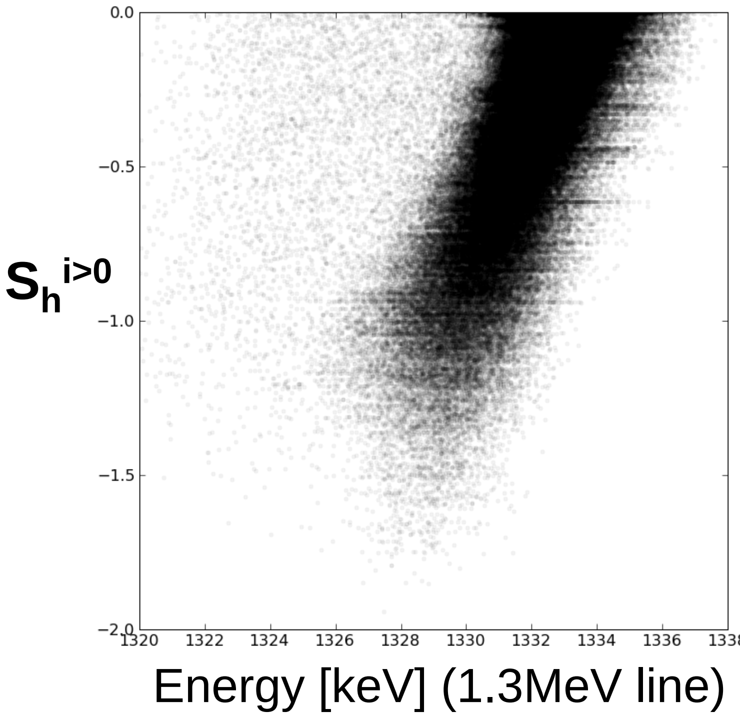
Correction of neutron damage

$$\eta^i_{tot}(\vec{x}_0) = 1 + \left[N_e s^i_e(\vec{x}_0) + N_h s^i_h(\vec{x}_0)\right]$$

•N_e fixed, Scan for N_h :



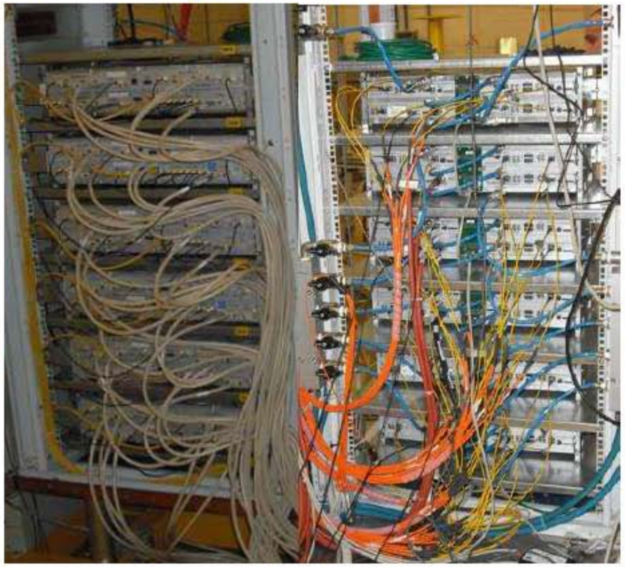
Segment $S_h^i(x)$ vs energy:



AGATA: Digital Electronics

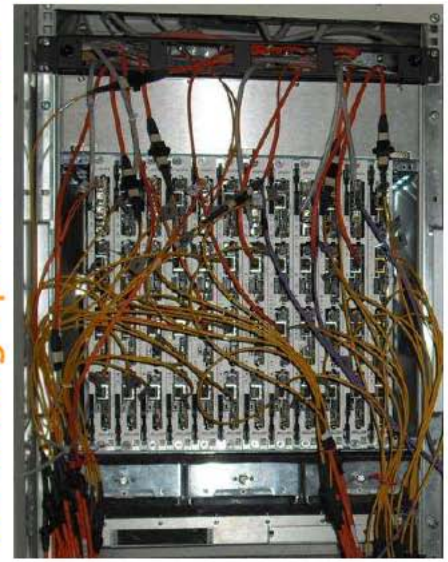
Digitisers
in the experimental hall

10 m long MDR cables



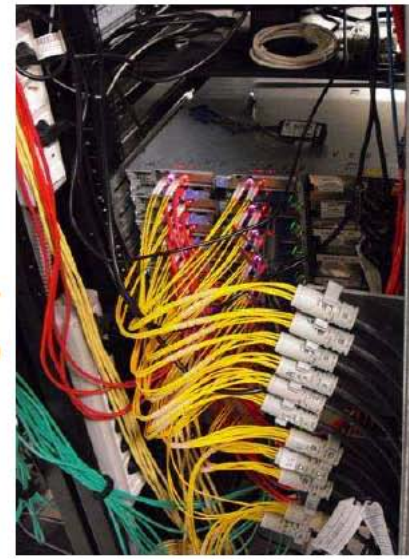
80 m long optical fibers

Digital proc. electronics
in the users area



20 m long optical fibers

Computer farm
in the computing room



LAN to the disk servers

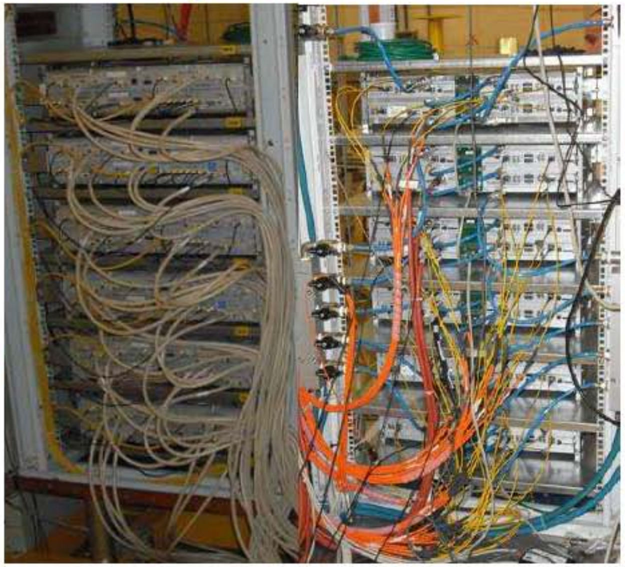
Digitizers:

- One module per crystal: 36 segment channels + dual core (high + low gain)
- 100Ms/s, 14 bit, all running on the same clock
- Synchronous readout to digital electronics of all samples (7.6GB/s/crystal)

AGATA: Digital Electronics

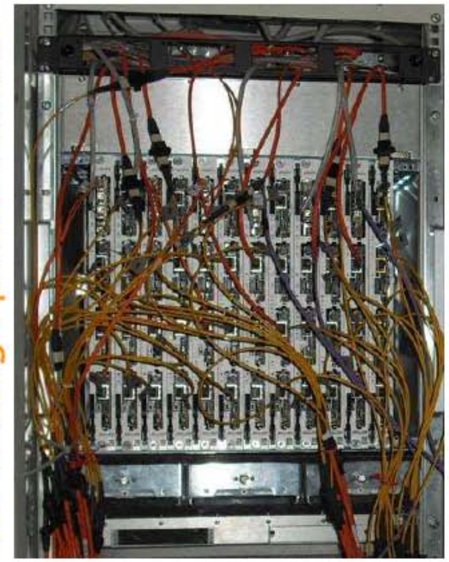
Digitisers
in the experimental hall

10 m long MDR cables



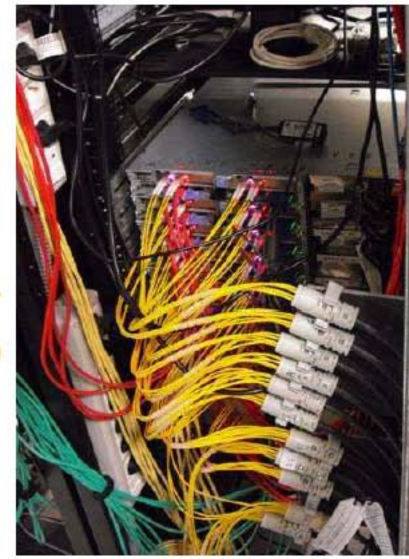
80 m long optical fibers

Digital proc. electronics
in the users area



20 m long optical fibers

Computer farm
in the computing room



LAN to the disk servers

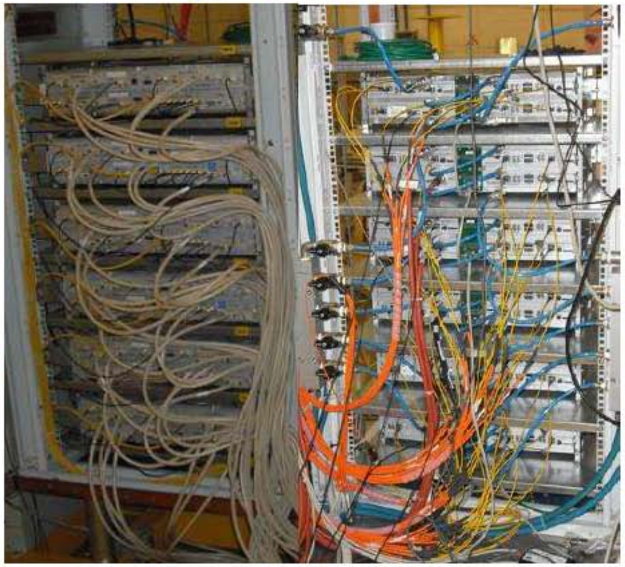
Digital processing electronics:

- 2 ATCA carriers per crystal: 4-slot carrier boards and processing mezzanines
- Local trigger on the core signal
- Trapezoidal shaping with baseline restoration
- Trace capture (100 samples/channel = 10 kB/event/crystal)

AGATA: Digital Electronics

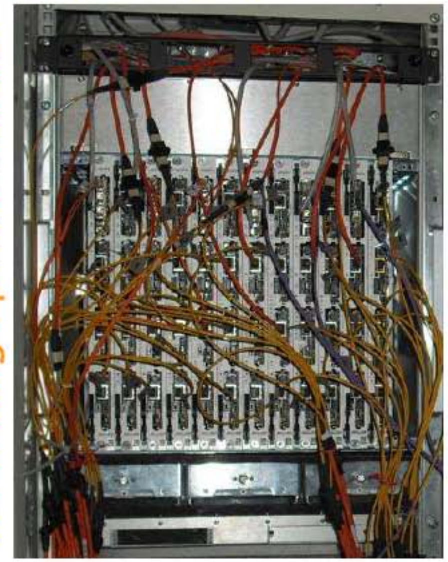
Digitisers
in the experimental hall

10 m long MDR cables



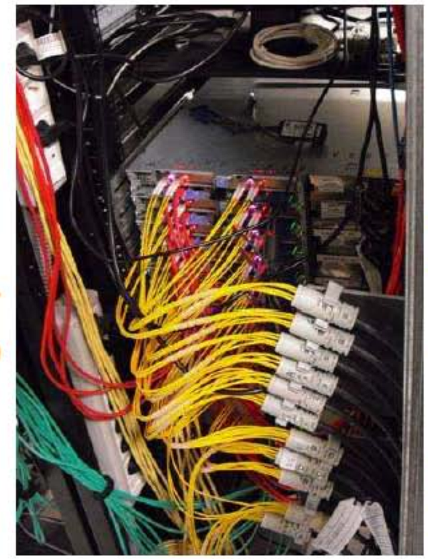
Digital proc. electronics
in the users area

80 m long optical fibers



Computer farm
in the computing room

20 m long optical fibers



LAN to the disk servers

Data processing farm:

- 1 pizza-box per crystal: Readout / Pre-processing / PSA (< 4.5 kEvt/s)
  (Pre-processing = gain matching, time alignment, Xtalk correction,…)
- 10 pizza-boxes: Event Builder / Online tracking, analysis & storage
- 120 TB of storage + Archiving on Grid T1

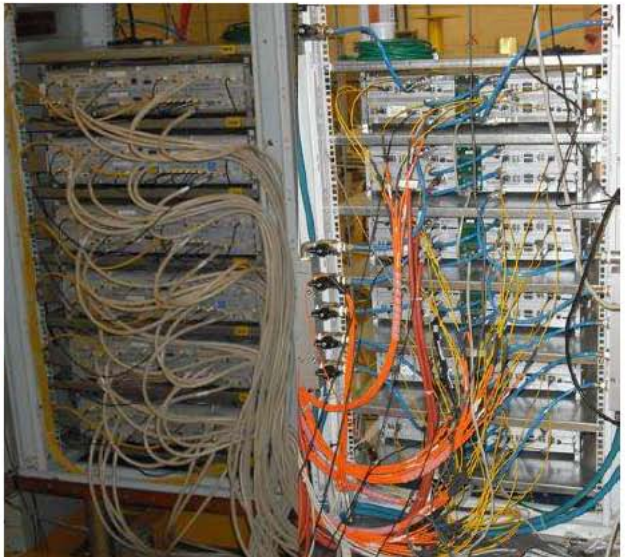
AGATA: Digital Electronics

Digitisers
in the experimental hall

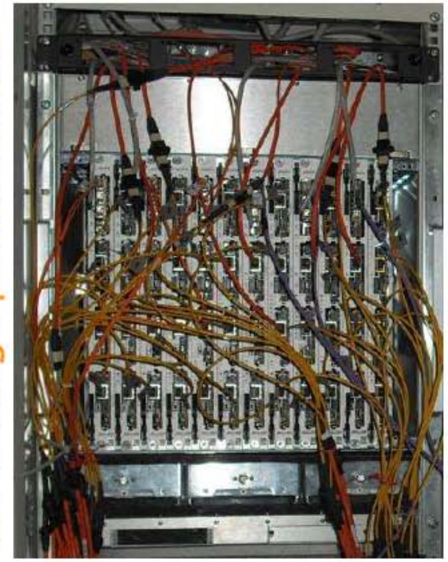
Digital proc. electronics
in the users area

Computer farm
in the computing room

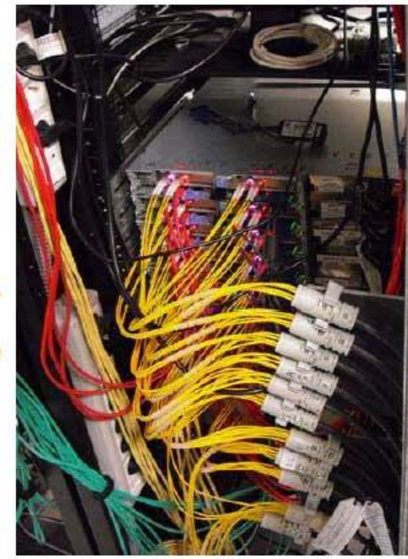
10 m long MDR cables



80 m long optical fibers



20 m long optical fibers

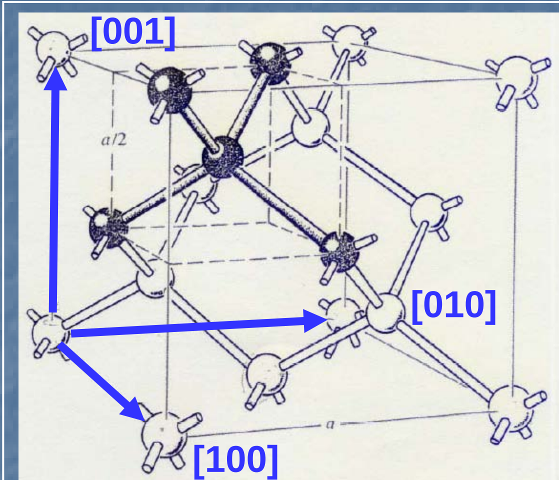


LAN to the disk servers

Global Triggering System (GTS):

- Provides a 100 MHz clock and a 48 bit timestamp
- Collects local triggers, determines global trigger
- Returns validation/rejection

Mobilities : Intro



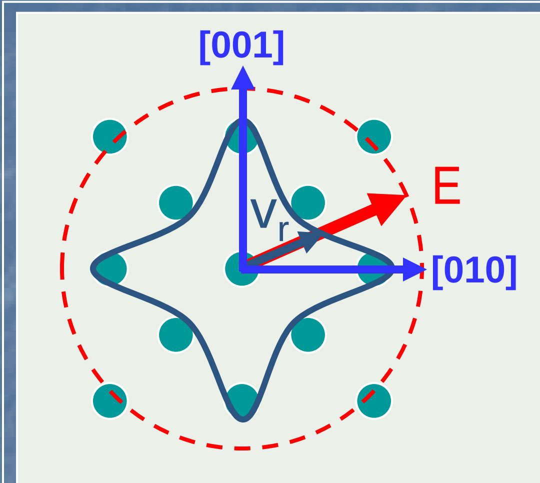
- Monocrystalline Ge
- Periodic potential

⇓

Bloch electrons:

$$\Psi_{n,\vec{k}}(\vec{r}),\ \varepsilon_{n,\vec{k}}$$

- Wave vector $\vec{k}$ in first Brillouin zone
- Band index n



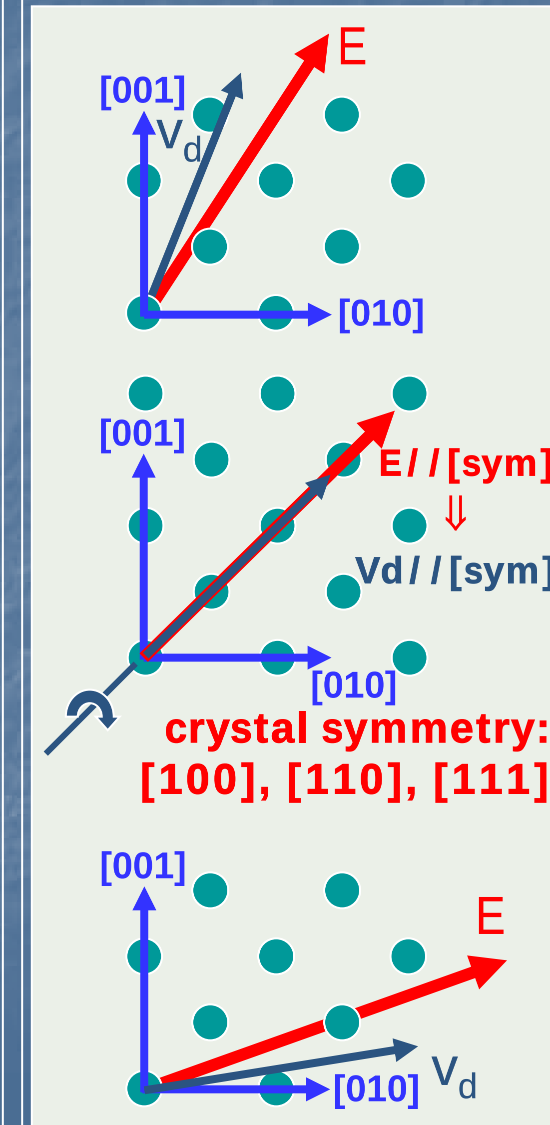
- Velocity:

$$\vec{\mathbf{v}}_{n,\vec{k}} = \frac{1}{\hbar}\vec{\nabla}_{\vec{k}}\varepsilon_n(\vec{k})$$

- Longitudinal anisotropy

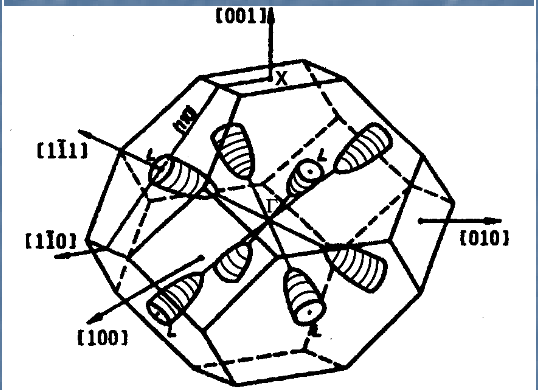
$|v_r|$ angle dependent

- Tangential anisotropy



Electron and Hole Mobility in Ge

Electrons



-Phys.Rev. 130(6):2201-2204,1963

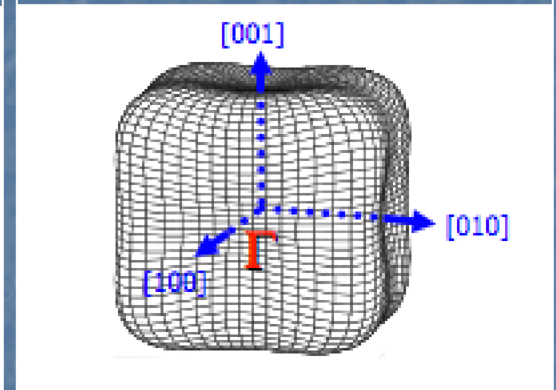
-distributed over 4 ellipsoidal valleys

-each valley is MB distributed, T(E)

-intervalley scattering ν(E) defines valley population

-v_{100}(E) and ν(E) defines all.

Holes



-B. Bruyneel et al. NIM A 569 (2006) 764-773-:

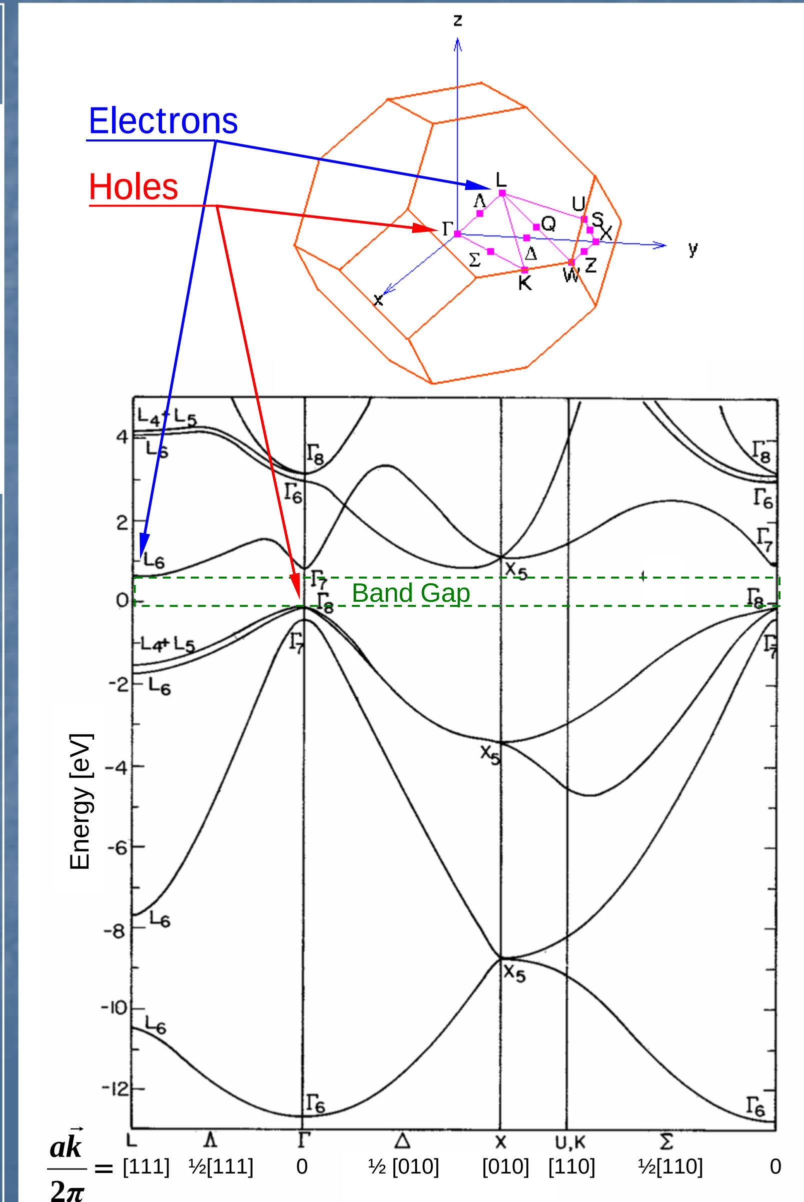
-only "warped" heavy hole band is important

-"Streaming motion" → drifted MB distribution:

$$f(\vec{k}) \propto \exp\left(-\hbar^2(\vec{k}-\vec{k}_0)^2/2mk_bT_e\right)$$

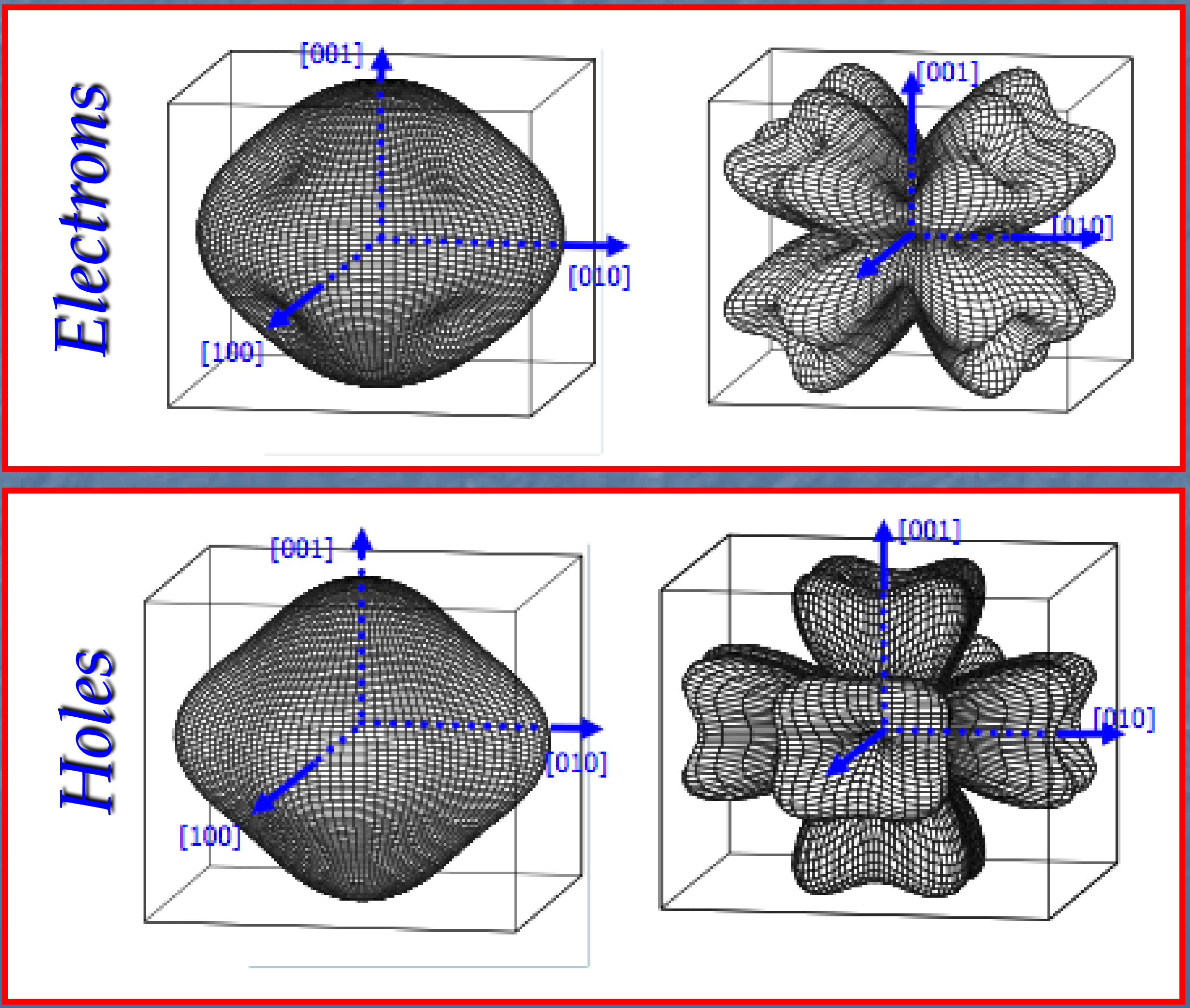
$$\vec{\mathbf{v}}_d \propto \int \mathbf{v}(\vec{k})\, f(\vec{k})\, d\vec{k}$$

- v_{100}(E) and v_{111}(E) defines all.

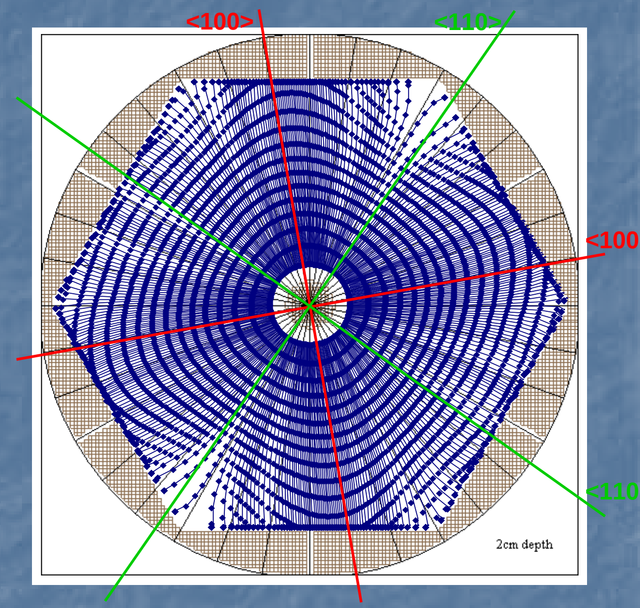


The anisotropic Hole mobility model

Anisotropy: Longitudinal *Tangential*



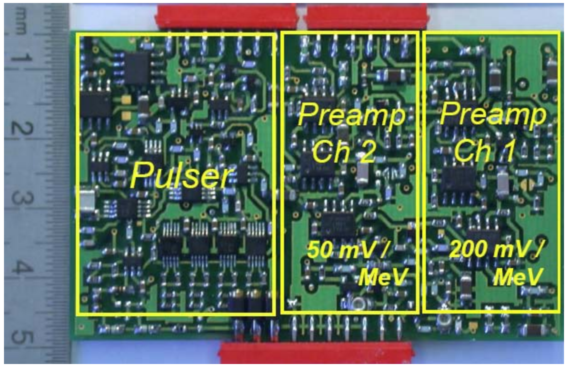
Example: hole trajectories



- Electrons v_r mainly slower near [111], Holes v_r mainly faster near [100]
- Tangential components 0 along symmetry axes and largest near same directions of largest v_r differences

AGATA: analog electronics

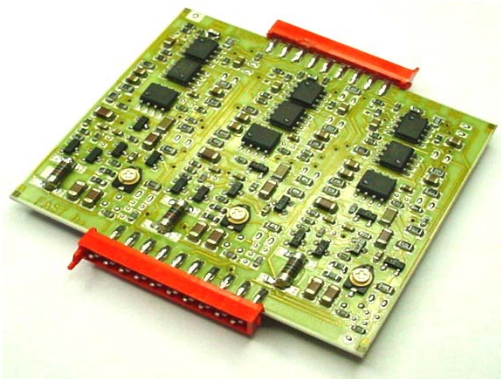
Core preamp + pulser :
(G. Pascovici, IKP Cologne)

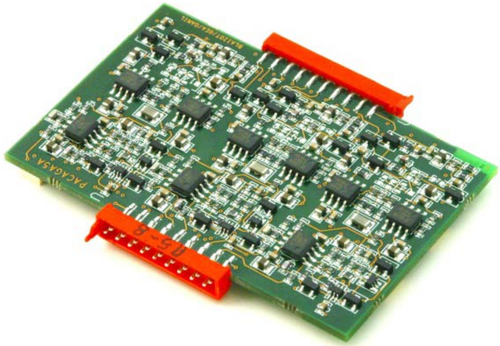


Requirement core preamp:

- low noise (energy + PSA)
- large bandwidth (PSA -> 30ns rise time)
- Wide dynamic range:
  + dual gain: 5MeV + 20MeV
  + desaturation circuitry (throughput x4)
  + TOT technique (~200MeV)

Segment preams (3channel):
Milano, Ganil:

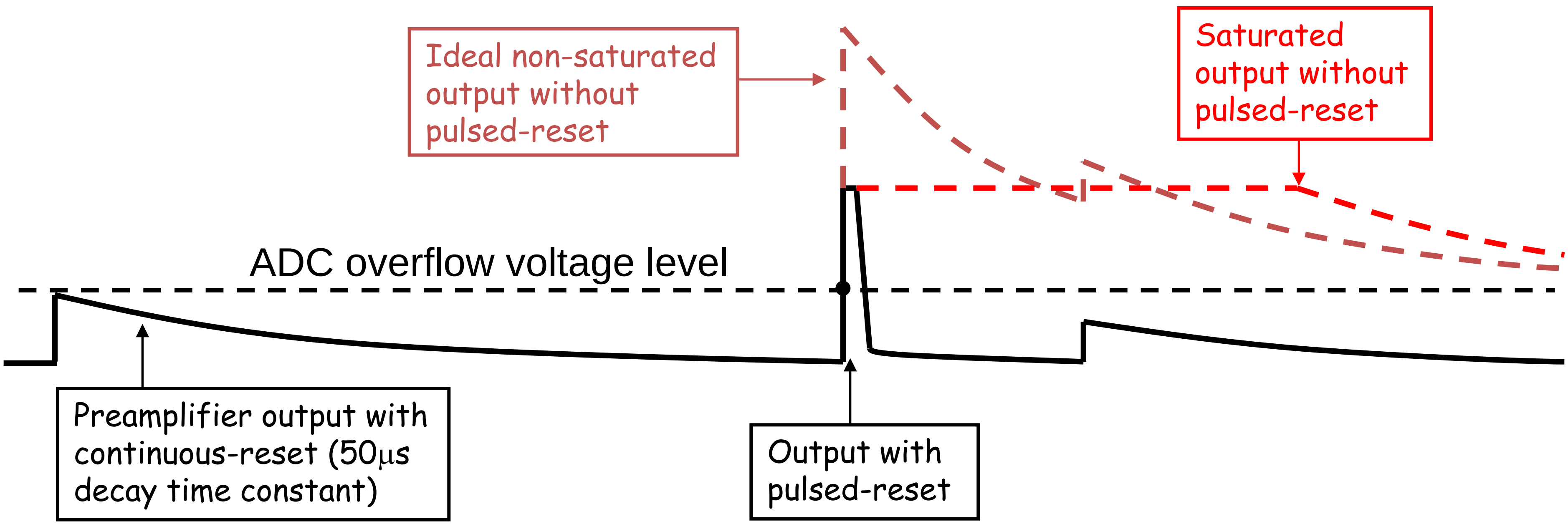




Differential out +MDR cable

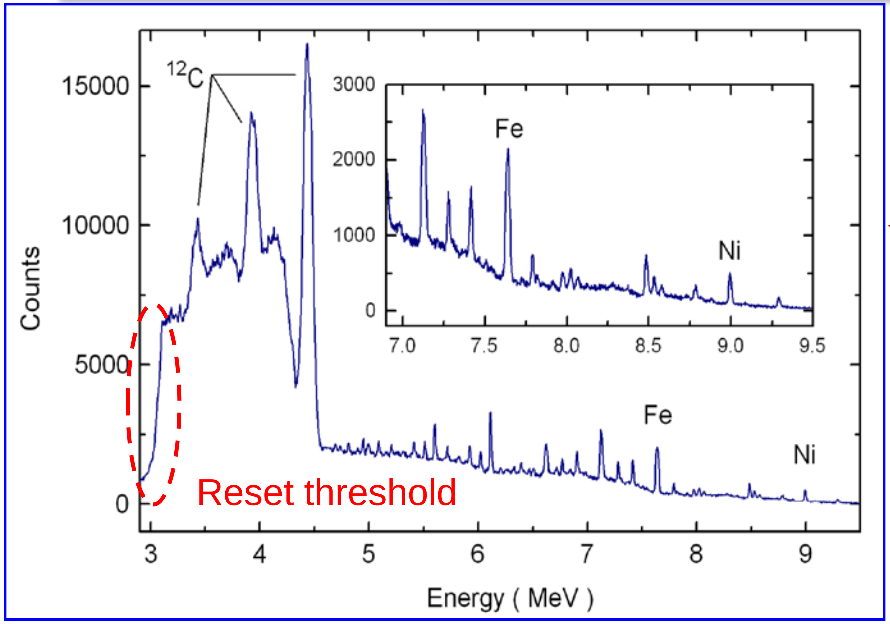
G. Pascovici et al. WSEAS trans. on circuits and systems (2008) Iss.6 Vol.7 p.470

Mixed reset technique: continuous + pulsed



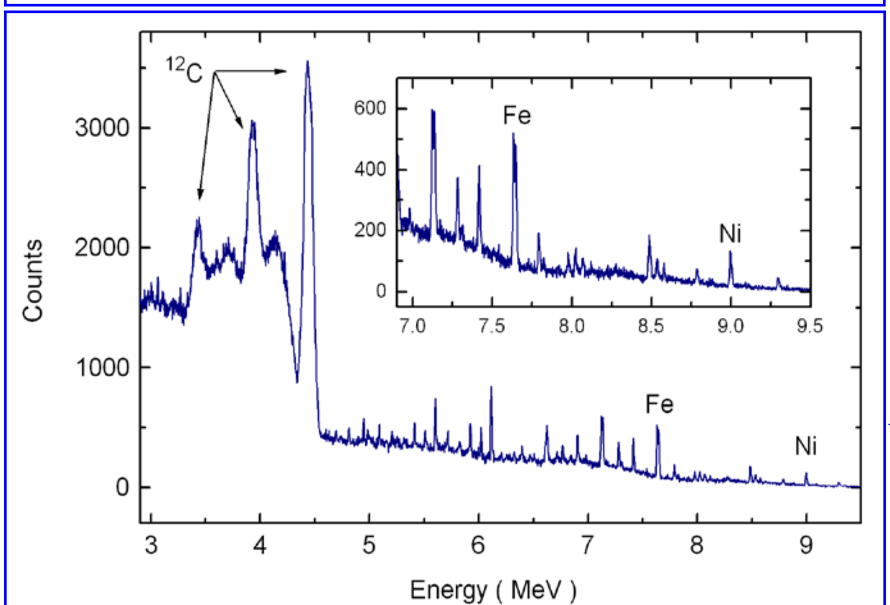
An ADC overflow condition would saturate the system for a long while ➡ Pulsed-reset mechanism allows fast recovery of the output

^{241}Am+Be spectrum



"reset" mode
(by TOT technique)

Energy	Resolution (fwhm) in pulse-height mode		Resolution (fwhm) in reset mode	
5.6 MeV	10.5 keV	0.14 %	18.8 keV	0.34 %
6.1 MeV	15.1 keV	0.17 %	17.1 keV	0.28 %
7.6 MeV	11 keV	0.14 %	18.8 keV	0.25 %
9.0 MeV	15 keV	**0.17 %**	18.9 keV	**0.21 %**



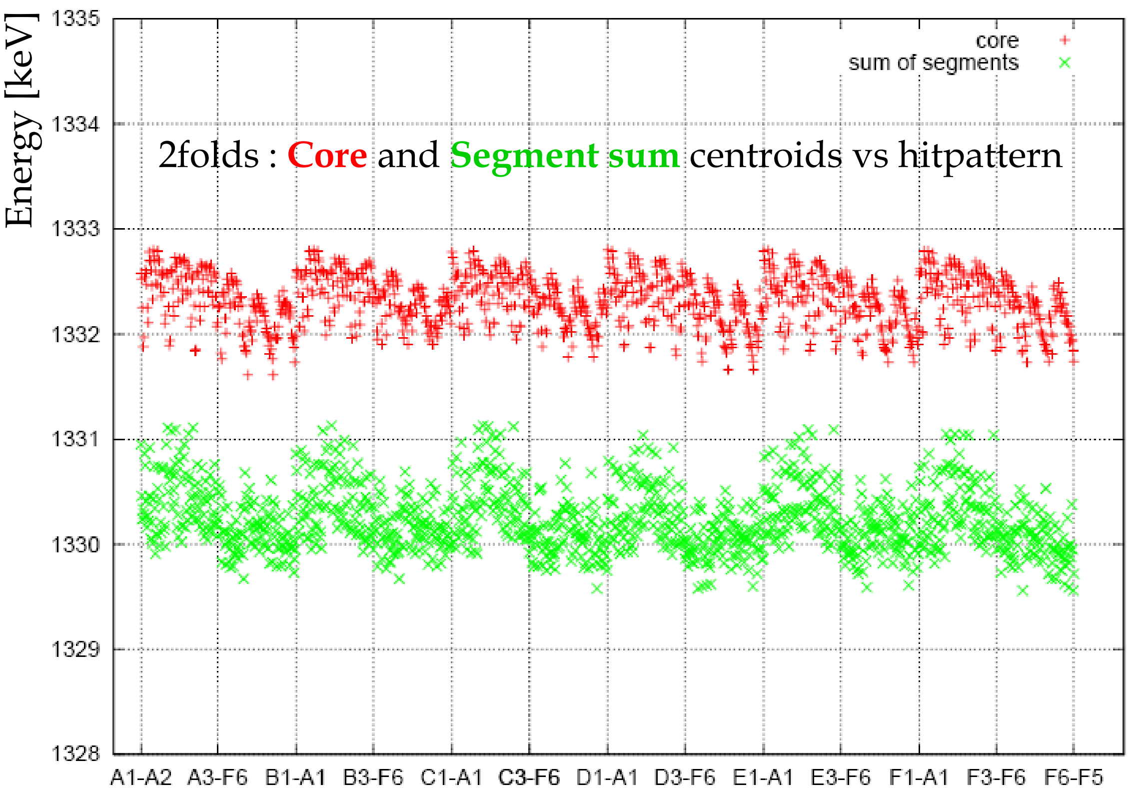
At high energies (> 10 MeV)

TOT mode ~ pulse-height mode

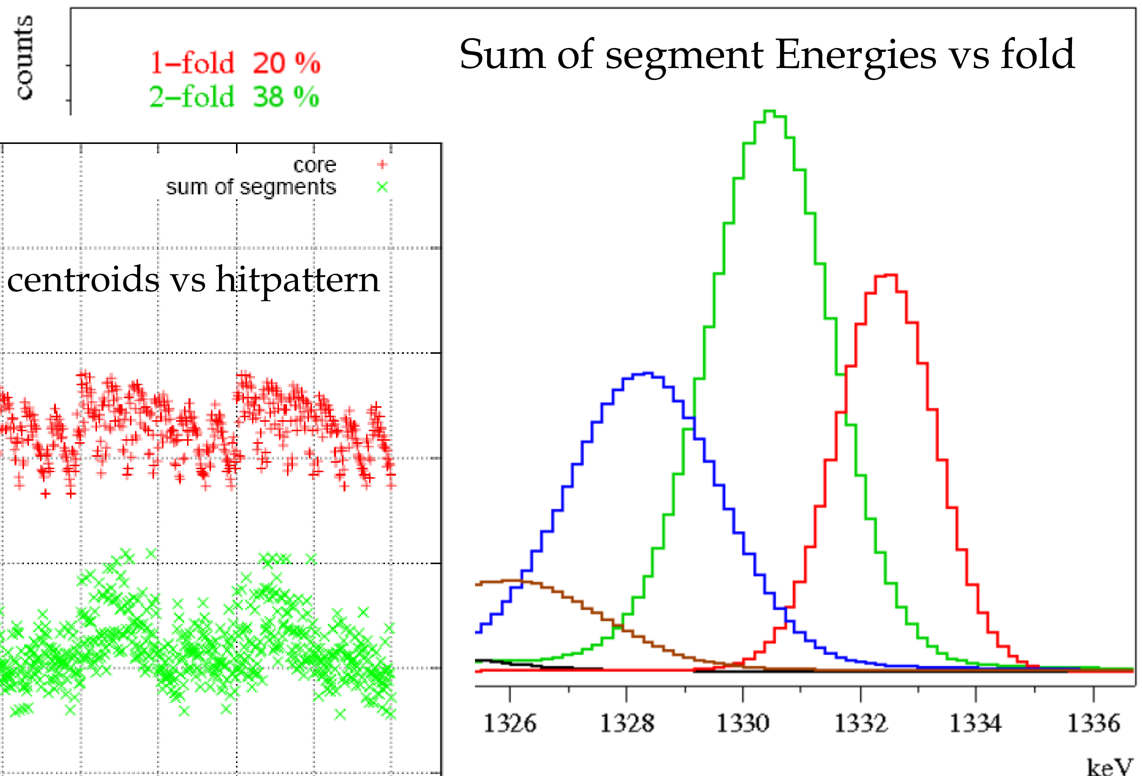
"pulse-height" mode

Performance: Cross talk

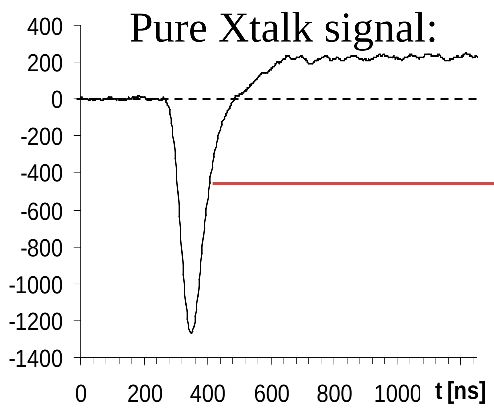
- Crosstalk is present in <u>any</u> segmented detector
- Creates strong energy shifts proportional to fold
- Tracking needs <u>segment energies</u> !



…All possible 2fold combinations

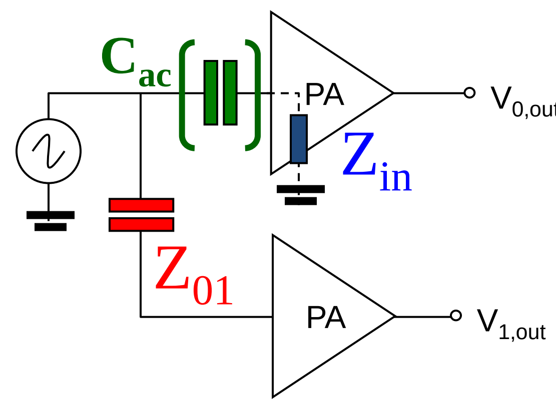


Origin of Crosstalk



Proportional Xtalk (50μs decay) → Energy

Differential Xtalk (only during risetime) → PSA



With $Z_{in} = 1/sAC_{fb} + (1/sC_{ac}) + R_{rise}$

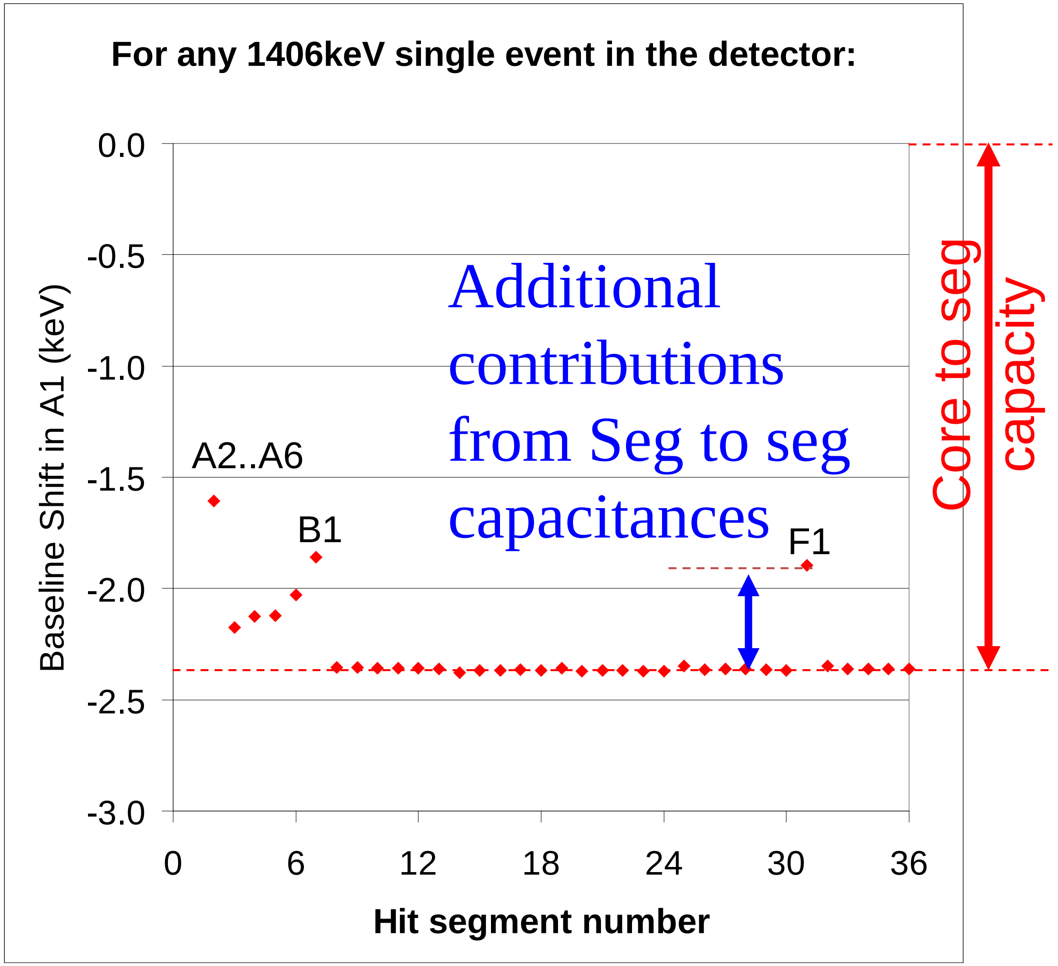
$$\text{Xtalk} \sim Z_{in} / Z_{01}$$

$$\sim \underbrace{C_{01}/AC_{fb} + (C_{01}/C_{ac})}_{\text{Proportional}} + \underbrace{s \,.\, R_{rise}\, C_{01}}_{\text{Differential Xtalk}}$$

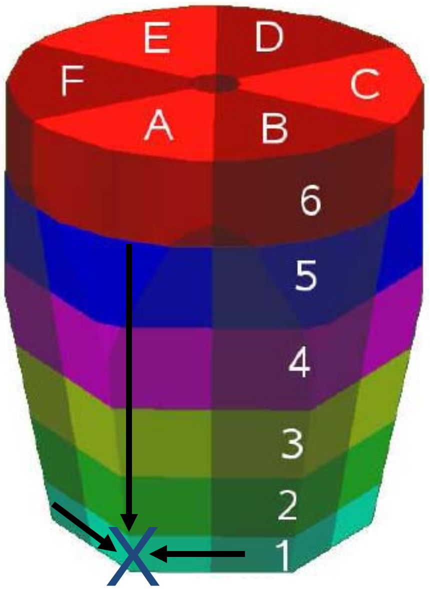
= Proportional + Differential Xtalk

!!! Proportional and Differential Xtalk are related !!!

Proportional Xtalk measurement



Segment labeling:

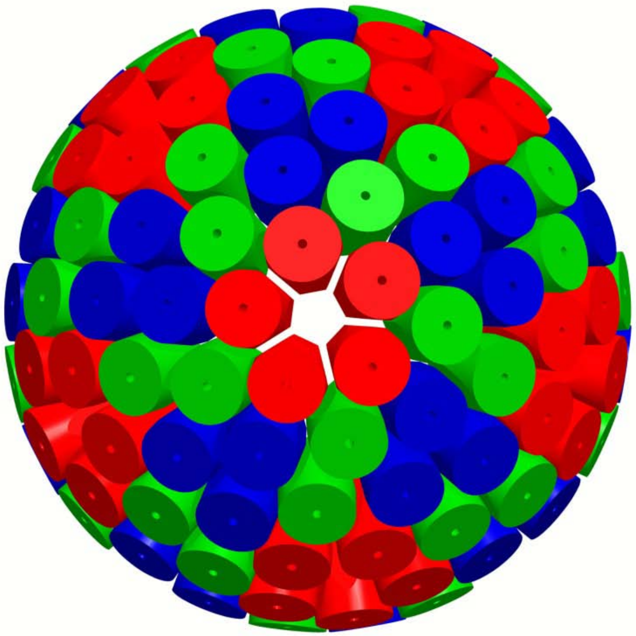


Sectors: A...F

Rings: 1...6

AGATA

(Design and characteristics)



Main features of AGATA

Efficiency: 43% (M_γ=1) 28% (M_γ=30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

Peak/Total: 58% (M_γ=1) 49% (M_γ=30)
today ~55% 40%

Angular Resolution: ~1° →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~ 40 keV

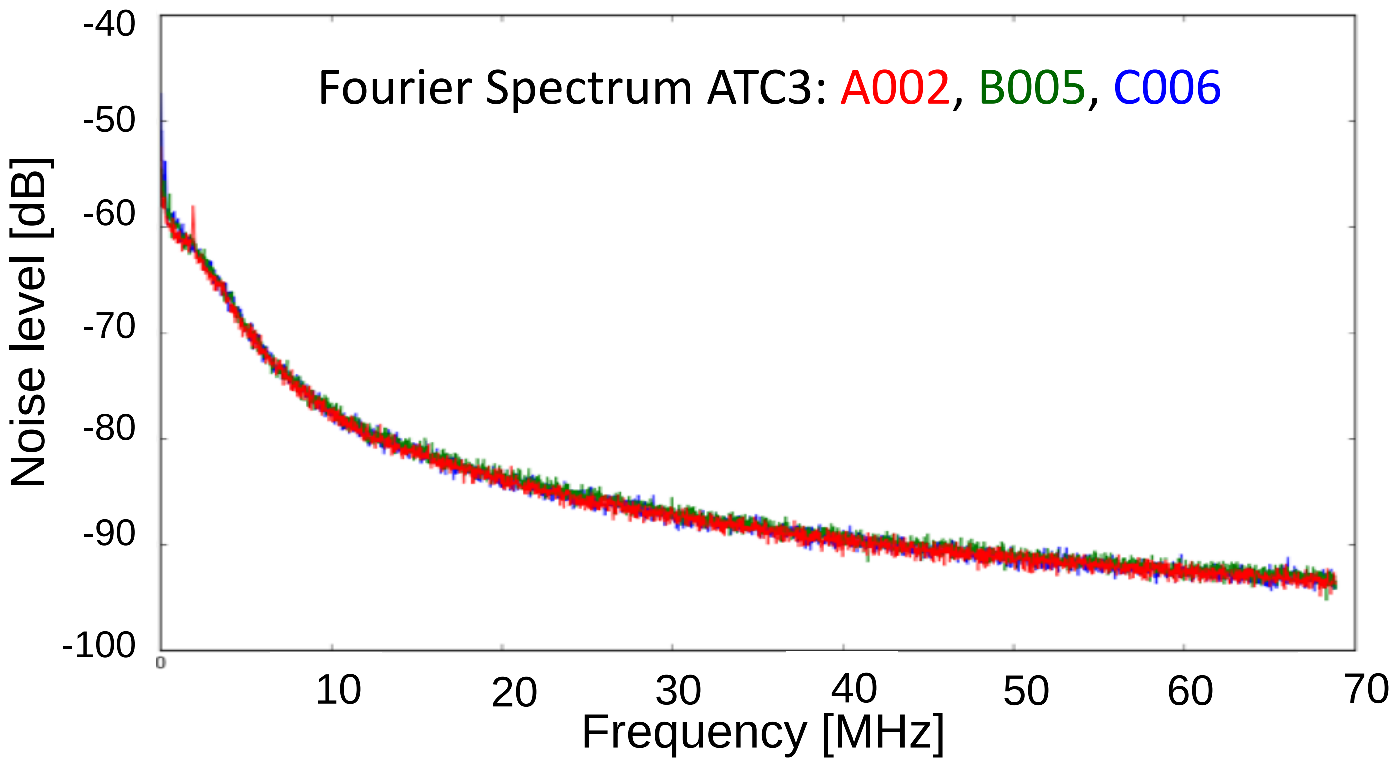
Rates: 3 MHz (M_γ=1) 300 kHz (M_γ=30)
today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow
- Operation of Ge detectors in position sensitive mode → γ-ray tracking

Experiments performed

- Coulomb Excitation of the Presumably Super-Deformed Band in ^{42}Ca (A.Maj, F.Azaiez, P.Napiórkowski) ✓
- Precision lifetime study in the neutron-rich N=84 isotone ^{140}Ba from DSAM measurements following Coulomb-barrier alpha-transfer reactions on a ^{136}Xe beam (J.Leske)
- Neutron-rich nuclei in the vicinity of ^{208}Pb (Zs.Podolyák) ✓
- Inelastic scattering as a tool to search for highly excited states up to the region of the Giant Quadrupole Resonance (R.Nicolini) ✓
- Lifetime measurements of the neutron-rich Cr isotopes (J.J.Valiente-Dobón)
- Lifetime measurement in neutron-rich Ni, Cu and Zn isotopes (E.Sahin, M.Doncel, A.Görgen)
- Lifetime measurement of the 6.792MeV state in ^{15}O (R.Menegazzo)
- Order-to-chaos transition in warm rotating ^{174}W nuclei (V.Vandone) ✓

Performance: Fourier Spectrum



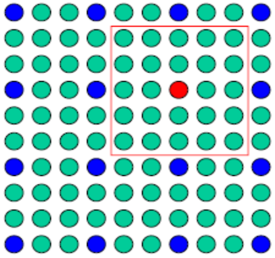
- Clean FFT spectra up and beyond the Nyquist frequency
- Low susceptibility to pickup noise (e.g. digital noise)

PSA Codes within AGATA

The classical PSA scheme consists of 3 components:

- Figure of Merrit (FOM) e.g. $\sum_{i \in ROI} (event1_i - event2_i)^n$ (n=0.3)

A. Grid search:



- Search Routine : optimization of FOM over library

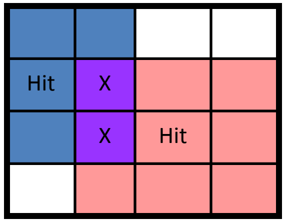
implemented

- Adaptive Grid Search (A. Venturelli)
- Particle Swarm Optimization (M. Schlarb, TU Munich)

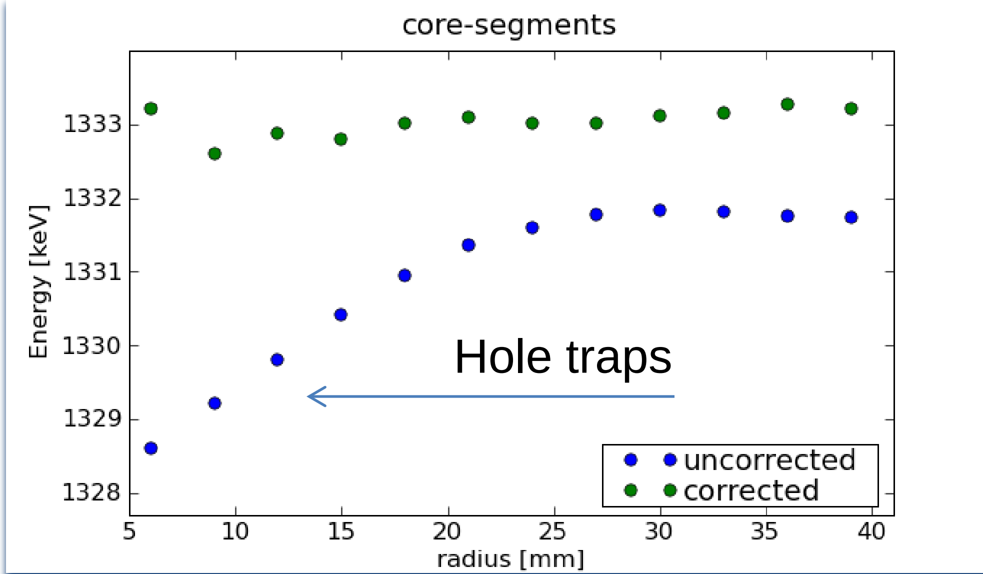
- Decomposition strategy for multiple interactions:

- assuming maximum 1 hit per segment
- segments influenced by multiple hits excluded

A. Grid search:



Correction for trapping



Neutron damaged detector:

2 parameter fit describes whole detector

	FWHM 1.3MeV	FWHM / FWTM
Corrected:	2.06	1.91
Uncorrected:	2.44	1.83

NEW detector:

	FWHM 1.3MeV	FWHM / FWTM
Corrected:	1.80	1.85
Uncorrected:	1.87	1.85