École Joliot-Curie 2015

``Instrumentation, detection and simulation in modern nuclear physics''

Nuclear Structure studies using *Advanced-GAmma-Tracking* techniques

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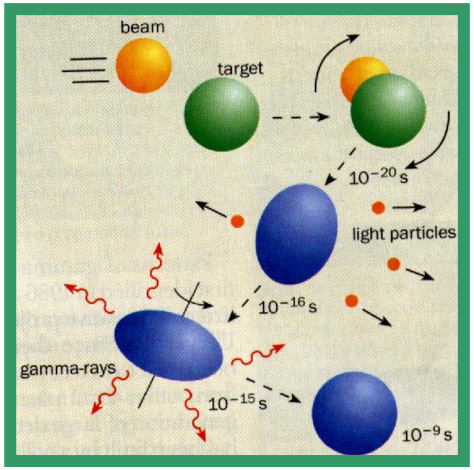
In-beam γ-ray spectroscopy: requirements



Energy resolution (E_γ ~10 keV -10 MeV),
in order to disentangle complex spectra
→ germanium detectors

Peak to Total ratio (large continuous Compton background),
in order to maximize "good events"
→ Compton background suppression

Doppler correction capability,
energy resolution dominated by Doppler broadening if the velocity vector and the emission angle of the γ-ray are not well known (β ~ 5-10%, up to 50%)

Good solid angle coverage (ideally 4π), in order to maximize efficiency

Good granularity ,
in order to reduce multiple hits on the detectors for high γ-ray multiplicity events

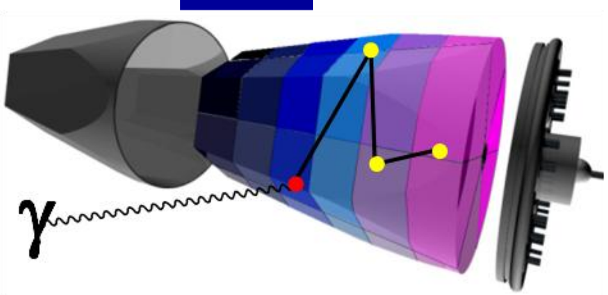
Avoid dead materials that could absorb radiation (→preserve low energies)

High counting rate capability (frequently background much stronger than channel of interest)

Time resolution (prompt events selection, lifetimes)

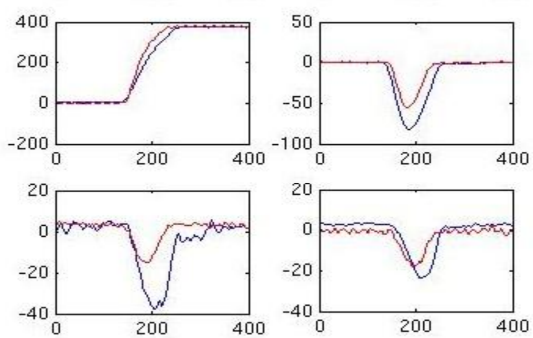
Position-sensitive operation mode and γ-ray tracking

highly segmented HPGe detectors



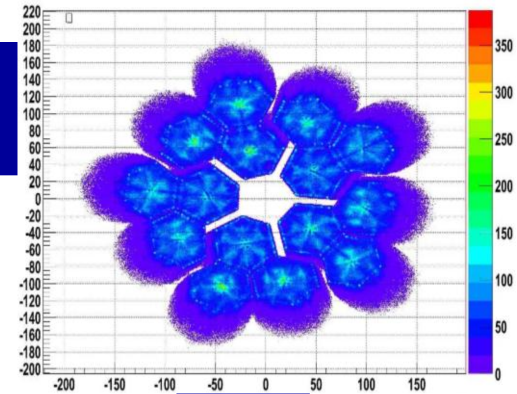
digital electronics to record sampled waveforms

Pulse Shape Analysis of the recorded waves

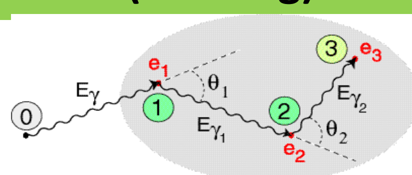


Identified interaction points (hits)

$(x,y,z,E,t)_i$



reconstruction of γ-rays from the hits (tracking)



Event by event:
how many gammas,
for each gamma: energy,
first interaction point, path

Outline

PART 2 (September 29th 2015)

Pulse Shape Analysis (PSA)

1. Signal bases calculation
2. Signal decomposition

Some results from Ge position sensitive mode operation and γ-ray tracking

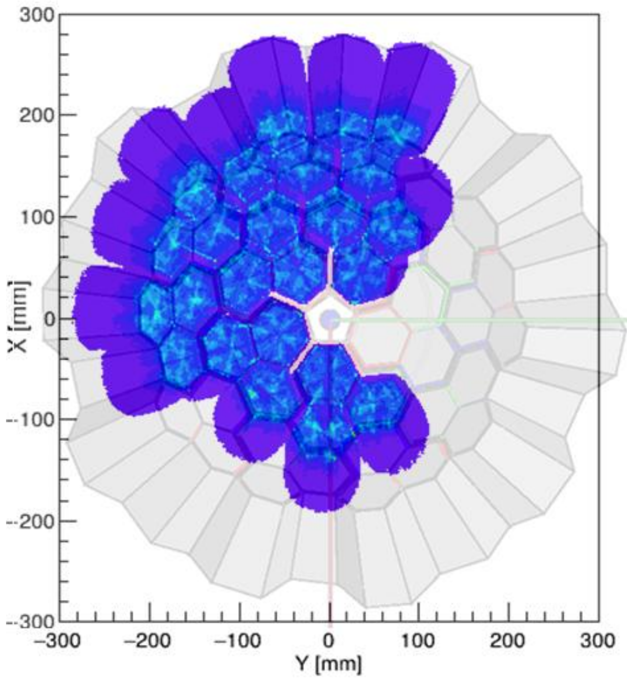
The AGATA array of segmented HPGe detectors

1. Implementation of Pulse Shape Analysis and Tracking concepts
2. The AGATA detectors and preamplifiers
3. The structure of electronics and data acquisition
4. Digital signal processing (at high counting rate)
5. (AGATA data processing)

AGATA+VAMOS (magnetic spectrometer) at GANIL

(be aware … personal ☺ selection of topics!)

Pulse Shape Analysis (PSA)



comparison of net charge/transient signals
with reference signal basis

How do we build a basis of
reference signals ??

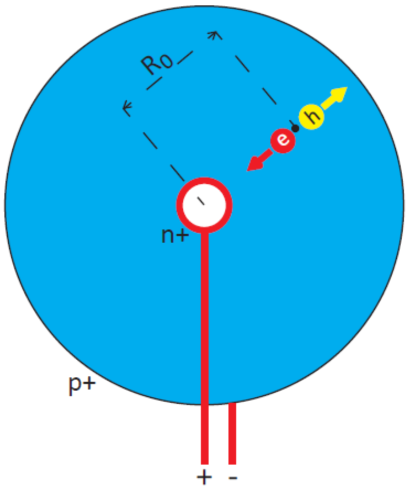
Detector scanning (scanning tables):
practically unfeasible

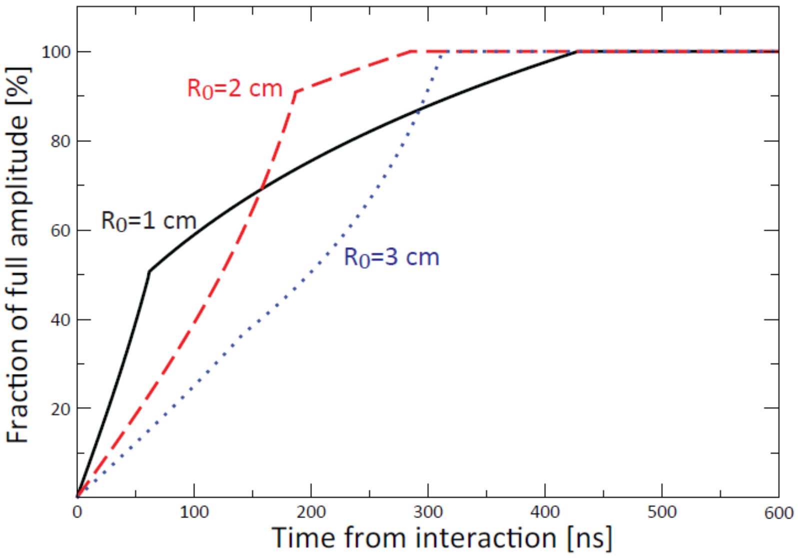
⇨ Signals Bases Calculations

Pulse shapes in a coaxial Ge detector

Reverse bias (-HV on p+ contact) depletes bulk and generates high electric filed

Radiation ➔ carriers in the bulk, swept out by electric field ➔ signal





On "true" coaxial detectors, the shape depends on initial radius

Signal Formation

- Signal : motion of charge carriers (e/h) inside the detector volume;
  $\vec{v}_{e/h} = \mu_{e/h}\vec{E}$ ($\mu_{e/h}$ = electron/hole mobility)

- Calculation of charge induced in an electrode due to motion of charge carriers in a detector: <u>Ramo Theorem</u> and concept of <u>weighting potential</u>

$$i(t) = q\,\vec{v}\,\vec{E}_W \qquad E_W\text{=weighting field}$$

$$Q = q\,\Delta\varphi_W \qquad \varphi_W\text{=weighting potential}$$

$\varphi_W = \varphi_W(\vec{x})$ solution of the Laplace equation (for given detector geometry) with voltage of the electrode for which induced charge is calculated = 1 and other electrodes at zero

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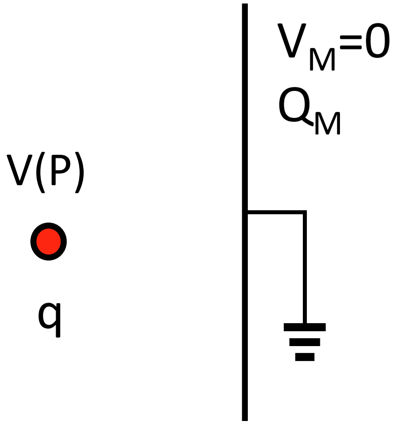
The Ramo theorem is based on the Green's reciprocity theorem

$$\sum_i V_i Q_i' = \sum_i V_i' Q_i$$

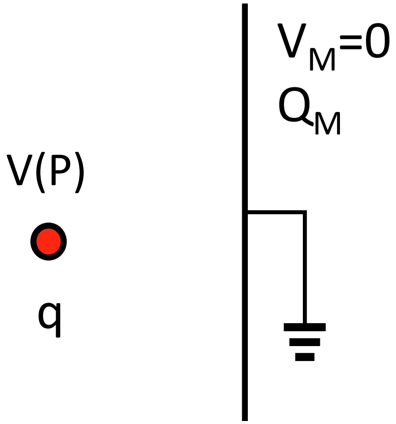
relation between two systems consisting of a distribution of charges and electrodes

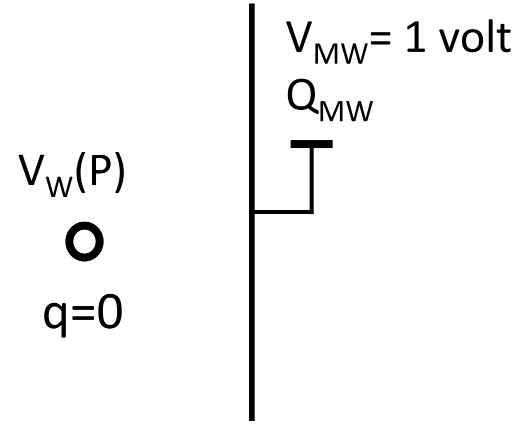
Induced Charge



State 1	On P	On M
Voltage	V(P)	0
Charge	q	Q_M

Induced Charge

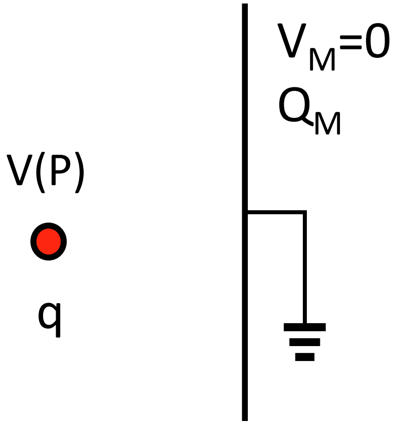


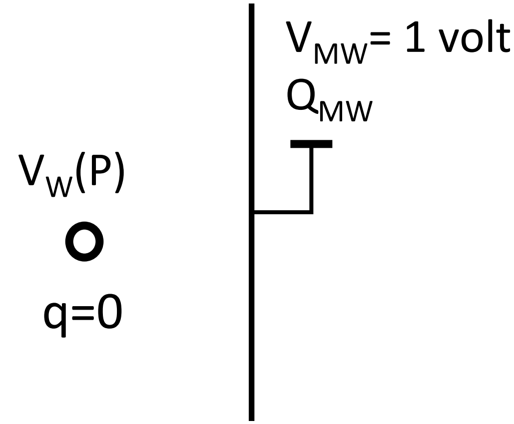


State 1	On P	On M
Voltage	V(P)	0
Charge	q	Q_M

State 2	On P	On M
Voltage	V_W(P)	V_{MV}
Charge	0	Q_{MW}

Induced Charge





State 1	On P	On M
Voltage	V(P)	0
Charge	q	Q_M

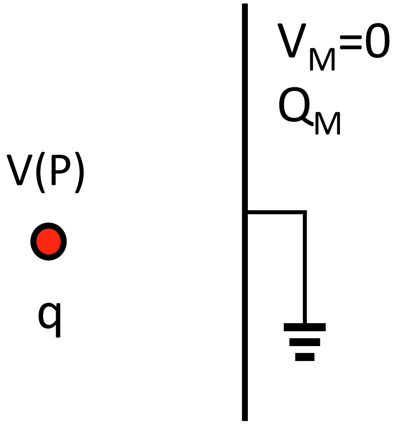
State 2	On P	On M
Voltage	V_W(P)	V_{MV}
Charge	0	Q_{MW}

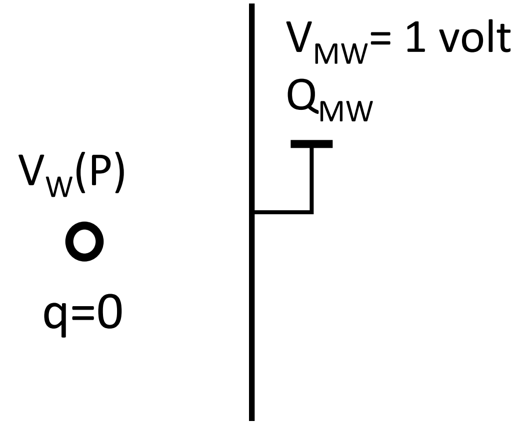
$$V(P)\cdot 0 + 0\cdot Q_{MW} = q\cdot V_W(P) + Q_M\cdot V_{MW}$$

$$\boxed{Q_M = -qV_W(P)}$$

V_w dimensionless

Induced Charge





State 1	On P	On M
Voltage	V(P)	0
Charge	q	Q_M

State 2	On P	On M
Voltage	V_W(P)	V_{MV}
Charge	0	Q_{MW}

$$V(P)\cdot 0 + 0\cdot Q_{MW} = q\cdot V_W(P) + Q_M\cdot V_{MW}$$

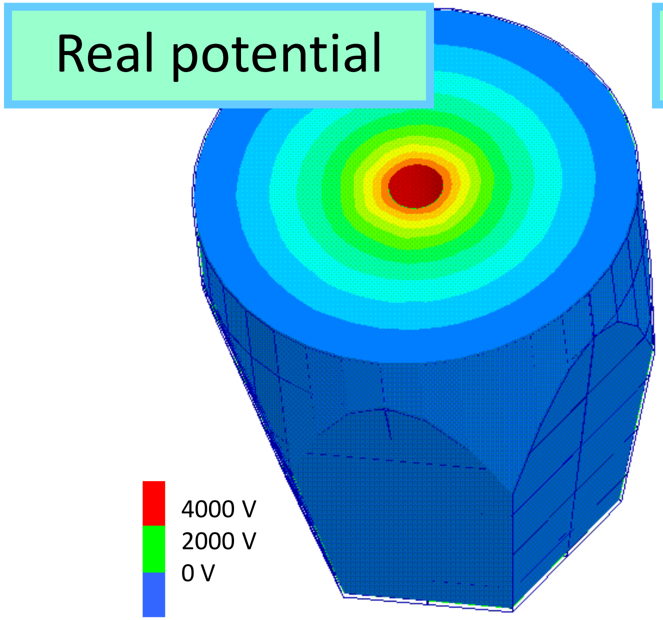
$$Q_M = -qV_W(P)$$

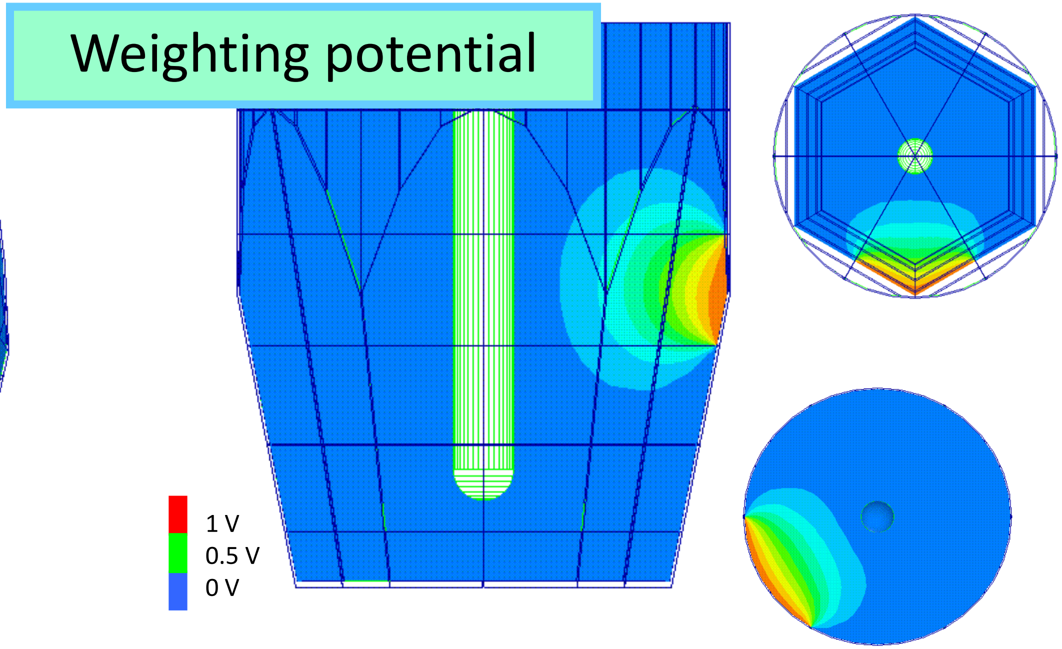
V_w dimensionless

The charge induced in one of an electrode of the system by the charge q is given by the product of the inducing charge times the potential generated at the position of the charge when the charge itself is removed, the electrode of interest (sensing) is put at V = 1 volt and all other electrodes of the system are put to ground.

Weighting potential

electrostatic coupling between the moving charge and the sensing electrode





Calculation of pulse shapes for real detectors

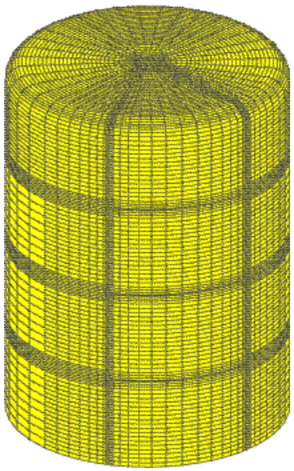
- Analytical solutions only for true coaxial
- Take a FEM modeler (your own, MAXWELL-3D, FEMLAB, …)
  - Specify geometry, and segmentation
  - Specify material, impurity concentration and distribution
- Solve Poisson equation and get electric potential
- Use mobility of e/h to calculate trajectories
- Solve Laplace equation for all electrodes and get V_w
- Calculate induced currents / induced charge

Calculation of pulse shapes for real detectors

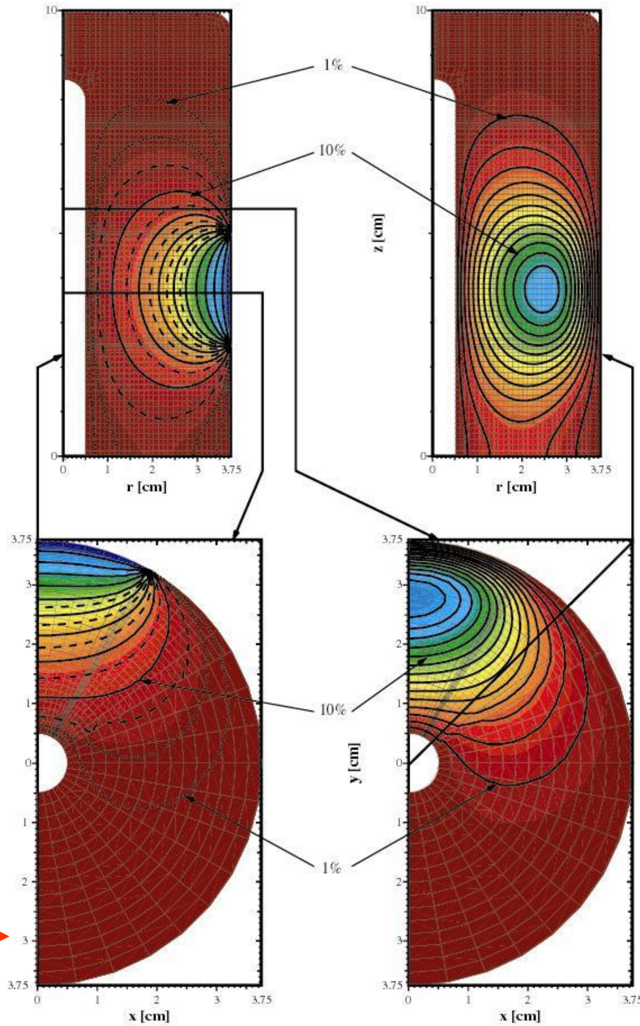
Calculation of the signals induced on the contacts using the weighting field method

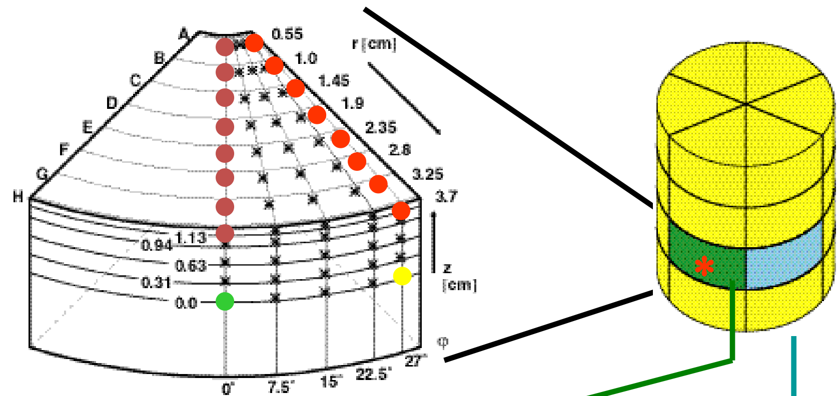
$$i_{e/h} = -q_{e/h} \cdot \vec{E}_W \cdot \vec{v}_{drift}\left(\vec{E}\right)$$

FEM-model of detector



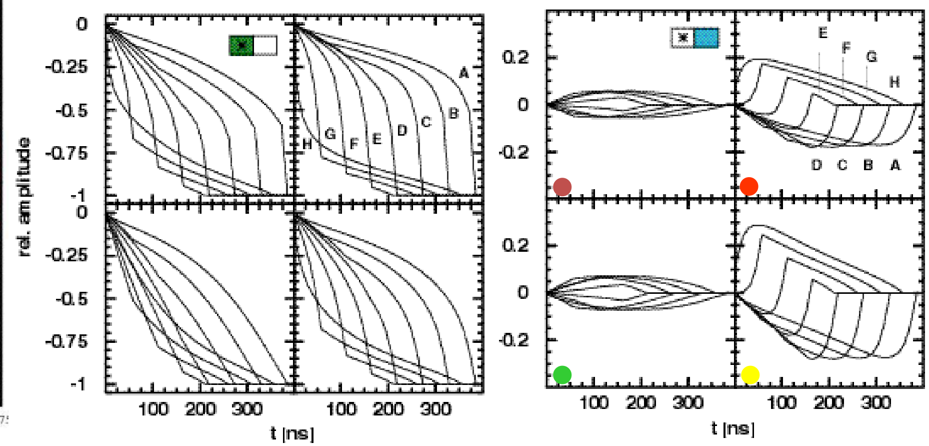
Calculate weighting fields





net charge signals

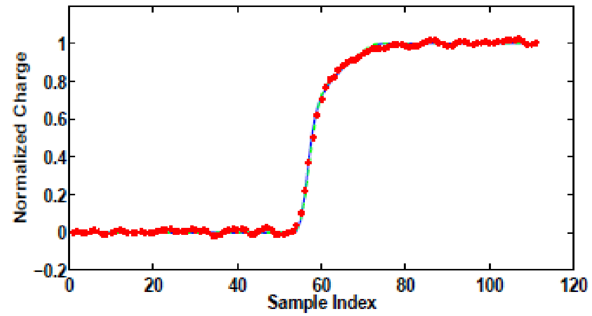
transient signals



Th. Kröll, NIM A 463 (2001) 227

Simulated Signals

Signals after folding with the preamplifier response function and the analog filter functions (some smearing)
Full signal for each point in the detector.

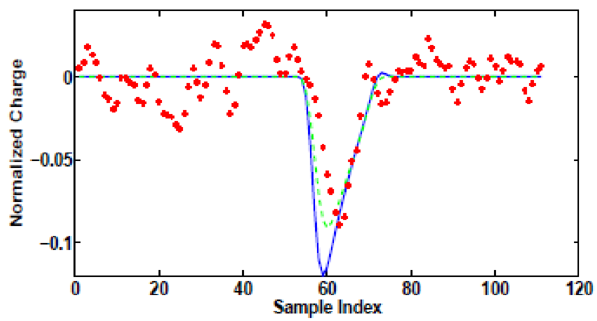


(a) Net charge signal in segment A4

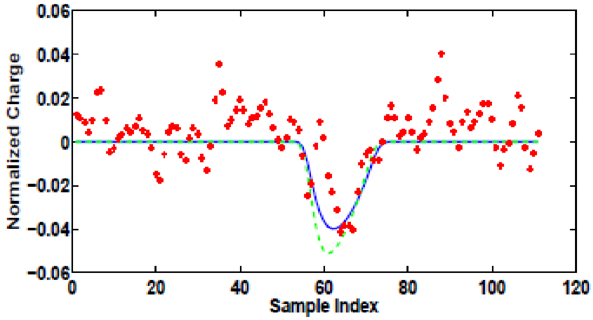
experiment

Set A

Set B

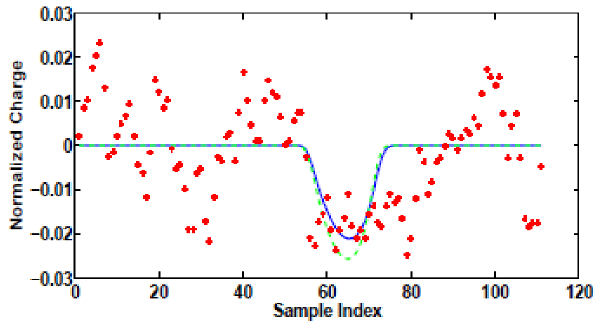


(b) Transient signal in segment A5.

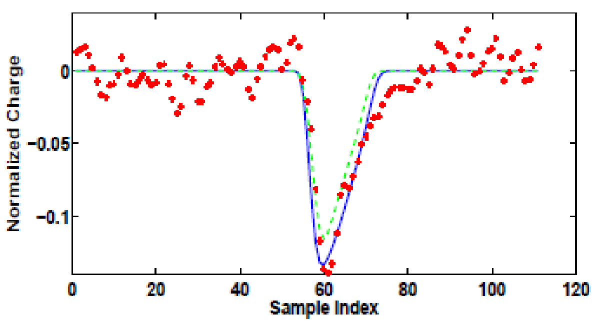


(c) Transient signal in segment A3.

Parameters from experiment



(d) Transient signal in segment B4.



(e) Transient signal in segment F4.

Signal Decomposition
or Pulse Shape Analysis (PSA)

Expand measured signals in terms of base signals
and determine expansion coefficients

$$S^{exp} = \sum_{i=1}^{N} A_i S_i^{base}$$

- Sampling every 10 ns, ~100 samples per involved segment
- Each base-point has 1 segment with net charge and 8-11 neighbours with transient signals
- With a grid of 1 mm a typical crystal has ~ 400000 base points (up to possible symmetries)

→ That's too much for a direct decomposition !!! ←

⇨ Grid Search Algorithm

Verifying quality of Pulse Shape Analysis

- From simulations and calculations
  - **Generate** interaction points by MC simulation
  - **Calculate** pulse shapes (adding noise)
  - **Decompose** pulses into interaction points

- From experimental data with defined position
  - Scanning tables and coincidence methods with well collimated, strong radioactive sources can provide ~mm^3 precision

- From experimental data: distribution of interaction points

- In-beam experiments with fast moving nuclei
  - Doppler shift correction depends on determination of gamma-emission angle, which depends on position of first interaction point

Complications for PSA

- No good theory for mobility for holes
- Mobility of charge carriers depend on collection path with respect to crystal lattice
- Detector irregular geometry (→ difficult bases calculation)
- Effective segmentation (electric field) ≠ geometrical segmentation
- Position sensitivity not uniform throughout the crystal

- Computationally “heavy”

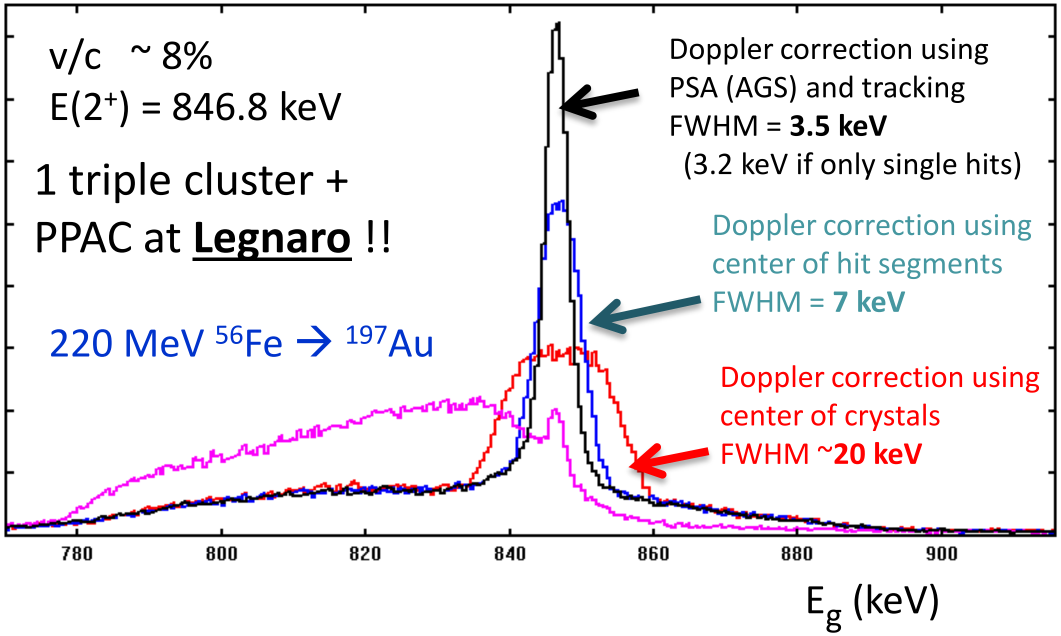
- Events with multiple hits per segment are difficult to analyze
- Low energy releases can end up far away from actual position

Performance of PSA

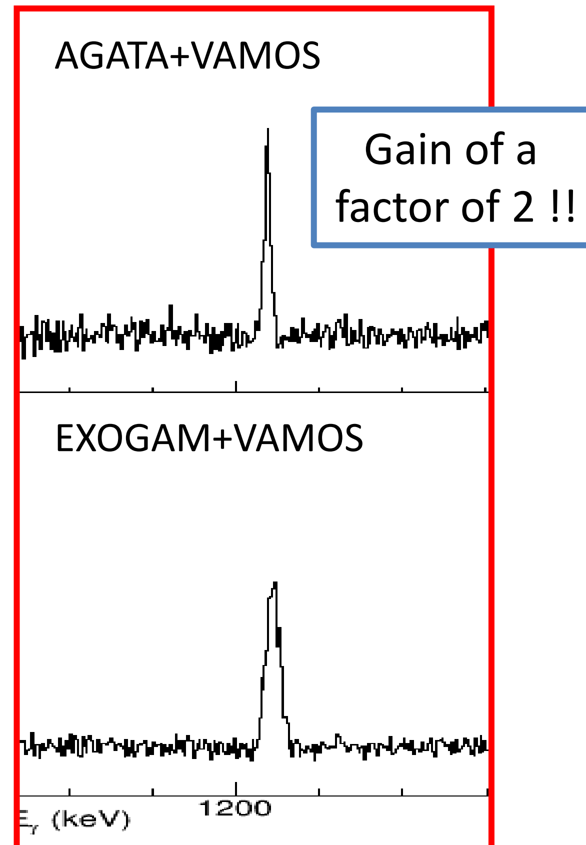
- Depends on the signal decomposition algorithm but of equal or more importance are:
- The quality of the signal basis
  - Physics of the detector
  - Impurity profile
  - Application of the detector response function to the calculated signals
- The preparation of the data
  - Energy calibration
  - Cross-talk correction (applied to the signals or to the basis!)
  - Time aligment of traces
- A well working decomposition has additional benefits, e.g.
  - Correction of energy losses due to neutron damage

Some benefits from position resolution and γ-ray tracking

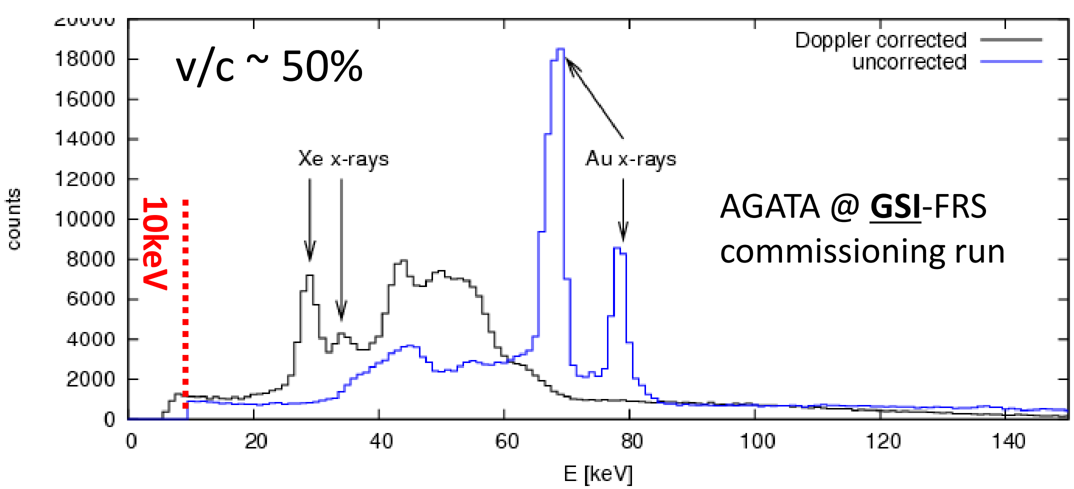
Doppler broadening: towards the intrinsic resolution in-beam



$2^+ \rightarrow 0^+$ ^{98}Zr
populated by fission
GANIL

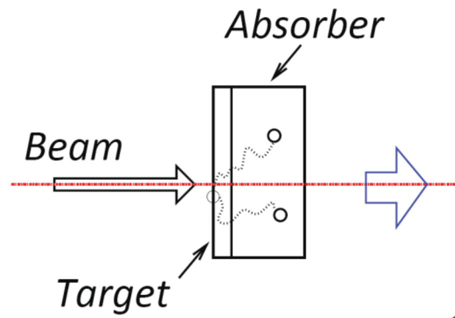


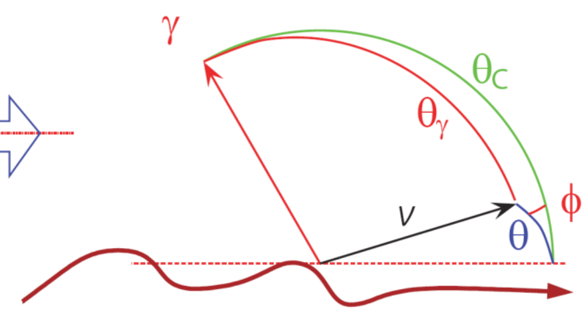
^{136}Xe (137 MeV/u) + ^{197}Au

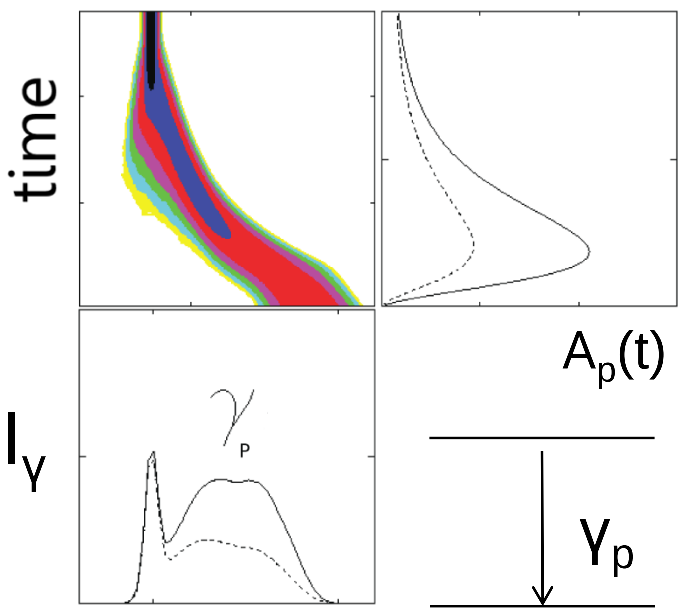


Doppler Shift Attenuation (DSA) for the measurement of nuclear level lifetimes

The lifetime of the excited state is compared with the slowing down time of the emitting nucleus in the absorbing material

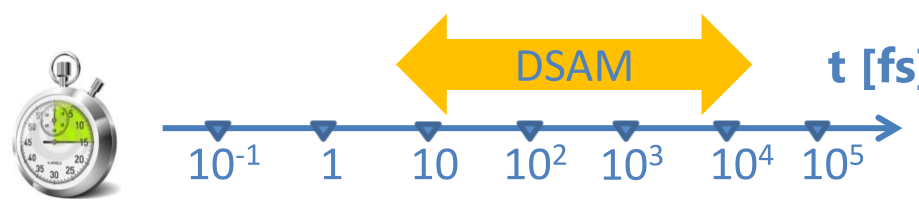






$$\overline{E_\gamma} = E_\gamma \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \qquad \beta = \left|\frac{\vec{v}}{c}\right|$$

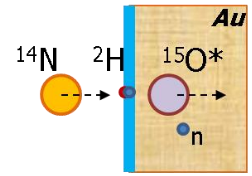
Monte Carlo simulations => lineshape analysis of the peaks observed in the γ spectrum

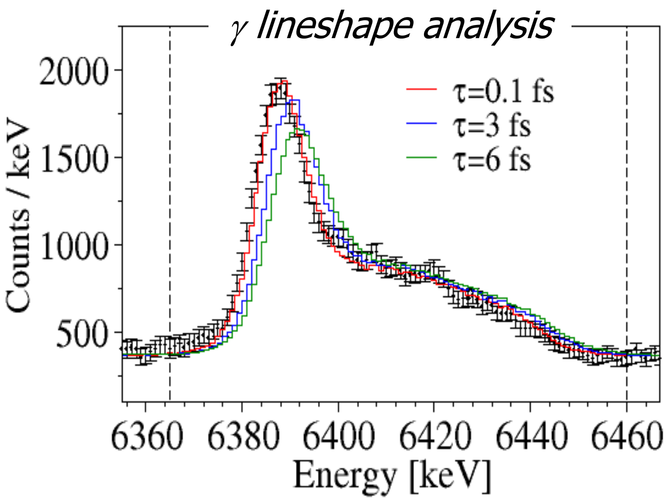


Sub-femtosecond lifetime measurements

AGATA Demonstrator at LNL

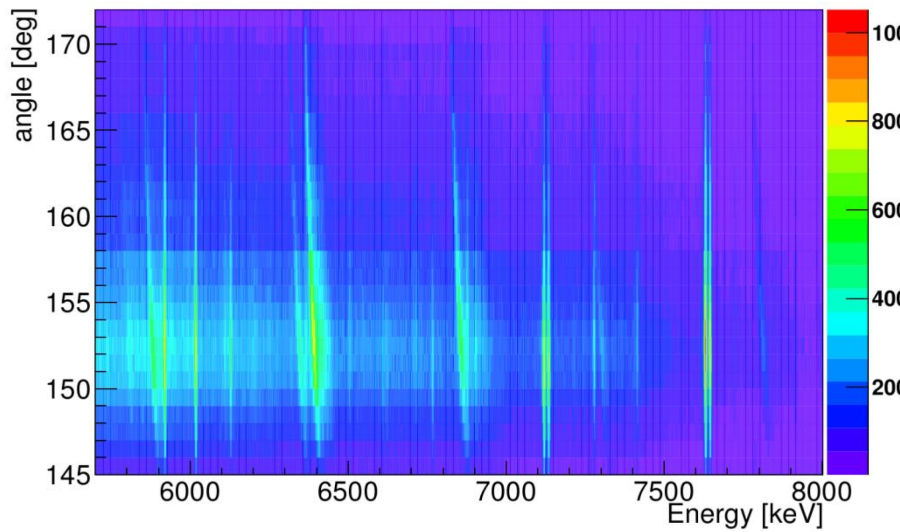
^{14}N (32 MeV) + ^{2}H → $^{15}O^{*}$(6793 keV) + n

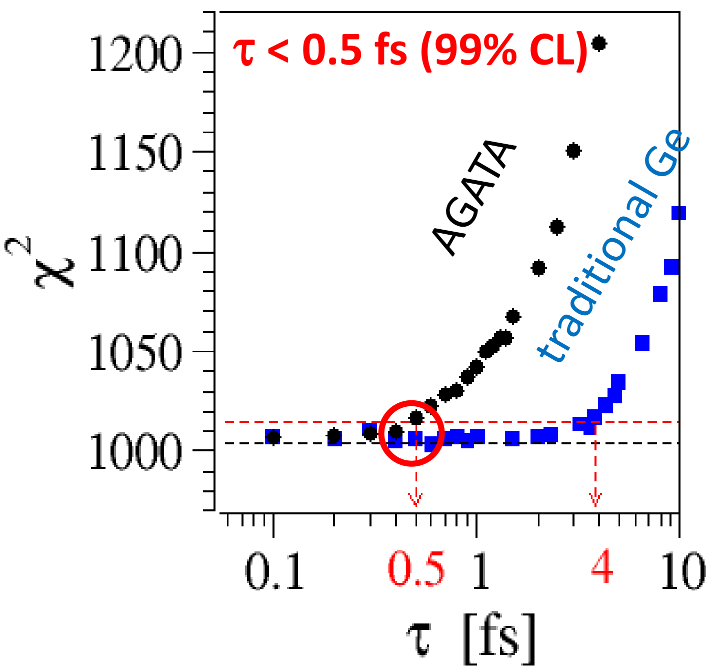


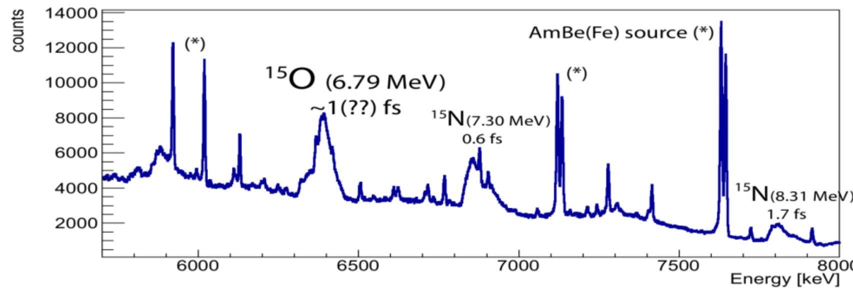


4 mm AGATA position resolution

2 degree "θ slices"



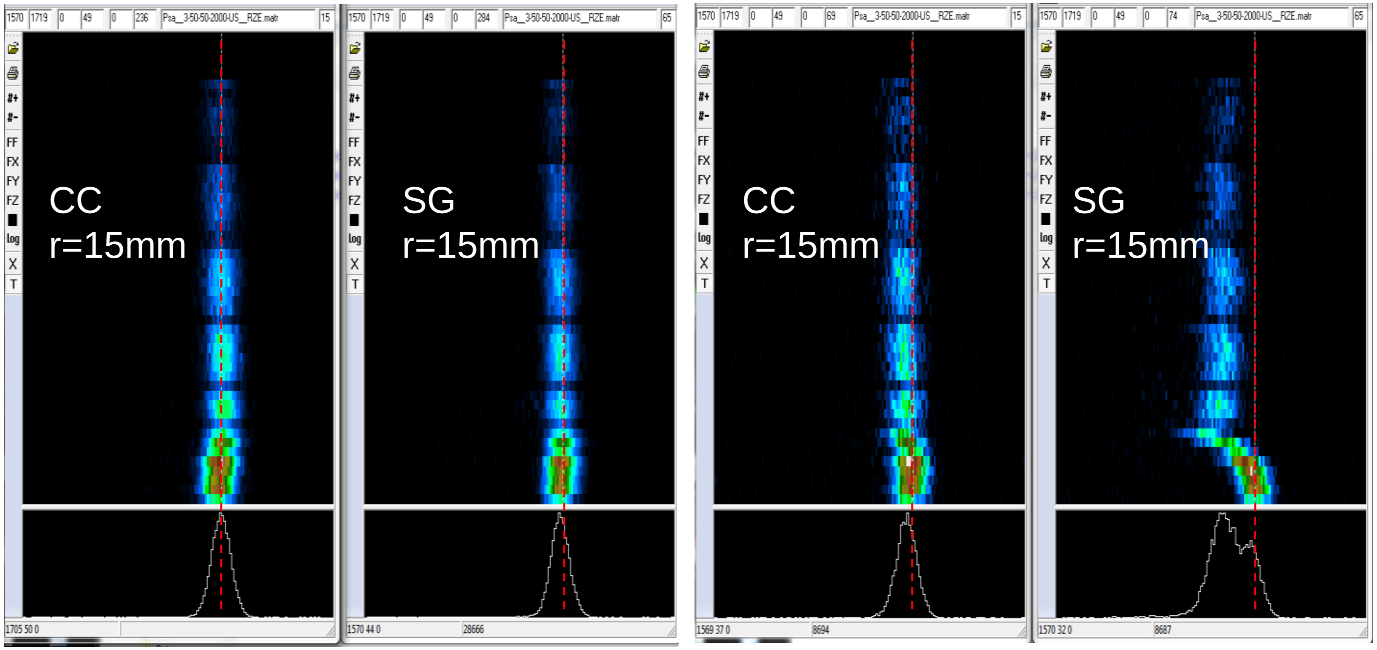


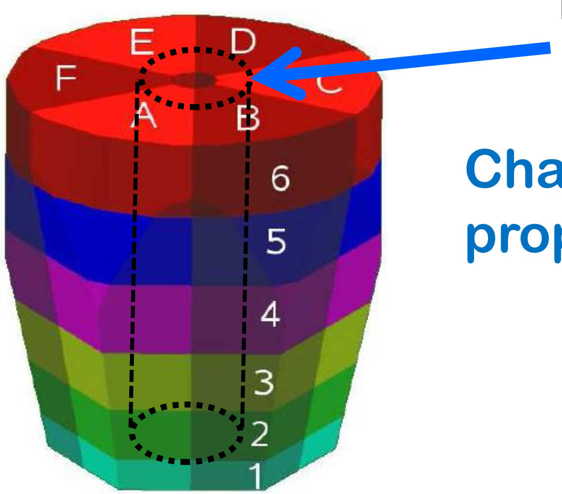


Doppler Shift Attenuation lifetime measurements by lineshape analysis over a continuous angular distribution

Neutron-damage correction

April 2010 **July 2010**



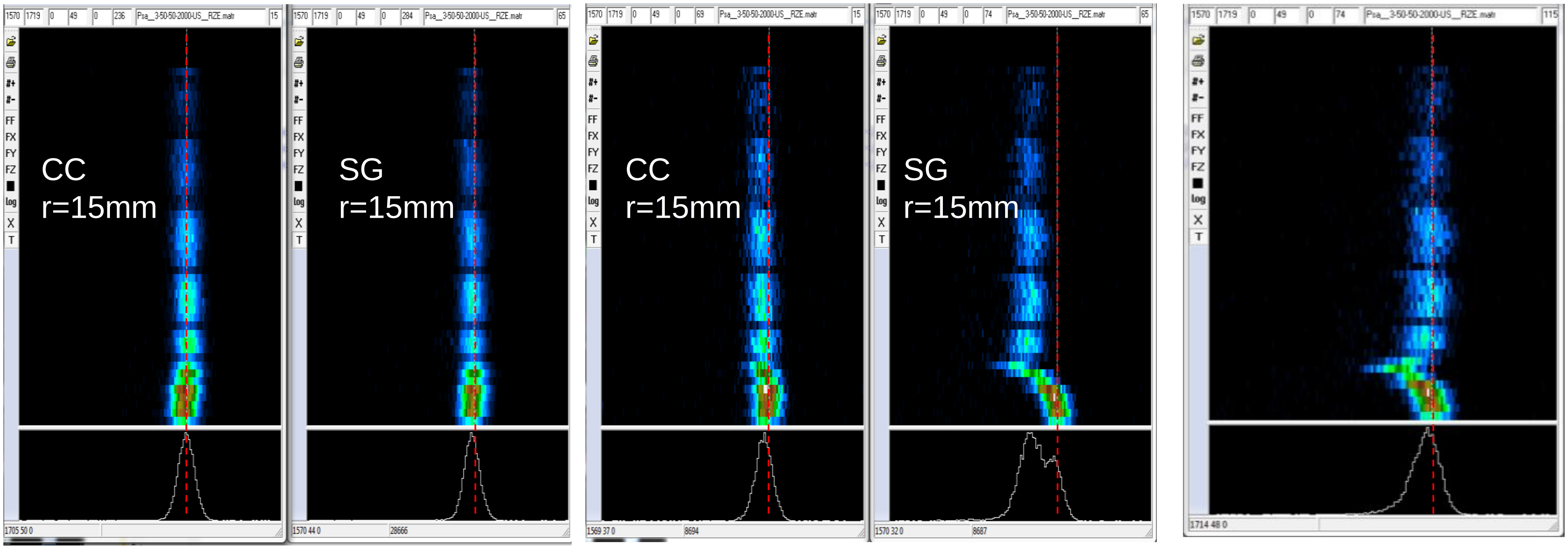


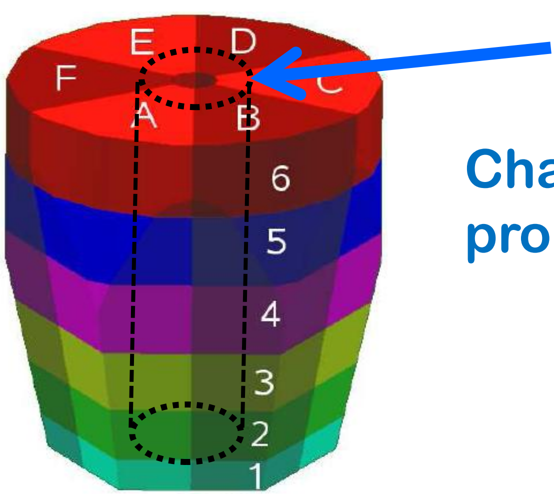
The 1332 keV peak as a function of crystal depth (z) for interactions at r = 15mm

Charge loss due to neutron damage → proportional to the path length to the electrodes

Neutron-damage correction

April 2010 | July 2010 | → corrected





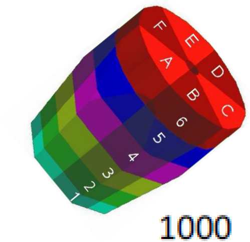
The 1332 keV peak as a function of crystal depth (z) for interactions at r = 15mm

Charge loss due to neutron damage → proportional to the path length to the electrodes

Use PSA interaction points and modeling of charge trapping to correct the effect

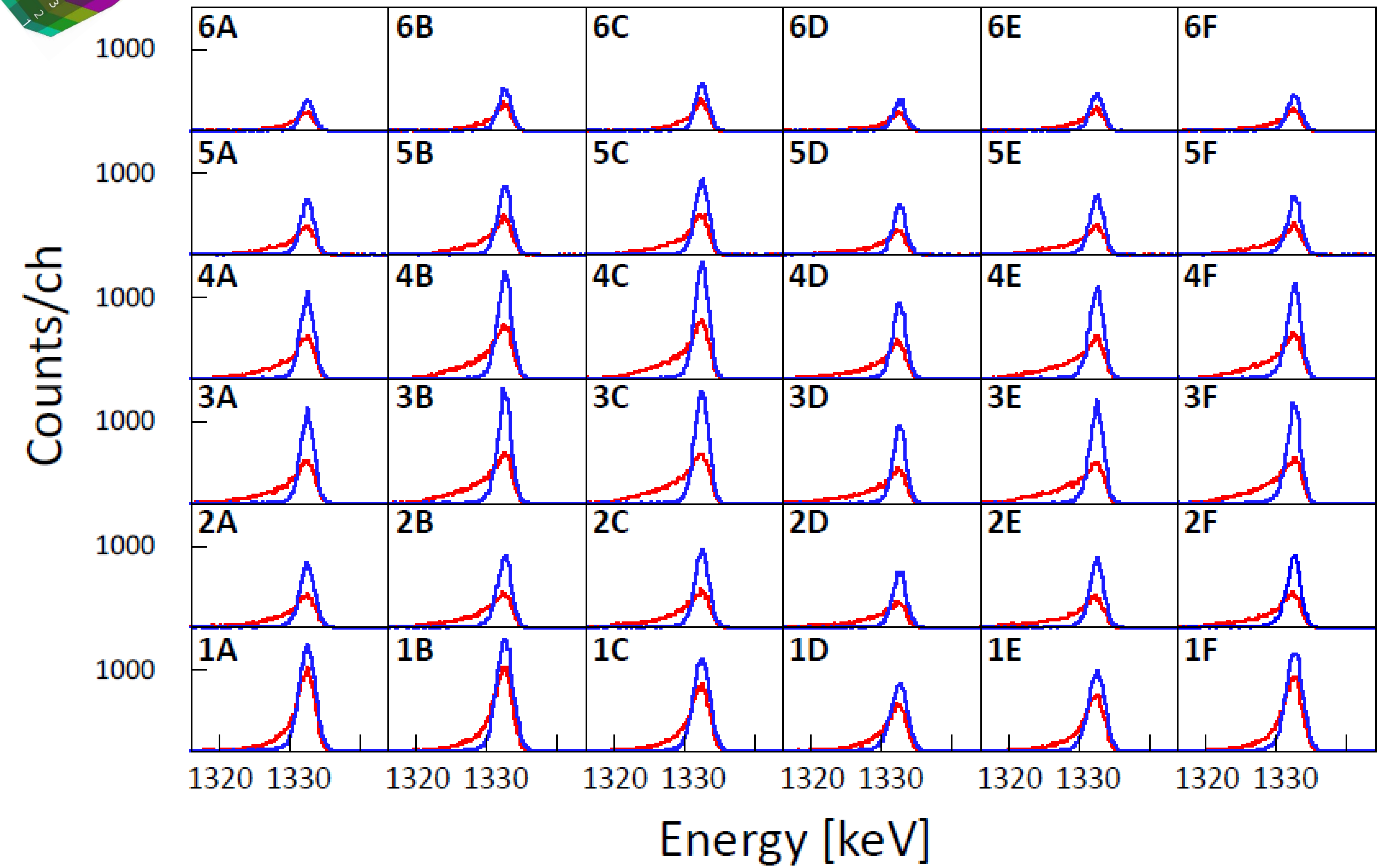
B.Bruyneel et al, Eur. Phys. J. A 49 (2013) 61

Effect of the correction on energy resolution



corrected
uncorrected

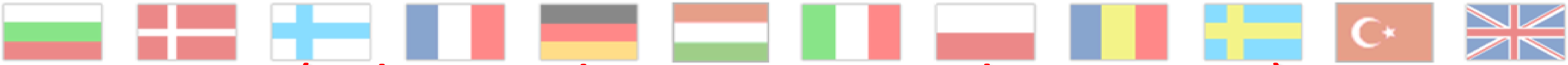
Sum of segments: 5.9 keV ➔ 2.9 keV



The Advanced-GAmma-Trackig-Array
AGATA

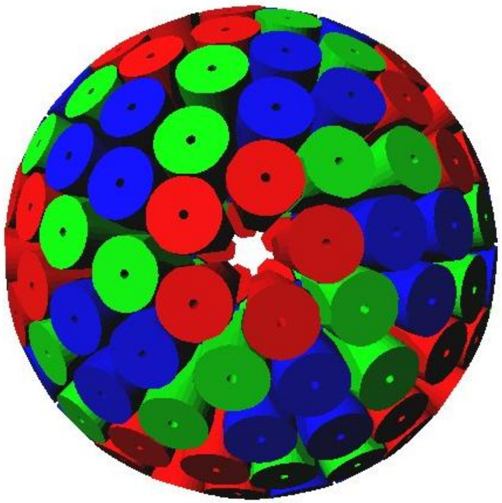
S. Akkoyun et al. NIM A 668 (2012) 26

AGATA

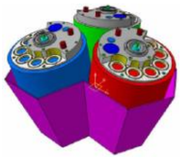


(Advanced-GAmma-Tracking-Array)

the "γ-ray spectroscopy dream"



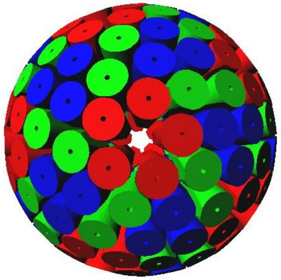
- High efficiency.
- Good position resolution on the individual γ interactions.
- Capability to stand a high counting rate.
- High granularity.
- Capability to measure the Compton scattering angles of the γ-rays within the detectors.
- Coupling to ancillary devices for added selectivity.



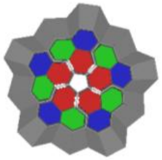
180 hexagonal crystals	3 shapes
60 triple clusters	all equal
inner radius	24 cm
amount of germanium	374 kg
solid angle coverage	79 %
6480 segments	
efficiency at 1MeV:	39% (M_g=1),
	25% (M_g=30)
Peak/Total:	53% (M_g=1),
	46% (M_g=30)

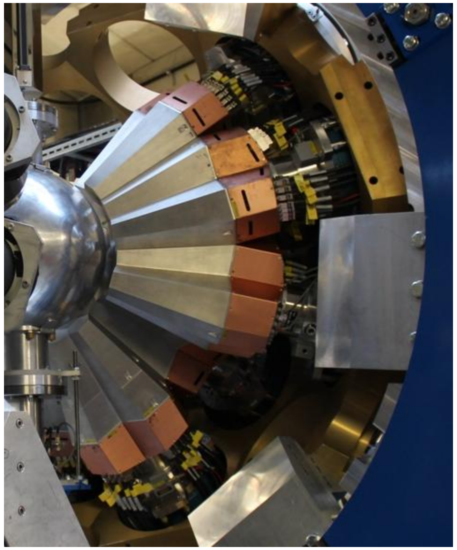
Geant4 Montecarlo simulations
E. Farnea, NIMA 621 (2010) 331

realization of the dream:
AGATA the *nomadic detector*



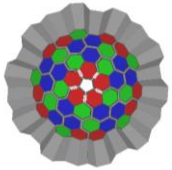
Demonstrator at the Legnaro National Lab., Italy
2009-2012

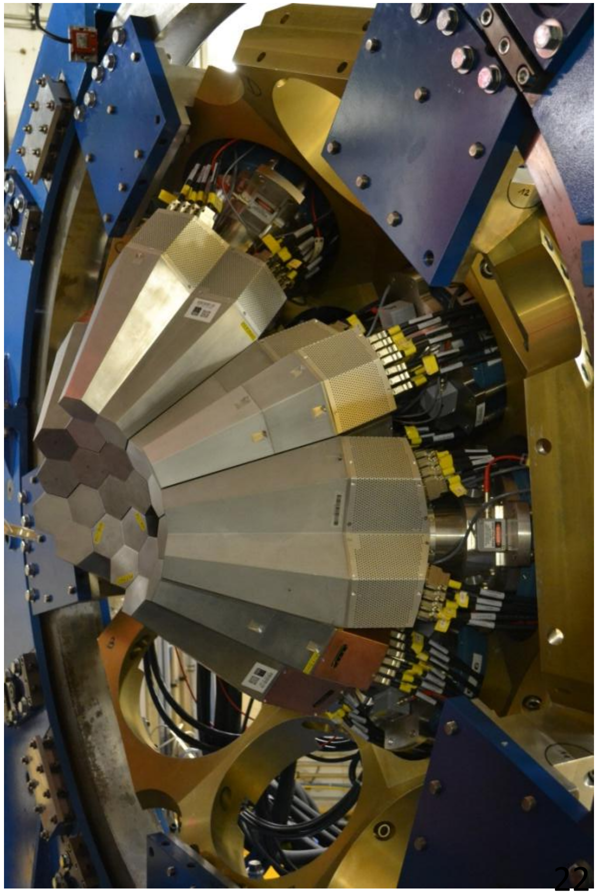




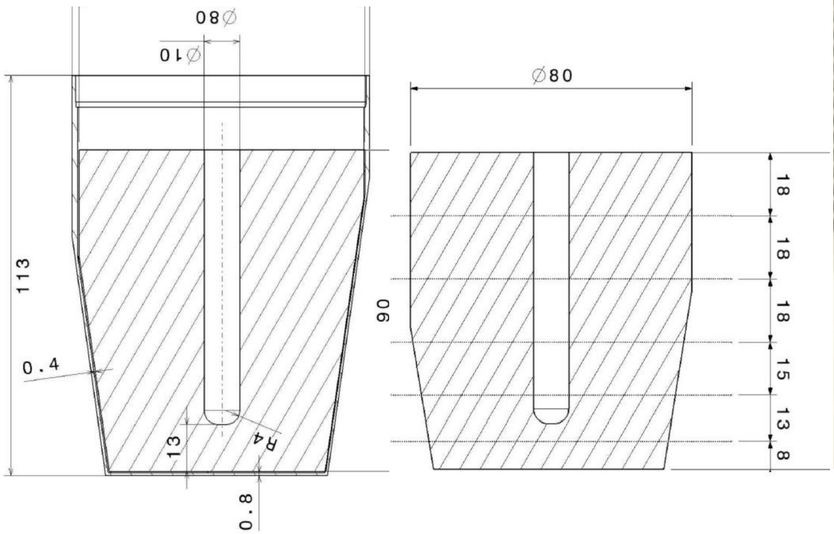
AGATA @ GSI
Germany
2012-2014

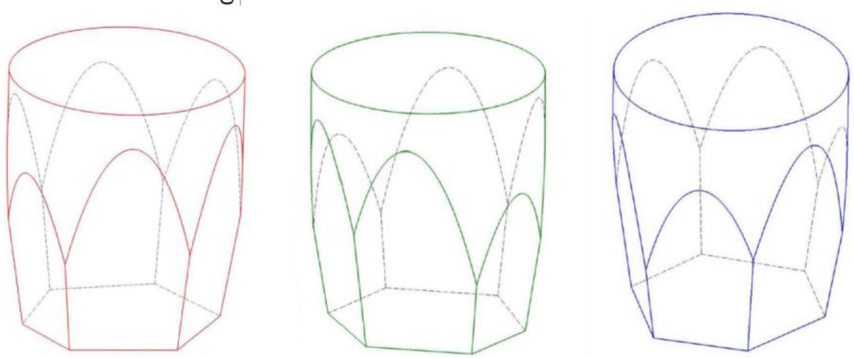
today AGATA is at GANIL,
2014-2018 France



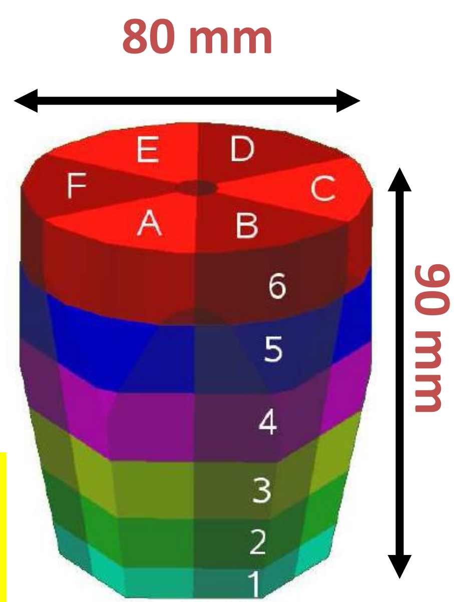


AGATA Crystals





(d) A - red (e) B - green (f) C - blue

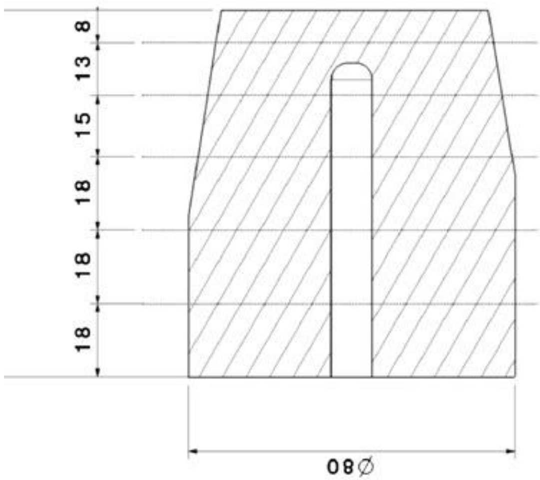


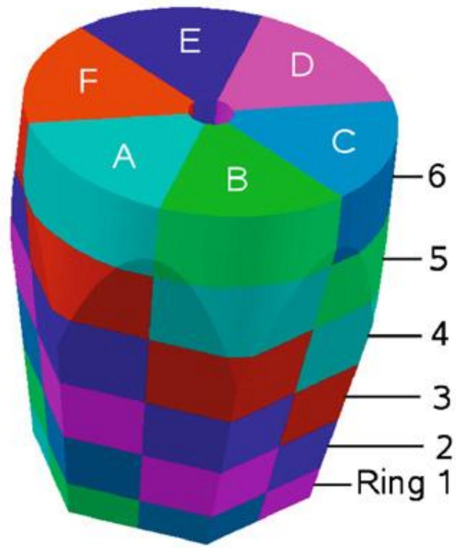
6x6 segmented cathode

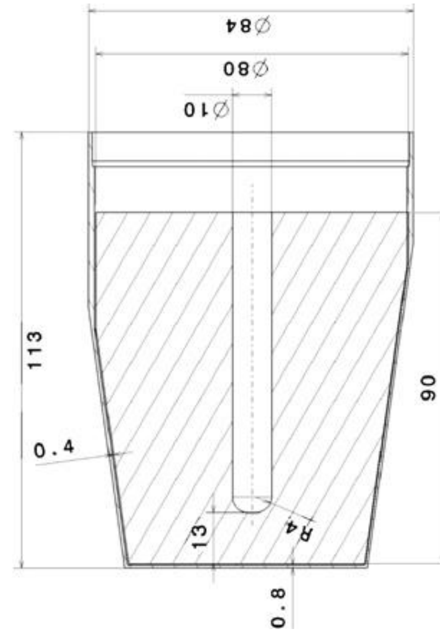
Volume ~370 cc   Weight ~2 kg

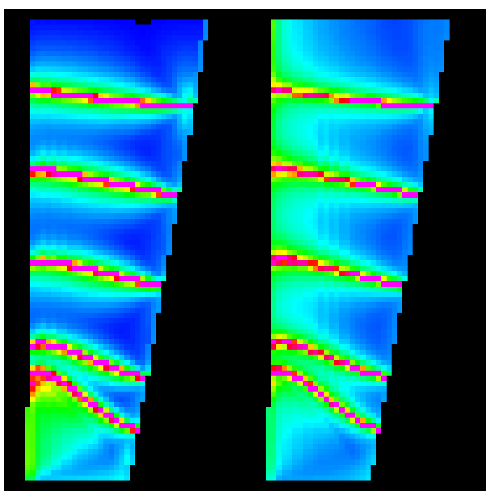
(the 3 shapes are volume-equalized to 1%)

Segmentation of the AGATA detector

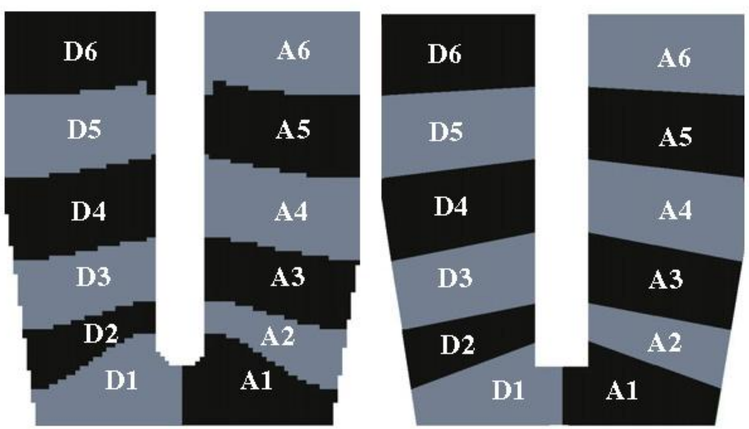








Pulse Shape Simulations
Th. Kröll, A. Görgen



Implementation in GEANT4

Signals:
2 central contact
36 segments

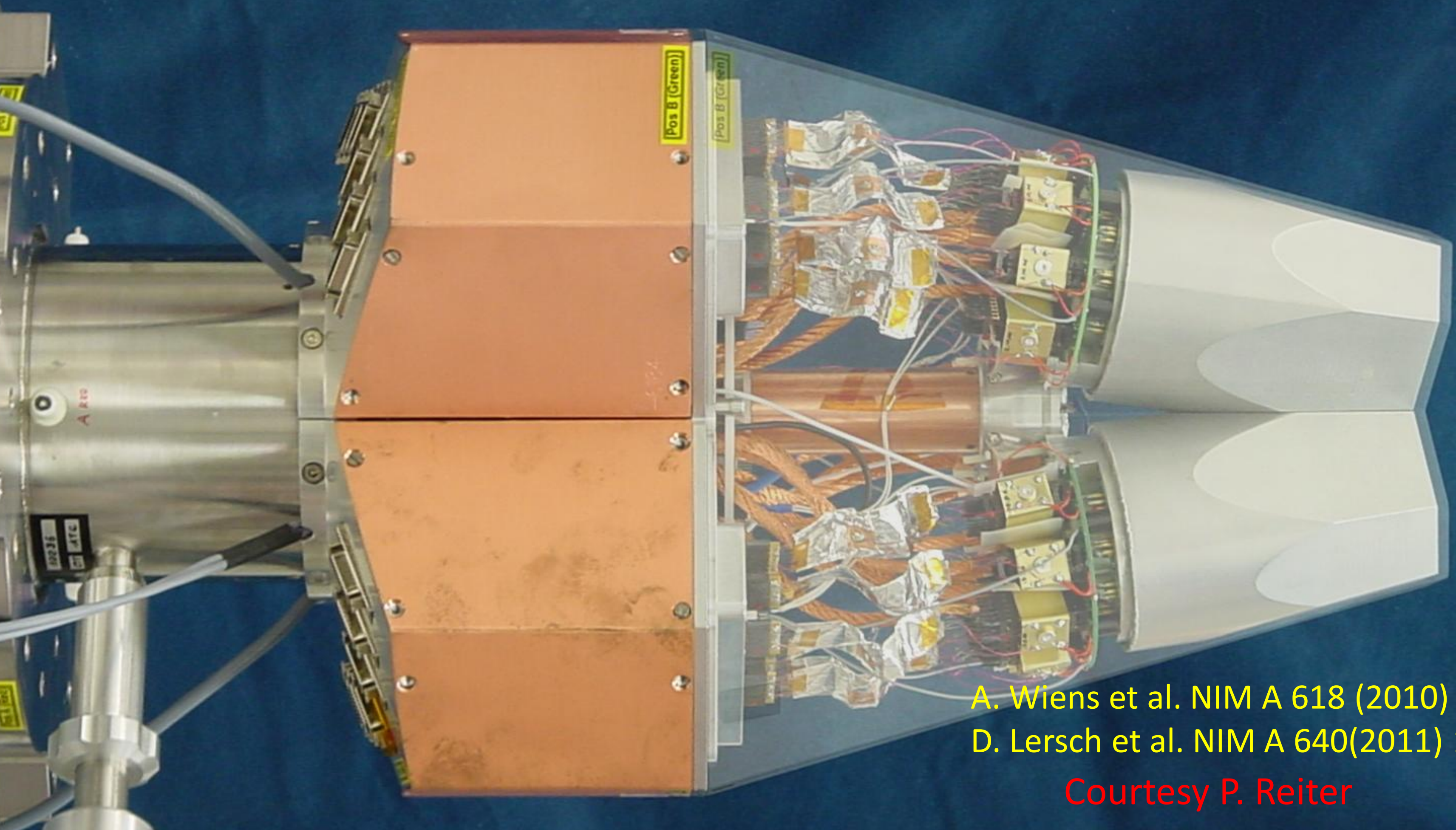
A.Wiens et al. NIMA 618 (2010) 223
E.Farnea et al. NIMA 621 (2010)331

Asymmetric AGATA Triple Cryostat

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

Challenges:

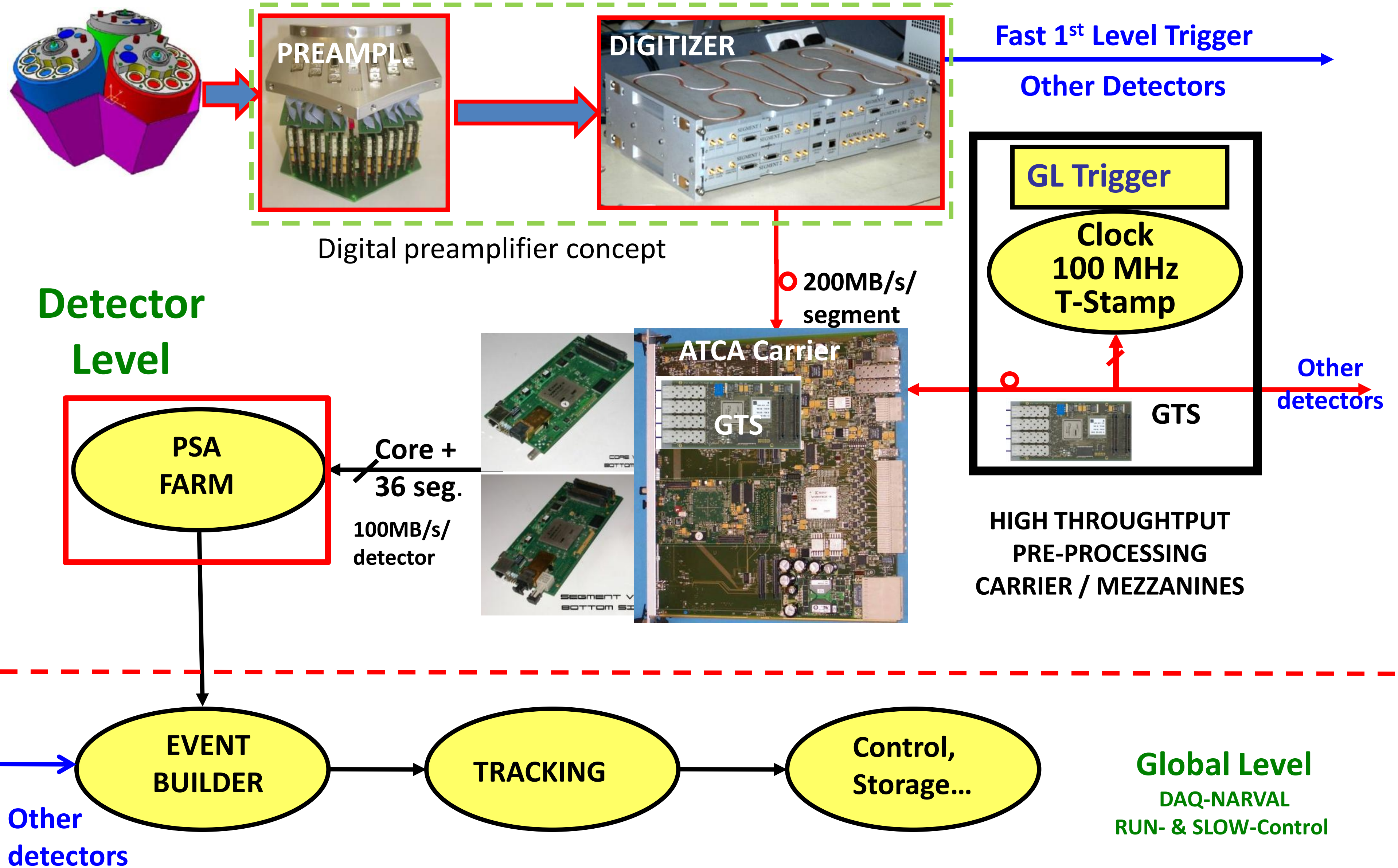
- mechanical precision
- heat development, LN2 consumption
- microphonics
- noise, high frequencies



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

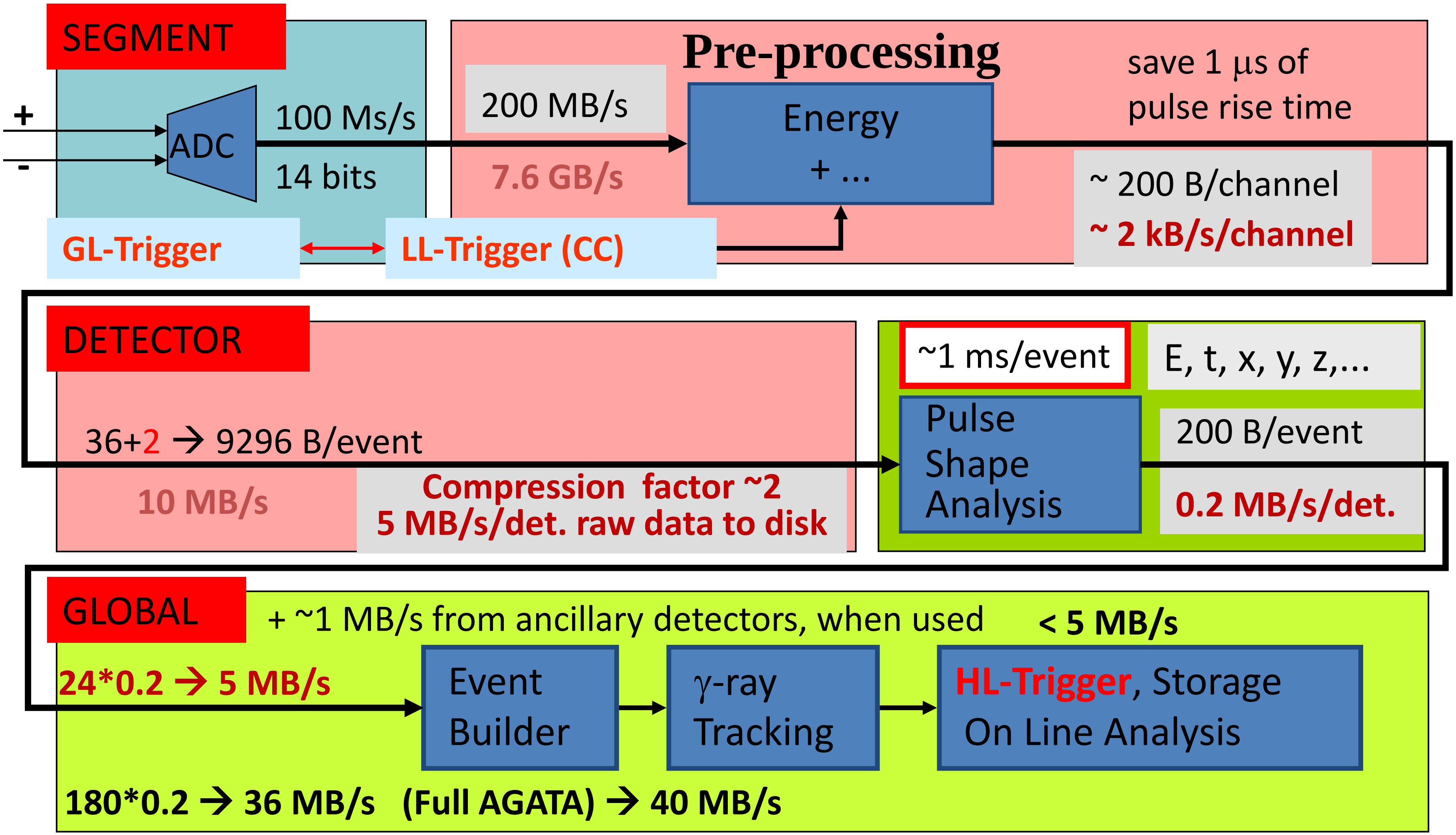
Courtesy P. Reiter

Structure of Electronics and DAQ



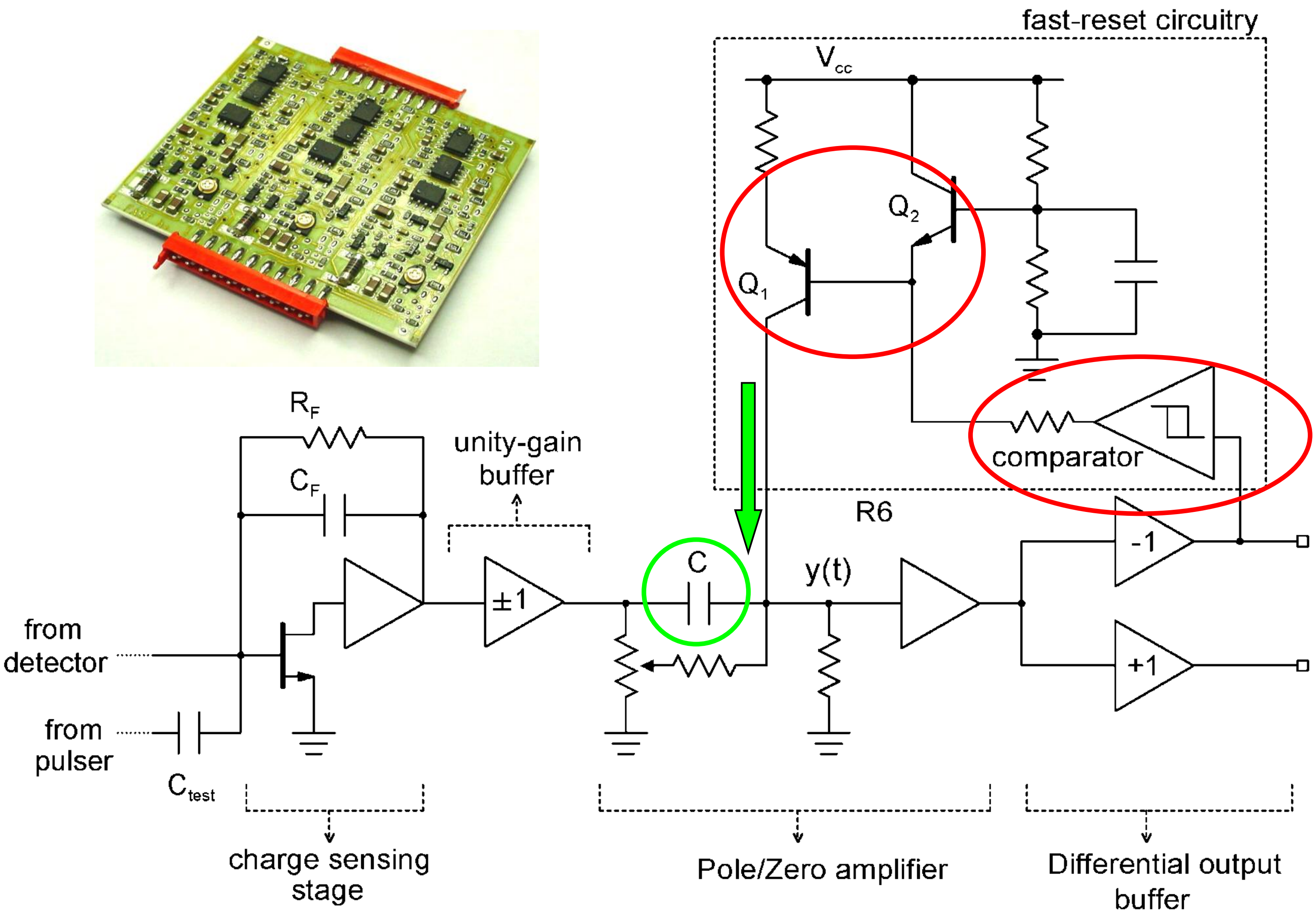
interface to GTS, merge time-stamped data into event builder, prompt local trigger from digitisers

Data rates in AGATA



Saving the original data produces ~5 ÷ 30 TB / experiment
Disk server (100 TB) is always almost full → data archived to the GRID

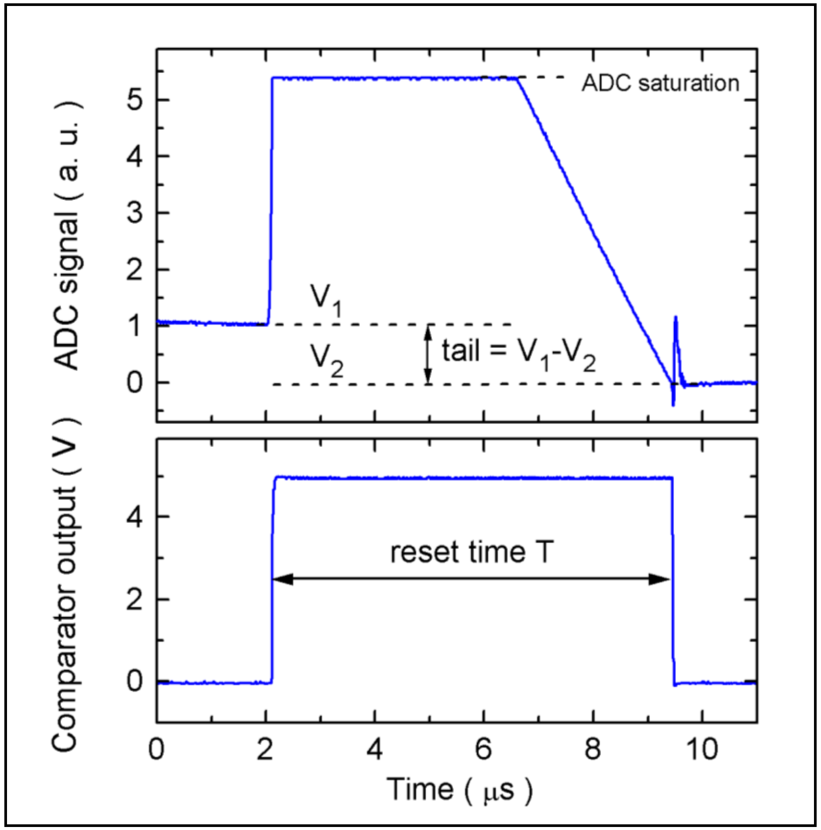
AGATA hybrid charge sensitive preamplifiers



INFN-Milano, GANIL, IKP-Köln

F.Zocca, A.Pullia, G.Pascovici

Time-Over-Threshold (TOT) technique



second-order time-energy relation

offset term

$$E = b_1 T + b_2 T^2 - k_1 (V_1 - V_2) + E_o$$

contribution of the tail due to previous events

***E* = energy of the large signal**

***T* = reset time**

V_1, V_2 = *pre-pulse and post-pulse baselines*

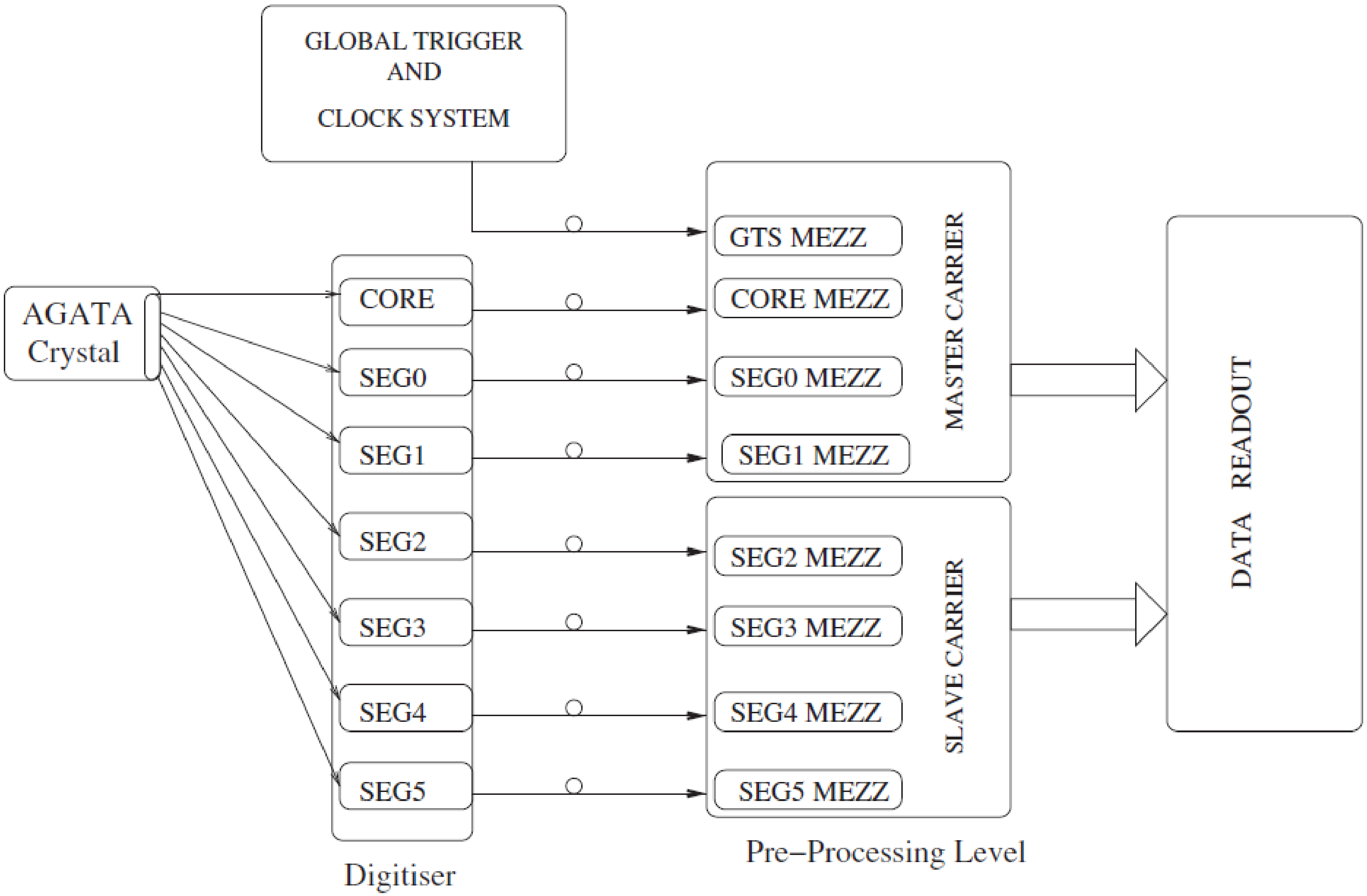
b_1, b_2, k_1, E_0 = *fitting parameters*

Within ADC range → standard "pulse-height mode" spectroscopy

Beyond ADC range → new "reset mode" spectroscopy

F.Zocca, A.Pullia, G.Pascovici

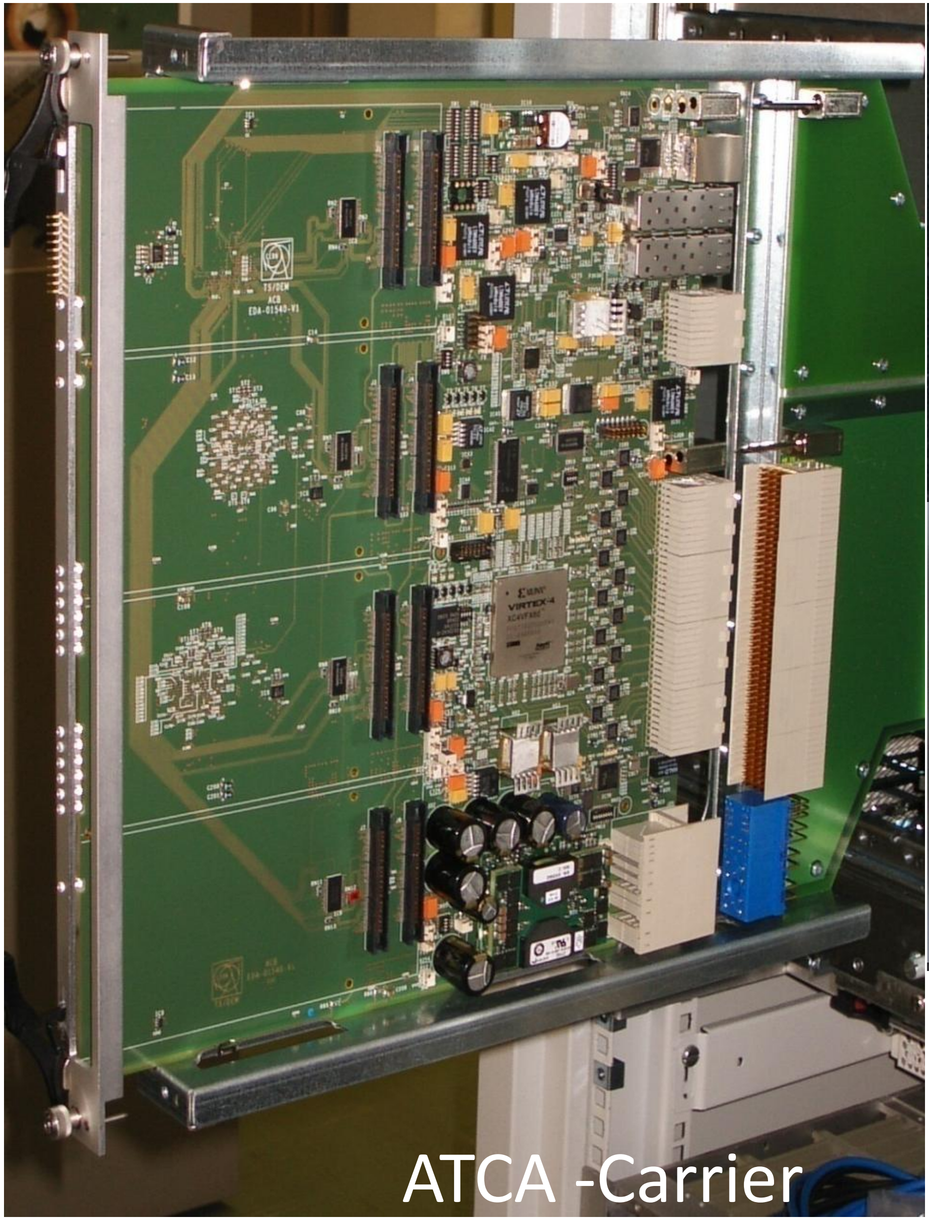
Schematic view of AGATA front-end electronics and data readout

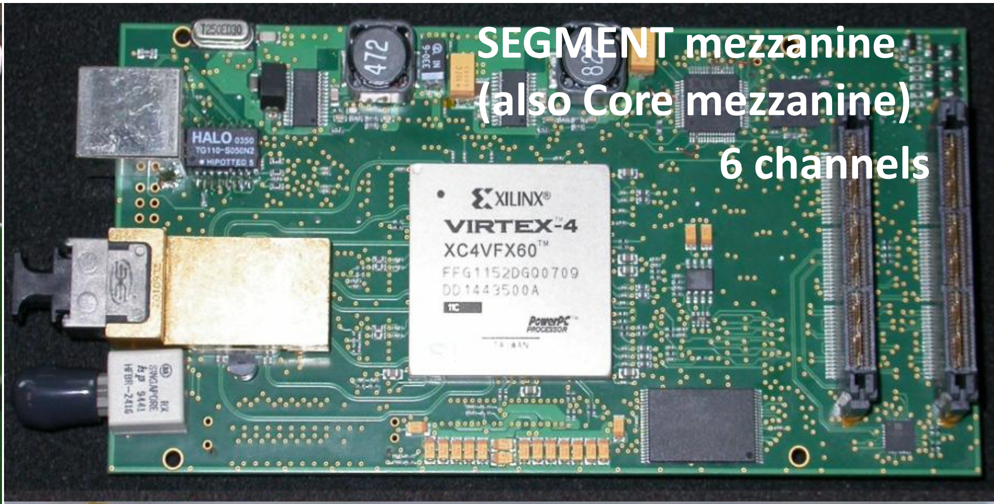


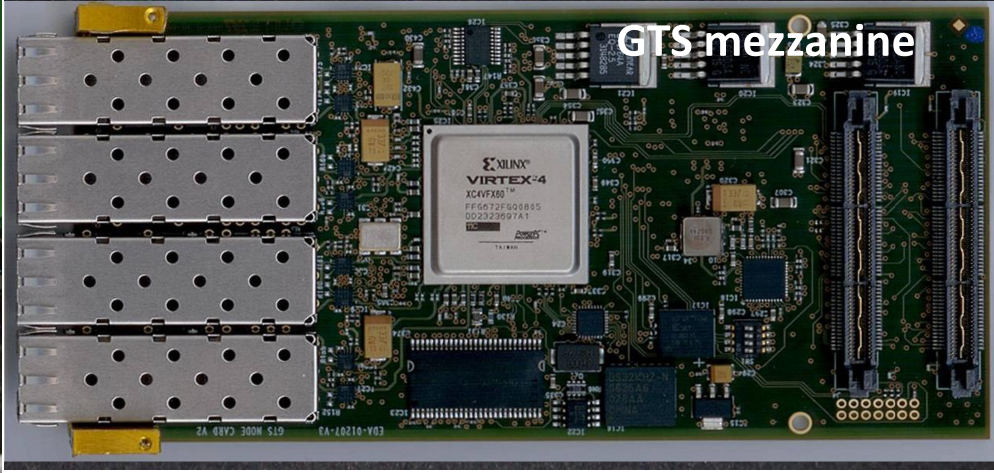
The AGATA Digitiser

- 100 MS/s
  - max frequency correctly handled is 50 MHz (Nyquist)
- 14 bits
  - Effective number of bits is ~12.5 (SNR ~75 db)
- 2 cores and 36 segments (in 6 boards)
- Core 2 ranges 5, 20 MeV nominal
- Segments either high or low gain
- The digitized samples are serialized and transmitted via optical fibre (1/channel) to the preprocessing electronics. Transmission rate is 2 Gbit/s on each of the 38 fibres.
- Power consumption 240 W
- Weight 35 kg
- Inspection lines and CFD Output

ATCA Pre-Processing Electronics





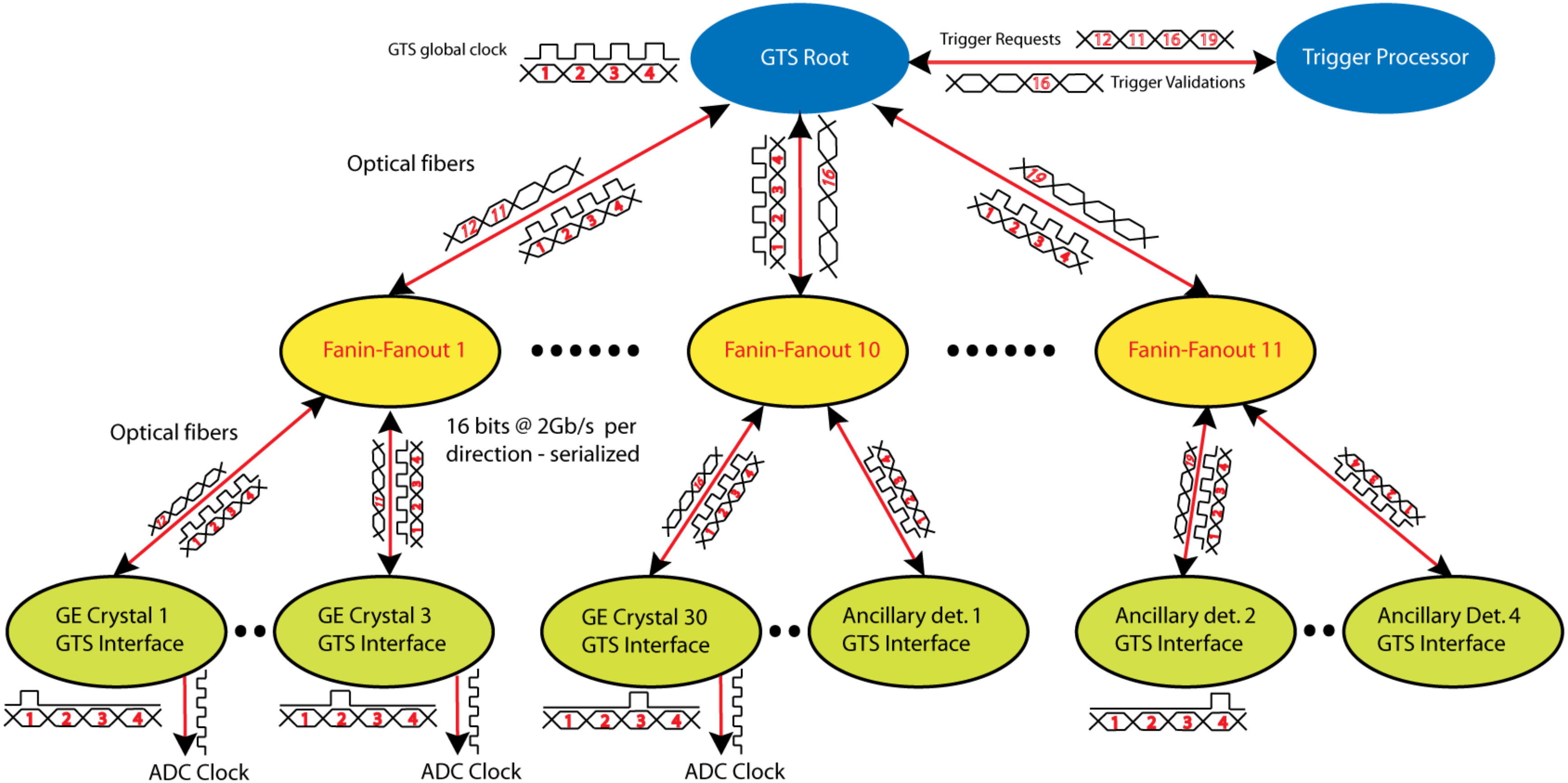


The Pre-Processing is the first level that can interact with the Global Trigger through the GTS mezzannine. It receives, and send to the Digitizer, the Global clock synchronizing the system.

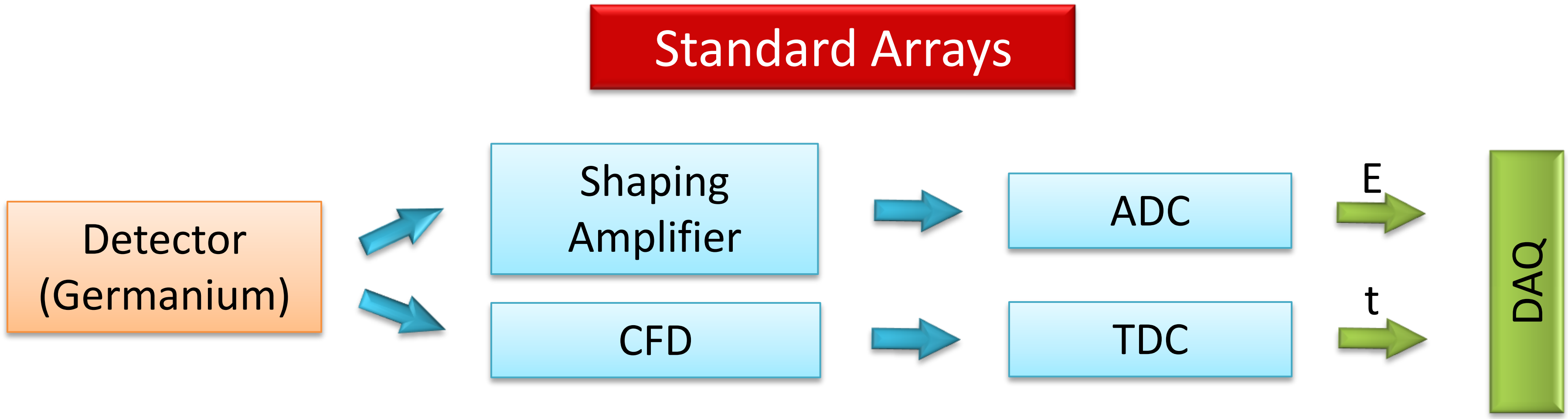
GTS : the system coordinator

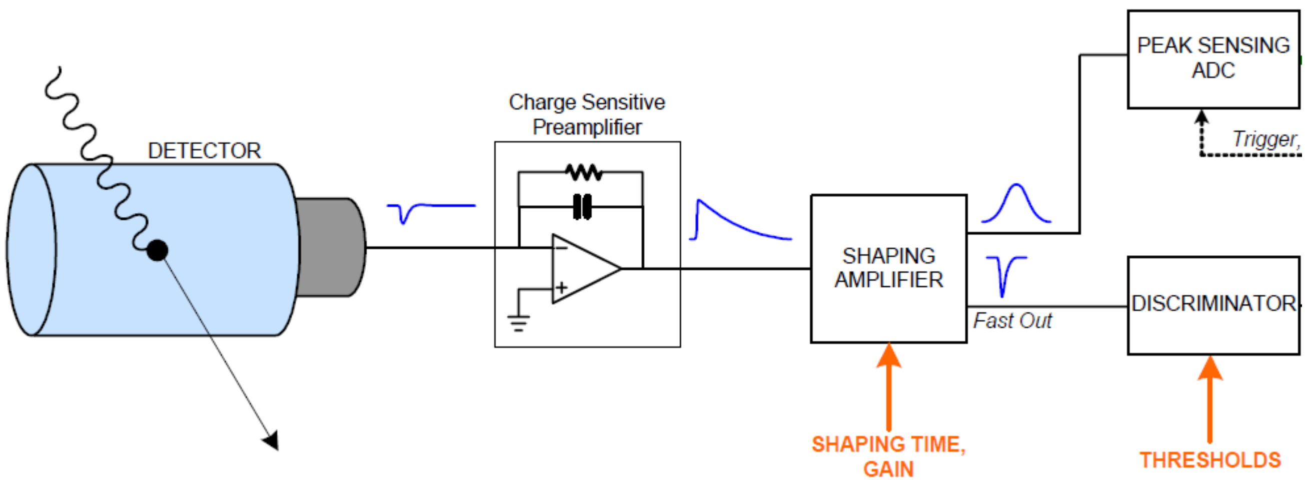
All detectors operated on the same 100 MHz clock

Downwards	100 MHz clock + 48 bit Timestamp (updated every 16 clock cycles)
Upwards	trigger requests, consisting of address (8 bit) and timestamp (16 bit)
	max request rate 10 MHz total, 1 MHz/detector
Downwards	validations/rejections, consisting or request + event number (24 bit)

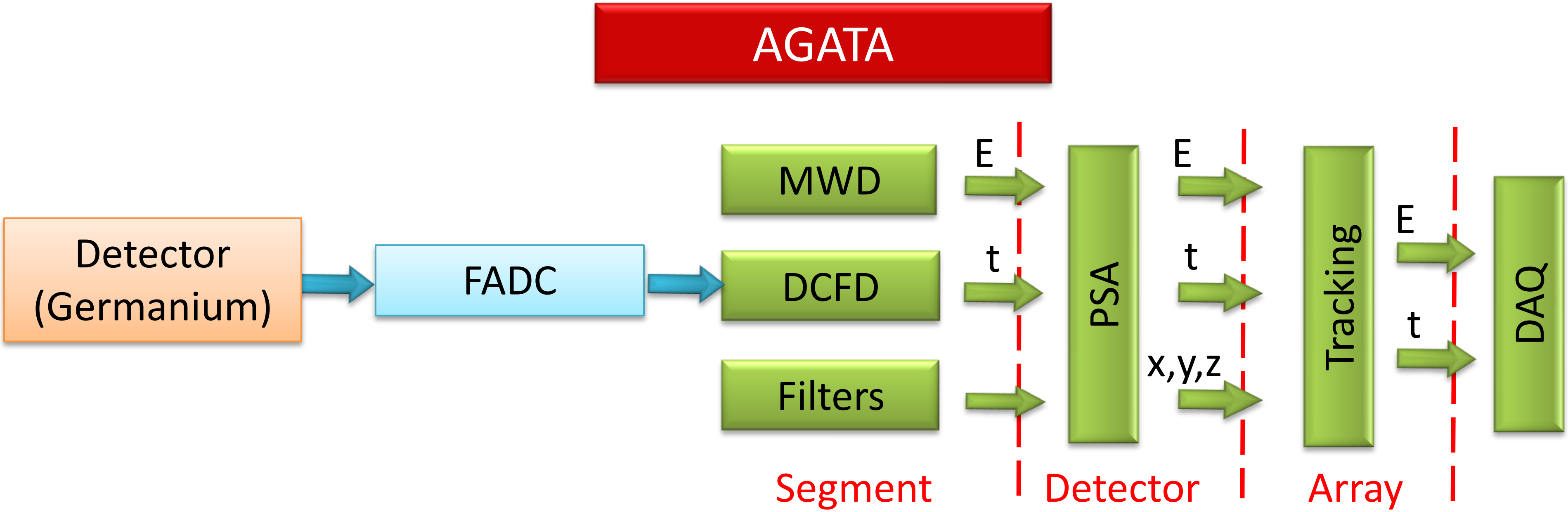


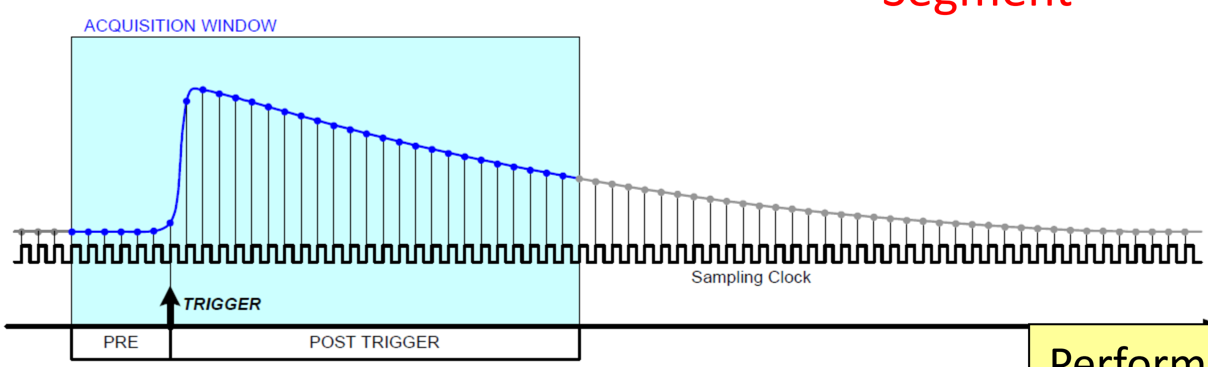
Analogue vs Digital Electronics





Analogue vs Digital Electronics





Performance comparable to best analog electronics.
Higher count rate capabilities

Digital processing of signals

The energy is obtained via trapezoidal filter (or *Moving Window Deconvolution, MWD*)

A.Georgiev and W. Gast, IEEE Trans. Nucl. Sci., 40(1993)770
V.T.Jordanov and G.F.Knoll, Nucl.Instr.Meth., A353(1994)261

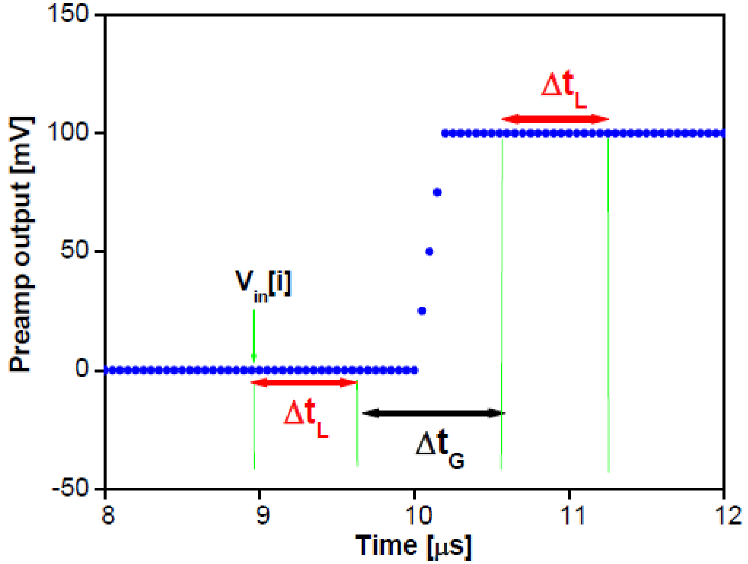


Fig. 6.26. Trapezoidal filter parameters.

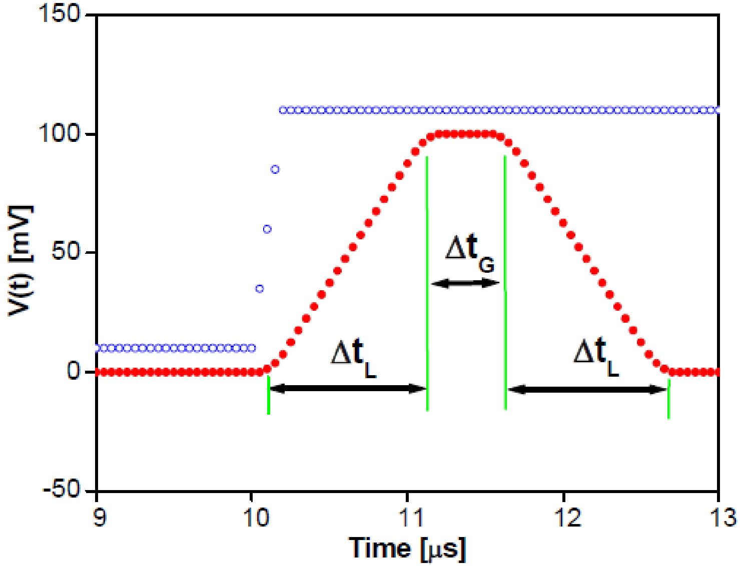


Fig. 6.27. Trapezoidal filter output.

1) $$V_{av1}[i] = \frac{1}{L}\sum_{j=0}^{L-1} V_{in}[i+j]$$

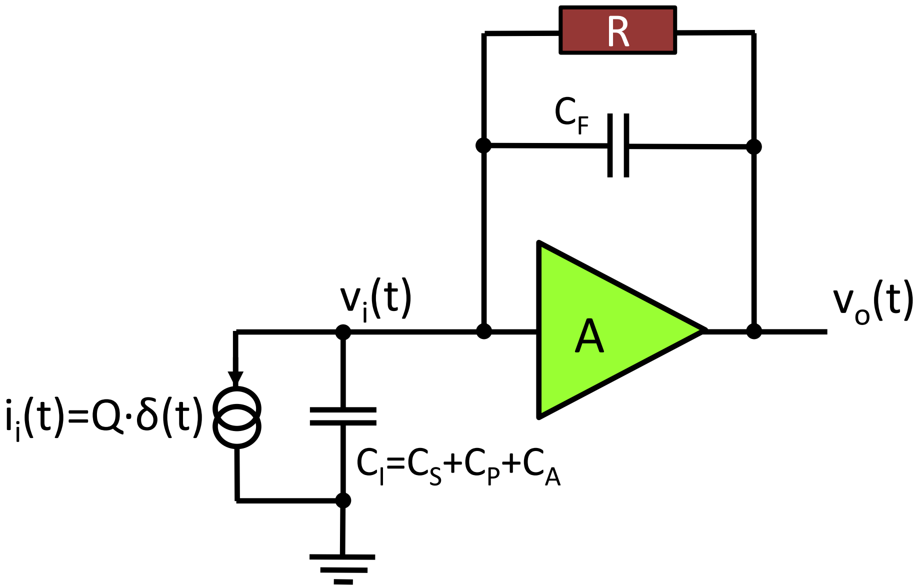
2) $$V_{av2}[i] = \frac{1}{L}\sum_{j=0}^{L-1} V_{in}[L+G+i+j]$$

3) $$V_{out}[i] = V_{av2}[i] - V_{av1}[i]$$

Signal amplitude = value at the top – value of the baseline

“Deconvolution” of Ge signals

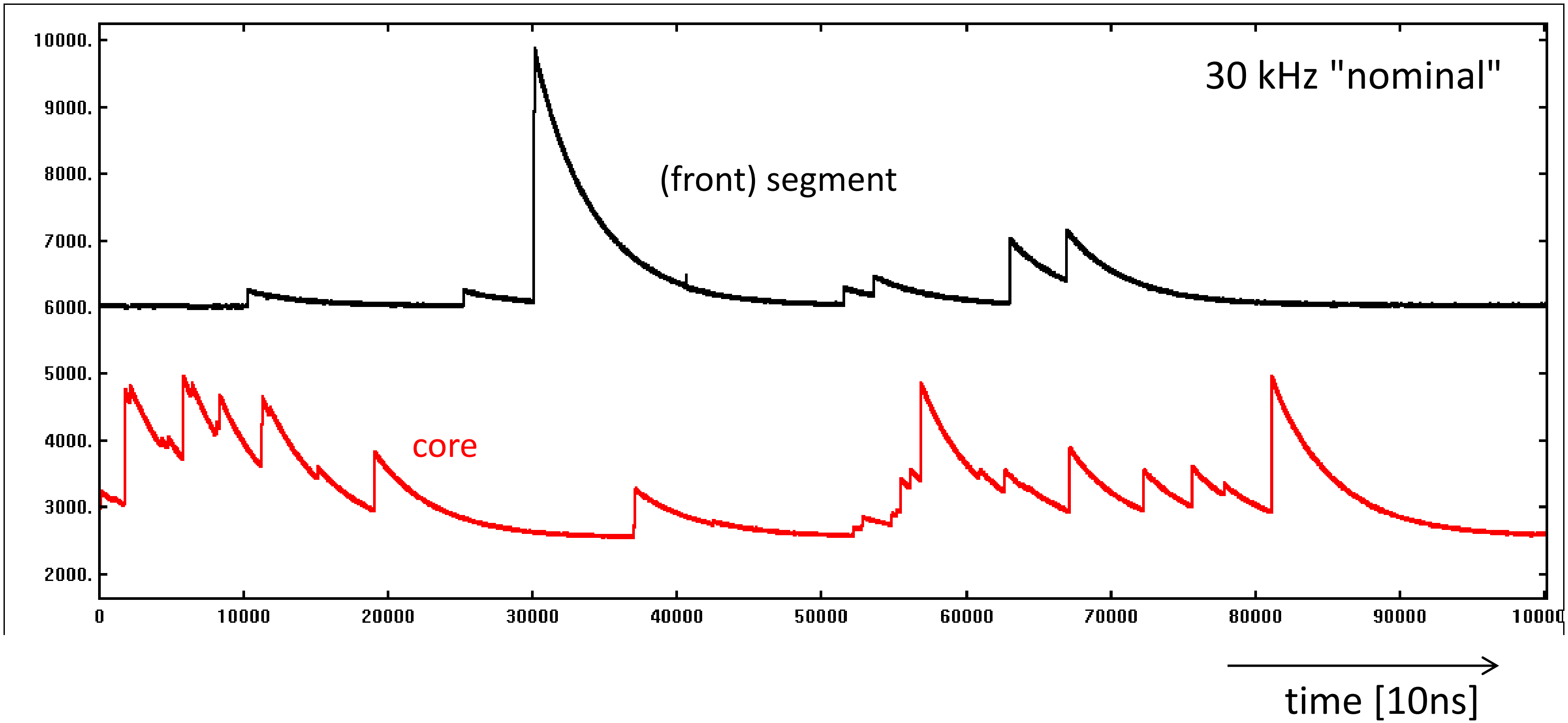
- Signals from Ge preamplifiers are, ideally, exponentials with only one decay constant



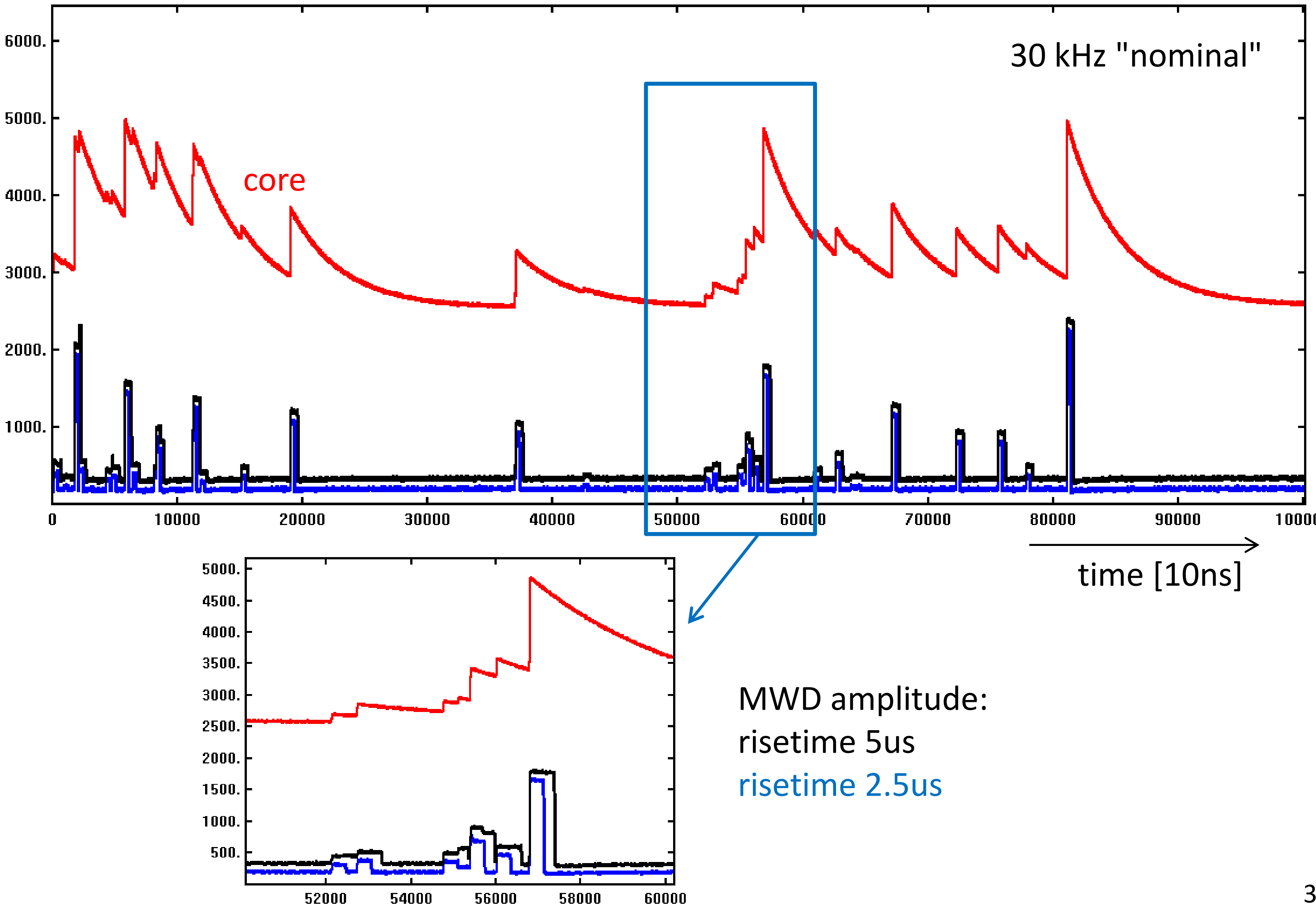
In practice the output exponential is produced in stages :
- RC_F charge loop with decay constant τ_0~1 ms
- CR differentiation to reduce the decay constant to τ_1 ~50 μs
- P/Z cancellation to remove the undershoot and the long recovery (with $\tau=\tau_0$) due to the differentiation of the first exponential.

- Task of the **deconvolution** is to remove the exponential to recover the original δ(t) at the input of the preamplifier
- **Trapezoidal shaping** is then just an integration followed by delayed subtraction followed by a moving average
- In practice **Trapezoidal shaping** is the optimum shaping if the noise is white and the collection time (width of the “delta”) varies a lot as in the large volume semi-coax Ge AGATA detectors

Signal processing at high counting rates

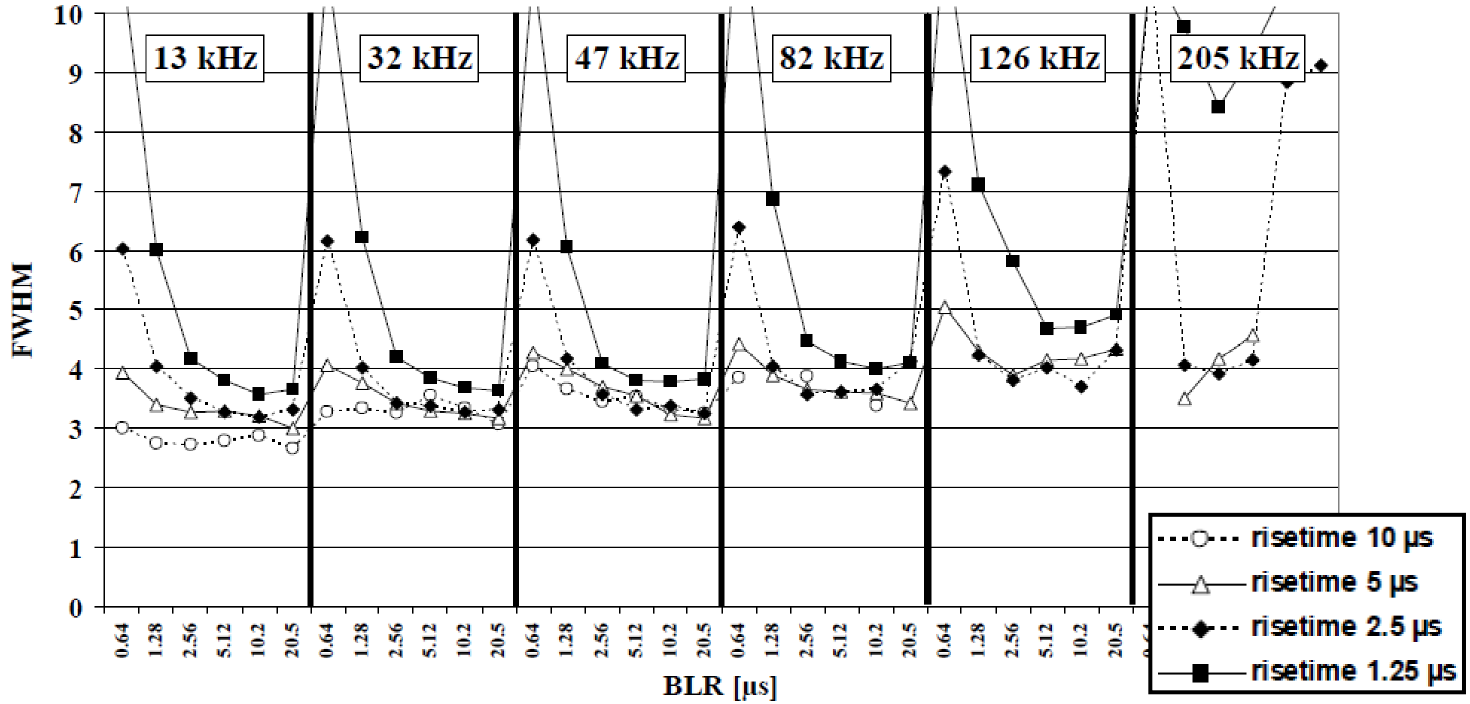


Signal processing at high counting rates



Singles rates and shaping time

6 different rates x 4 trapezoid risetimes x 6 BLR lengths



Singles rates and shaping time

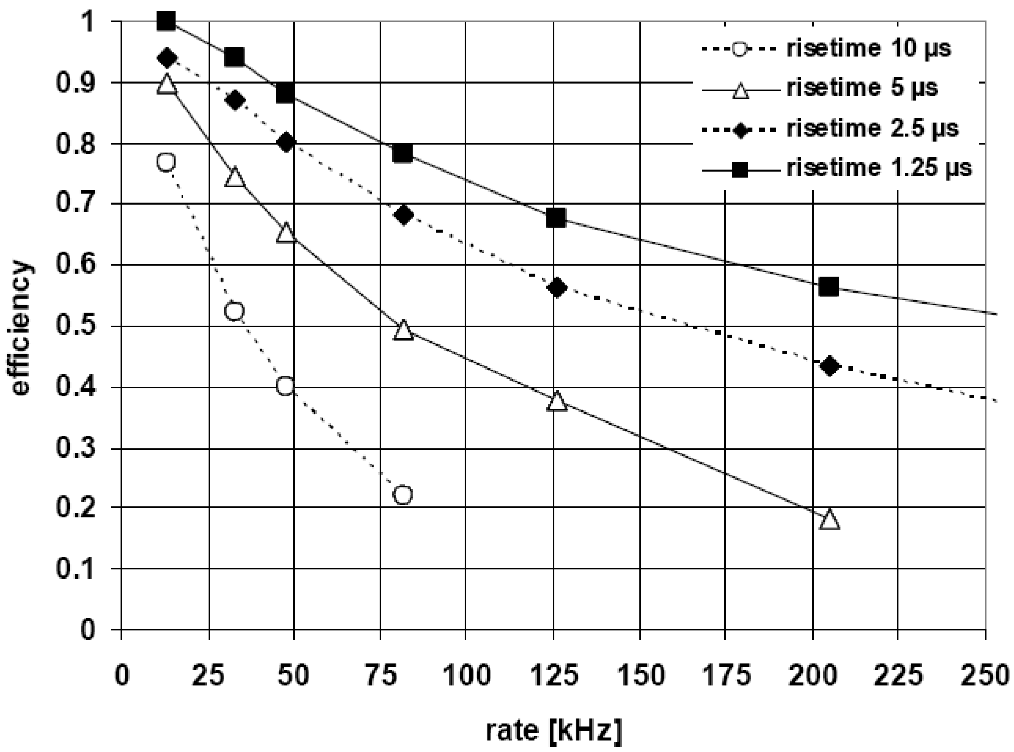


Fig. 1. Efficiency as a function of rate.

F. Recchia LNL Annual Report 2012 137

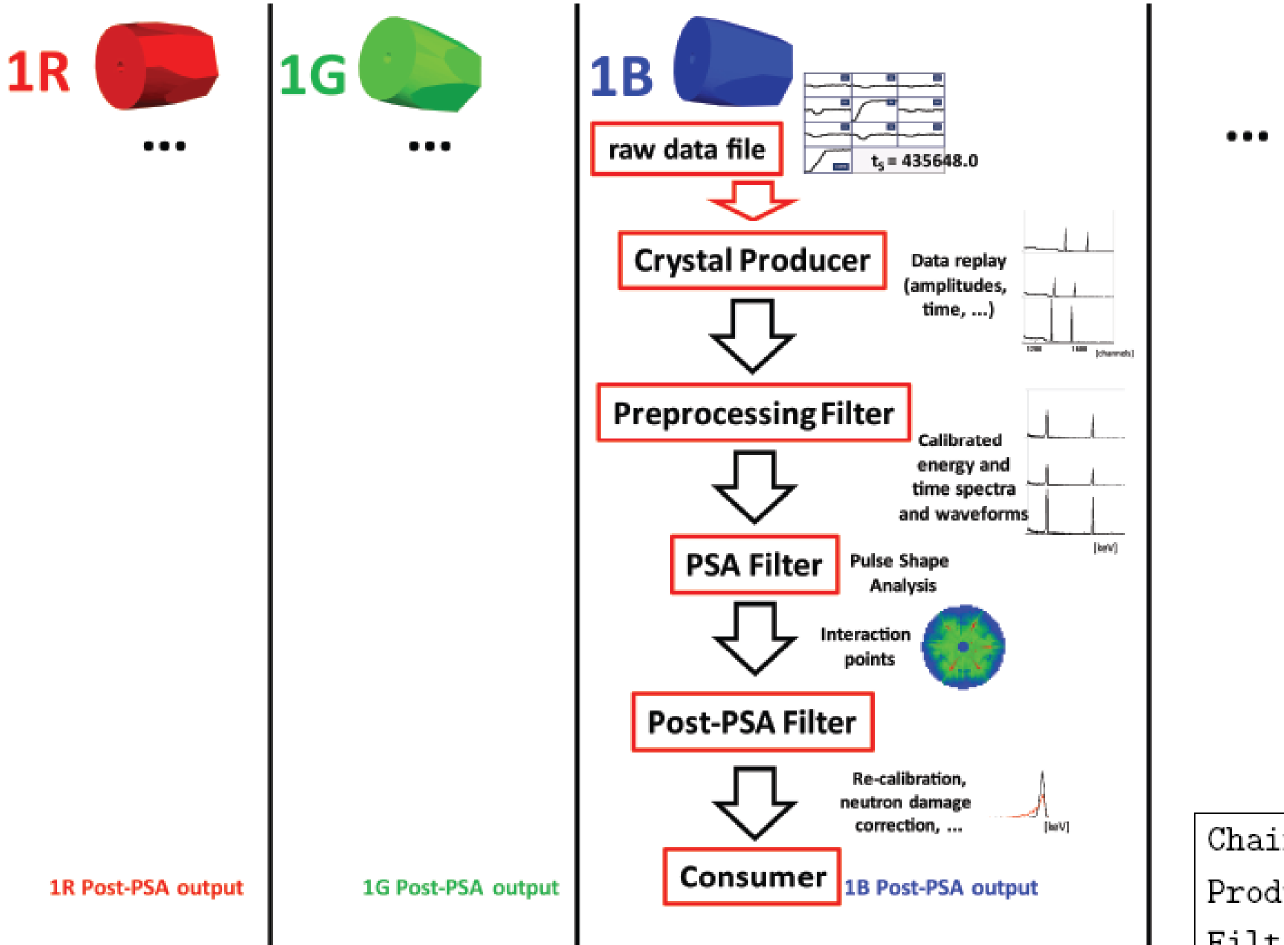
AGATA Data Processing

(from raw data to reconstructed "good" gamma rays)

Offline data processing = Online data processing

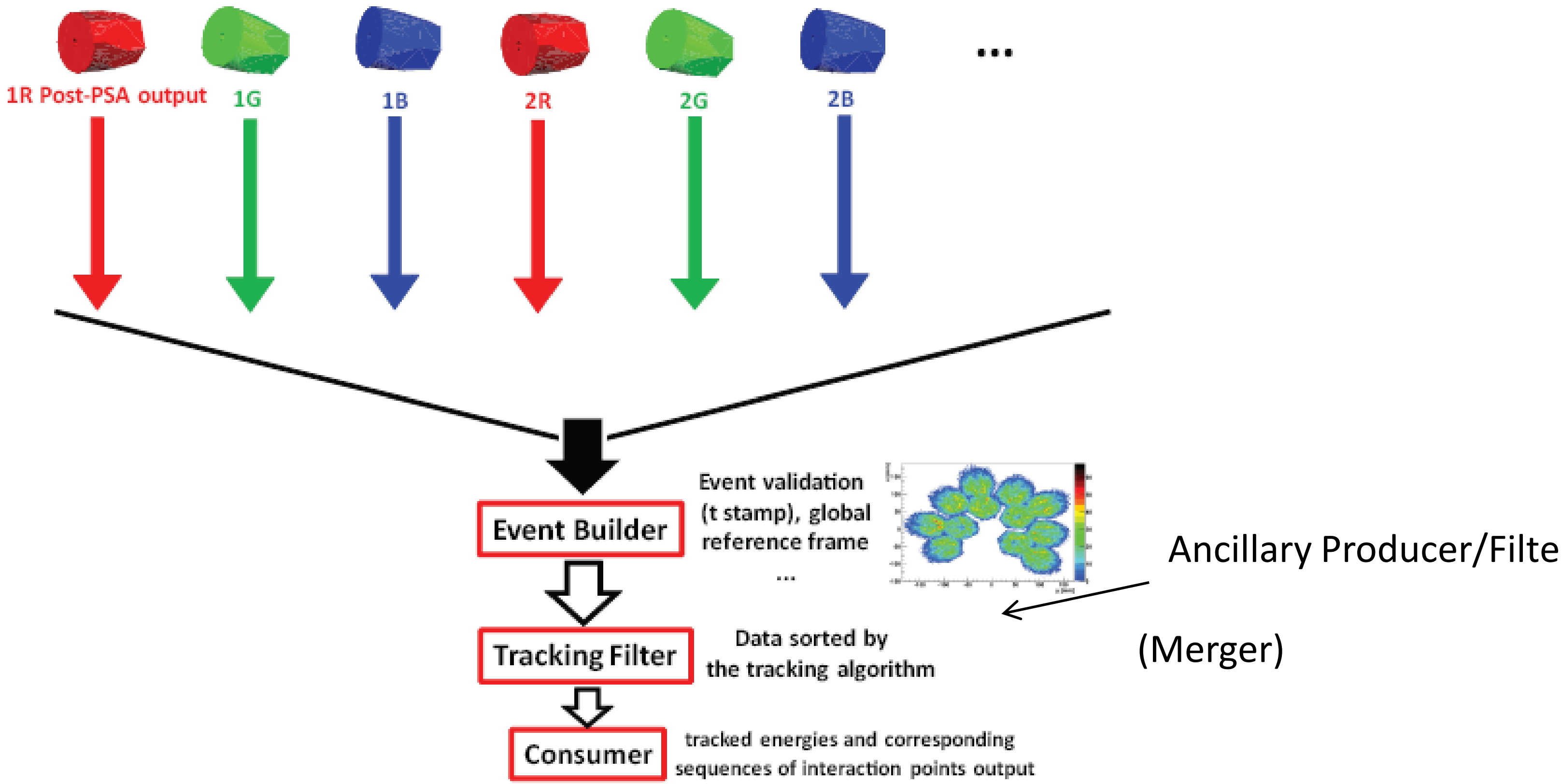
Structure of Data Processing

Local Level Processing

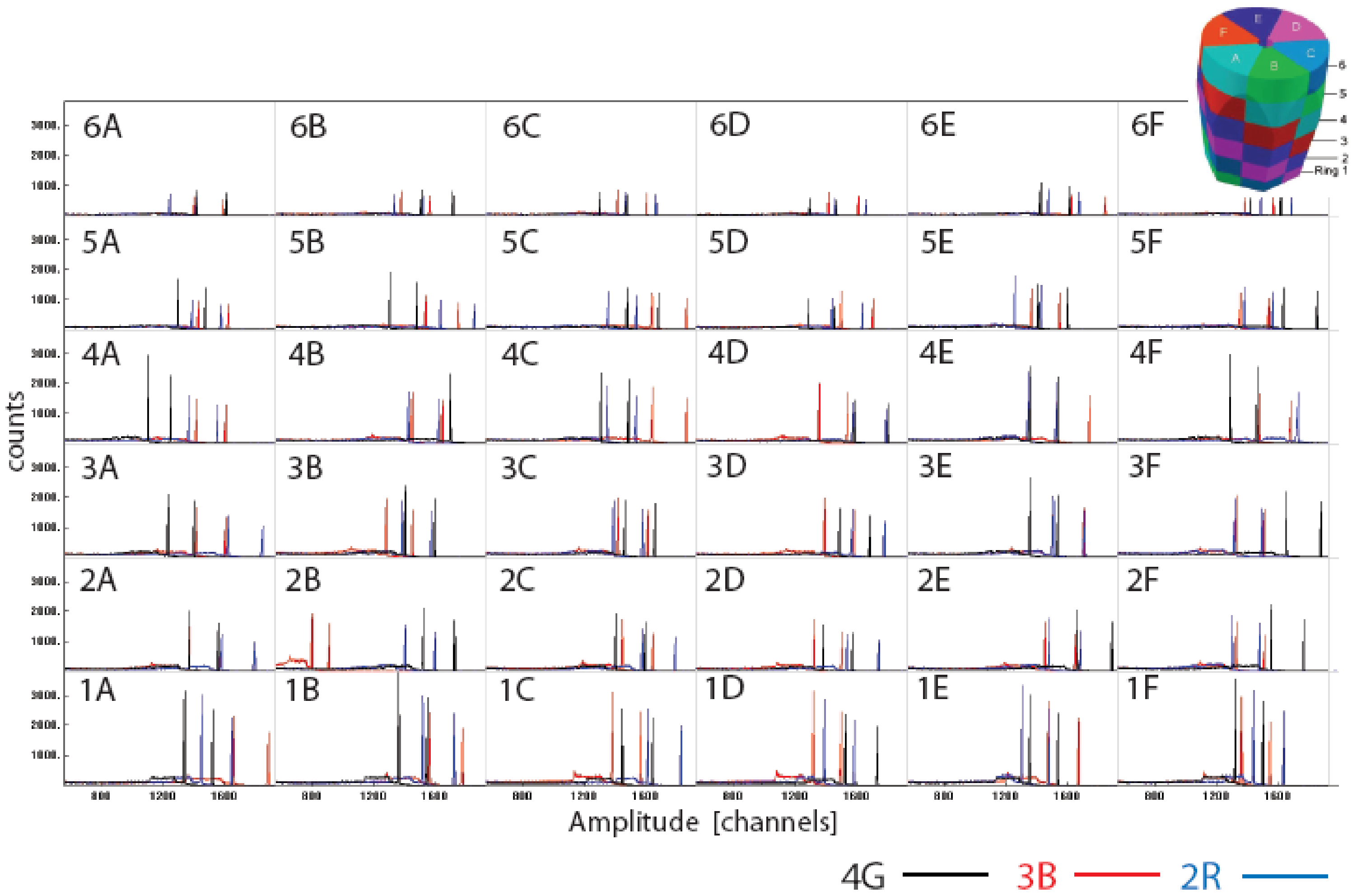



```
Chain 4 1B/
Producer CrystalProducerATCA
Filter PreprocessingFilterPSA
Filter PSAFilterGridSearch
Consumer BasicAFC
```

Structure of Data Processing
Global Level Processing



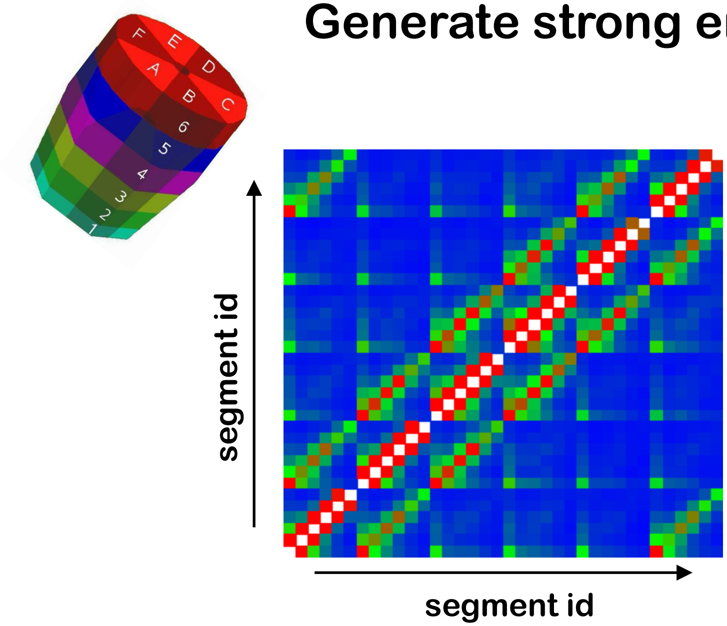
Data preparation to the PSA: energy calibrations

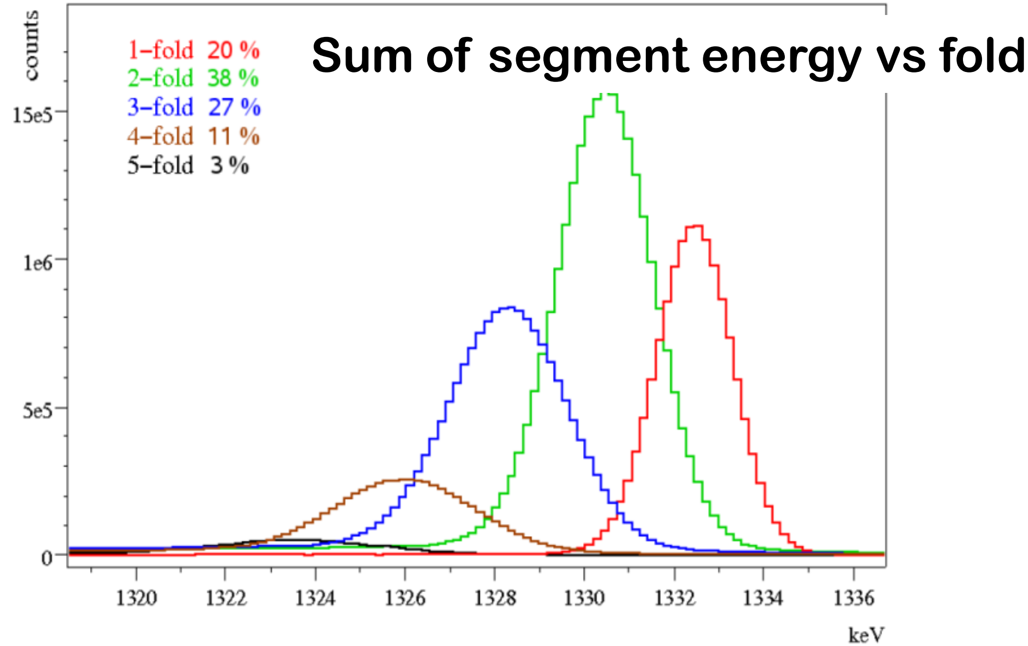


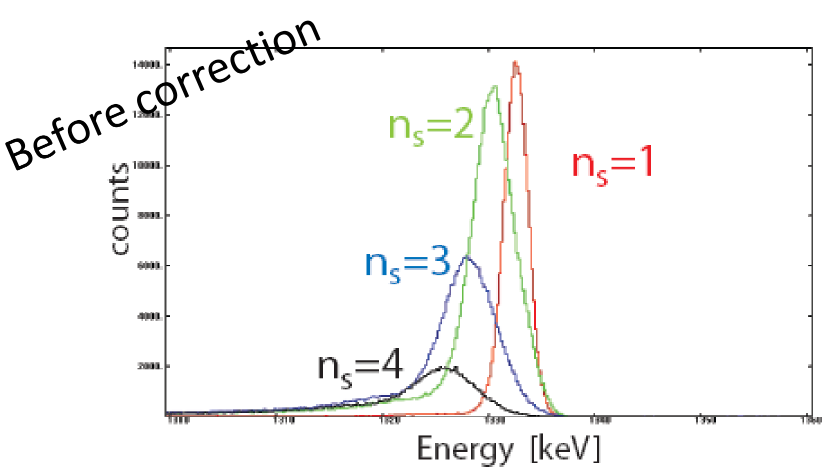
Calibration of traces: from calibrations of amplitudes and MWD parameters

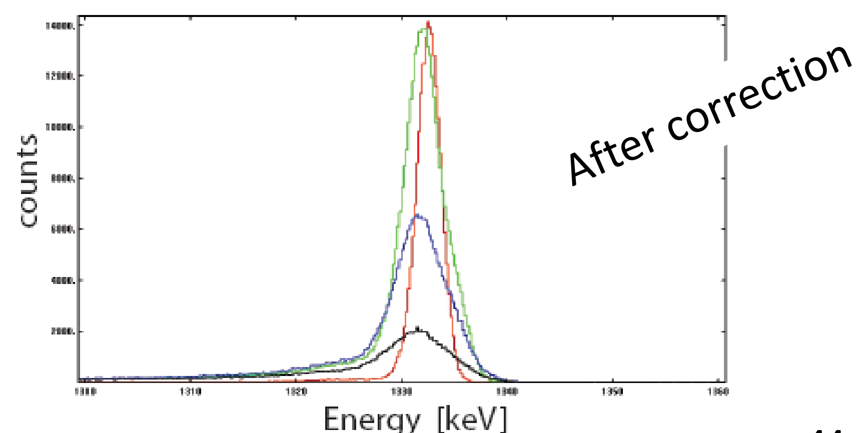
Data preparation to the PSA: Cross-talk Correction

Generate strong energy shifts proportional to the segment fold

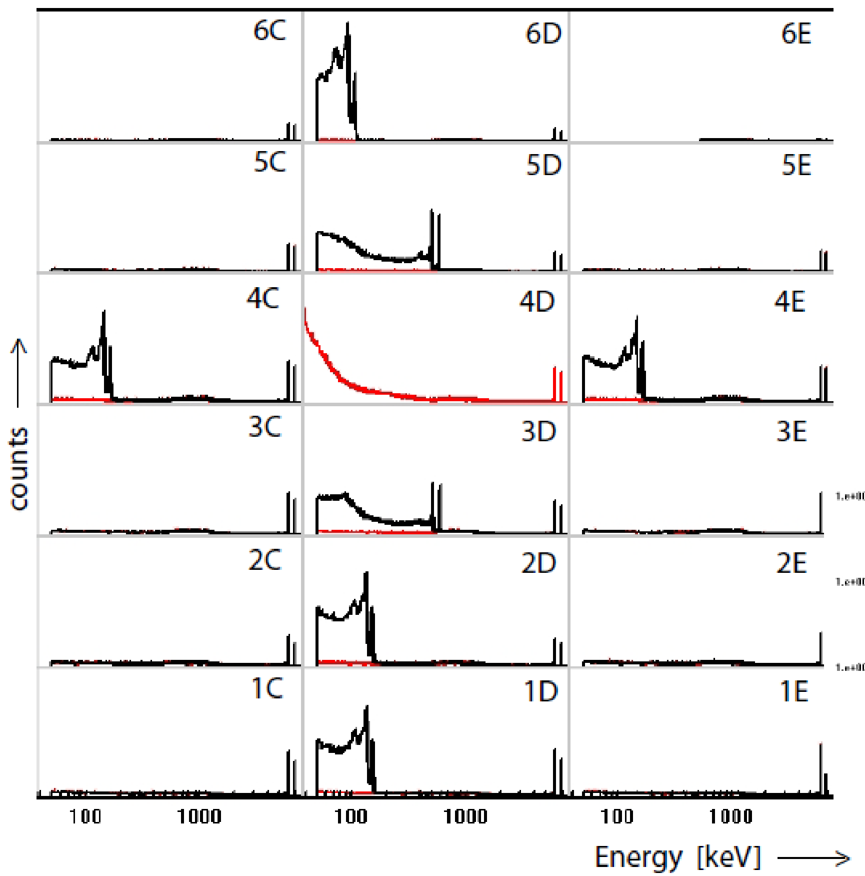


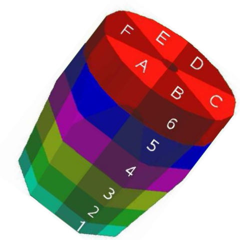


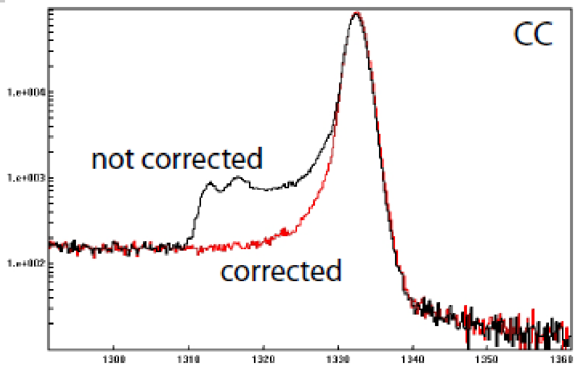




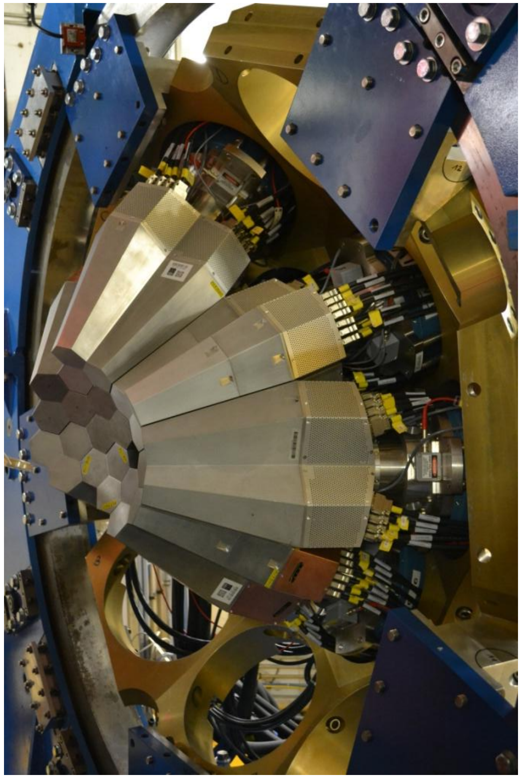
Data preparation to the PSA: recovery of missing segment



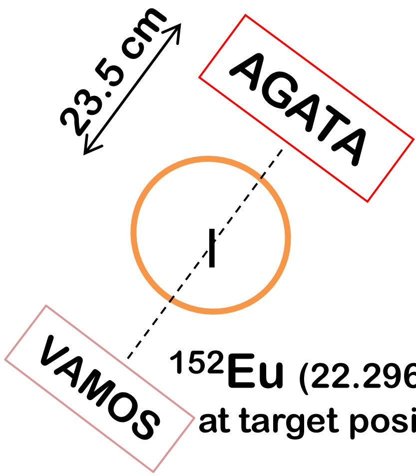




Some results from the commissioning runs in GANIL



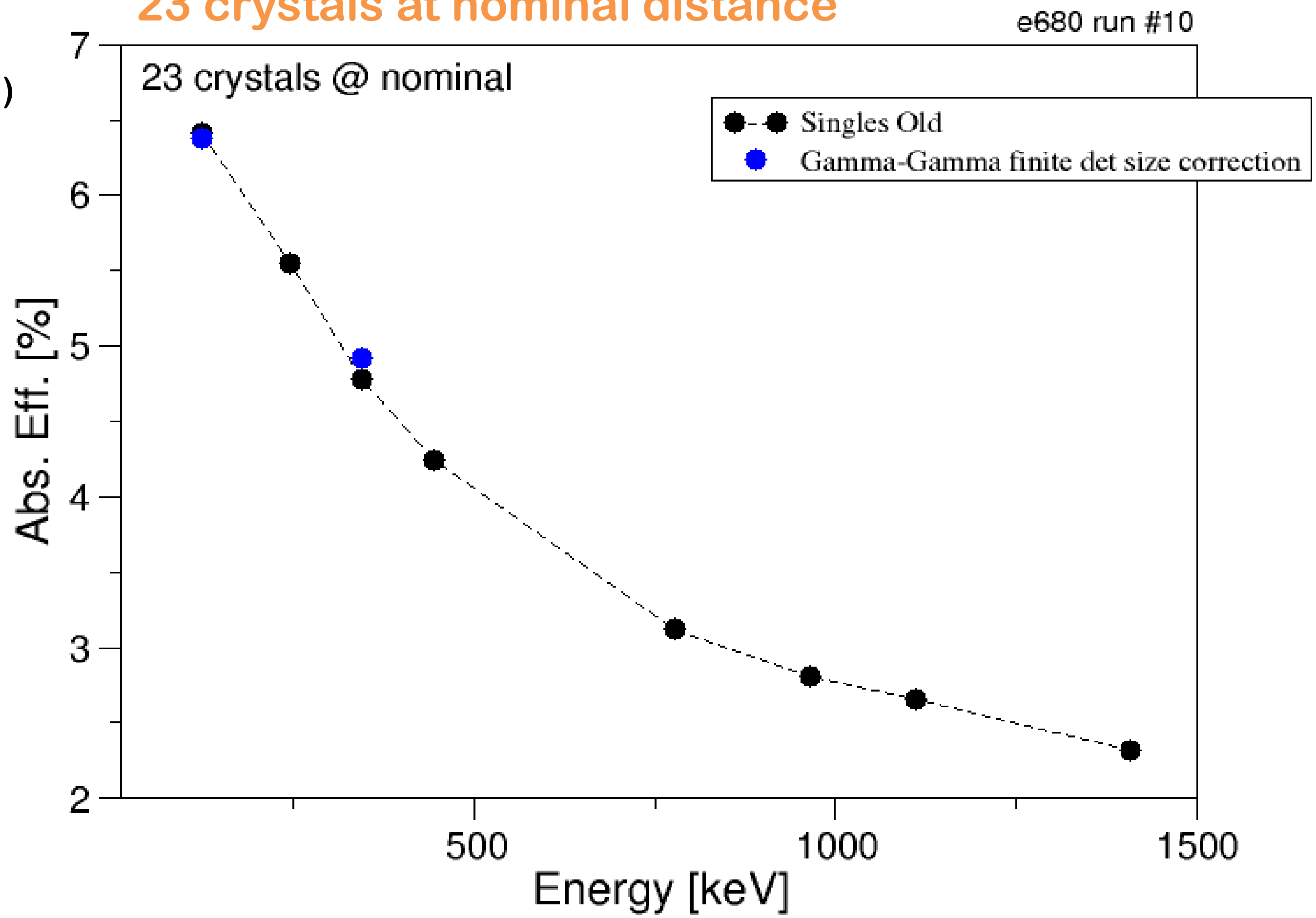
Absolute efficiency vs Energy



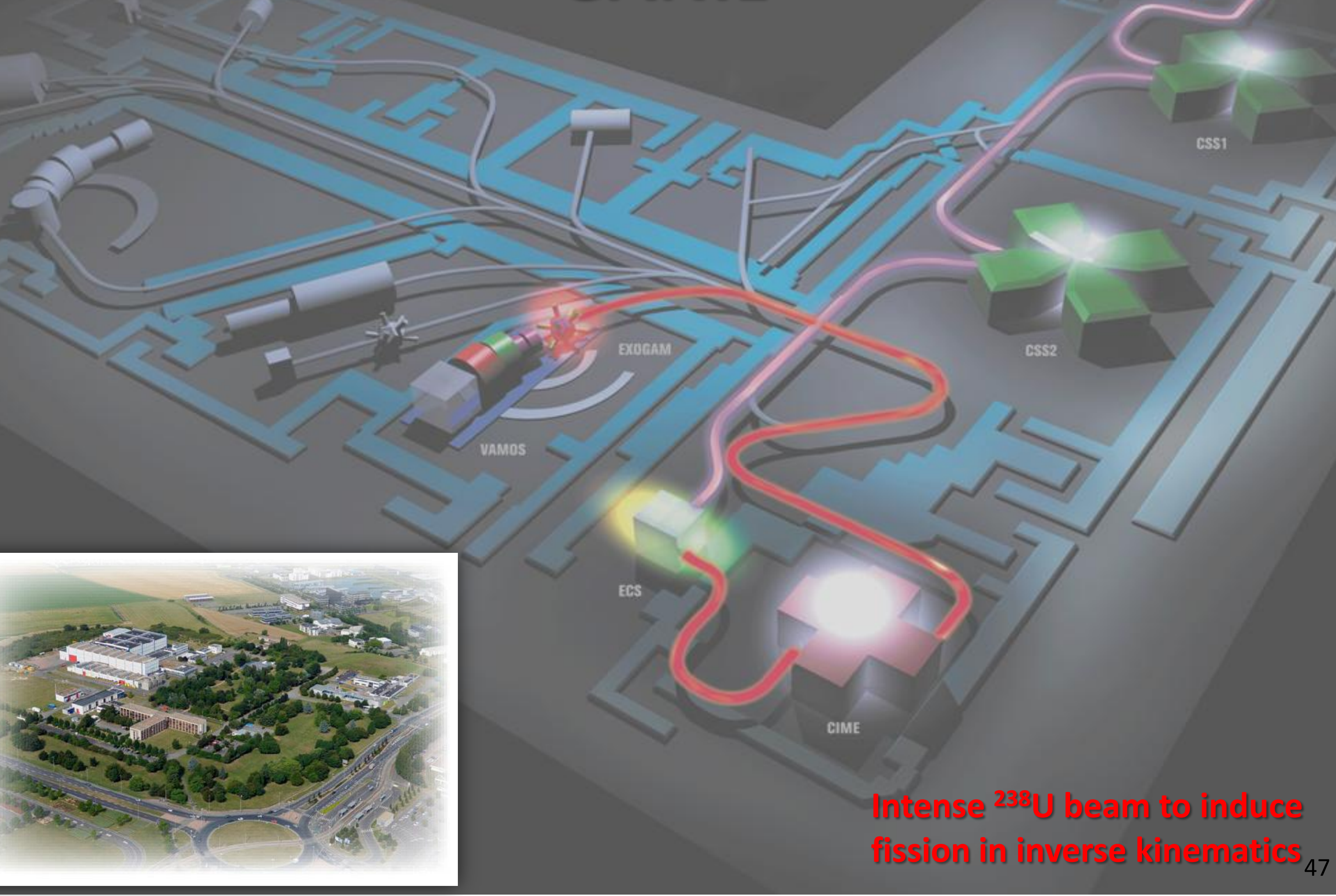
^{152}Eu (22.296 kBq)
at target position

AGATA Cores triggering through VAMOS electronics (same trigger partitions as in-beam experiments)

Core Common Abs. Efficiency
23 crystals at nominal distance



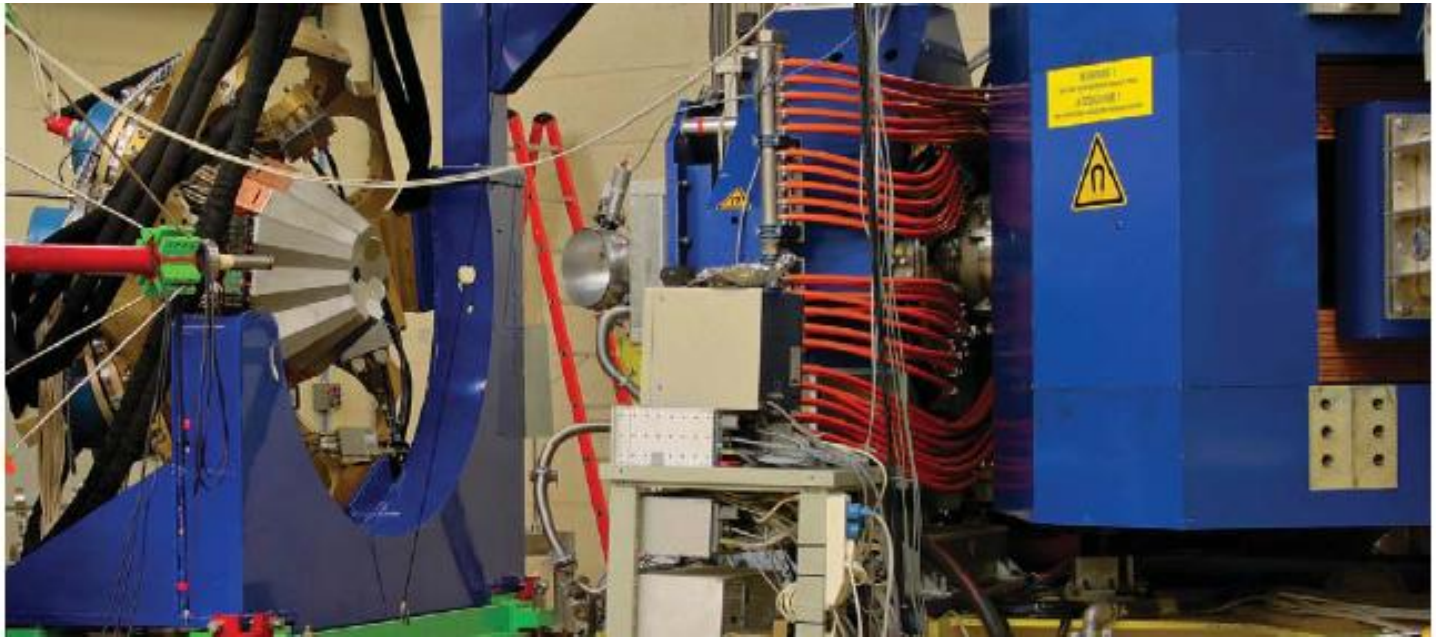
GANIL



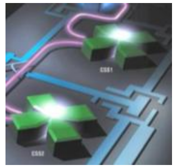
Intense ^{238}U beam to induce fission in inverse kinematics

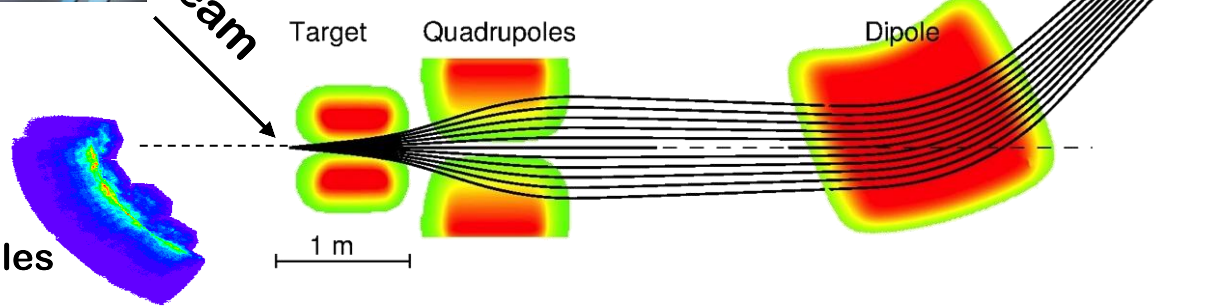
Experimental setup:
AGATA + ~~VAMOS~~ @ ~~GANIL~~

PRISMA LNL



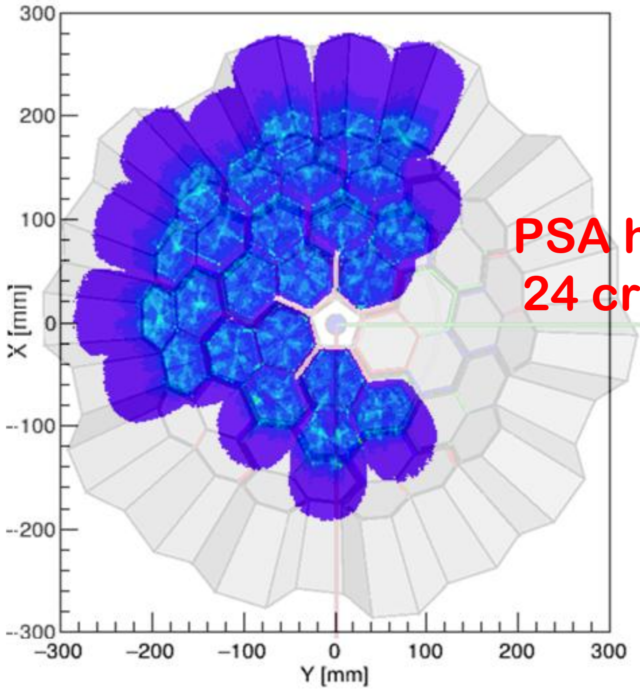
AGATA + VAMOS @ GANIL

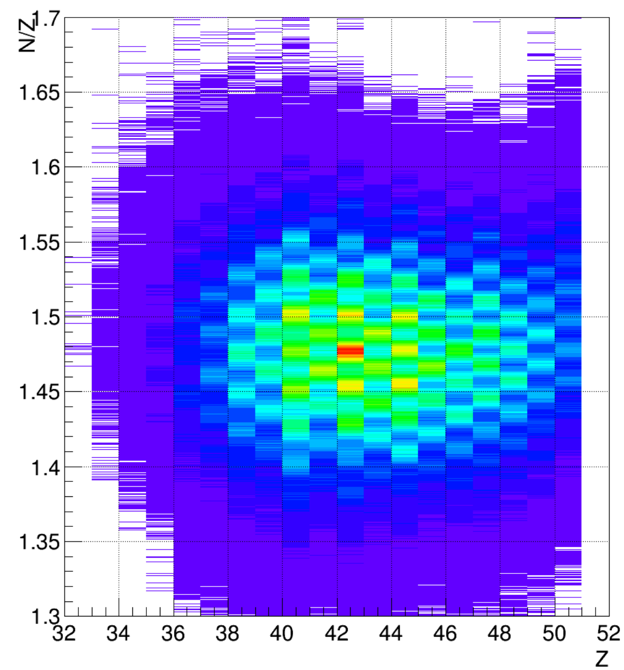




AGATA
at backward angles

Event by event: AGATA: γ energy and interaction points; VAMOS: A, Z, $\vec{\beta}$



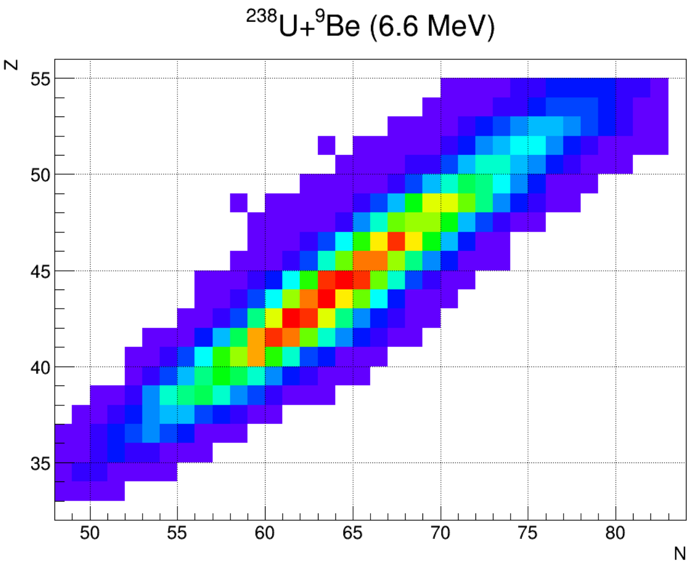


$^{238}U+^{9}Be$ @ 6.6 MeV/u
commissioning run
December 2014

γ rays from isotopically id. fission fragments $^{238}U+^{9}Be$ @ 6.6 MeV/u

AGATA+VAMOS commissioning run, December 2014

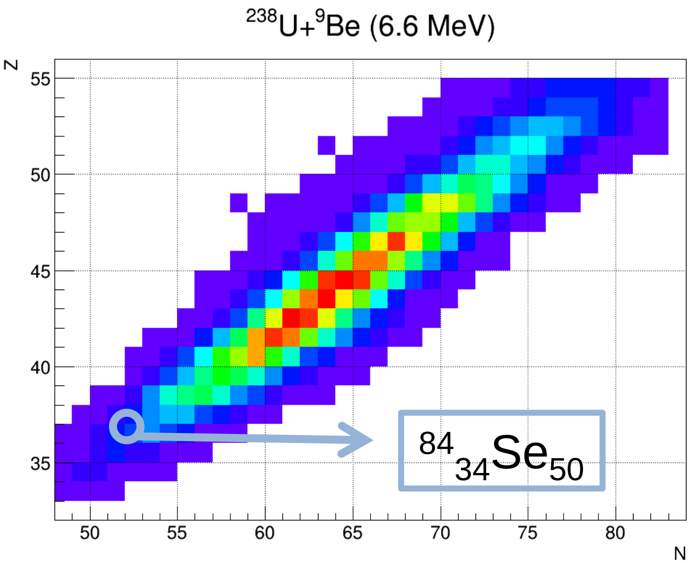
the fission nuclide chart



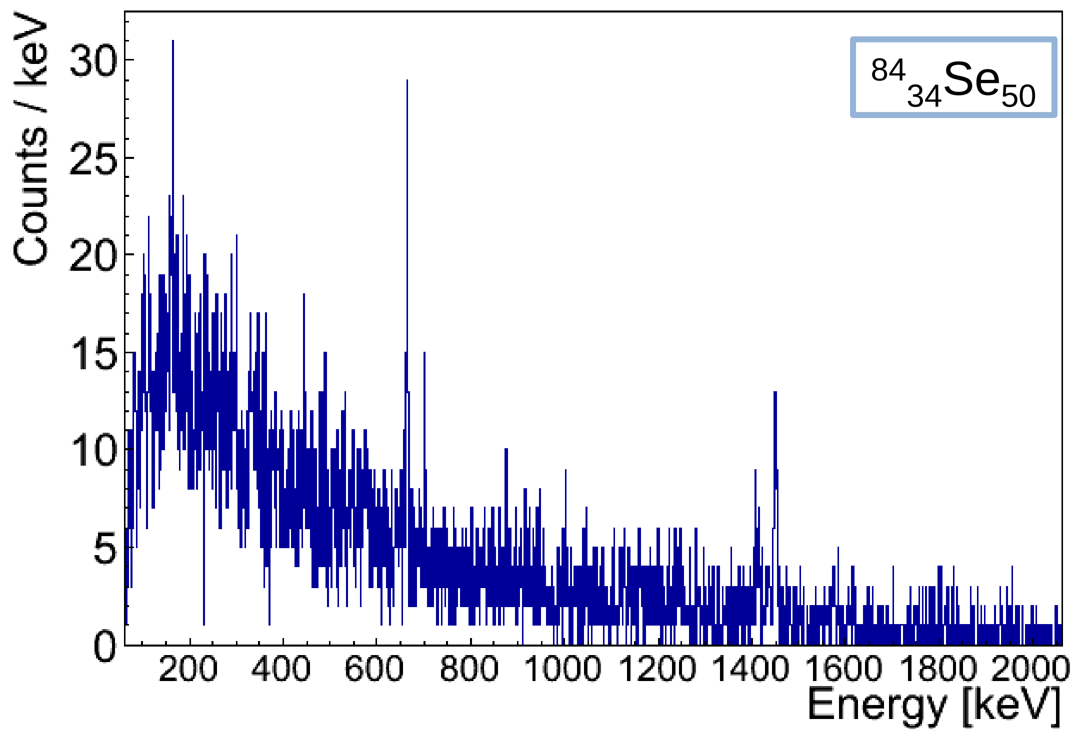
γ rays from isotopically id. fission fragments
$^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014



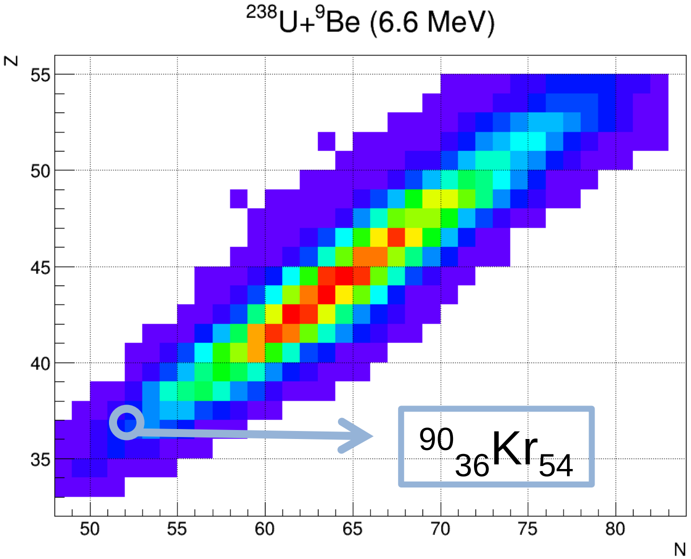
N/Z = 1.47



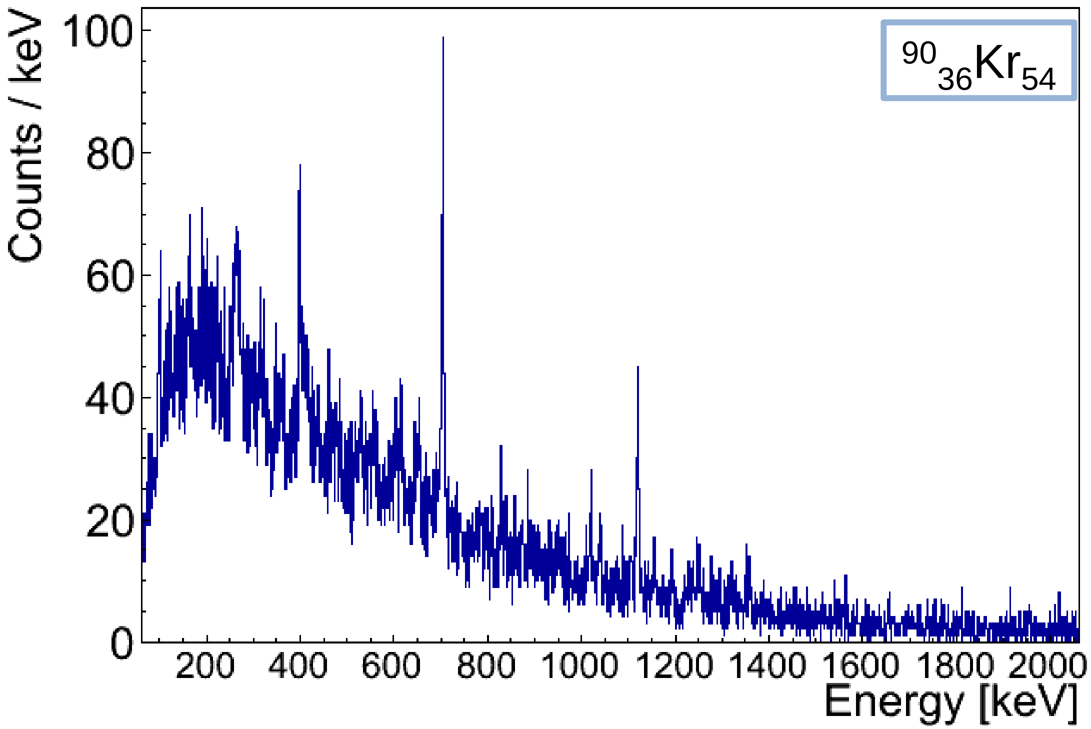
γ rays from isotopically id. fission fragments
$^{238}U + ^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014



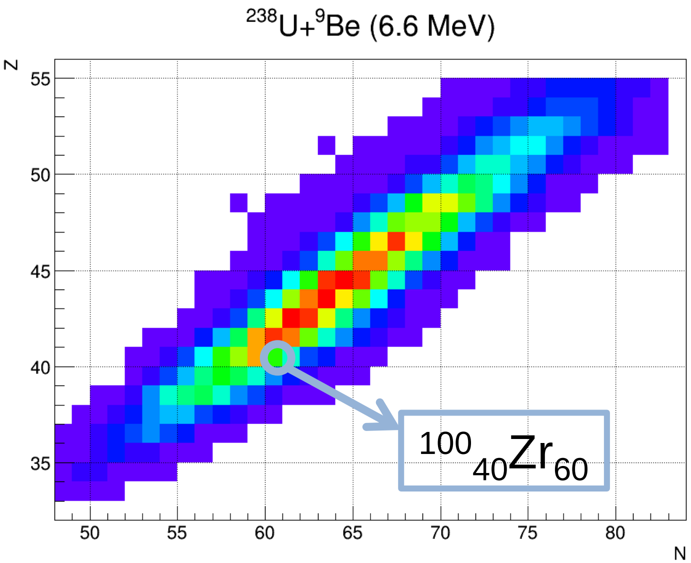
N/Z = 1.50



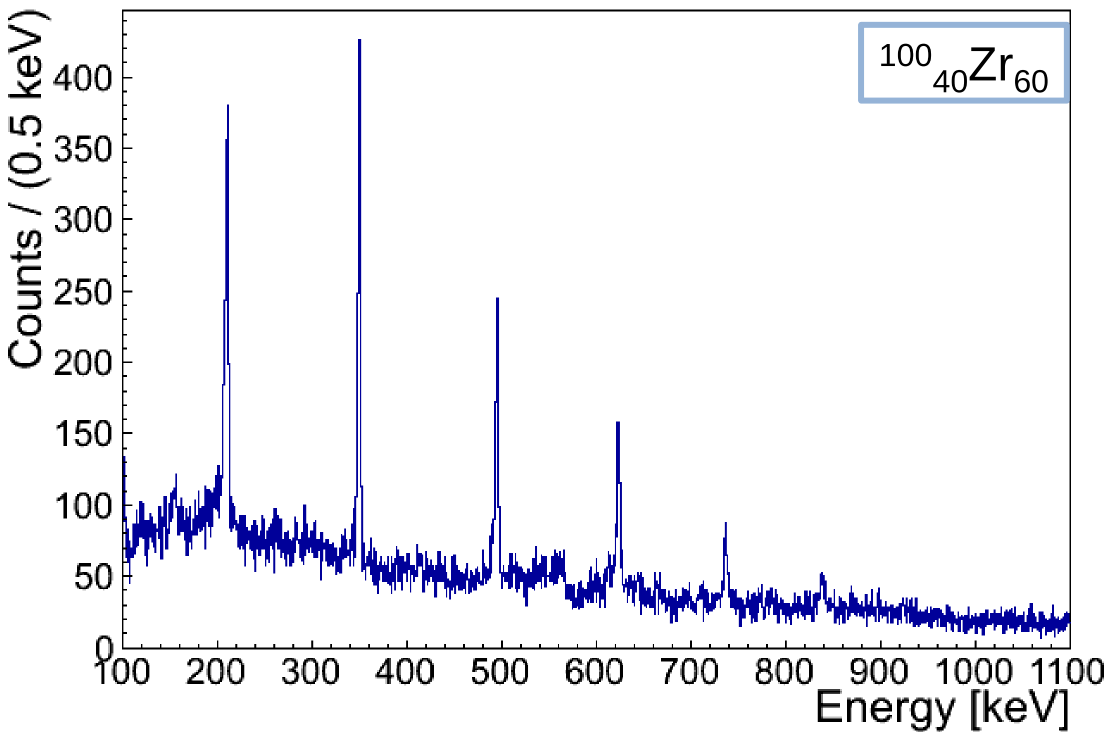
γ rays from isotopically id. fission fragments
$^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014



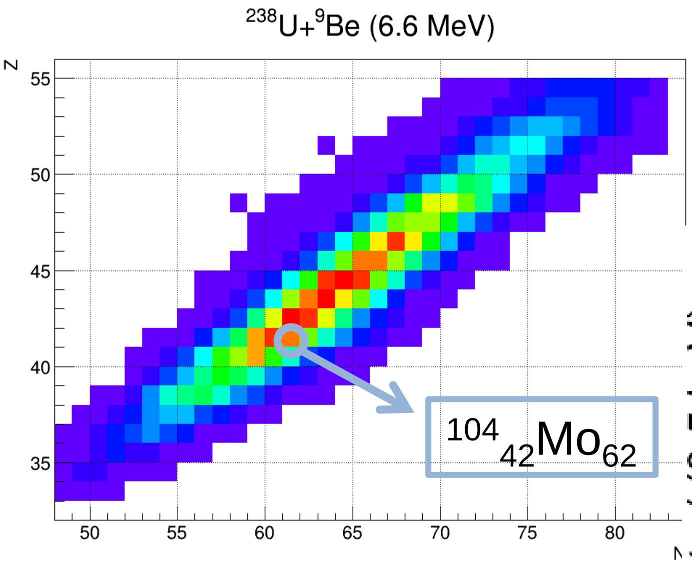
N/Z = 1.50



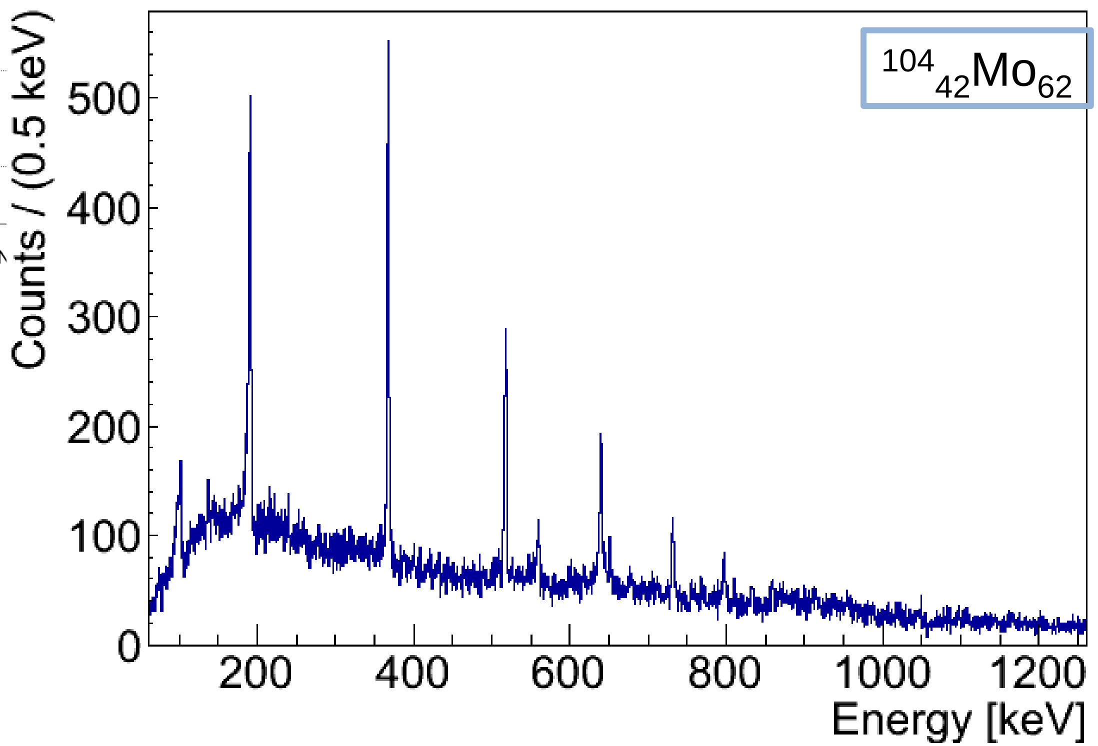
γ rays from isotopically id. fission fragments
$^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014



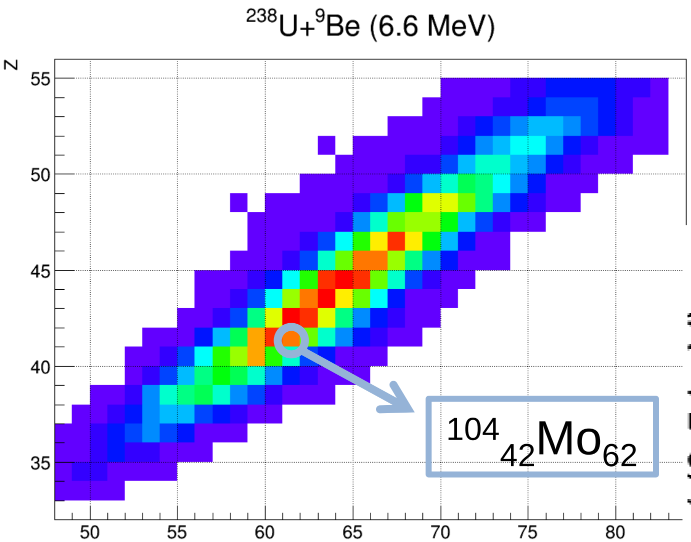
N/Z = 1.48



γ rays from isotopically id. fission fragments
$^{238}U + ^{9}Be$ @ 6.6 MeV/u

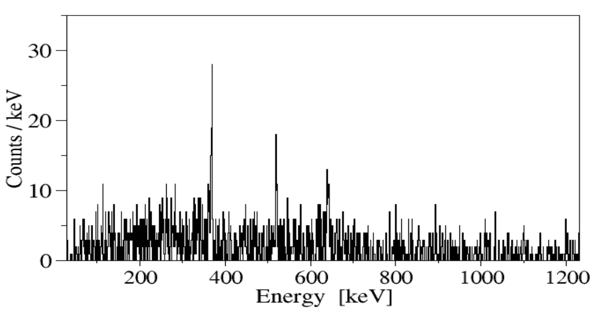
the fission nuclide chart

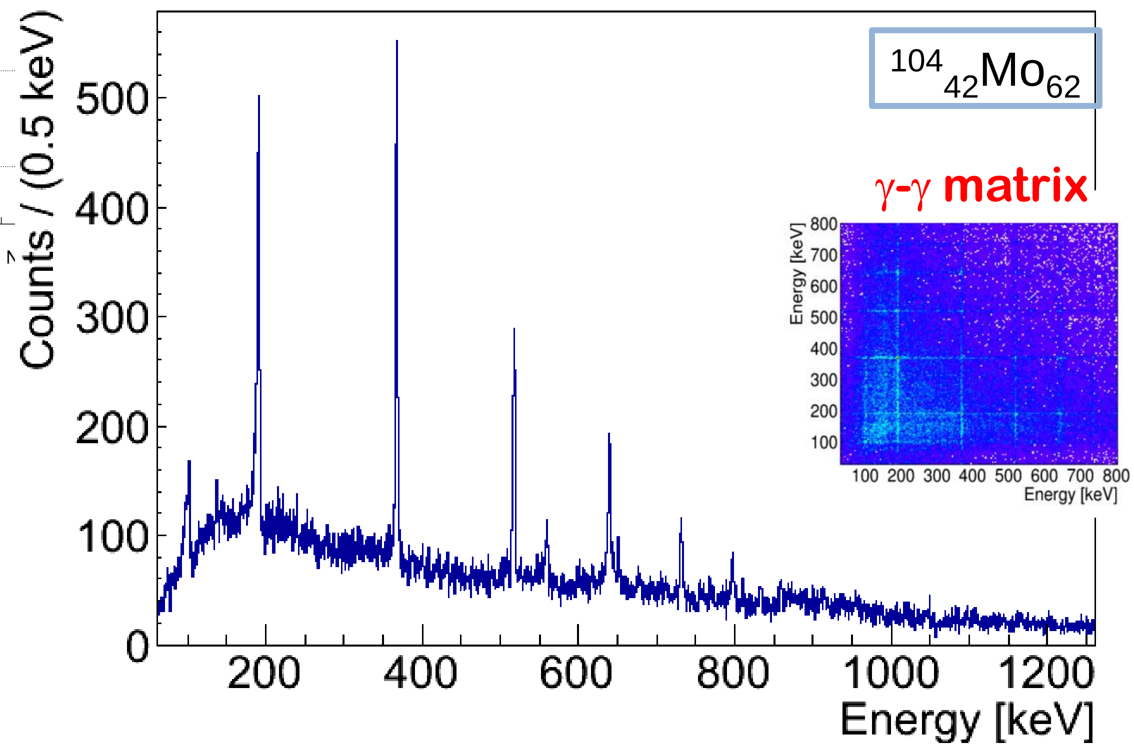
AGATA+VAMOS commissioning run, December 2014



N/Z = 1.48

gate on 2⁺ → 0⁺

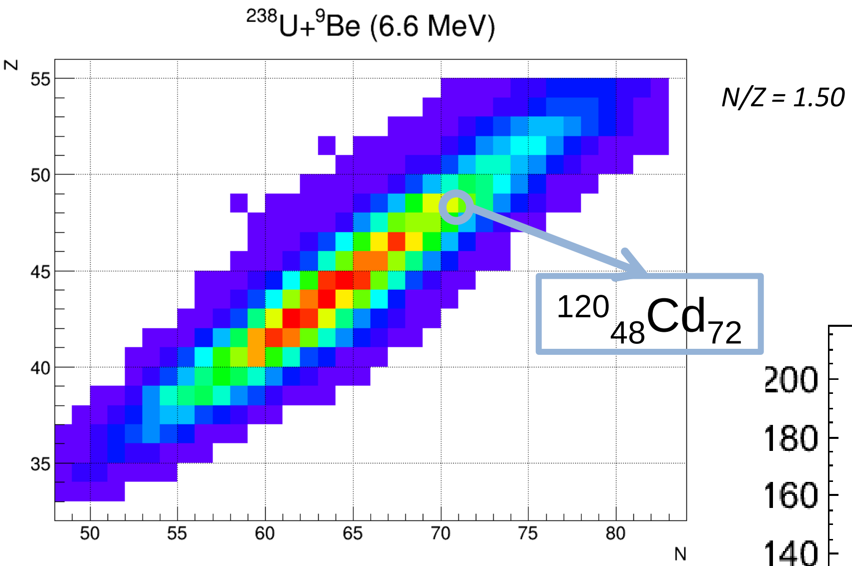


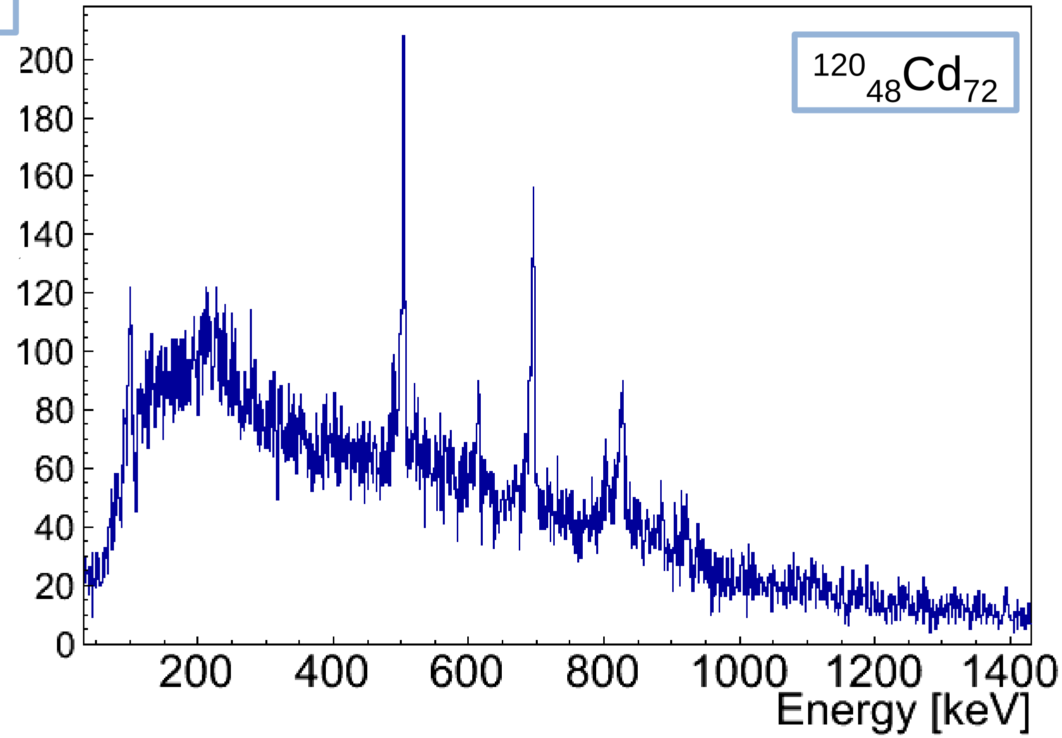


γ rays from isotopically id. fission fragments $^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014

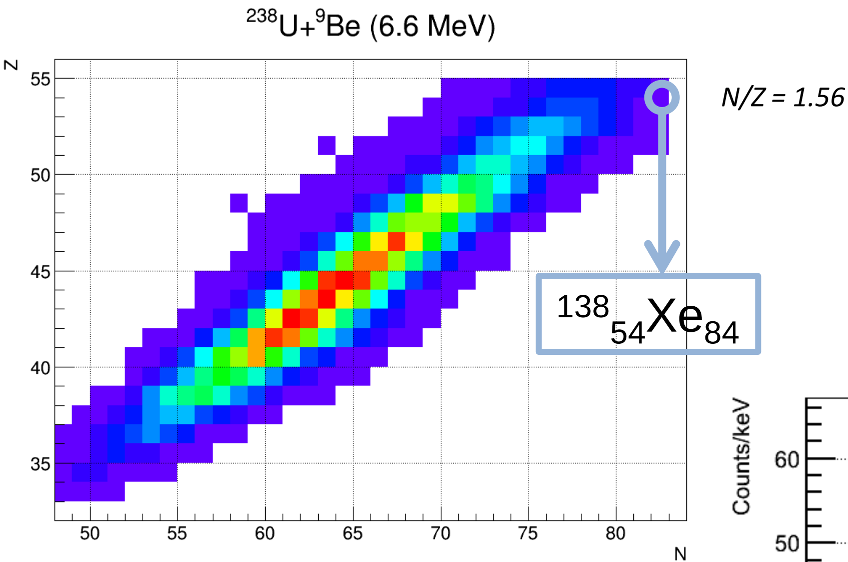


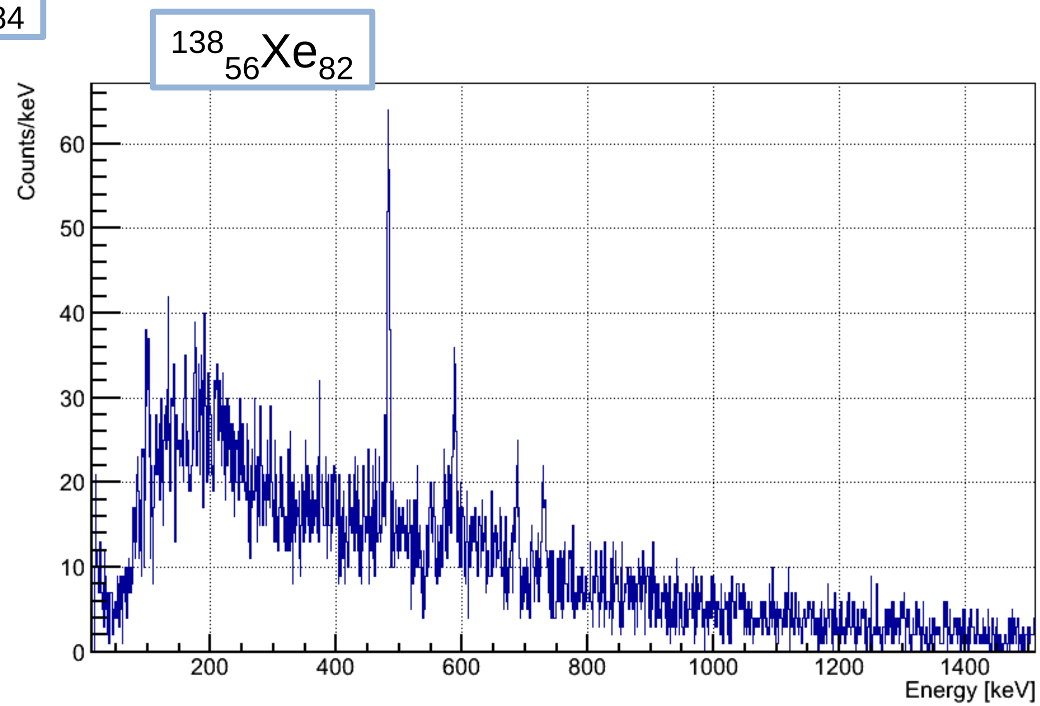


γ rays from isotopically id. fission fragments
$^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014

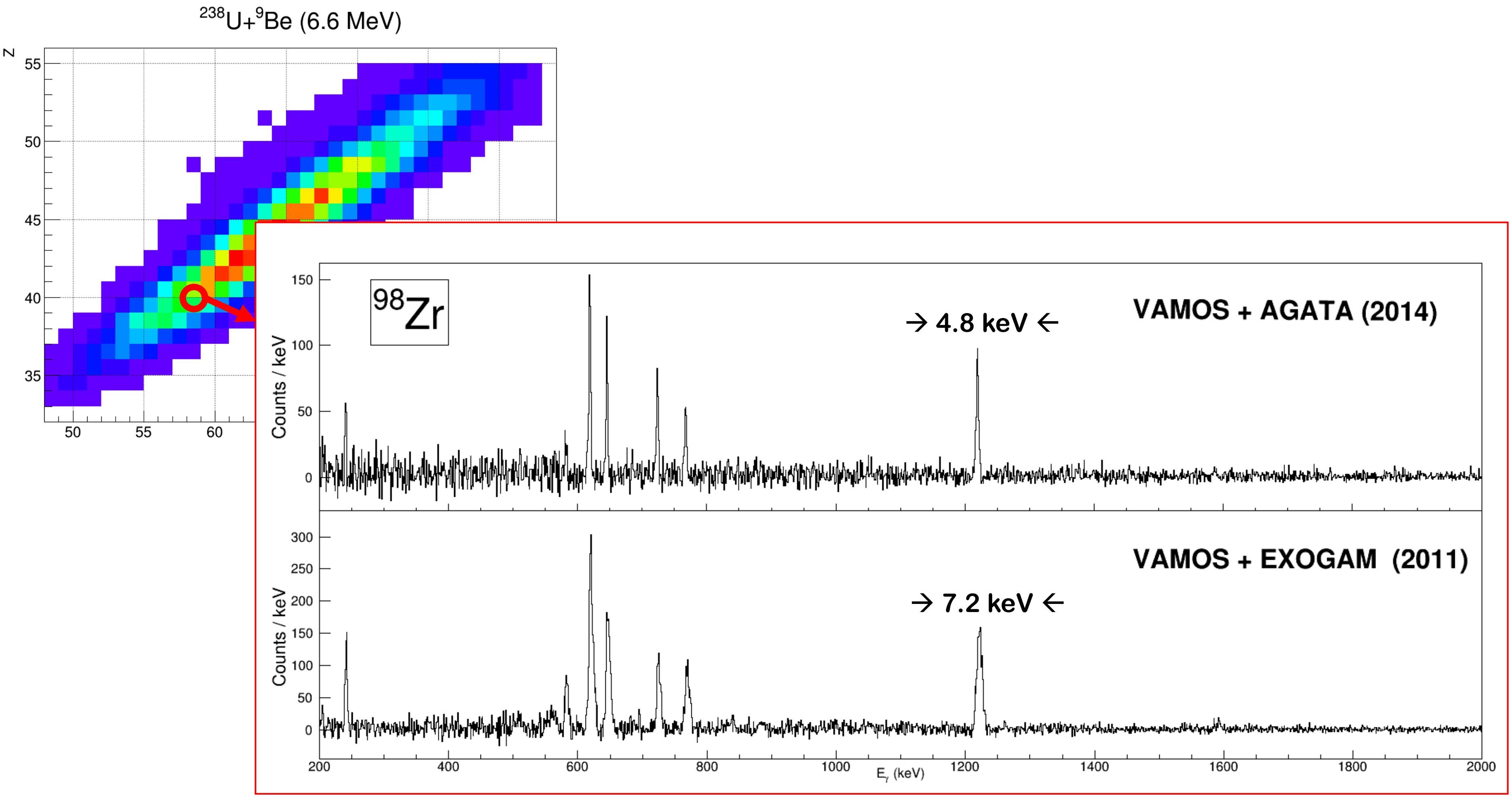




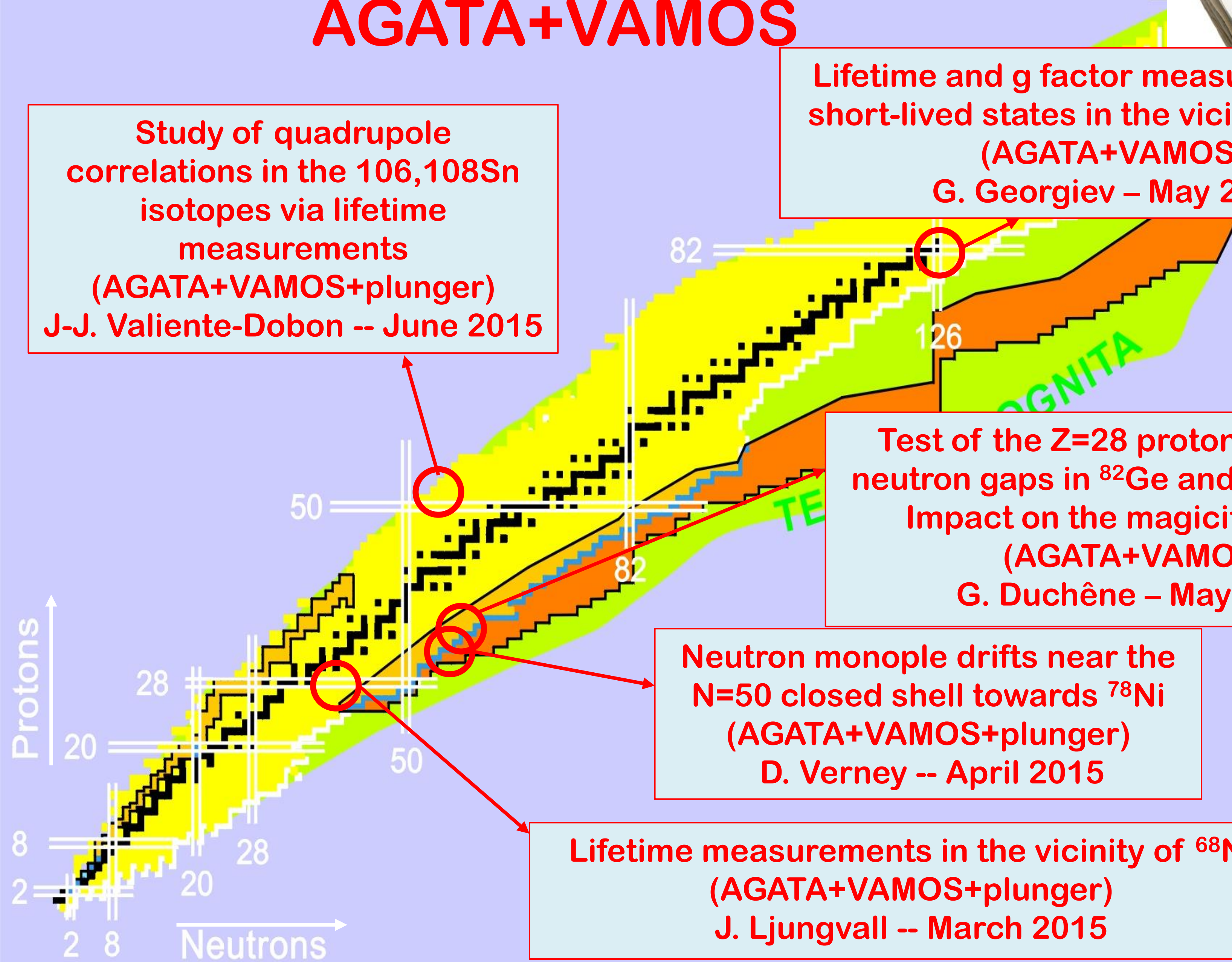
γ rays from isotopically id. fission fragments $^{238}U+^{9}Be$ @ 6.6 MeV/u

the fission nuclide chart

AGATA+VAMOS commissioning run, December 2014



Experimental campaign at GANIL AGATA+VAMOS



Lifetime and g factor measurements of short-lived states in the vicinity of ^{208}Pb
(AGATA+VAMOS)
G. Georgiev – May 2015

Study of quadrupole correlations in the 106,108Sn isotopes via lifetime measurements
(AGATA+VAMOS+plunger)
J-J. Valiente-Dobon -- June 2015

Test of the Z=28 proton and N=50 neutron gaps in ^{82}Ge and ^{80}Zn nuclei. Impact on the magicity of ^{78}Ni
(AGATA+VAMOS)
G. Duchêne – May 2015

Neutron monople drifts near the N=50 closed shell towards ^{78}Ni
(AGATA+VAMOS+plunger)
D. Verney -- April 2015

Lifetime measurements in the vicinity of ^{68}Ni
(AGATA+VAMOS+plunger)
J. Ljungvall -- March 2015