Selected Gamma spectroscopy experiments with future high intensity stable ions beams: opportunities and challenges

S. Leoni
University of Milano and INFN sez. Milano

on behalf of the AGATA collaboration

ECOS 2012, Loveno di Menaggio, 18-21 June 2012

OUTLINE:

❑SELECTED EXAMPLES OF GAMMA SPECTROSCOPY IN 0 – 20 MEV RANGE:

*FOCUS on Spectroscopy at **High-Energy** γ (GDR studies…)*

1. **Radiative Fusion from symmetric reactions:** *Vanishing of Shell Effects with T*
2. **GDR decay from selected (I,E*) regions**
3. **Isospin Mixing at Finite Temperature**
4. **Superdeformed shapes:** *Population mechanism*
5. **Particle-Phonon coupled states**

Large profit from HIGH Intensity Beams

Status with I_{beam} = 1-10 pnA

❑TECHNICAL CHALLENGES at HIGH Rates:

Complex experimental setups (Ge Arrays + Large Volume Scintillators + Ancillaries):

1. **Performances (energy resolution, gain stability, …)**
2. **Radiation Hardness**
3. **Coupling to Ancillaries (Electronics, Acquisition, …)**
4. **Shielding**

EXAMPLE 1 - Radiative Fusion from symmetric reactions:

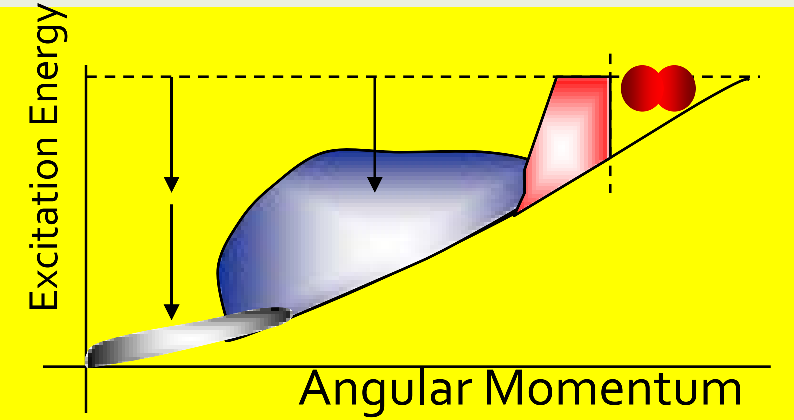
Vanishing of SHELL Effects with Temperature

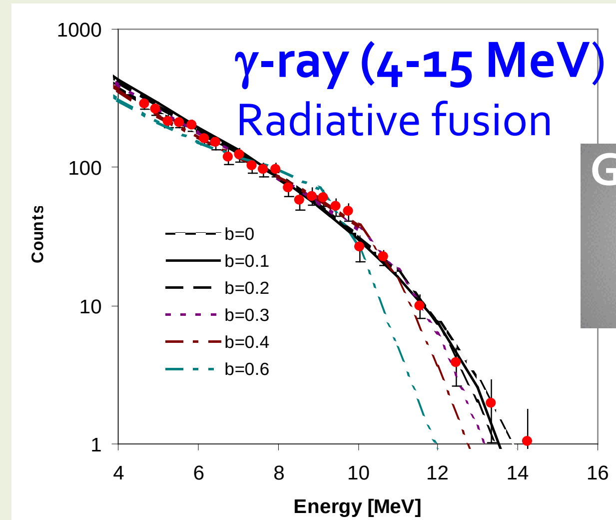
Cold Reaction $^{90}Zr + ^{90}Zr\ (^{89}Y) \rightarrow ^{179}Au$:

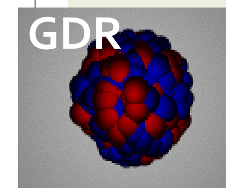
T = 0.7 MeV, E* = 26 MeV

Radiative Fusion: Only γ emission

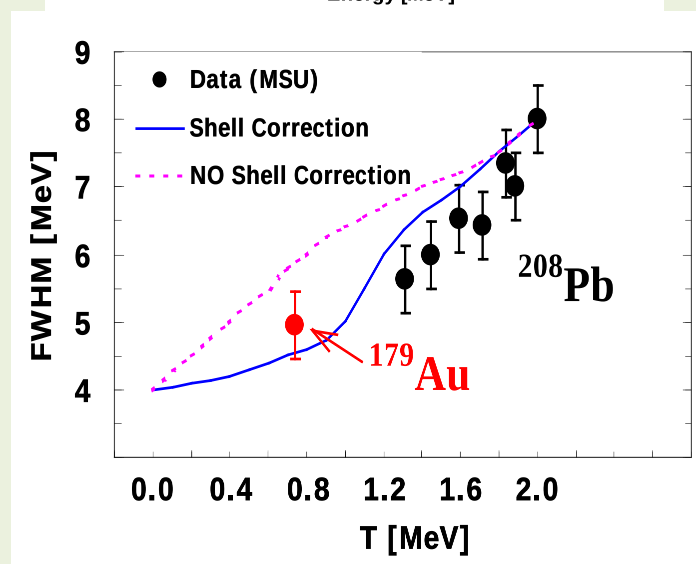
$\sigma \approx$ 1 mb







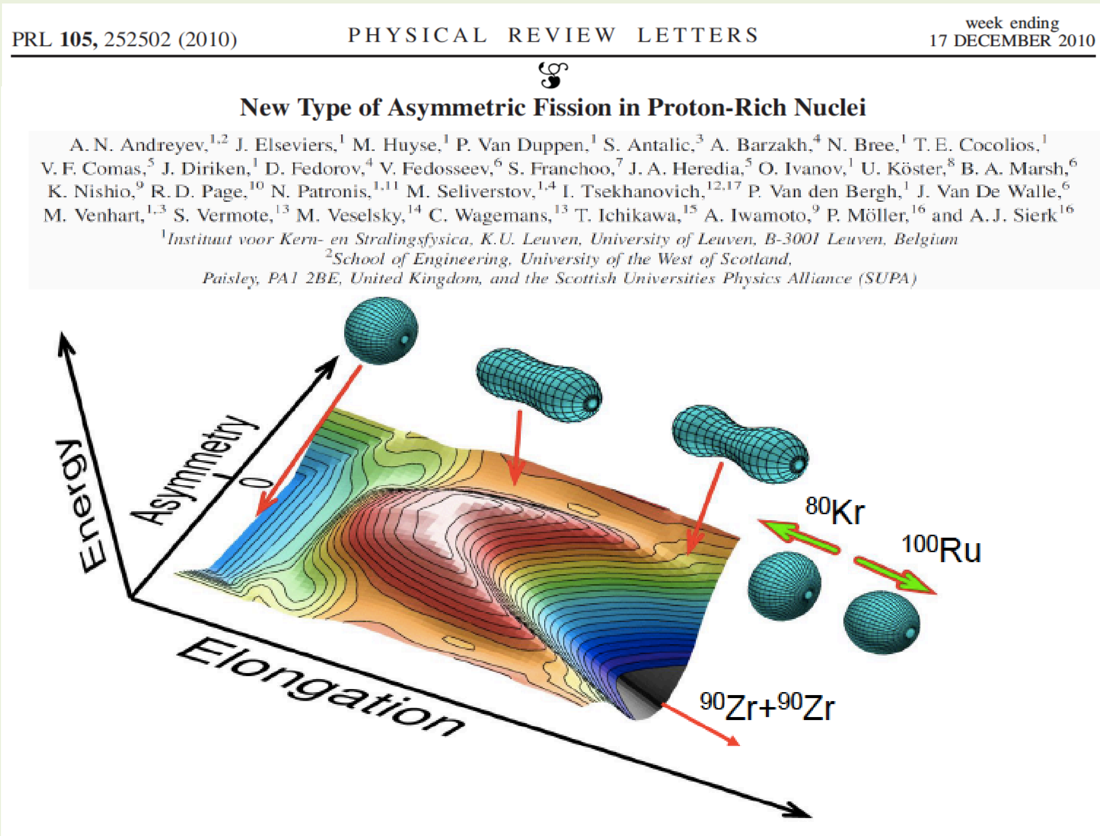
- High spin
- Competition with fission
- Phase space for warm GDR γ-decay
- Strong sensitivity to deformation
- **Strong SHELL EFFECTS**



F. Camera , A Bracco, V. Nanal et al., PLB560(2003) 155-160

Fission properties of PROTON-rich Nuclei at $E^* \approx B_f$

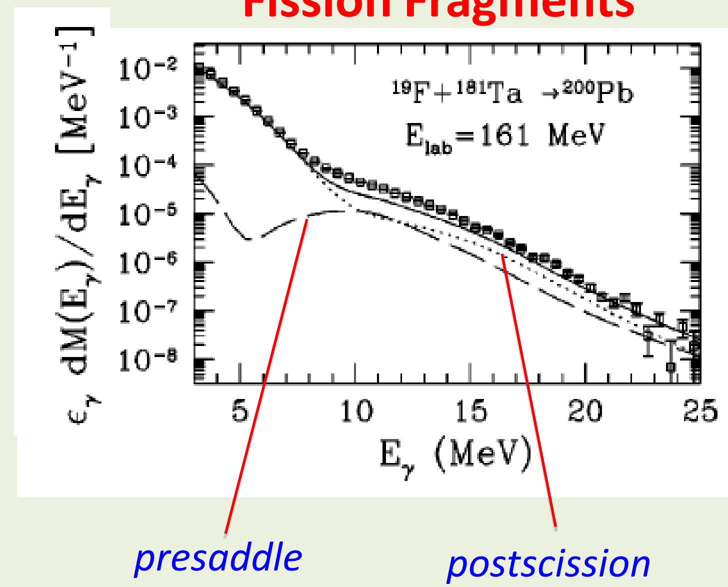
Observation of Asymmetric Fission in ^{180}Hg (β-delayed)


PRL 105, 252502 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

New Type of Asymmetric Fission in Proton-Rich Nuclei

A. N. Andreyev,[1,2] J. Elseviers,[1] M. Huyse,[1] P. Van Duppen,[1] S. Antalic,[3] A. Barzakh,[4] N. Bree,[1] T. E. Cocolios,[1] V. F. Comas,[5] J. Diriken,[1] D. Fedorov,[4] V. Fedosseev,[6] S. Franchoo,[7] J. A. Heredia,[5] O. Ivanov,[1] U. Köster,[8] B. A. Marsh,[6] K. Nishio,[9] R. D. Page,[10] N. Patronis,[1,11] M. Seliverstov,[1,4] I. Tsekhanovich,[12,17] P. Van den Bergh,[1] J. Van De Walle,[6] M. Venhart,[1,3] S. Vermote,[13] M. Veselsky,[14] C. Wagemans,[13] T. Ichikawa,[15] A. Iwamoto,[9] P. Möller,[16] and A. J. Sierk[16]
[1]Instituut voor Kern- en Stralingsfysica, K.U. Leuven, B-3001 Leuven, Belgium
[2]School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)

High energy γ- spectra of Fission Fragments



- **Strong sensitivity to deformation**
- **Nuclear Viscosity**

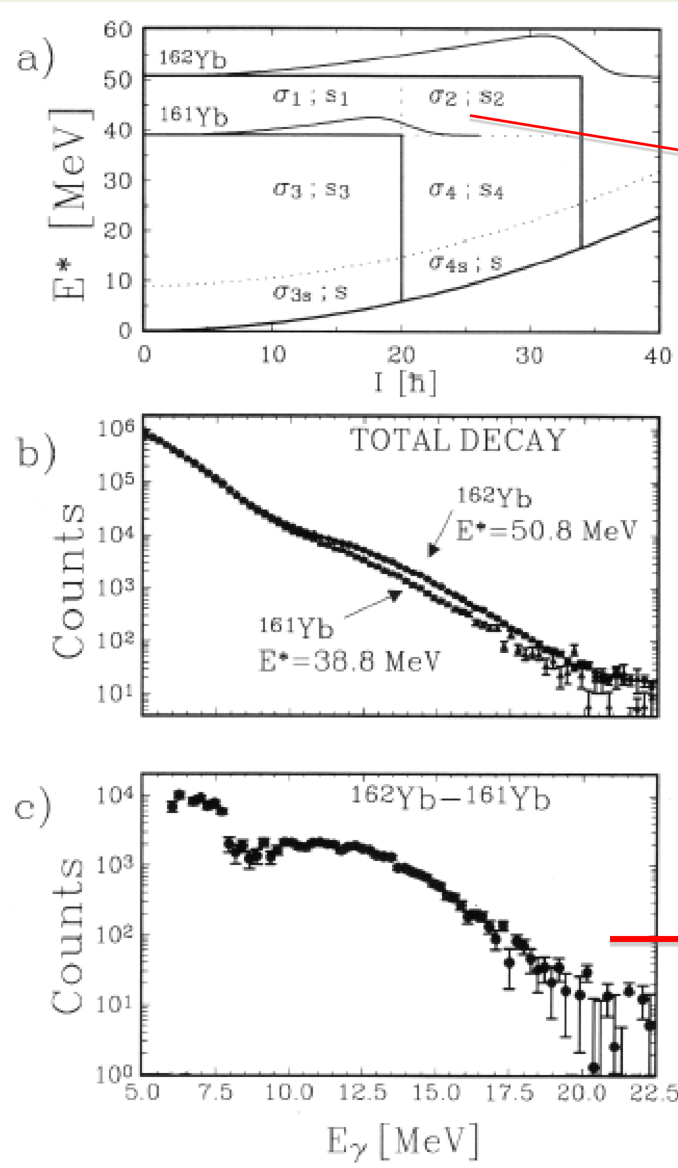
Dioszegi, A Bracco, F. Camera et al., PRC63(2000) 014611

Absence of proton/neutron shell effects
In FISSION of proton-rich Nuclei

In **contrast to the fission of neutron rich nuclei** for which shell effects play an important role (see ^{132}Sn for the fission of U)

EXAMPLE 2 - GDR decay from specific Excitation regions

Exclusive Studies of GDR from ***first step decay***



A. Maj et al NPA 571(1994)185

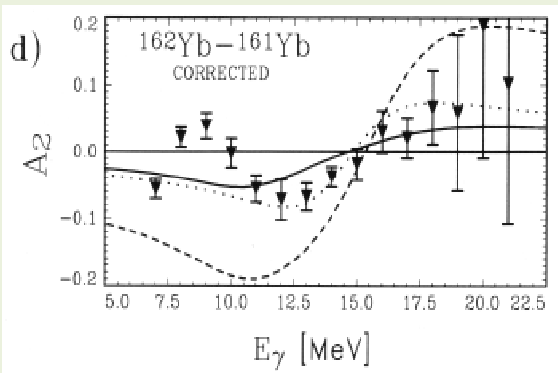
Two Reactions:

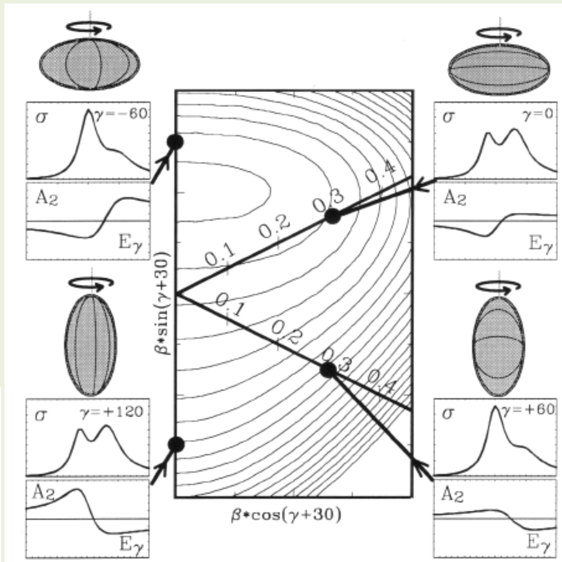
Phase space difference corresponding to **1 neutron evaporation**

→ Clean selection of (E*,I): **No averaging over T**

Angular Distribution of Difference Spectrum:

A clean probe of nuclear shape



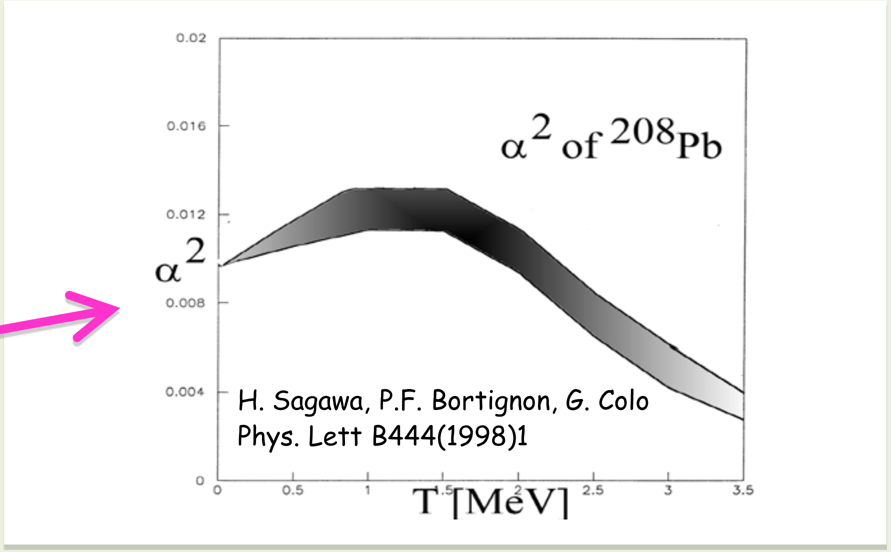


Stringent test for Jacobi and Poincarè transitions?

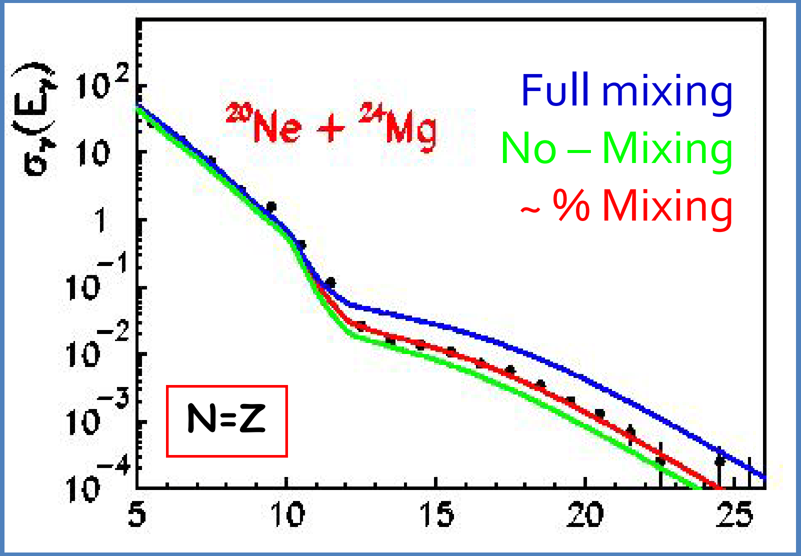
EXAMPLE 3 - Isospin Mixing at T≠0

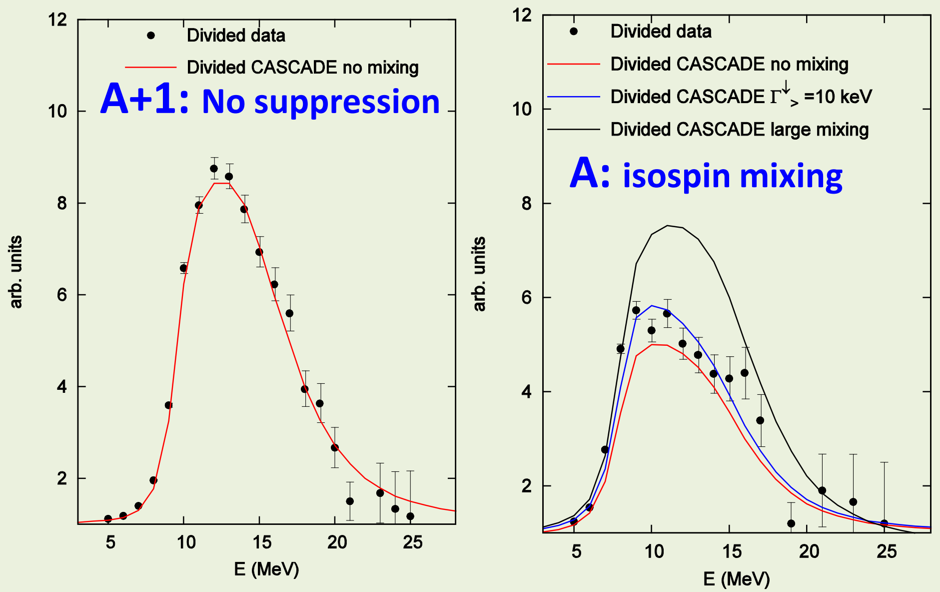
Restoration of isospin symmetry at high T

- **Isospin is a good quantum number:**
  Nuclear Hamiltonian is symmetric for p and n exchange
- **Coulomb interaction breaks isospin:**
  at T=0: isospin mixing is small **(< 5%)**
  at high T: expected restoration of isospin symmetry due to finite lifetime of CN



GDR Supression depends on degree of mixing





^{80}**Zr**: A. Corsi et al., PRC84, 041304(R) (2011)

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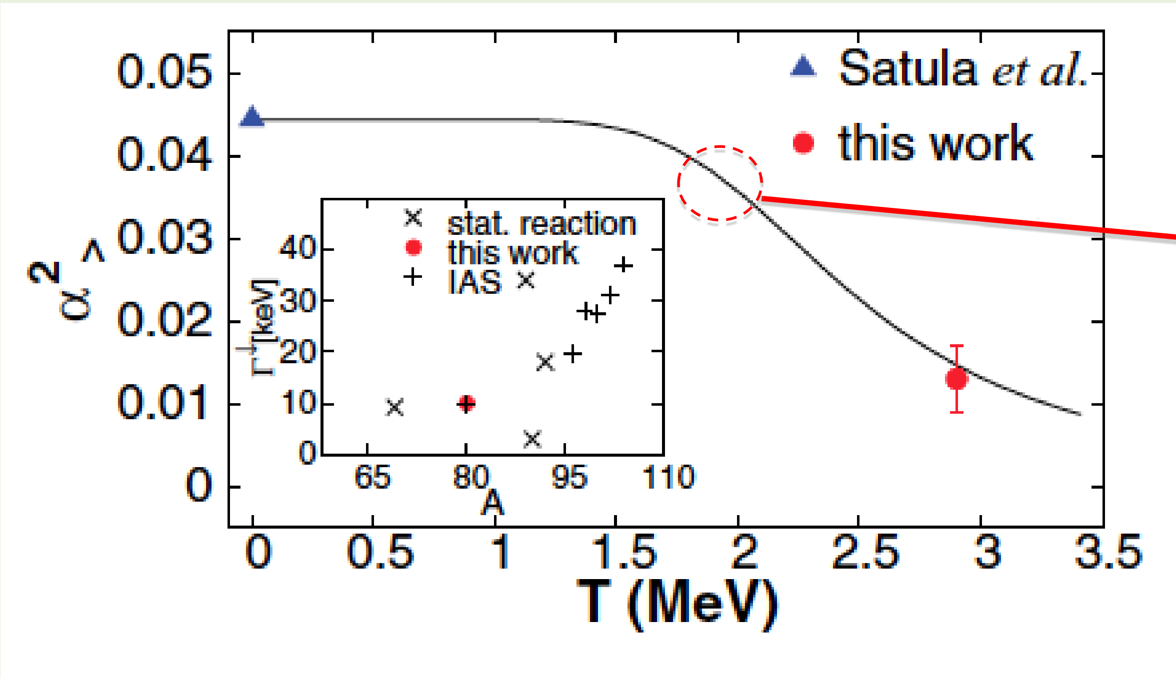


AGATA +

Large size $LaBr_3$

F. Camera et al., …

Under Analysis

More points, more cases, …

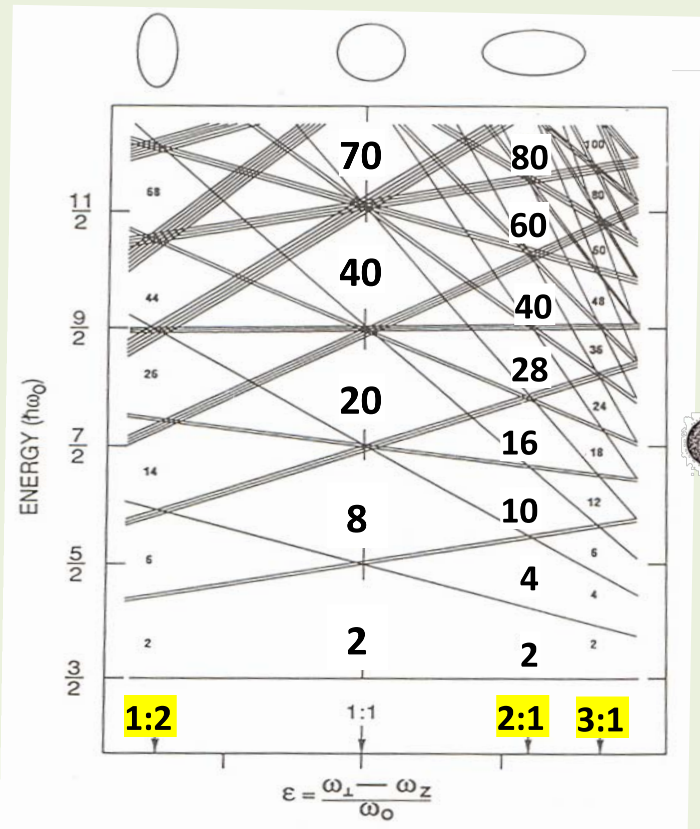
→**Comparison between two High-energy spectra**

→ **% effect**

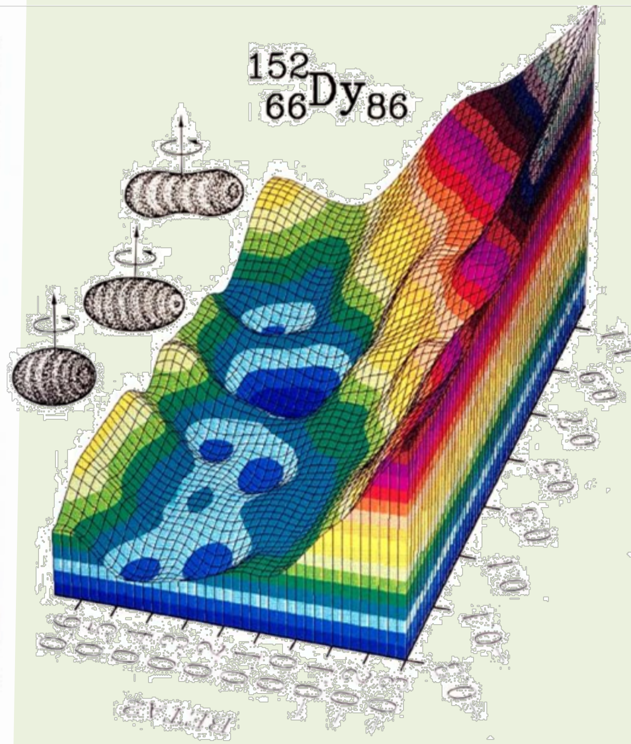
EXAMPLE 4 - Superdeformed/Hyperdeformed shapes

Stringent test of Shell structure and *Strong effective force*

harmonic oscillator



New magic numbers:
- SuperDef nuclei (2:1)
- HyperDef nuclei (3:1)



Appearance of **favorite deformed** minima at **high spins**

EUROBALL GAMMASPHERE

≈ 200 SuperDef bands

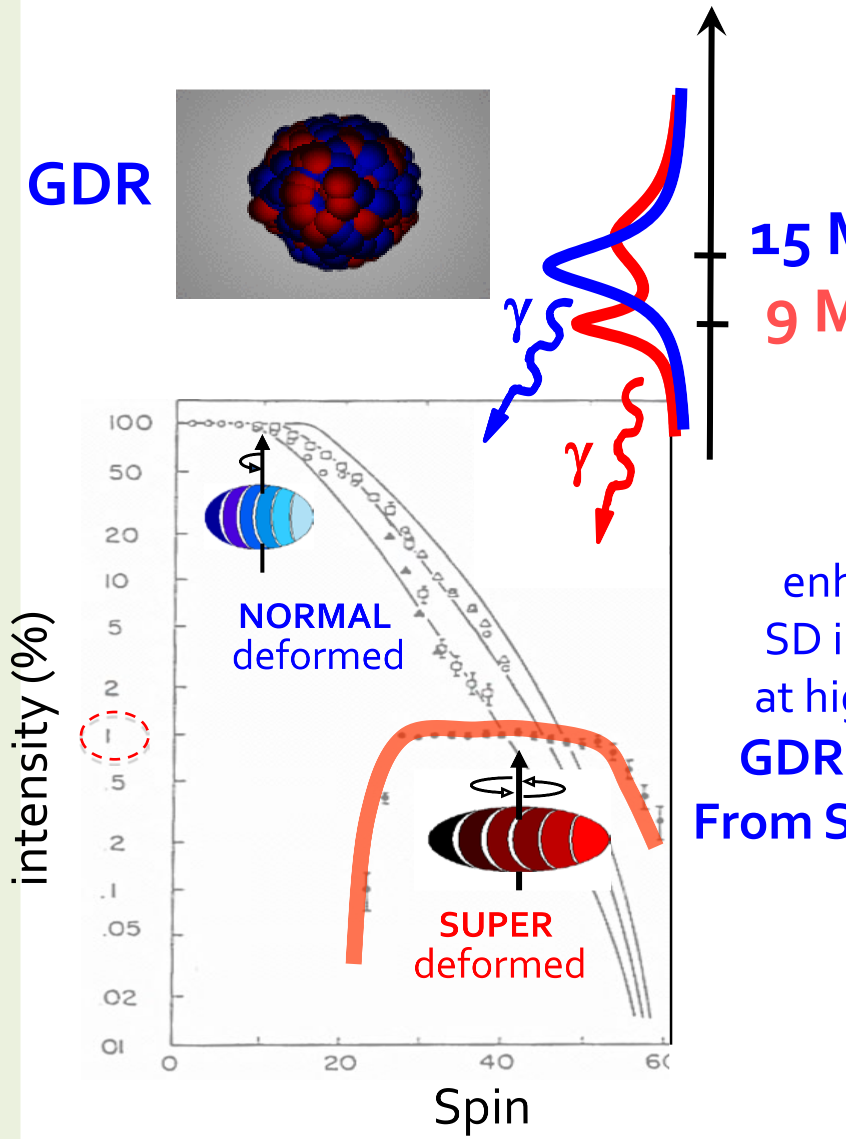
A = 80, 130, 150, 190

Open questions

- ❑ No evidence for HyperDef
- ❑ Decay Mechanism
- ❑ **Population Mechanism**

Population of super deformed bands

Feeding from Giant Dipole Resonance

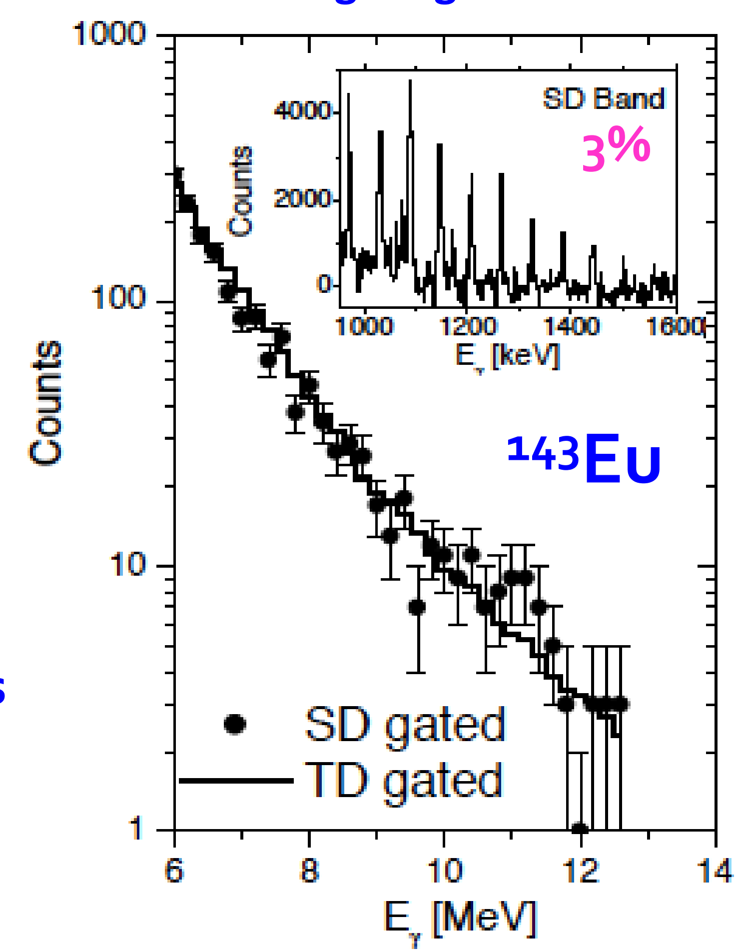


enhanced
SD intensity
at high spins:
GDR feeding
From SD nucleus

EUROBALL+ 8 Large BaF2

$^{37}Cl+^{110}Pd \rightarrow {}^{143}Eu+4n$

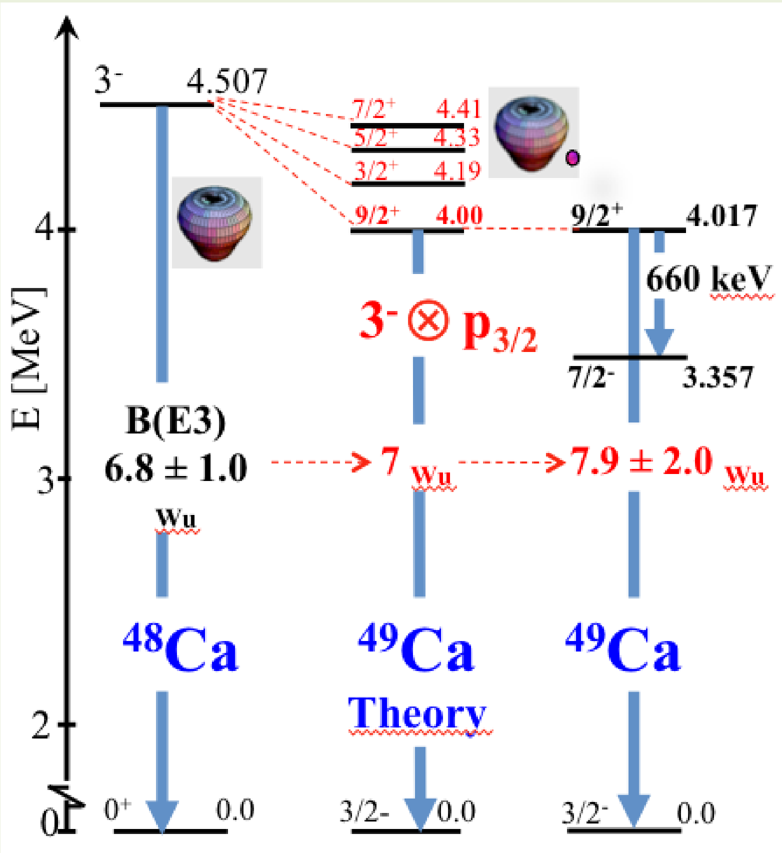
Direct gating on SD band



F.Camera et al., EPJ A2 1-2(1998)

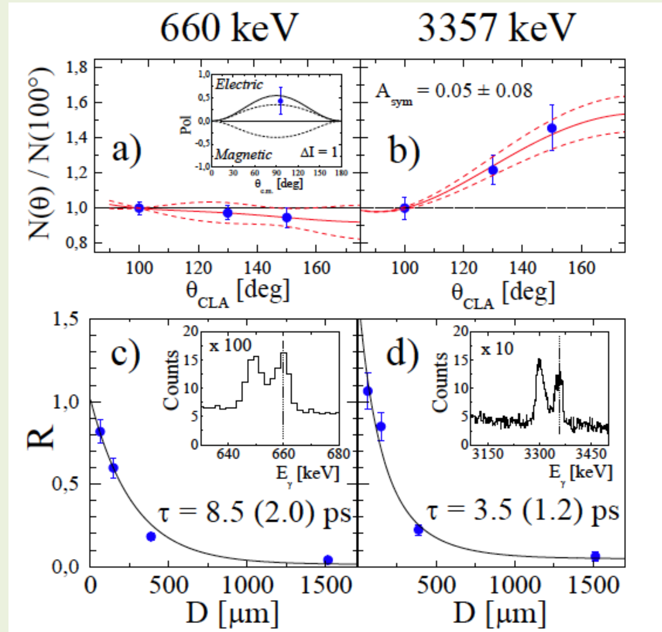
EXAMPLE 5 – Search for Particle-Phonon coupled states

- *key process for anharmonicities of vibrational spectra*
- *Damping of collective excitations (**Giant Resonances** …)*



Heavy-Ion ***multi-nucleon transfer*** Reaction
^{48}Ca+^{64}Ni @ 6MeV/A

PRISMA-CLARA



Angular distributions
Polarizations
Lifetimes

to firmly establish
I^π and $B(E/M\lambda)$

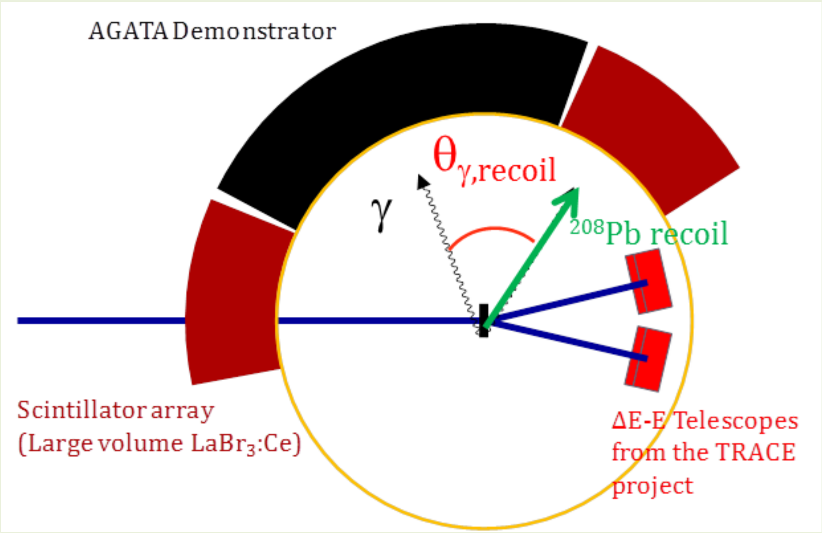
at HIGH Rates:
- More Exotic systems
- High precision measurements of ***W(θ)*** and ***Pol*** with AGATA

D. Montanari, S. Leoni et al., PLB697(2011)288

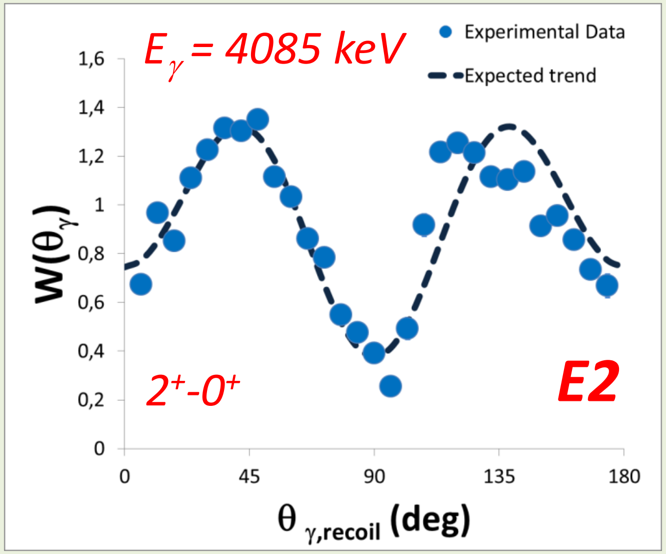
AGATA experiment at LNL:

inelastic scattering of light ion beams + γ-decay

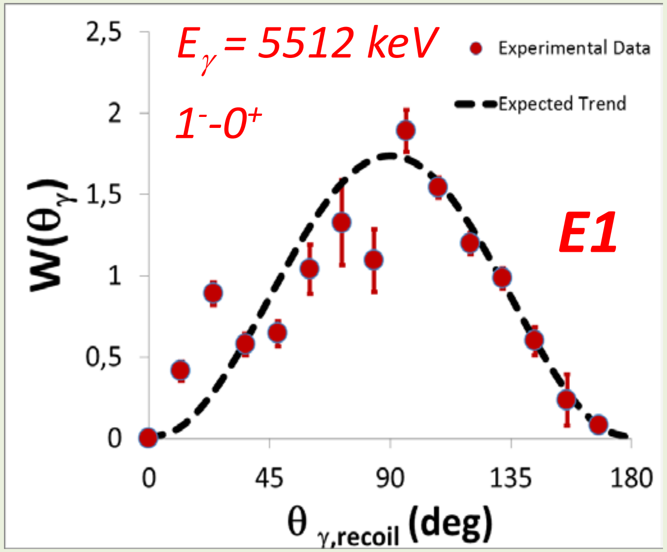
^{17}O @ 20 MeV/A on ^{208}Pb, ^{90}Zr, ^{140}Ce, ^{124}Sn



^{208}Pb



Angular Distribution of γ's obtained exploiting ***position sensitivity*** of **AGATA** and **E-ΔE Si** telescopes (pixel type)



PRELIMINARY

F. Crespi, A. Bracco, et al.
(Milano University)

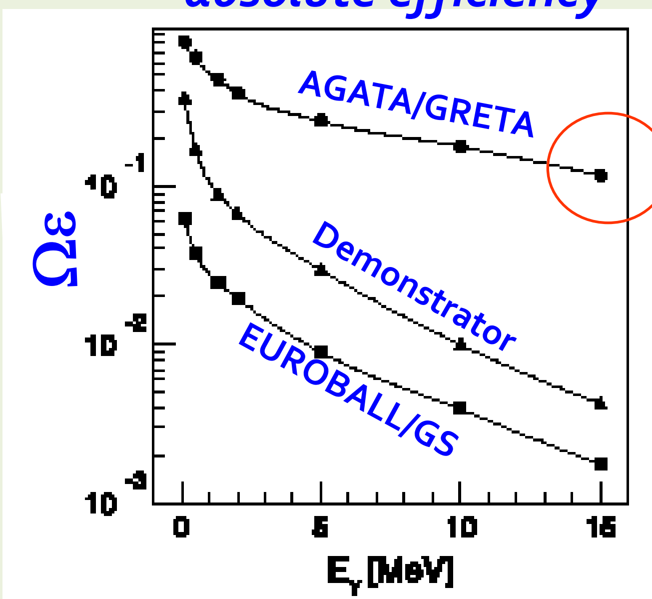
What is the BEST Experimental Setup ?

Ge Arrays for High Energy Detection ?

PLUS

large photopeak efficiency
for high-energy γ-rays

absolute efficiency

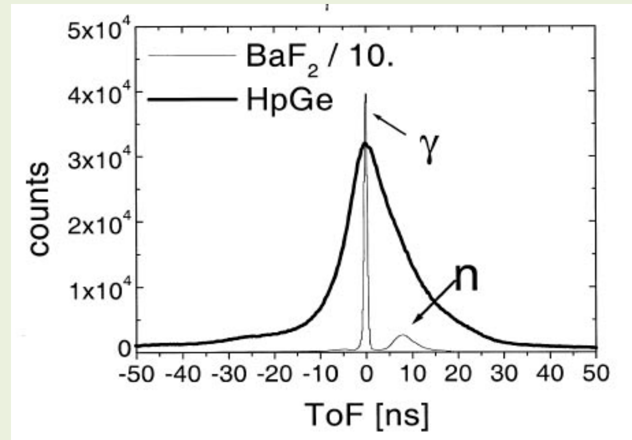


- Efficiency comparable wih scintillators arrays
- Optimum Energy Resolution

MINUS

NO γ-n discrimination

- TOF measurement: not very good



- Pulse Shape Analysis: not very good

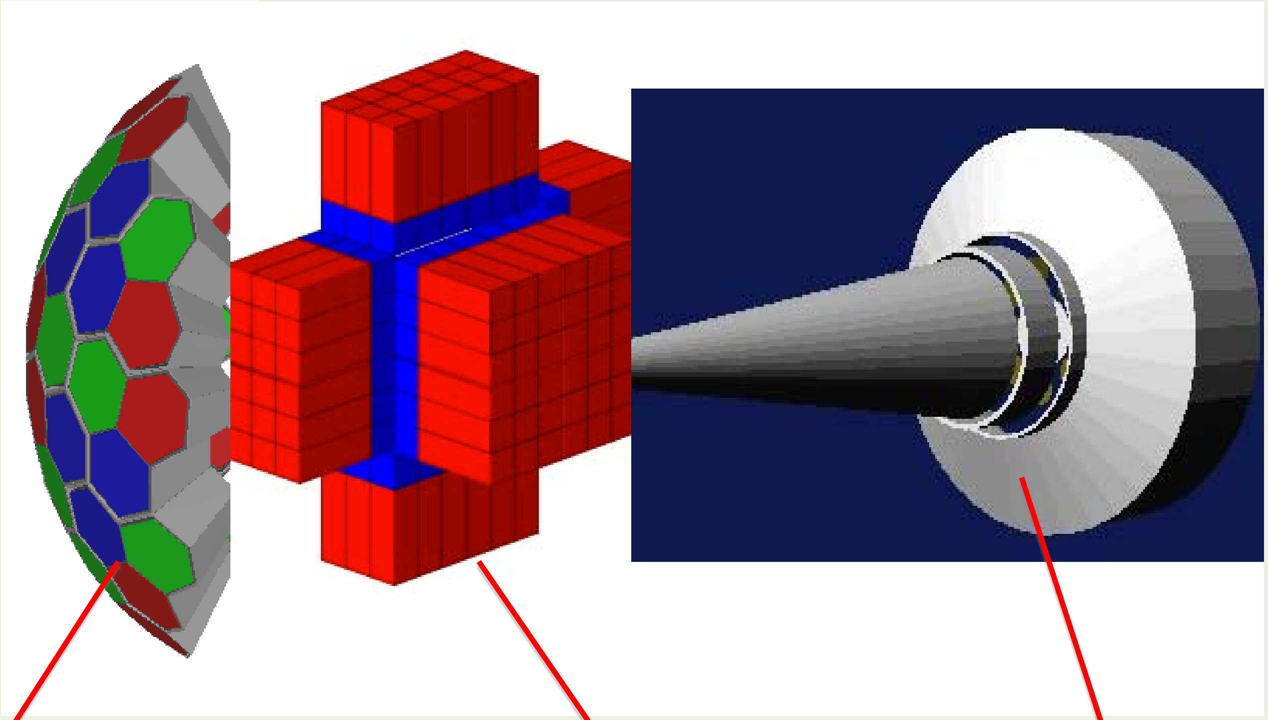
γ and n interactions in Ge produce electric signals with similar shapes

- tracking ? under study

γ and n produce different cluster of events
→ Loss of efficiency
P/T increased by 1.6, ε = 60%

A. Atac et al., NIMA607(2009)554

Complex Detection Systems are needed



AGATA/EXOGAM/GALILEO + PARIS/LaBr3 + Recoil Filter/
Spectrometers/
NeutronWall/Si-Arrays

Experimental challenge … at HIGH Rates …

→ **up to 100 (?) times more current…**

❑ **TECHNICAL CHALLENGES at HIGH Rates for both Ge and Scintillators Arrays:**

1. **Performances:**
   energy resolution, linearity, …

2. **Radiation Hardness:**
   Ge: neutron damage, annealing …
   $LaBr_3$: tests at MHz count rates, …

3. **Ancillary (coupling at high rates):**
   New generation arrays: PARIS, NEDA, GASPARD, …
   Existing Detectors: $LABr_3$, PRISMA, RFD, TRACE, …

4. **Shielding:**
   careful control of background sources

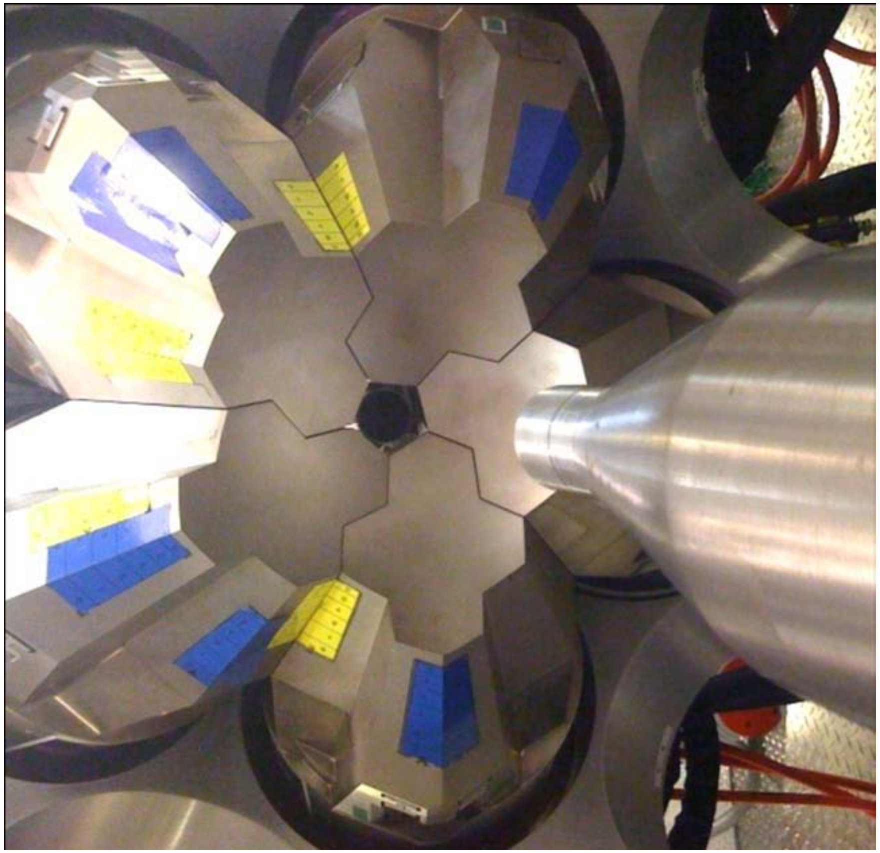
Ge ARRAYS

TRACKING ARRAYS (AGATA/GRETA): *STATE of the ART detectors*

AGATA Demonstrator

15 crystals in 5 Triple Clusters
Commissioned in 2009 at LNL (with 3 TC)
Experiments at LNL in 2010-2011
LNL/GSI campaigns

GRETINA

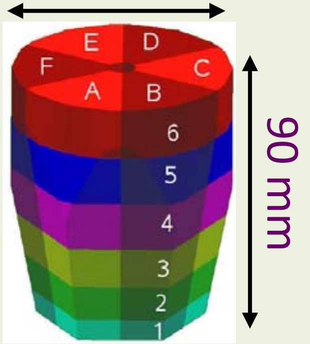


28 crystals in 7 Quadruple Clusters
Engineering runs started early 2011 at LBNL
Experiments at LBNL in 2011
Berkley/MSU campaigns

Ge ARRAYS

TRACKING ARRAYS (AGATA/GRETA): *STATE of the ART detectors*

80 mm



6x6 segmented cathode

1. **Detection efficiency divided between a small number of crystals**

   → *huge singles counting rates are possible*

2. **Digital signal processing**

   → *possiblity to operate the detectors at high (singles) counting rates*

   Specifications for Maximum event rates:

   3 MHz for $M_\gamma = 1$

   300 kHz for $M_\gamma = 30$

   much more in practice…

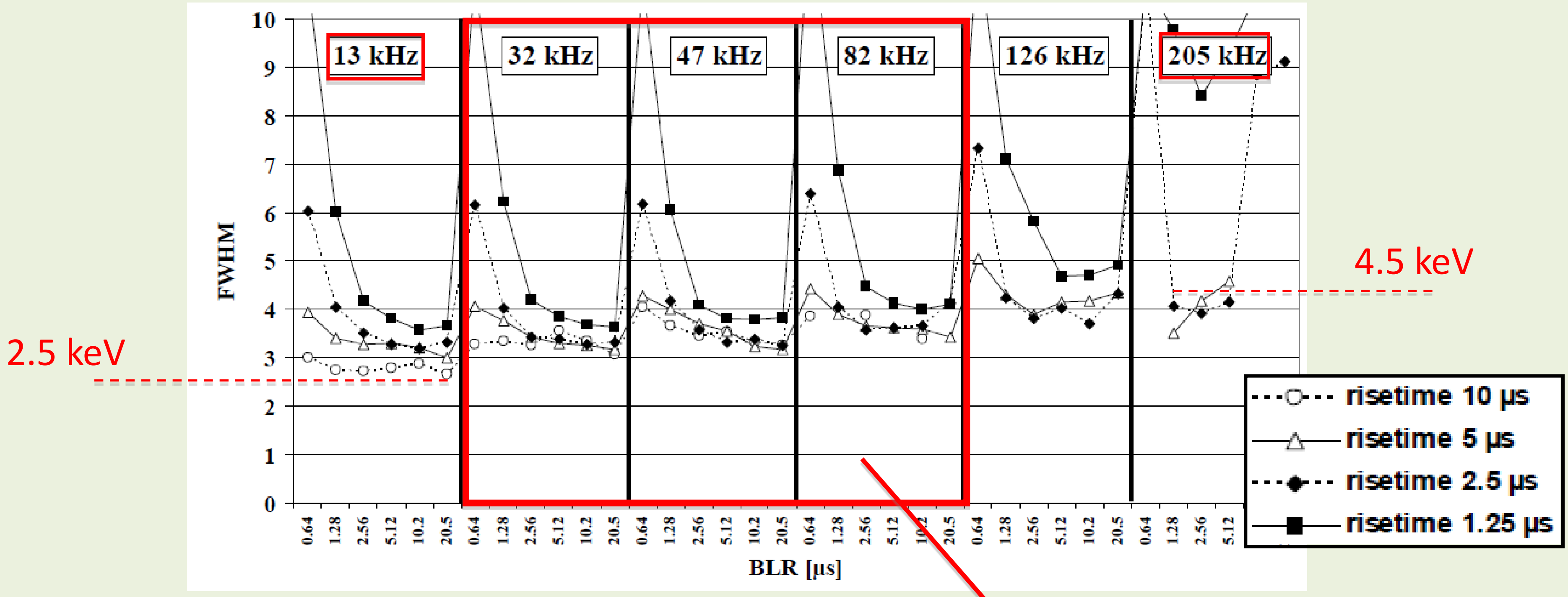
3. **No Significant technical improvement is expected**

→ *Need to learn how to operate these detectors, …*

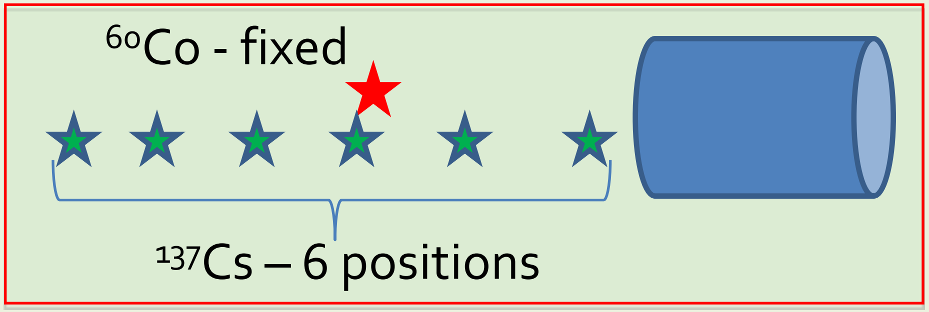
AGATA: Resolution vs Singles Rate

SCAN of possible values of the ***shaping time*** *and* ***baseline restorer*** *width:*

6 different rates x 4 trapezoid risetime x 6 blr length



Present working conditions



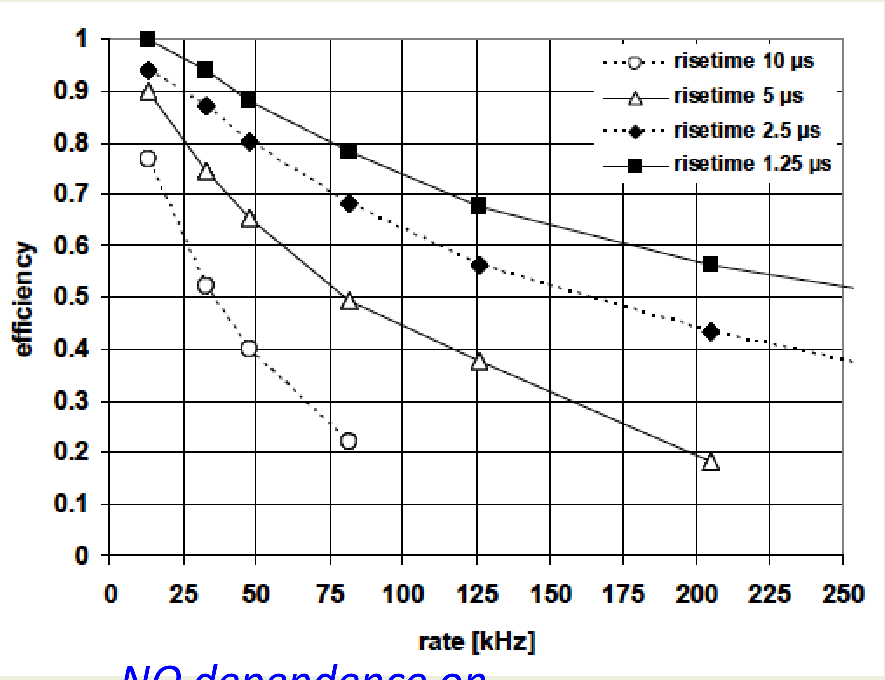
Two independent sources of dead-time:

- pile-up rejector
- GTS

F.Recchia et al., LNL Annual Report 2012

PRICE to PAY…

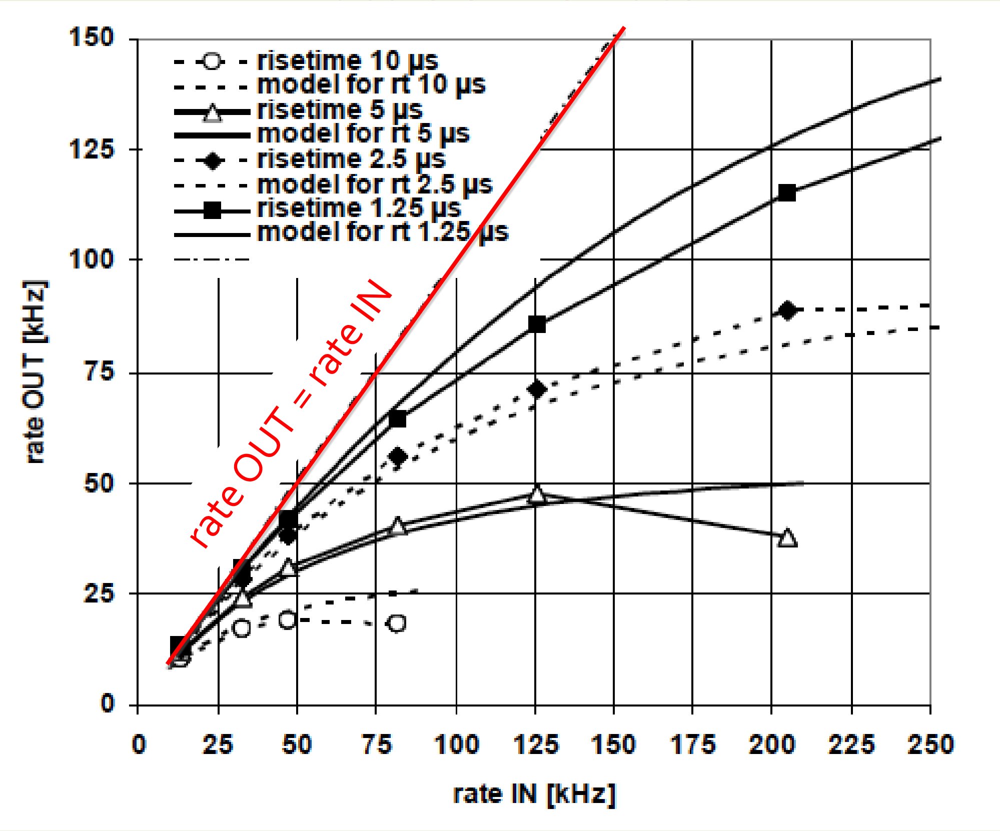
Reduction of Efficiency with Rates



NO dependence on length of the baseline restorer only on RiseTime

… GOOD understanding by simple paralyzable model

rate OUT vs. rate IN



Present Working Conditions

30÷80 kHz/crystal without affecting significantly the energy resolution

Real limitation: ***ACQ*** which can store original data ***(including traces)***

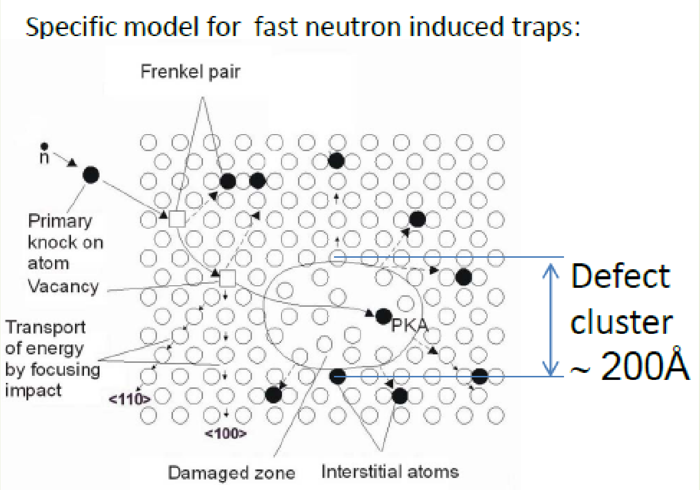
up to **1 kHz/crystal** *(≈ 60 Mb/s write out)* → ***ONLINE ANALYSIS … ?***

F.Recchia et al., LNL Annual Report 2012

AGATA: Neutron Damage

- **Flux of fast neutrons** from the reaction scales with the counting rate
  → ***10-15 times more*** *fast neutrons/s than in the past*

- **Result: accelerated neutron damage**

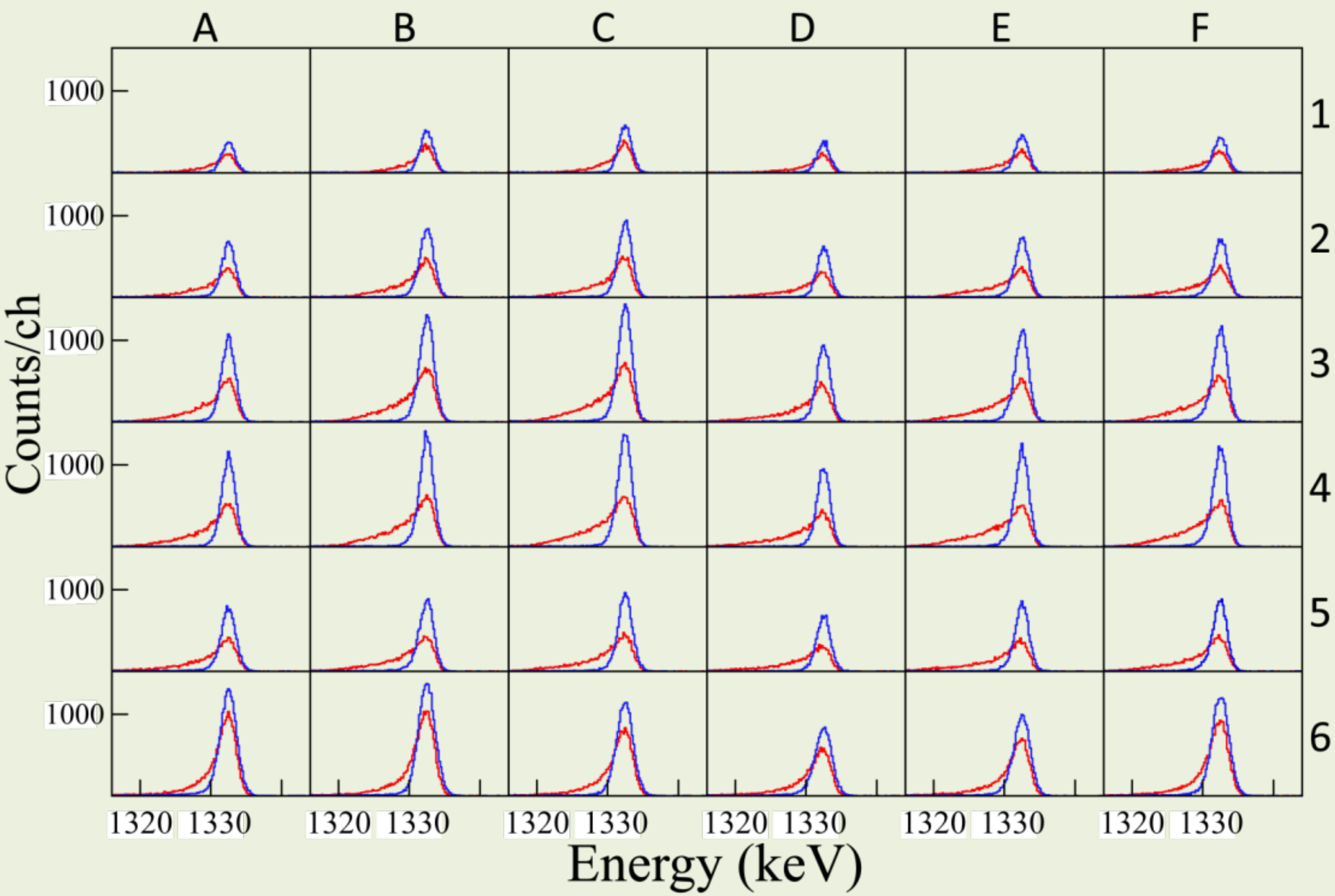


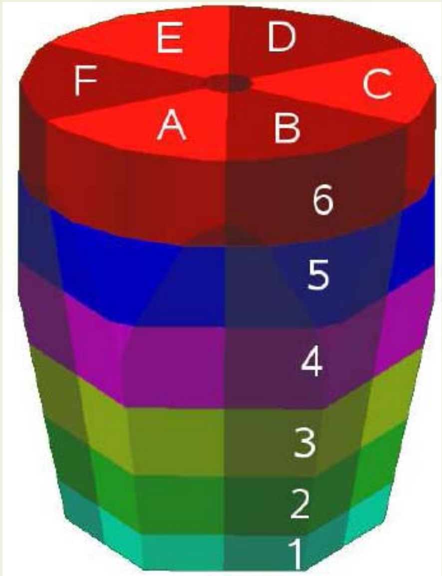
- **Effect:**
  increased hole trapping
  slight reduction of pulse amplitude
  → *no significant change in pulse shape*

  Energy resolution of Core is degraded only slightly
  Energy resolution of Segments is degraded significantly
  Pulse shape analysis is **almost insensitive** to neutron damage
  PSA provides the information to correct OFF-LINE for this effect

- **Real recovery of neutron damage**: *ANNEALING* the detectors
  → ***Risky operation*** *which can be delayed by the PSA-based corrections*

Neutron damage: shape of the 1332 keV line





Blue: April 2010 → FWHM(core) ~**2.3 keV** FWHM(segments) ~**2.0 keV**

Red: July 2010 → FWHM(core) ~**2.4 keV** FWHM(segments) ~**3 keV**

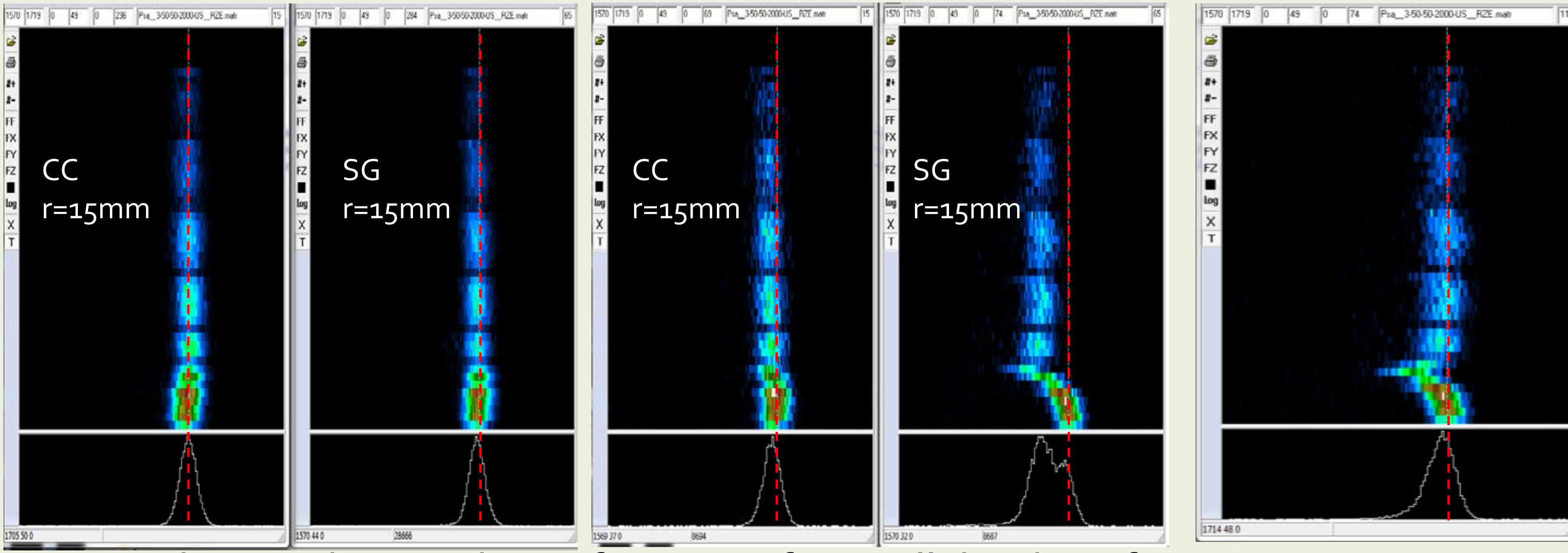
Damage after 3 high counting-rate experiments (**3 weeks of beam at 30-80 kHz singles**)

Worsening seen in most of the detectors; more severe on the forward crystals;

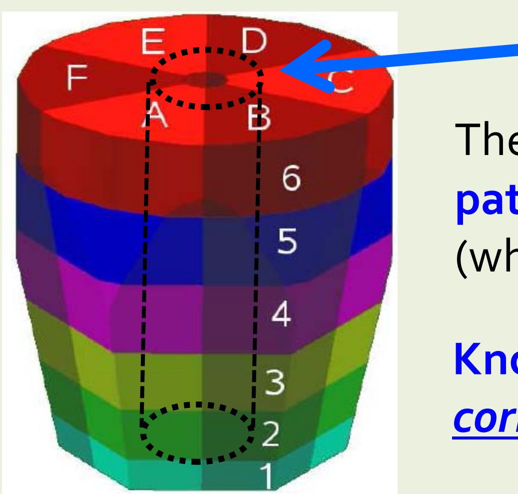
segments are the most affected, cores almost unchanged (as expected for n-type HPGe)

Crystal C002

April 2010 **July 2010** **→ corrected**



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



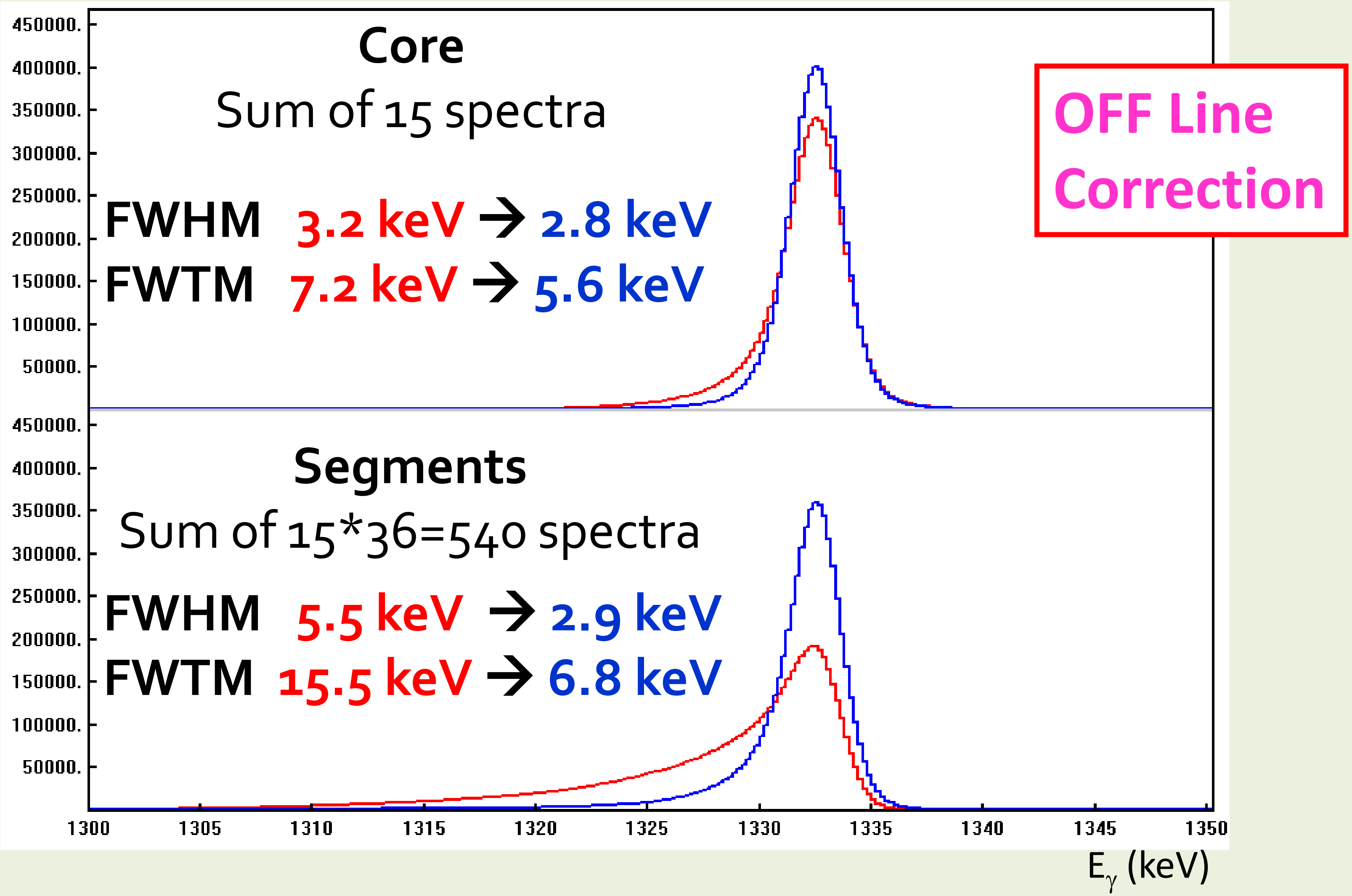
The **charge loss** due to neutron damage is **proportional to the path length** to the electrodes. The **position** is provided by the **PSA** (which is barely affected by the amplitude loss).

Knowing the path, the *charge trapping can be modeled and corrected away* (Bart Bruyneel, IKP Köln)

Energy resolution at the end of the LNL campaign

Before and ***After*** charge-trapping correction

cold detectors …

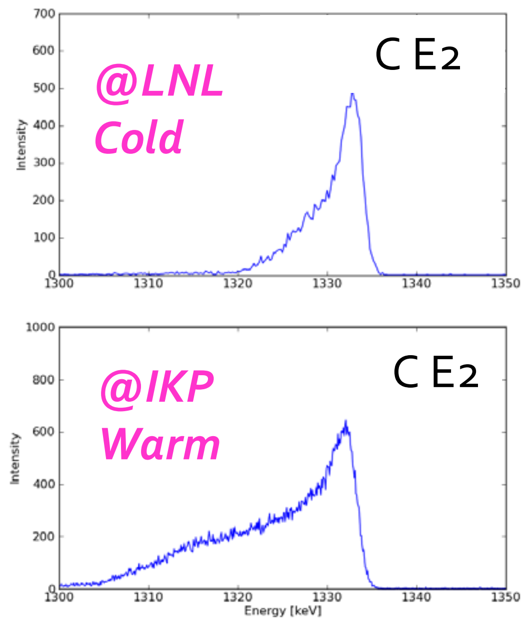


Undamaged detectors: FWHM ~2.5 keV, FWTM ~4.8 keV

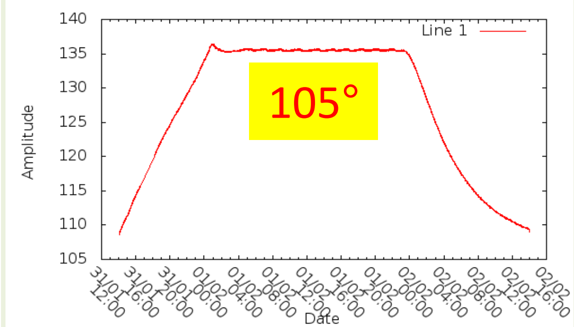
Real Recovery: Crystal Annealing

courtesy of P. Reiter (IKP)

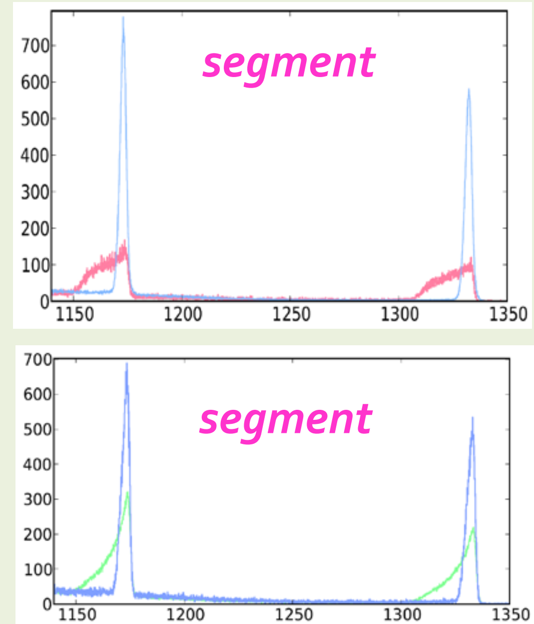
ATC 1 detector

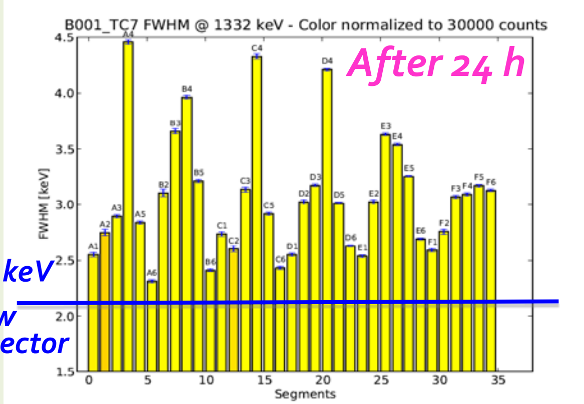


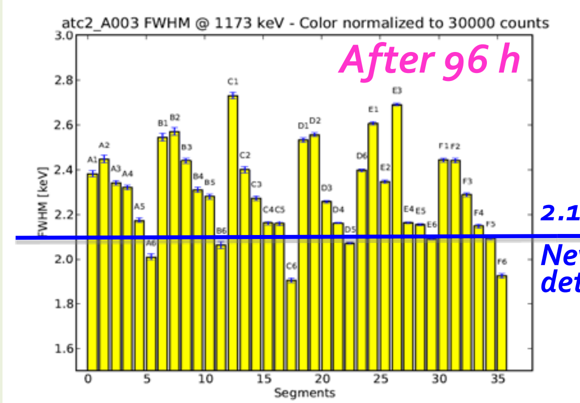
ANNEALING

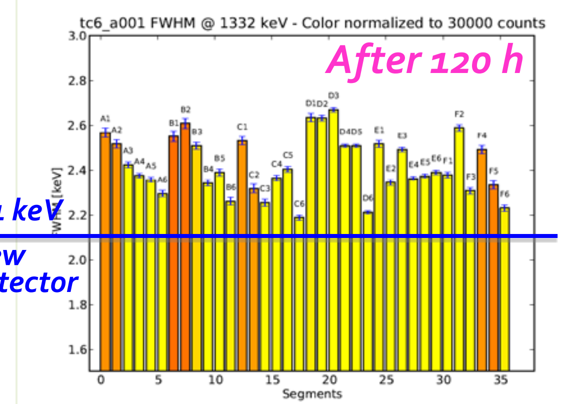


After 24 h Annealing









→ 120 hours of annealing do not recover from neutron damage @ 1.3 MeV

Present Status of Crystal Annealing

courtesy of P. Reiter (IKP)

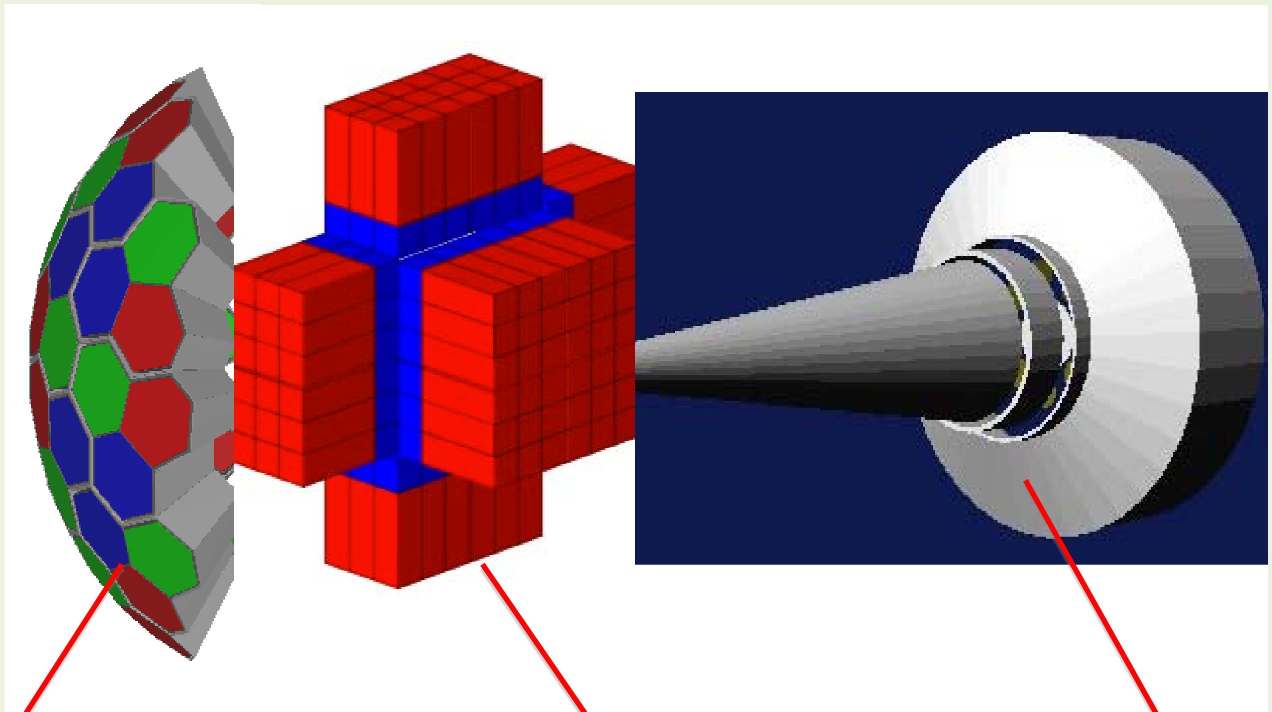
- **Core** is Fully recovered:
  - @ 59.5 keV   FWHM = 1.22 keV
  - @ ^{60}Co   FWHM = 2.19/2.27 keV

- **Segments**:
  - Energy resolution at low energies reproduced
    → electronic noise properties of detector ok
  - Energy resolution at 1.3 MeV clearly reduced with respect to new detector
  - Even 120 hours of annealing do NOT recover neutron damage

Can we improve present STATUS ?

- *Longer Annealing Time*
- *More frequent Annealing*
- *Higher Temperature (risky for contacts…???)*

Complex Detection Systems are needed



Scintillators

AGATA/EXOGAM/GALILEO + PARIS/LaBr3 +

Adam Maj
http://paris.ifj.edu.pl/

Recoil Filter/ Spectrometers/ NeutronWall/Si-Arrays

Experimental challenge … at HIGH Rates …

Scintillators ARRAYS

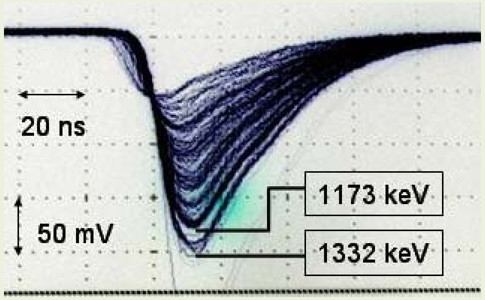
Large Volume Scintillators: NaI vs. LaBr3

Very Large NaI detectors	**Large $LaBr_3$:Ce detectors**
Energy Resolution ~ **6 %** at 662 keV	Energy Resolution ~ **3 %** at 662 keV
Time Resolution **~ 2-3 ns**	Time Resolution **~ 0.5 ns**
Linearity bad	Linearity good
Density 3.7 g/cm^3	Density 5.2 g/cm^3
Z(I) 53	Z(I) 57
- **Very Large Crystals** (10" x 10")	- **Large Crystals** (3.5" x 8")
- Very high efficiency	- high efficiency
- small 1EP (with collimator)	- small 1EP (with collimator)
- No 2EP	- No 2EP
No Sensitivity to neutron damage	**No Sensitivity to neutron damage**
Easy Handling	Easy Handling
PMT non idealities	PMT non idealities
Low Costs	**High Costs**

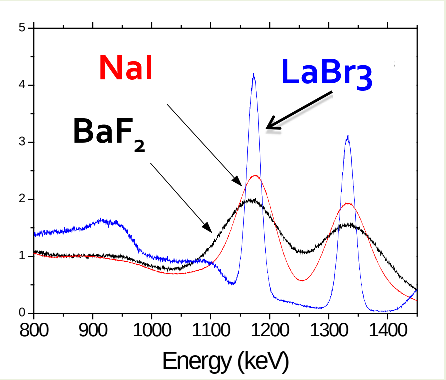
very fast signal

Rise time 25 ns
Fall time 60-80 ns
→ Total 100 ns

→ count rates up to **1 MHz**



L.Y. ≈ 63 ph/keV
Decay Time ≈ 16 ns
λ ≈ 380 nm, N ≈ 1.9

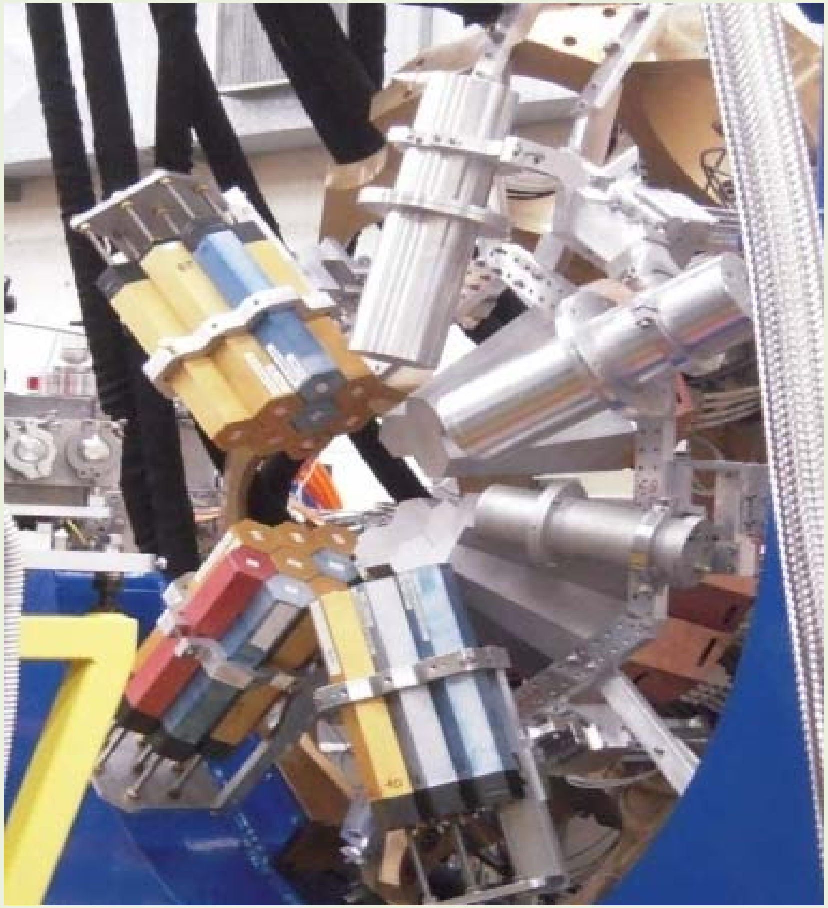


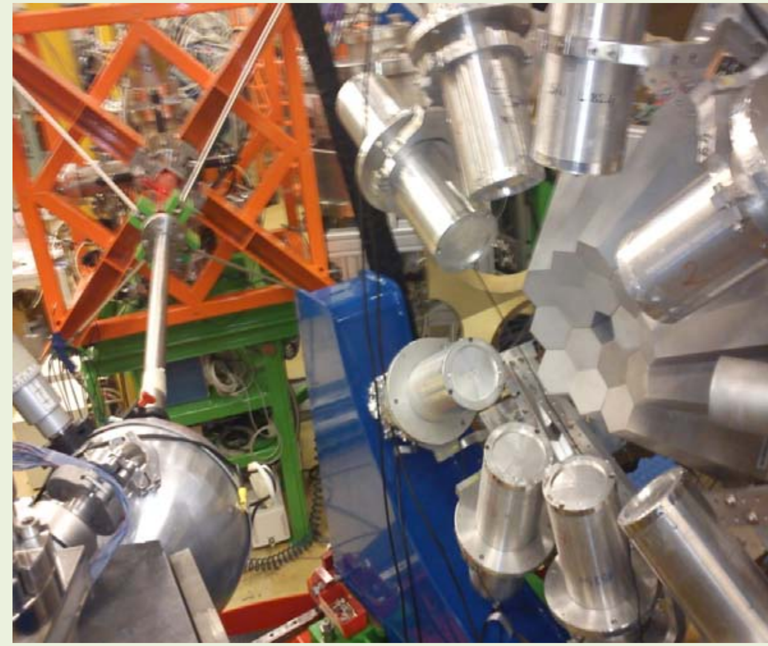
1. **Energy Resolution, Linearity**
2. **Gain Stability**
3. **Resistance to γ radiation**

at High rates…

In MILANO:
Array of 10 large (9x20 cm) LaBr3(Ce) crystals

Test of Detectors
PMT's
Electronics developments…





Campaigns @ LNL, Oslo, Debrecen, GSI, …
with AGATA, Si-TRACE, Helena, …

Project coordinator: Franco Camera

HIGH Count Rates:

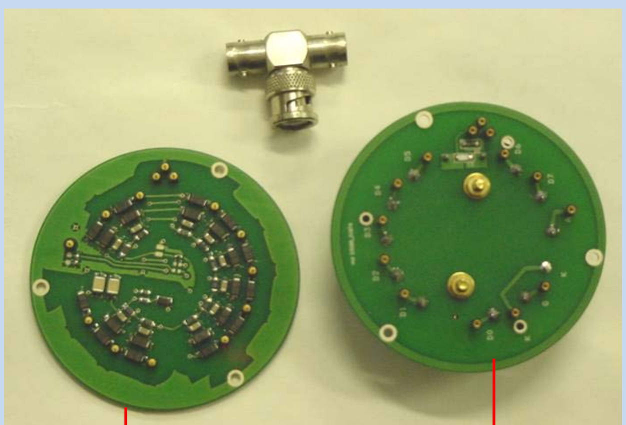
→ increase the average current inside PMT
→Tendency to reduce the potential ***last dinode-anode***
→***Increase in PMT Gain***

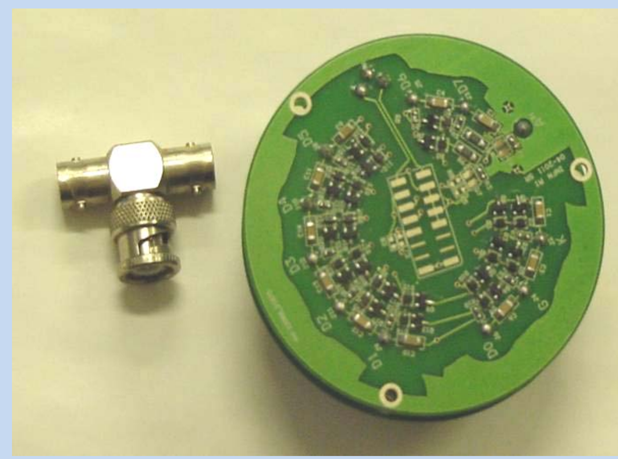
❑***Use of passive Voltage Divider is dangerous…***
❑***Active VD** (transistors in last stages) **can be a solution….***

Well known problem in Plasma Physics: at JET need to measure at MHz rates, dedicated hardware…
M. Tardocchi et al., Rev. Sci. Instum. 79(2008)10E524

Milano Active Voltage Divider for Large Size $LaBr_3$

S. Riboldi, S. Brambilla, C. Boiano





Adapter PCB
(to fit to different PMT sockets)

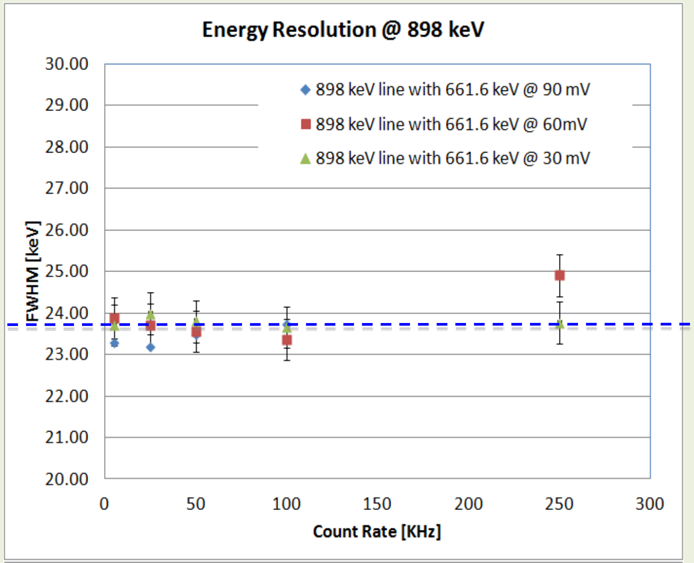
Active voltage divider PCB
(bottom side, showing protecting diodes)

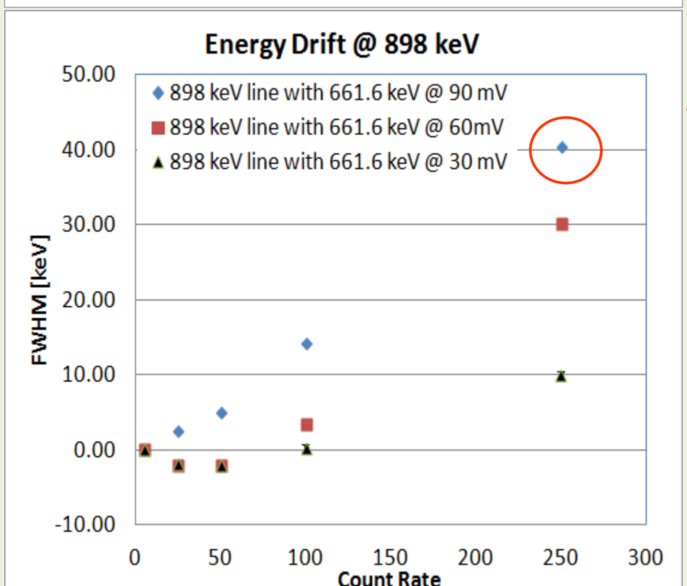
The two PCBs coupled together
(top side of VD, showing main electronics: BJTs, MOSFETs, etc.)

Constant Count Rate

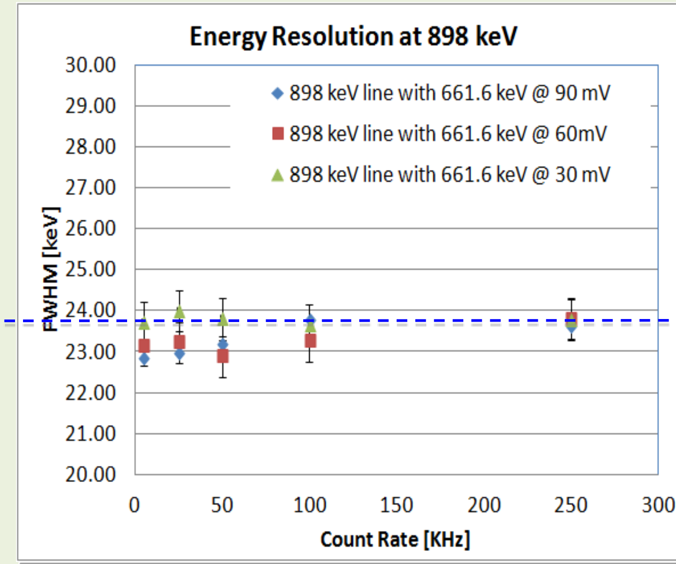
TEST with Digitized signals and offline analysis with integration algorithm

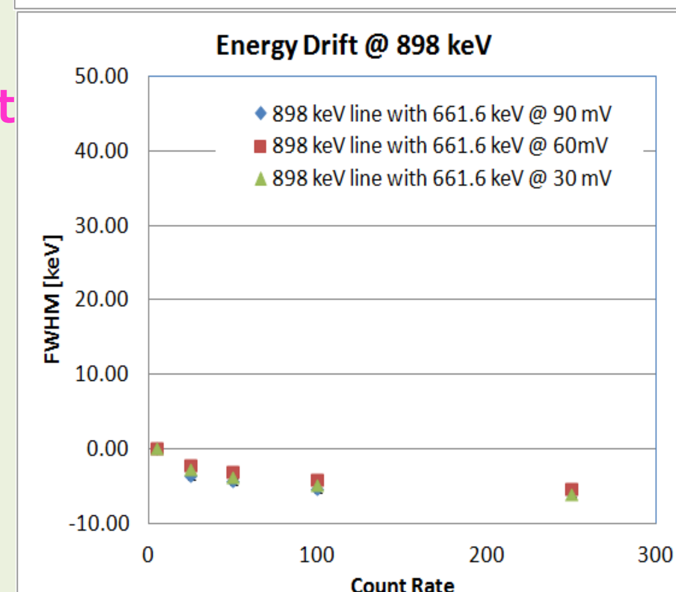
PASSIVE Voltage Divider
Commercial Hamamatsu





Milano-ACTIVE Voltage Divider
In house development for Large LaBr3





No deterioration in $\Delta E/E$ up to 250 kHz

← Significant gain drift ≈ 40 keV

NO gain drift →

- 5 keV
due to PMT
temperature increase

In-Beam Count Rate

Large variation due to beam fluctuations

Gain monitor

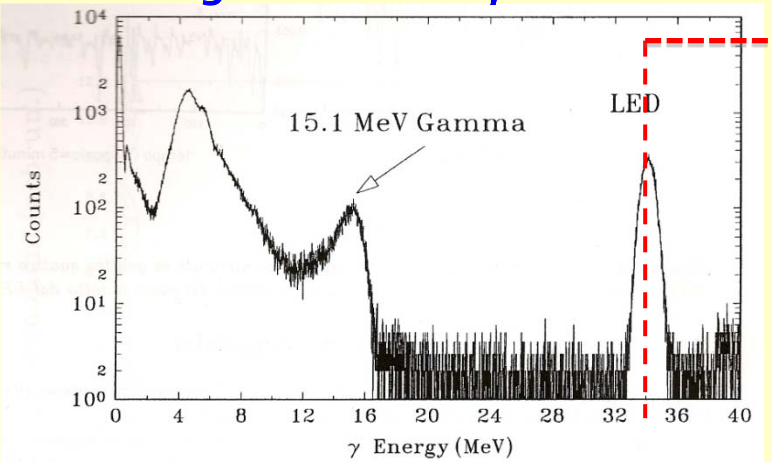
by LED source inside the detector

$\nu \sim$ 1 Hz - 10 kHz

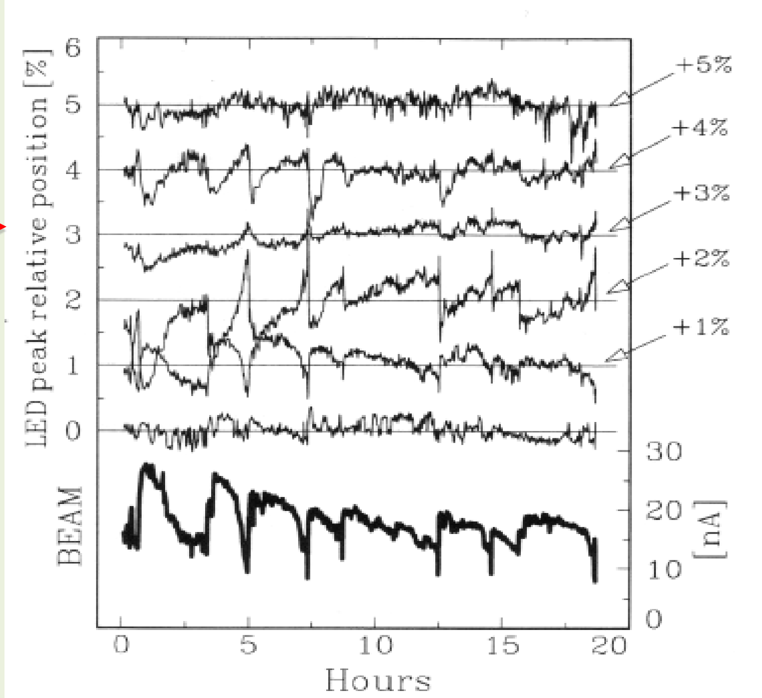
$\lambda \sim$ 568 nm

$E_\gamma \sim$ 25-30 MeV

Large Size BaF2 Spectrum



Additional complexity of Experimental setup ...

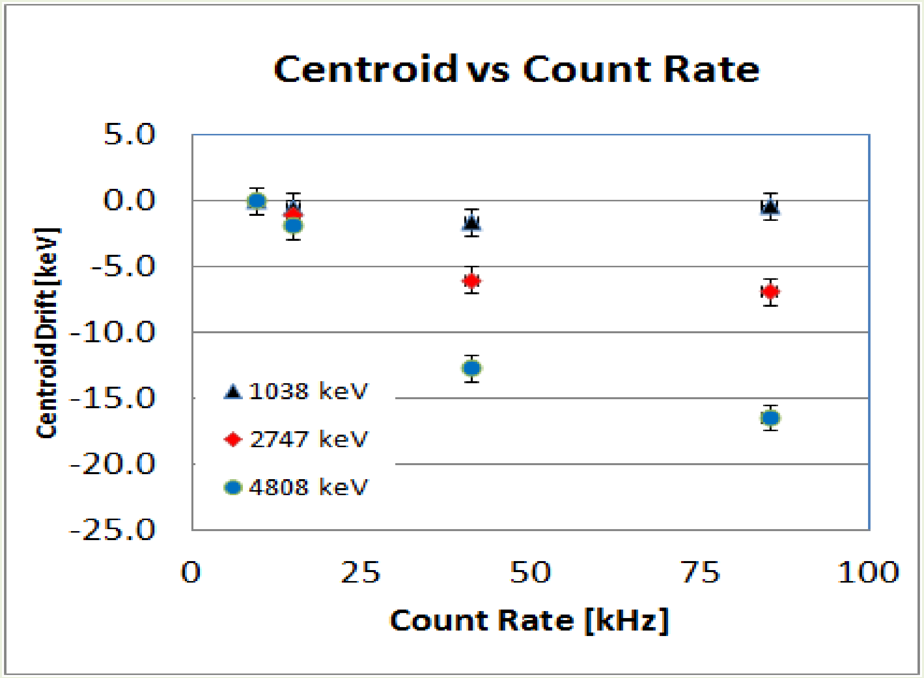


A. Maj et al NPA 571(1994)185

Count Rate affects Spectroscopic Amplifiers

especially with no pile-up rejection

Final detector response → PMT + Voltage Divider + Amplifier



Test with high energy γ-rays
3.5"x8" $LaBr_3$:Ce

Gain stability vs Count Rate

- ***Analog electronics*** processing PMT (BAFPRO ampl., 700 ns shaping)
- ***No pile up Rejection***
- ***Standard ADC***

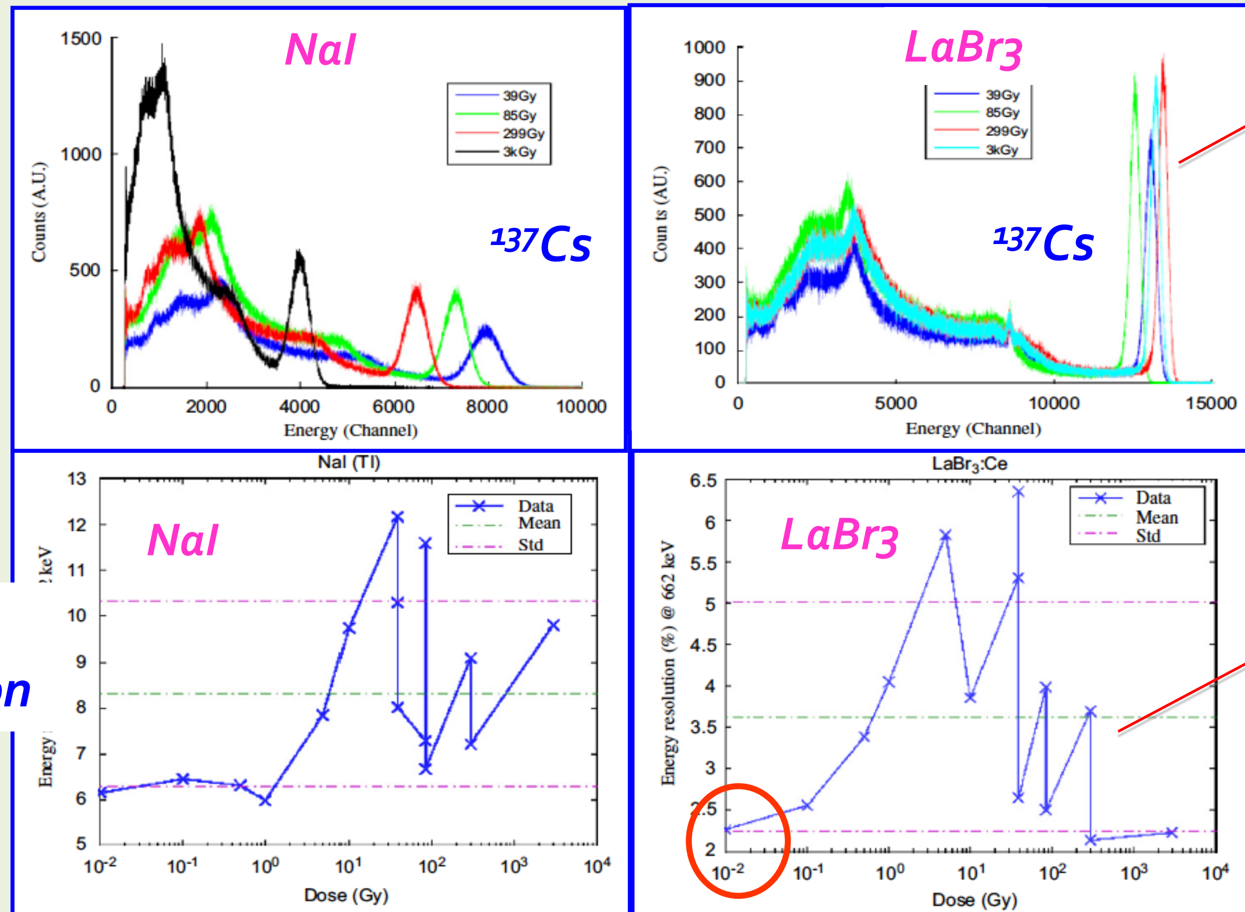
→ *Measured effect mainly due to amplifier*

... room for improvement → Digital Electronics ...

LaBr3: Radiation Hardness

S. Normand et al., NIMA572(2007)754

- *NO sensitivity to neutron and proton interaction* *(Jenkins, Iltis, … measurements)*
- *TEST under severe γ-flux: up to 3.4 kGy dose*



Constant Light output

Energy resolution

- Temporary degradation

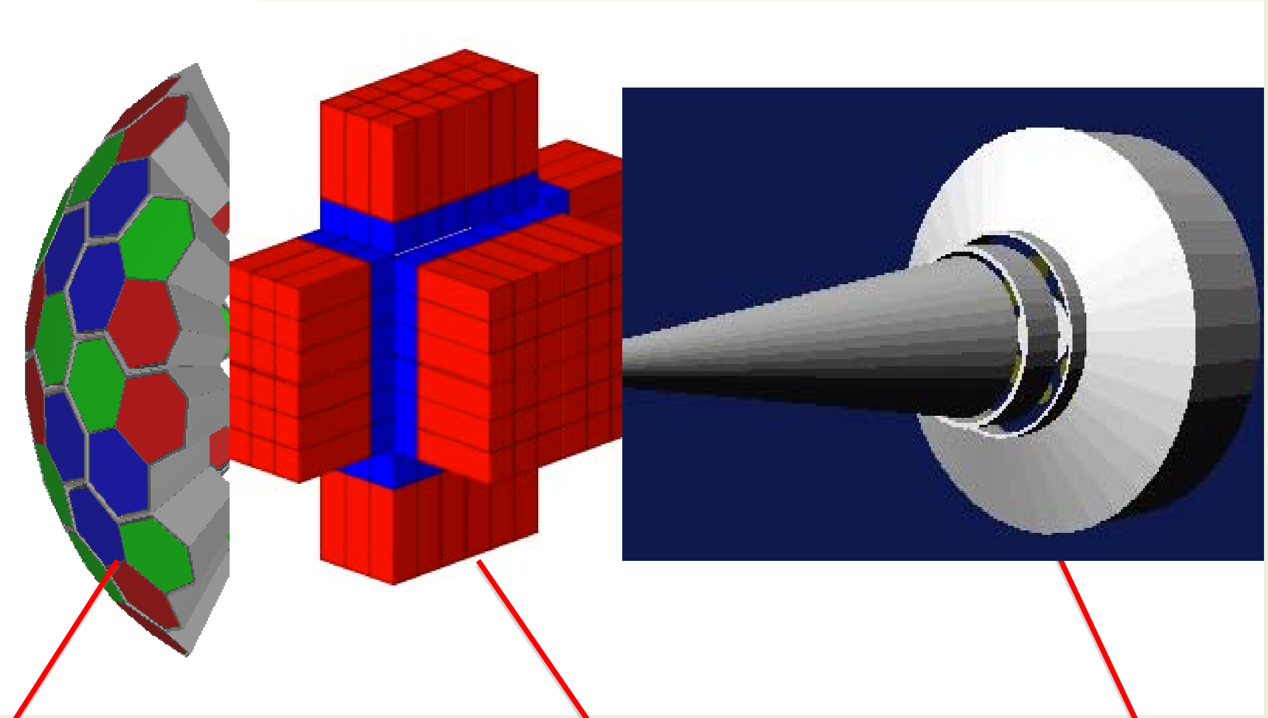
- Recovery in few hours

- Heating helps…

3.5"x8" LaBr3
3 months, 10 pnA

NaI: permanent damage above 1 Gy; color change, transparency change, …
LaBr3: ***No permanent effects observed up to 3 kGy***

Complex Detection Systems are needed



Ancillaries

AGATA/EXOGAM/GALILEO + PARIS/LaBr3 + Recoil Filter/ Spectrometers/ NeutronWall/Si-Arrays

Experimental challenge … at HIGH Rates …

Ancillaries

COUPLING of COMPLEMENTARY DETECTORS

Complementay detectors have played a major role
in γ-spectroscopy with EUROBALL/GAMMASPHERE
HUGE improvement in selectivity: light charged particles, heavy-ions, ...

In connection with AGATA project:

- **New complementary detection systems**

  PARIS (high-energy γs), **NEDA** (neutrons),
  GASPARD (charged particles and γs) **, ...**

  → *looking for* ***fully digital solution*** *... for example EXOGAM2-NUMEXO2 board*

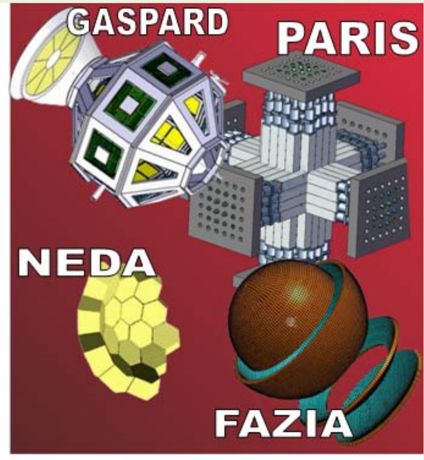
- **Adapting of existing-operational ancillaries**

  PRISMA/VAMOS (heavy-ion spectrometer), **RFD** (recoil filter detector),
  TRACE (Si pixel type detectors), **HECTOR/HECTORplus** (Large size BaF_2 and $LaBr_3$), ...

  → **Present:** ***AGAVA interface***

  → **Future:** ***Digital electronics...***

❑ New complementary detection systems



High-Energy γ□s:
Design Study
Prototype

Neutrons:
Design Study
Prototype

Charged Particles:
Design Study
On the way to Prototype

FAZIA
Charged Particles
Heavy-Ions
Fully Digital
Demonstrator-Phase

*Looking for **fully digital solution***
to maximize compatibility, high count rates, …

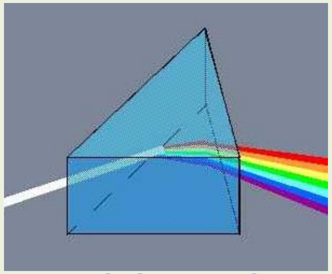
→ ***Synergies with NUMEXO2 Mother Board for EXOGAM2***
→ ***Similar Approach for scintillators***

NIM digitizer + GTS

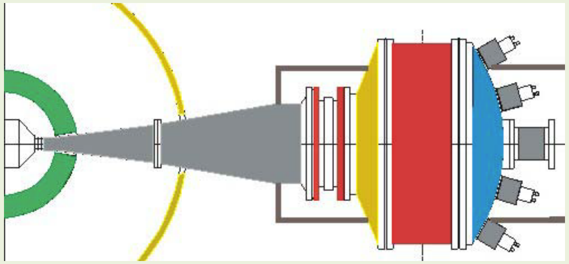
- *16 Channels*
- *14 bits, 200-250MHz → syncronization with AGATA*
- *GTS for AGATA implemented in NUMEXO FPGA*
- *Dedicated add on **analog conditioning board** for different detectors…*
  to be defined** depending on tests of detectors prototypes **(PMT, Voltage Divider,…)
- *online processing in FPGA*

WORK in PROGRESS…

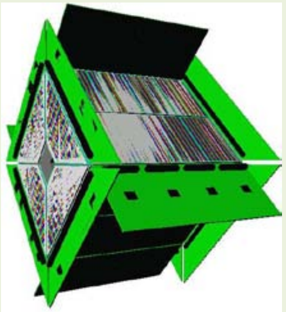
❑ Adapting of existing-operational ancillaries



VAMOS/PRISMA
Spectrometer
Heavy-Ions



Heavy-Ion
Recoil Filter Detector



TRACE
Charged Particles
Si-Pixel detectors

PRESENT STATUS: AGAVA (AGATA-VME Adapter)

- *Traditional detectors with AGAVA board (single trigger request)*
- *Analog electronics*
- *Variable Number of parameters*
- *10-20 μs for event processing*

→ Typical Rates: 5-10 kHz, upper limit 30-50 kHz
in Stand Alone Mode < 100 kHz (upper limit)

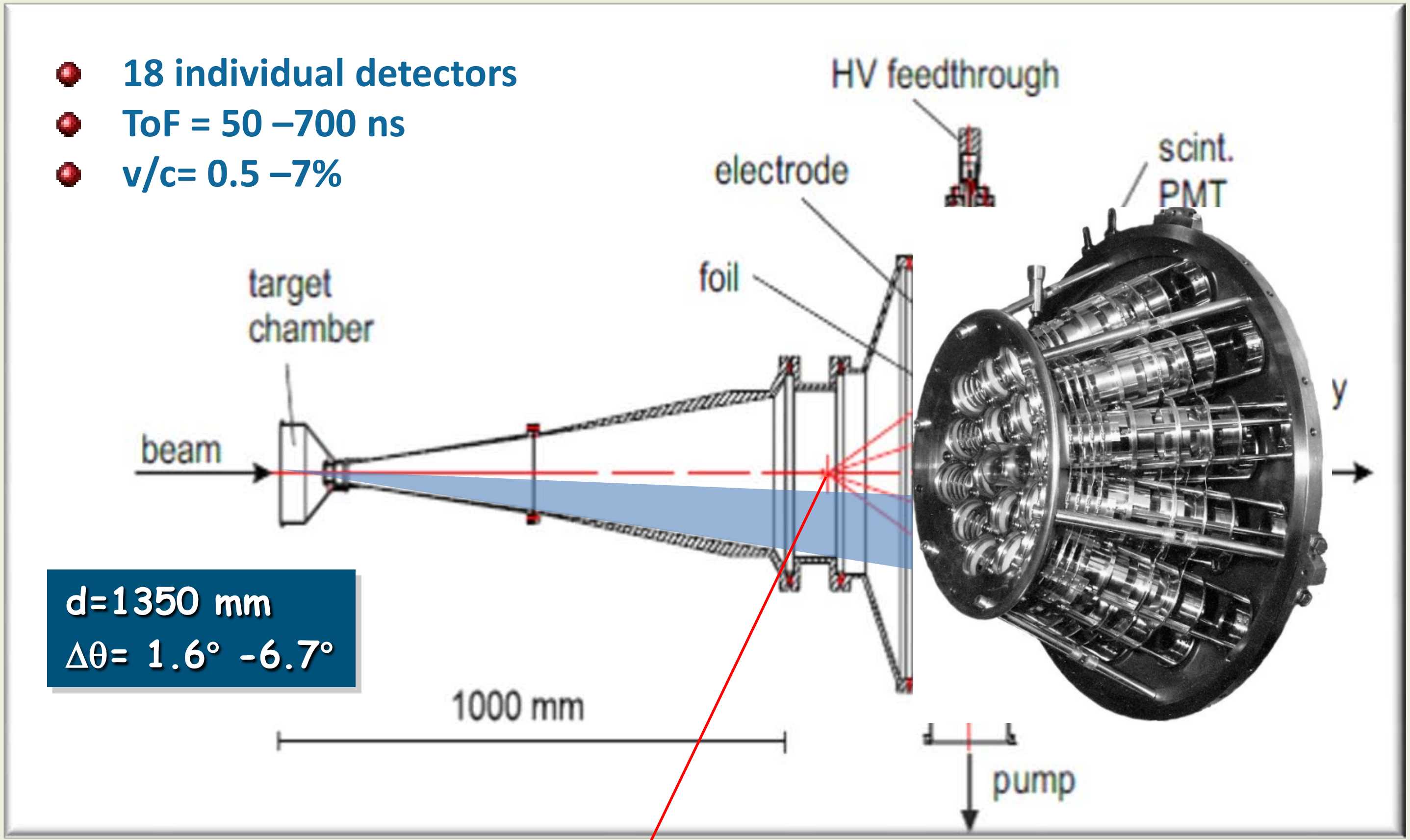
PERSPECTIVES: Digital Electronics

- *Online processing (FPGA...) → time stamp, energy, time*
  - *Monitoring of online processing via signal shapes ...?*
- *Feedback for better online analysis ...?*

To be investigated...

Ancillaries Working Conditions with HIGH-RATES ??

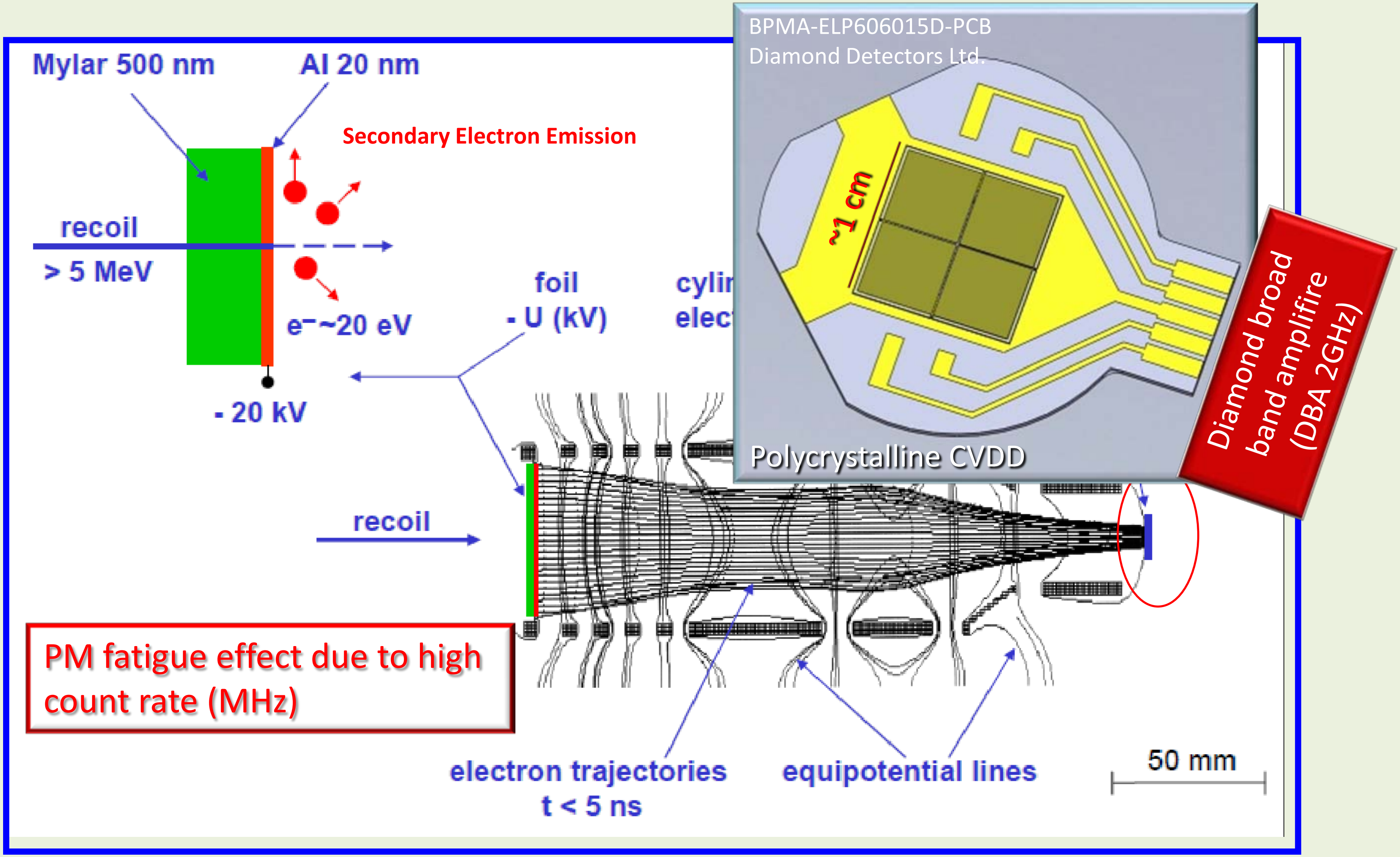
Recoil Filter Detector (Krakow):
Heavy-Ion Detection Technique



Insensitive on direct radiation from a target

P. Bednarczyk, A. Maj, W.Męczyński, M. Zieblinski et al., …

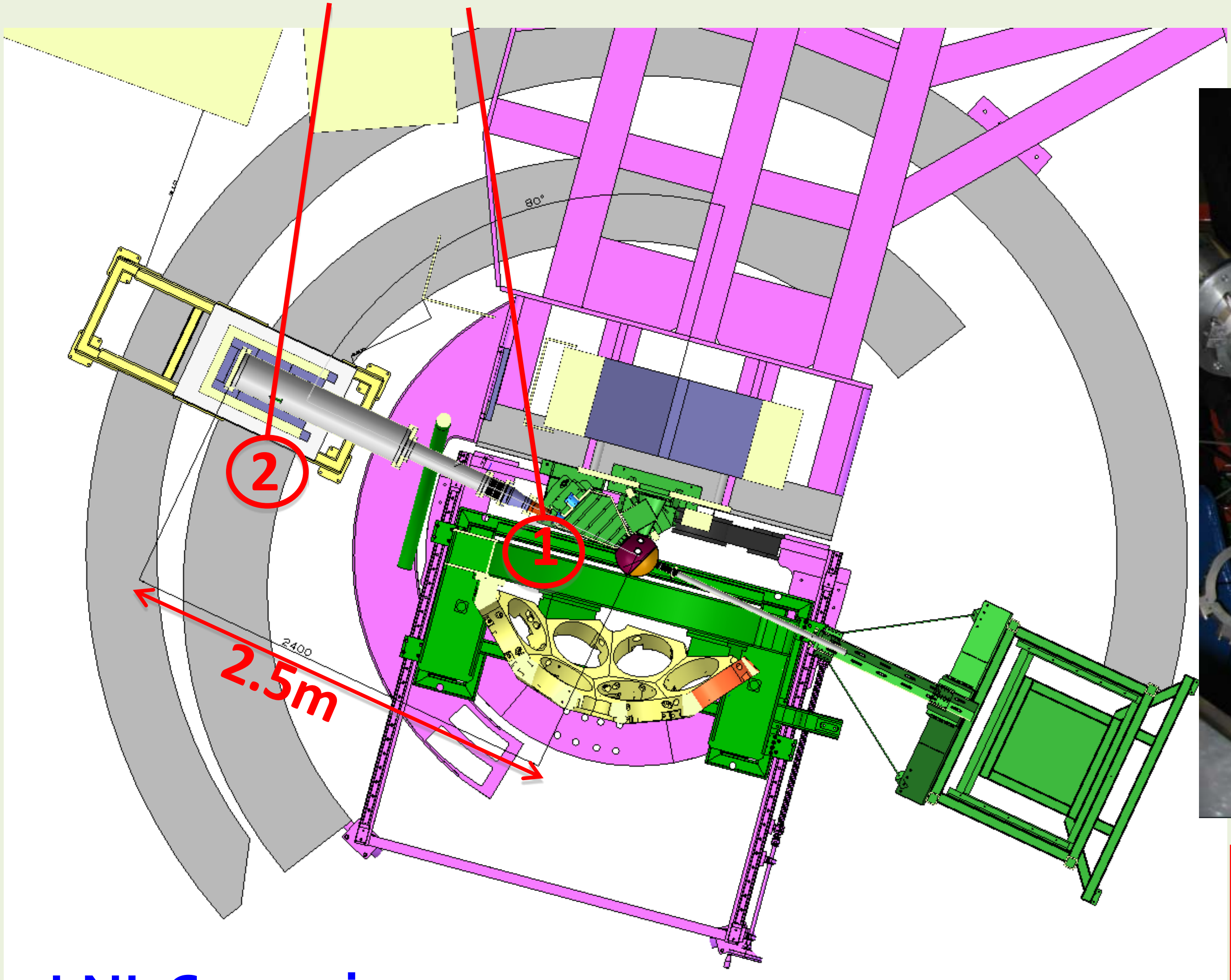
PM deficiency at intense beams



*Use of **DIAMOND DETECTORS** may further improve the performance at high rates (not if polycrystalline)*

WARNING: Careful control of background sources….

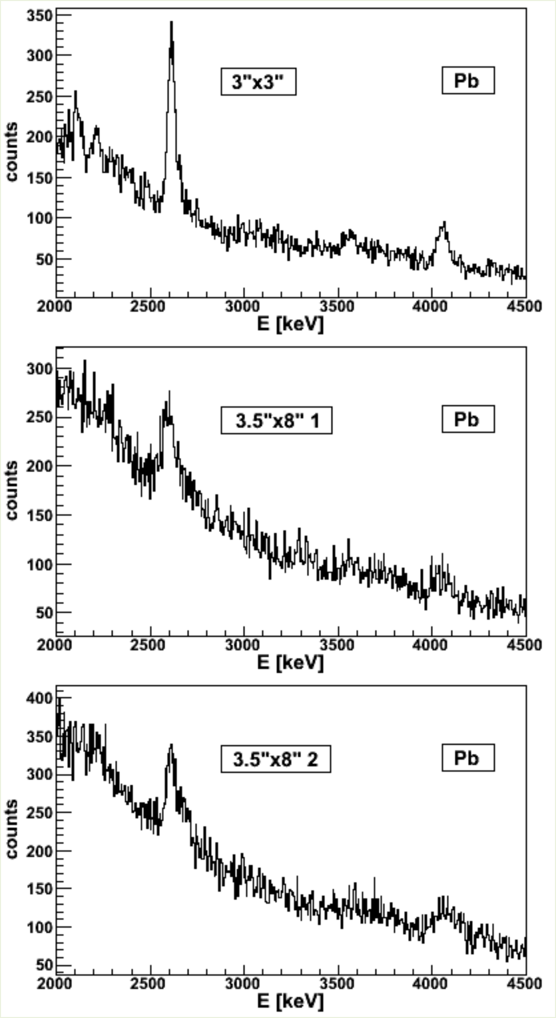
…. Beam Dump position



LaBr3 detectors
In front of Beam Dump 1
(shielding AGATA)

LNL Campaign
AGATA + Large Volume $LaBr_3$ + Si Telescopes

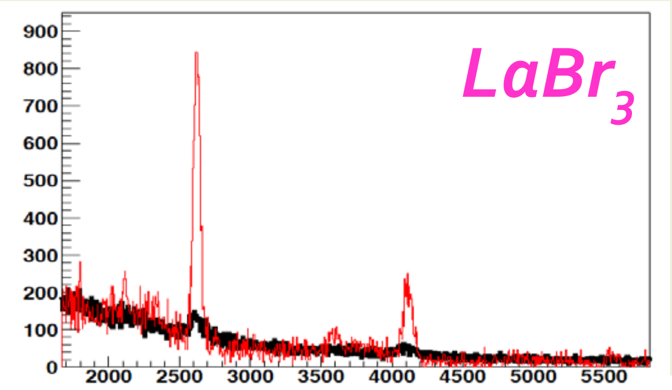
Close Beam Dump Setup
$LaBr_3$ with Passive VD

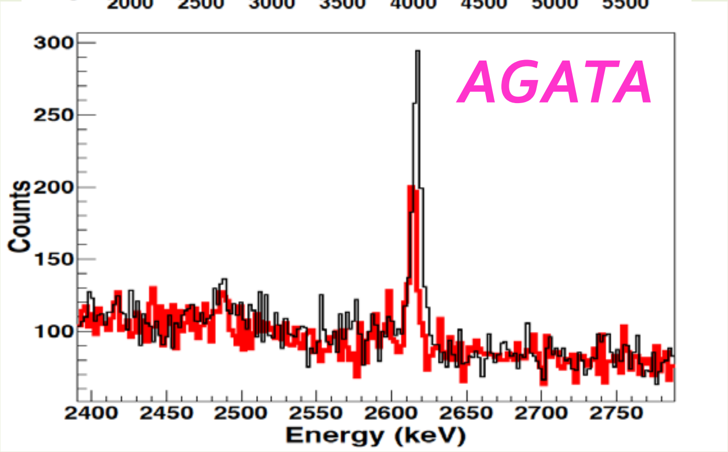


Rates up to 300 kHz:

Clear Deterioration
of Energy Resolution

I_{beam} = 0.5 – 1 pnA





→ ***Significant improvement***

in spectrum quality
due to

better Beam Dump position

Take Home Message:

γ-spectroscopy 0-20 MeV range at High-Rates is the physics of Complex Detection Systems

Ge Arrays + Large Volume Scintillators (BaF2/LaBr2)+ Ancillaries

+ ***Radiation Hardness:***

  AGATA (Ge) → severe, annealing procedure ?
  Scintillators LaBr3 → not a serious problem
  Ancillaries → severe, to be evaluated case by case

+ ***Detector Performance:***

  AGATA (Ge) → acceptable up to 250 MHz
  Scintillators LaBr3 → very sensitive to PMT+subsequent electronics
  Ancillaries → to be evaluated case by case

+ ***Electronics:***

  AGATA is born digital but Coupling with other detectors…?
  Digital pulse processing is needed

  → Synergies with NUMEXO2 Mother Board for EXOGAM2 (NEDA, …)
  → Other similar Cases ?

+ ***Careful control of background sources****: not to be overlooked…*

Thank You for the Attention