



Nuclear observables

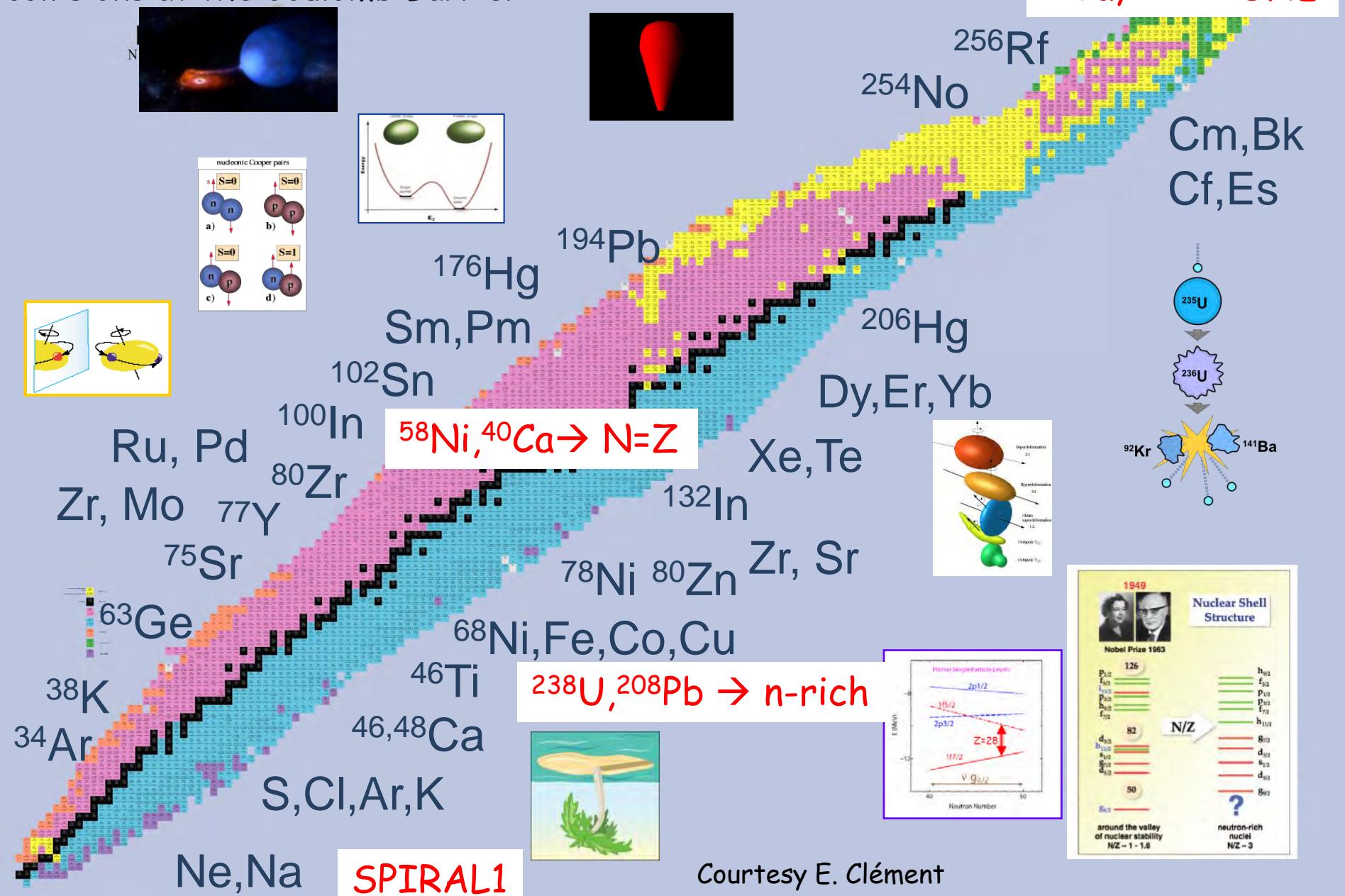
G. Duchêne

Du noyau aux étoiles (From nuclei to stars)
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Lecture plan

- 1. Introduction**
- 2. Nuclear structure and observables - *What can you measure or deduce?***
- 3. Nuclear reactions - *How to create your nucleus of interest?***
- 4. Radiation-matter interactions and detectors for charged particle and γ rays - *Tool kit***
- 5. Perspectives**

The physics case of AGATA@GANIL is the in-beam γ -ray spectroscopy of exotic nuclei populated by heavy-ions collisions at the Coulomb Barrier



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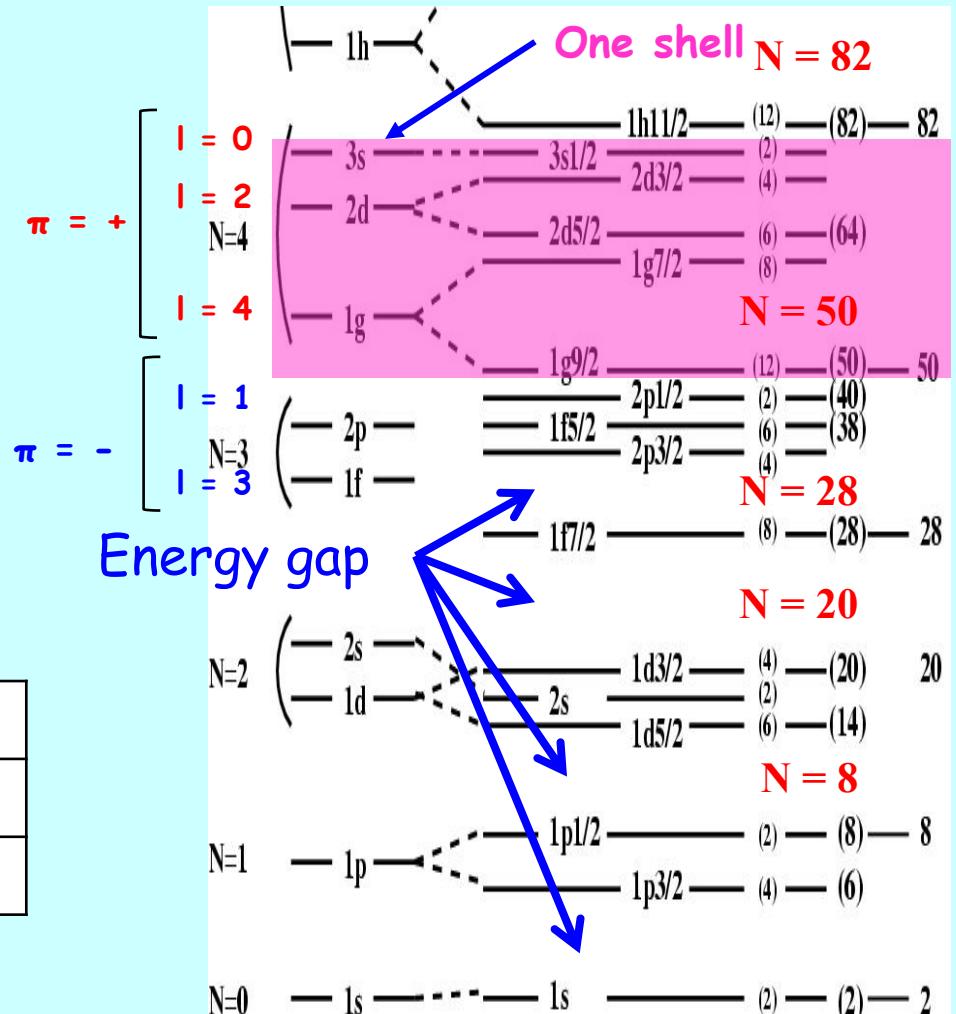
Basic rules

Spin coupling

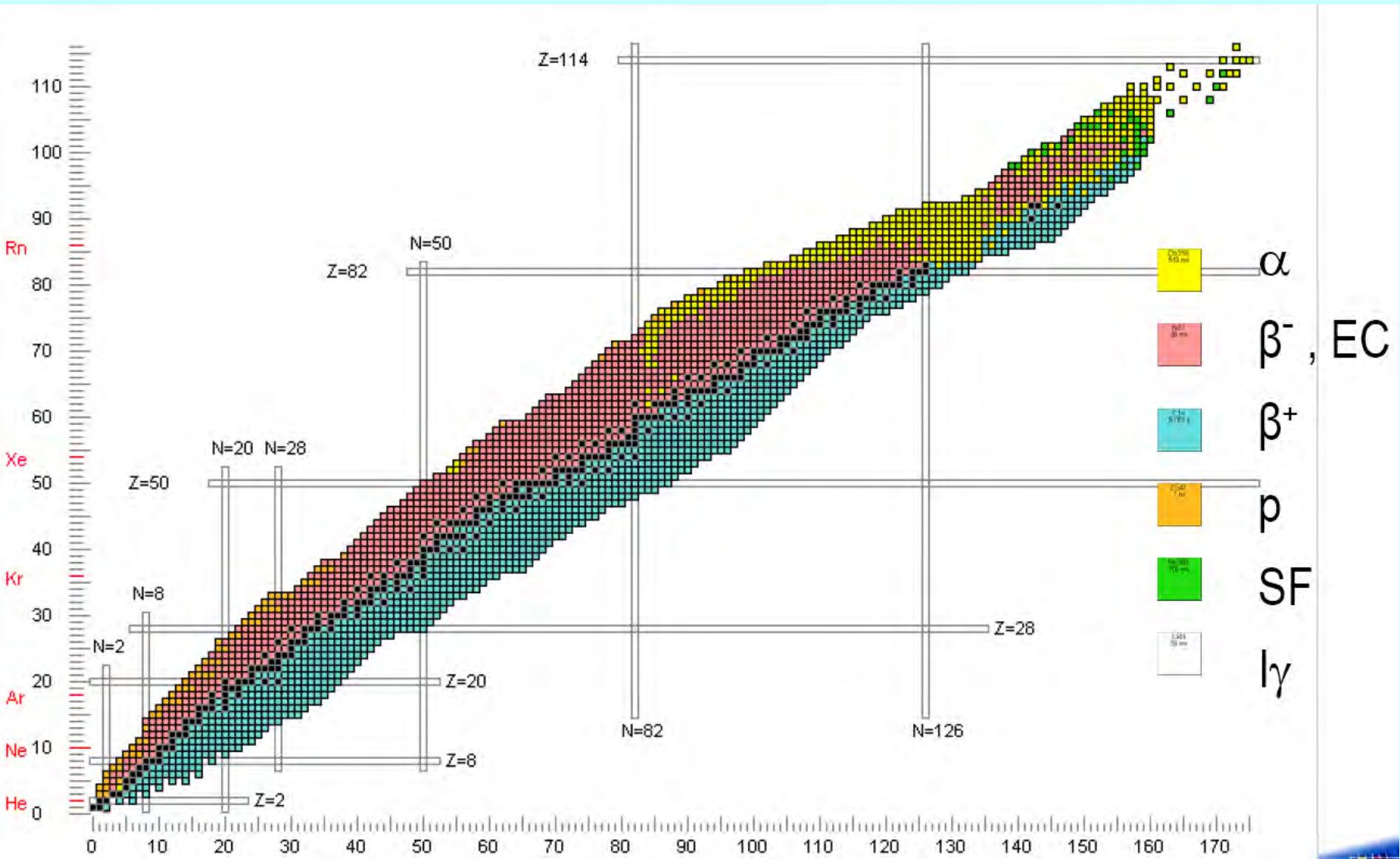
- $\vec{J} = \vec{I}_1 + \vec{I}_2$ $|I_1 - I_2| \leq J \leq I_1 + I_2$
- Nucleons are fermion: $s=1/2$
- On orbitals with momentum I
- Nucleon spin $j = l + s$ $j = l + \frac{1}{2}$ or $l - \frac{1}{2}$

Orbital parity: $\pi = (-1)^l$

l	0	1	2	3	4	5
	s	p	d	f	g	h
π	+	-	+	-	+	-



Magic numbers



Basic rules

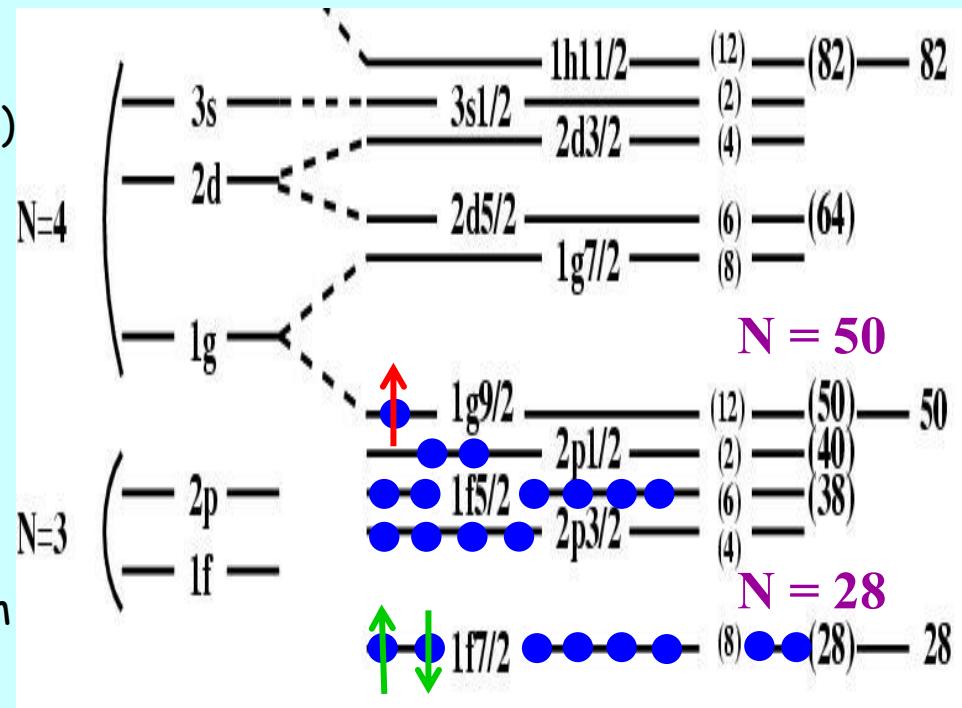
Nucleus

- Composed of two liquids, protons (Z) and neutrons (N)
- Protons and neutrons are placed on orbitals independently
- Number of nucleon per orbital
 $n = 2j+1$
- Spin J of the nucleus; projections m_J
 $J = \sum_i j_i$ with $-J \leq m_J \leq J$
- Parity of the nucleus

$$\pi_{\text{nucleus}} = \prod_i \pi_i$$

- Pairing: 2 nucleons on same orbital couple their spin to zero

- Ground state spin of even-even nuclei: $J = 0$
- Ground state spin of odd-even nuclei: $J = j_{\text{single nucleon}}$



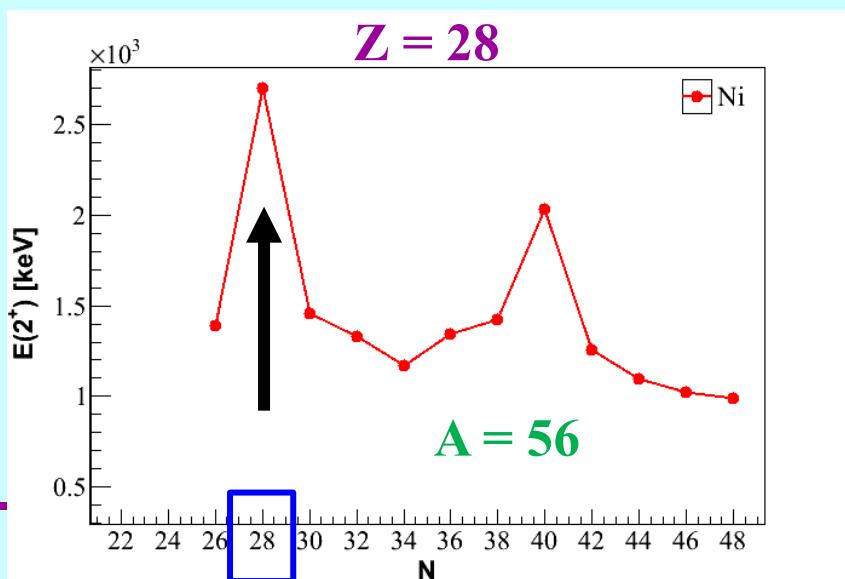
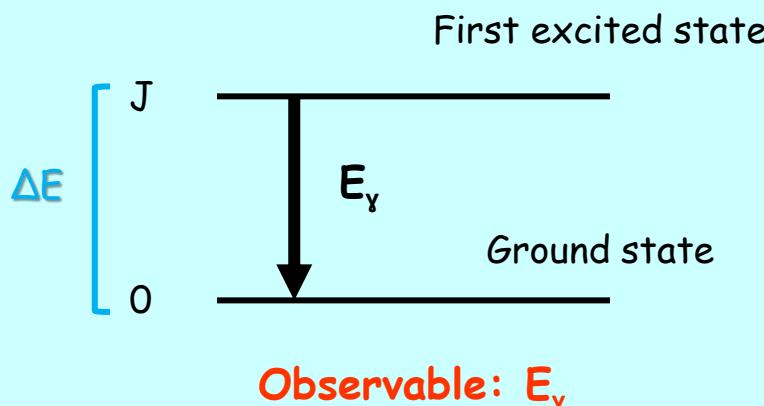
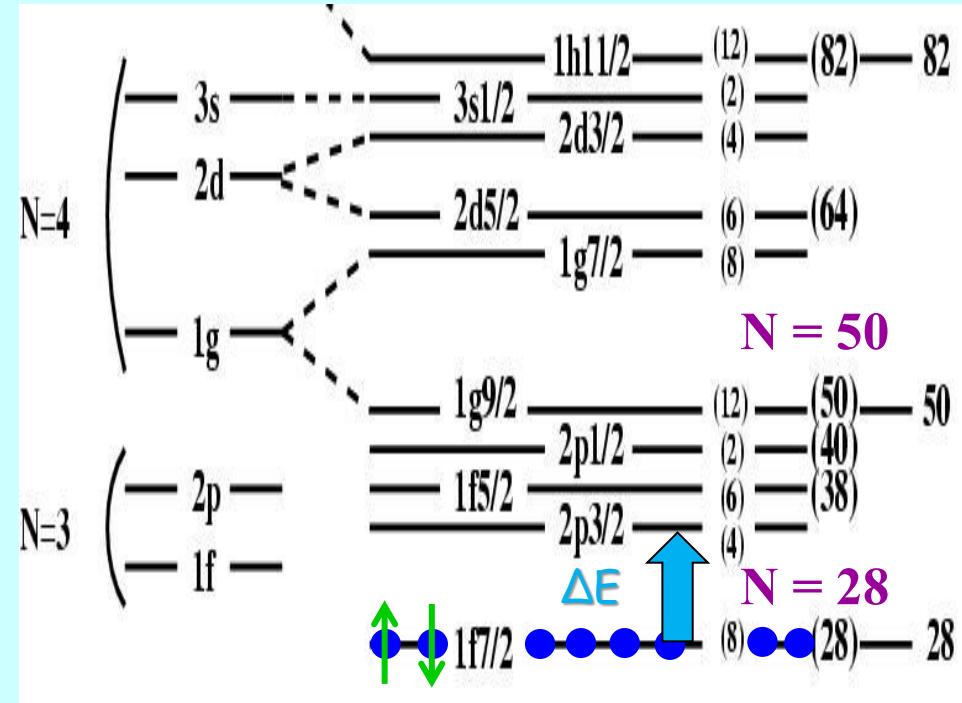
Protons (π) or neutrons (ν)

Basic rules

Nucleus

- Nucleon excitations within a shell need moderate energy
- Nucleon excitations across a shell gap need large energy
- Nucleus level scheme

$$\Delta E = E_{\text{gap}} + E_{\text{pairing}} + E_{\text{correlations}}$$

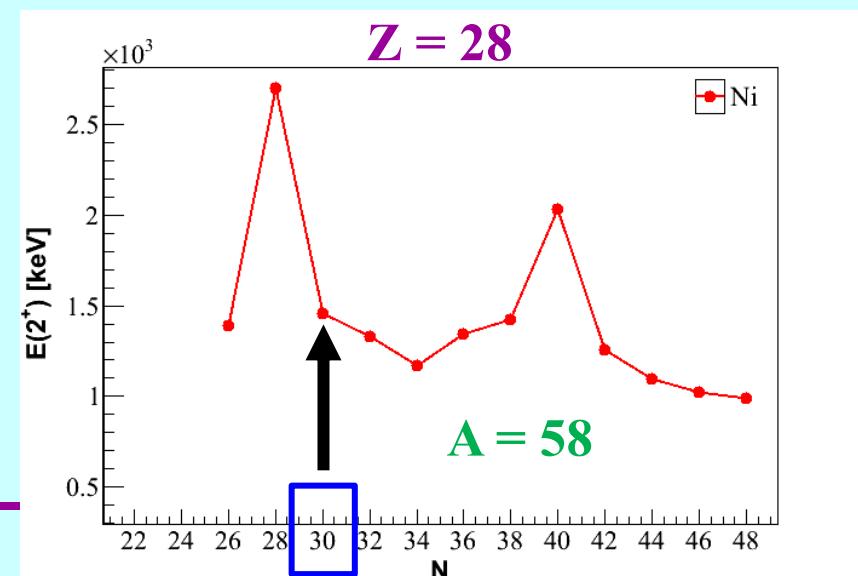
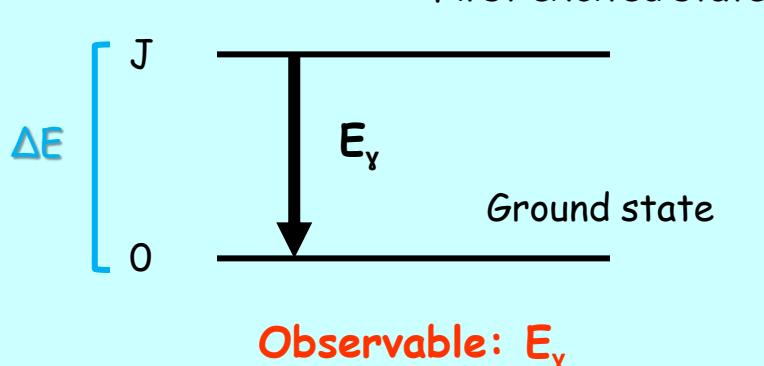
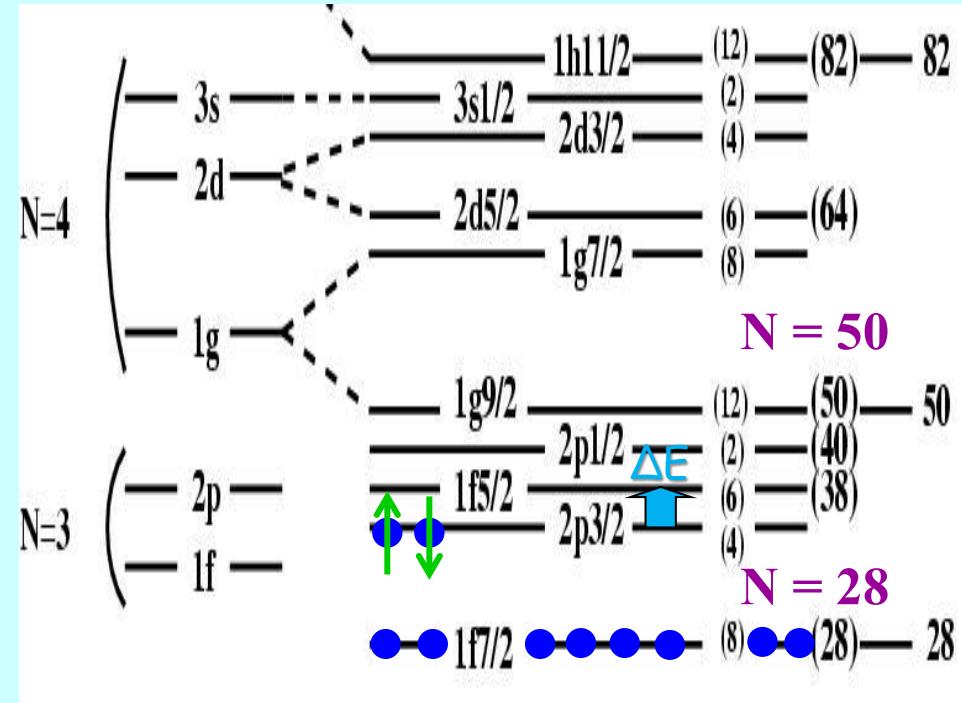


Basic rules

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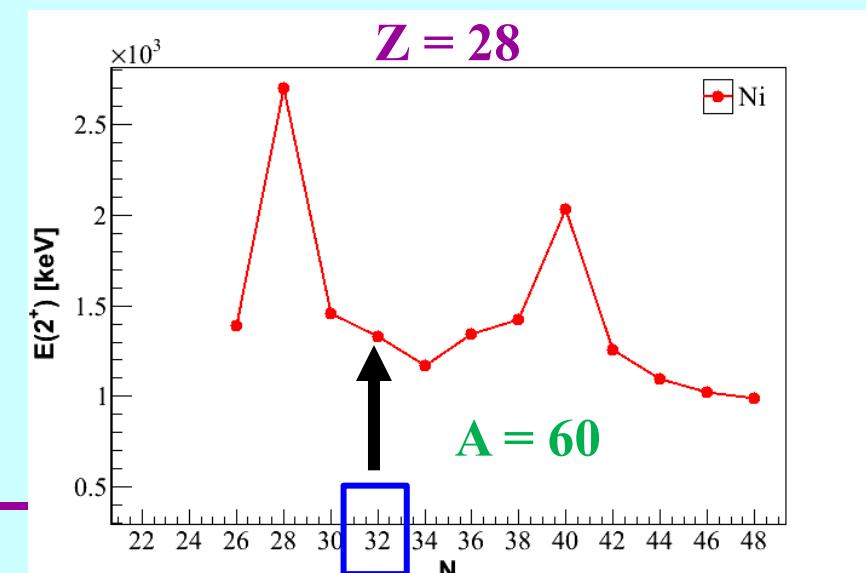
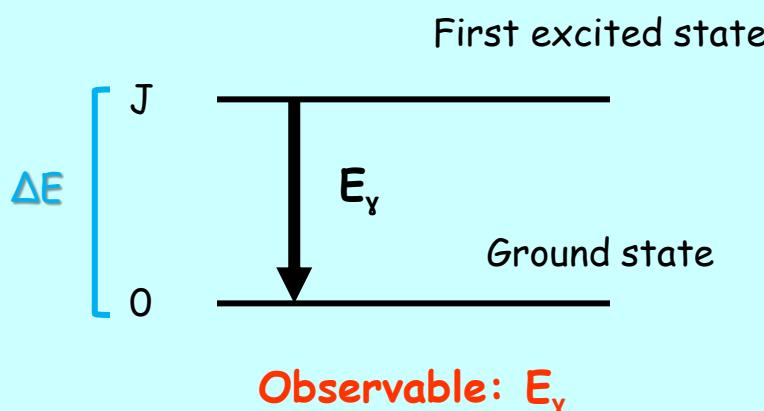
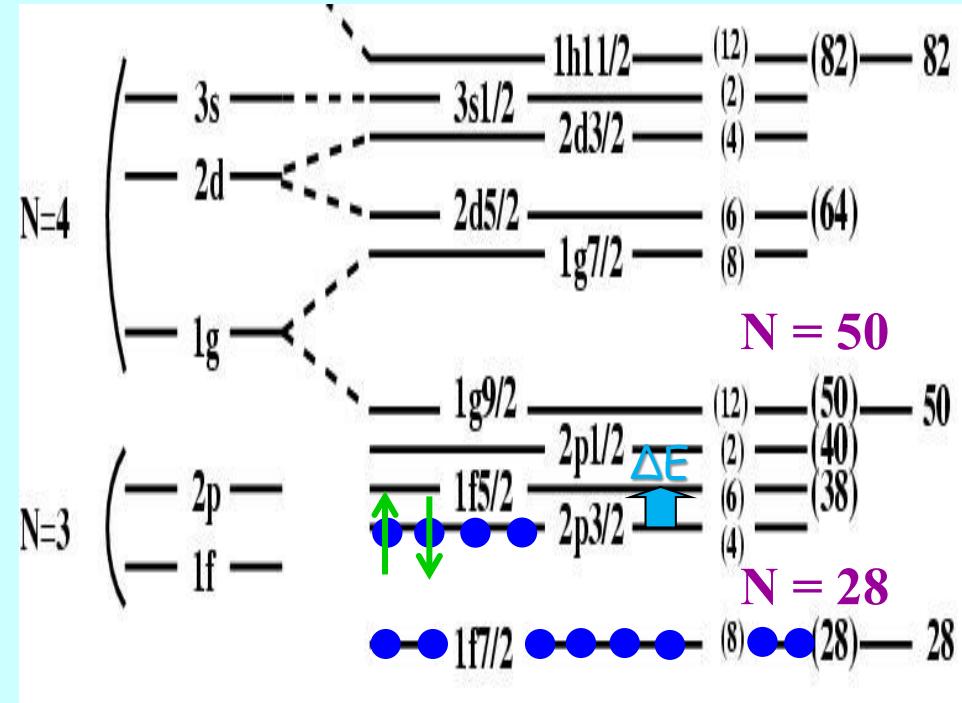


Basic rules

Nucleus

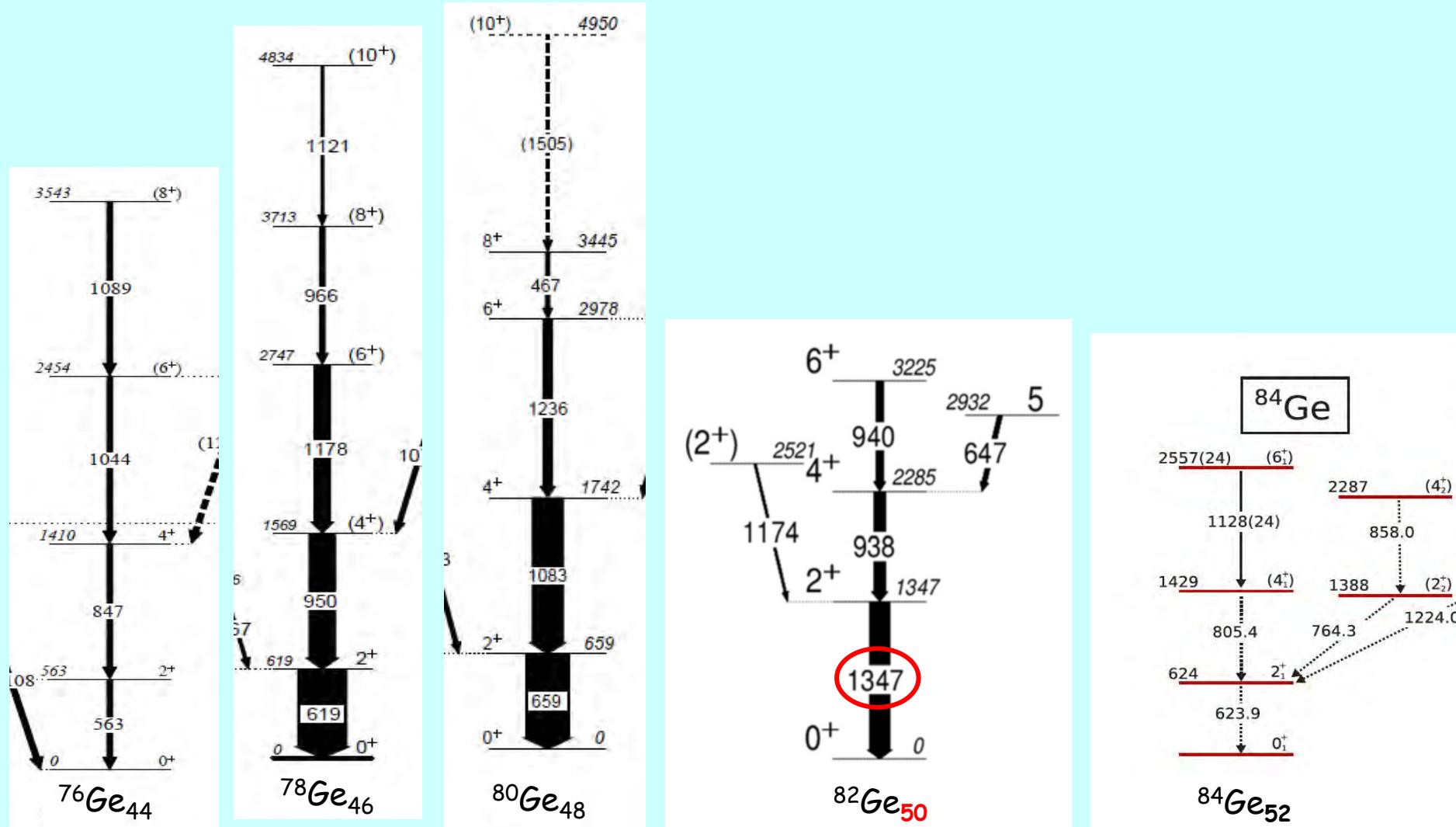
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$$\Delta E = E_{\text{gap}} + E_{\text{pairing}} + E_{\text{correlations}}$$



First 2^+ excitation energy $E^*(2^+)$

Even Ge isotopes: $Z=32$

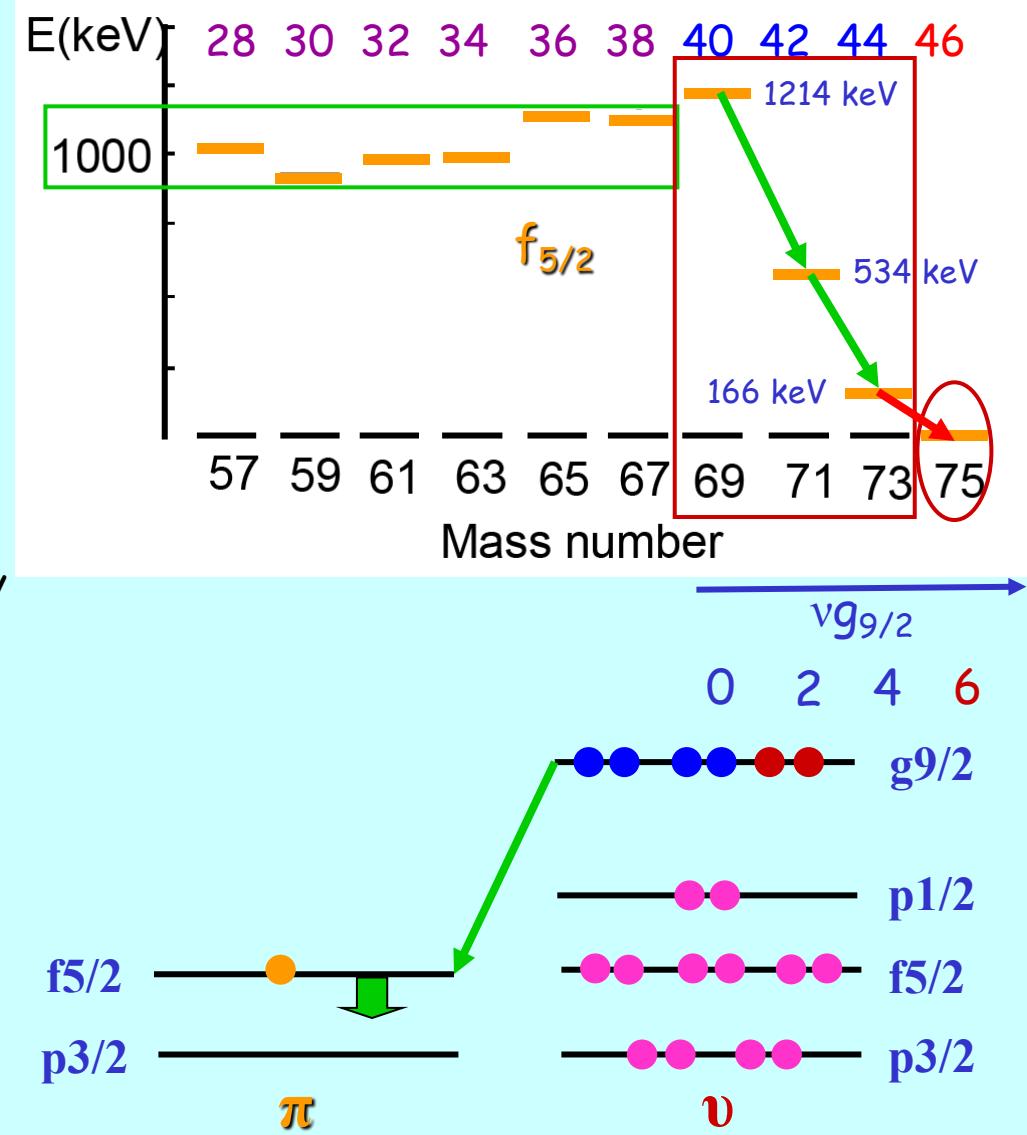


Odd Cu case

Systematics

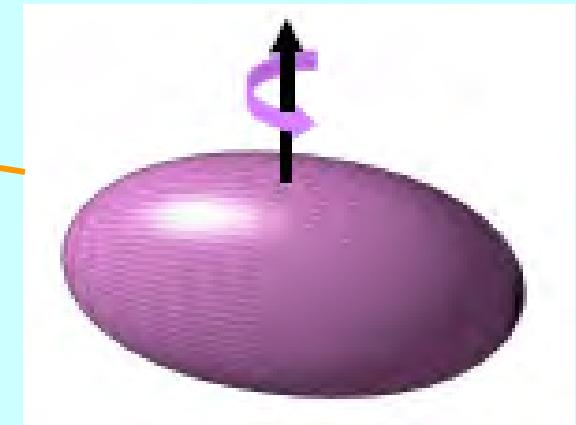
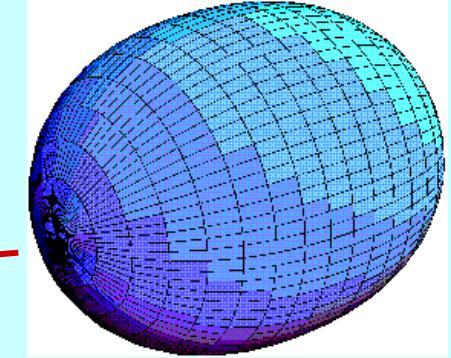
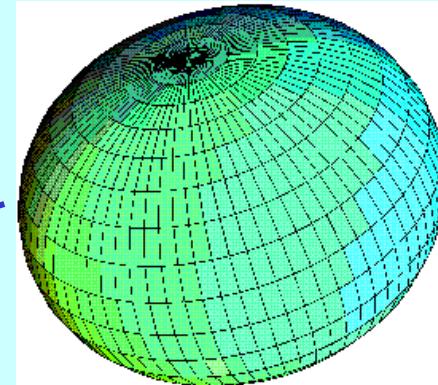
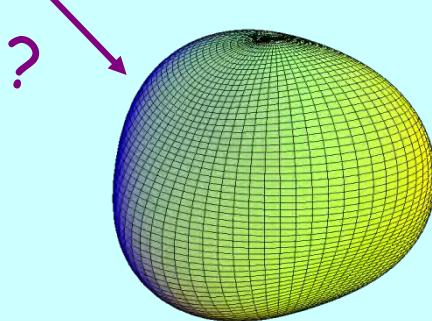
- Evolution of level energy (Indicator)
- Odd Cu: $Z=29$, even N
- Ground state $3/2^-$ (orbital $p_{3/2}$)
- Excited state $5/2^-$ (orbital $f_{5/2}$)
- One proton promoted from $p_{3/2}$ to $f_{5/2}$
- Almost constant excitation energy $E^* \sim 1$ MeV of the $5/2^-$ state up to N=40
- For $N > 40$ ($A > 69$) $g_{9/2}$ neutron orbital start to fill
- $E^*(5/2^-)$ strongly reduces

Proton $\pi f_{5/2}$ – neutron $\nu g_{9/2}$ interaction



Nuclear shapes

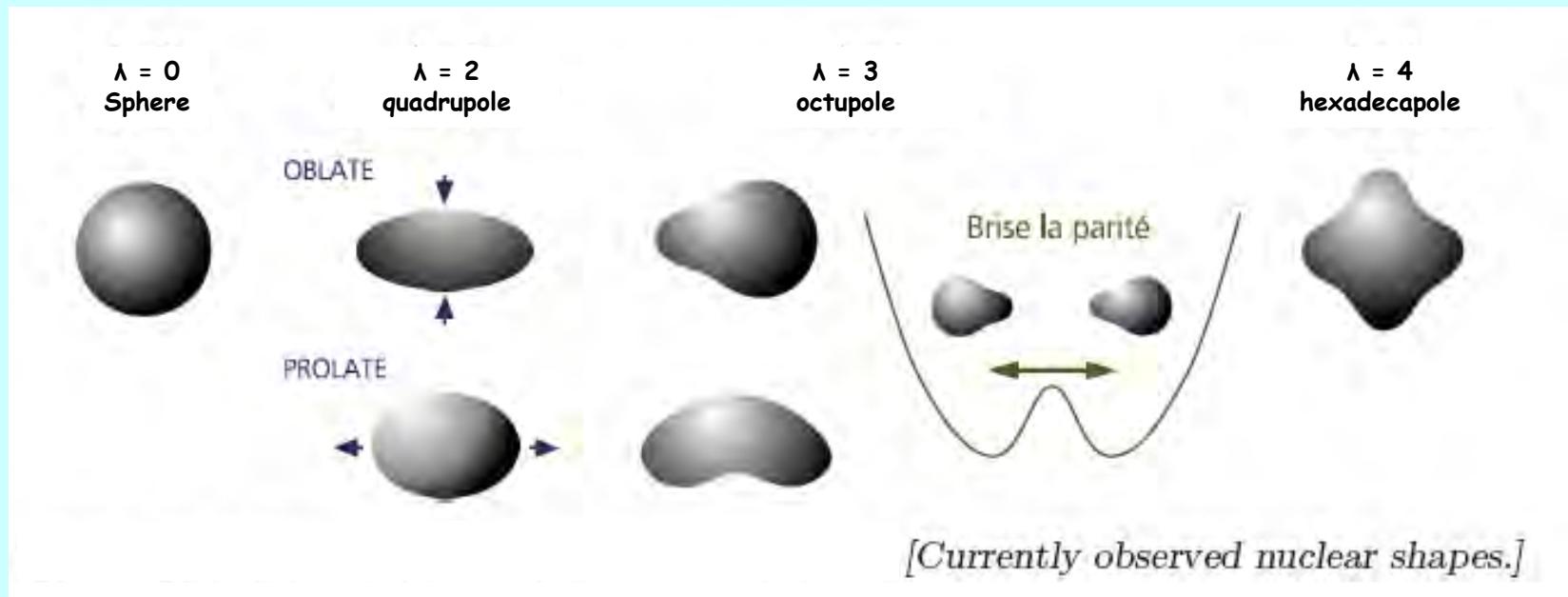
- Spherical
- Oblate
- Prolate
- Super deformed
- Triaxial
- Pyramidal ?



Nuclear shapes

Nuclear shape parametrisation

$$R(\theta, \phi) = R_0 \left[1 + \sum_{\lambda=2}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu}^* Y_{\lambda\mu}(\theta, \phi) \right].$$



Rotational bands

Excitation energy

$$E_{rot} = \frac{\hbar^2 [I(I+1) - K^2]}{2\mathfrak{J}}$$

γ -ray transition energy

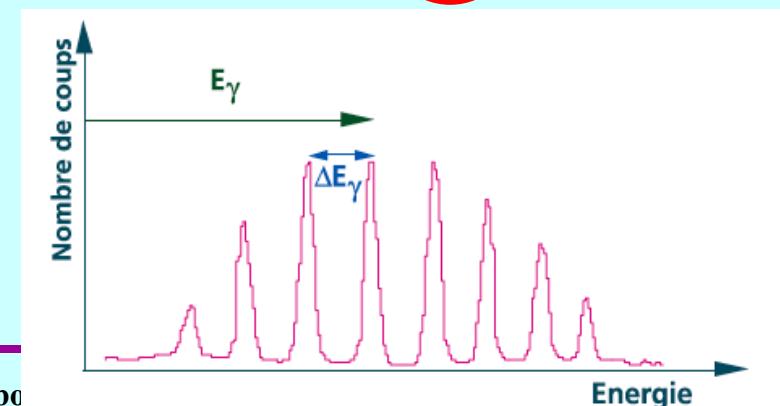
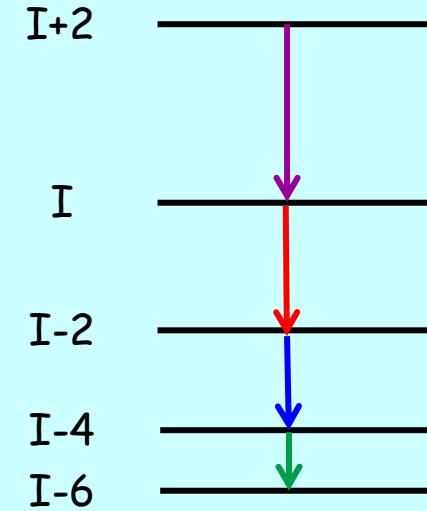
$$E_\gamma = \Delta E_{rot}$$

$$E_\gamma (I \rightarrow I-2) = \frac{\hbar^2 [I(I+1) - (I-2)(I-1)]}{2\mathfrak{J}} = \frac{\hbar^2 [4I-2]}{2\mathfrak{J}}$$

Difference between two consecutive transitions

$$\Delta E_\gamma (I, I-2) = \frac{\hbar^2 [4I-2]}{2\mathfrak{J}} - \frac{\hbar^2 [4(I-2)-2]}{2\mathfrak{J}} = \frac{4\hbar^2 [I - (I-2)]}{2\mathfrak{J}} = \frac{4\hbar^2}{\mathfrak{J}}$$
Constant !!

Regular spacing of γ rays



Nuclear shapes

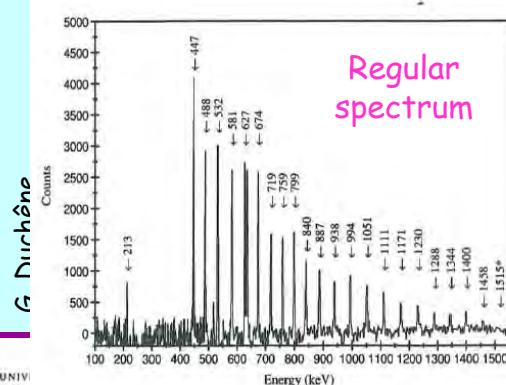
Collective

$$\vec{I} = \vec{R}$$

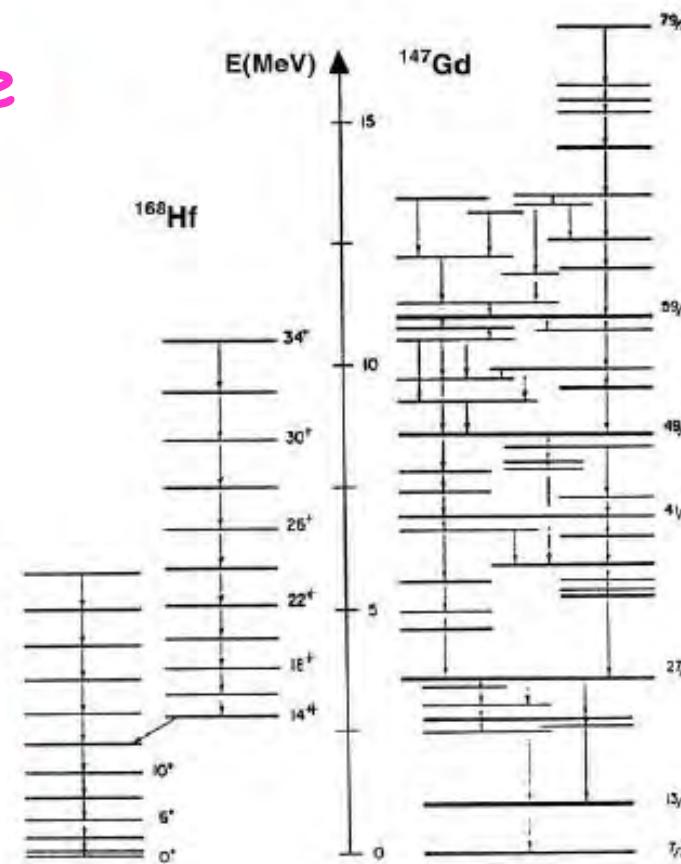
$$\Gamma \sim 100 \text{ Wu}$$

$$\tau \sim 100 \text{ fs}$$

Regular level scheme



Regular spectrum



Individual

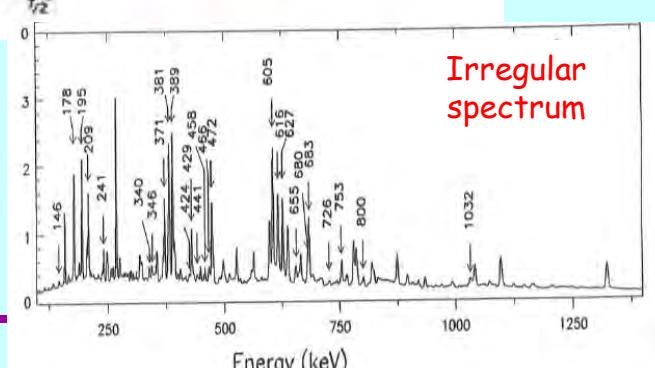
$$\vec{I} = \sum \vec{j}_i$$

$$\Gamma \sim \text{few Wu}$$

$$\tau > 10 \text{ ps}$$



Irregular level scheme

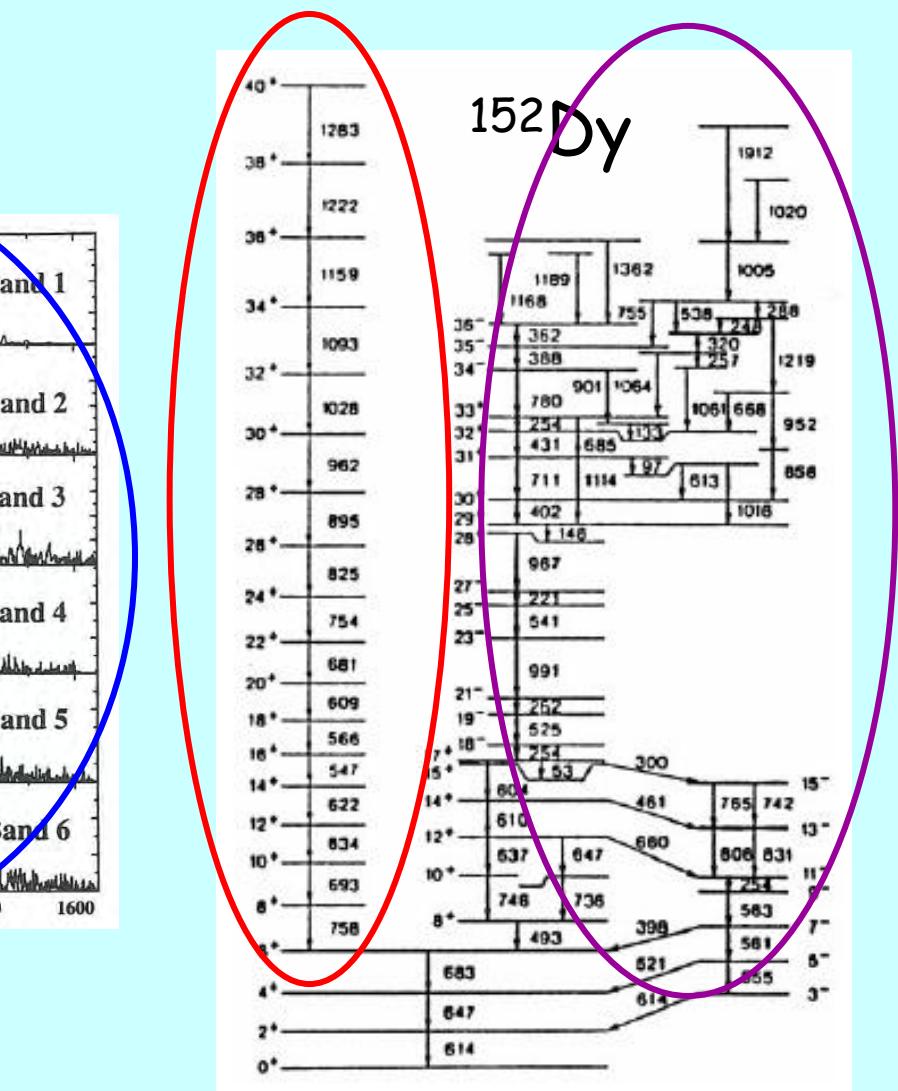
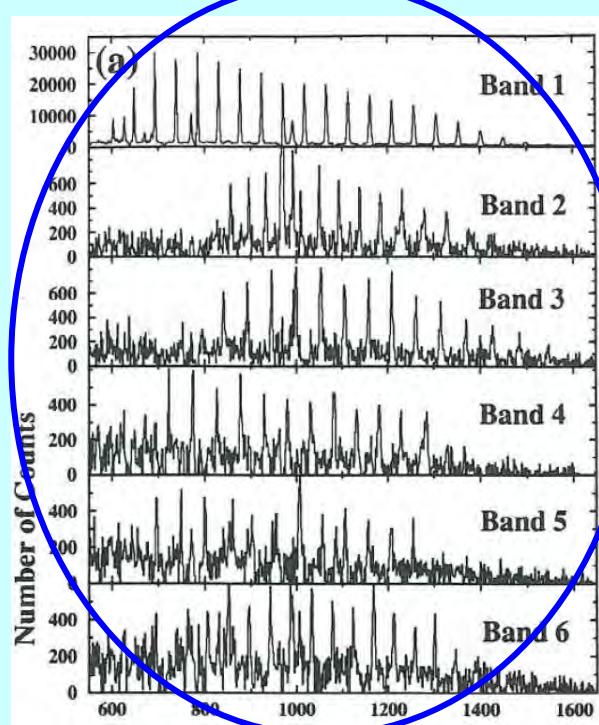


Irregular spectrum

Nuclear shapes

Super deformed prolate shape

- $\Gamma \sim 2000 \text{ Wu}$
 - $\tau \sim 10 \text{ fs}$



- Shape coexistence with normal deformed, single-particle and superdeformed

Observables

Excitation energy of the first excited state

$E(2+)$ for even-even nuclei $\longrightarrow E_\gamma$

Change of the excitation energy of specific states

Orbital displacement and shell-gap quenching and/or opening \longrightarrow change in E_γ versus number of neutrons or protons

Level scheme structure

- Organised: collective/rotational bands \rightarrow moment of inertia (E_γ), short-lived states (E_γ)
- Irregular: single-particle structure \rightarrow long lived states (E_γ) and isomers (**timing + E_γ**)
- Shape coexistence
- Spin (**angle + E_γ**), parity (**E_γ scattering**), momentum I (**particule angular distribution**), lifetime (E_γ)

Which reactions to populate the nucleus of interest?

Which tools for measuring these observables?

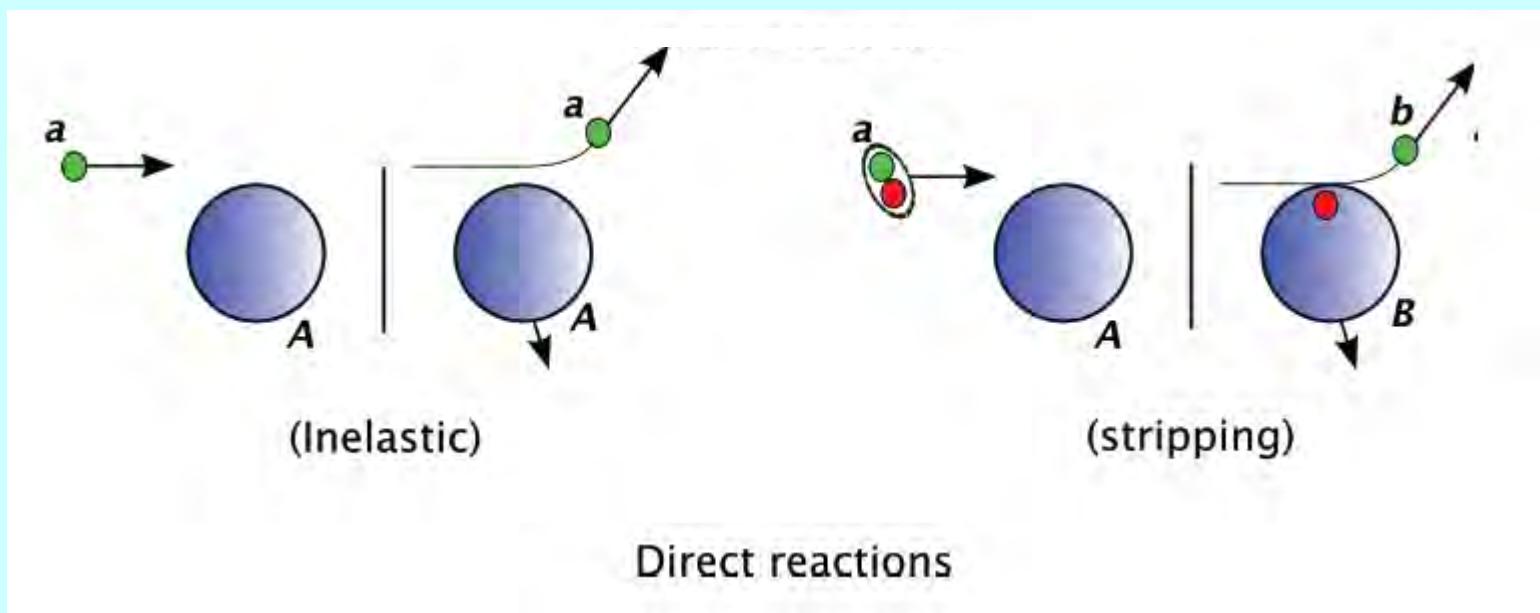
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Nuclear reactions

Transfert of nucleon

- Peripheral collisions (direct reactions) with 10 - 25 MeV/u beam energy
- Energy exchange, internal excitation \rightarrow inelastic channel
- Energy exchange, internal excitation and transfer of few nucleons \rightarrow transfer
 - Stripping channel: one nucleon of the projectile is transferred to the target
 - Pick up channel: one nucleon of the target is transferred to the projectile



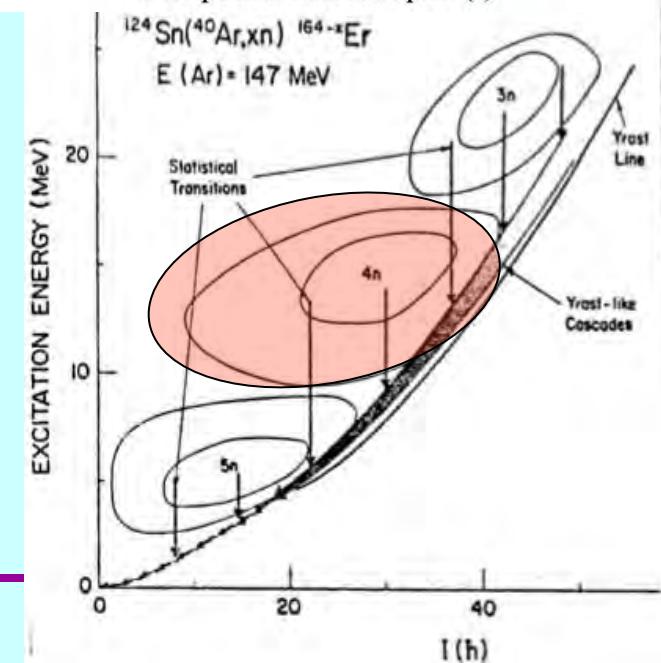
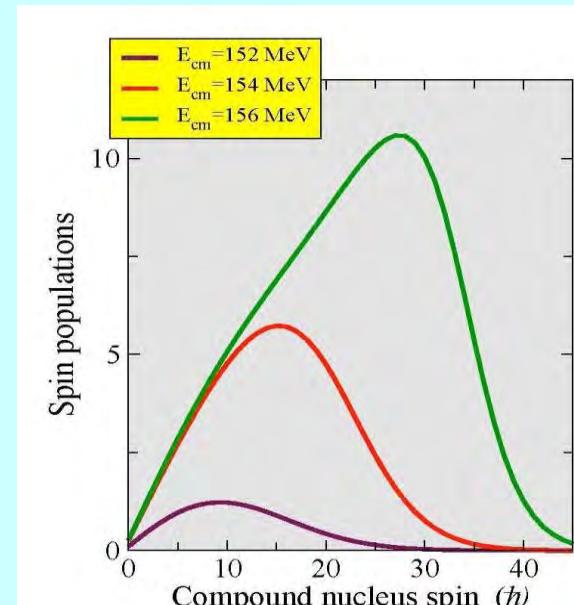
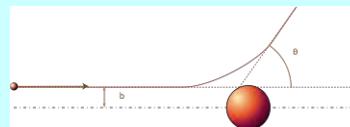
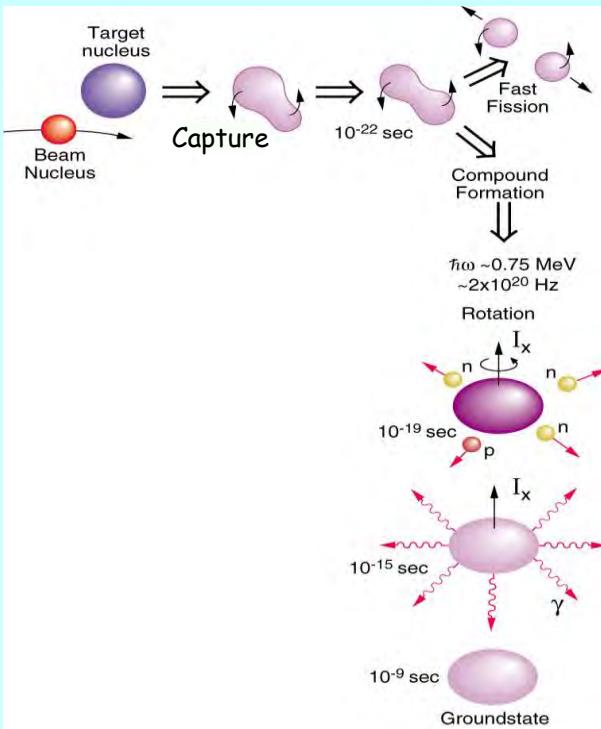
- Get information on the orbital on which the nucleon has been transferred

Nuclear reactions

Fusion -evaporation

- Central collisions ($E_{beam} \sim 6 \text{ MeV/u}$)

$$\vec{l} = \vec{r} \wedge \vec{p}$$



Nuclear reactions

Fusion-fission

- Fusion → compound nucleus → fission
 - ❑ Production of hundreds fragments can be identified
 - ❑ Neutron-rich isotopes populated
 - ❑ Large total cross-section (~ 250 mb)
 - ❑ Angular momentum transfer ($\sim 20\text{-}30 \hbar$)
- Inverse kinematics
 - ❑ Fast recoiling fission fragments
 - ❑ Forward focused fragments better entering in the magnet
- Systematic study of exotic-nuclei structure

Case of an experiment @ GANIL

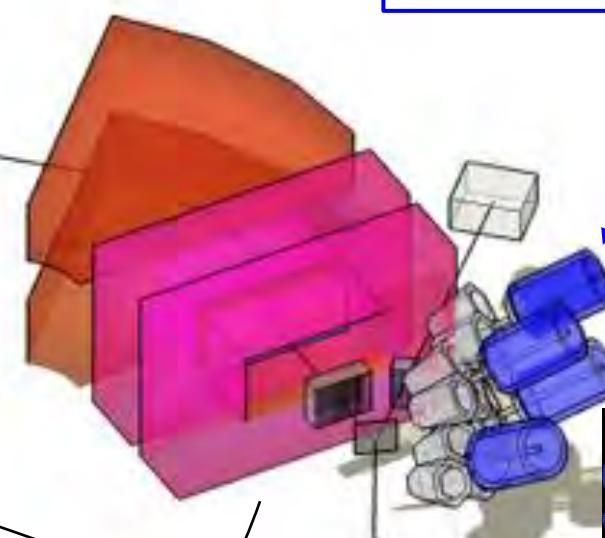
AGATA-VAMOS++ (exp at GANIL)

- Ge detector coupled to a spectrometer

^{238}U @ 6.2 MeV/u + ^9Be

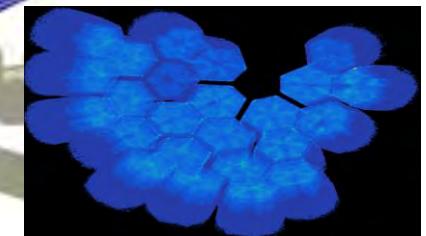
VAMOS++

GANIL

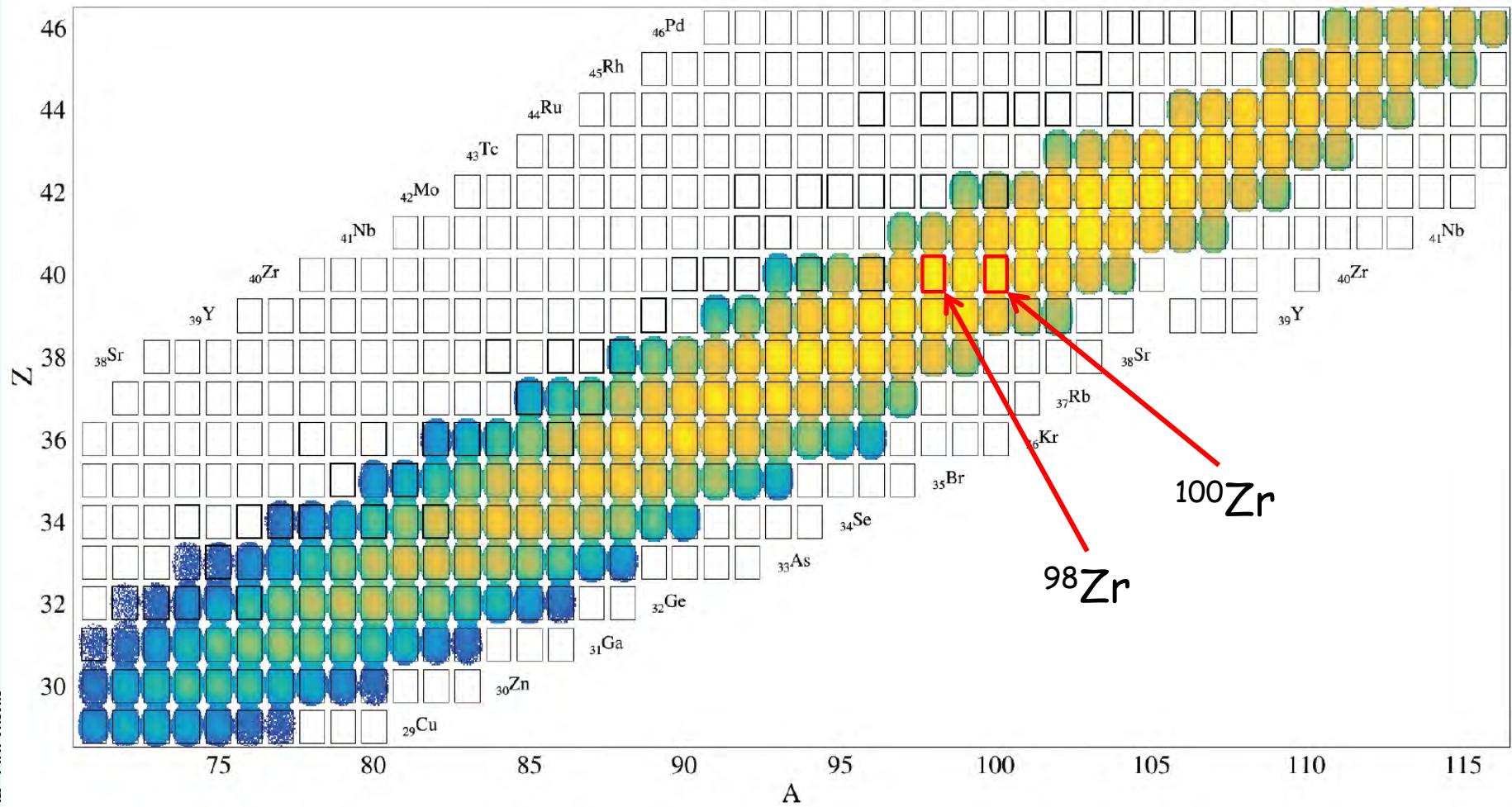


AGATA
24 crystals (2015)

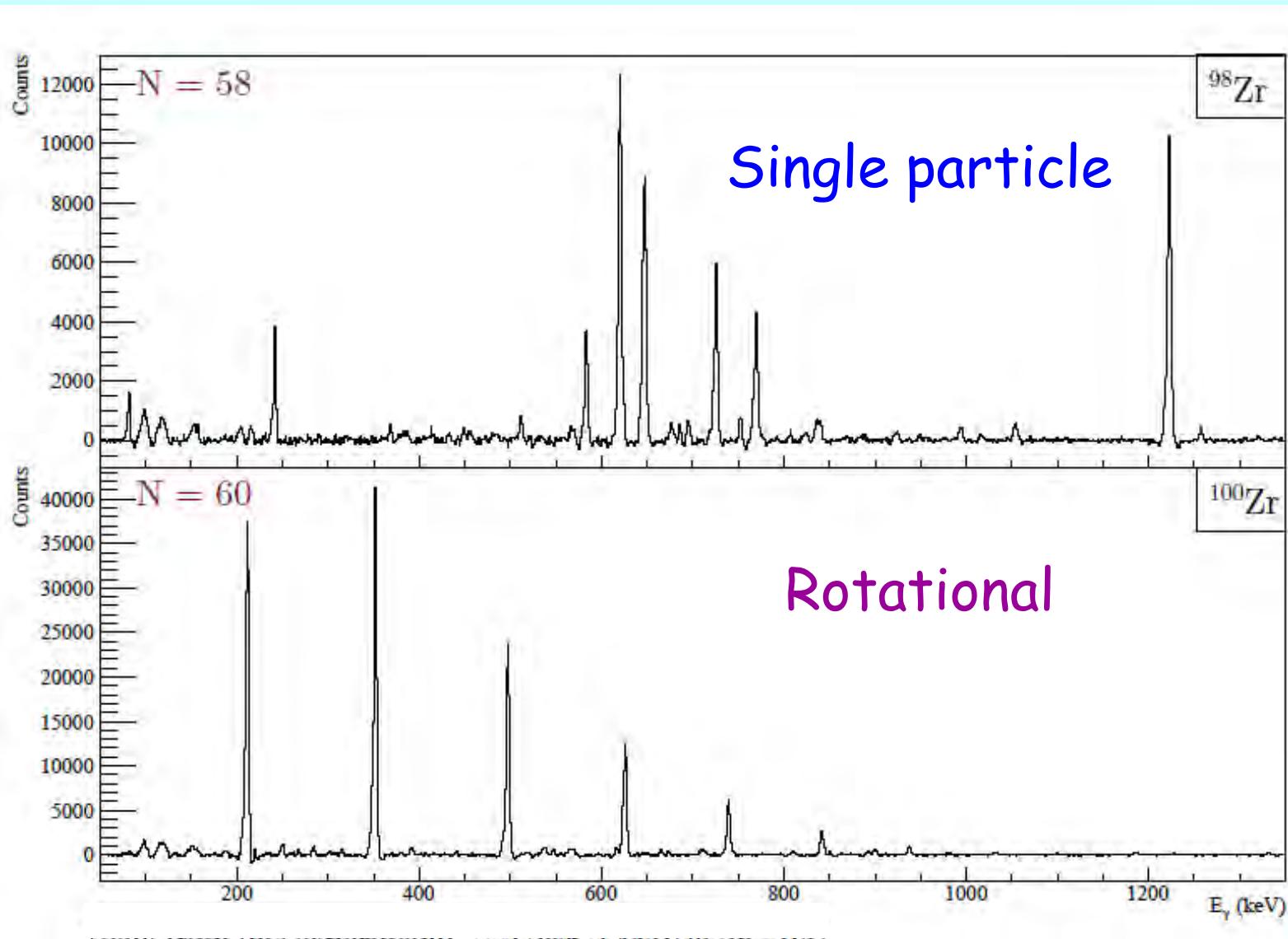
VAMOS++
 $\theta_{\text{Vamos}} = 28^\circ$, $B_p = 1.05$
205 identified frag.



Case of an experiment @ GANIL



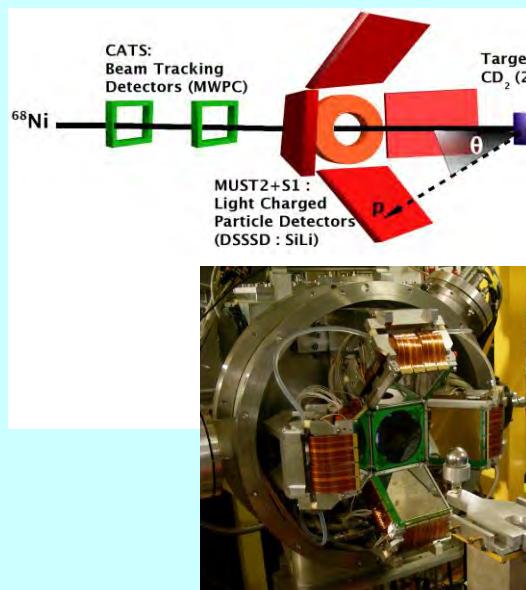
Selected nucleus in VAMOS - Prompt gamma-rays in AGATA



Orbital momentum assignment

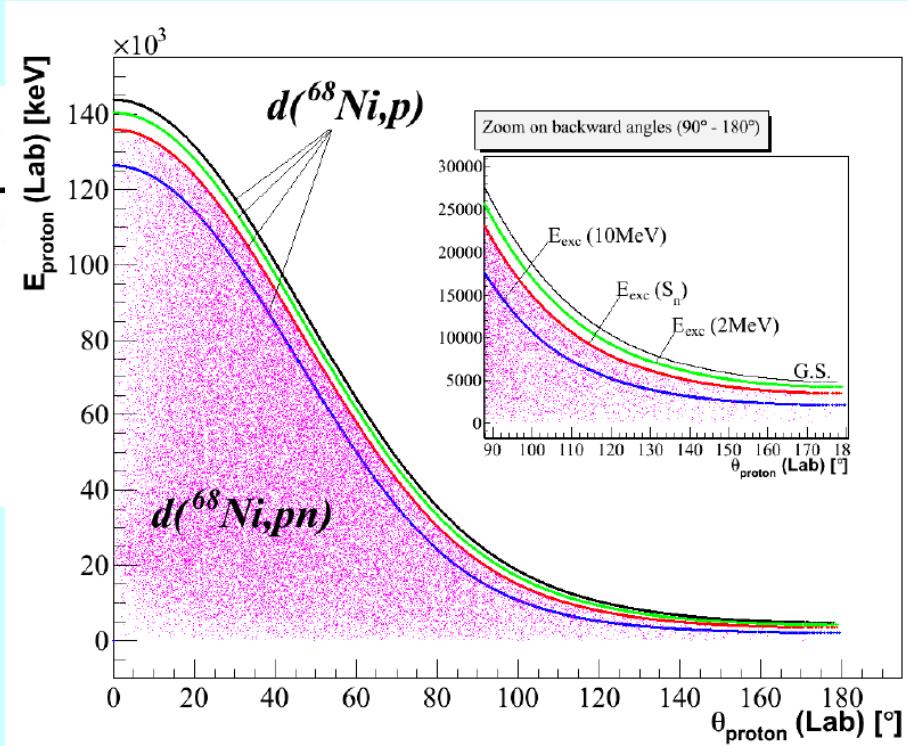
Direct reaction

- $^{68}\text{Ni} + d \rightarrow {}^{69}\text{Ni} + p$
- Orbital populated by the neutron with momentum $|l|$
- Proton energy and angular distribution is affected by the neutron destination

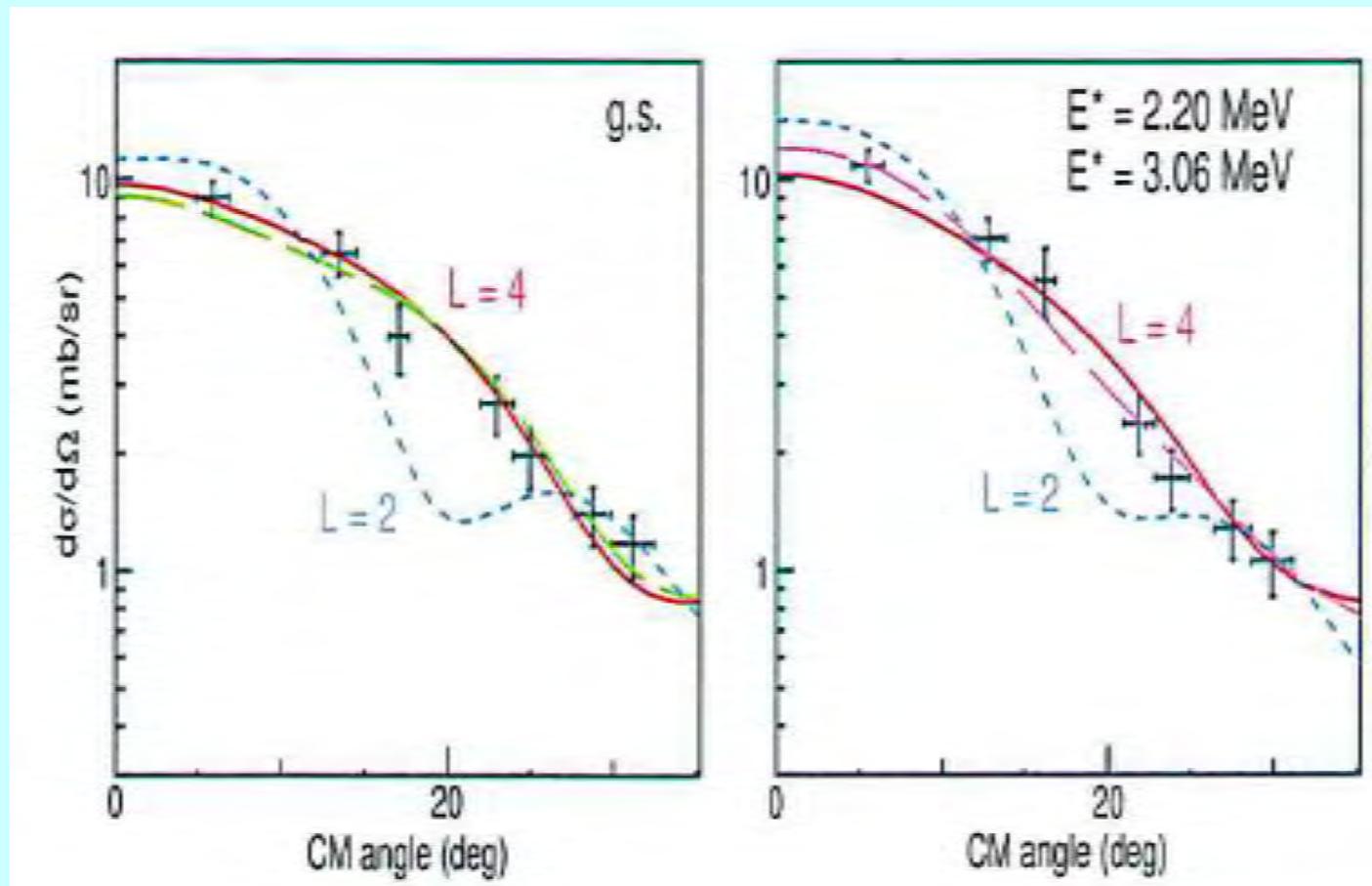


Observables

- p energy → excitation energy of the level populated
- p angular distribution → $|l|$



Orbital momentum assignment



Direct reaction

- With polarised $d \rightarrow j = l \pm \frac{1}{2}$

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Radiation-matter interactions and detectors

Emitted particles in nuclear reactions

- Charged particles (protons, alphas, electrons)
- Fragments (Z, A)
- γ rays
- Neutrons

Radiation-matter interactions and detectors

Charged particles

- Bethe formula

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} N Z \left[\ln \frac{2m_e c^2}{I} \beta^2 \gamma^2 - \beta^2 \right]$$

Linear stopping power

- incident particle
 - ❑ z charge state of the particle
 - ❑ $\beta = v/c$
 - ❑ $\gamma = 1/(1 - \beta^2)^{1/2}$
- penetrated material
 - ❑ Z atomic number of the material
 - ❑ N number of atoms per volume unit
 - ❑ I ionisation potential (~ 10 eV to few 10 keV)

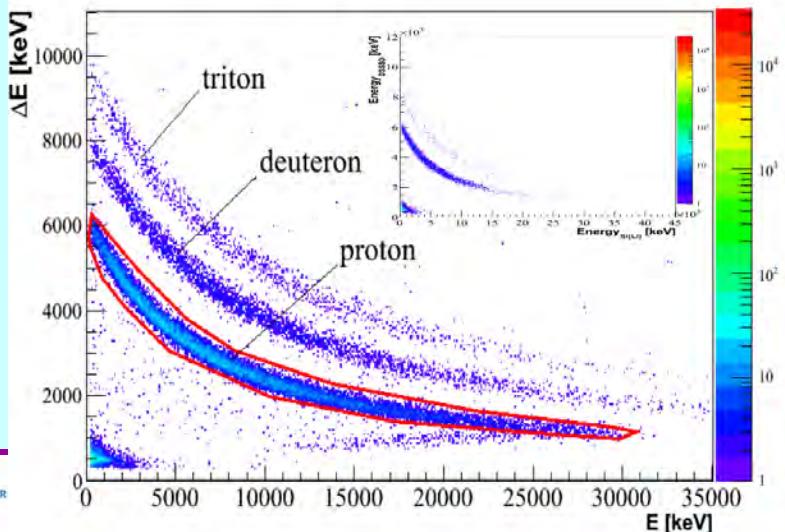
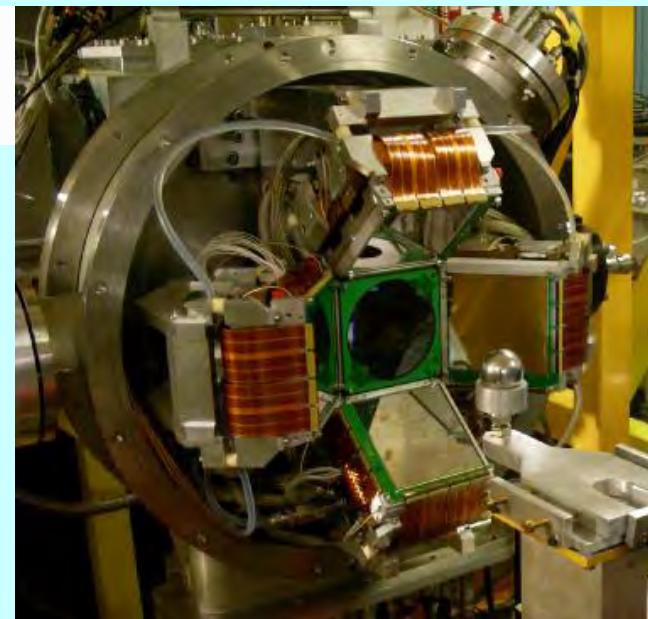
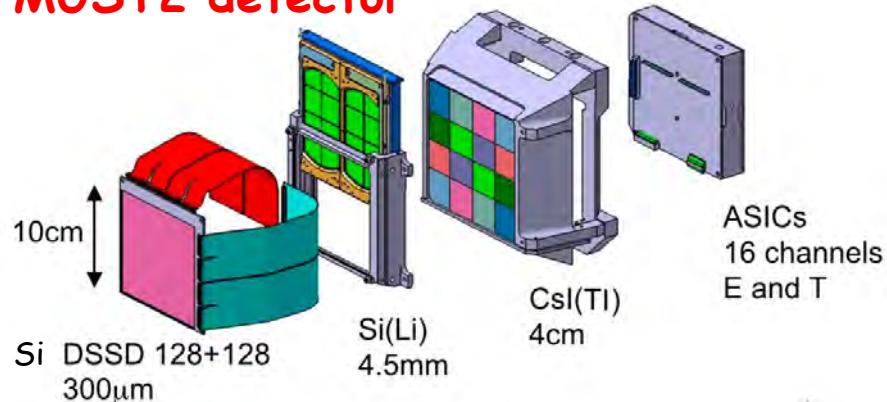
Radiation-matter interactions and detectors

Charged particles

- Particle identification

$$E \times \Delta E \propto A z^2$$

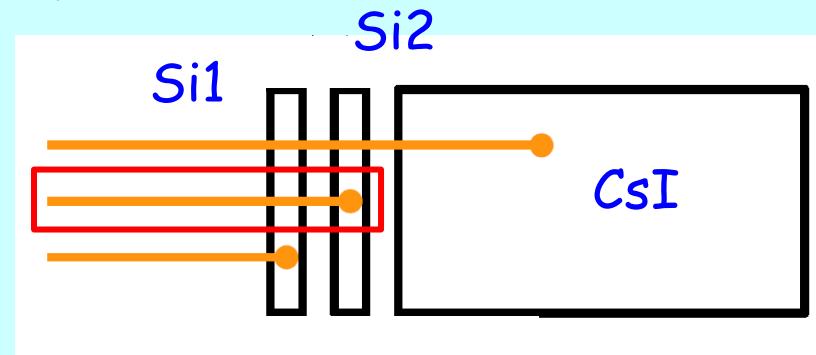
MUST2 detector



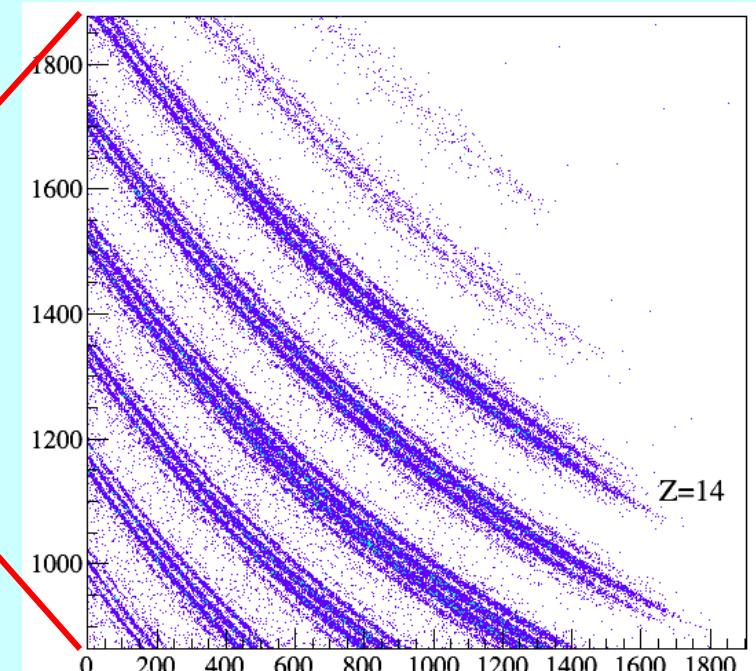
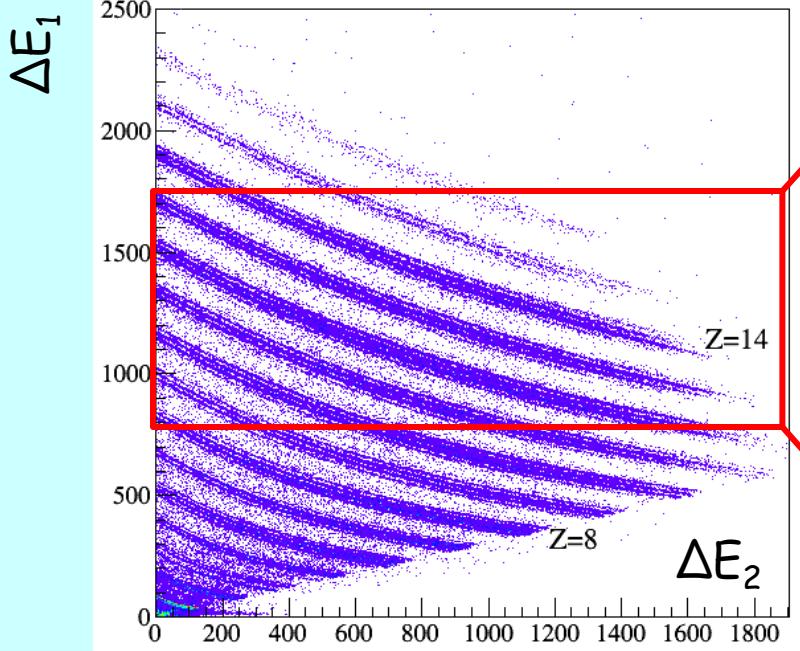
Radiation-matter interactions and detectors

Fragments

- Particle identification
 - ❑ Si detectors (FAZIA)
 - ❑ Telescope of 2 ΔE Si det. and 1 CsI det.
 - ❑ Pulse-shape analysis



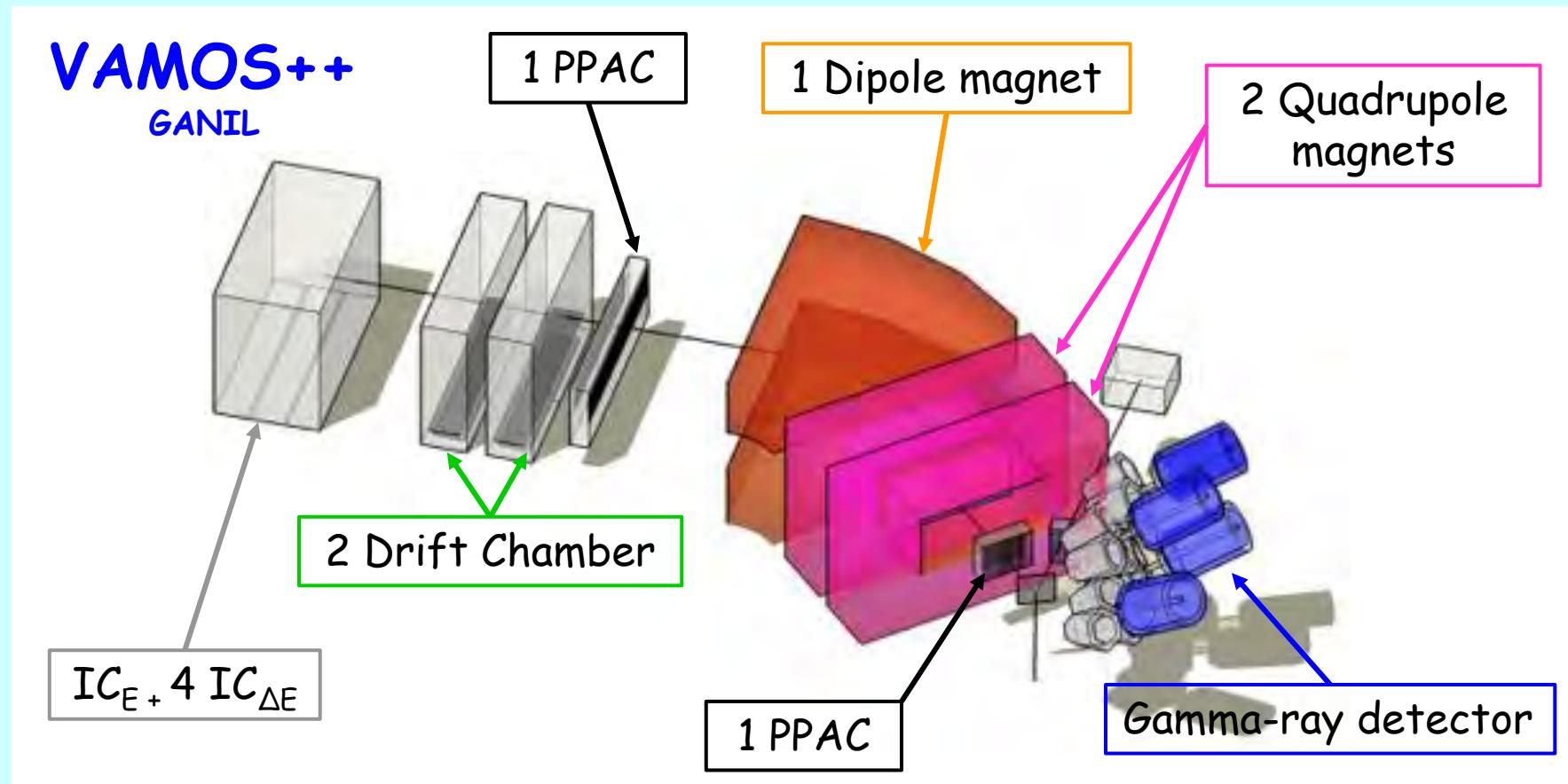
Case of fragments stopped in the Si2



Radiation-matter interactions and detectors

Fragments

- Particle identification
 - Spectrometer

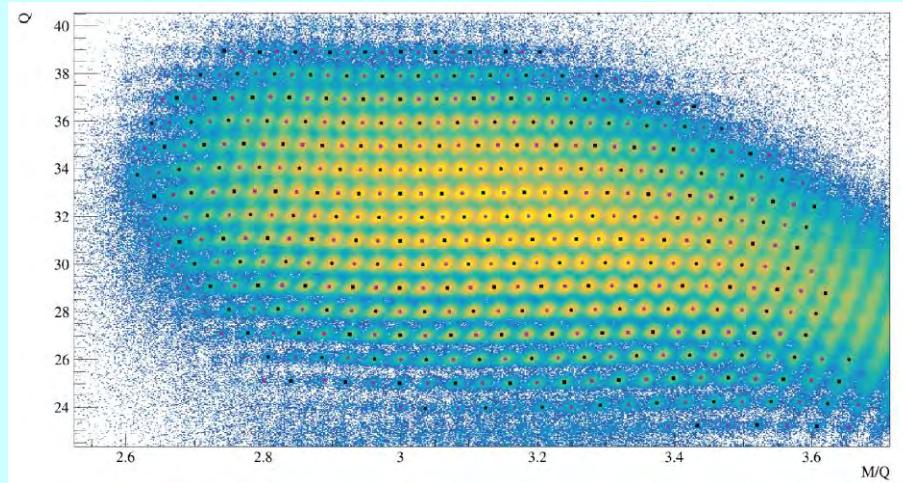
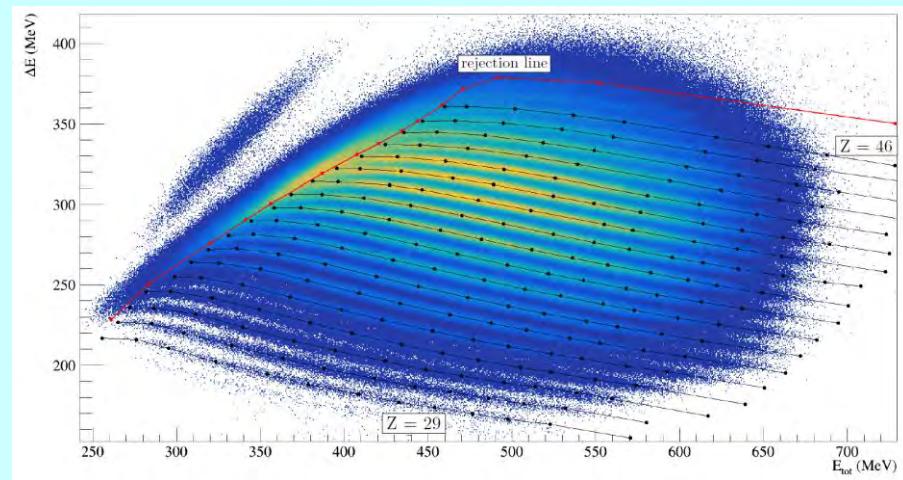


Radiation-matter interactions and detectors

Fragments

➤ Spectrometer

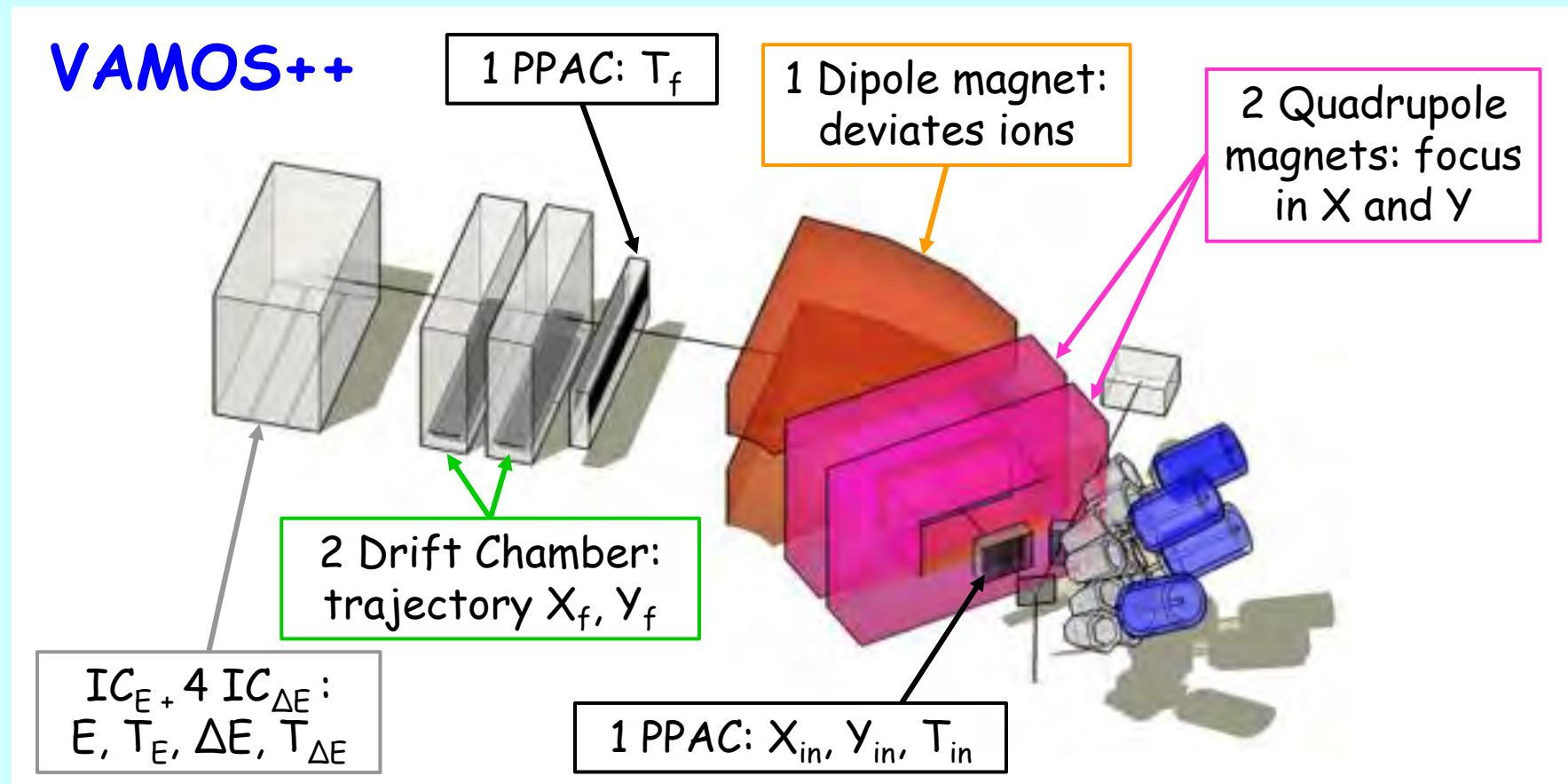
- ❑ Magnets: focus in X and Y (quadripoles) and deviate the ions for mass selection (dipole)
- ❑ PPAC: (Parallel Plate Avalanche Counter)
 - ❖ Gaseous detector
 - ❖ Ion trajectory (X_{in}, Y_{in})
 - ❖ Time of flight ($ToF = T_f - T_{in}$)
 - ❖ Velocity ($v = L/ToF$)
- ❑ Drift chamber:
 - ❖ Gaseous detector
 - ❖ Ion trajectory (X_f, Y_f)
- ❑ IC: (Ionisation chamber)
 - ❖ Gaseous detector
 - ❖ Z identification ($\Delta E, E$)
 - ❖ Mass/Charge state (M/Q) determination
 - ❖ Mass determination



Radiation-matter interactions and detectors

Fragments

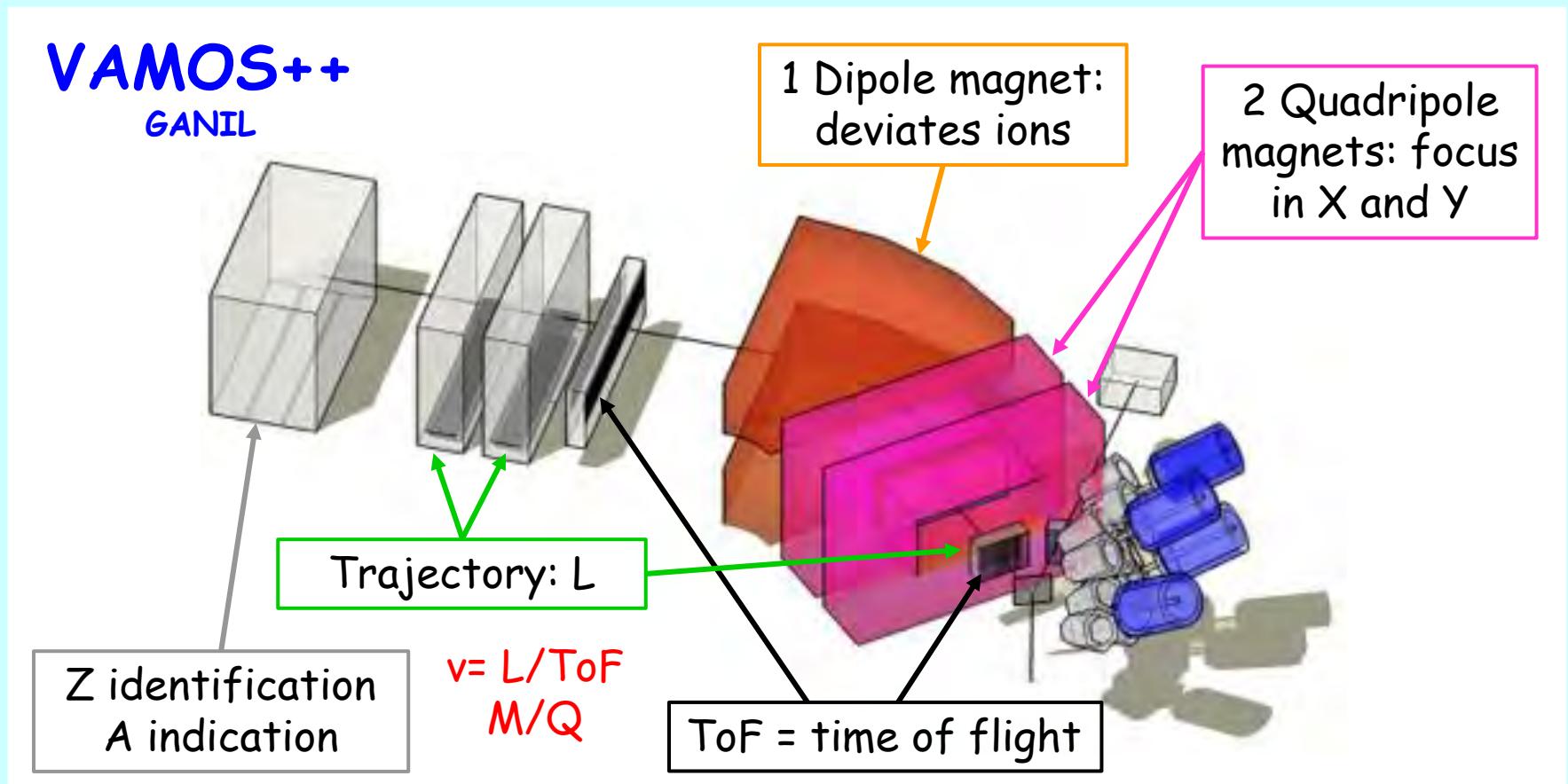
- Particle identification
- Spectrometer



Radiation-matter interactions and detectors

Fragments

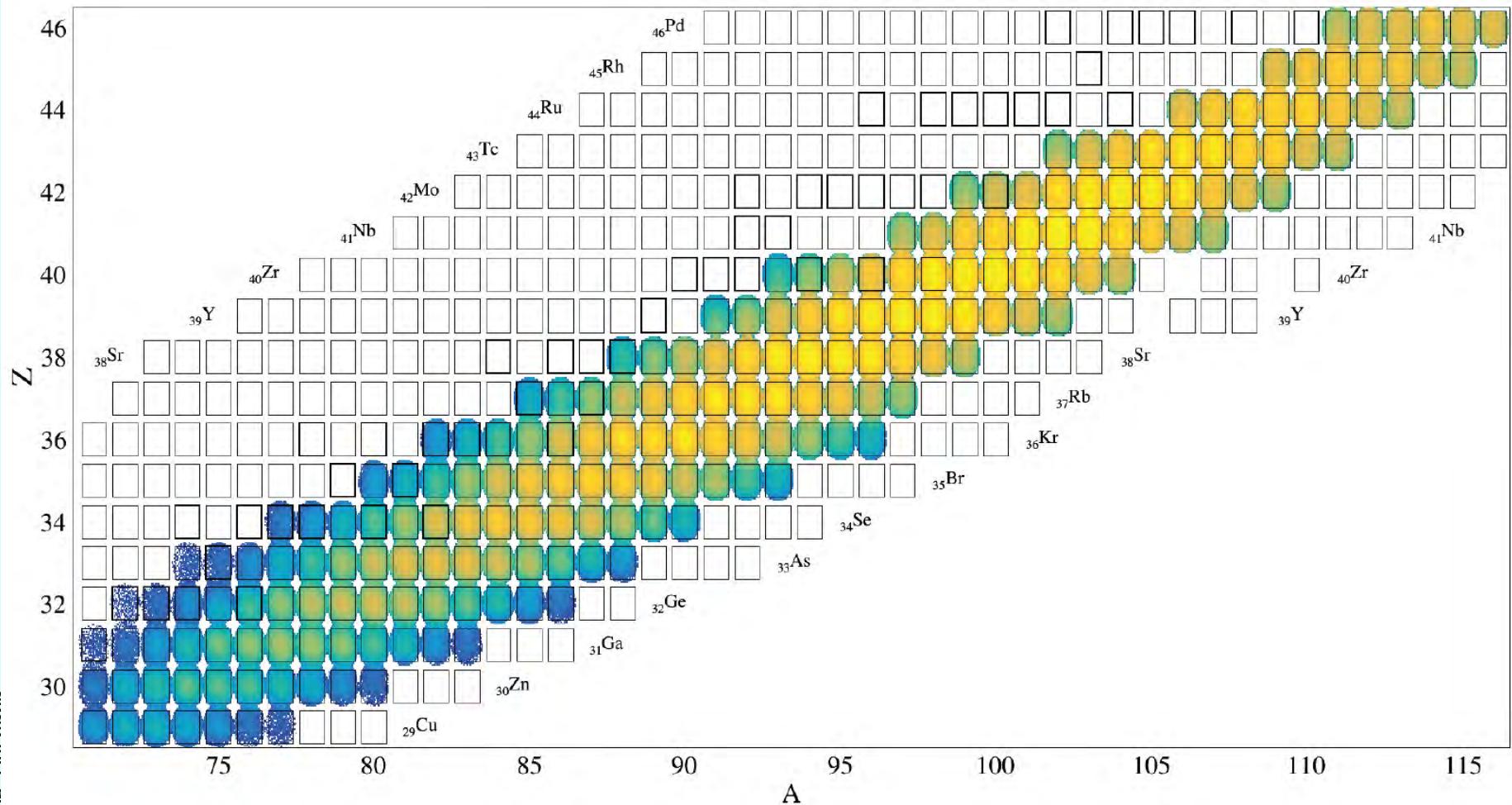
- Particle identification
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Radiation-matter interactions and detectors

Fragments

- Spectrometer



γ rays

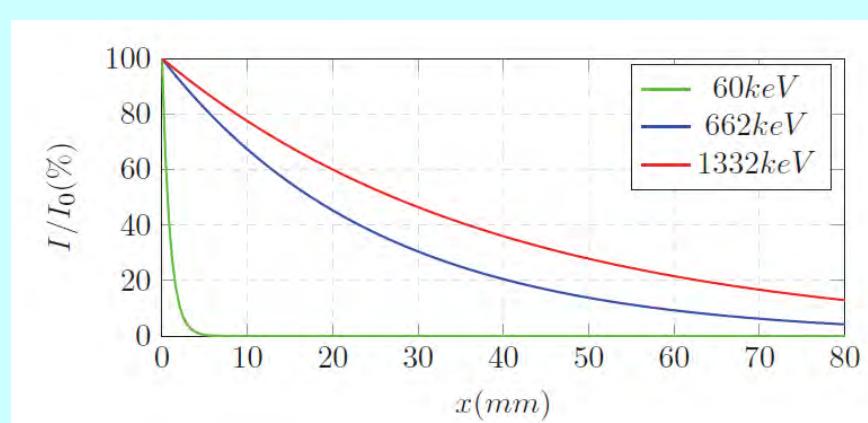
➤ Transmission

$$I(x) = I_0 e^{-\mu x}$$

- ❑ μ is the total absorption coefficient
- ❑ x thickness of material
- ❑ μ depends on the material and on the γ -ray energy

➤ γ -ray detection

- ❑ Energy transfer to primary charged particle and secondary ones
- ❑ Detection of the charges



Radiation-matter interactions and detectors

γ rays

- Photoelectric effect
 - Full photon energy transfer to one electron

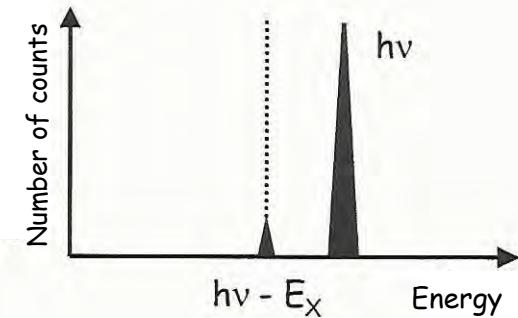
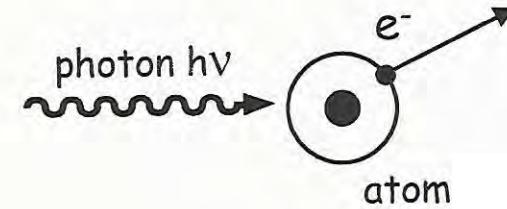
$$E_\gamma = h\nu$$

$$E_{e^-} = h\nu - B_{e^-}$$

$$\sigma_{\text{photo}} \sim (h\nu)^{-3.5} \cdot Z^5$$

Fast cross section reduction with energy

Strongly depend of Z of material/detector



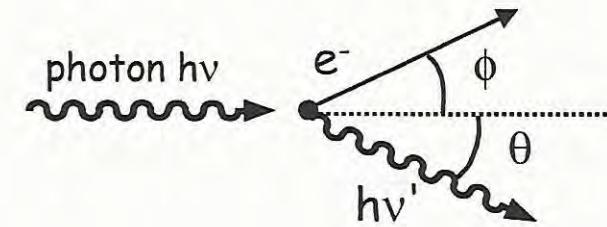
Radiation-matter interactions and detectors

γ rays

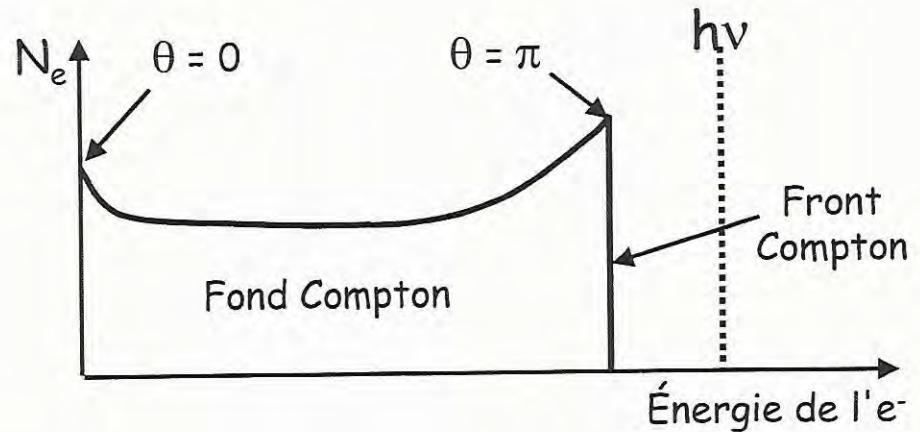
- Compton effect
 - Elastic scattering of a photon on a quasi-free electron

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2} (1 - \cos \theta)}$$

$$E_{e^-} = h\nu - h\nu'$$



The electron energy varies
continuously with θ



Radiation-matter interactions and detectors

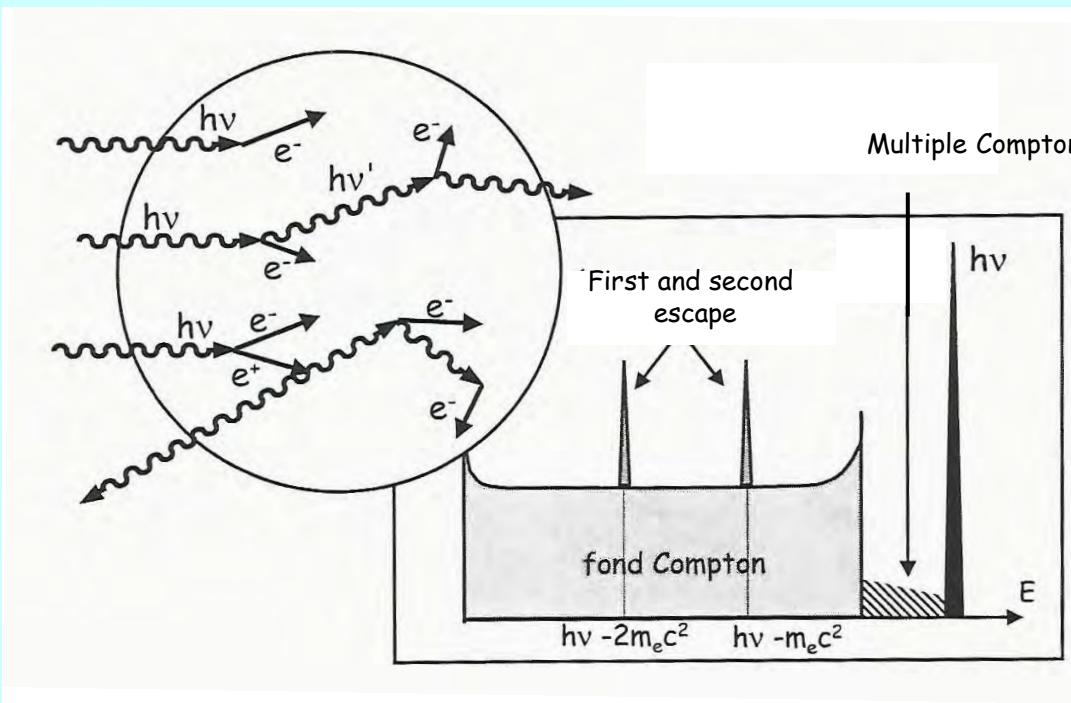
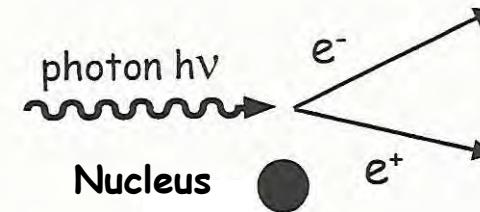
γ rays

► Pair creation

- A photon is materialised in one electron and one positron

$$h\nu > 2 m_e c^2 (1,022 \text{ MeV})$$

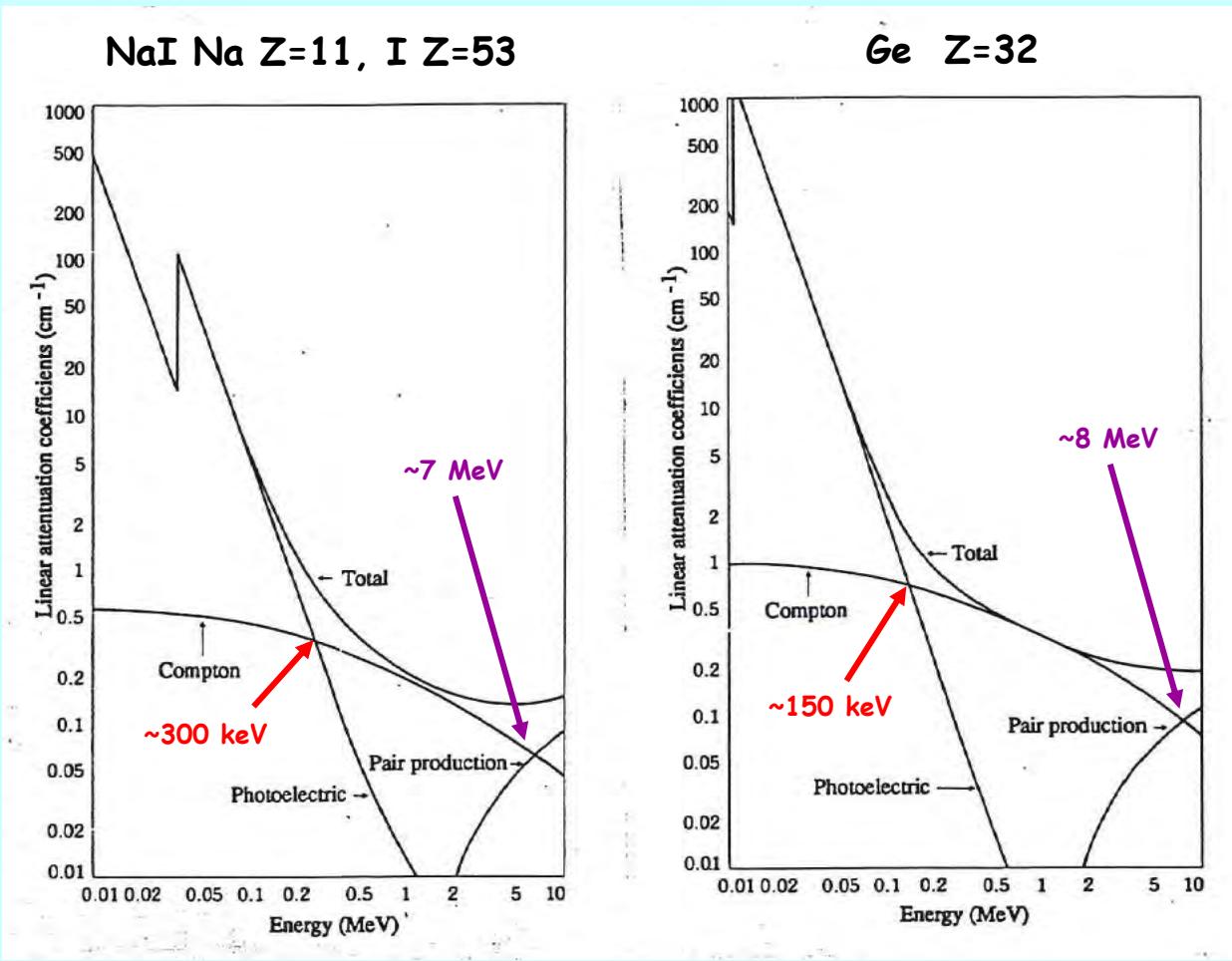
$$E_{e^-} = E_{e^+} = \frac{1}{2}(h\nu - 2 m_e c^2)$$



Radiation-matter interactions and detectors

γ rays

- Total absorption coefficient $\mu = \mu_{\text{Photoelectric}} + \mu_{\text{Compton}} + \mu_{\text{Pair creation}}$

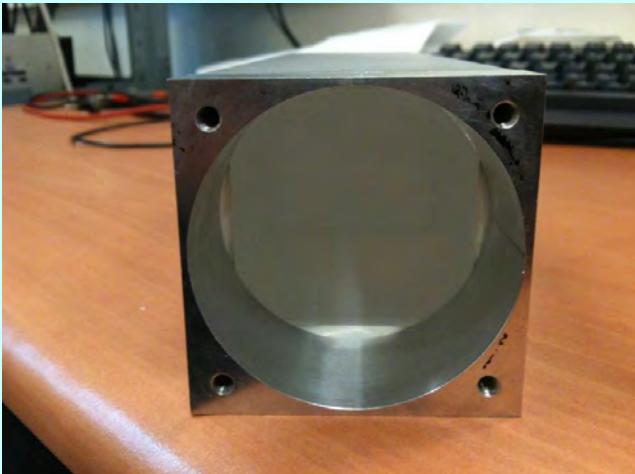
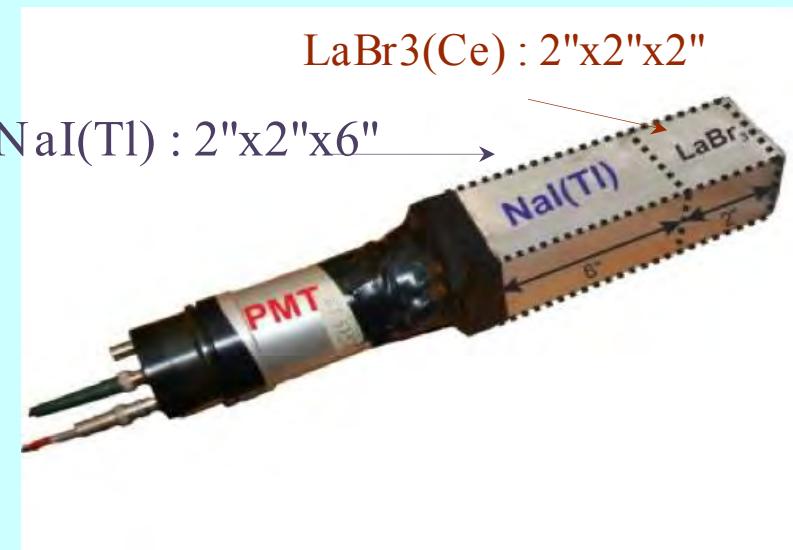


Radiation-matter interactions and detectors

γ rays

➤ Gamma-ray detectors

- ❑ Scintillators -> PARIS detector
- ❑ Phoswitch: front LaBr_3 crystal
back NaI crystal
One photomultiplier (PMT)
- ❑ Large detection efficiency
- ❑ Fast timing response and good energy resolution (LaBr_3)

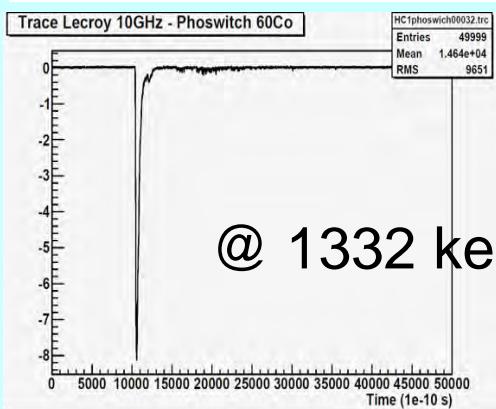


Radiation-matter interactions and detectors

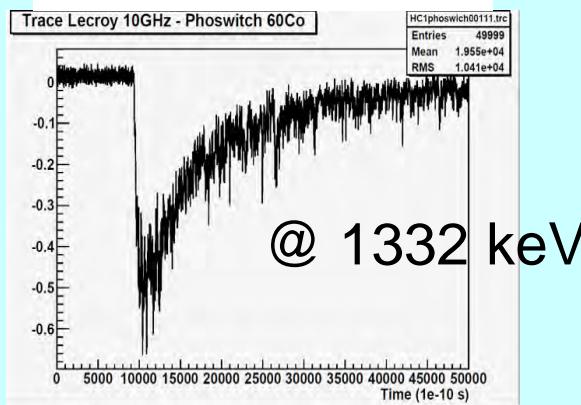
γ rays

- Gamma-ray detectors
- PARIS detector performance

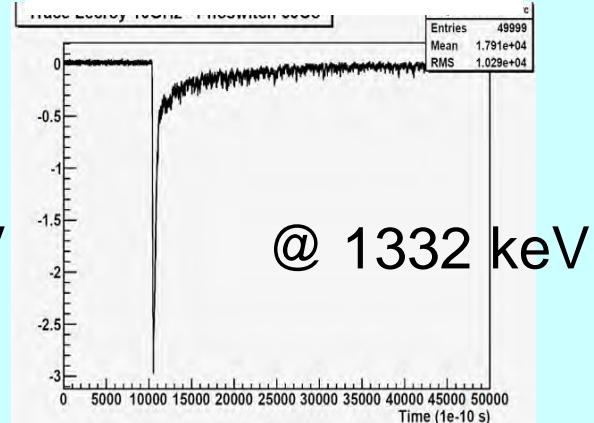
γ interaction in LaBr₃
only



γ interaction in NaI
only

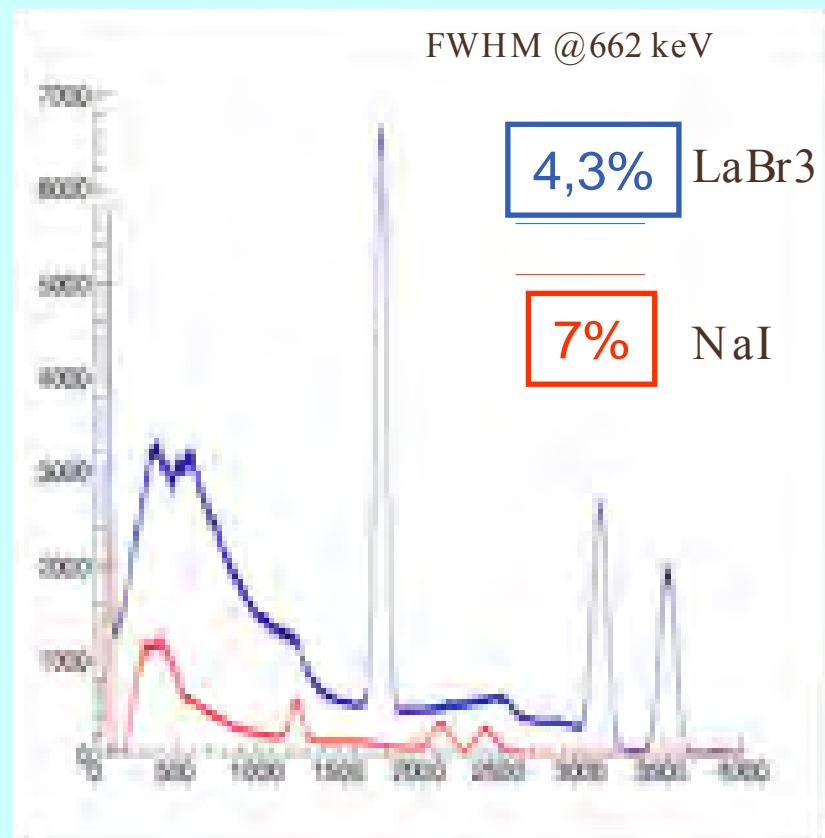
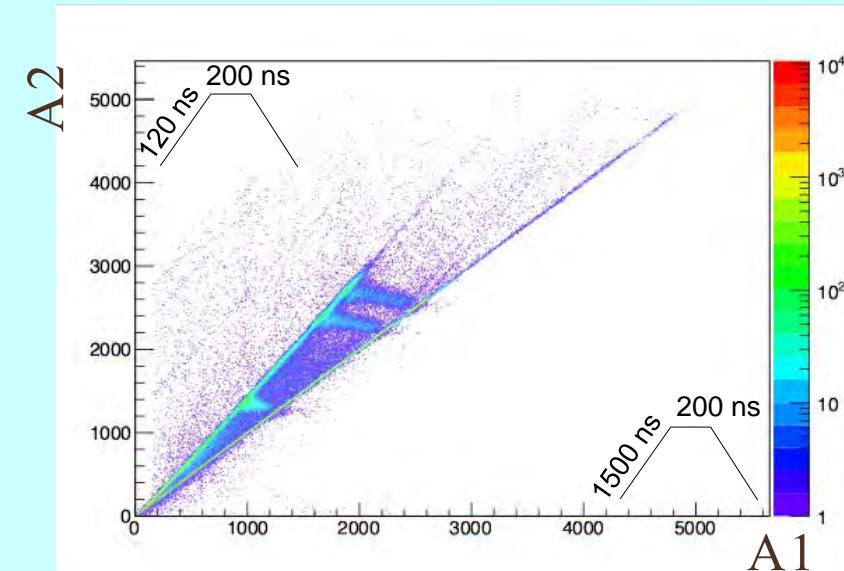


γ interaction in both
shells



γ rays

- Gamma-ray detectors
 - PARIS detector performance using digital electronics

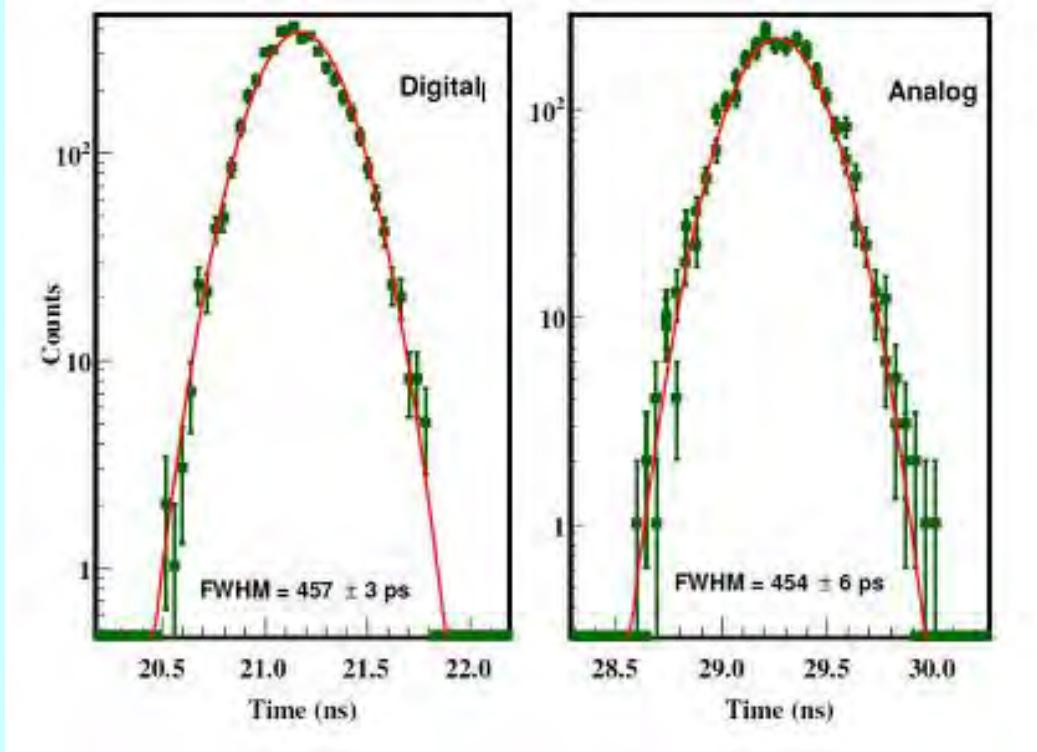


Radiation-matter interactions and detectors

γ rays

- Gamma-ray detectors
 - PARIS detector timing performance

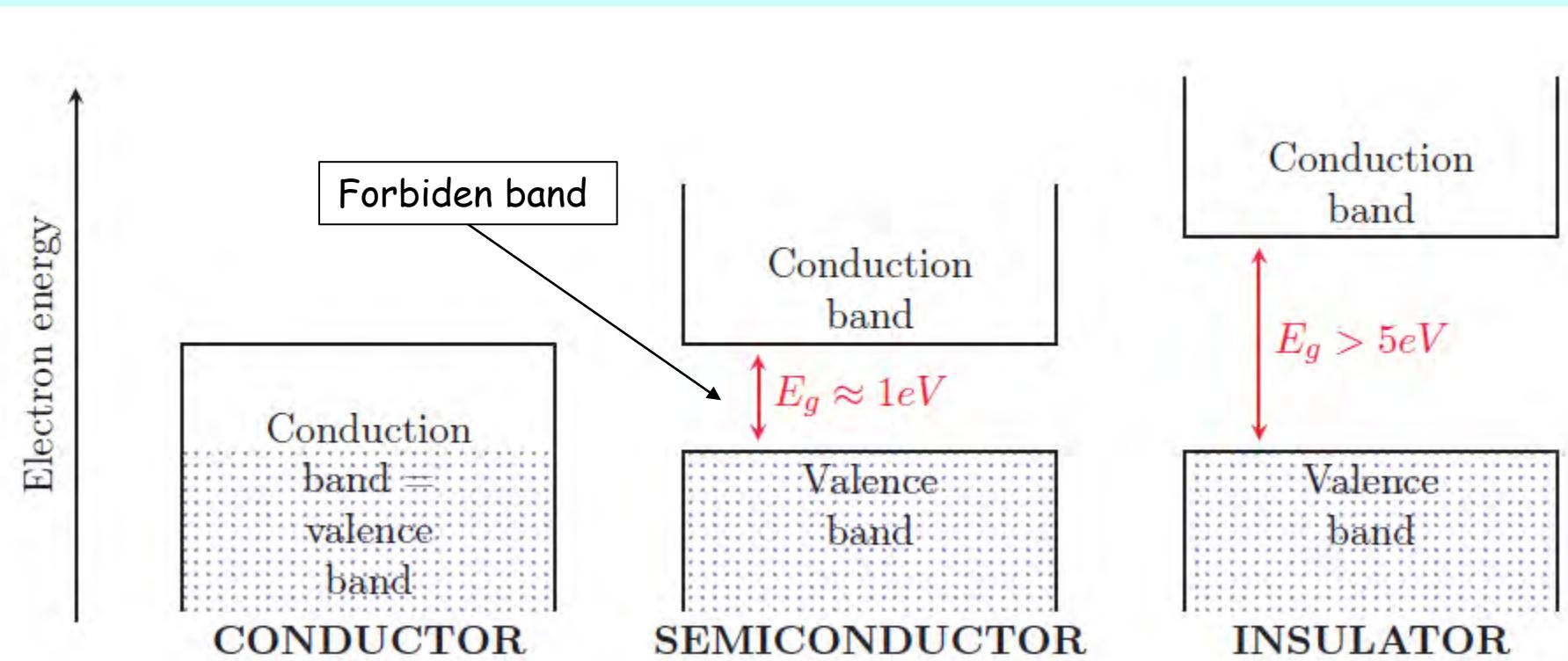
(see C. Ghosh et al., JINST 11 P05023 (2016))



Radiation-matter interactions and detectors

γ rays

- Gamma-ray detectors
 - Semiconductors (Si, Ge)



Radiation-matter interactions and detectors

γ rays

- Gamma-ray detectors
- Semiconductors characteristics

Semiconductors	Forbiden band at 300 K	Electron-hole pair creation energy W
Z=14 Si	1.12 eV	3.61 eV (300 K)
Z=32 Ge	0.67 eV	2.96 eV (90 K)
Z=6 Diamant C	5.47 eV	13.2 eV (300K)
Z=31/33 GaAs	1.43 eV	4.27 eV
Z=48/52 CdTe	1.5 eV	4.43 eV (300 K)
Z=80/53 HgI ₂	2.1 eV	4.15 eV

$N = E_\gamma / W$
for Ge and a 1 MeV γ ray
 $N > 300\,000$ pairs e-h

Good energy resolution

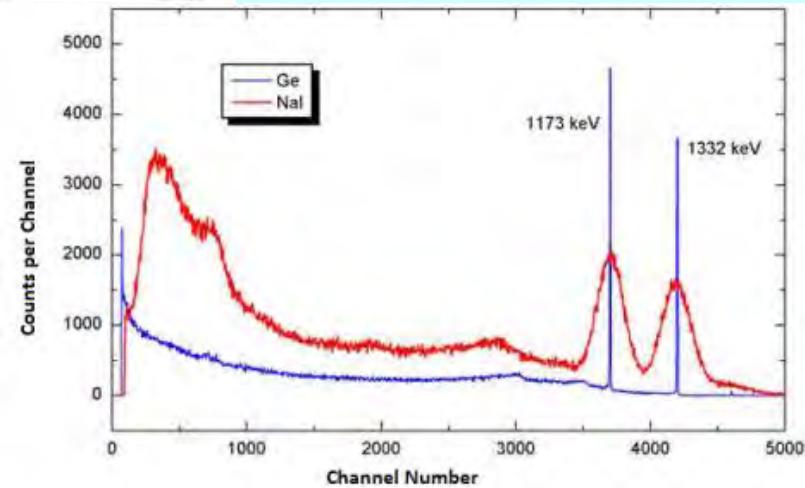
FWHM = Full Width Half Maximum

FWHM (NaI) / E ~ 8%

FWHM (LaBr₃) / E ~ 3-4%

FWHM (₁₄Si) / E ~ 1.5% → X rays

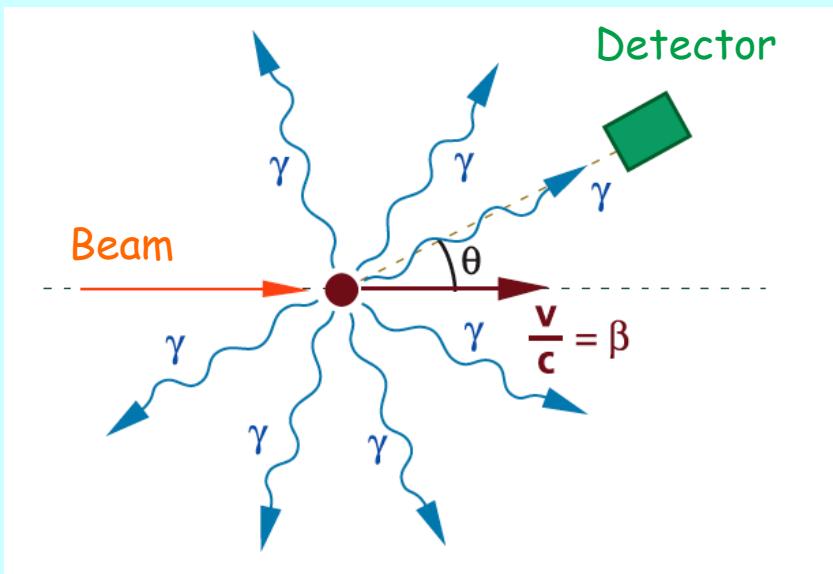
FWHM (₃₂Ge) / E ~ 0.2% → γ rays



Doppler effect

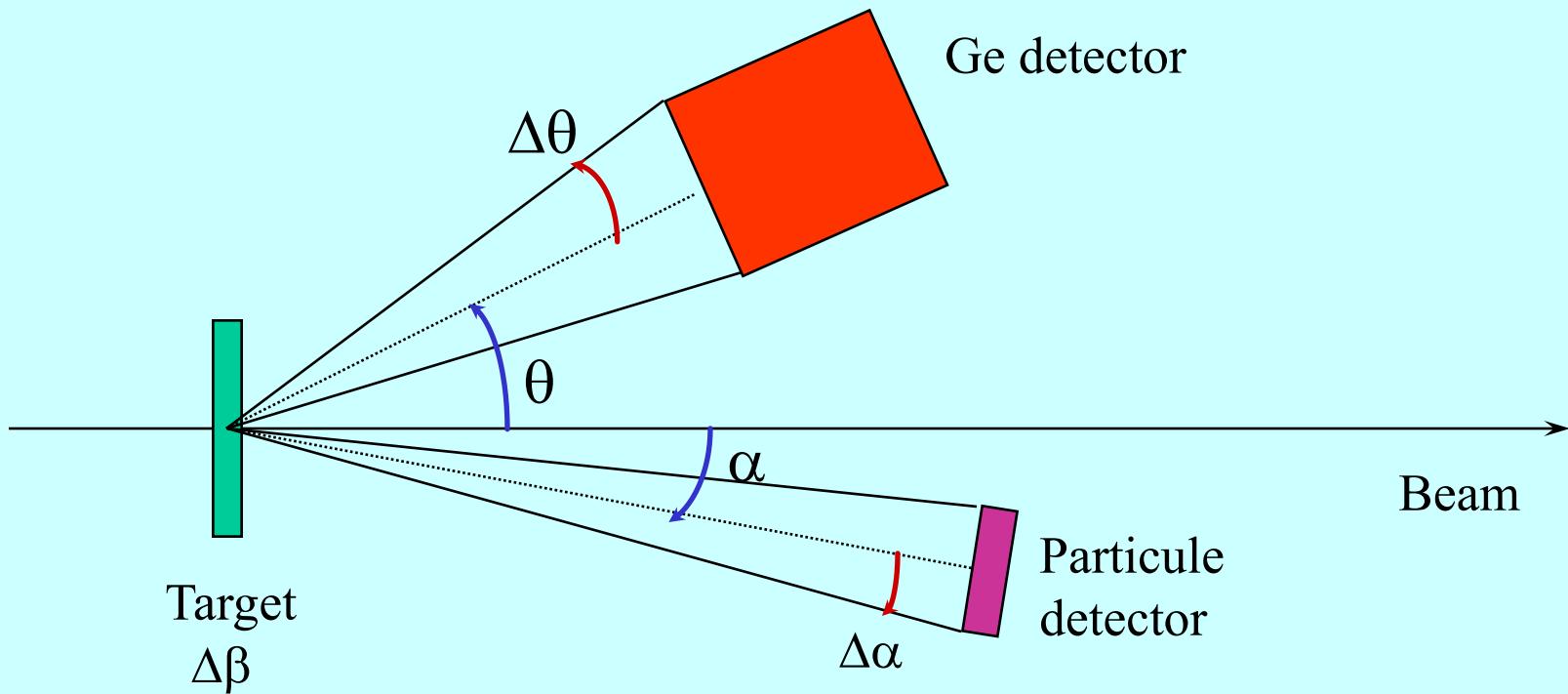
Doppler effect

- v = recoil velocity of the nucleus
- Detected energy depend on the angle of the detector relative to the beam axis



$$\Delta E_\gamma(\theta, E_\gamma) = E_\gamma \frac{v}{c} \cos(\theta).$$

Doppler effect



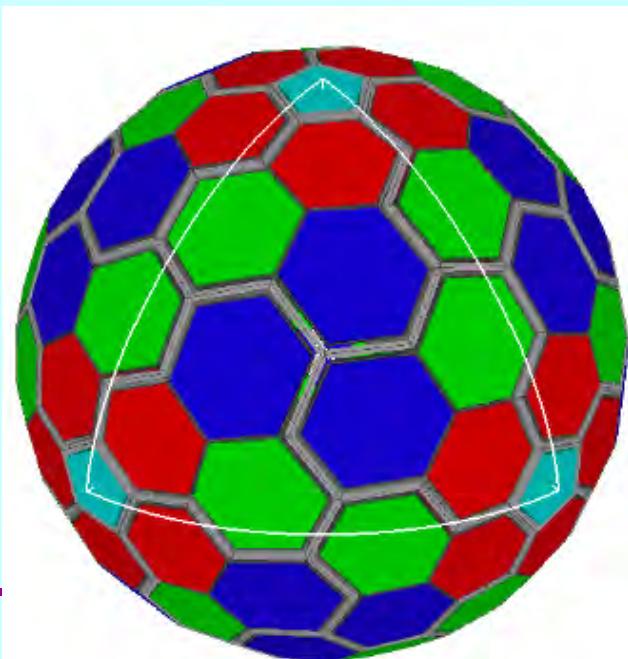
$$\text{FWHM} = \left\{ \text{FWHM}_{\text{int}}^2 + \boxed{\text{FWHM}_{\Delta\theta}^2} + \boxed{\text{FWHM}_{\Delta\alpha}^2} + \boxed{\text{FWHM}_{\Delta\beta}^2} \right\}^{1/2}$$

Multi-detector AGATA for γ -ray detection

Solely composed of Ge crystals

Pulse-shape analysis + γ -ray tracking

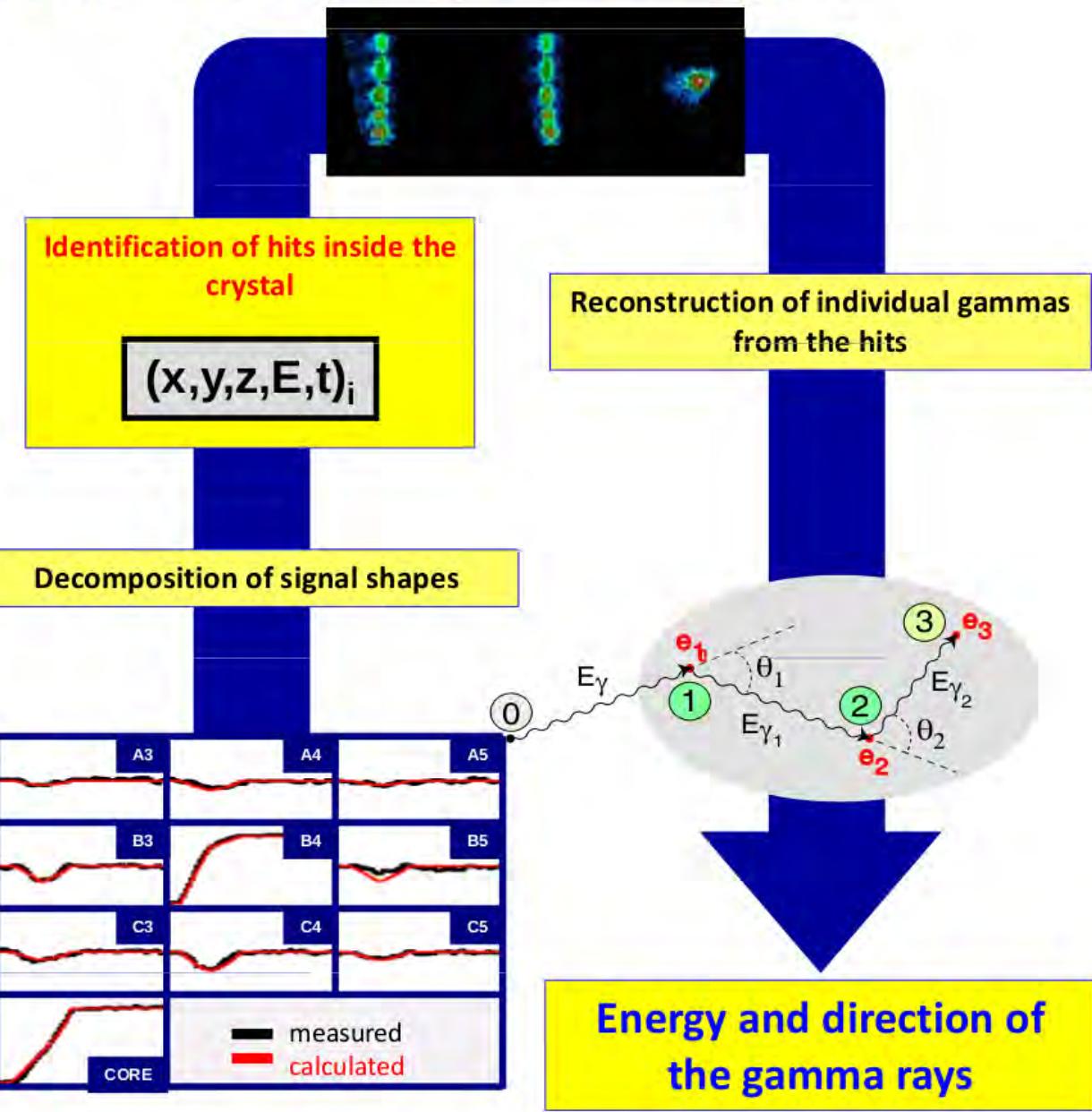
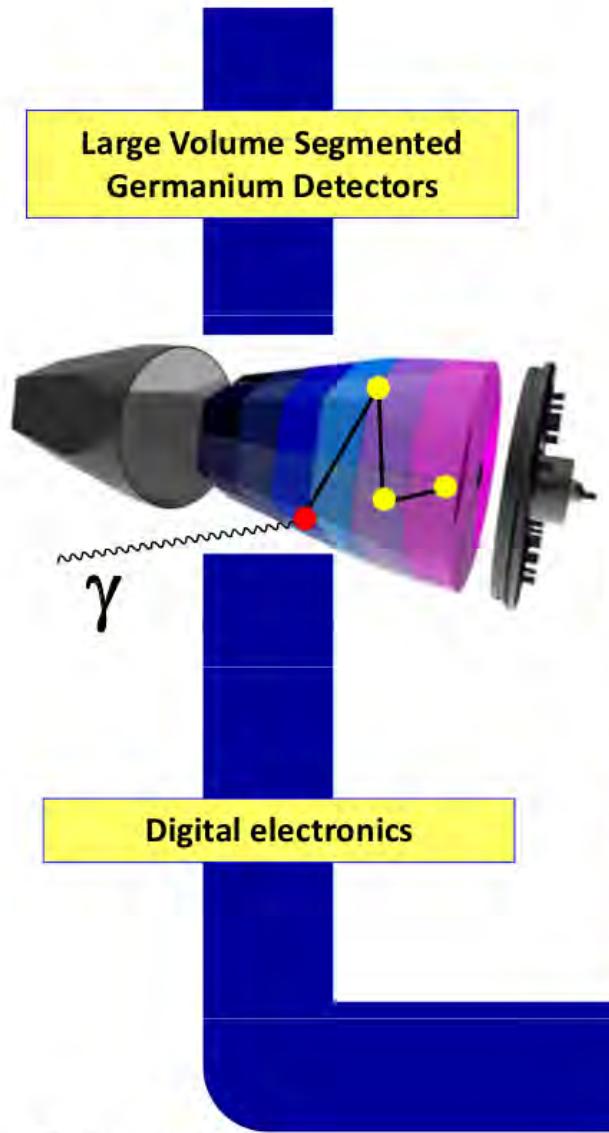
- Today: 35 Ge crystals each segmented in 36+1 (1295 channels)
- In 2030: 180 crystals (6660 channels)



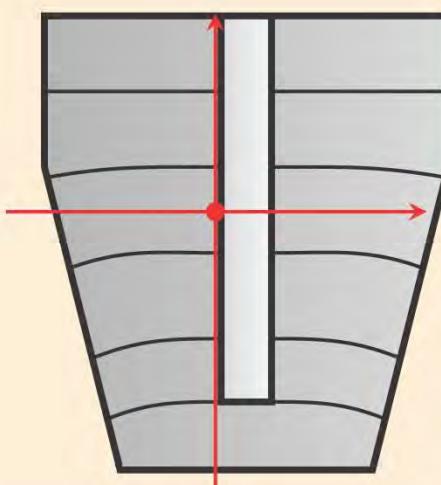
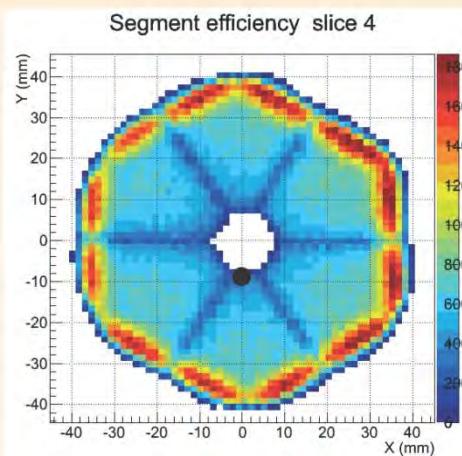
Multi-detector AGATA for γ -ray detection



Gamma-Ray Tracking Paradigm



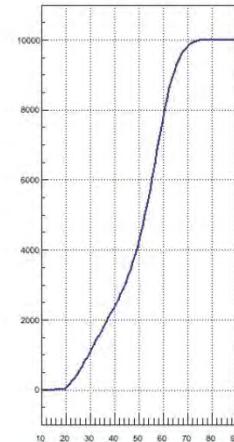
3D partial PSCS


 $(0; -6.5; 50)$

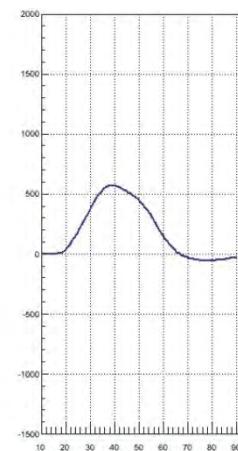
Core



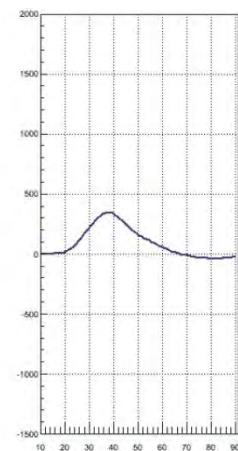
Segment hit



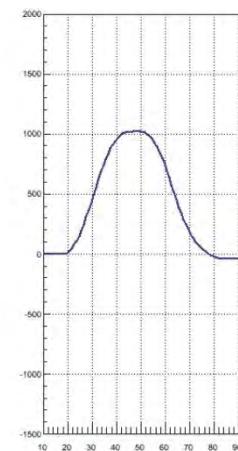
Left seg.



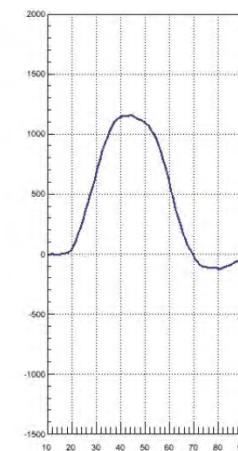
Right seg.



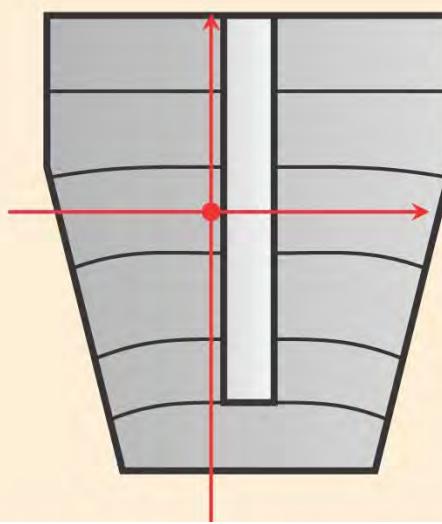
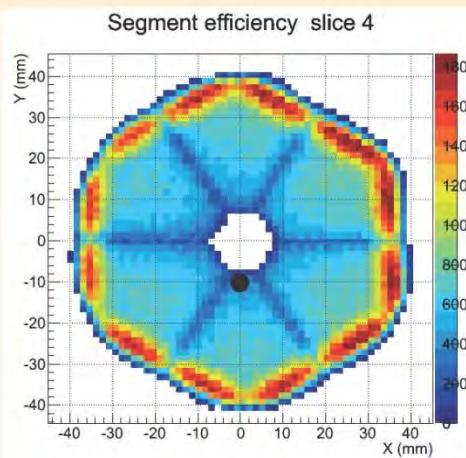
Top seg.



Bottom seg.

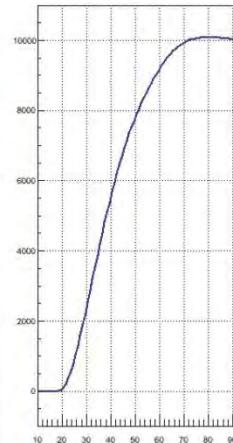


3D partial PSCS

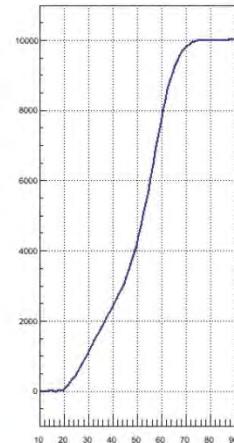


(0 ; -8.0 ; 50)

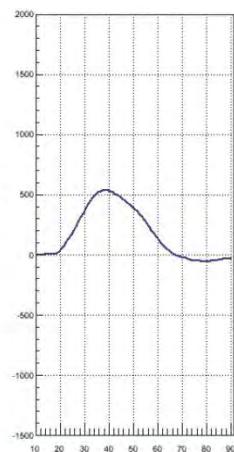
Core



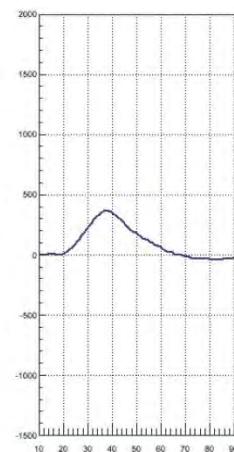
Segment hit



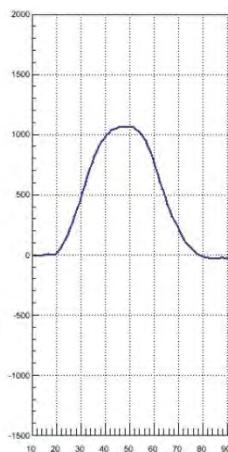
Left seg.



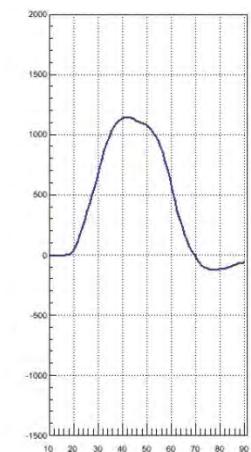
Right seg



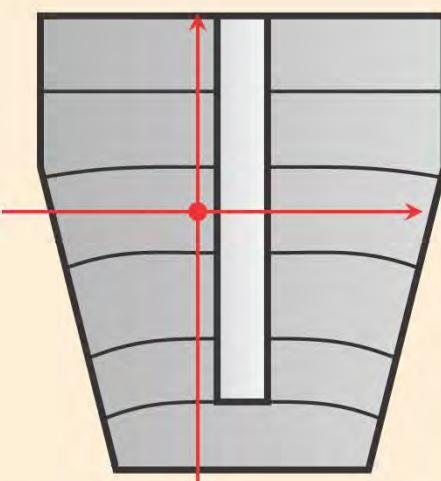
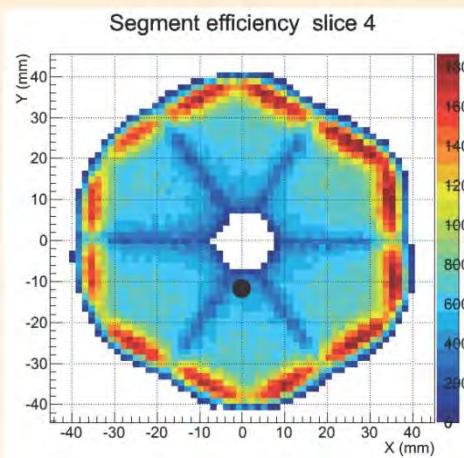
Top seg.



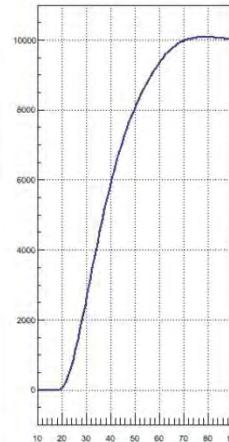
Bottom seg.



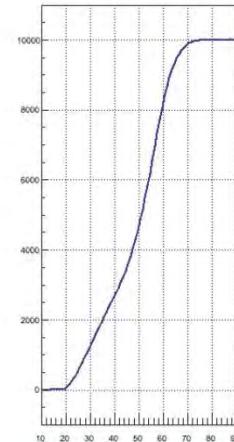
3D partial PSCS


 $(0; -9.5; 50)$

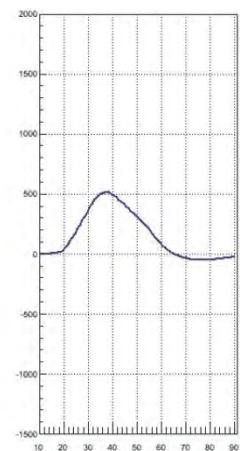
Core



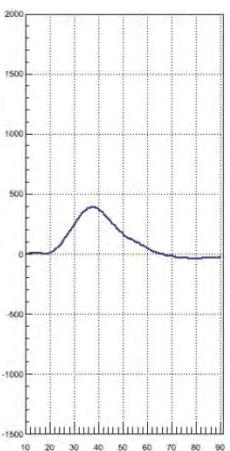
Segment hit



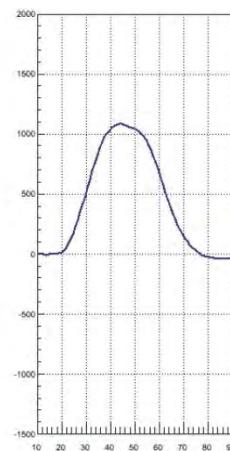
Left seg.



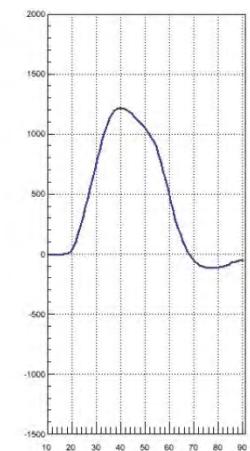
Right seg.



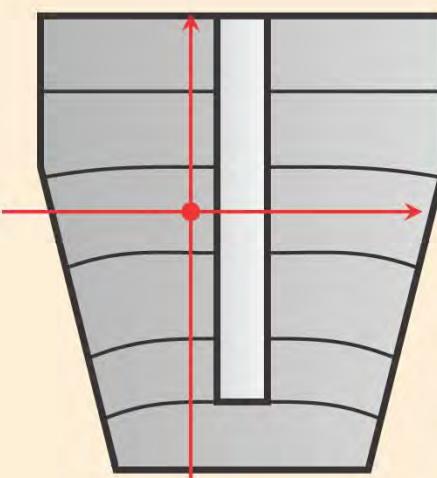
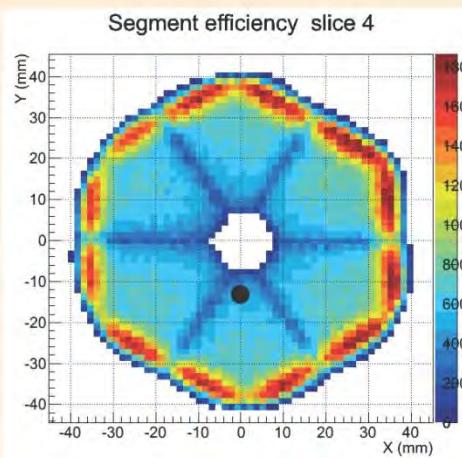
Top seg.



Bottom seg.

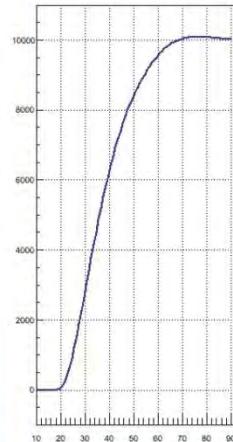


3D partial PSCS

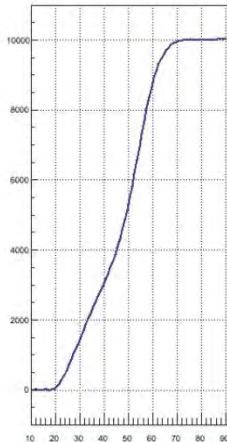


(0 ; -11.0 ; 50)

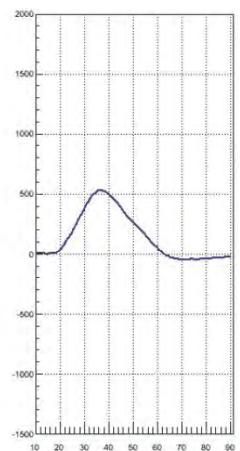
Core



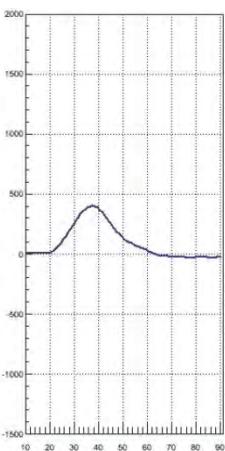
Segment hit



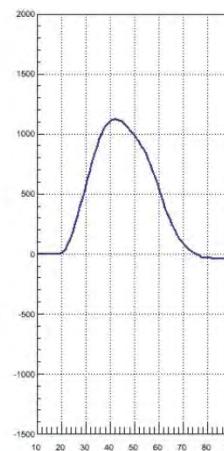
Left seg.



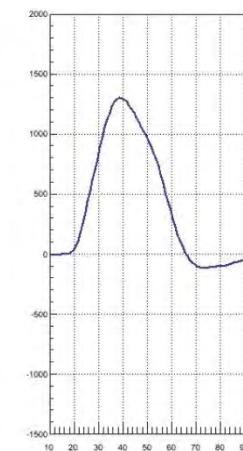
Right seg.



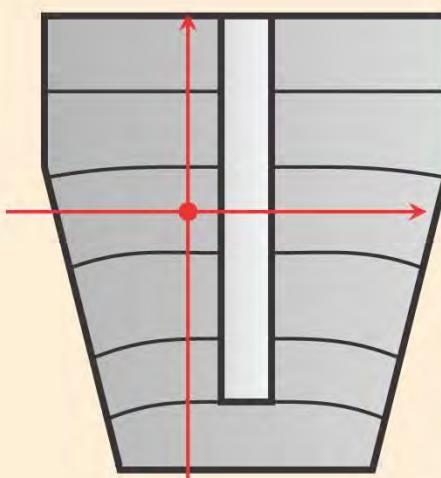
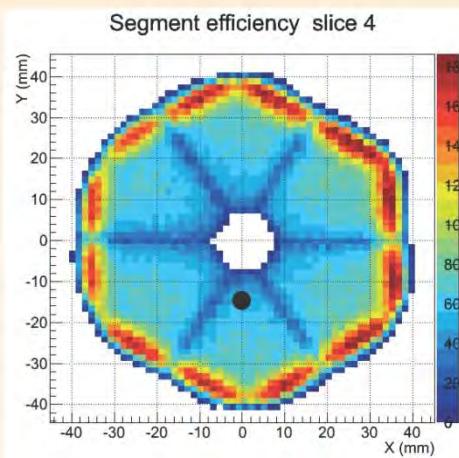
Top seg.



Bottom seg.



3D partial PSCS

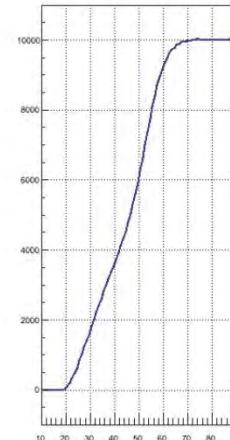


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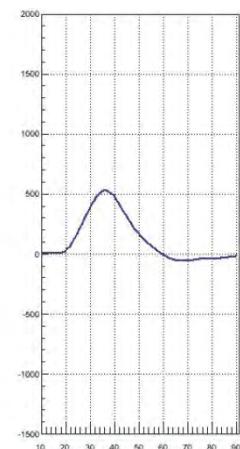
Core



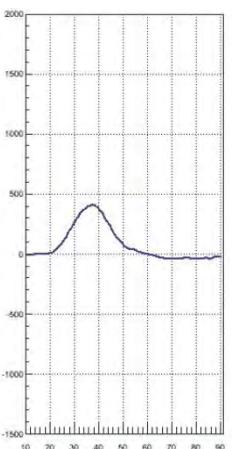
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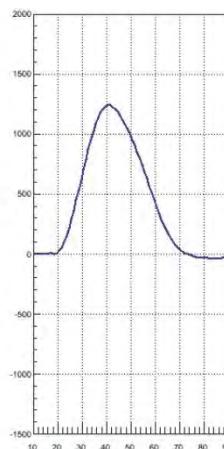
Left seg.



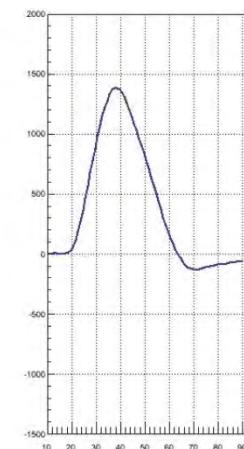
Right seg.



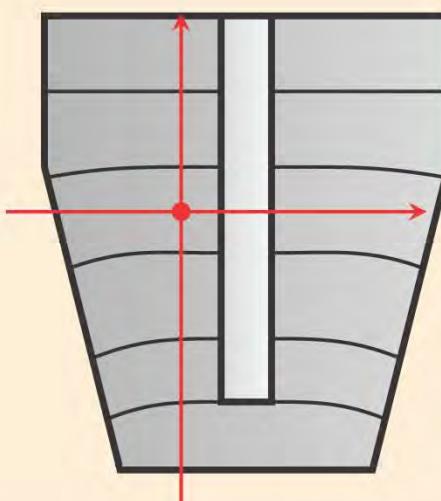
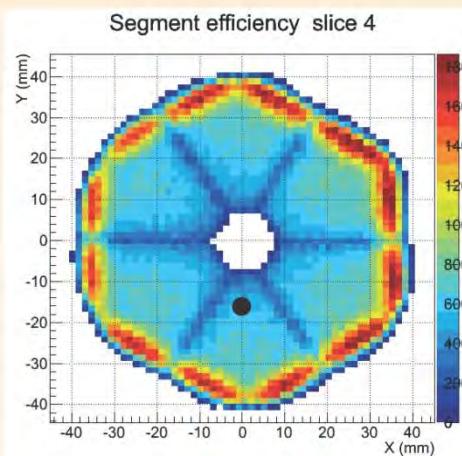
Top seg.



Bottom seg.



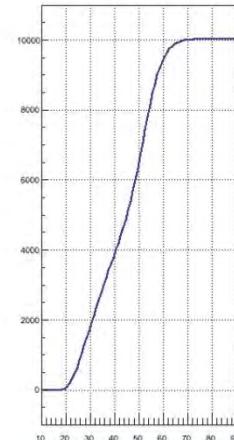
3D partial PSCS


 $(0; -14.0; 50)$

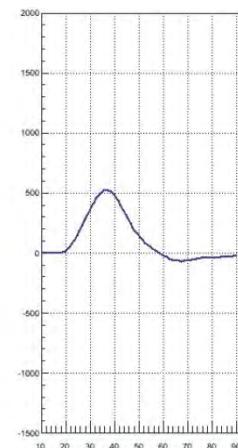
Core



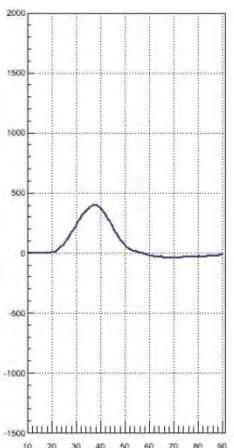
Segment hit



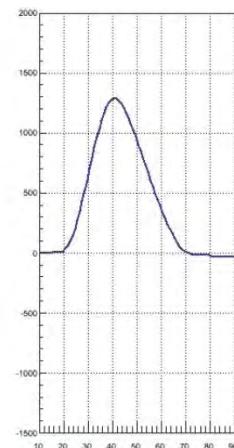
Left seg.



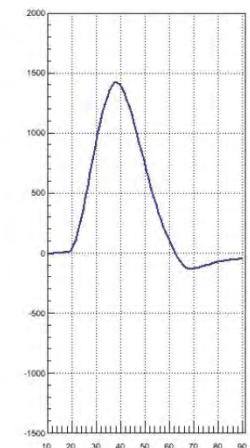
Right seg



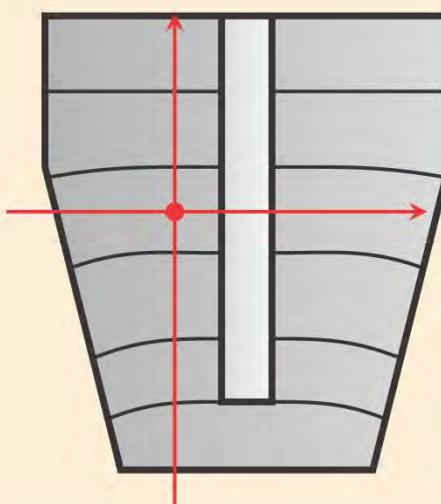
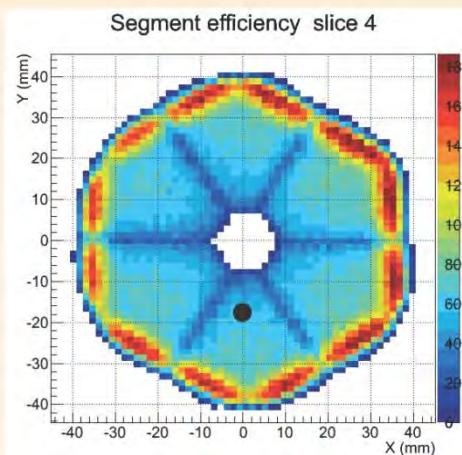
Top seg.



Bottom seg.



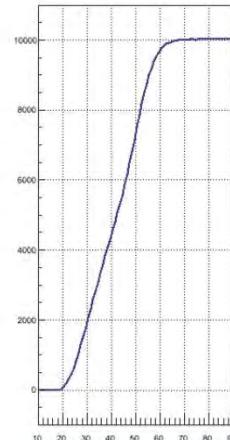
3D partial PSCS


 $(0; -15.5; 50)$

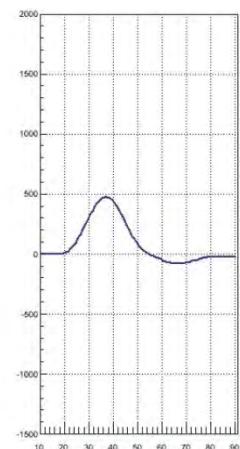
Core



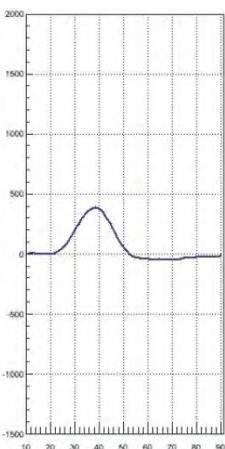
Segment hit



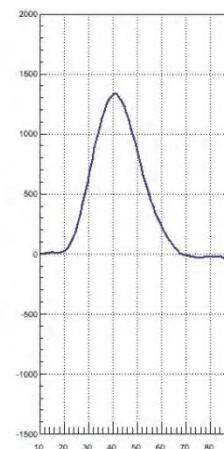
Left seg.



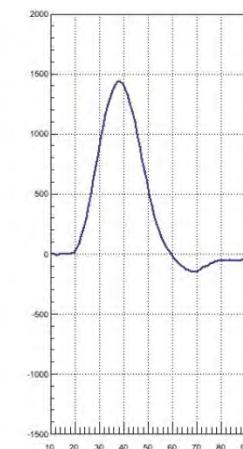
Right seg



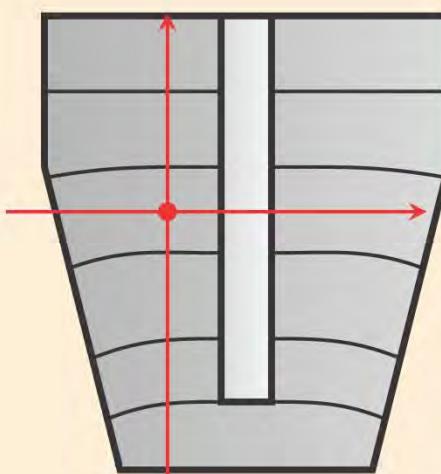
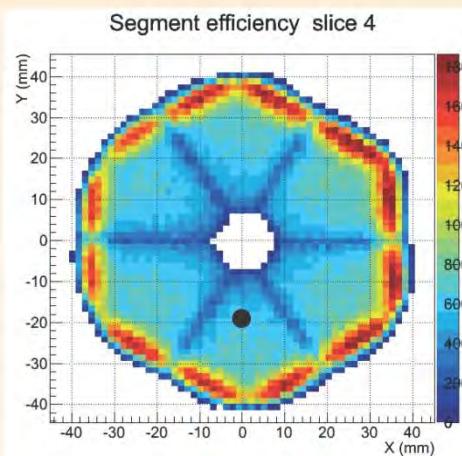
Top seg.



Bottom seg.



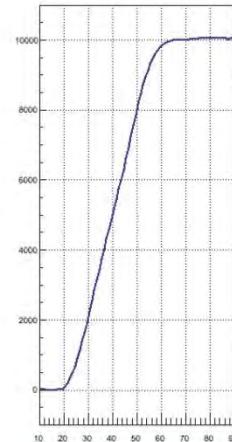
3D partial PSCS


 $(0; -17.0; 50)$

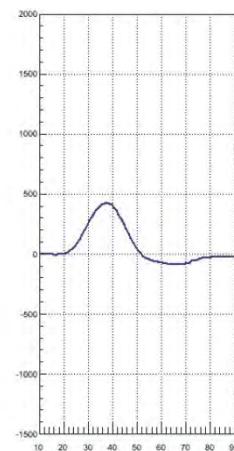
Core



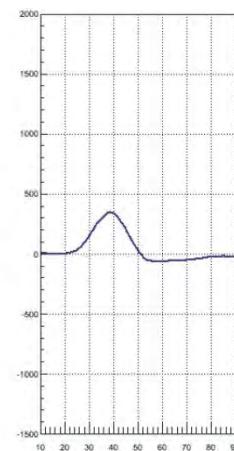
Segment hit



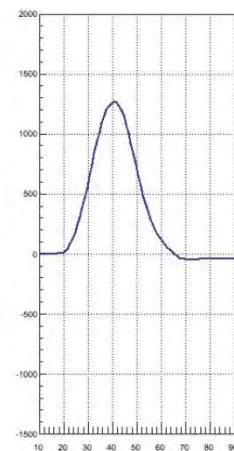
Left seg.



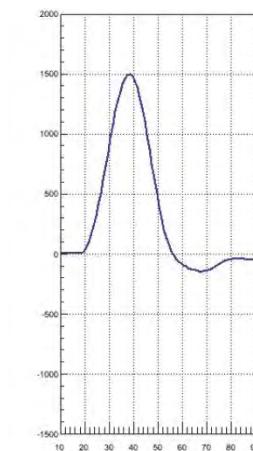
Right seg



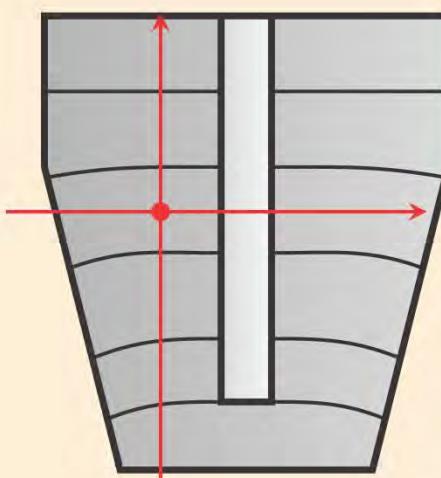
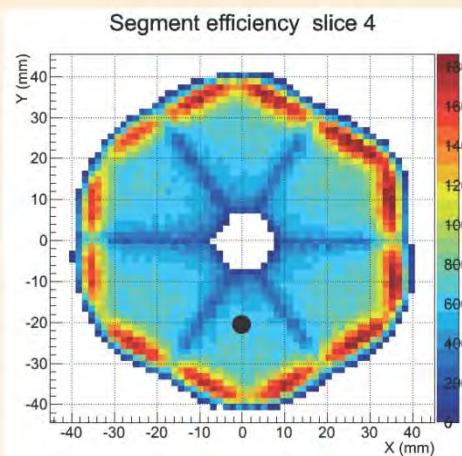
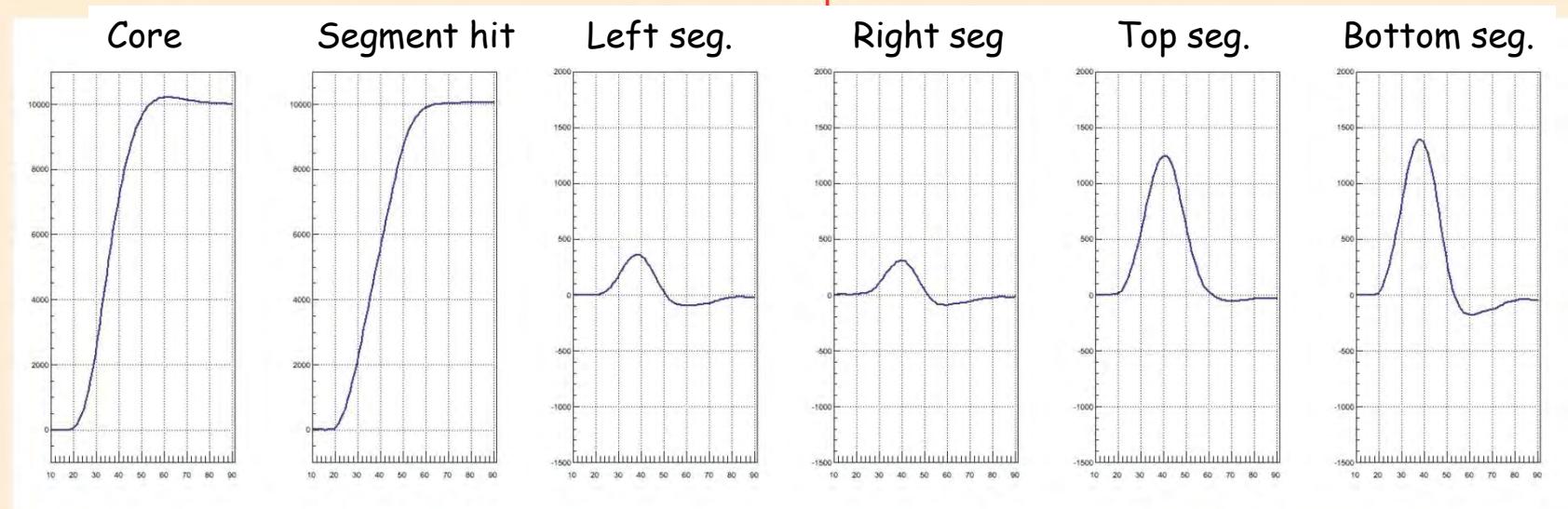
Top seg.



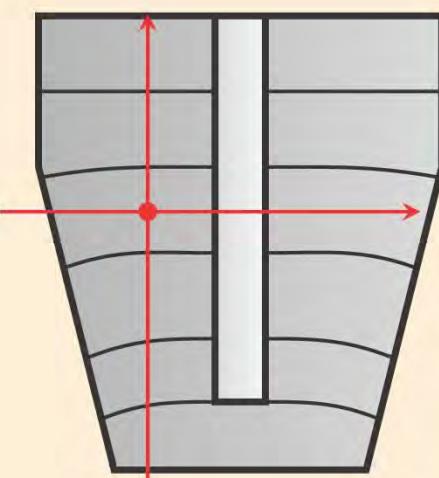
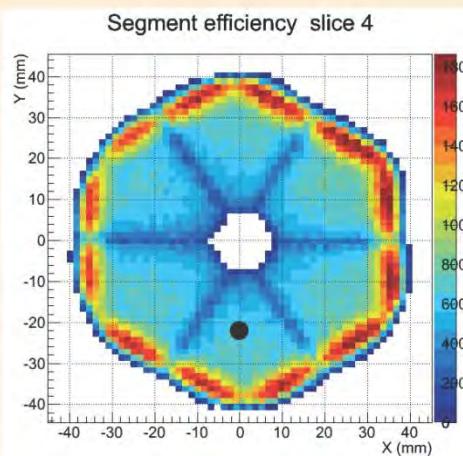
Bottom seg.



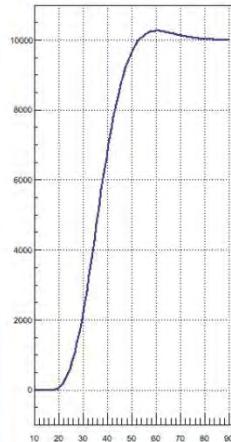
3D partial PSCS


 $(0; -18.5; 50)$


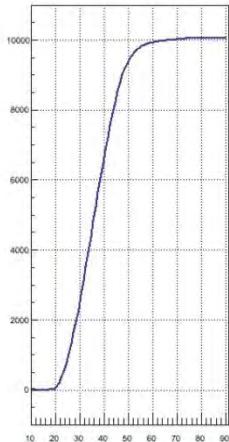
3D partial PSCS


 $(0; -20.0; 50)$

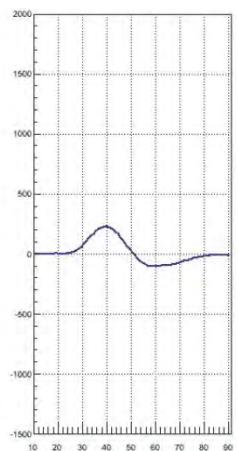
Core



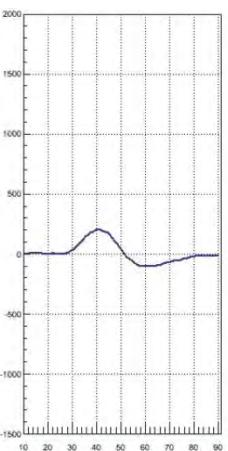
Segment hit



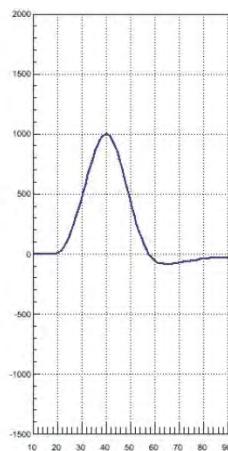
Left seg.



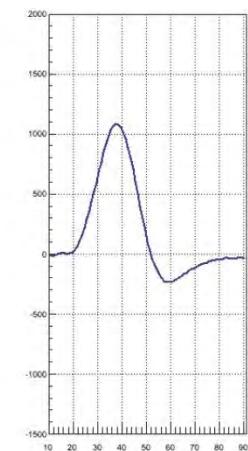
Right seg



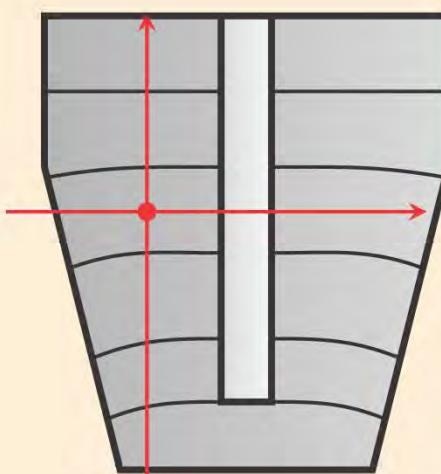
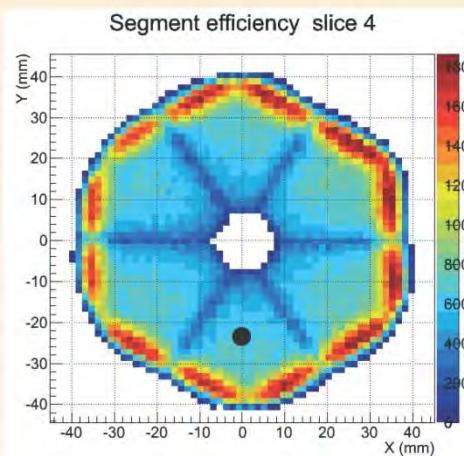
Top seg.



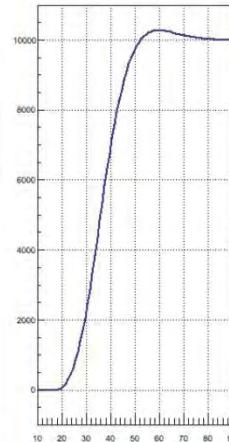
Bottom seg.



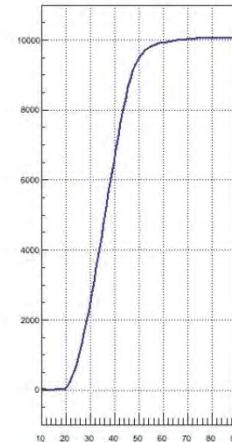
3D partial PSCS


 $(0; -21.5; 50)$

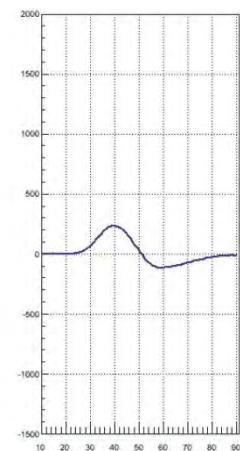
Core



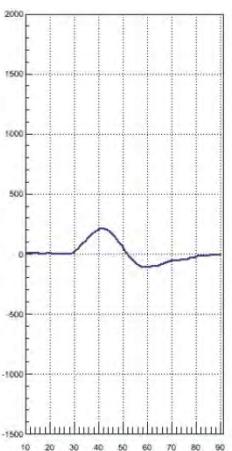
Segment hit



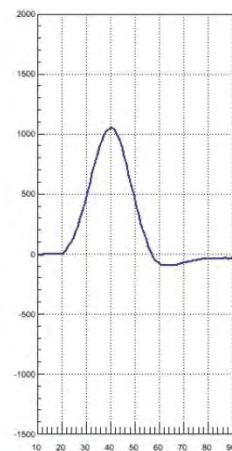
Left seg.



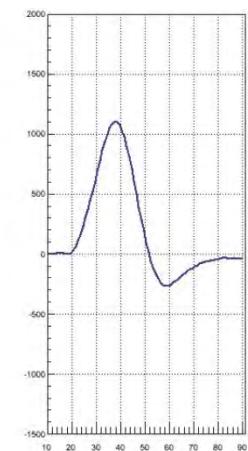
Right seg



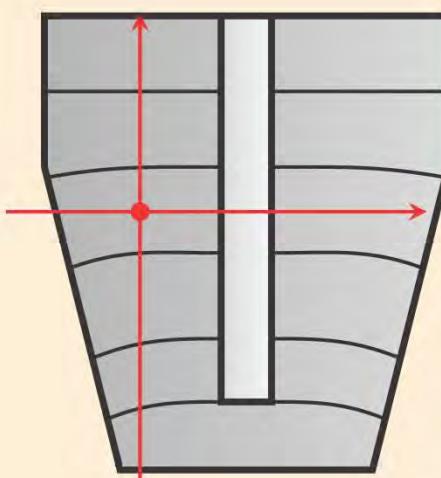
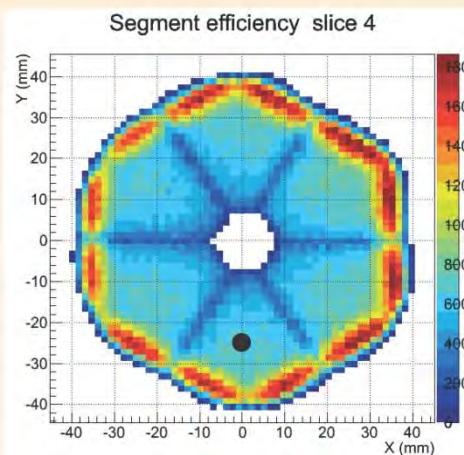
Top seg.



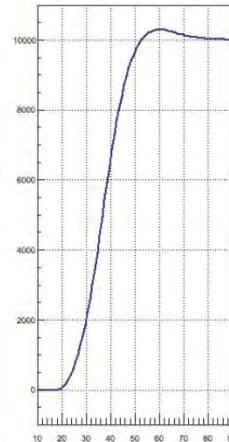
Bottom seg.



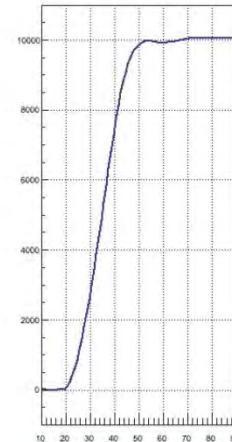
3D partial PSCS


 $(0; -23.0; 50)$

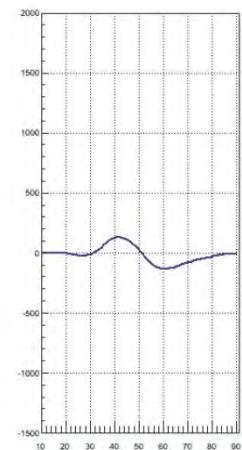
Core



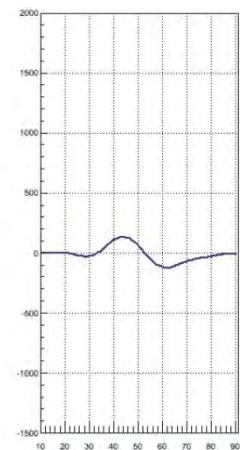
Segment hit



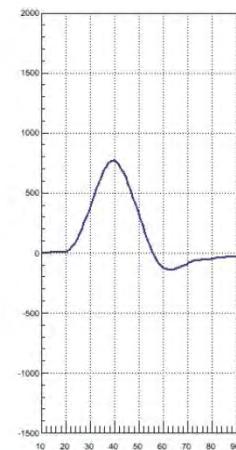
Left seg.



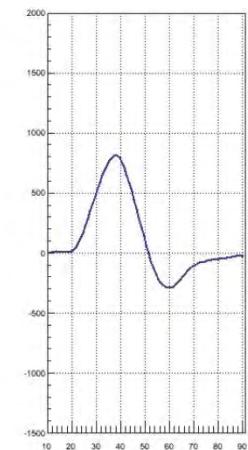
Right seg



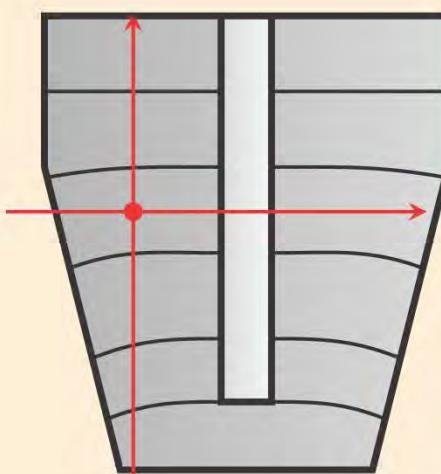
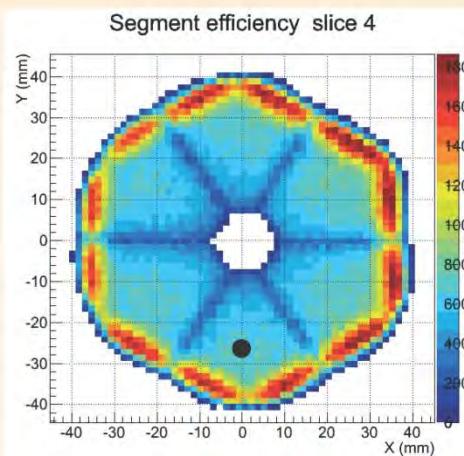
Top seg.



Bottom seg.

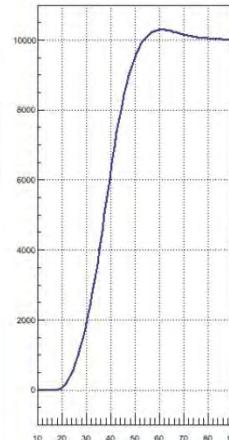


3D partial PSCS

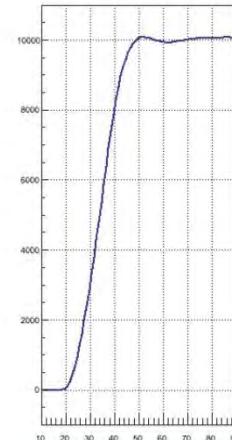


(0 ; -24.5 ; 50)

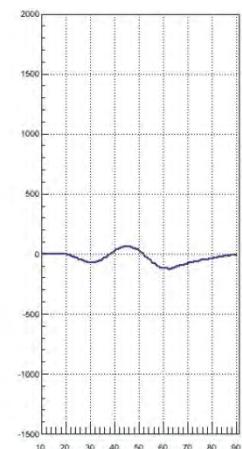
Core



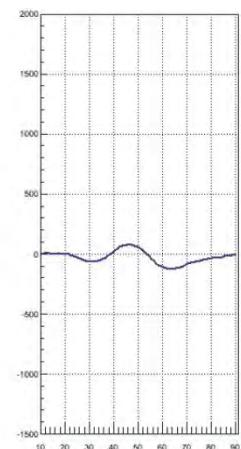
Segment hit



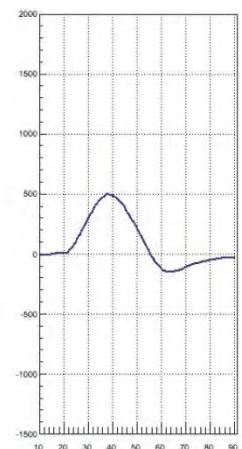
Left seg.



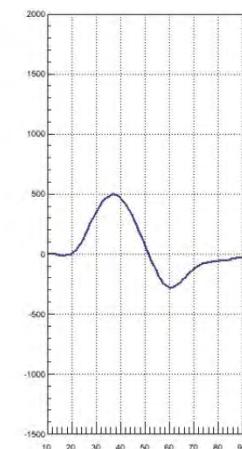
Right seg



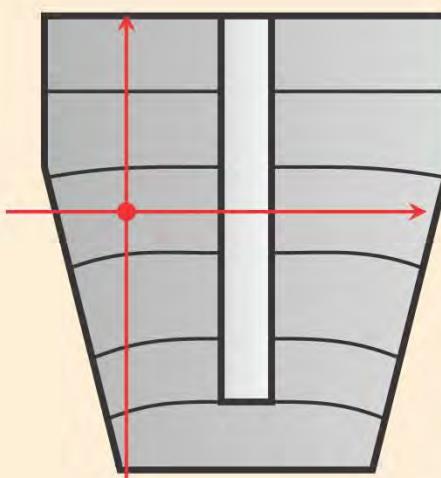
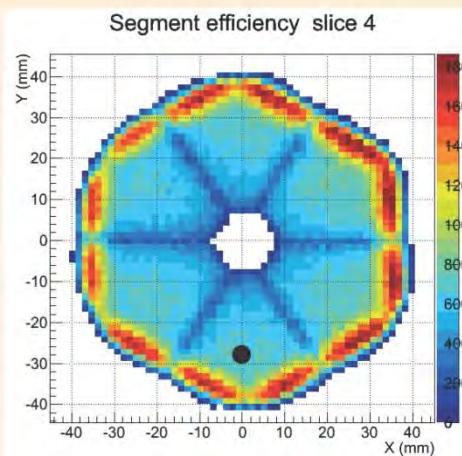
Top seg.



Bottom seg.



3D partial PSCS


 $(0; -26.0; 50)$

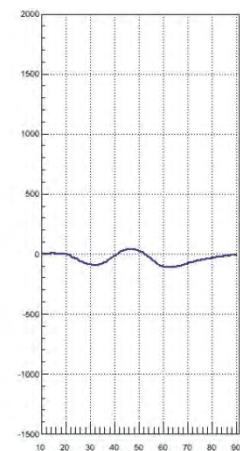
Core



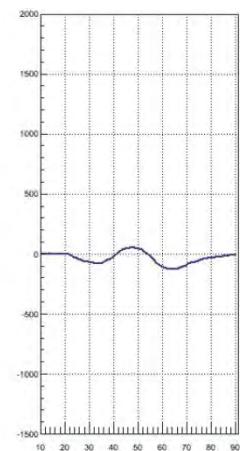
Segment hit



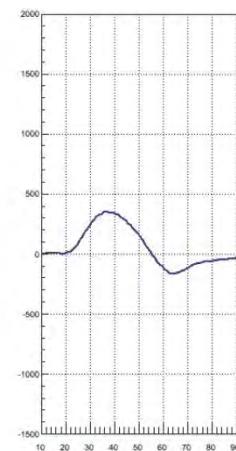
Left seg.



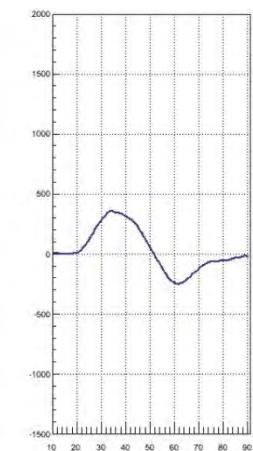
Right seg



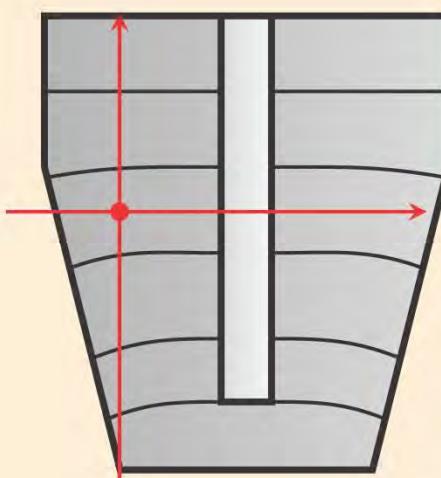
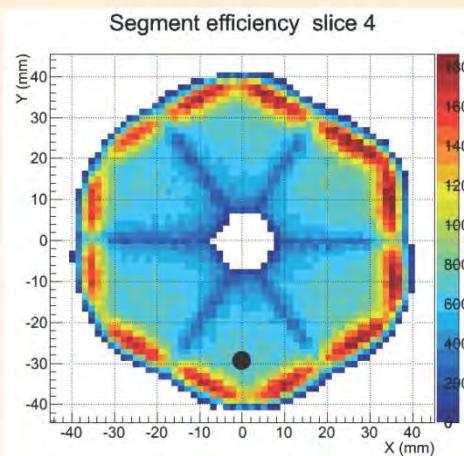
Top seg.



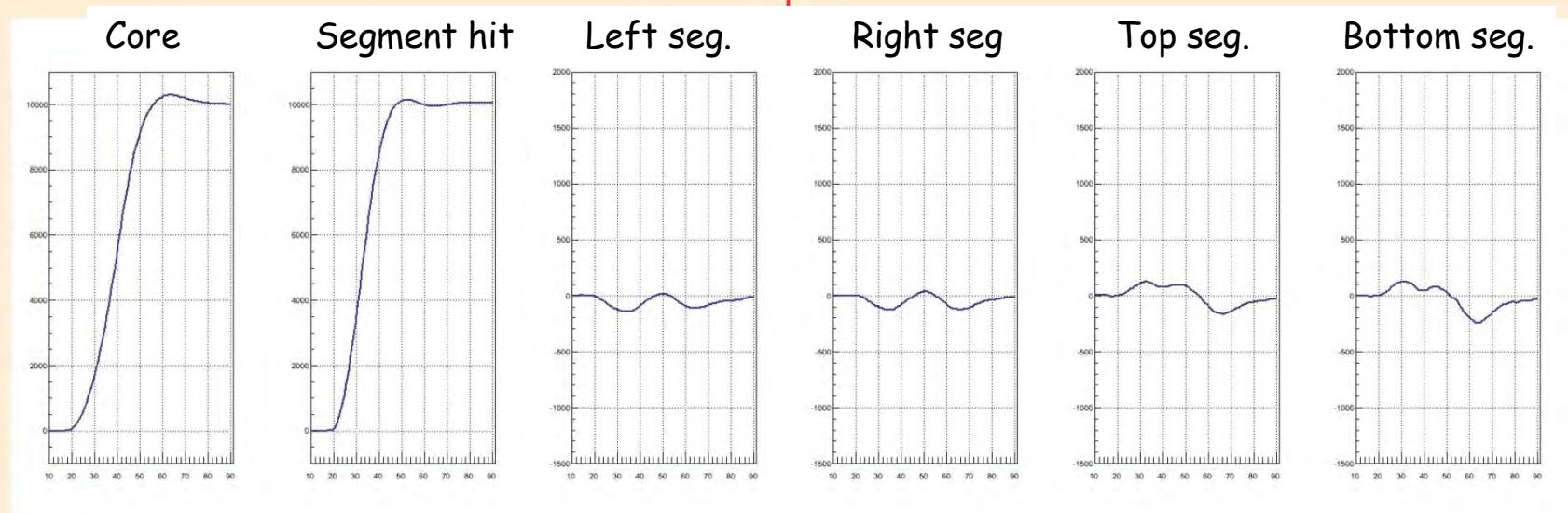
Bottom seg.



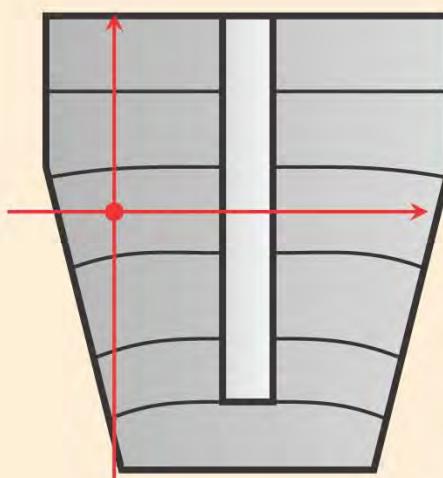
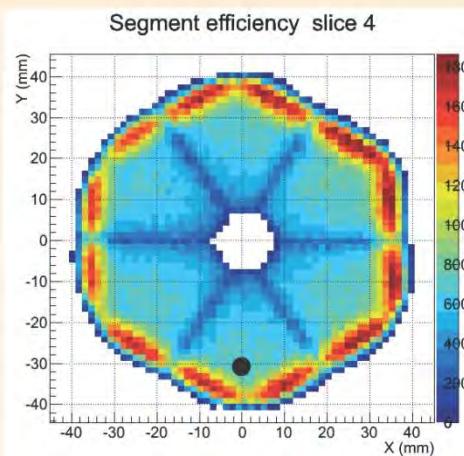
3D partial PSCS



(0 ; -27.5 ; 50)

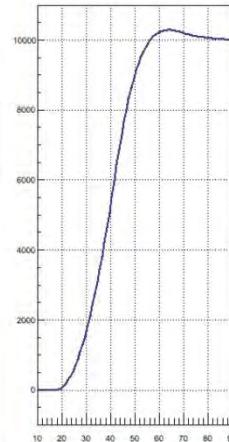


3D partial PSCS

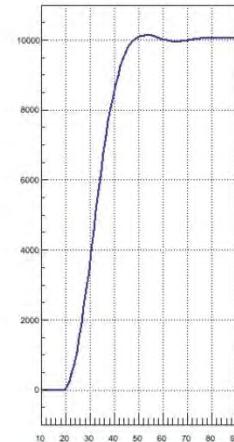


(0 ; -29.0 ; 50)

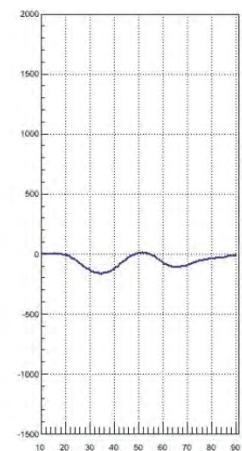
Core



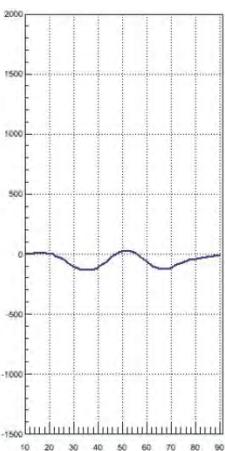
Segment hit



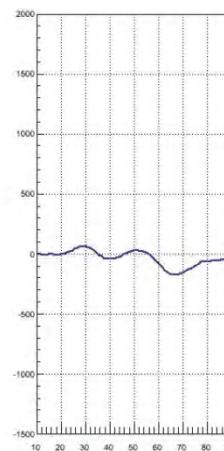
Left seg.



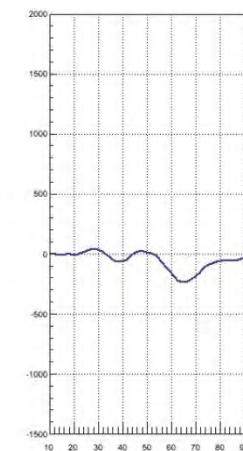
Right seg.



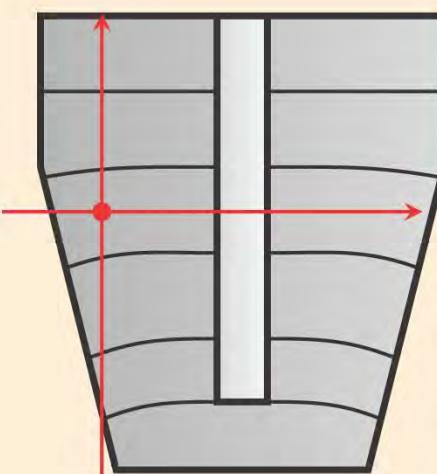
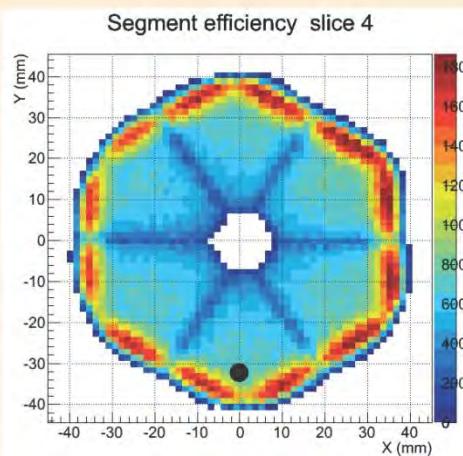
Top seg.



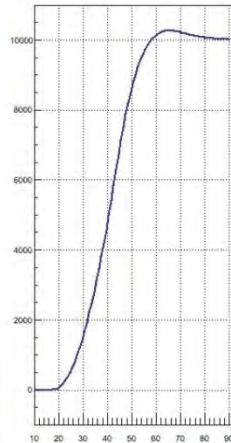
Bottom seg.



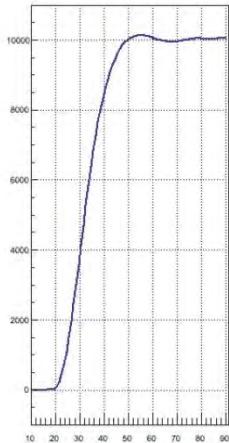
3D partial PSCS


 $(0; -30.5; 50)$

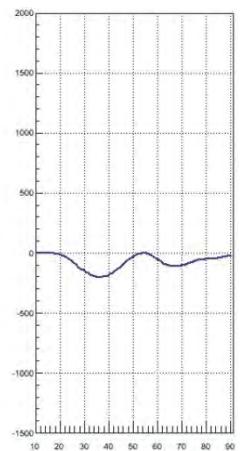
Core



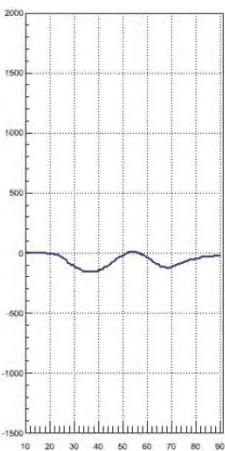
Segment hit



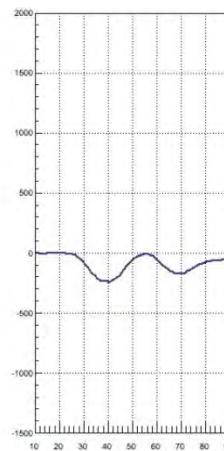
Left seg.



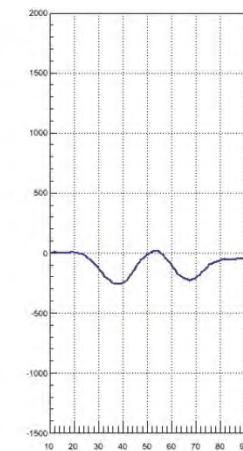
Right seg



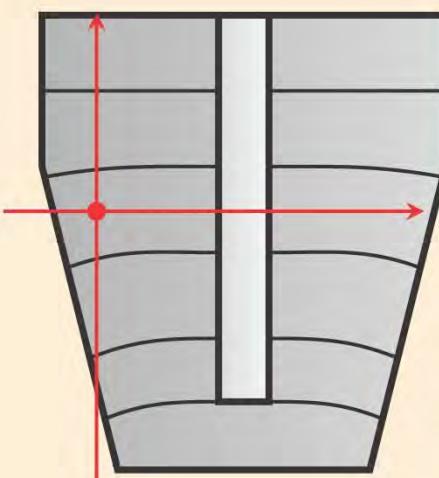
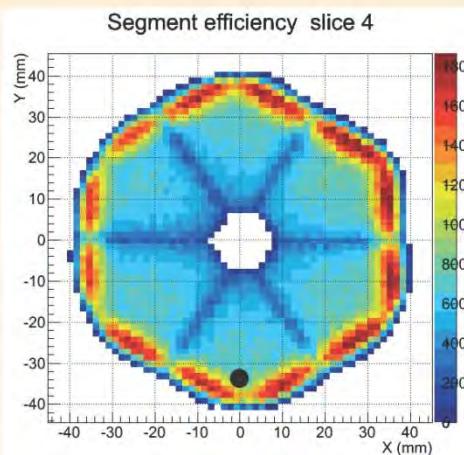
Top seg.



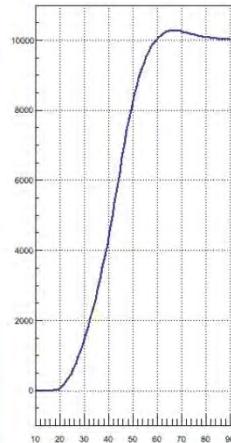
Bottom seg.



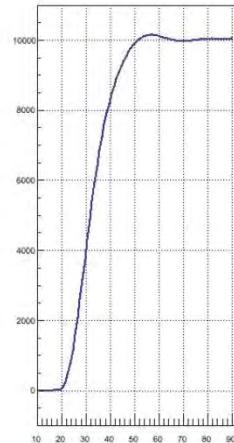
3D partial PSCS


 $(0; -32.0; 50)$

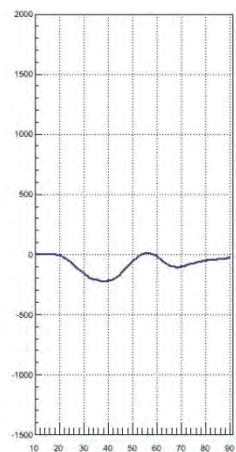
Core



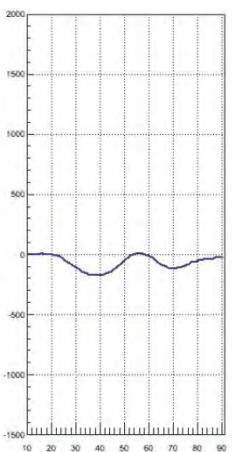
Segment hit



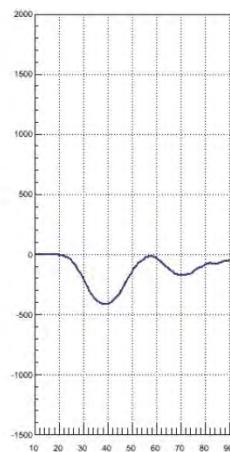
Left seg.



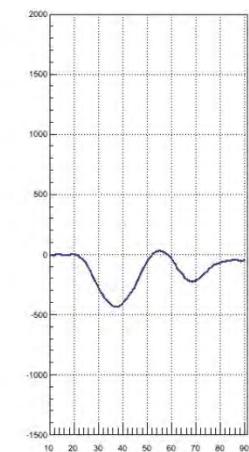
Right seg.



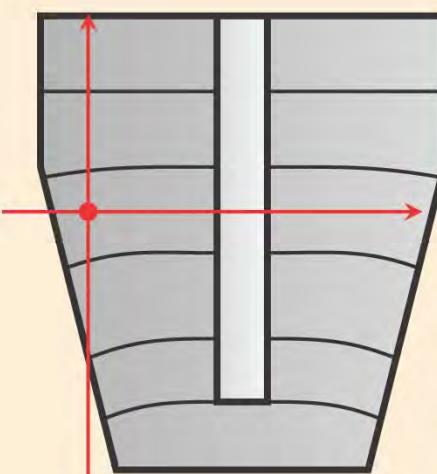
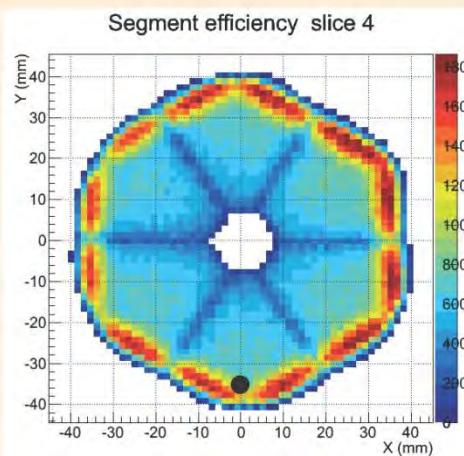
Top seg.



Bottom seg.

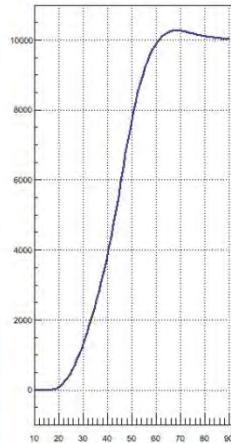


3D partial PSCS

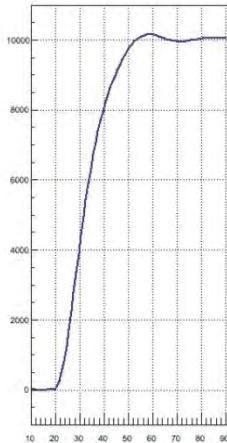


(0 ; -33.5 ; 50)

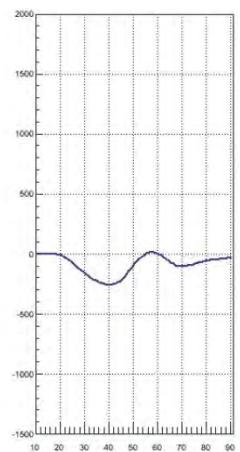
Core



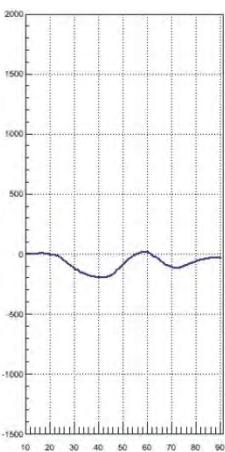
Segment hit



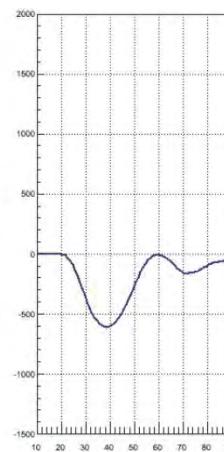
Left seg.



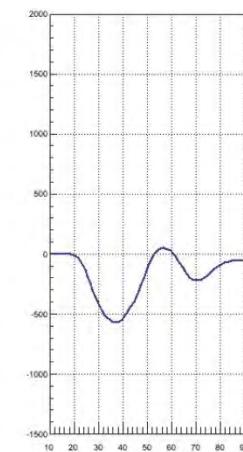
Right seg



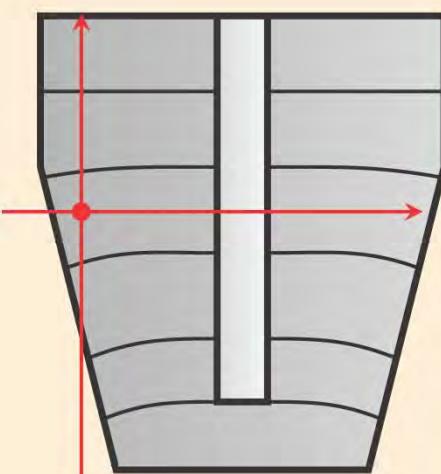
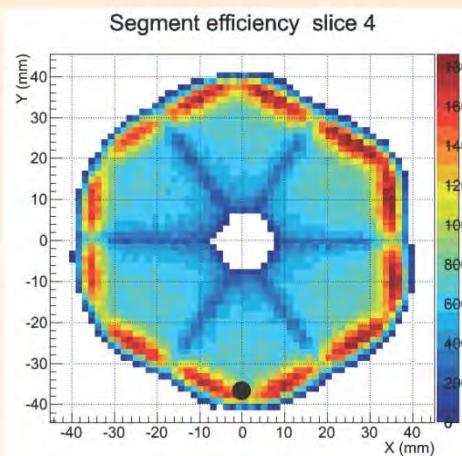
Top seg.



Bottom seg.

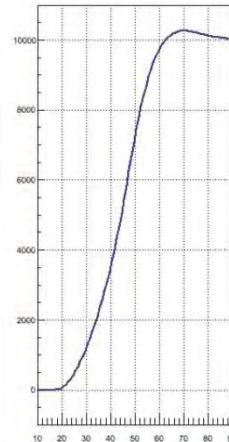


3D partial PSCS

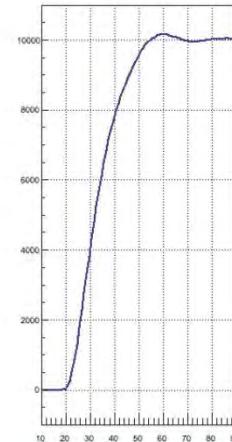


(0 ; -35.0 ; 50)

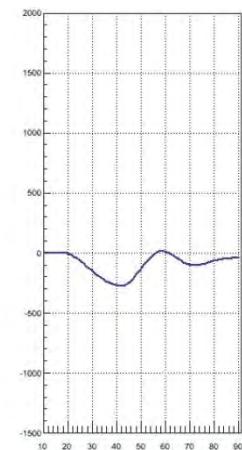
Core



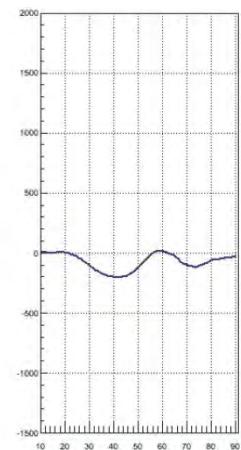
Segment hit



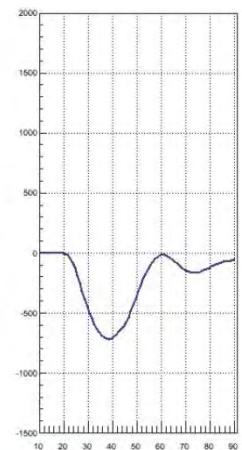
Left seg.



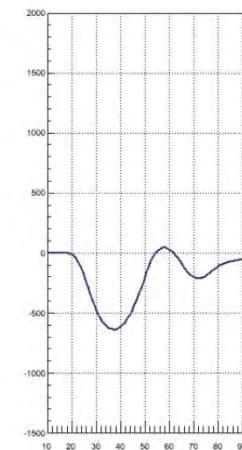
Right seg.



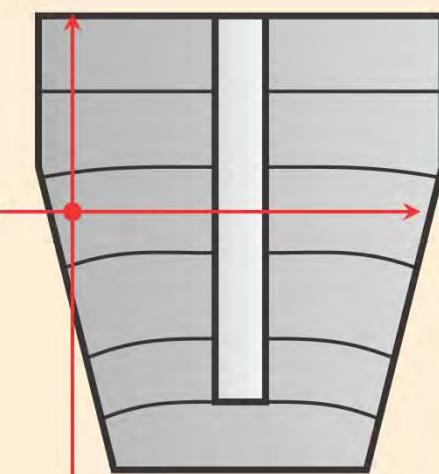
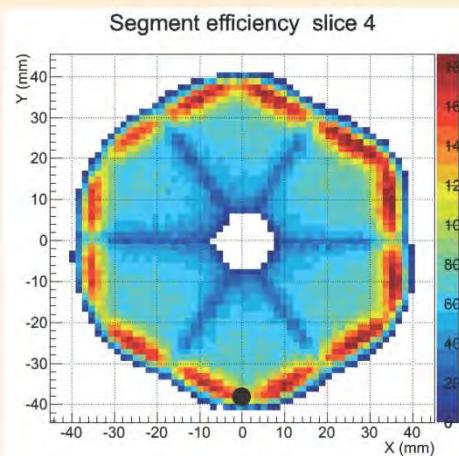
Top seg.



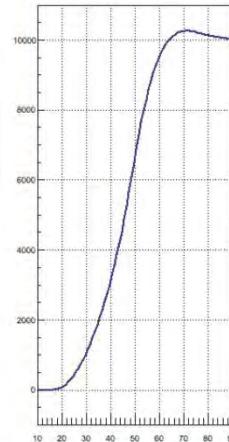
Bottom seg.



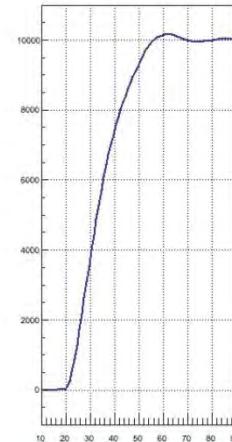
3D partial PSCS


 $(0; -36.5; 50)$

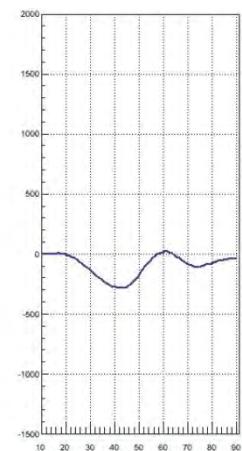
Core



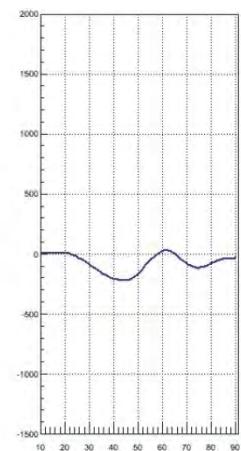
Segment hit



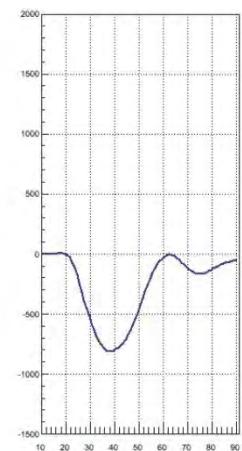
Left seg.



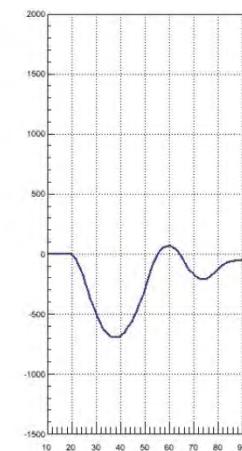
Right seg



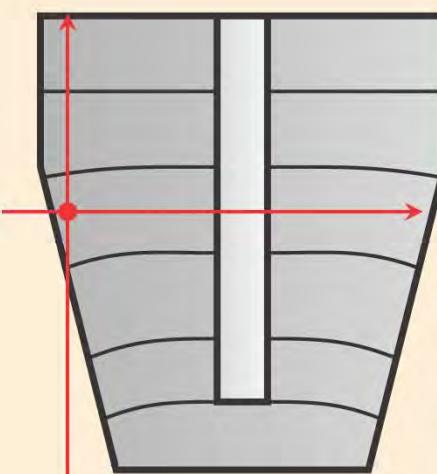
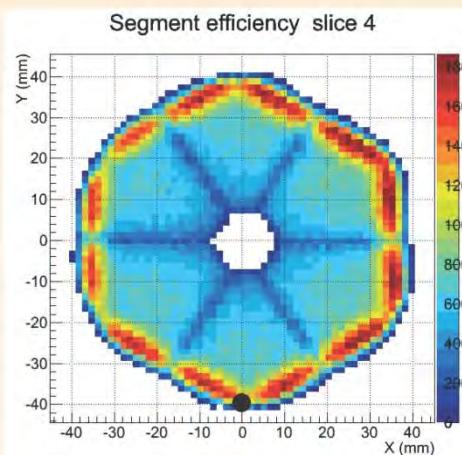
Top seg.



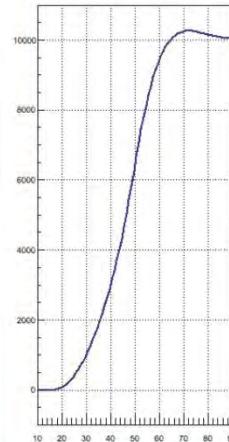
Bottom seg.



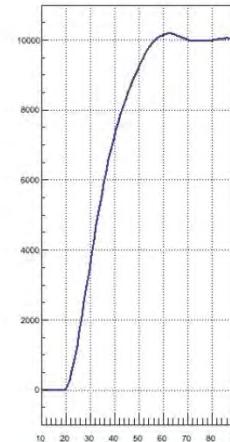
3D partial PSCS



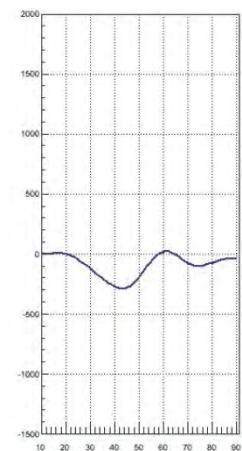
Core



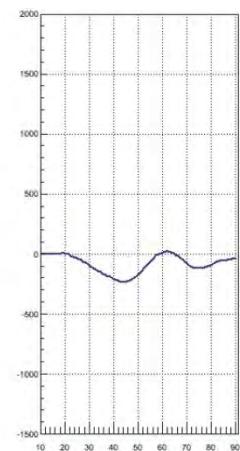
Segment hit



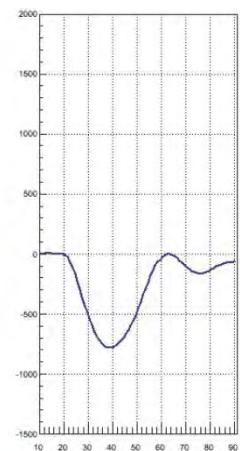
Left seg.



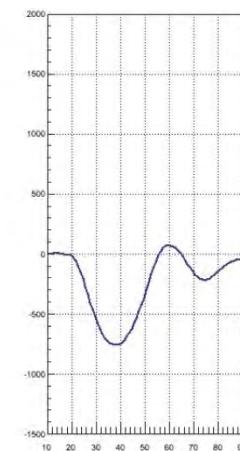
Right seg



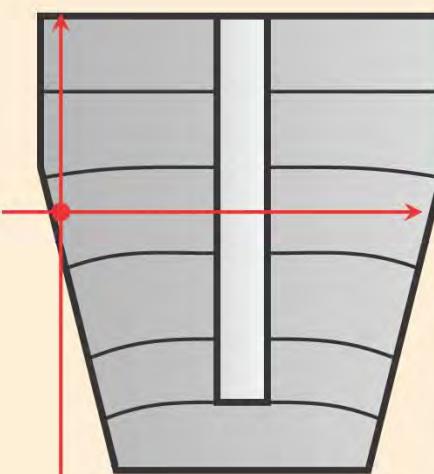
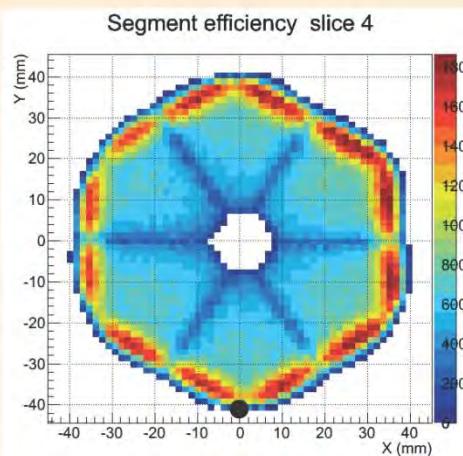
Top seg.



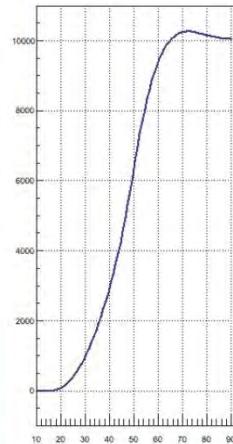
Bottom seg.



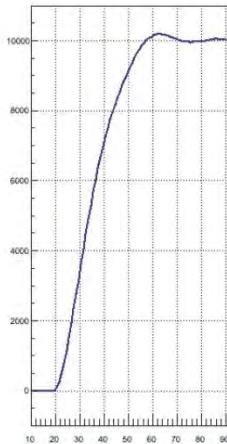
3D partial PSCS



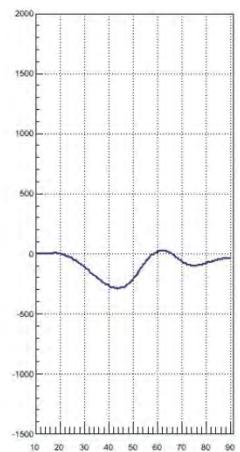
Core



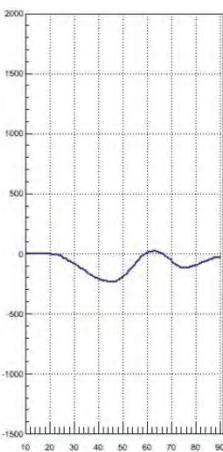
Segment hit



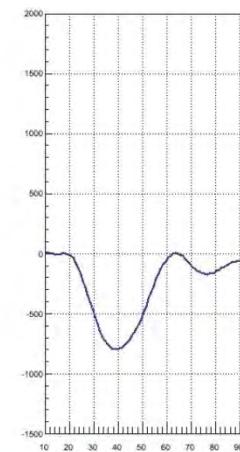
Left seg.



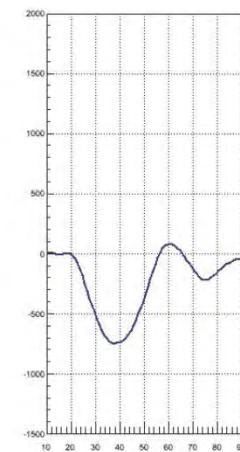
Right seg



Top seg.

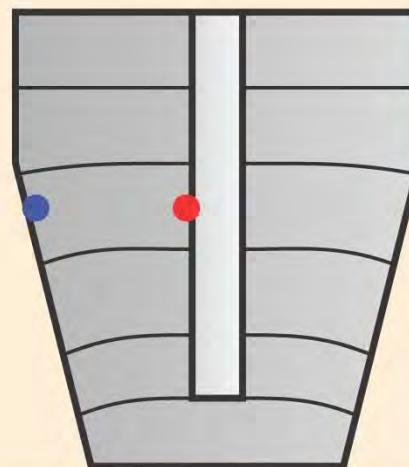
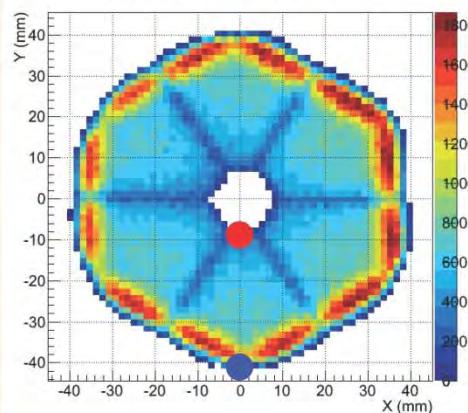


Bottom seg.

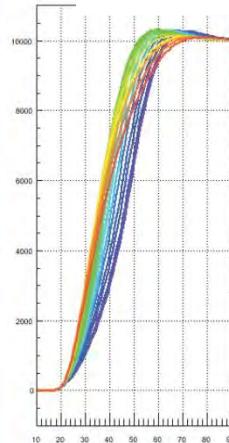


3D partial PSCS

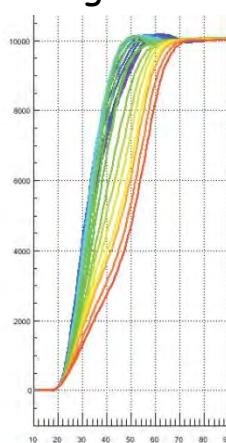
Segment efficiency slice 4



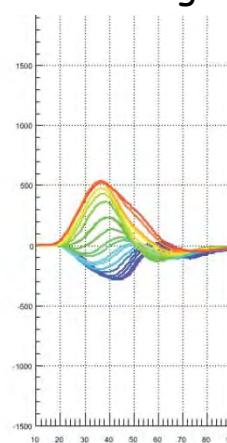
Core



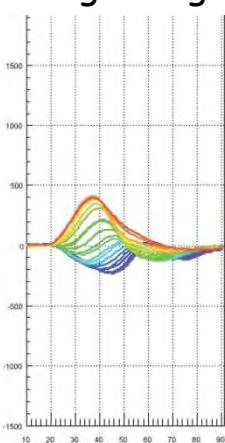
Segment hit



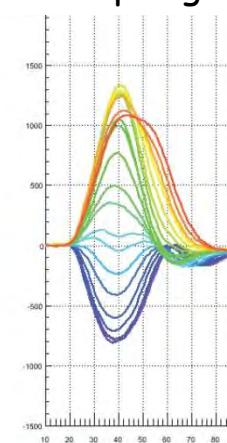
Left seg.



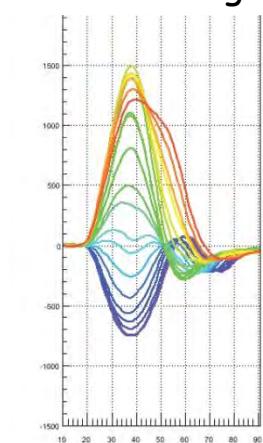
Right seg.



Top seg.

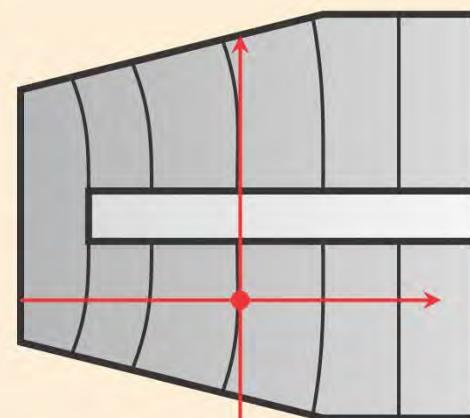
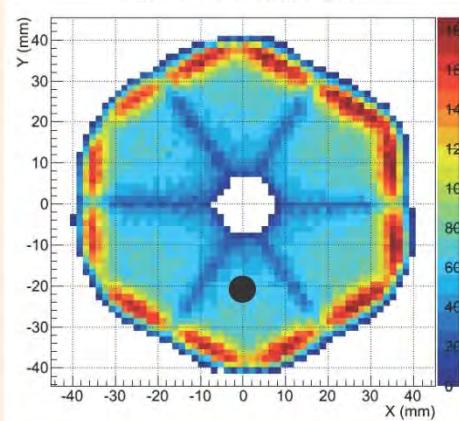


Bottom seg.



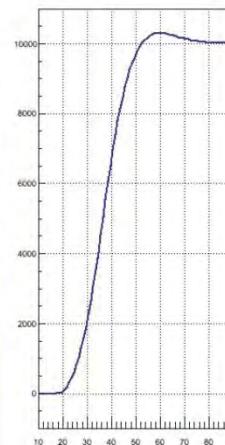
3D partial PSCS

Segment efficiency slice 4

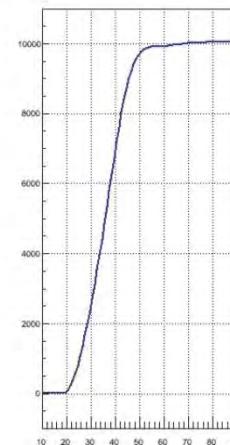


(0 ; -23 ; 43)

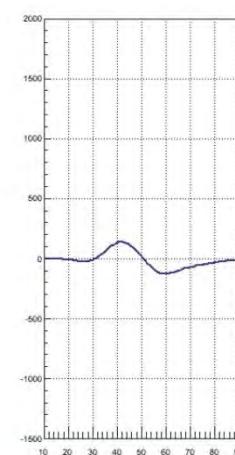
Core



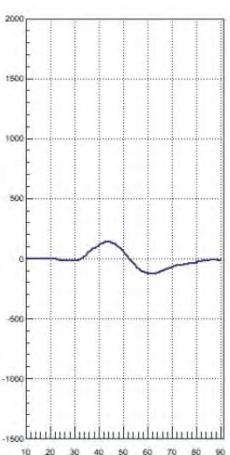
Segment hit



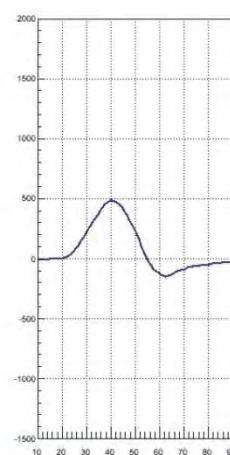
Left seg.



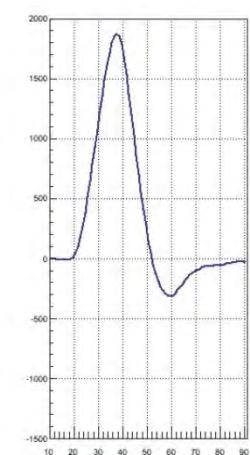
Right seg



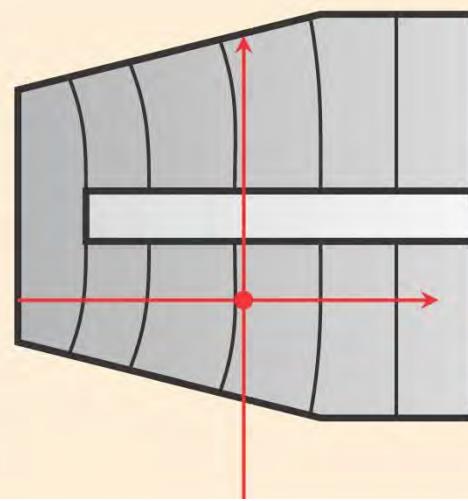
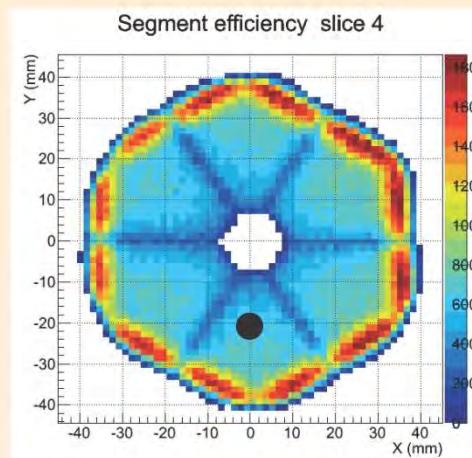
Top seg.



Bottom seg.

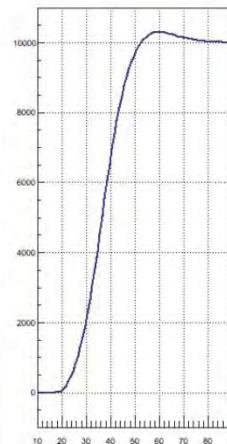


3D partial PSCS

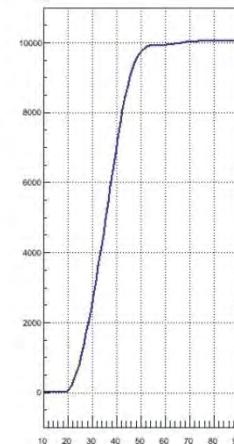


(0 ; -23 ; 44)

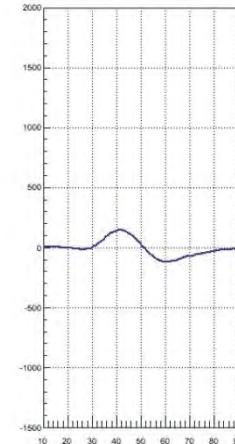
Core



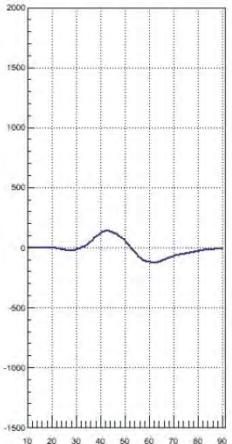
Segment hit



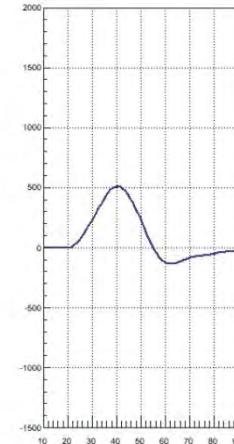
Left seg.



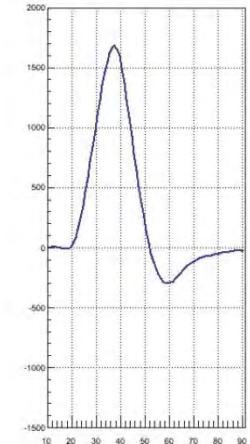
Right seg



Top seg.

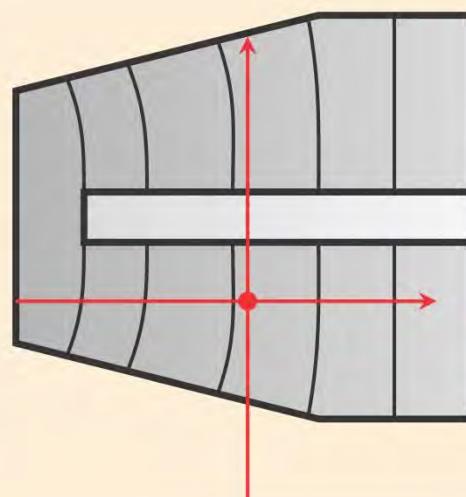
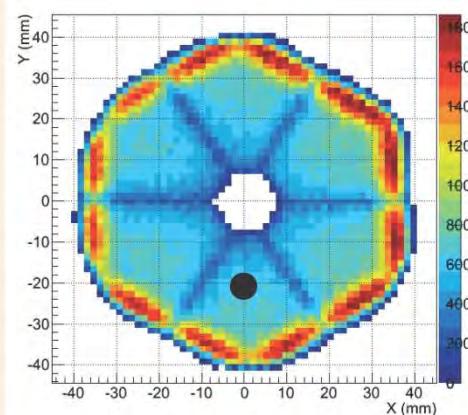


Bottom seg.



3D partial PSCS

Segment efficiency slice 4

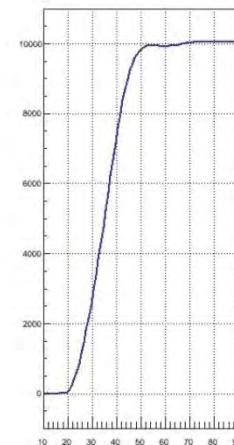


(0 ; -23 ; 45)

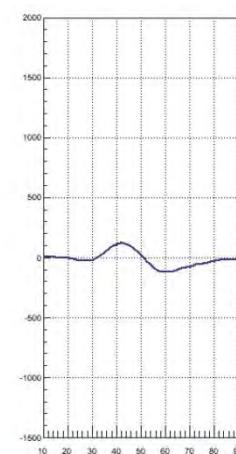
Core



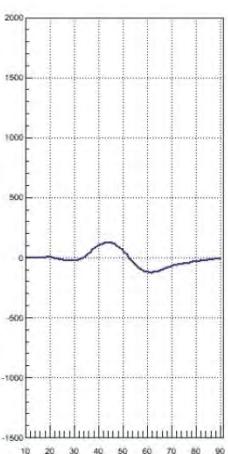
Segment hit



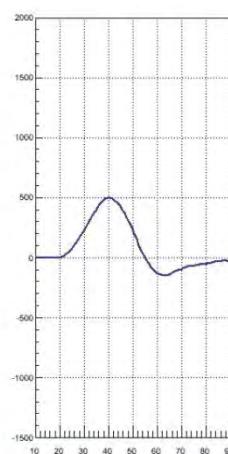
Left seg.



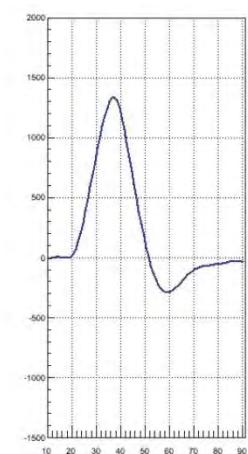
Right seg



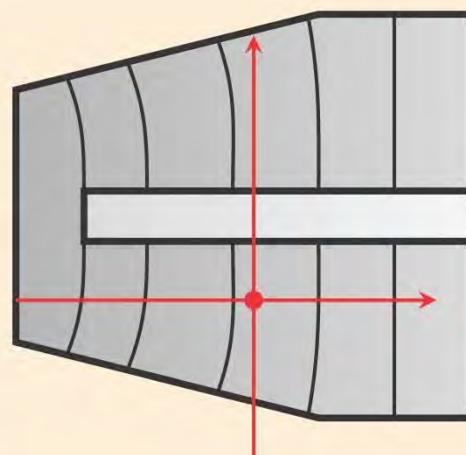
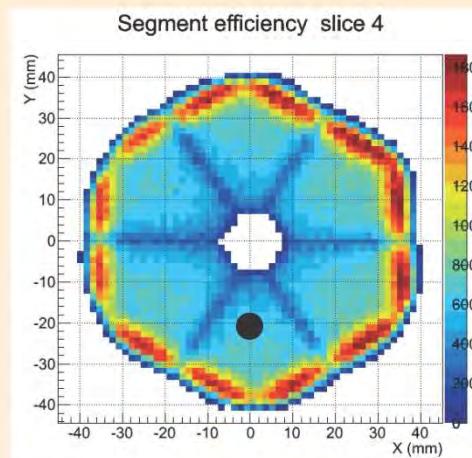
Top seg.



Bottom seg.

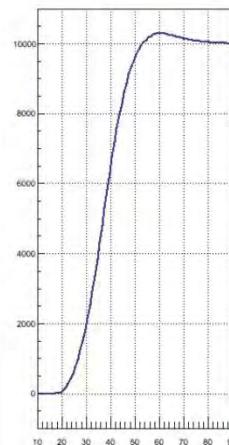


3D partial PSCS

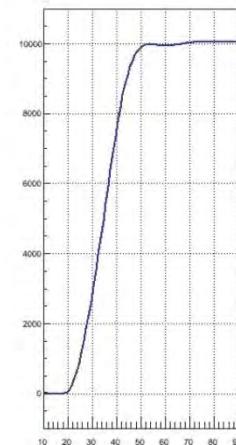


(0 ; -23 ; 46)

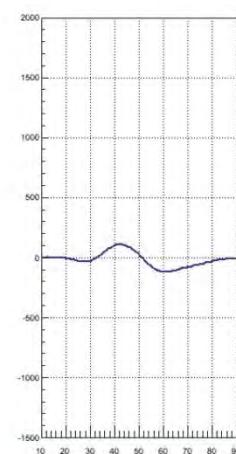
Core



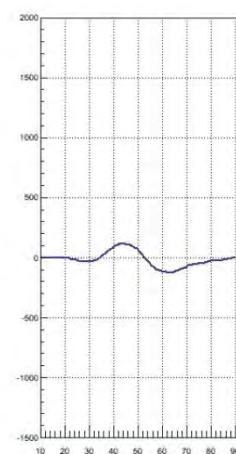
Segment hit



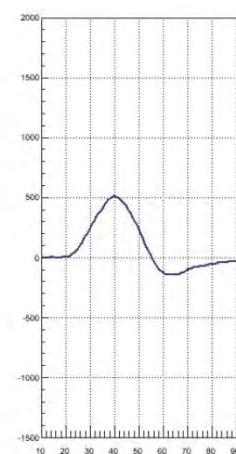
Left seg.



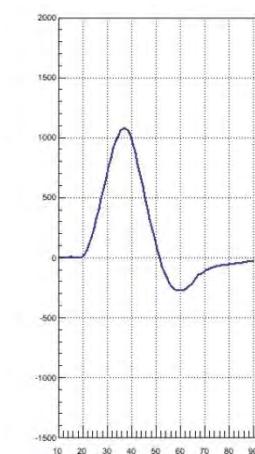
Right seg



Top seg.

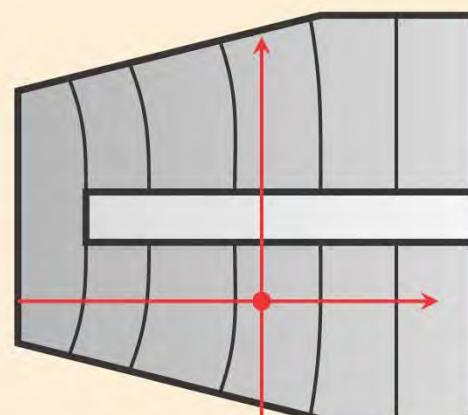
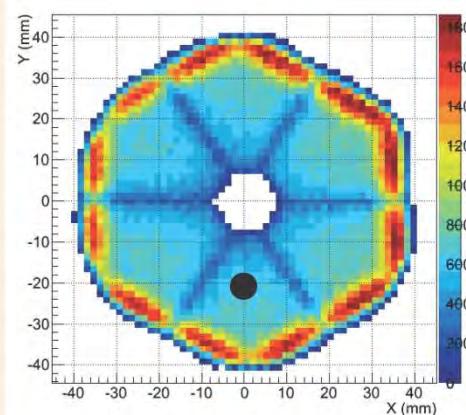


Bottom seg.



3D partial PSCS

Segment efficiency slice 4

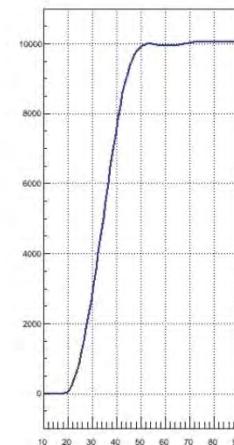


(0 ; -23 ; 47)

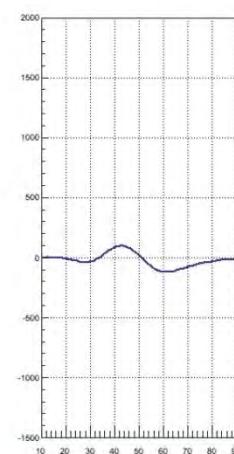
Core



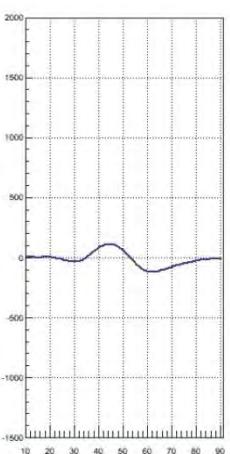
Segment hit



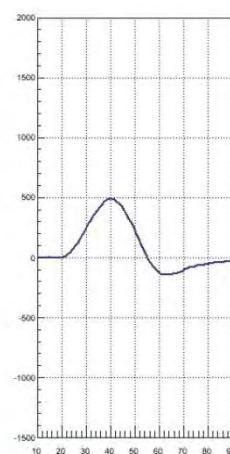
Left seg.



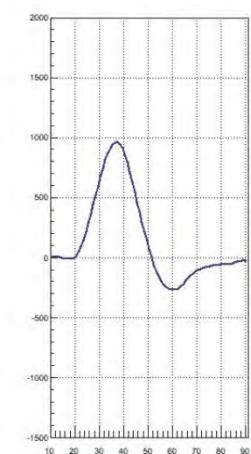
Right seg



Top seg.

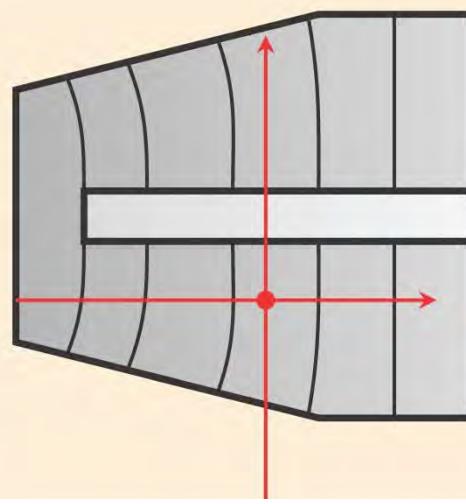
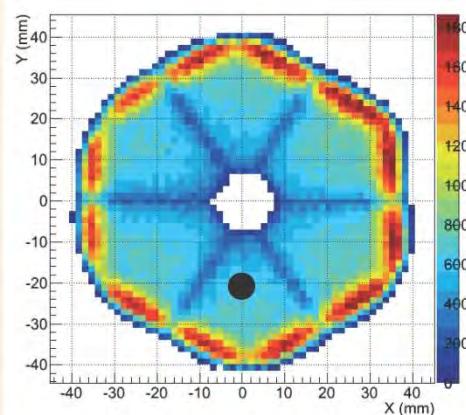


Bottom seg.



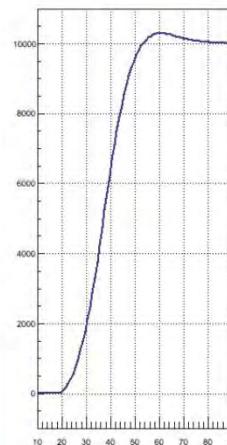
3D partial PSCS

Segment efficiency slice 4

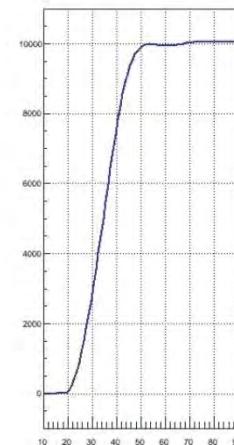


(0 ; -23 ; 48)

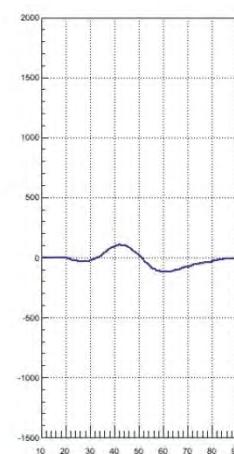
Core



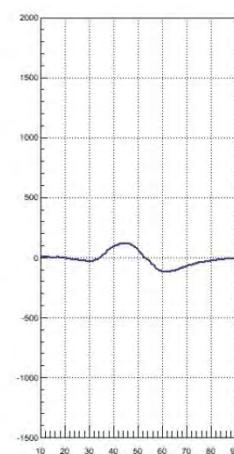
Segment hit



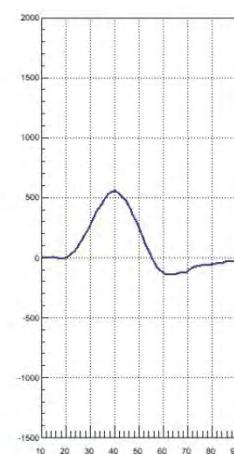
Left seg.



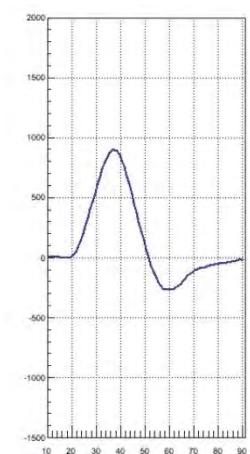
Right seg



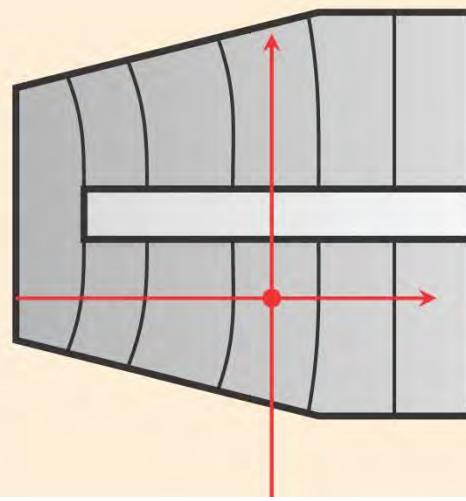
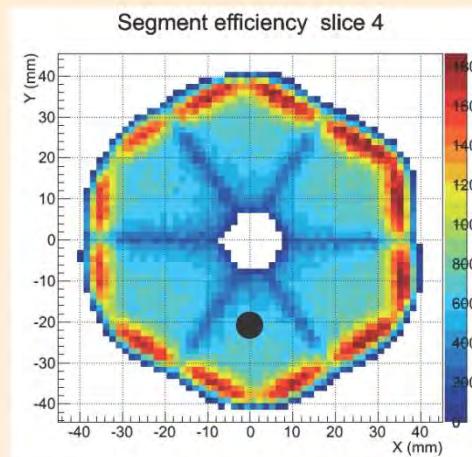
Top seg.



Bottom seg.

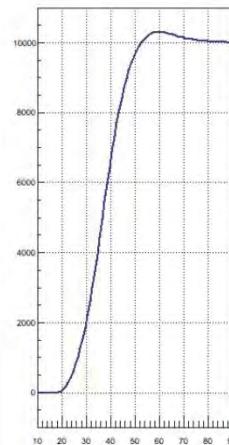


3D partial PSCS

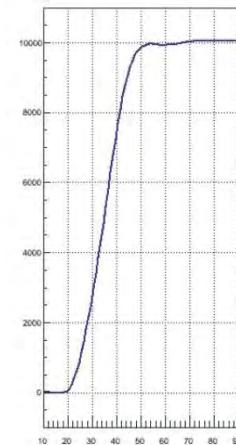


(0 ; -23 ; 49)

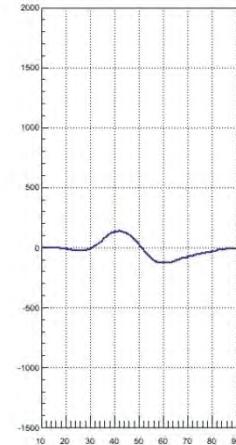
Core



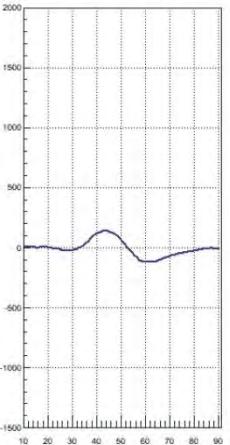
Segment hit



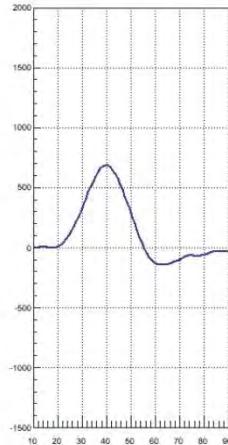
Left seg.



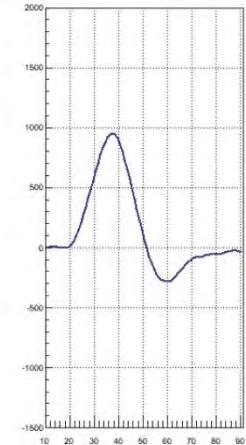
Right seg



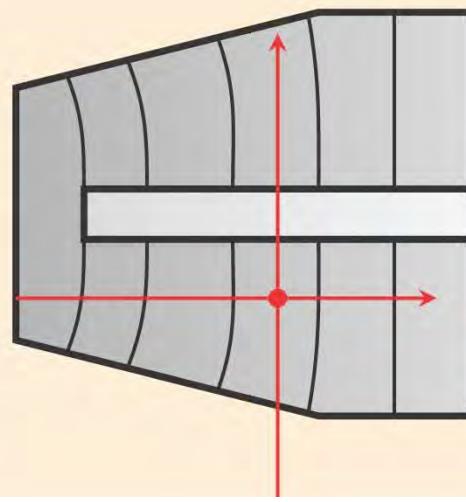
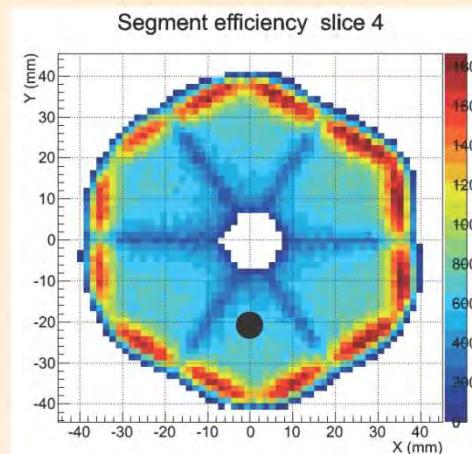
Top seg.



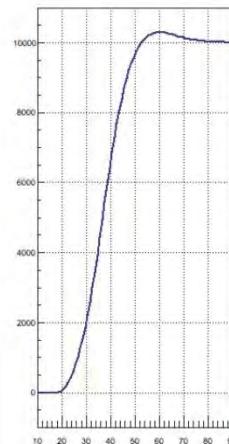
Bottom seg.



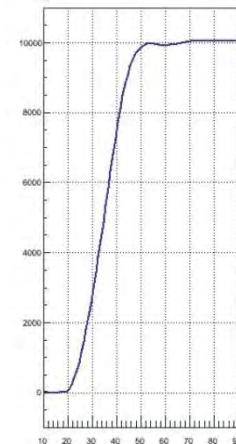
3D partial PSCS


 $(0; -23; 50)$

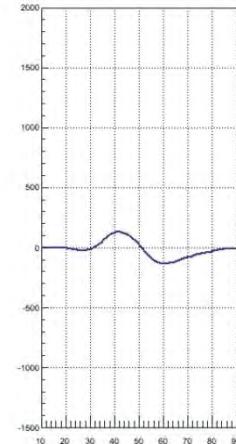
Core



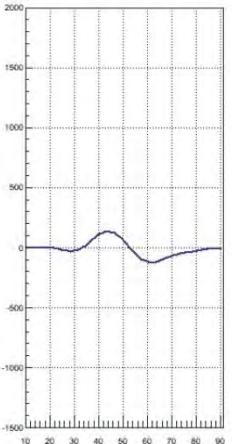
Segment hit



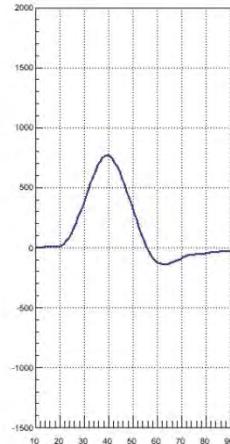
Left seg.



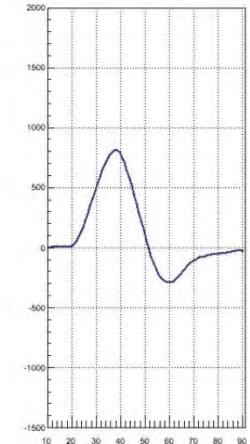
Right seg



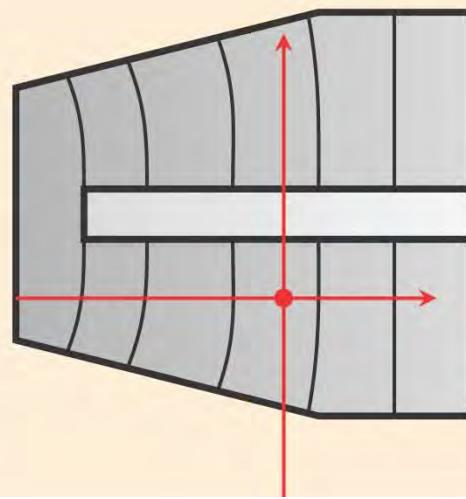
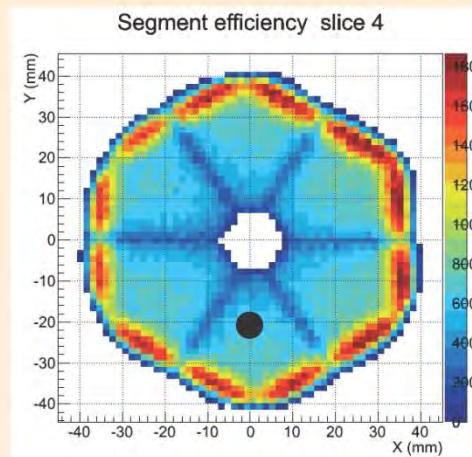
Top seg.



Bottom seg.

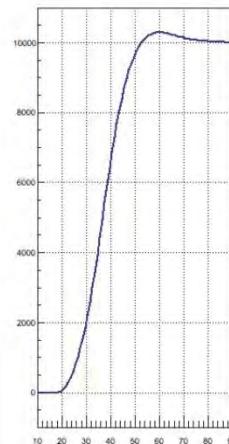


3D partial PSCS

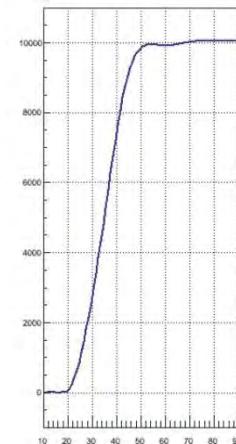


(0 ; -23 ; 51)

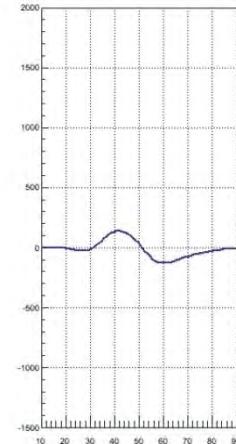
Core



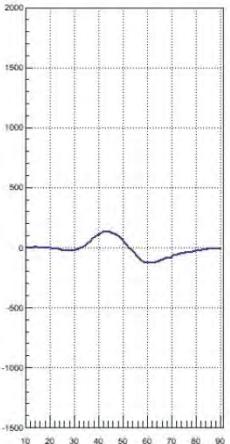
Segment hit



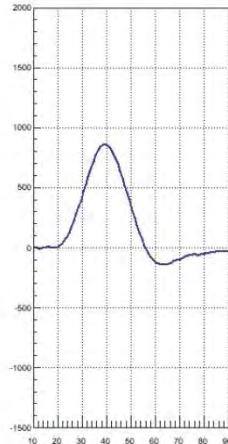
Left seg.



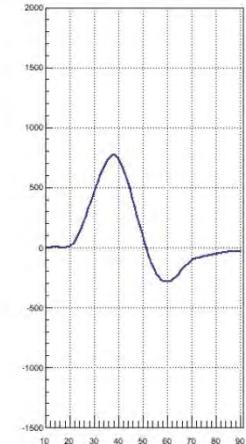
Right seg



Top seg.

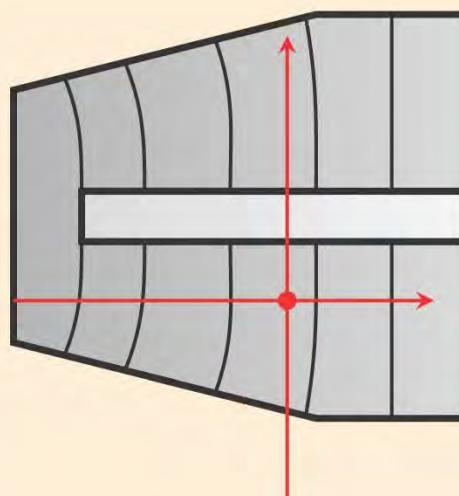
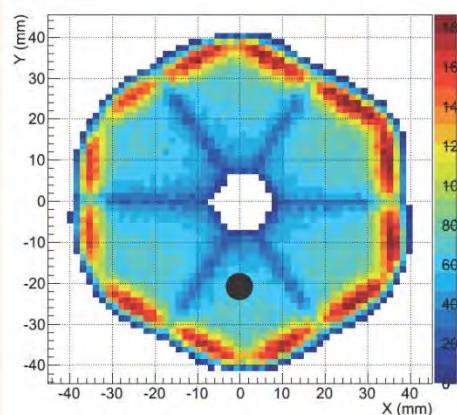


Bottom seg.



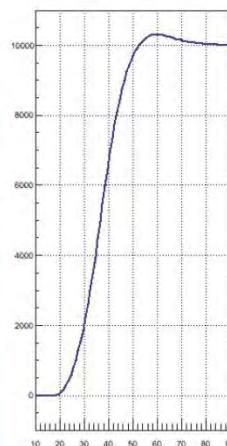
3D partial PSCS

Segment efficiency slice 4

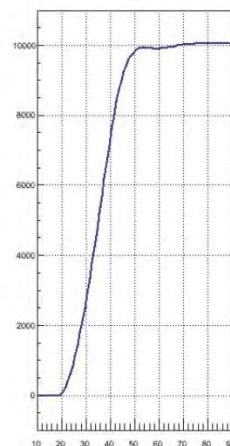


(0 ; -23 ; 52)

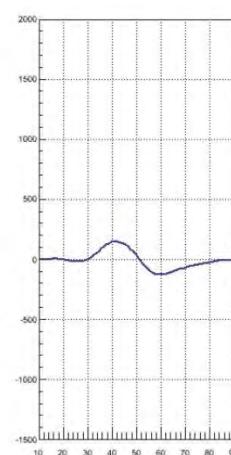
Core



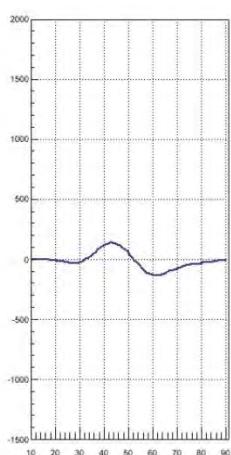
Segment hit



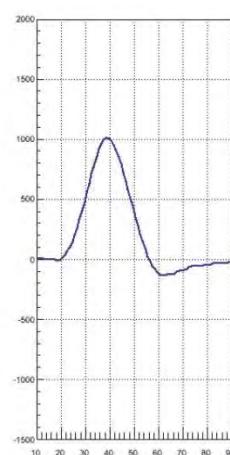
Left seg.



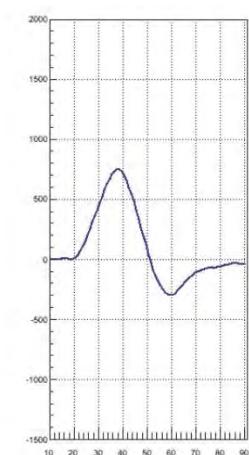
Right seg



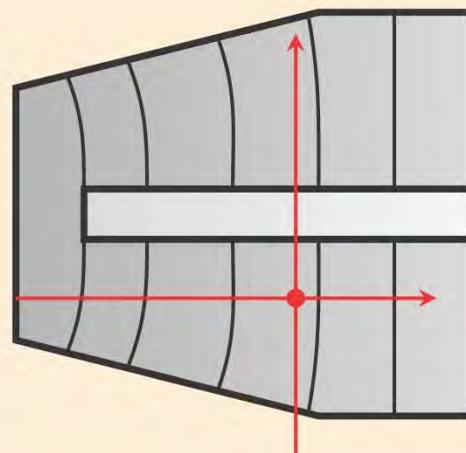
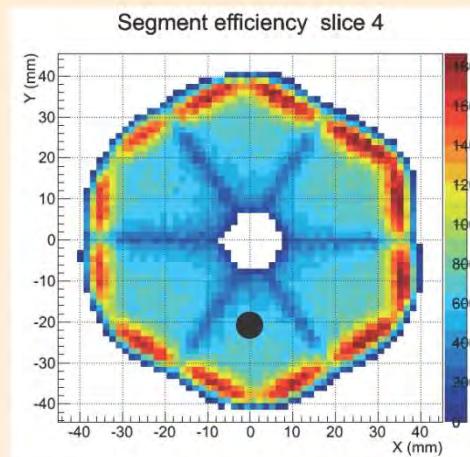
Top seg.



Bottom seg.

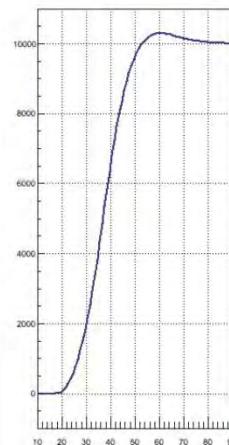


3D partial PSCS

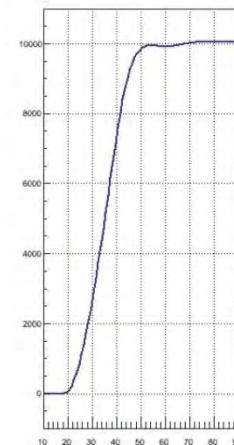


(0 ; -23 ; 53)

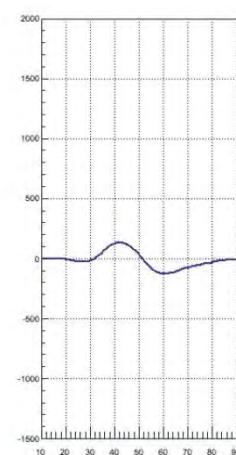
Core



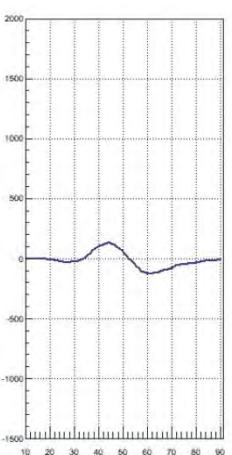
Segment hit



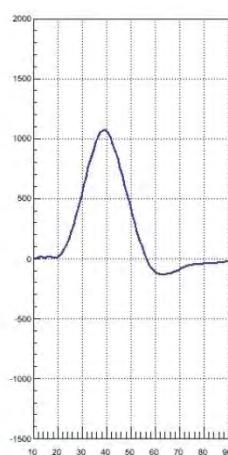
Left seg.



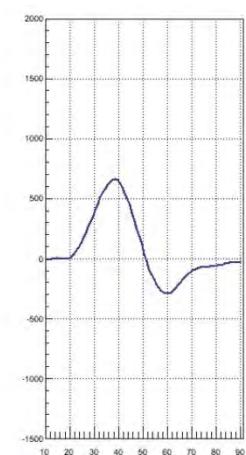
Right seg.



Top seg.

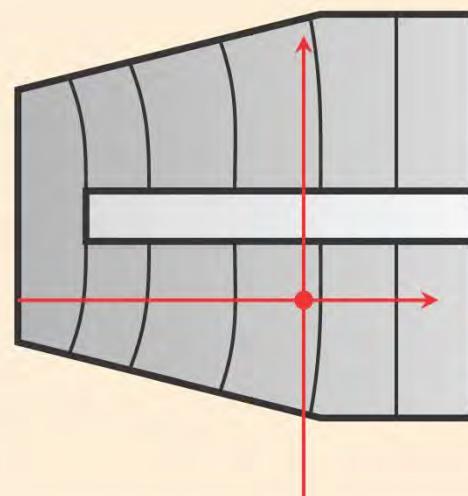
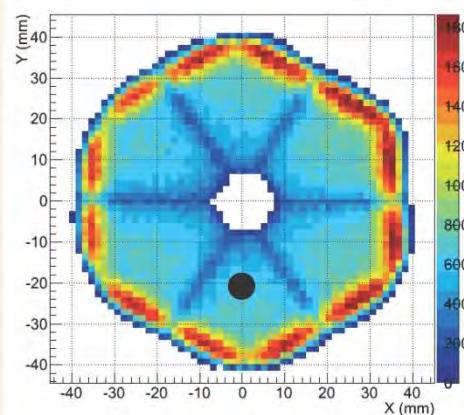


Bottom seg.



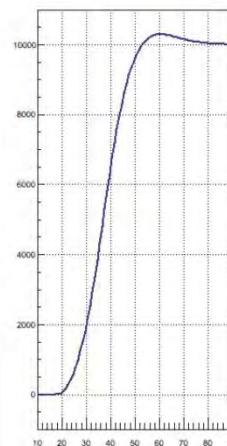
3D partial PSCS

Segment efficiency slice 4

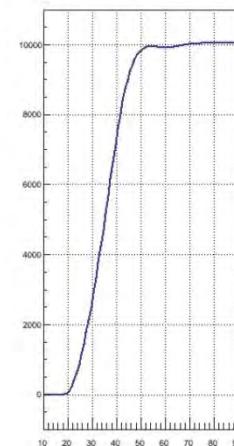


(0 ; -23 ; 54)

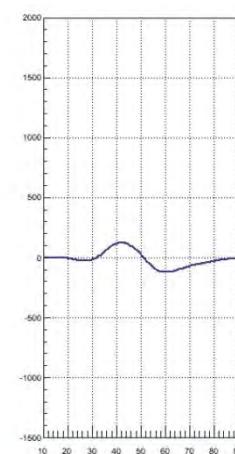
Core



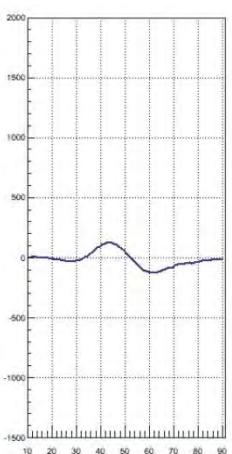
Segment hit



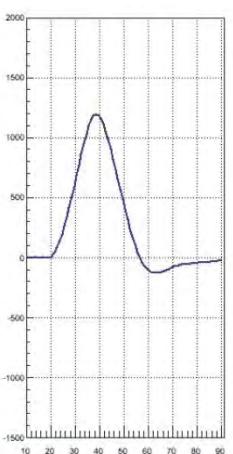
Left seg.



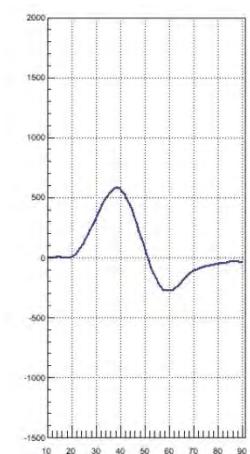
Right seg.



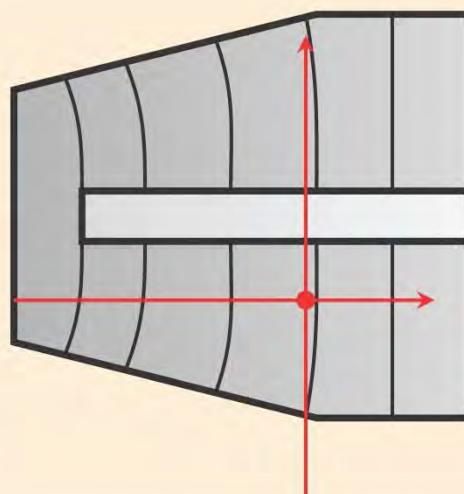
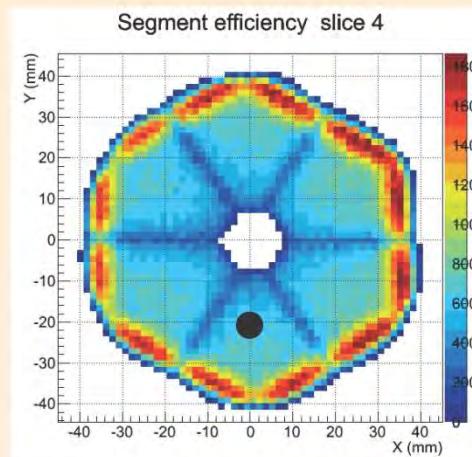
Top seg.



Bottom seg.

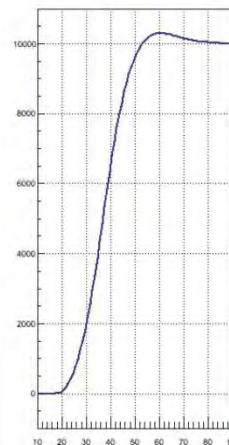


3D partial PSCS

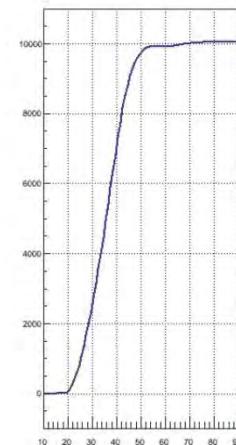


(0 ; -23 ; 55)

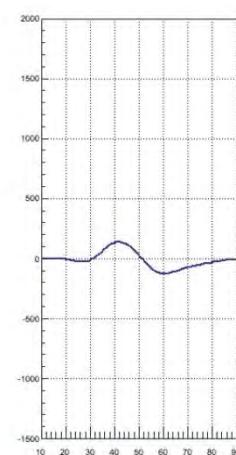
Core



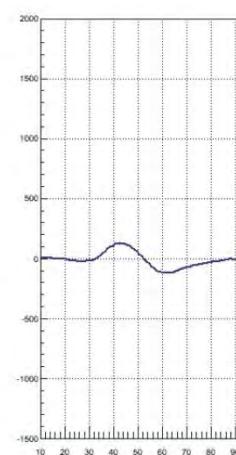
Segment hit



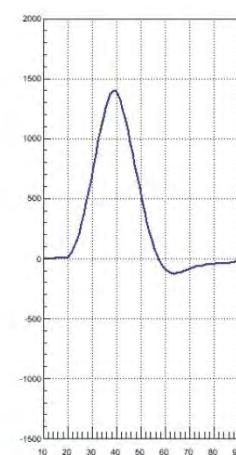
Left seg.



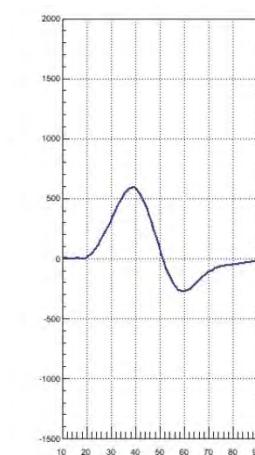
Right seg



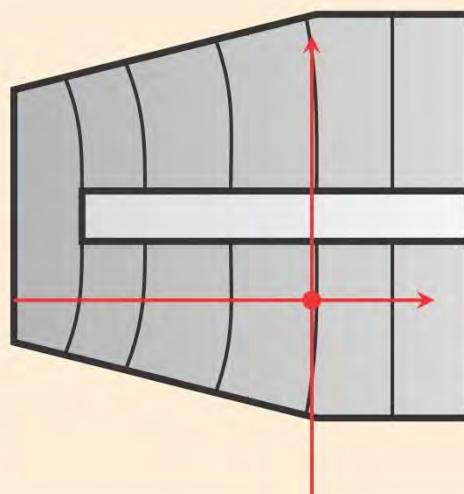
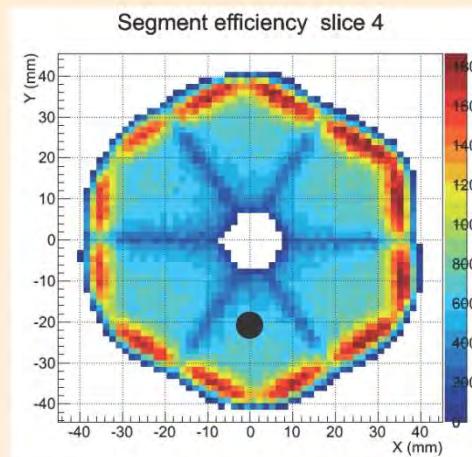
Top seg.



Bottom seg.

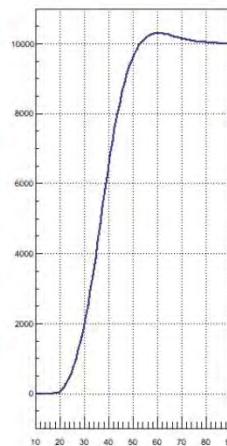


3D partial PSCS

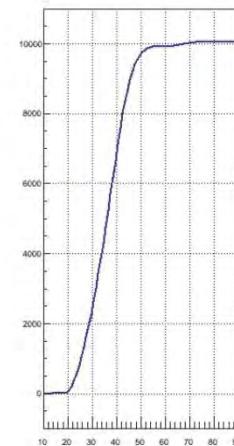


(0 ; -23 ; 56)

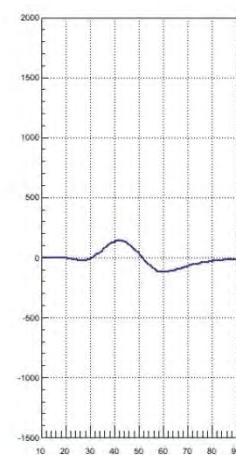
Core



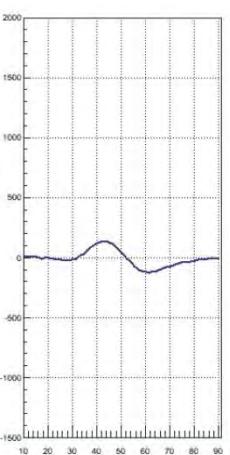
Segment hit



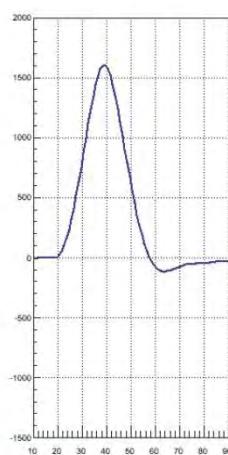
Left seg.



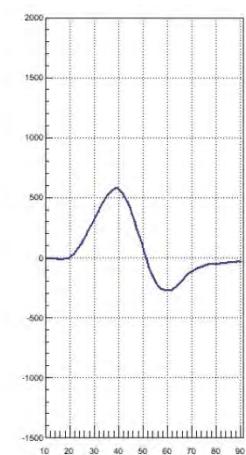
Right seg



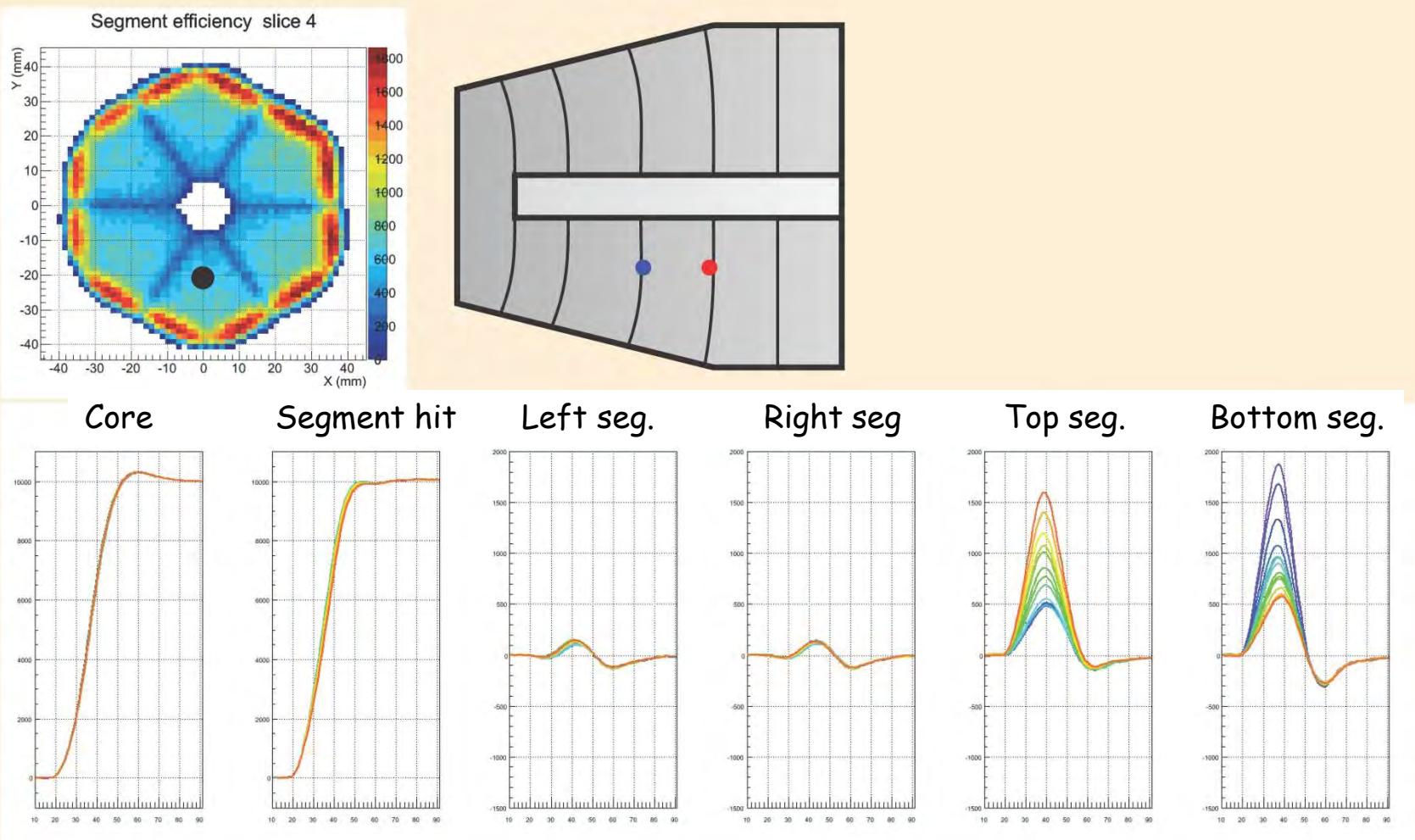
Top seg.



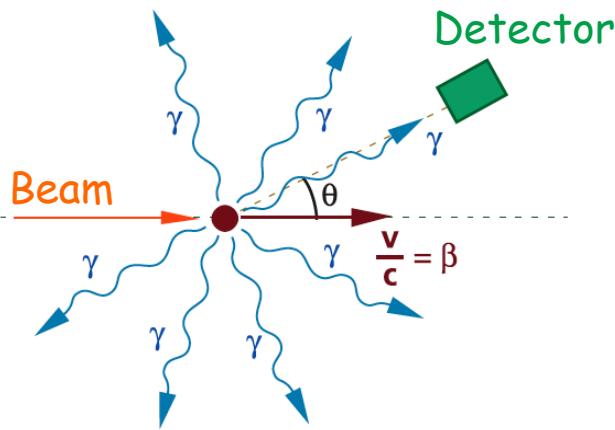
Bottom seg.



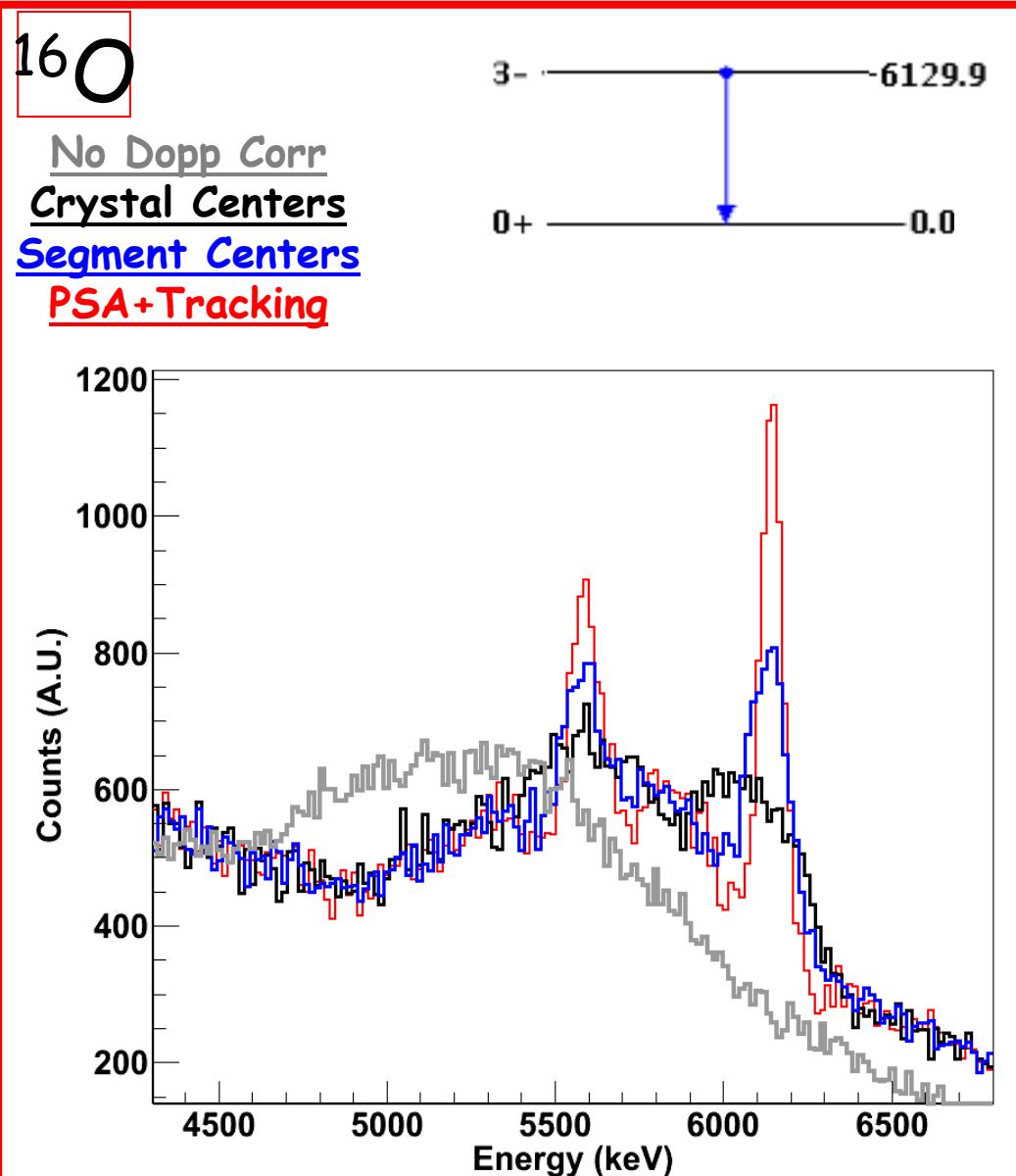
3D partial PSCS



Multi-detector AGATA for γ -ray detection



$$\Delta E_\gamma(\theta, E_\gamma) = E_\gamma \frac{v}{c} \cos(\theta).$$



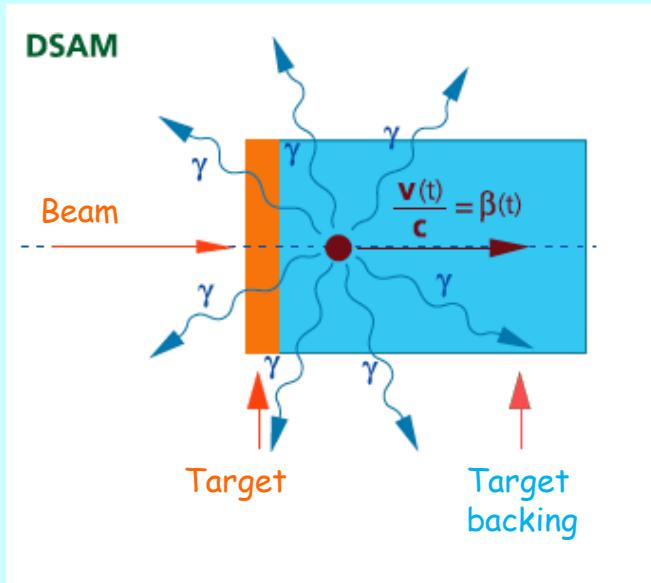
Nuclear lifetime measurements

Many techniques

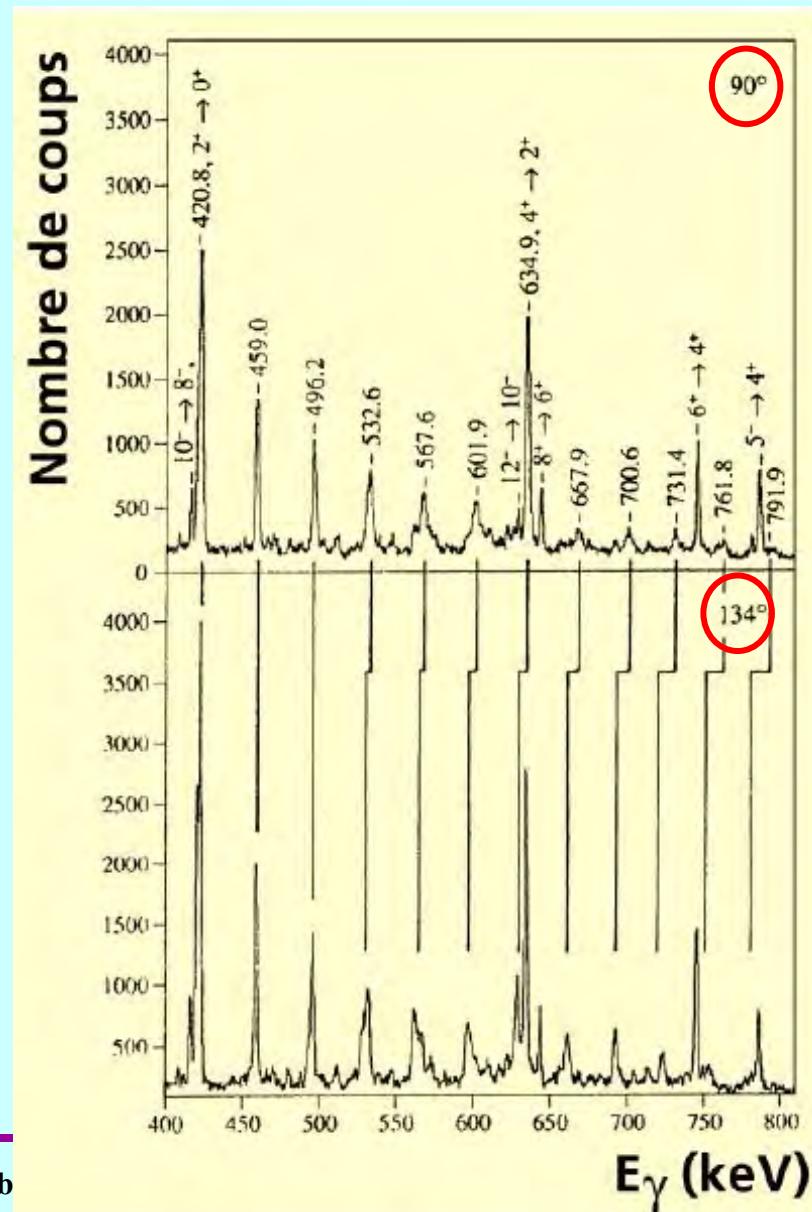
- Using the Doppler effect
 - ❑ DSAM (Doppler Shift Attenuation Method) -> below ps
 - ❑ Plunger -> ps to ns
- No Doppler effect
 - ❑ Fast timing scintillators (LaBr_3) -> ps to ns
 - ❑ ToF -> $> \mu\text{s}$

Nuclear lifetime measurements

DSAM

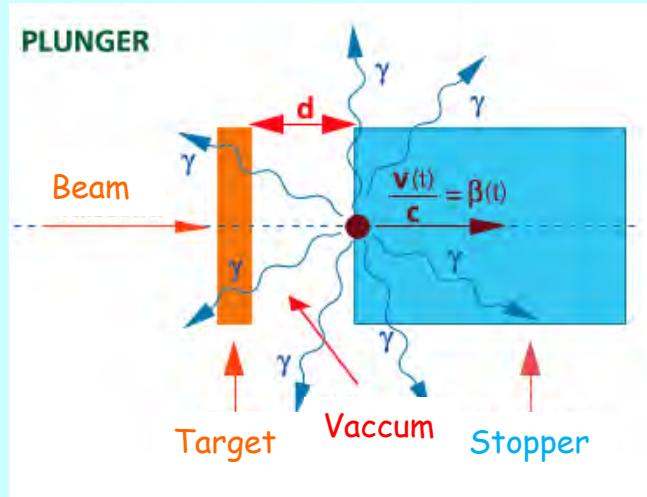


- Nucleus de-excitation during the slowing down in the backing of the target
- Varying velocity \rightarrow different Doppler shift
- Depend on the stopping power of the target and backing
- Lifetimes from 10 fs to few 100 fs



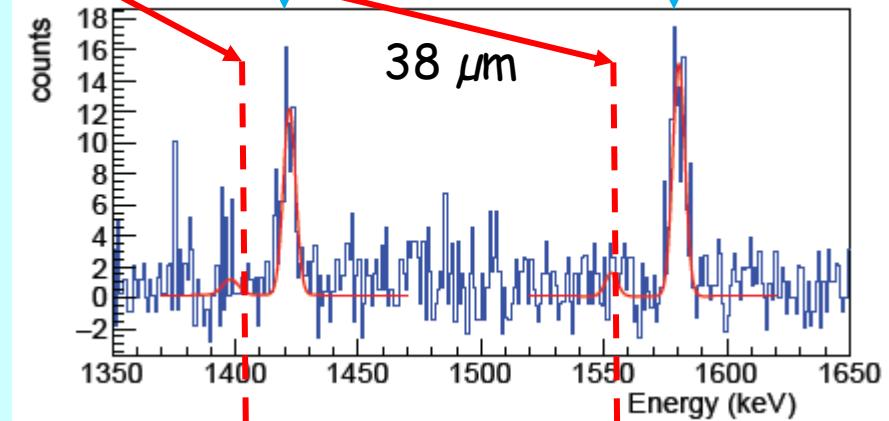
Nuclear lifetime measurements

Plunger

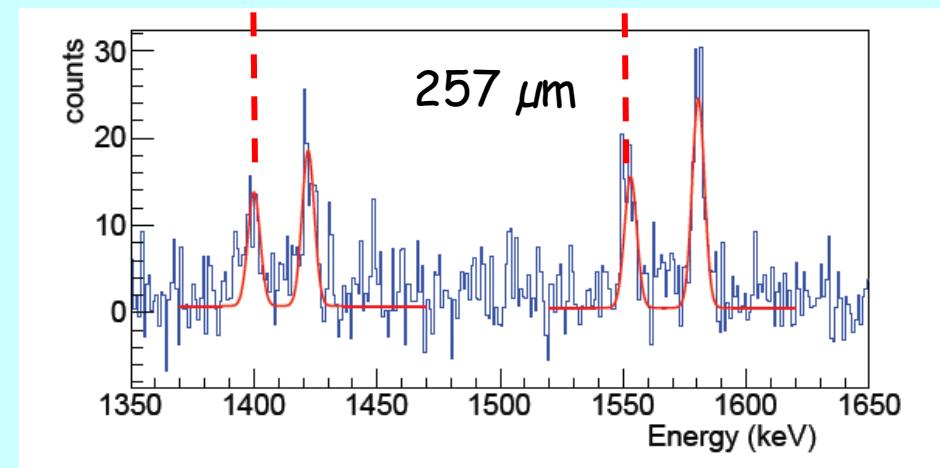


N flight component

Stopped components



- Nucleus de-excitation
 - ❑ during the flight in vacuum (**Doppler shifted**)
 - ❑ At rest in the **stopper**
- Two velocities → two peaks
- Varies with distance **d** and lifetime τ
- Lifetimes from ps to ns



Angular distributions

to deduce state spins

Spin alignment

- In the plan perpendicular to the beam
- Aligned nuclear states ($m \sim 0$)
- Anisotropic γ -ray emission (not uniform emission in 4π)

$$\vec{l} = \vec{r} \wedge \vec{p}$$

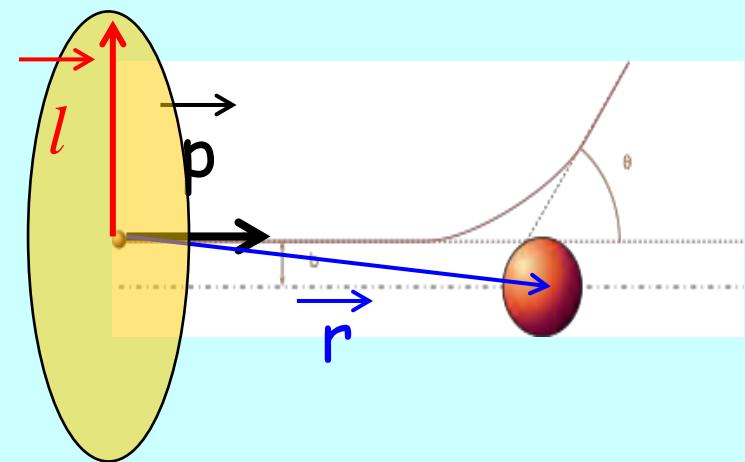
Angular distribution

- Distribution of normalised intensity

$$w(\theta) = \frac{I_\gamma(\theta)}{I_\gamma} = 1 + a_2 P_2(\cos \theta) + a_4 P_4(\cos \theta) + \dots$$

where

- ❑ θ = angle between γ ray (detector) and beam axis
- ❑ $P_i(\cos \theta)$ = Legendre polynomials
- ❑ Pure dipole ($l=1$): a_2 negative and $a_4=0$
- ❑ Stretched quadripole ($l=2$): a_2 positive and $a_4 < 0$ and small

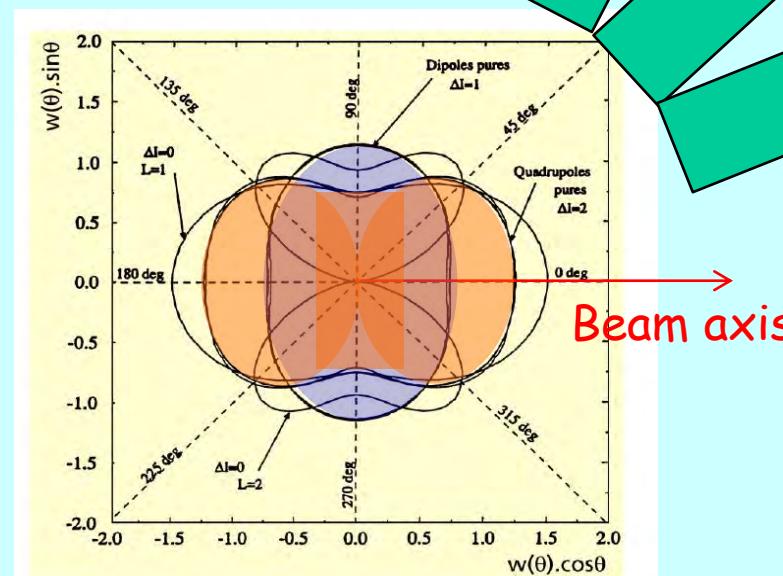
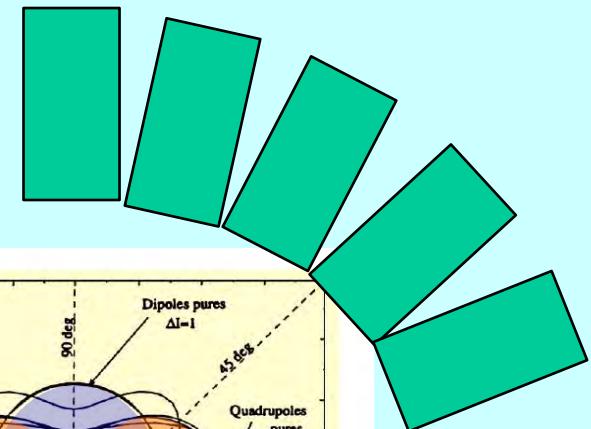


Angular distributions

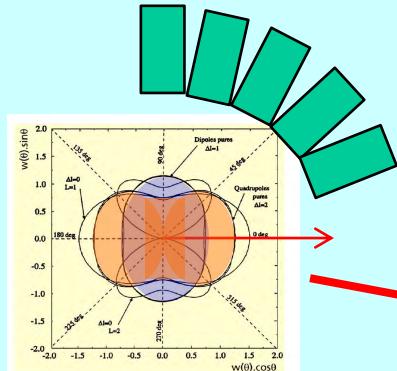
to deduce state spins

Angular distribution

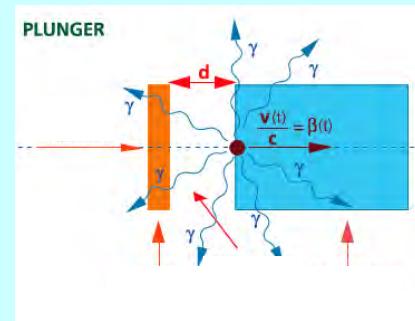
- γ -ray intensity varies with angle θ versus beam axis
- For pure stretched ($\Delta I=1$) dipole transitions
 - ❑ max at 90°
 - ❑ Smallest at 0°
- For pure stretched ($\Delta I=2$) quadrupole transitions
 - ❑ max at $\sim 55^\circ$
 - ❑ Important at 0°
 - ❑ Smallest at 90°



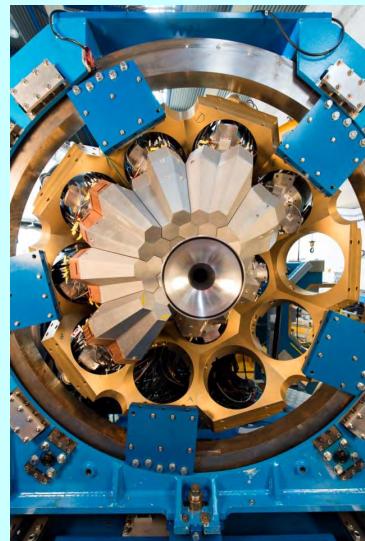
In summary



Angular distributions
Gamma-ray multipolarity
Spin assignment

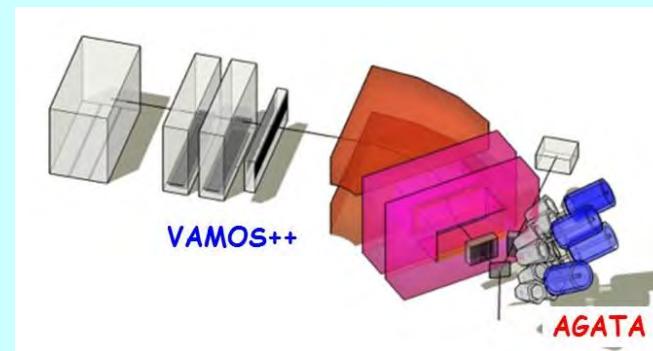


State lifetime

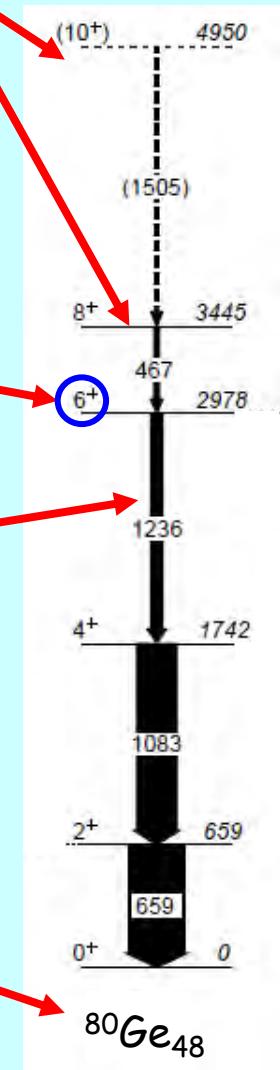


AGATA

Gamma-ray detection
Level scheme
Shell structure & evolution



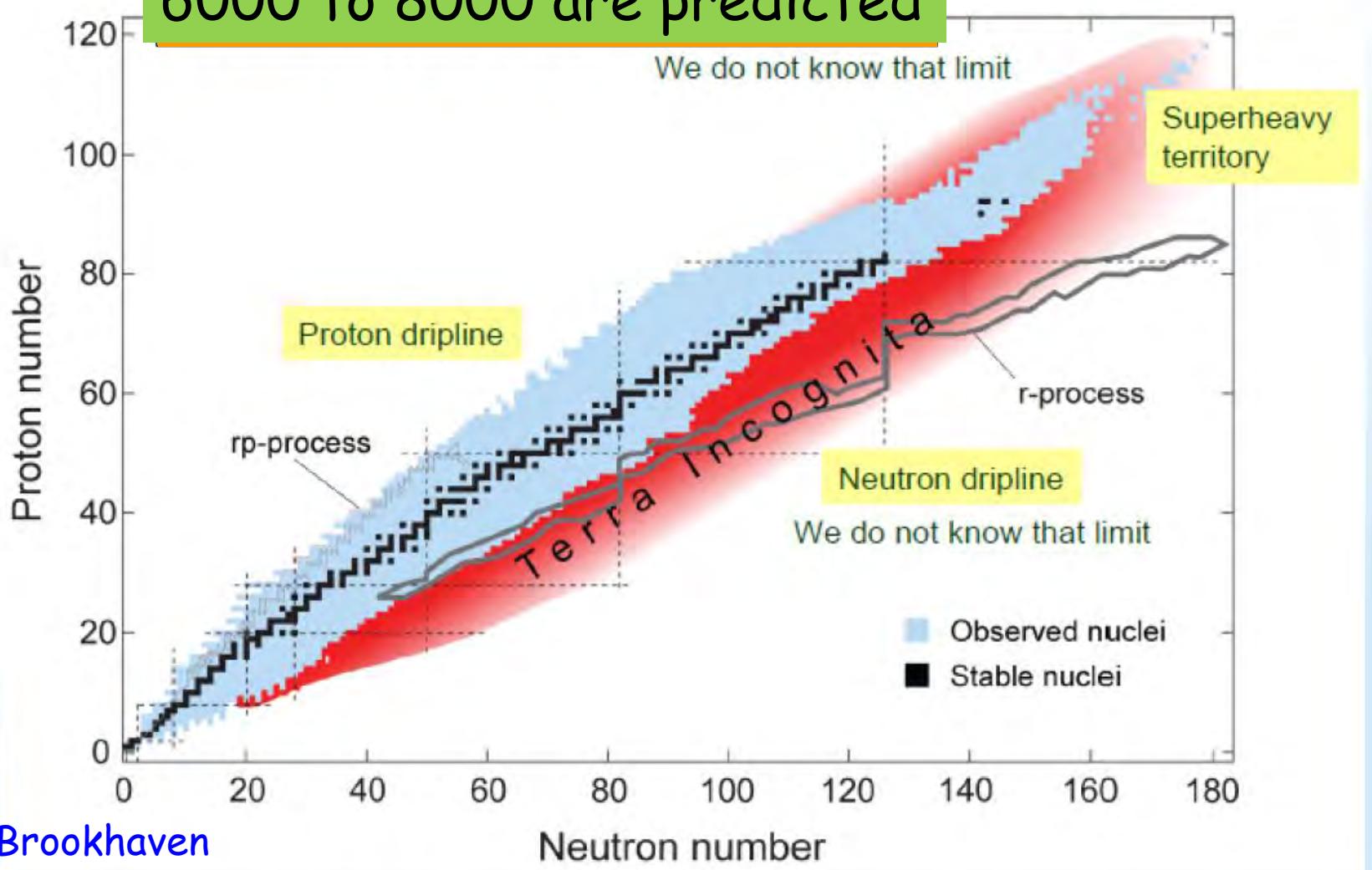
Recoil selection



Lecture plan

- 1. Introduction**
- 2. Nuclear structure and observables - *What can you measure or deduce ?***
- 3. Nuclear reactions - *How to create your nucleus of interest?***
- 4. Radiation-matter interactions and detectors for charged particle and γ rays - *Tool kit***
- 5. Perspectives**

6000 to 8000 are predicted



Brookhaven

G. Duchêne

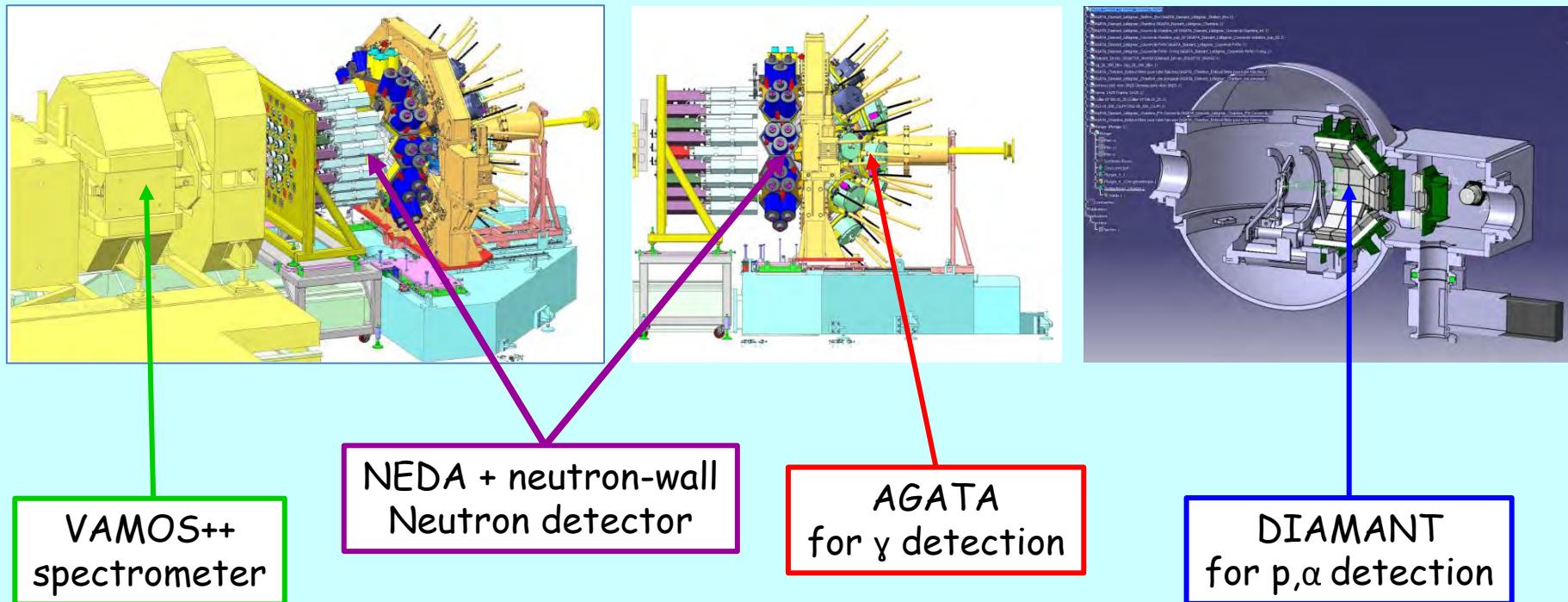
Perspectives

Coupling of different detectors to AGATA

➤ GANIL physics campaigns

2018

8 experiments using AGATA+NEDA (+DIAMANT) (+LaBr₃) (+plunger)



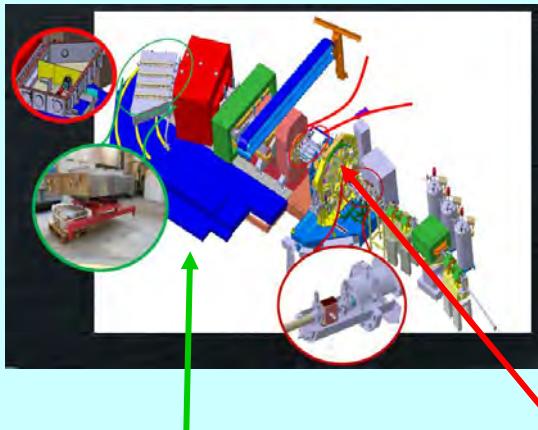
Structure study of N~Z nuclei and around ^{100}Sn

Perspectives

Coupling of different detectors to AGATA

➤ GANIL physics campaigns

2019 - 2020

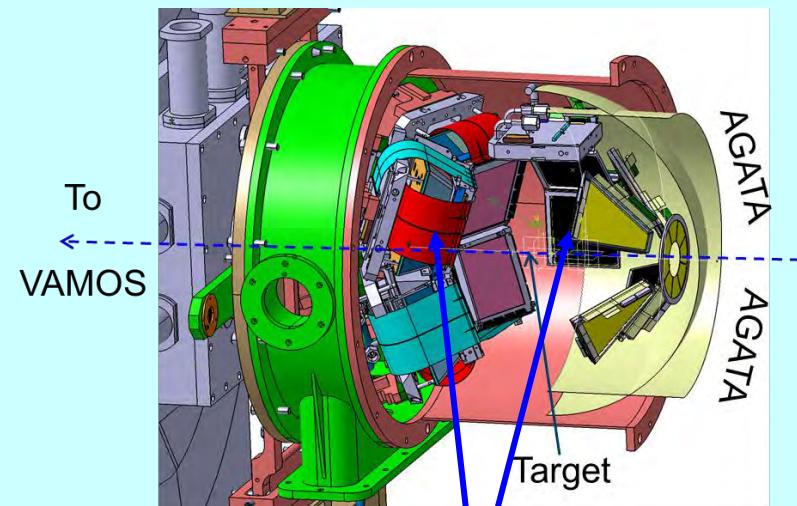


VAMOS
spectrometer
in Gas Filled Mode
(GFM)

AGATA
for γ detection

Structure study of
superheavy elements

Nucleon transfer spectroscopy
using **SPIRAL1** beams



MUGAST
for p, α detection

Perspectives

New accelerators for exotic beam

- SPES in 2022 (Legnaro, Italy) → radioactive beams up to 10^8 particule per sec
- HIE-ISOLDE in 2021 (CERN, Switzerland) → radioactive beams up to 10^8 part. per sec
 - ISOL technique (fission products reaccelerated)

Structure study of neutron-rich nuclei around ^{78}Ni and above

- FAIR in 2025 (Darmstadt, Germany) → intense radioactive beams at high energy
 - Fragmentation technique

Structure study of very exotic, short-lived nuclei

- GANIL SPIRAL2 (Caen, France)
 - very intense stable beams (2022)
 - intense exotic beams (SPIRAL1 - 2019)

Structure study of $\text{N} \sim \text{Z}$, superheavy and exotic nuclei

