Nuclear observables

G. Duchêne

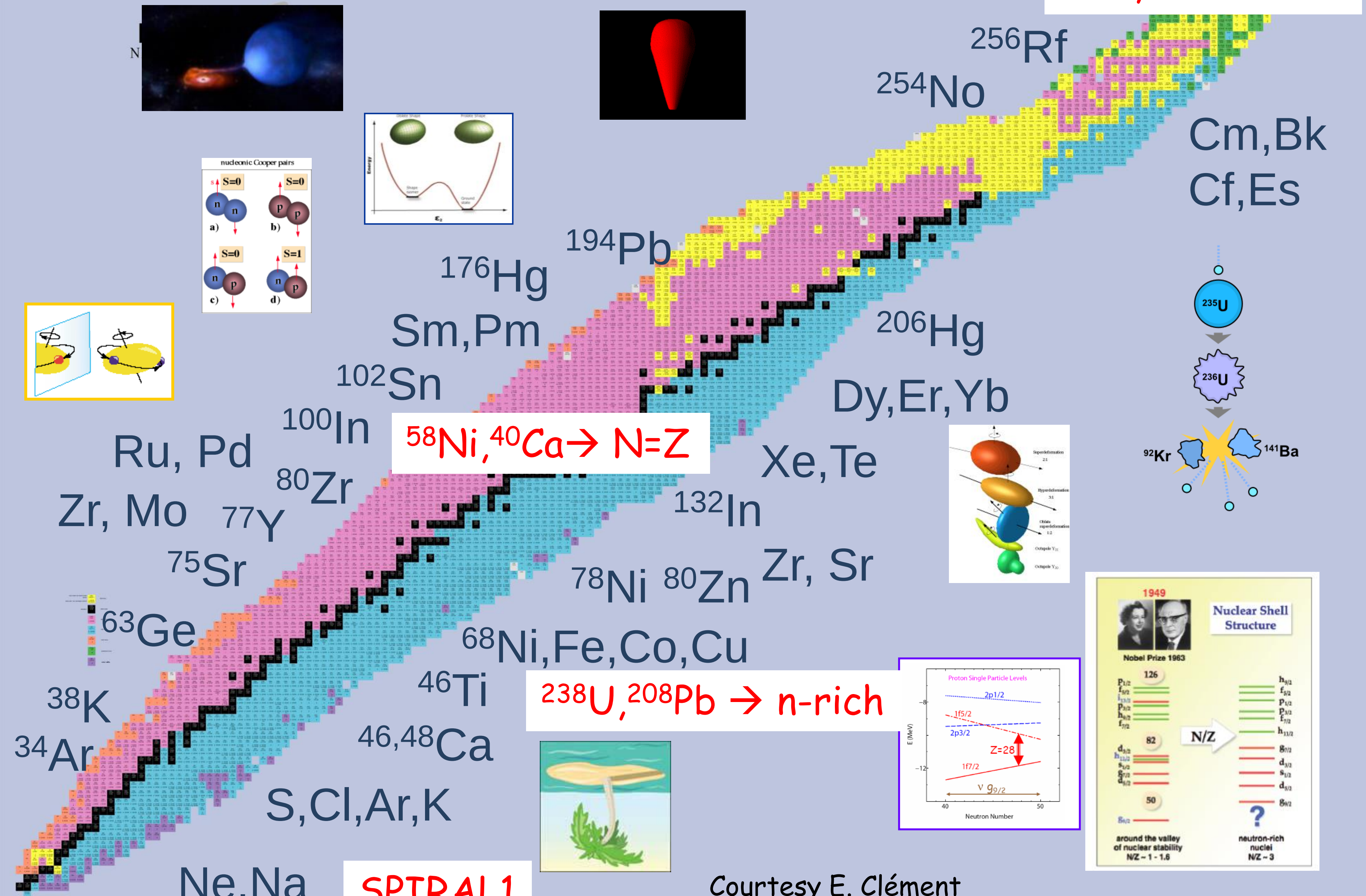
Du noyau aux étoiles (From nuclei to stars)

e-mail : gilbert.duchene@iphc.cnrs.fr

Lecture plan

1. Introduction
2. Radiation-matter interactions and detectors for charged particle and γ rays
3. Nuclear reactions
4. Nuclear structure and observables
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



Courtesy E. Clément

Lecture plan

1. Introduction
2. **Radiation-matter interactions and detectors for charged particle and γ rays**
3. Nuclear reactions
4. Nuclear structure and observables
5. Perspectives

G. Duchêne

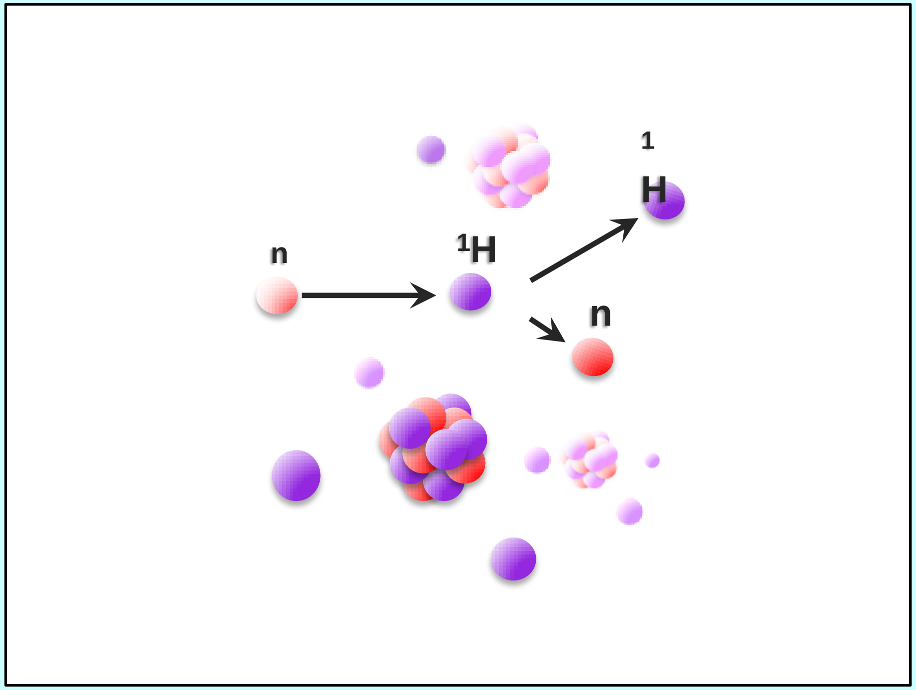
Radiation-matter interactions and detectors

Emitted particles in nuclear reactions

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

Neutrons

- For En > 500 keV mainly elastic scattering n + H -> n + H
- Recoil induces atomic excitations
- Prompt and delayed fluorescence

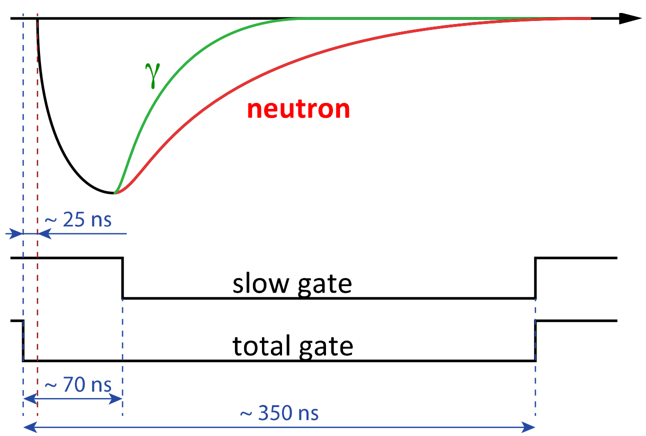


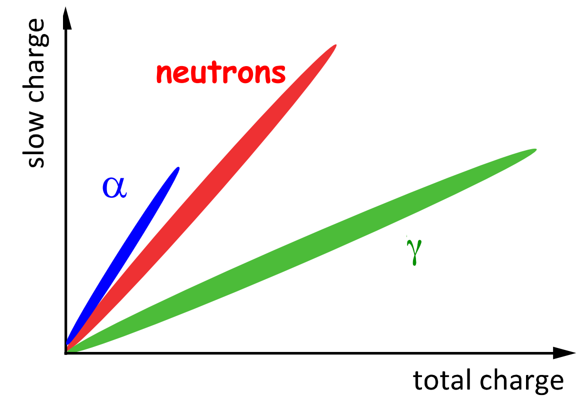
G. Duchêne

Radiation-matter interactions and detectors

Neutrons

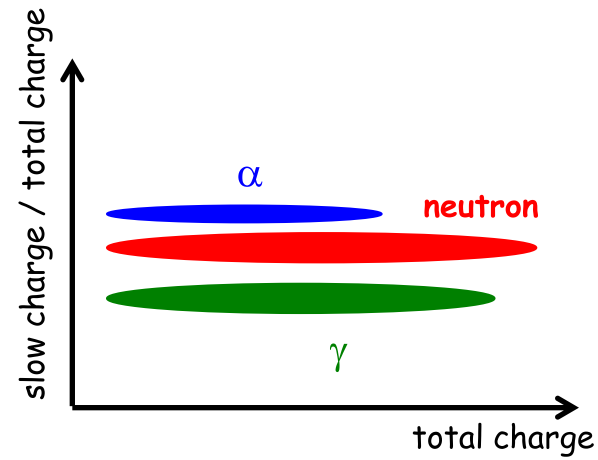
- Neutron - γ discrimination





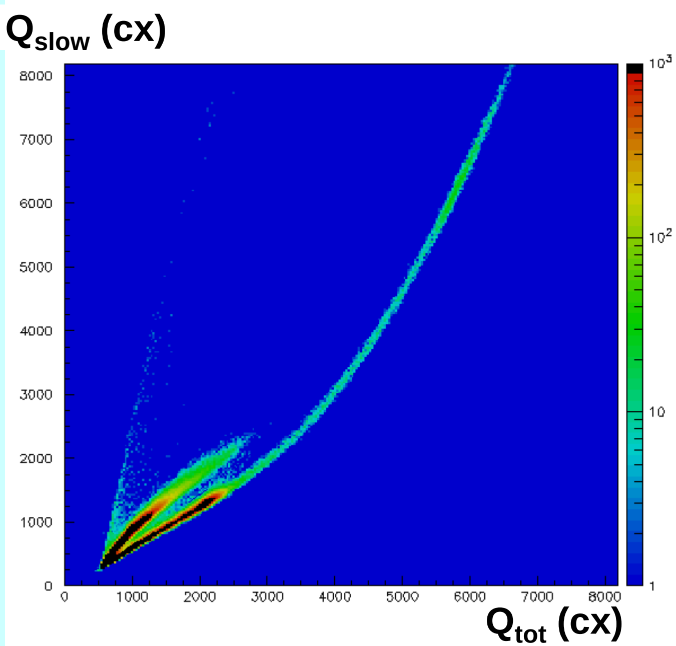
- organic liquids : NE213, BC501A,…
- crystals: anthracen, stilben (organics)
  clyc (Cs_2LiYCl_6)
  (also for slow neutrons)
- plastics: (no n-γ discrimination)
  except EJ299 … (new)

mainly…

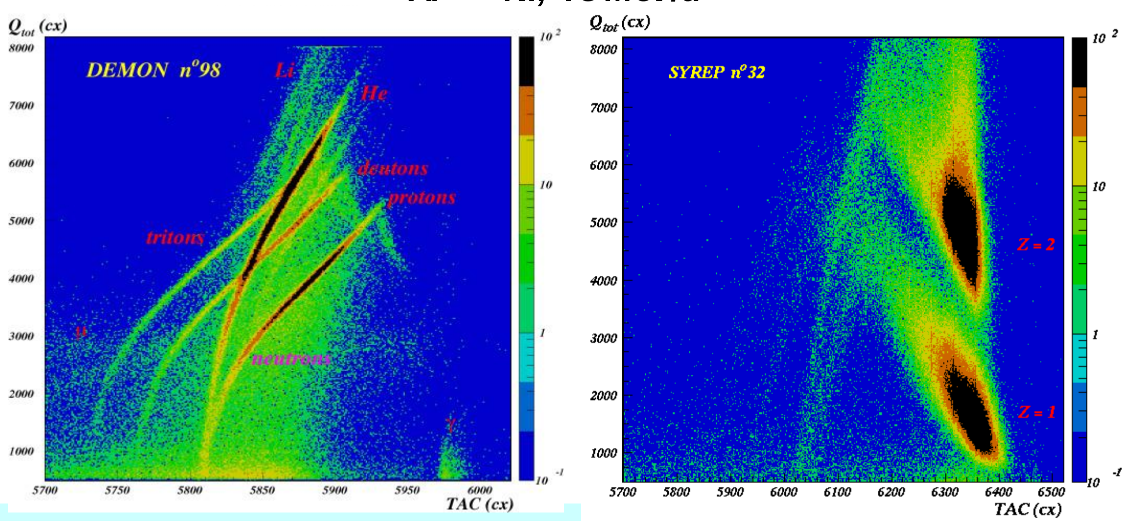


Neutrons

- Neutron - γ discrimination

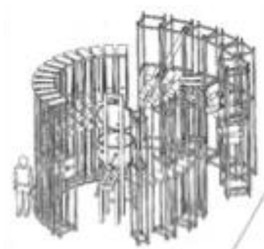


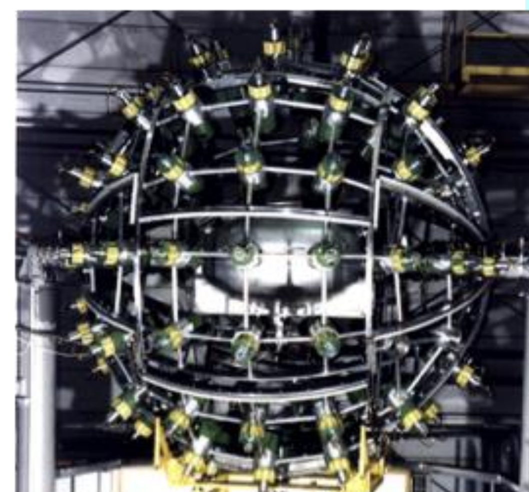
$^{40}Ar + ^{58}Ni$, 78 MeV/u



DEMON:

modular neutron detector





Charged particles

- Bethe formula

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

Linear stopping power

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

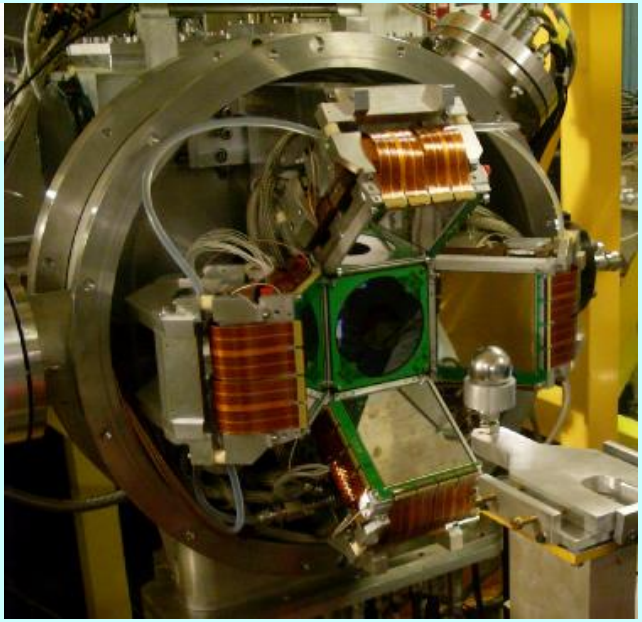
G. Duchêne

Radiation-matter interactions and detectors

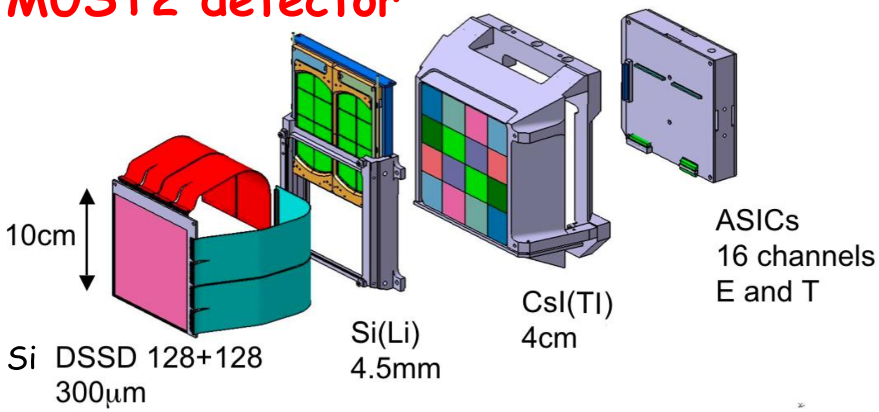
Charged particles

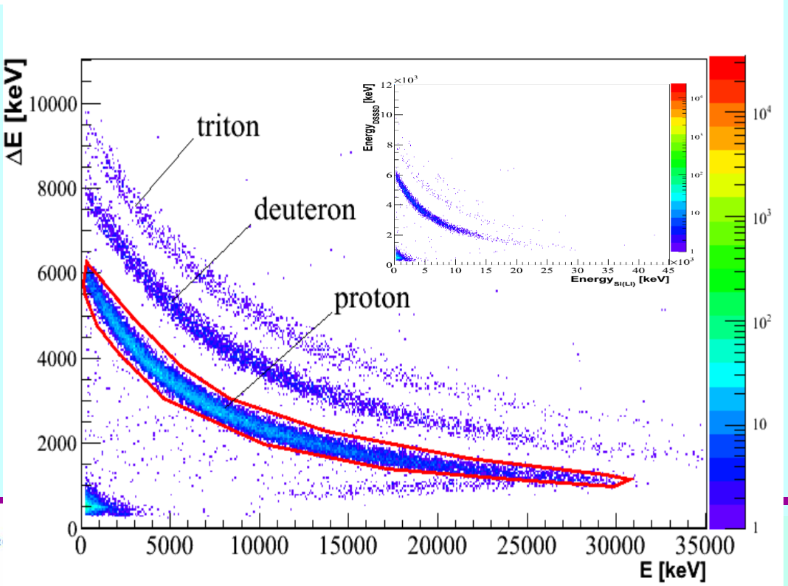
- Particle identification

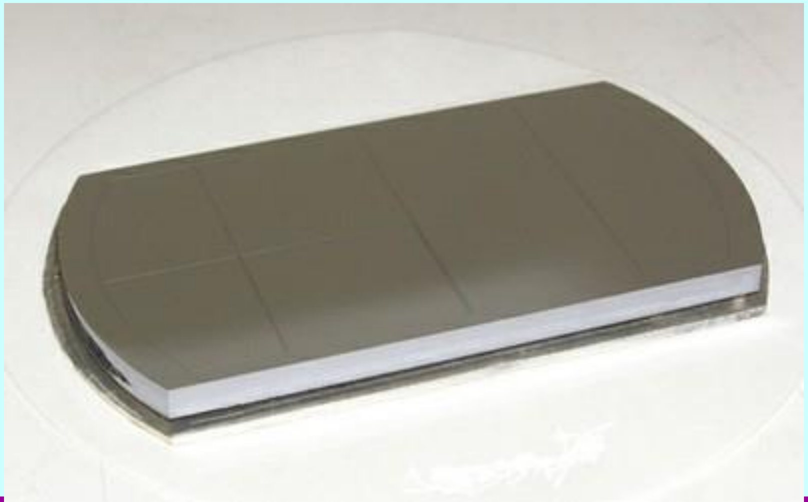
$$E \times \Delta E \propto Az^2$$



MUST2 detector





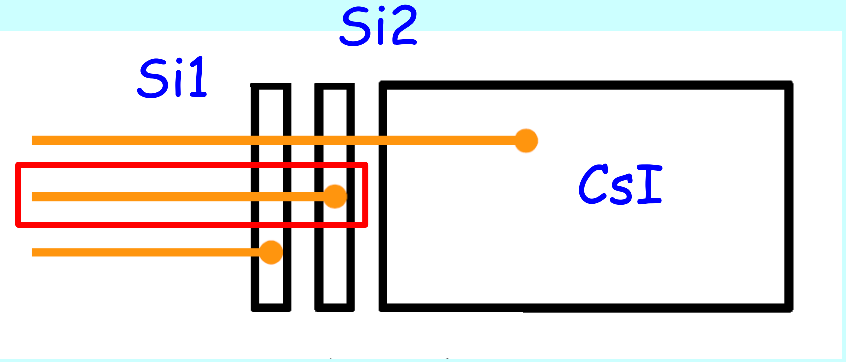


G. Duchêne

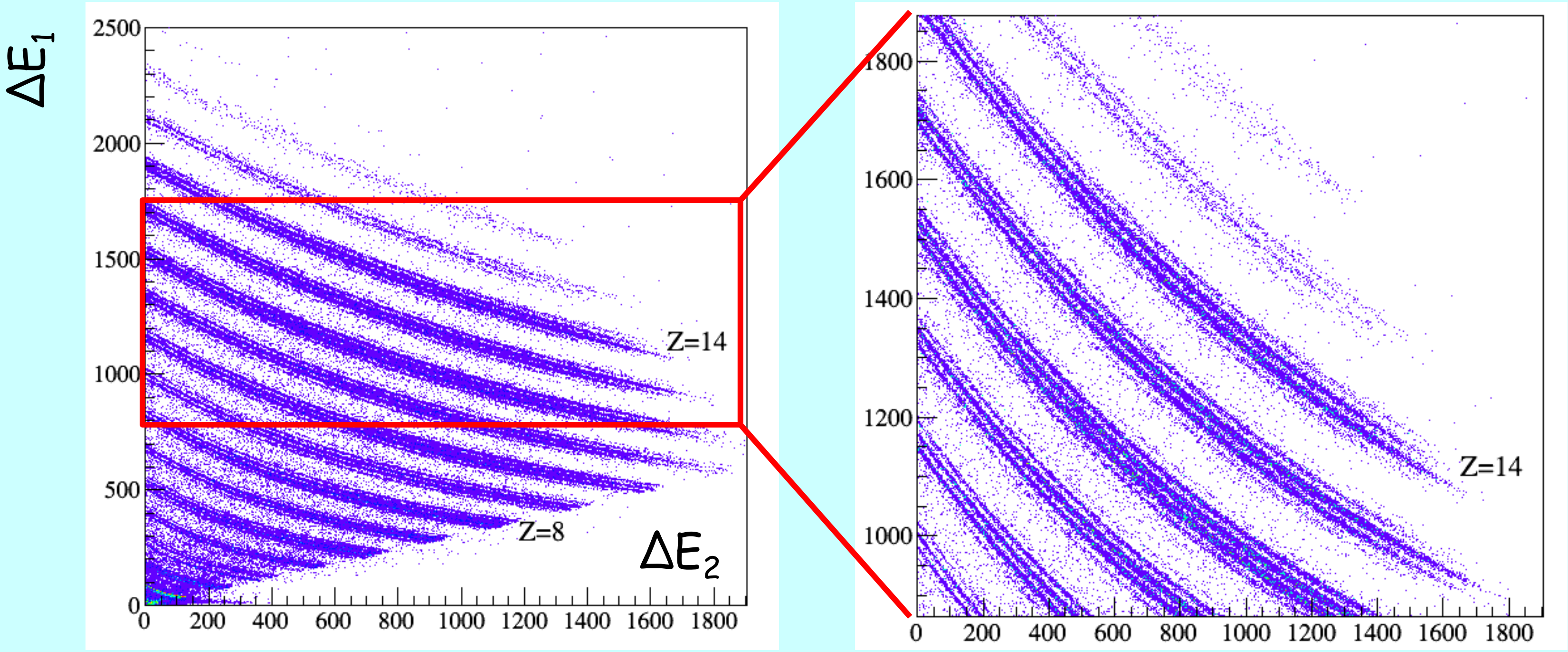
Radiation-matter interactions and detectors

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



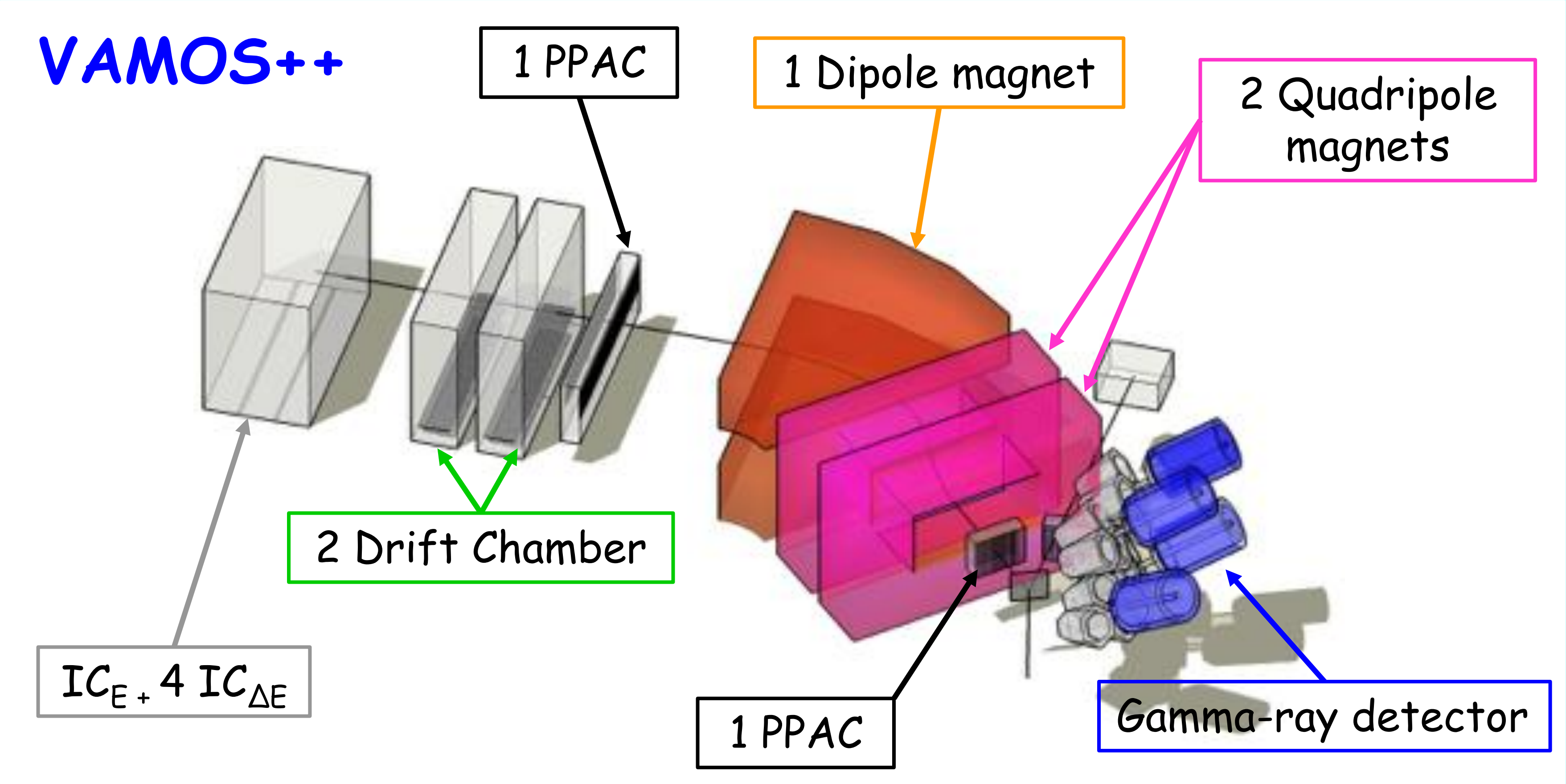
Courtesy G. Verde and D. Gruyer

G. Duchêne

Radiation-matter interactions and detectors

Fragments

- Particle identification
  - Spectrometer

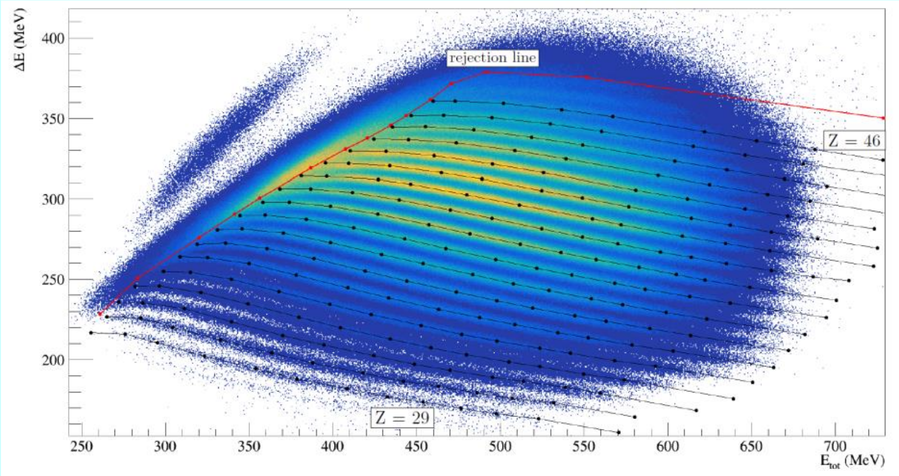


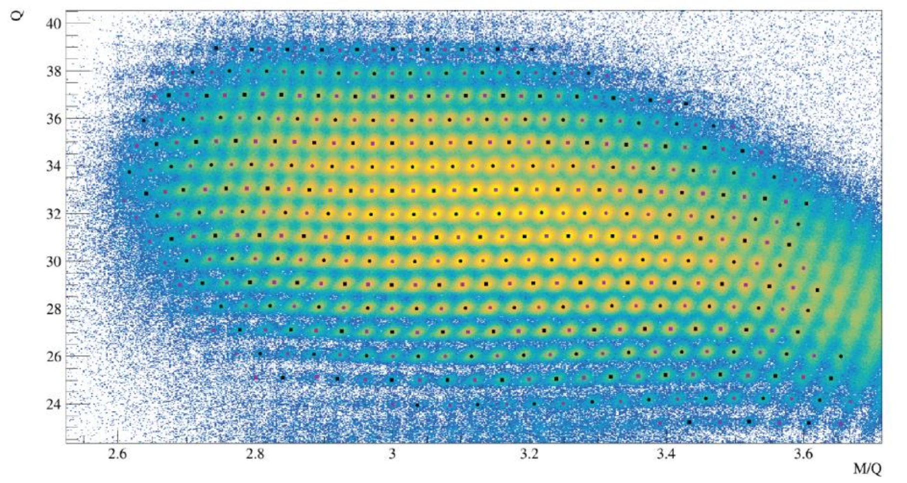
VAMOS drawing courtesy A. Lemasson

G. Duchêne

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 (ΔE, E)
    - Mass/Charge state (M/Q) determination
    - Mass determination



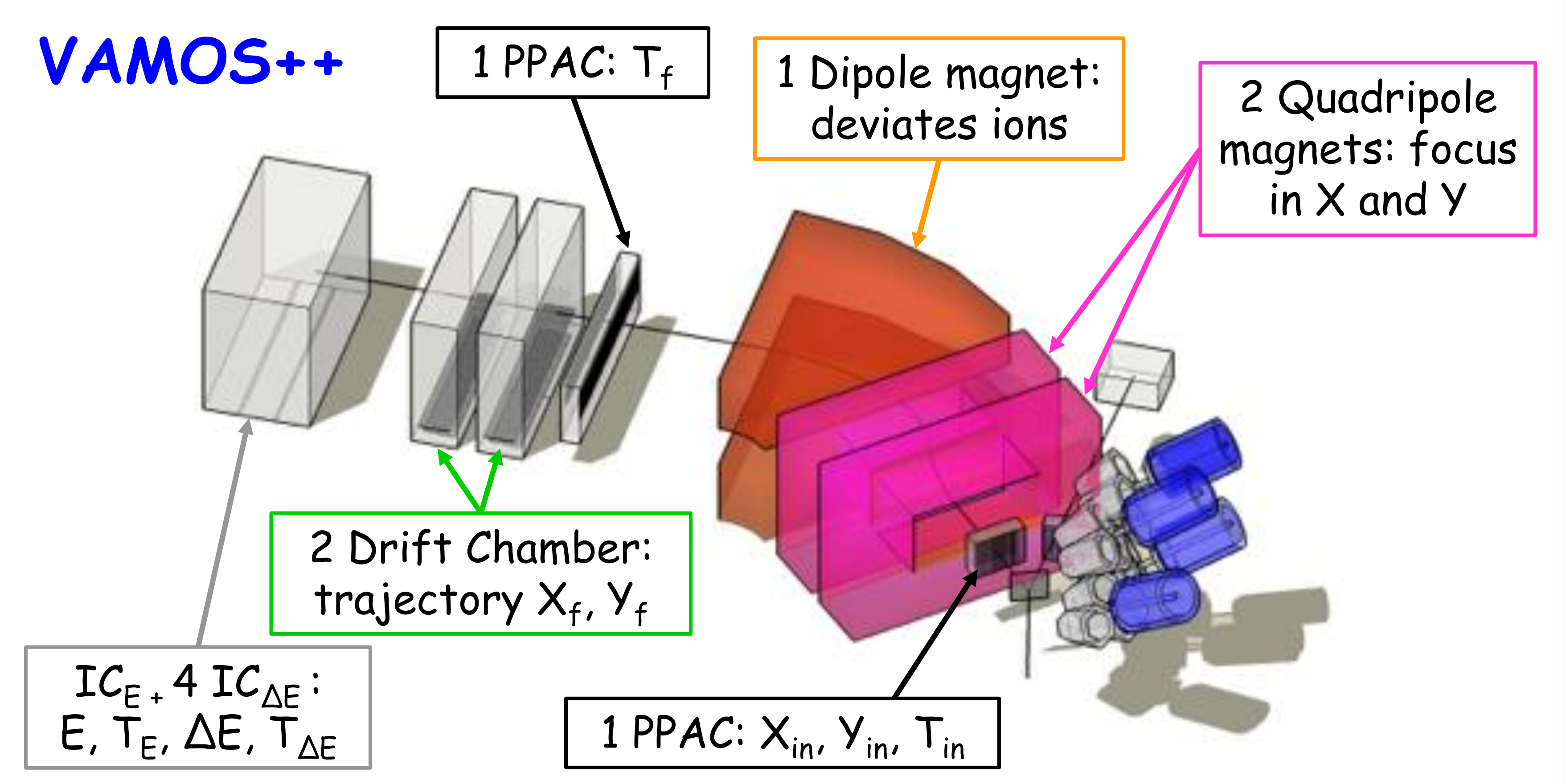


G. Duchêne

Radiation-matter interactions and detectors

Fragments

- Particle identification
  - Spectrometer

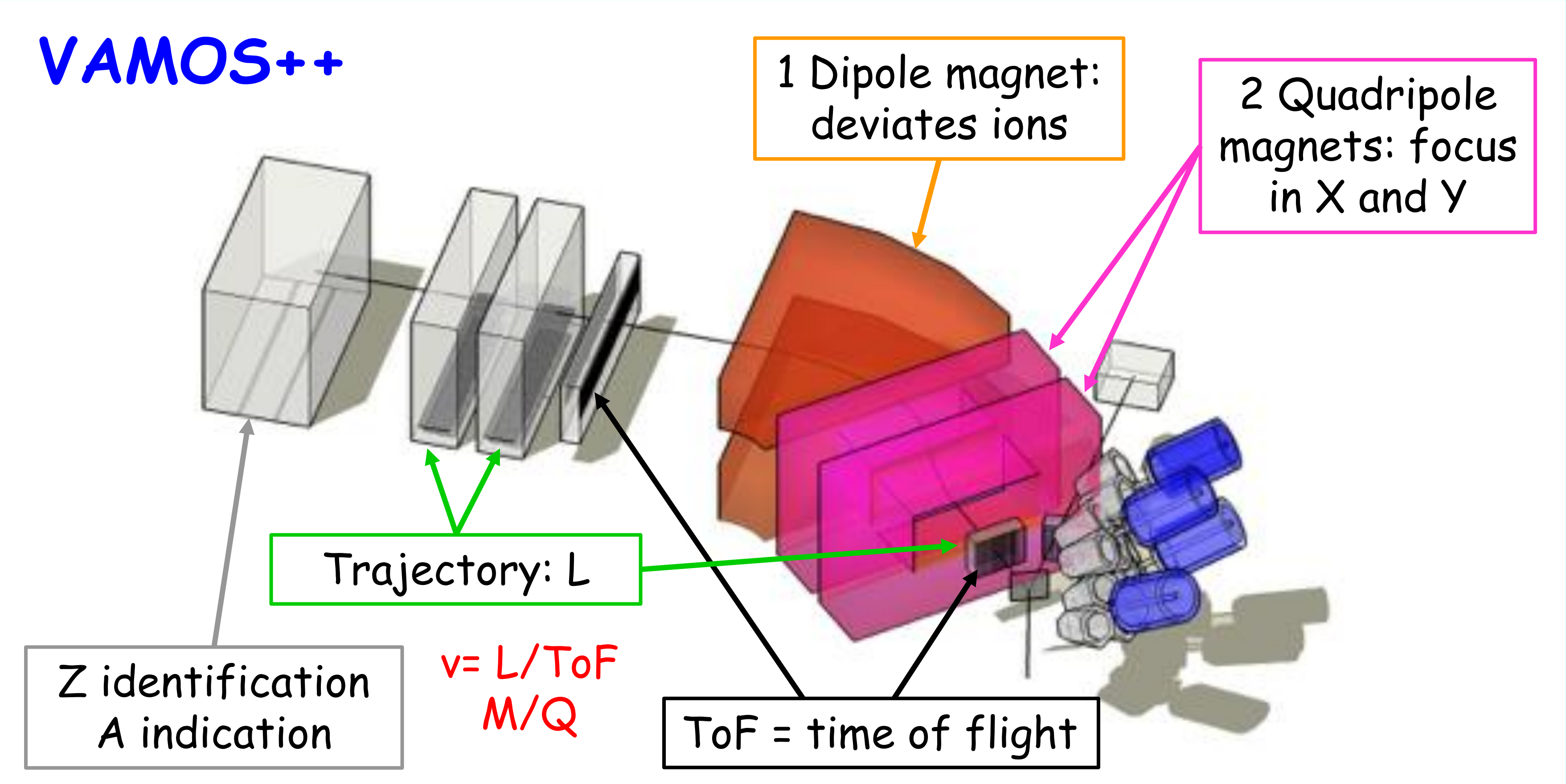


G. Duchêne

Radiation-matter interactions and detectors

Fragments

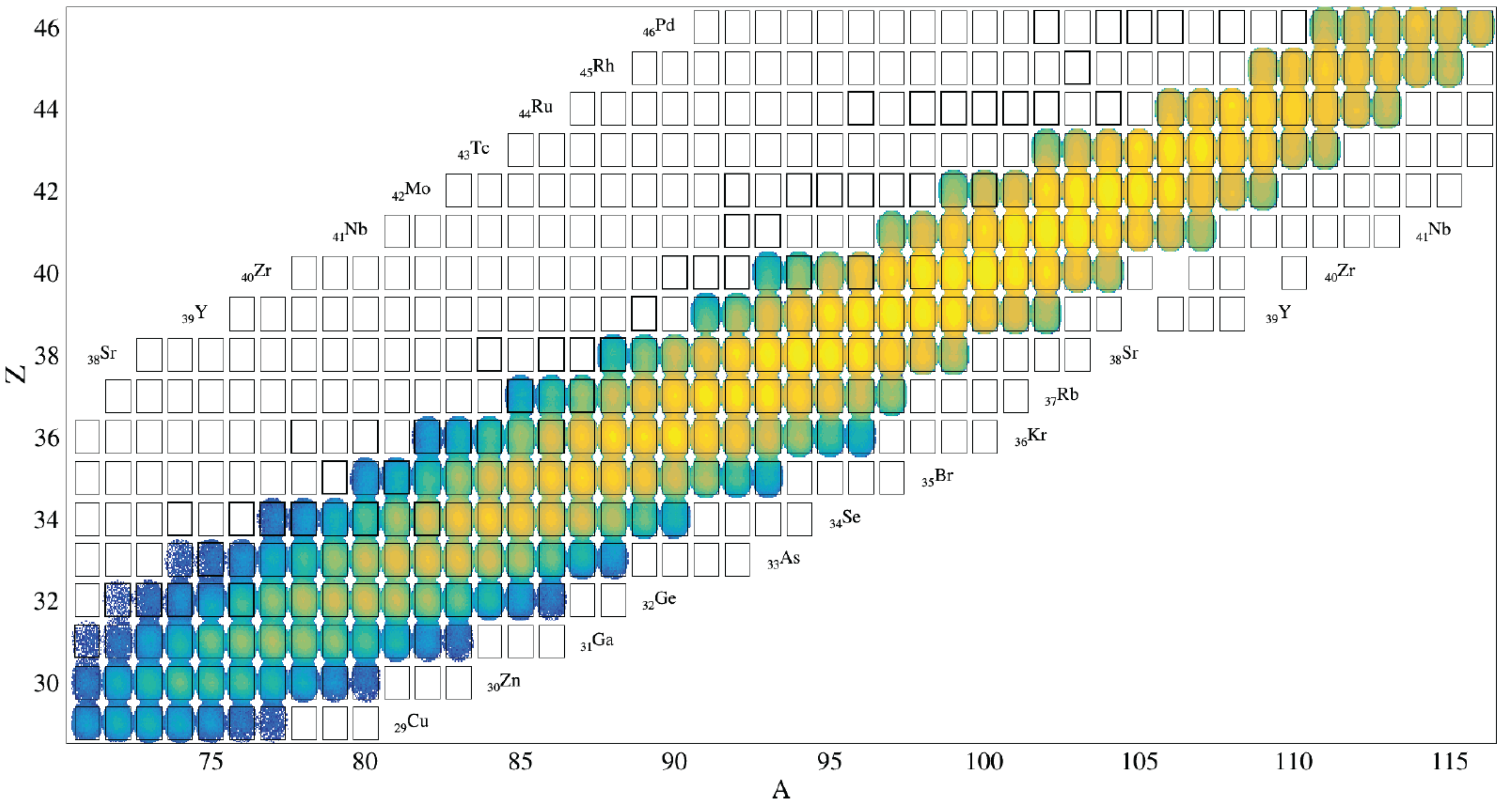
- Particle identification
  - Spectrometer



G. Duchêne

Fragments

- Spectrometer



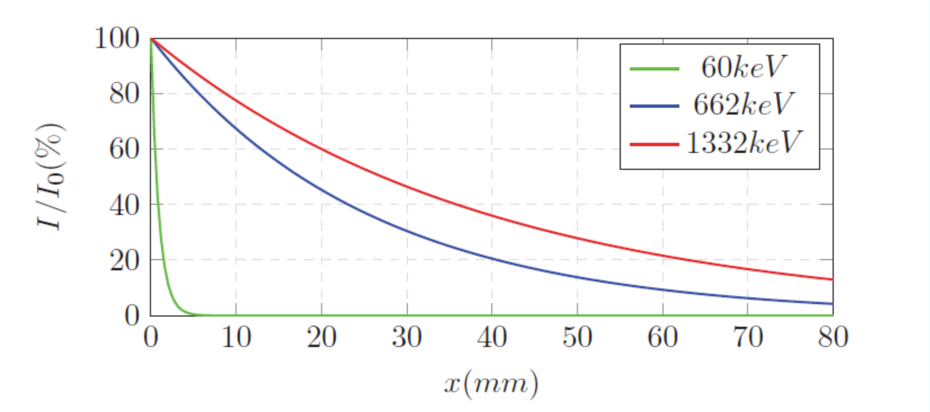
Radiation-matter interactions and detectors

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

G. Duchêne

γ rays

- Photoelectric effect
  - Full photon energy transfer to one electron

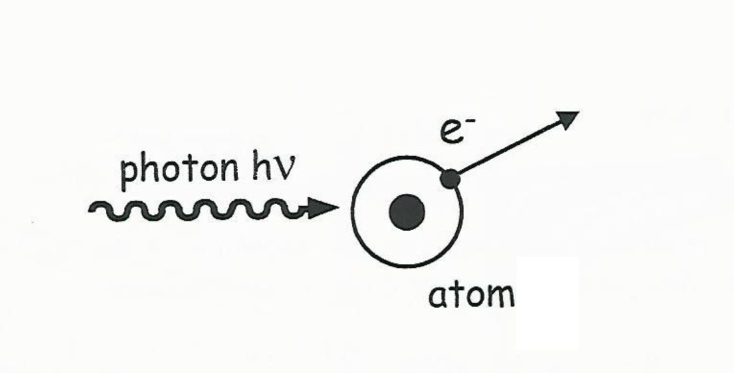
$E_\gamma = h\nu$

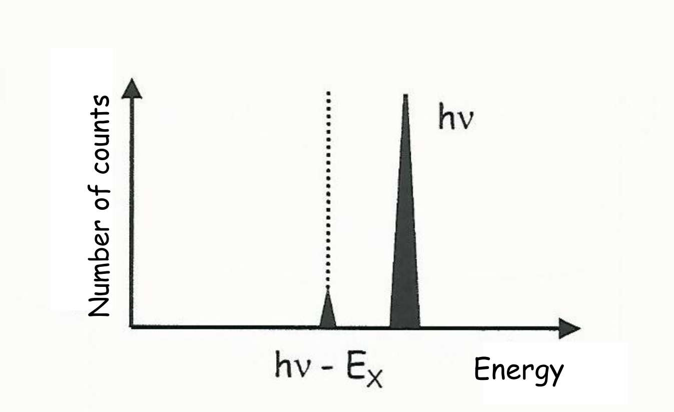
$E_{e-} = h\nu - B_{e-}$

$\sigma_{photo} \sim (h\nu)^{-3,5} \cdot Z^5$

Fast cross section reduction with energy

Strongly depend of Z of material/detector



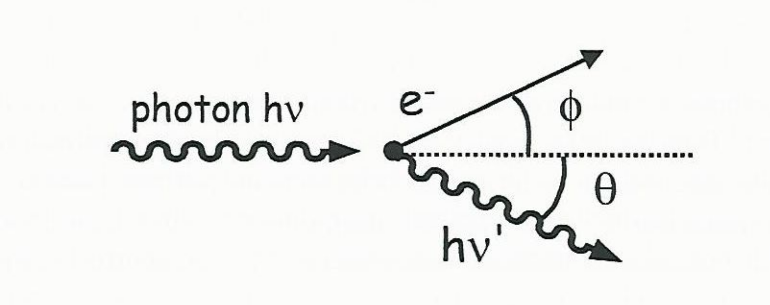


G. Duchêne

γ rays

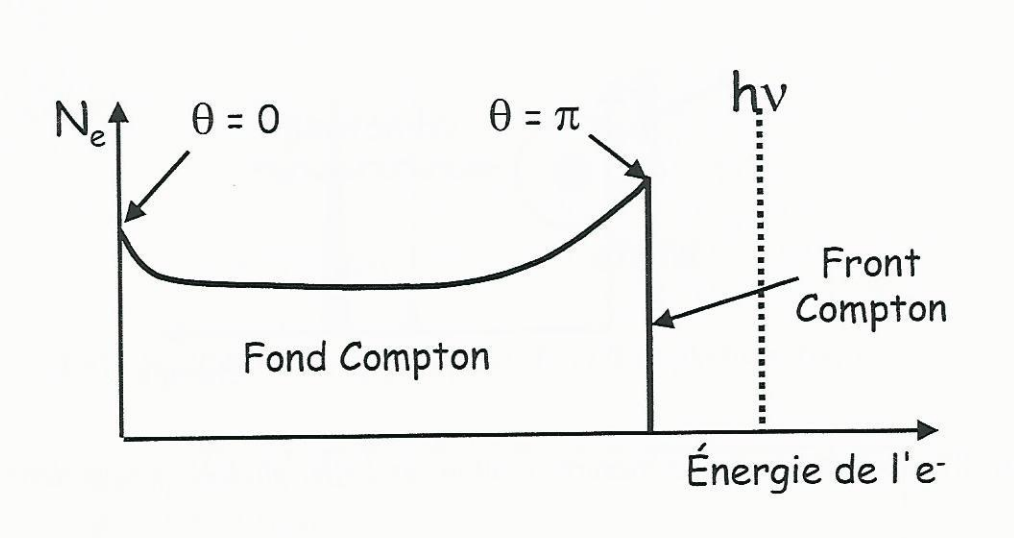
- Compton effect
  - Elastic scattering of a photon on a quasi-free electron

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



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

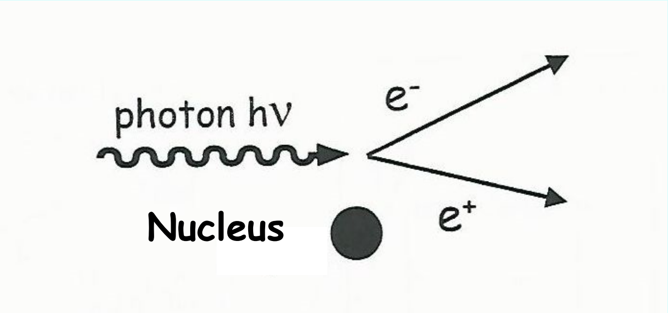
The electron energy varies continously with θ



G. Duchêne

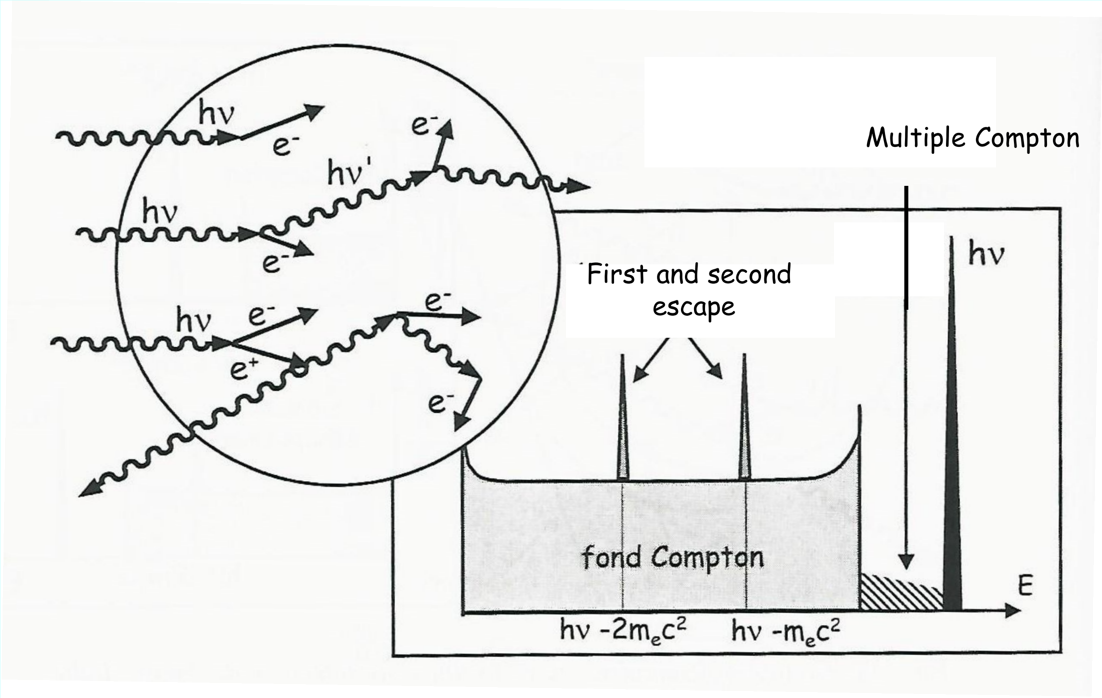
γ rays

- Pair creation
  - A photon is materialised in one electron and one positron



$h\nu > 2\, m_{e^-}c^2$ (1,022 MeV)

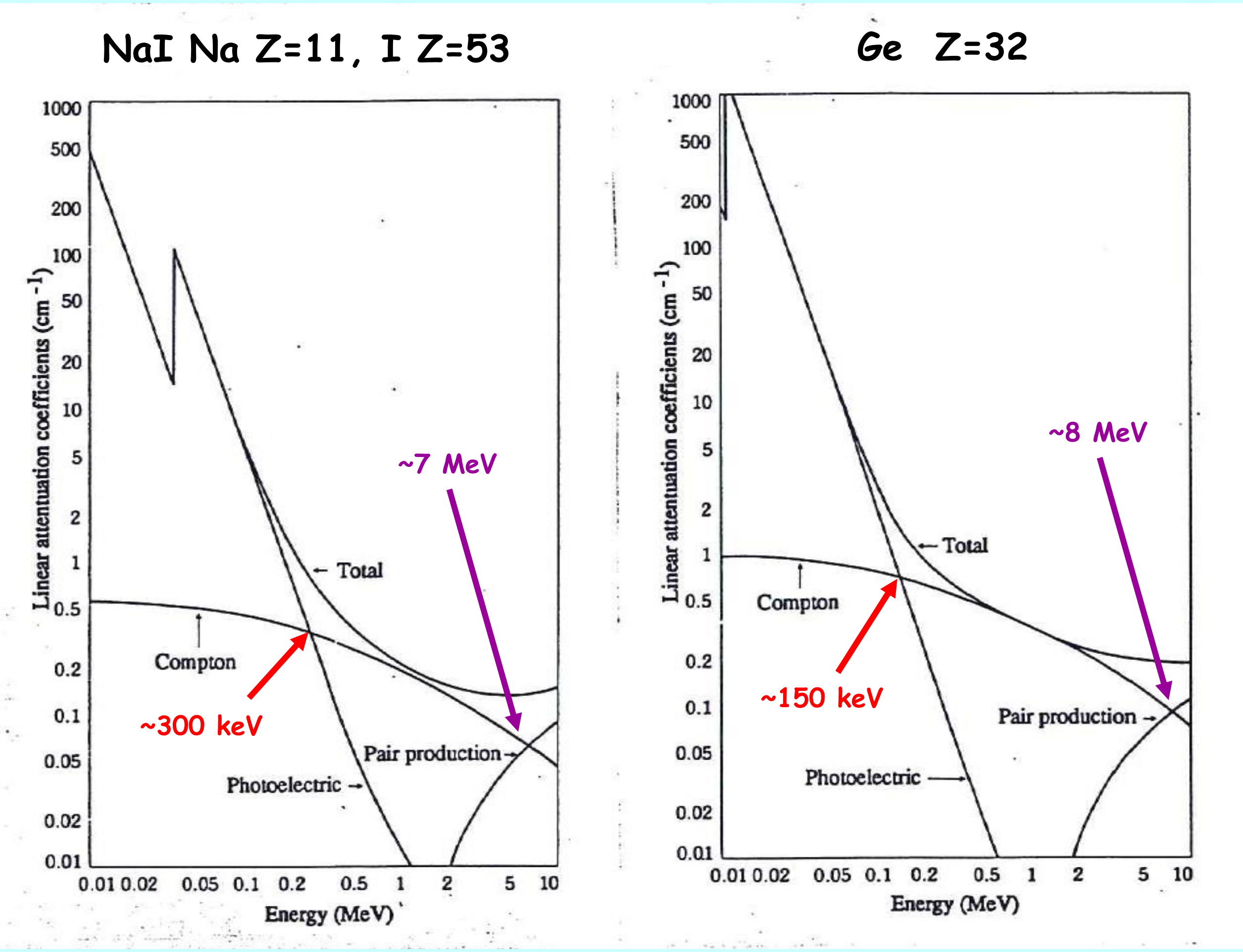
$E_{e^-} = E_{e^+} = \frac{1}{2}(h\nu - 2\, m_{e^-}c^2)$



G. Duchêne

γ rays

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

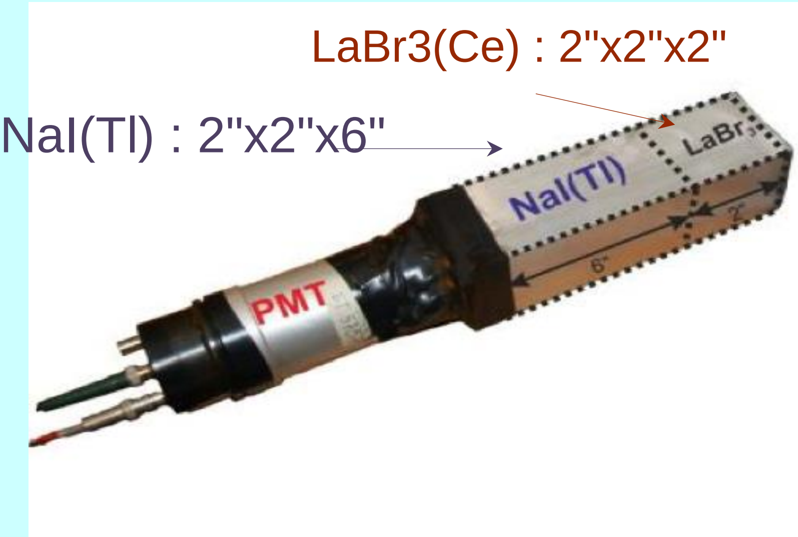


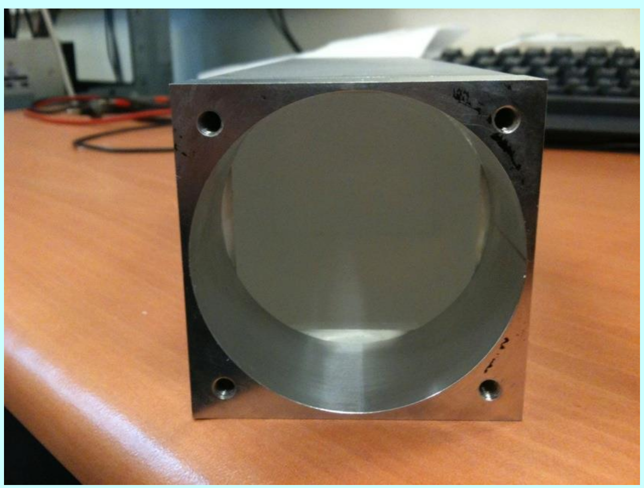
G. Duchêne

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 ($LaBr_3$)





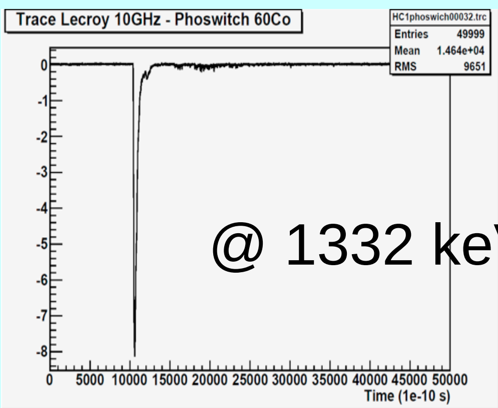
G. Duchêne

Radiation-matter interactions and detectors

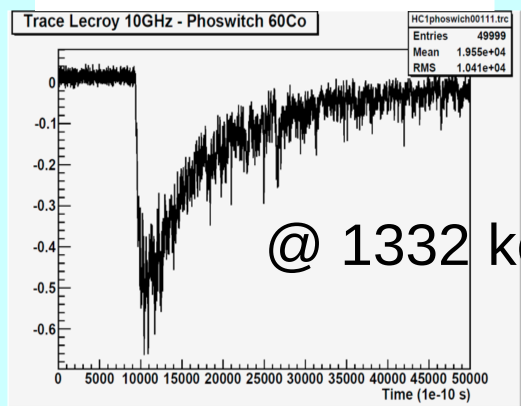
γ rays

- Gamma-ray detectors
  - PARIS detector performance

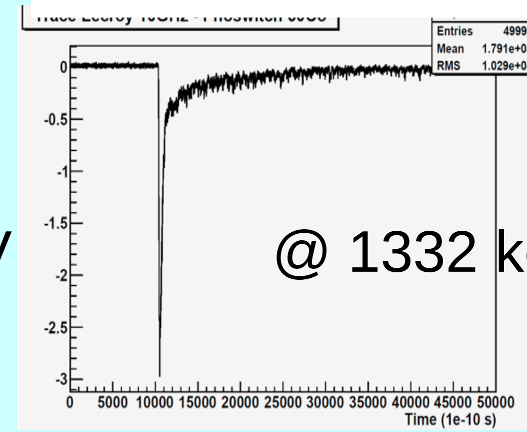
γ interaction in $LaBr_3$ only



γ interaction in NaI only



γ interaction in both shells

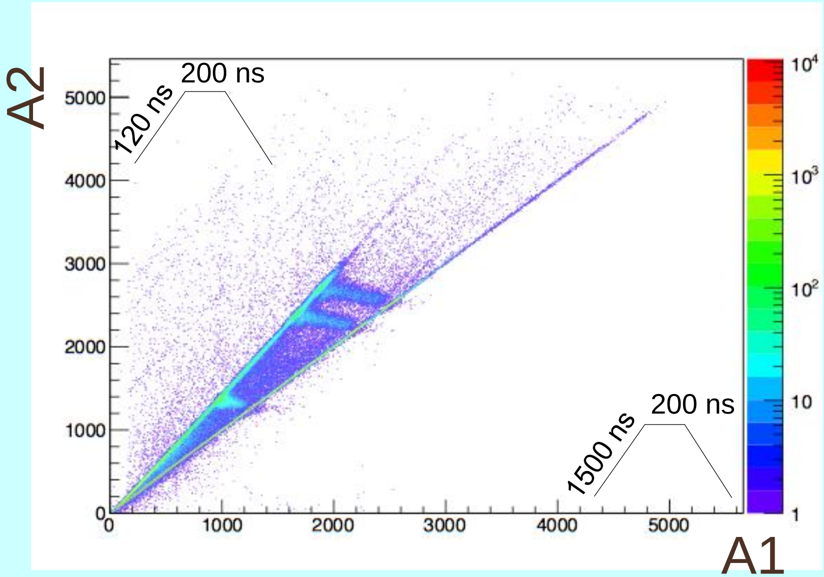


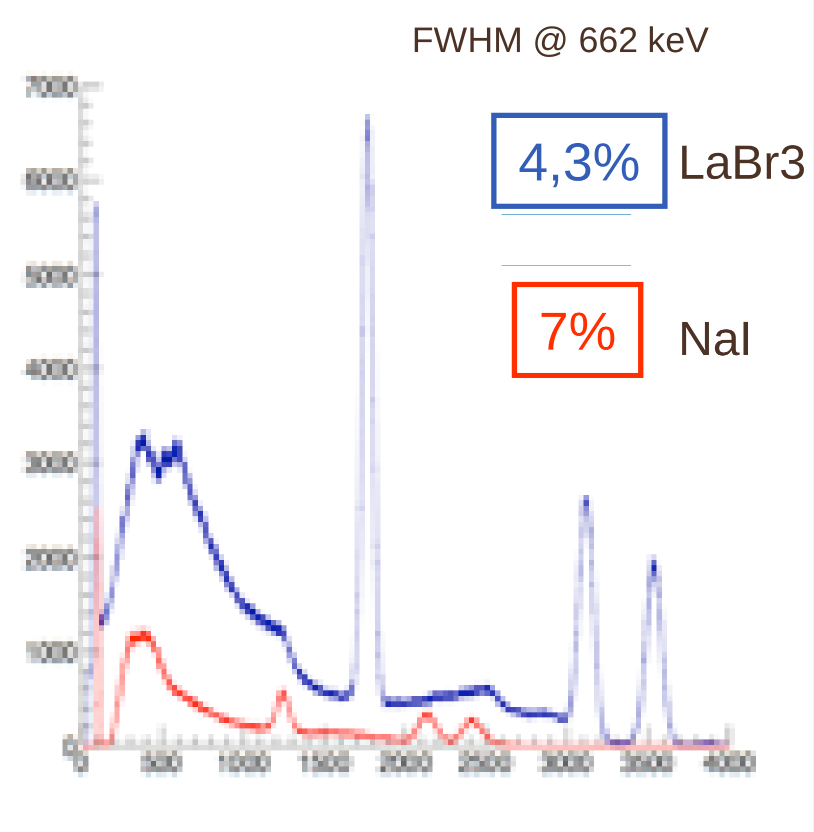
G. Duchêne

Radiation-matter interactions and detectors

ɣ rays

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





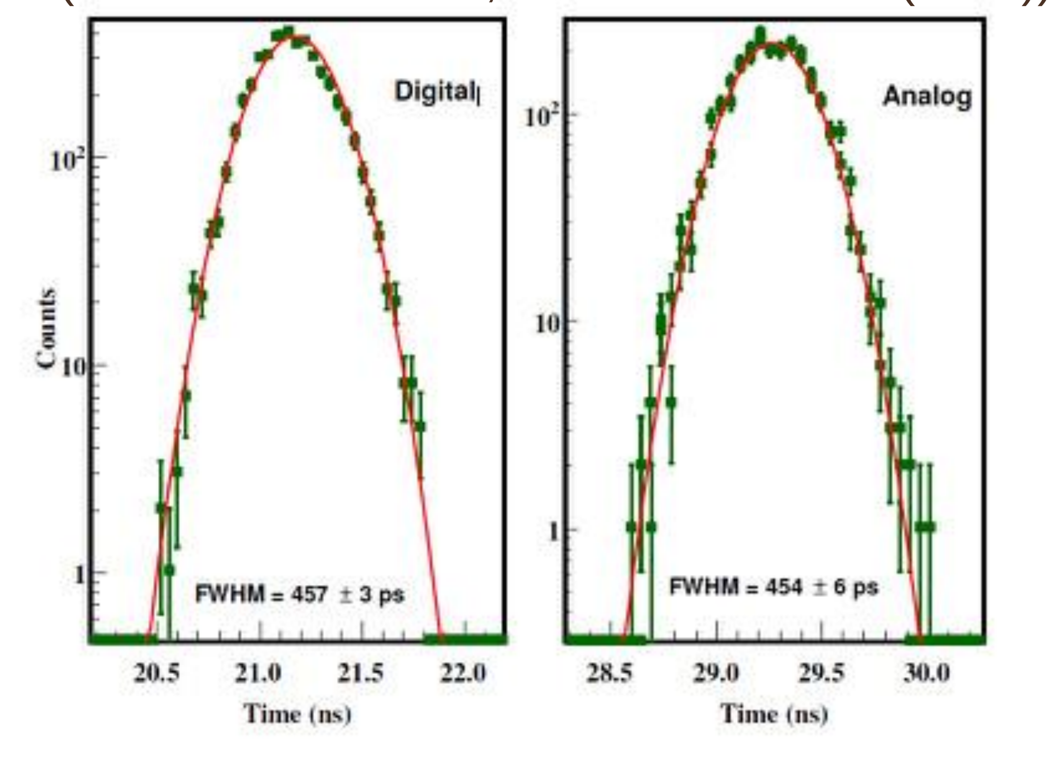
G. Duchêne

Radiation-matter interactions and detectors

γ rays

- Gamma-ray detectors
  - PARIS detector timing performance

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

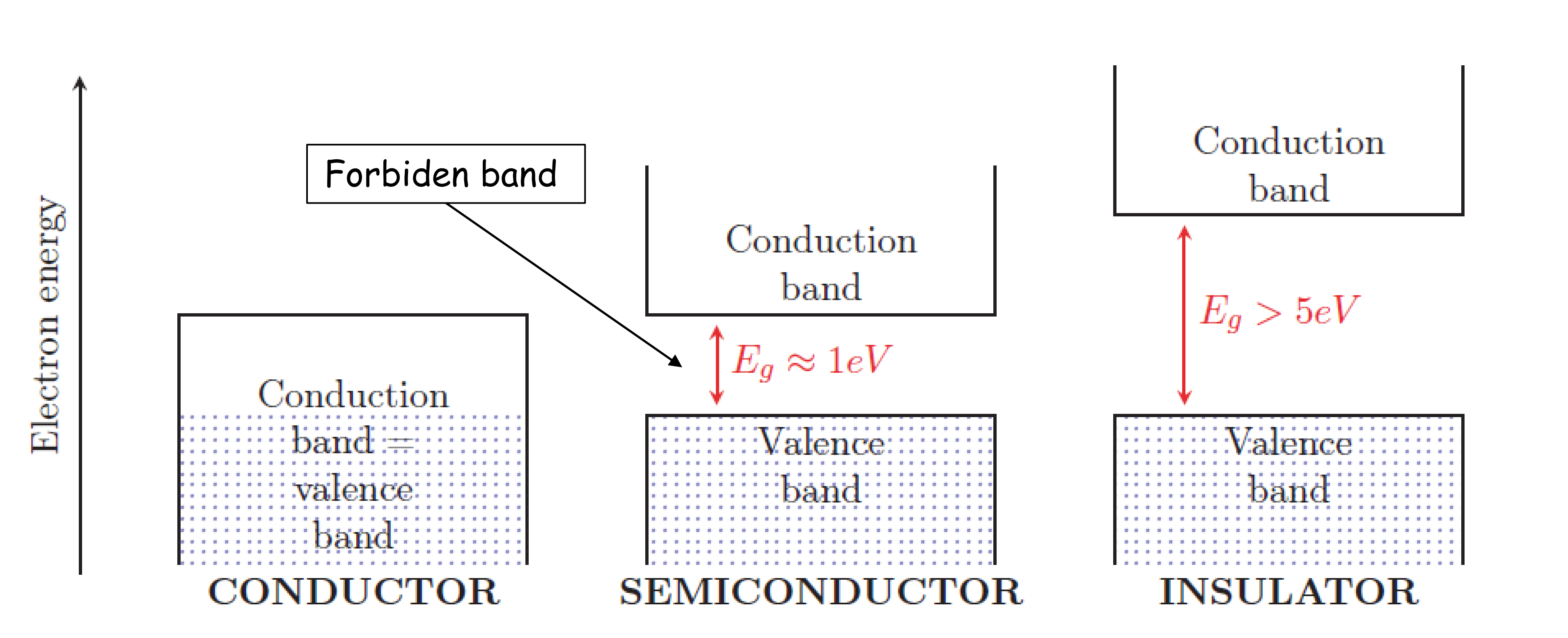


G. Duchêne

Radiation-matter interactions and detectors

γ rays

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



G. Duchêne

Radiation-matter interactions and detectors

γ rays

- Gamma-ray detectors
  - Semiconductors characteristics

Semiconductors	Forbiden band at 300 K	Electron-hole pair creation energy W
Si	1.12 eV	3.61 eV (300 K)
Ge	0.67 eV	2.96 eV (90 K)
Diamant C	5.47 eV	13.2 eV (300K)
GaAs	1.43 eV	4.27 eV
CdTe	1.5 eV	4.43 eV (300 K)
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

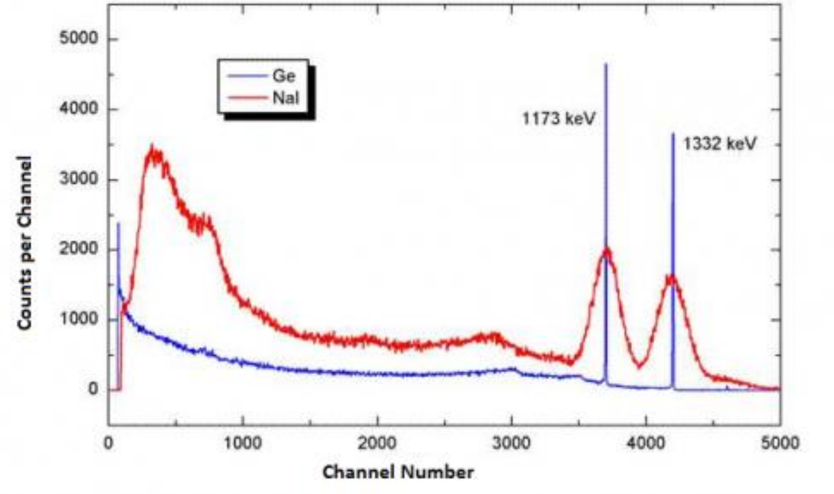
FWHM = Full Width Half Maximum

FWHM (NaI) / E ~ 8%

FWHM ($LaBr_3$) / E ~ 3-4%

FWHM ($_{14}Si$) / E ~ 1.5% -> X rays

FWHM ($_{32}Ge$) / E ~ 0.2% -> γ rays



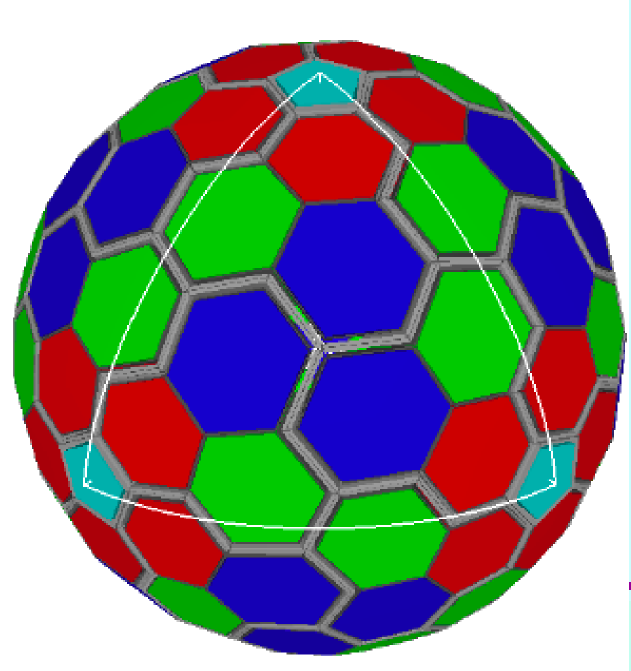
G. Duchêne

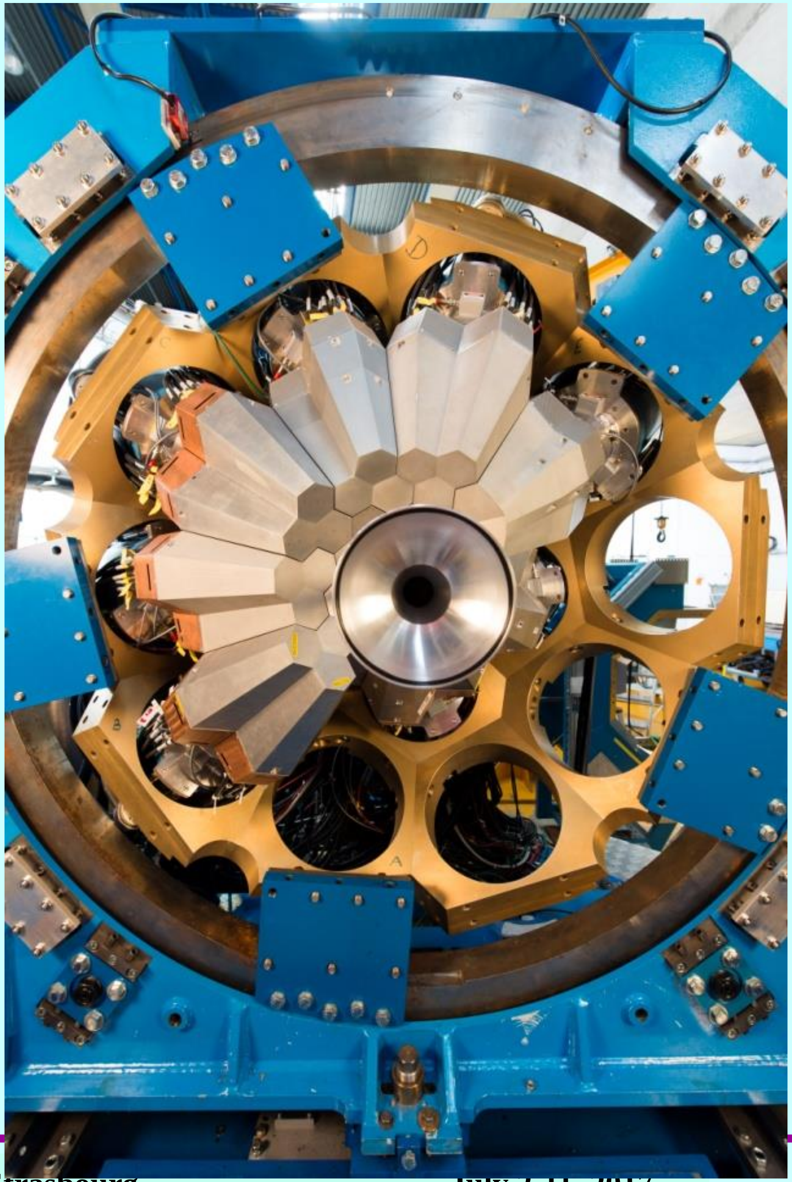
Multi-detector AGATA for γ-ray detection

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)



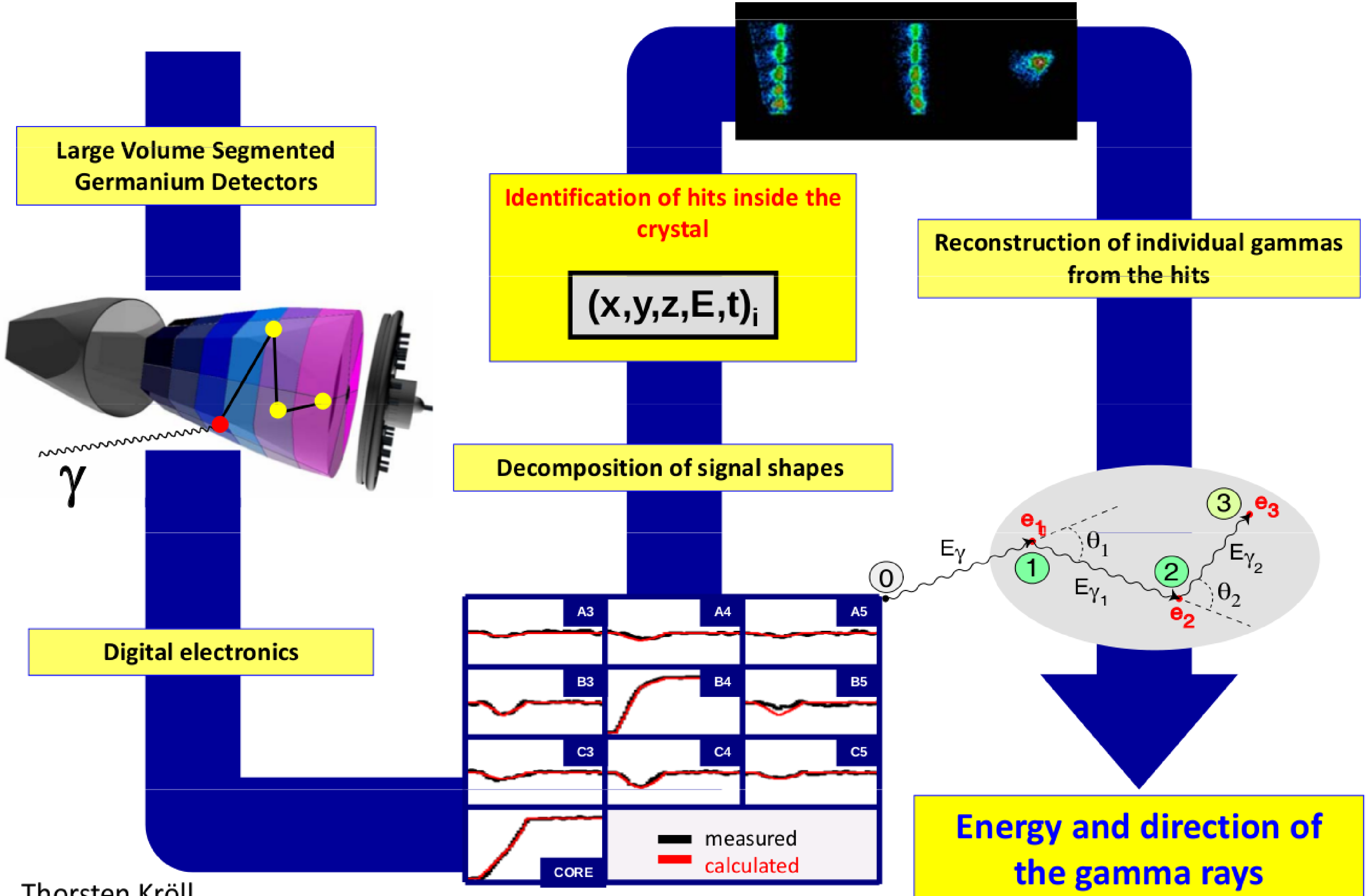


G. Duchêne

Multi-detector AGATA for γ–ray detection

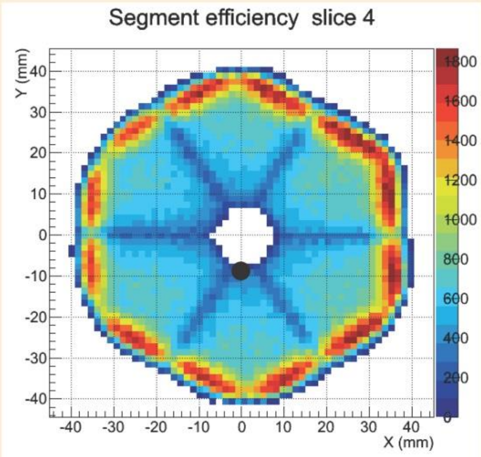
G. Duchêne

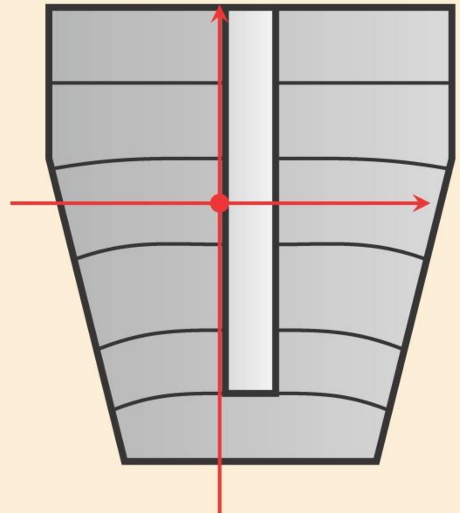
Gamma-Ray Tracking Paradigm



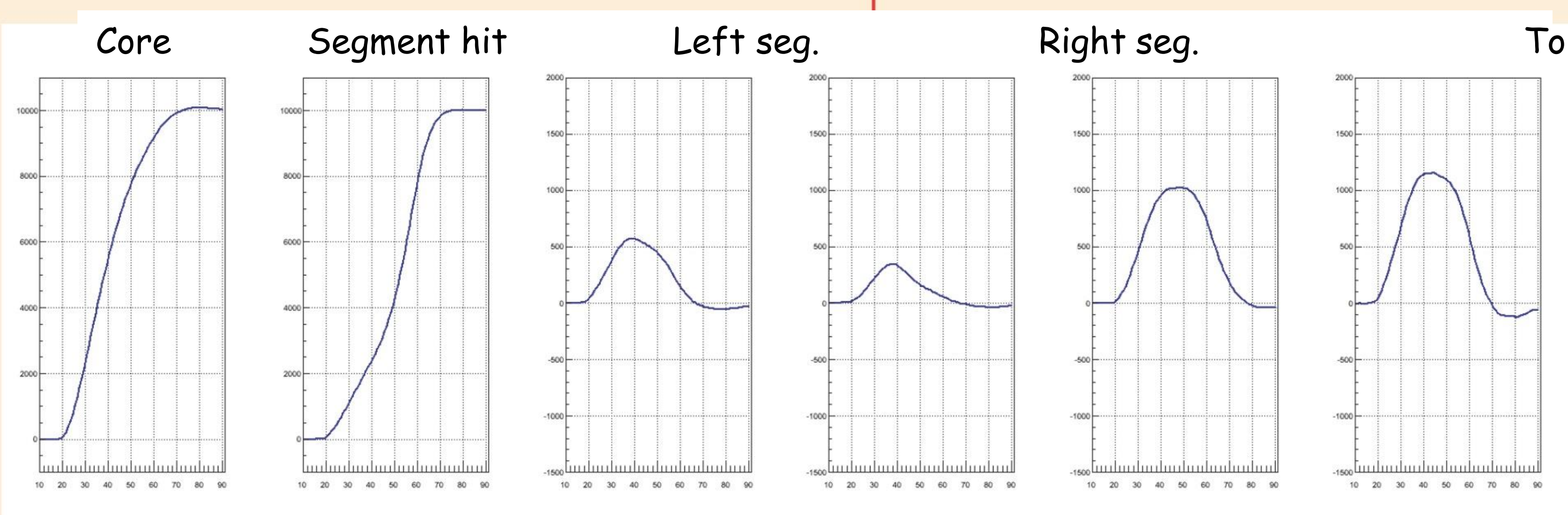
Thorsten Kröll

3D partial PSCS

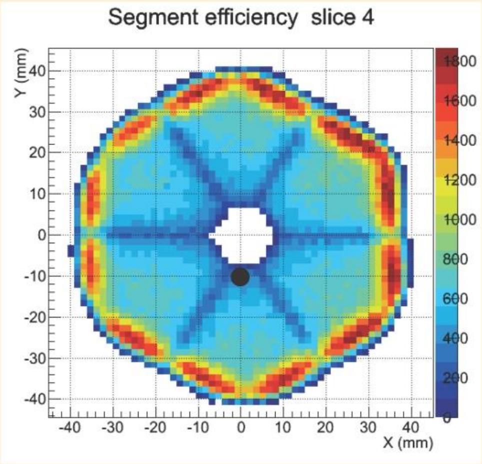


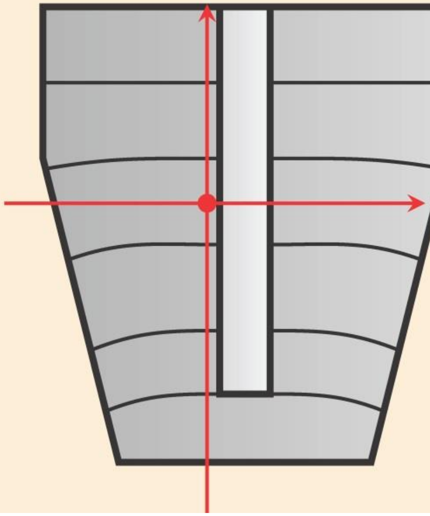


(0 ; -6.5 ; 50)

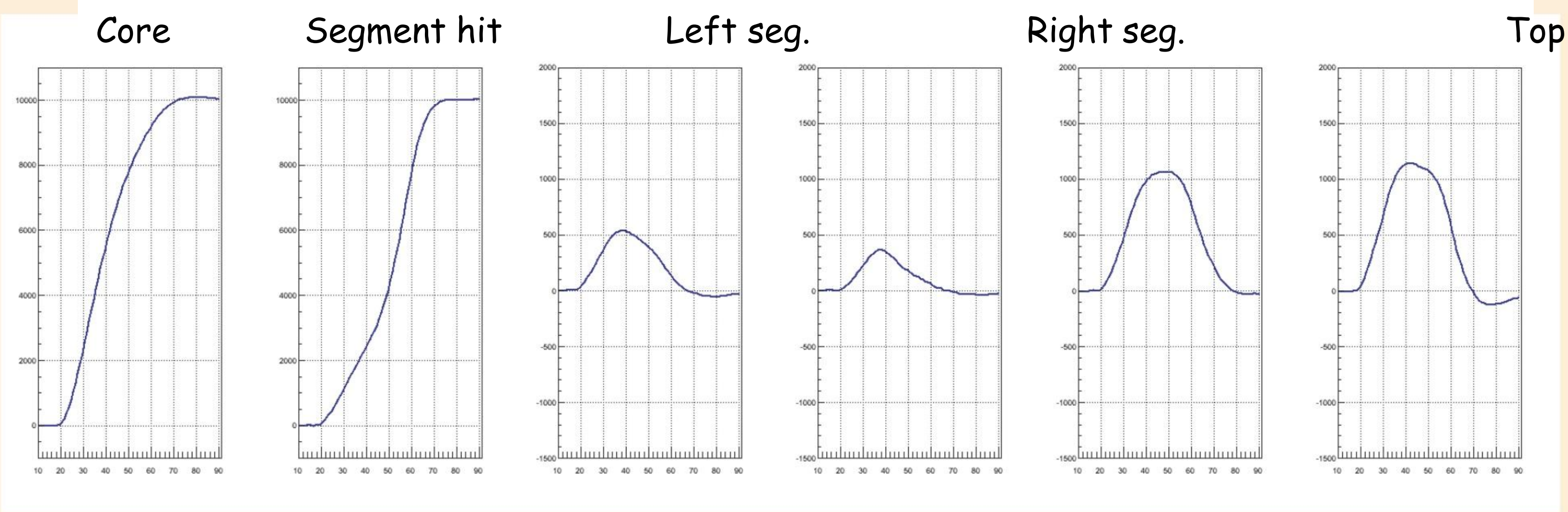


3D partial PSCS

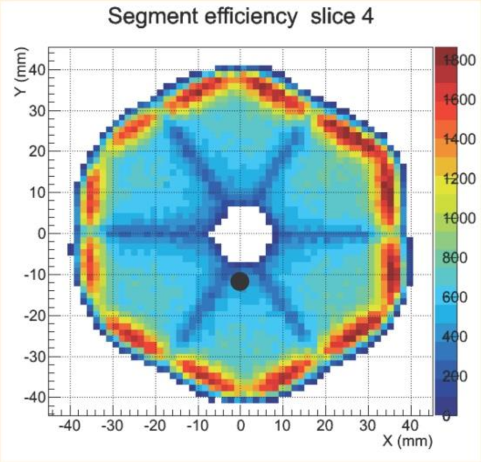


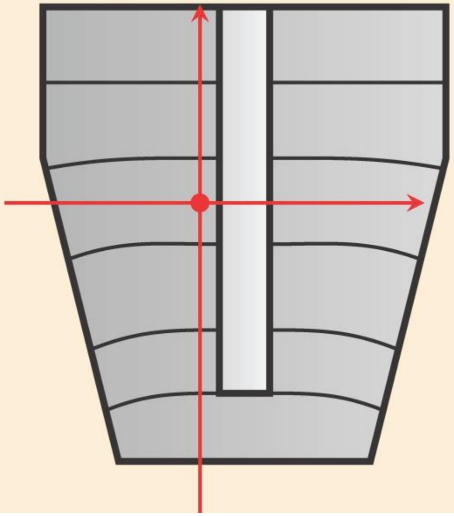


(0 ; -8.0 ; 50)

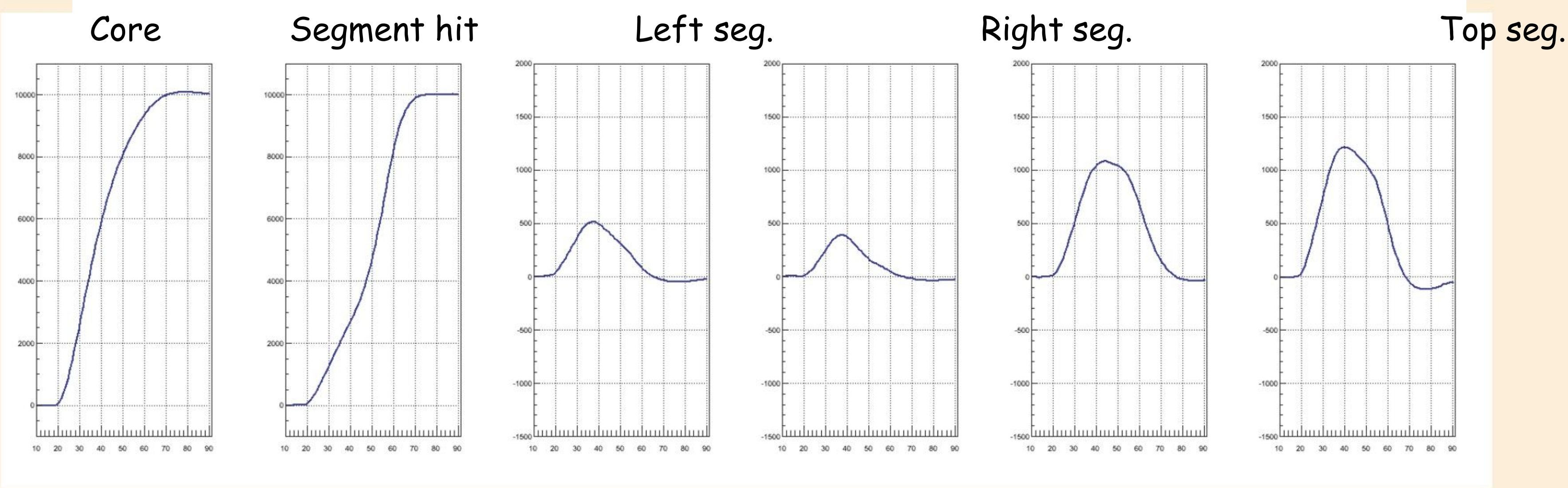


3D partial PSCS

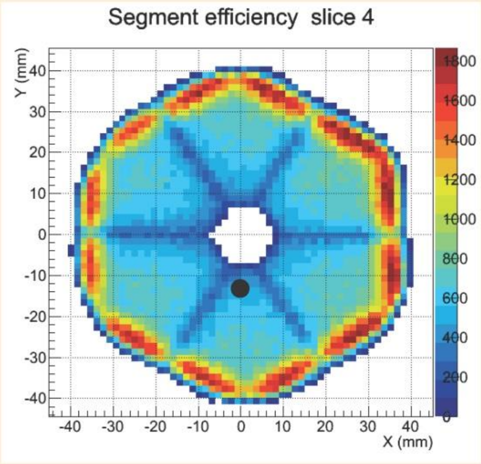


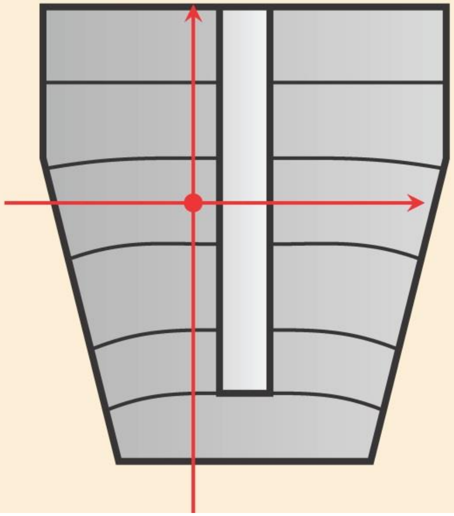


(0 ; -9.5 ; 50)

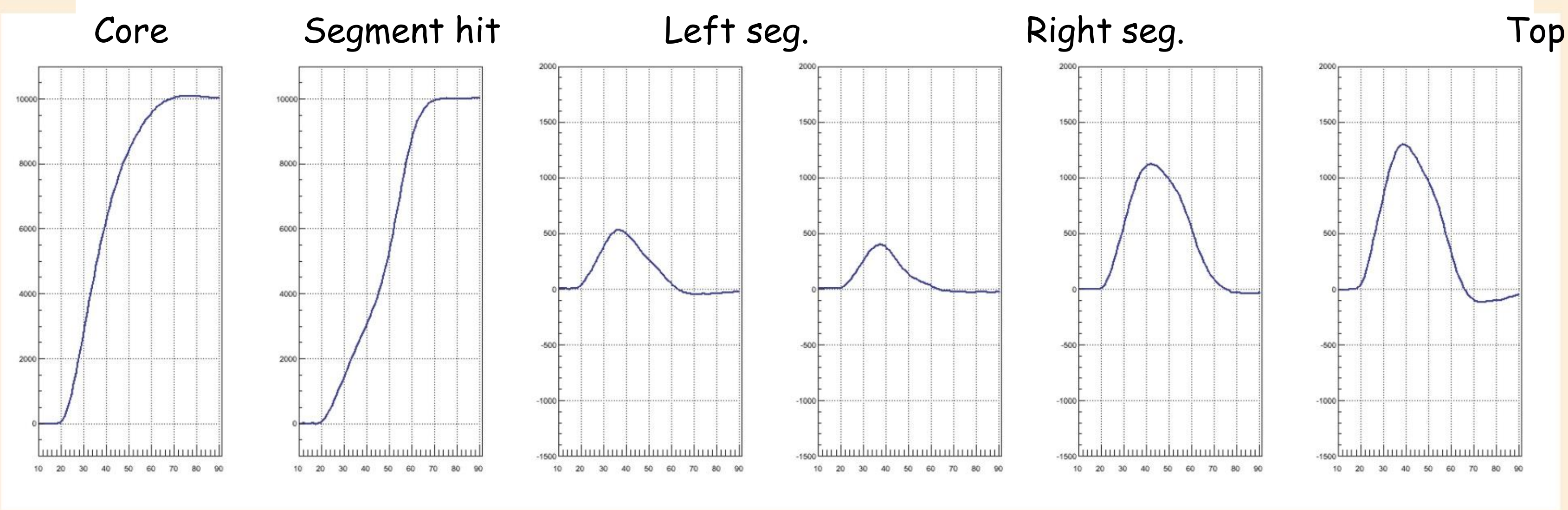


3D partial PSCS

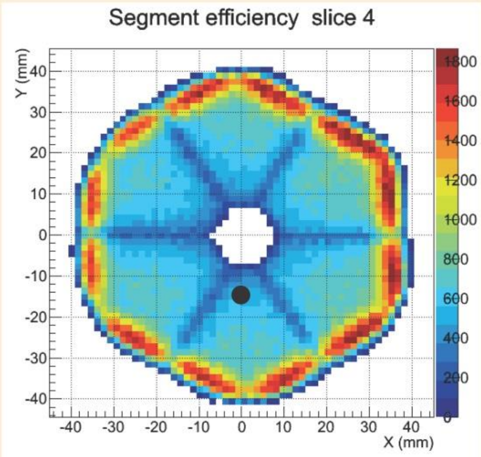


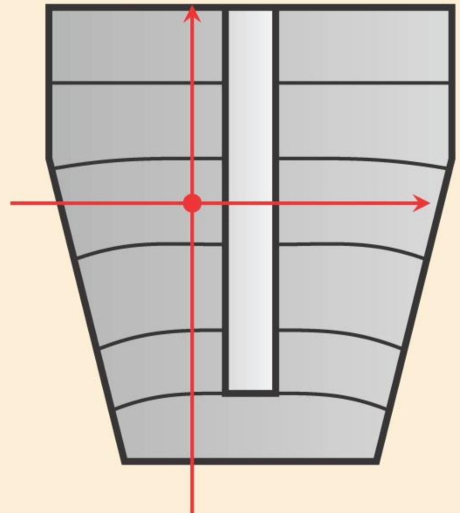


(0 ; -11.0 ; 50)

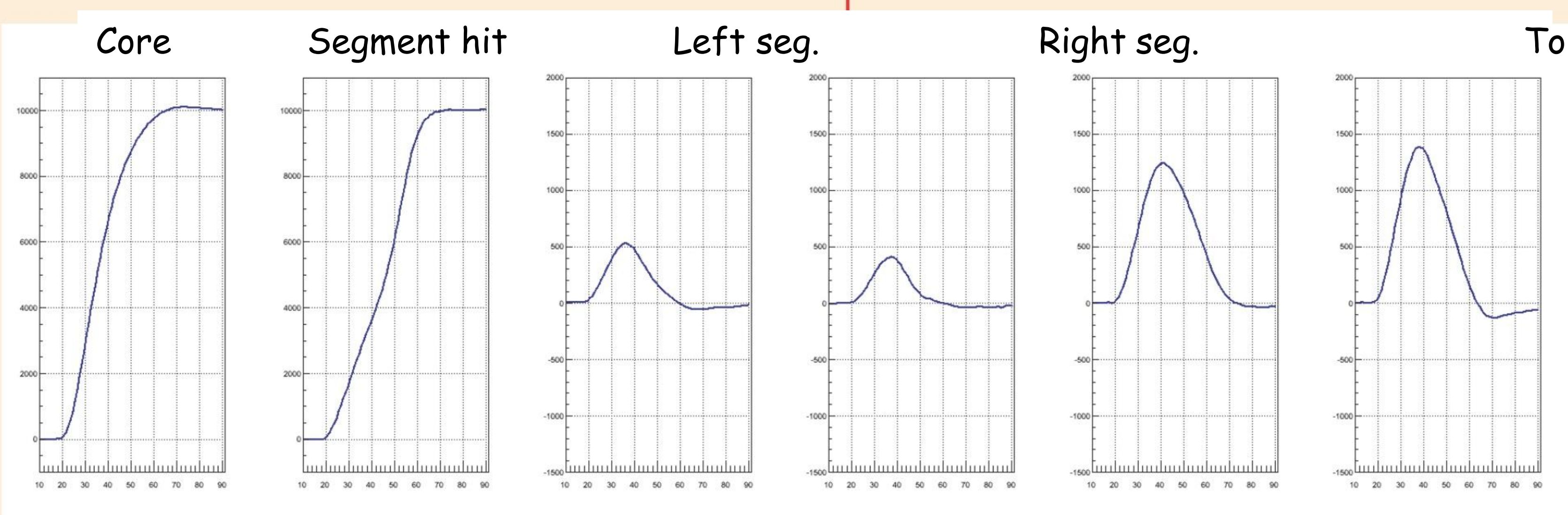


3D partial PSCS

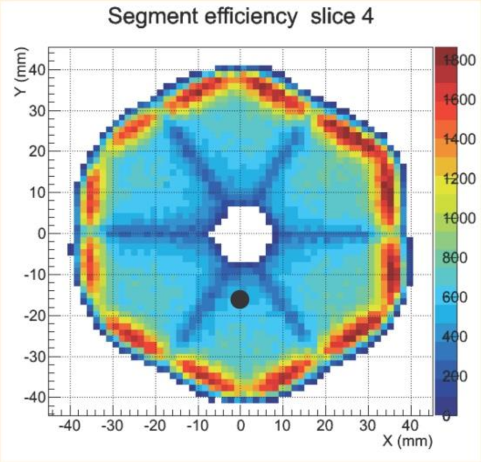


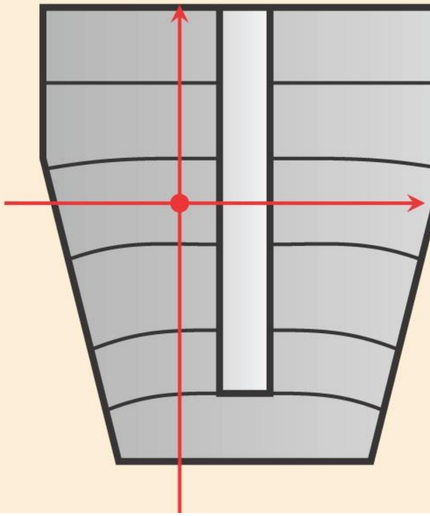


(0 ; -12.5 ; 50)

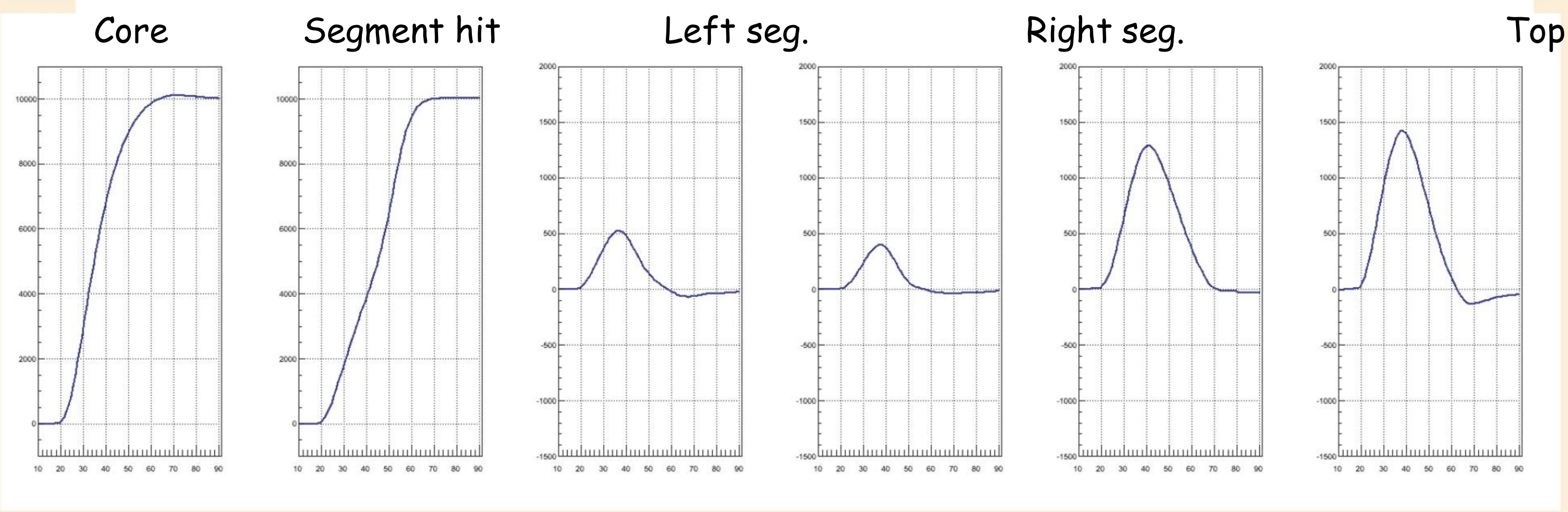


3D partial PSCS

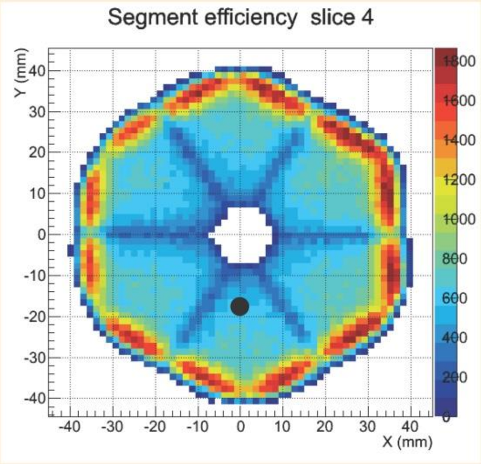


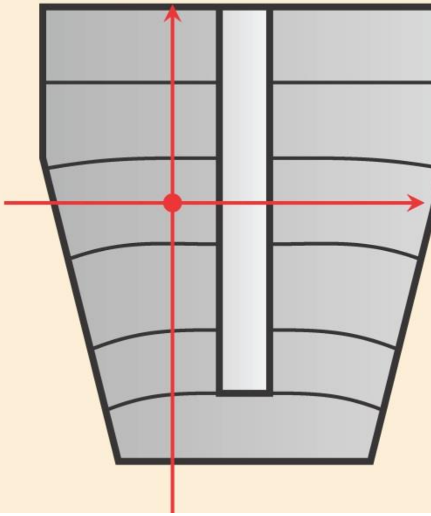


(0 ; -14.0 ; 50)

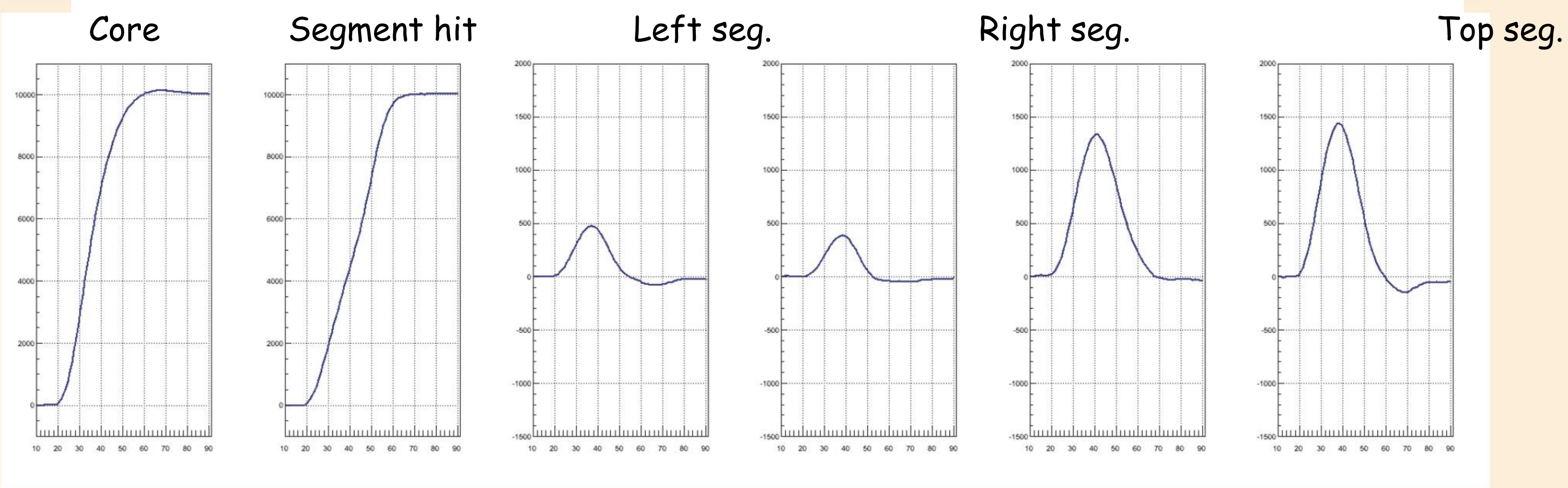


3D partial PSCS

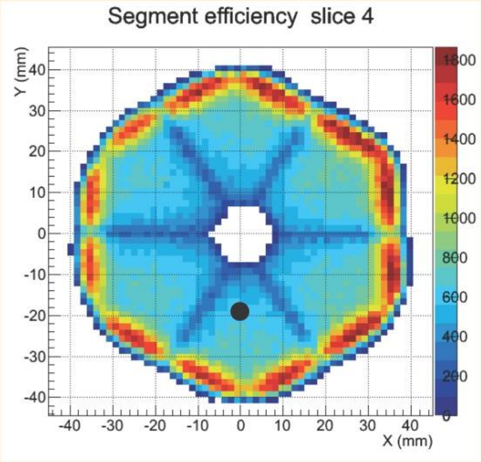


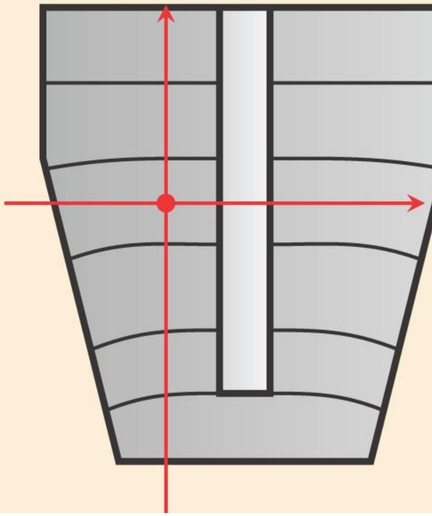


(0 ; -15.5 ; 50)

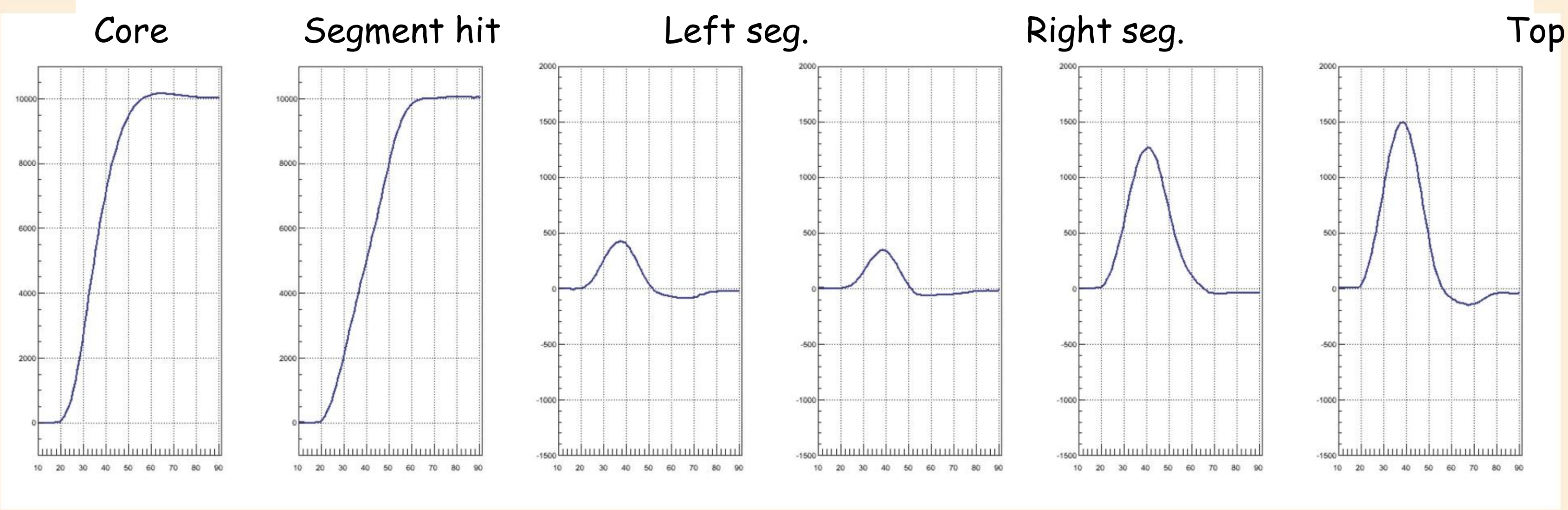


3D partial PSCS

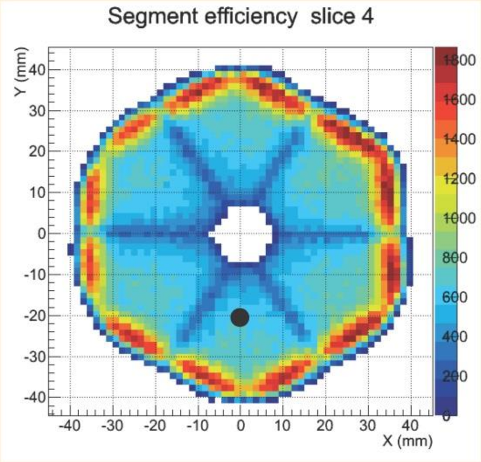


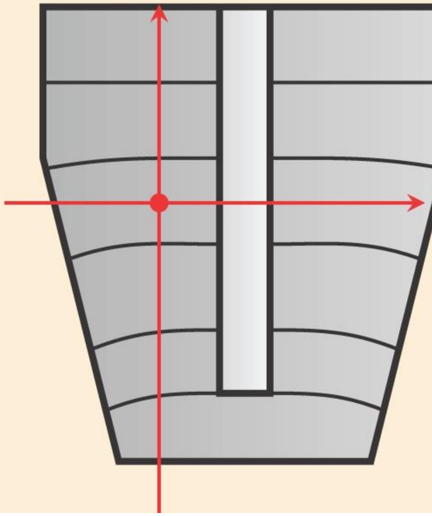


(0 ; -17.0 ; 50)

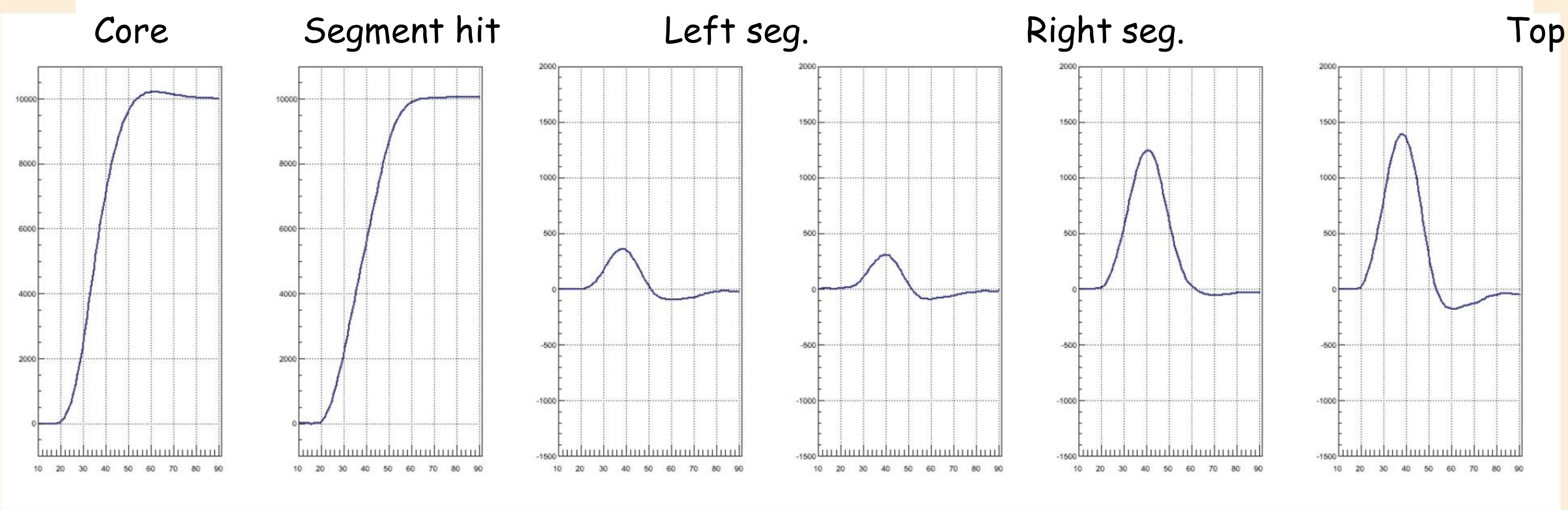


3D partial PSCS

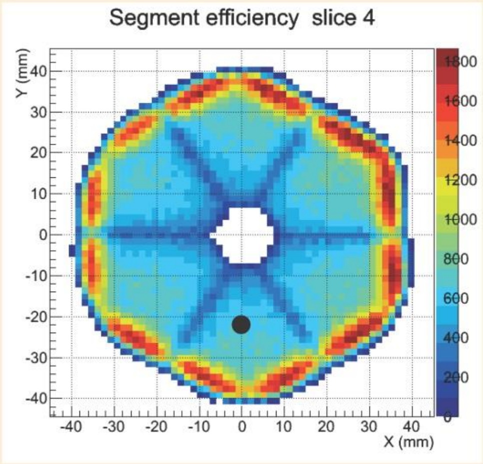


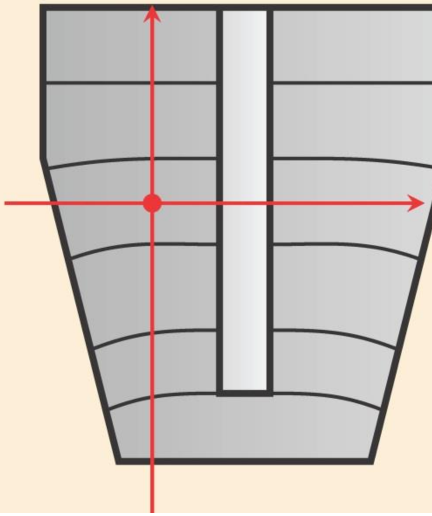


(0 ; -18.5 ; 50)

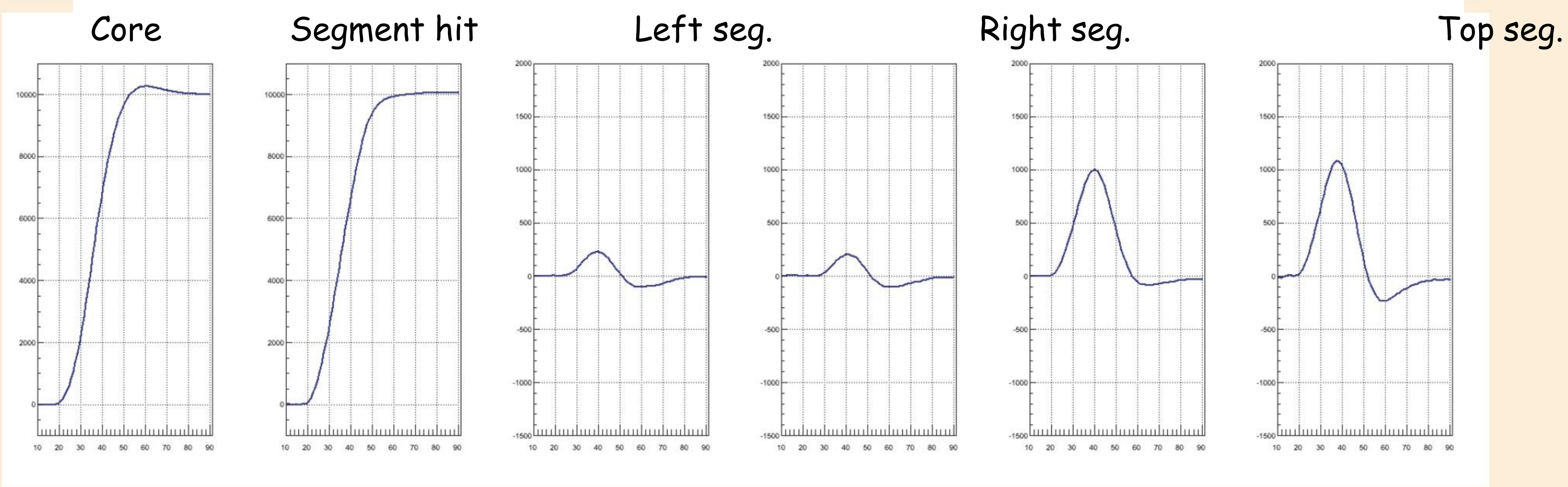


3D partial PSCS

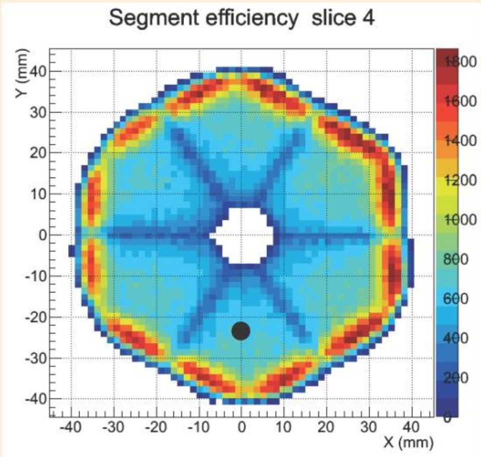


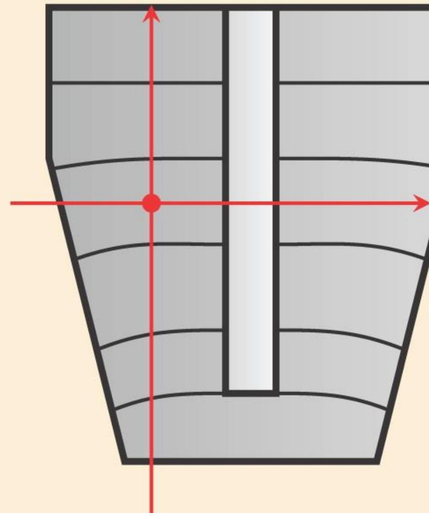


(0 ; -20.0 ; 50)

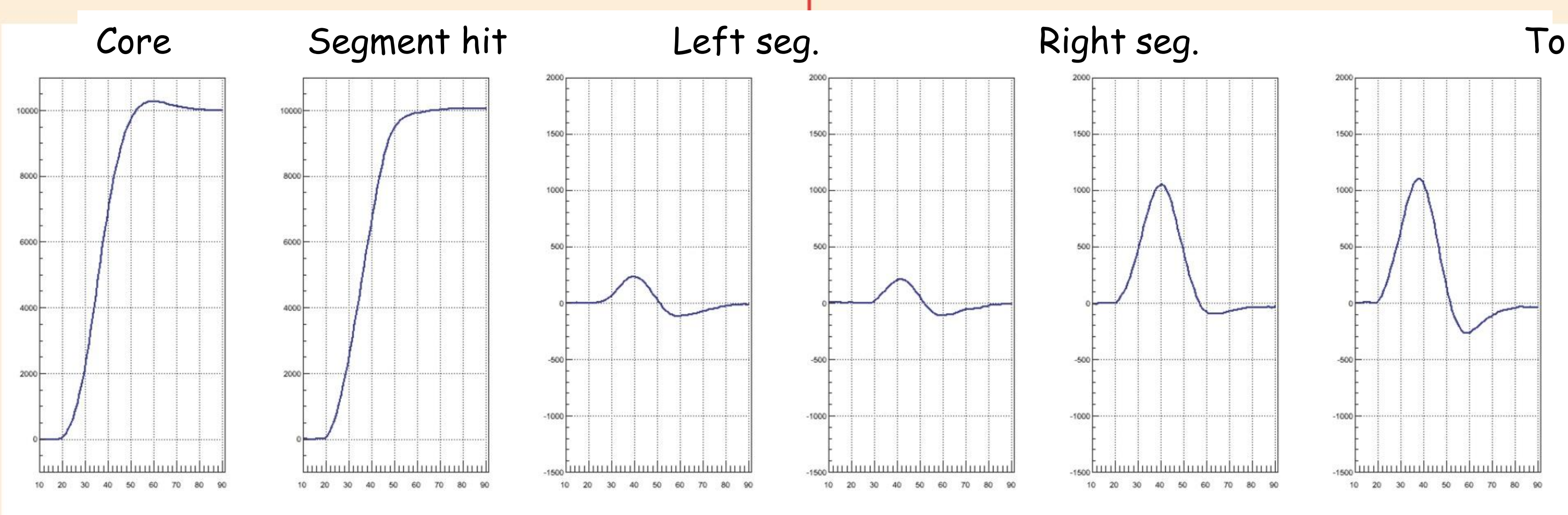


3D partial PSCS

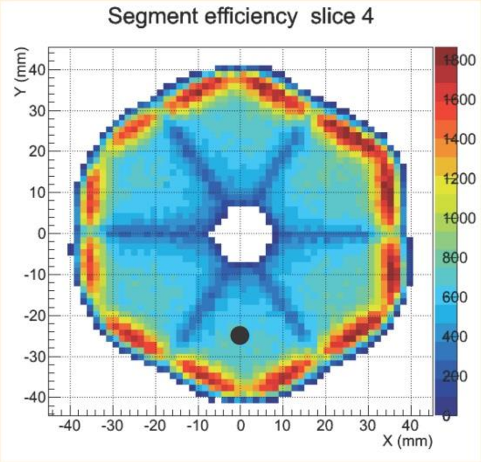


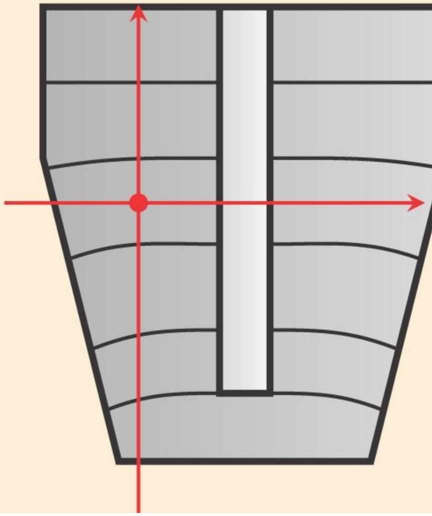


(0 ; -21.5 ; 50)

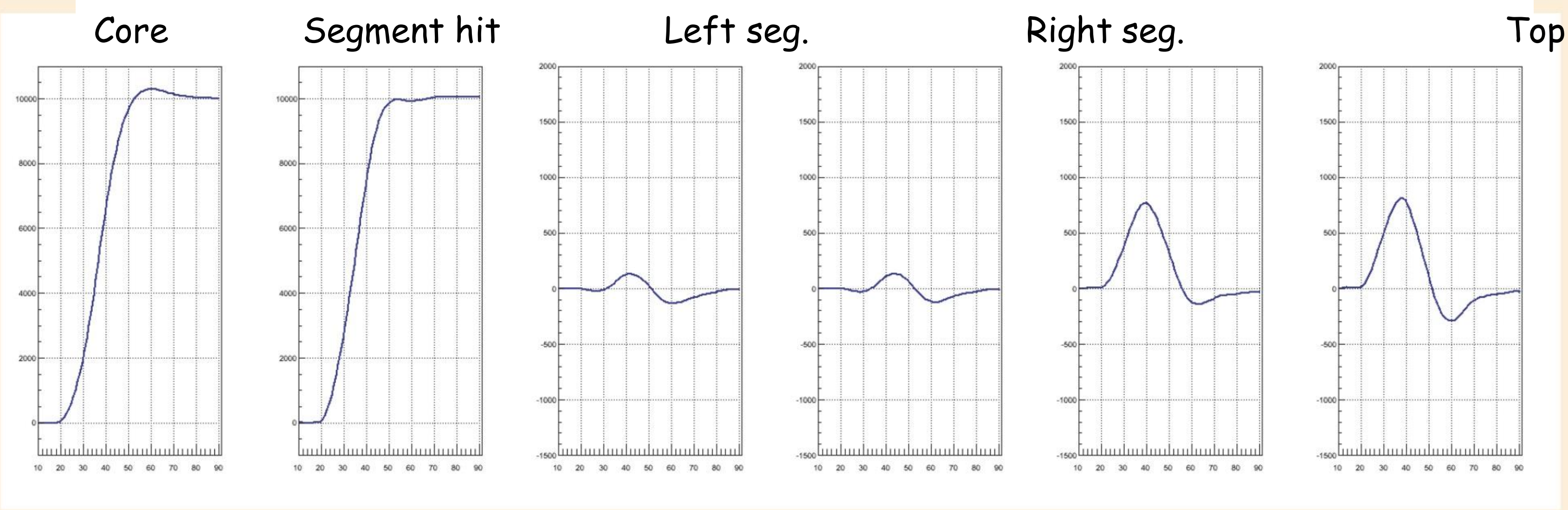


3D partial PSCS

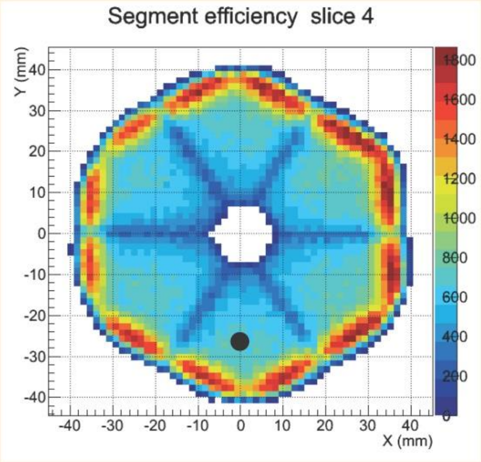


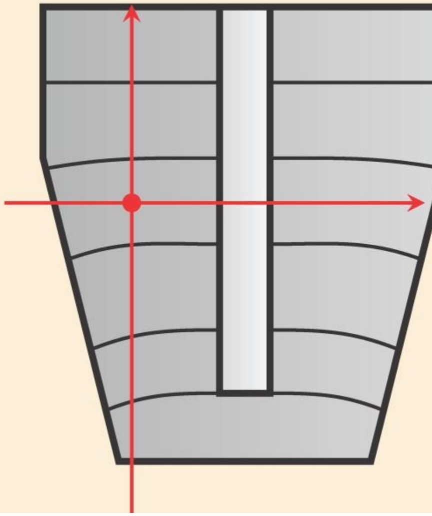


(0 ; -23.0 ; 50)

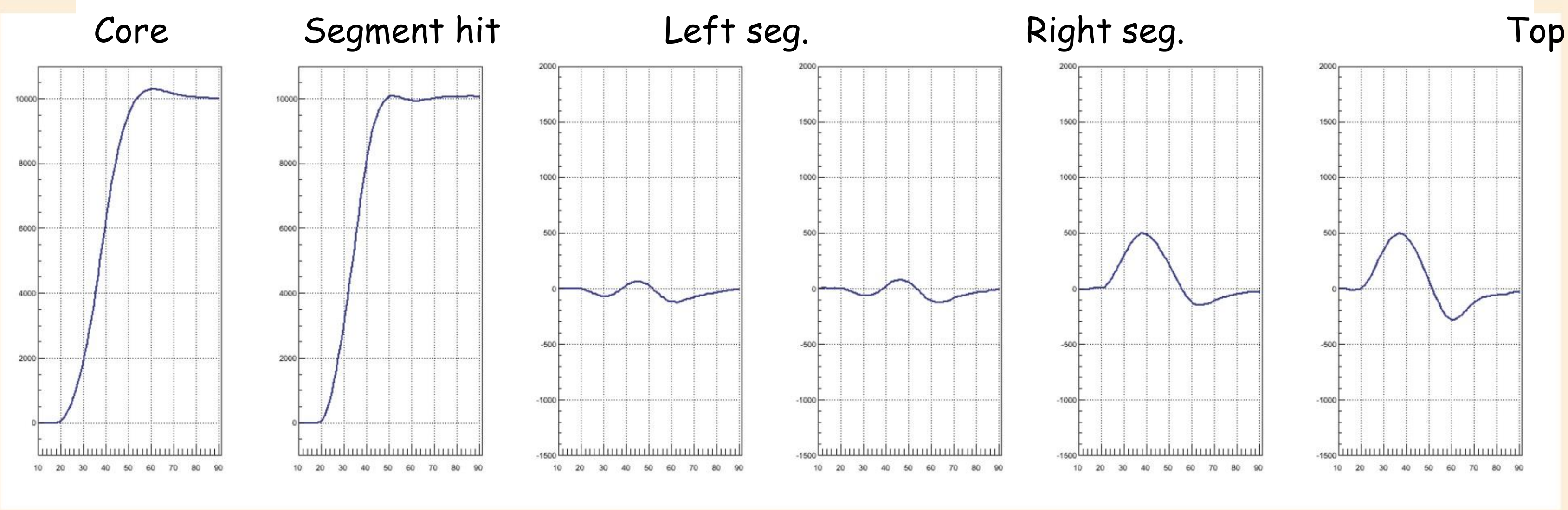


3D partial PSCS

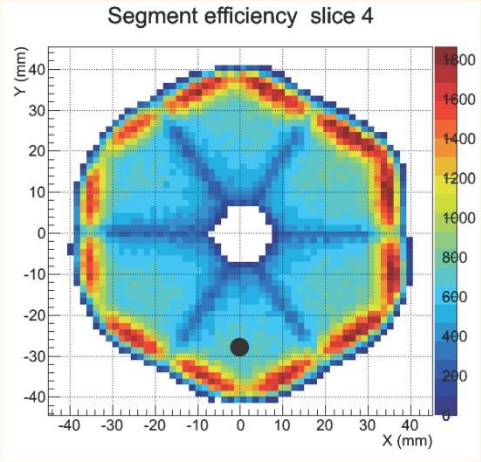


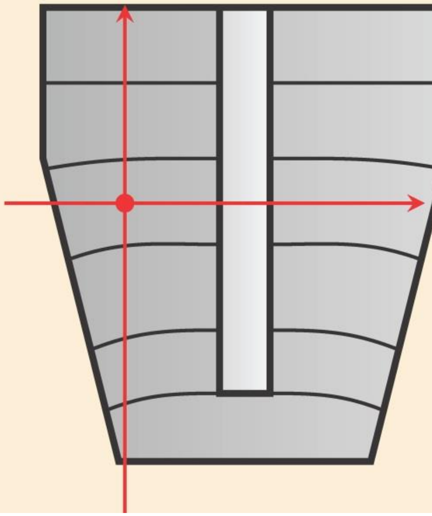


(0 ; -24.5 ; 50)

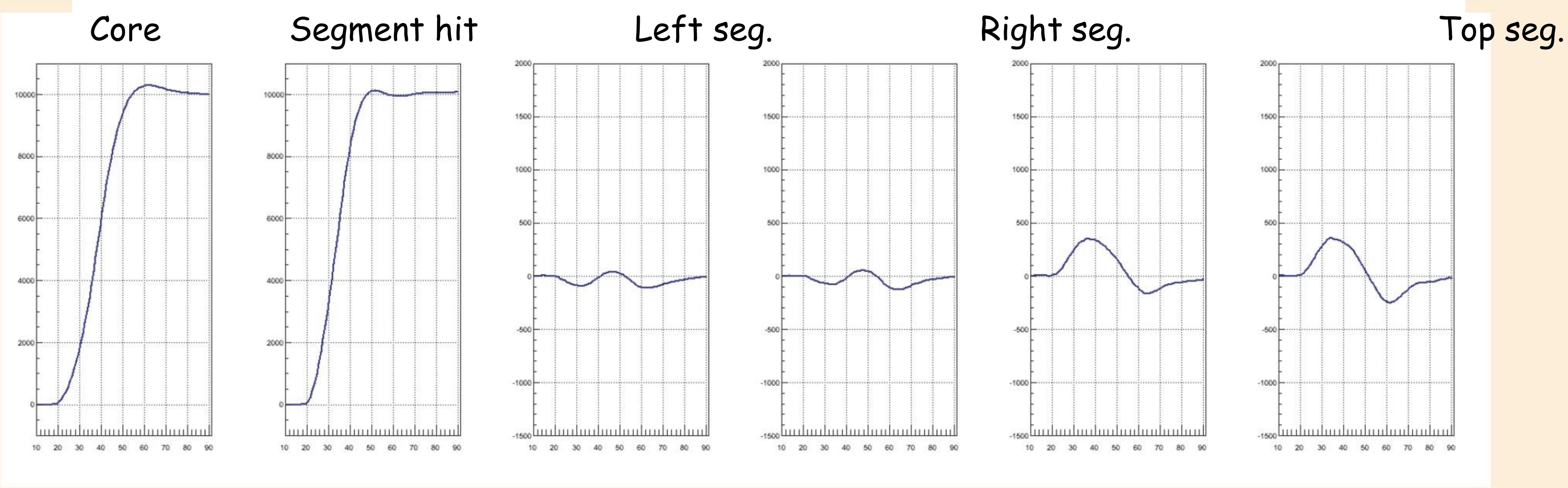


3D partial PSCS

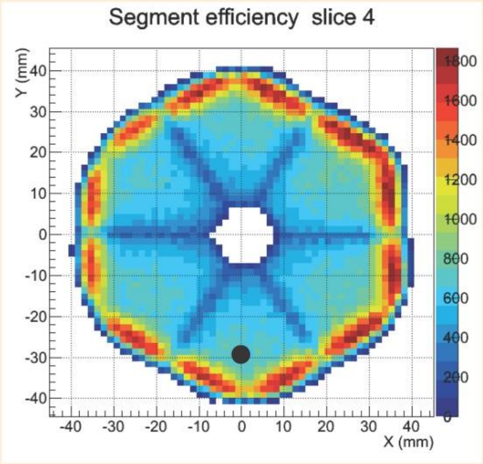


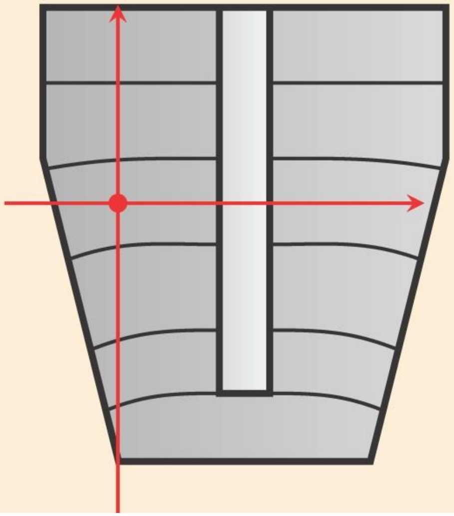


(0 ; -26.0 ; 50)

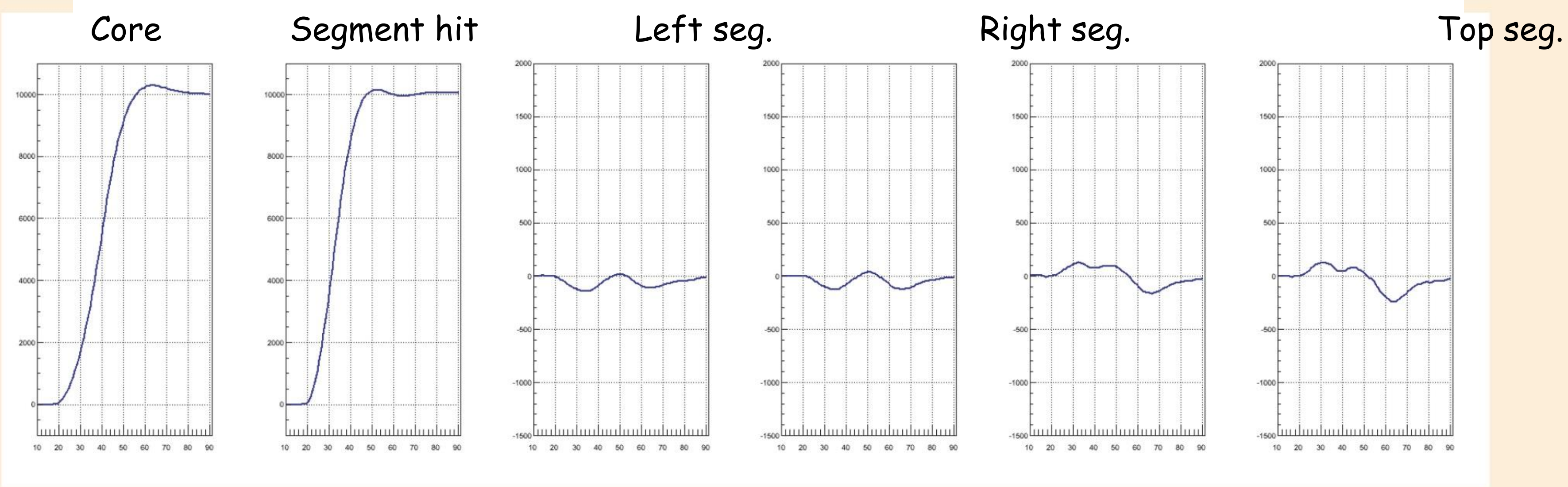


3D partial PSCS

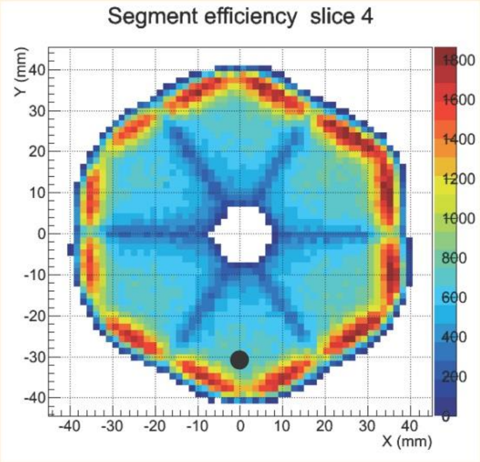


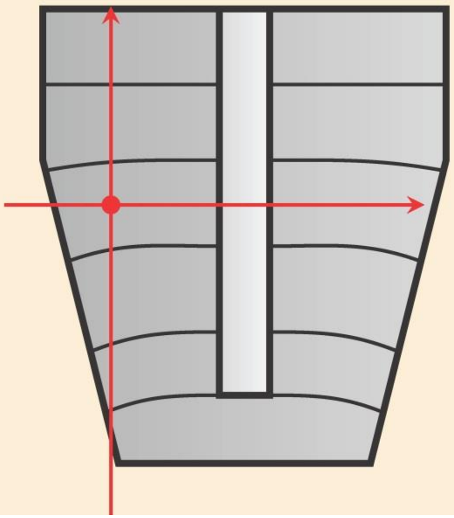


(0 ; -27.5 ; 50)

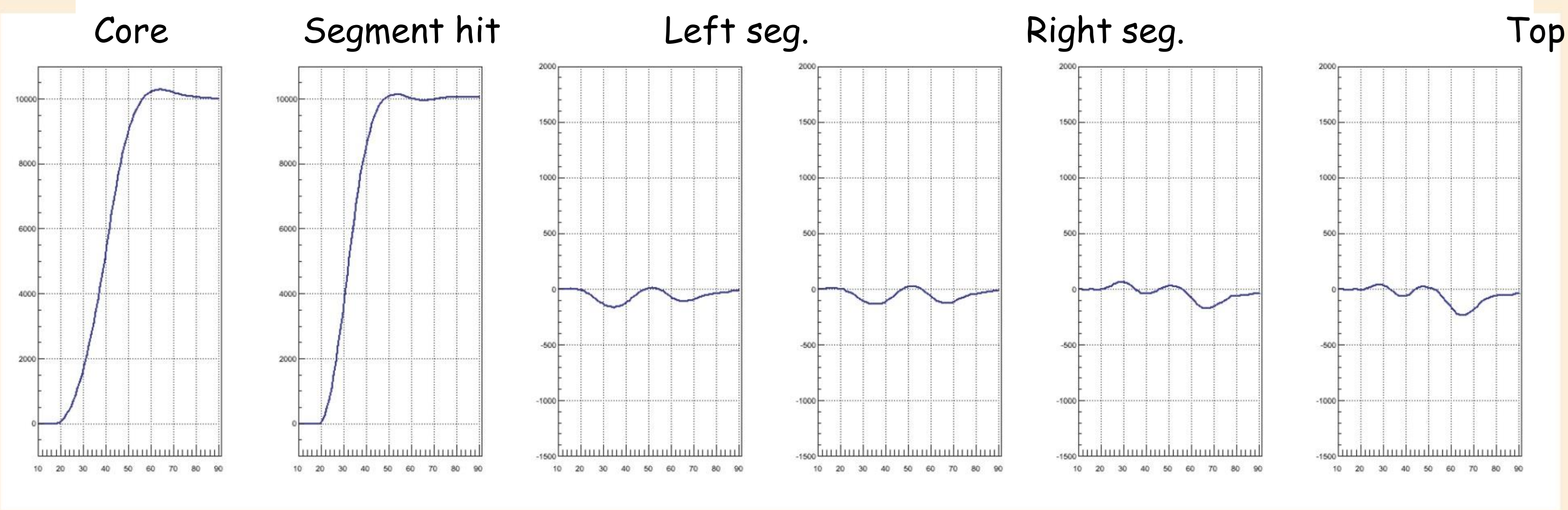


3D partial PSCS

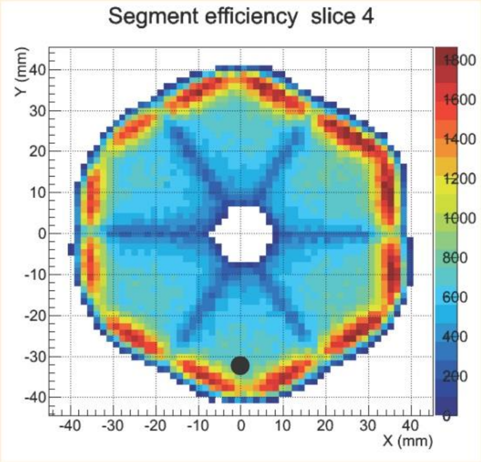


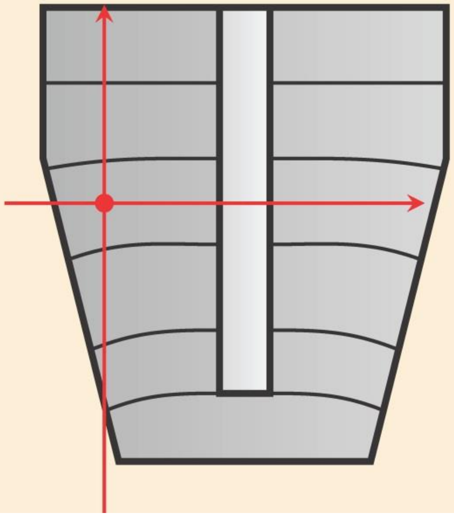


(0 ; -29.0 ; 50)

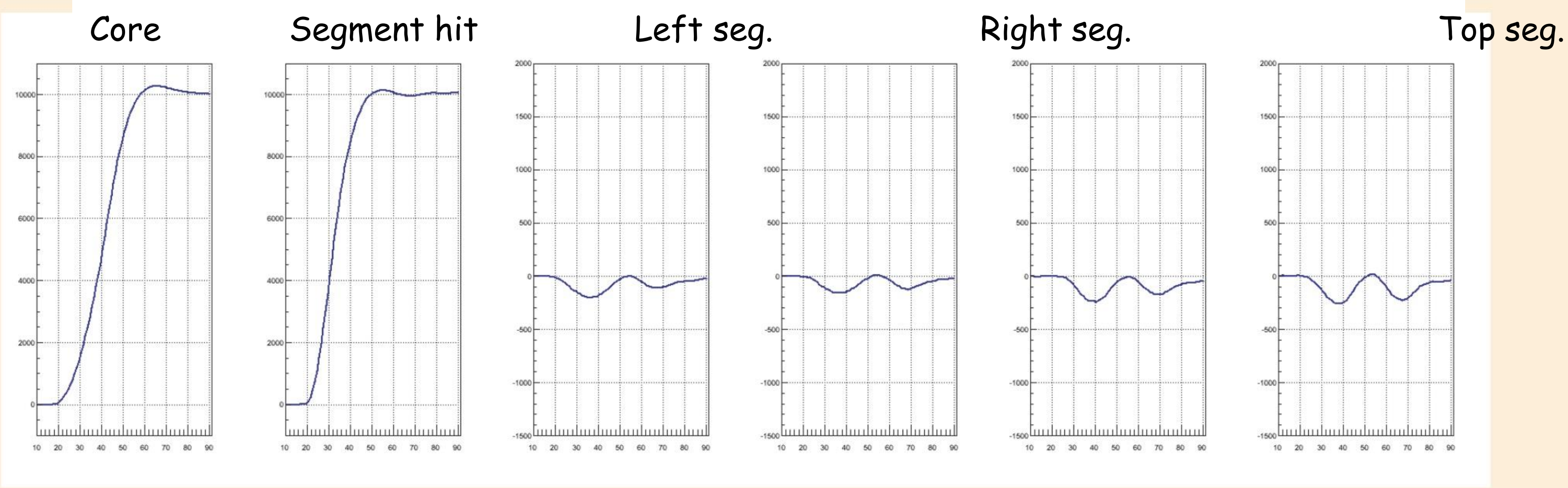


3D partial PSCS

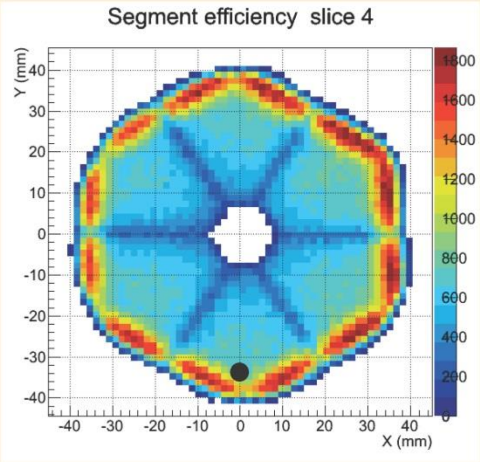


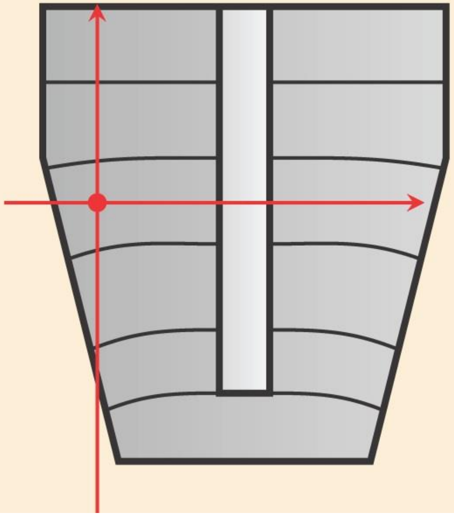


(0 ; -30.5 ; 50)

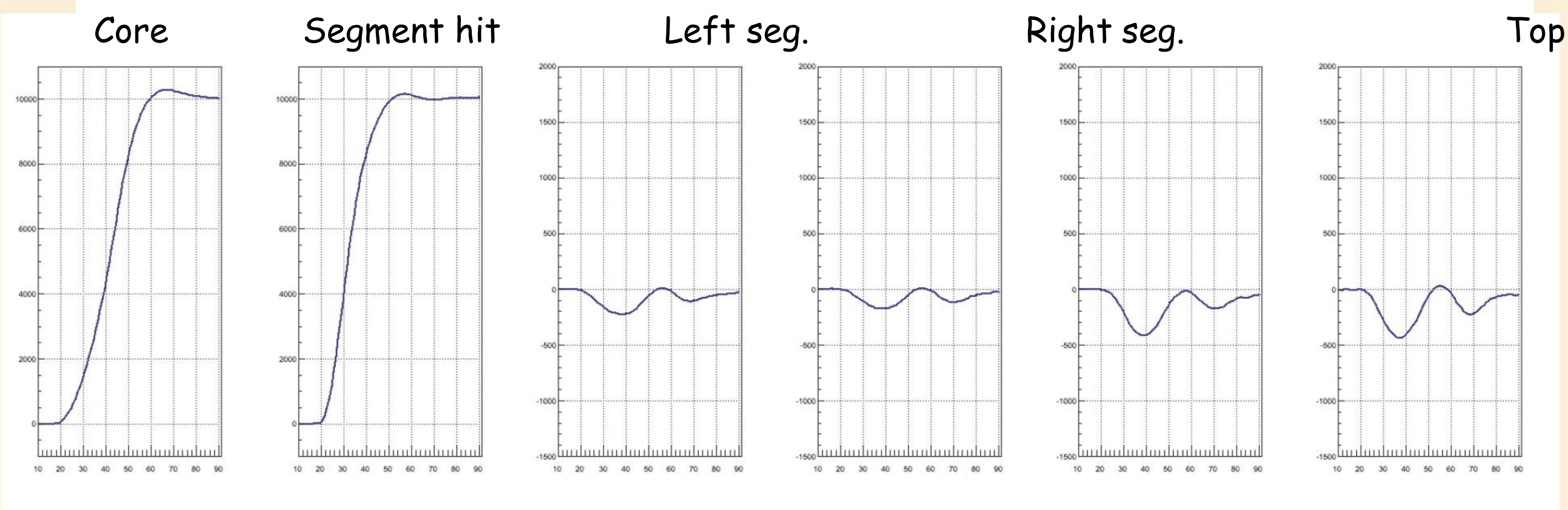


3D partial PSCS

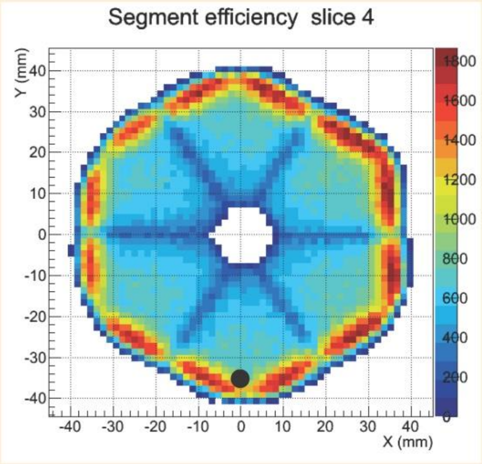


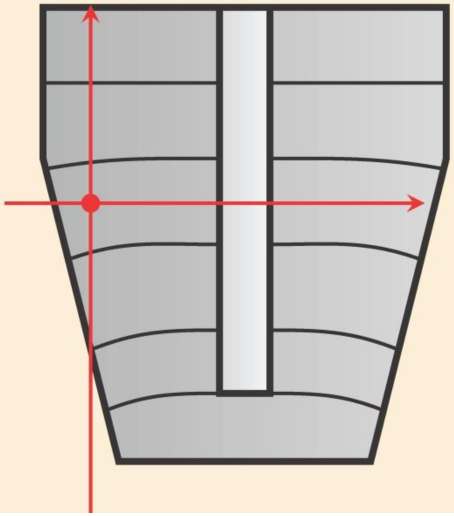


(0 ; -32.0 ; 50)

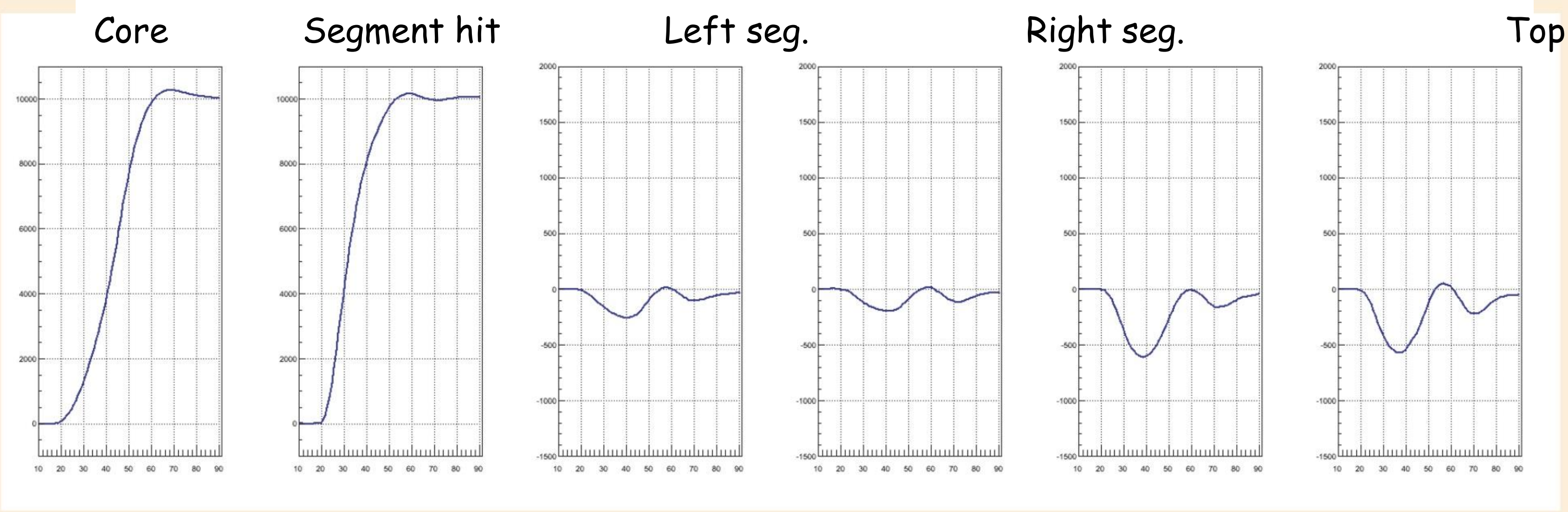


3D partial PSCS

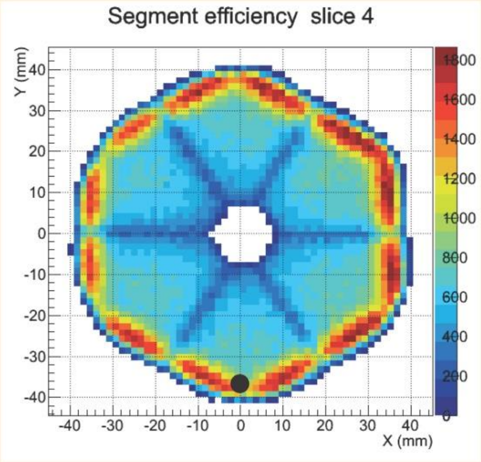


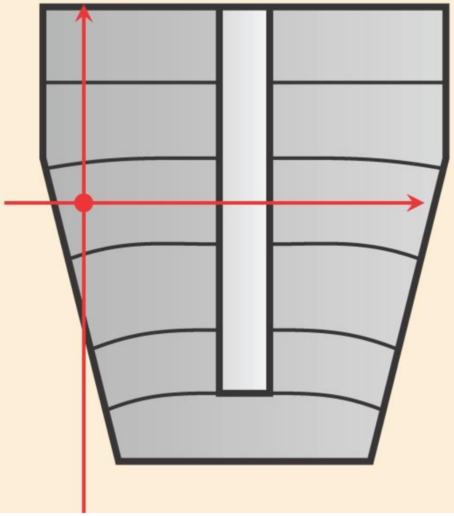


(0 ; -33.5 ; 50)

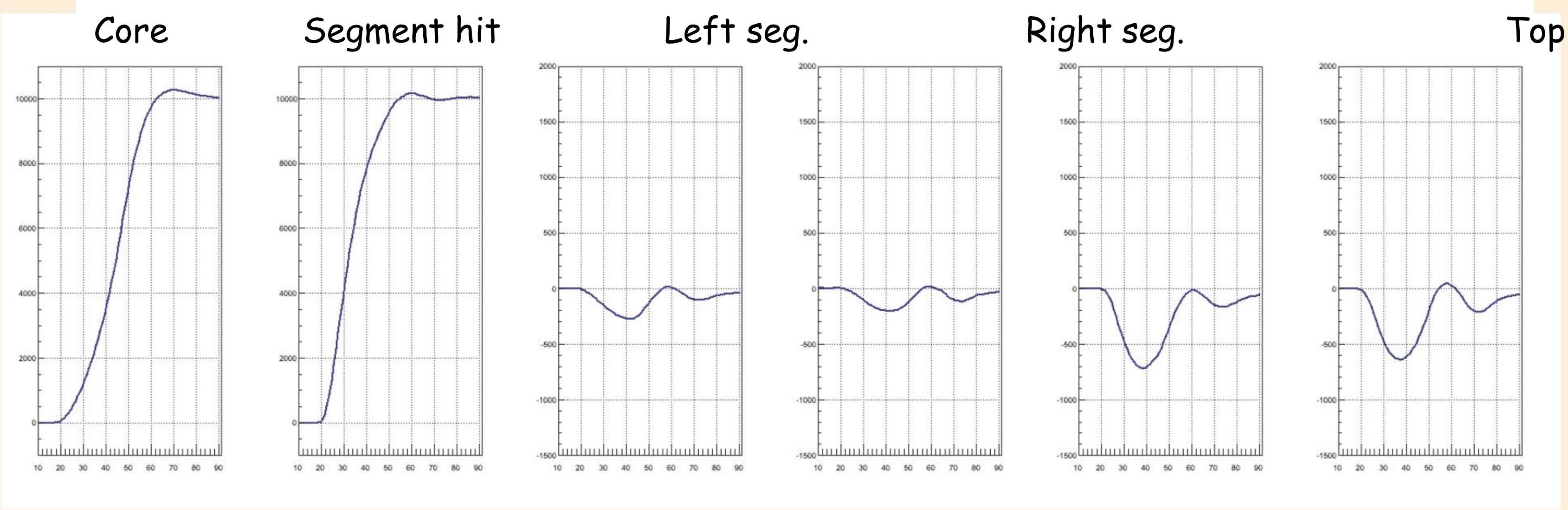


3D partial PSCS

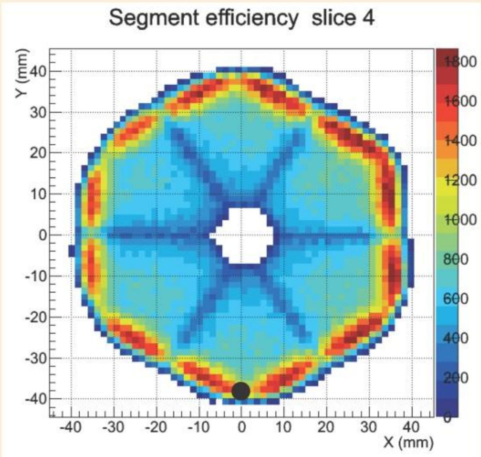


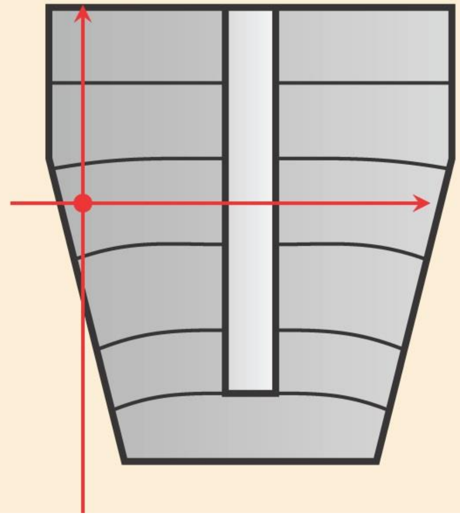


(0 ; -35.0 ; 50)

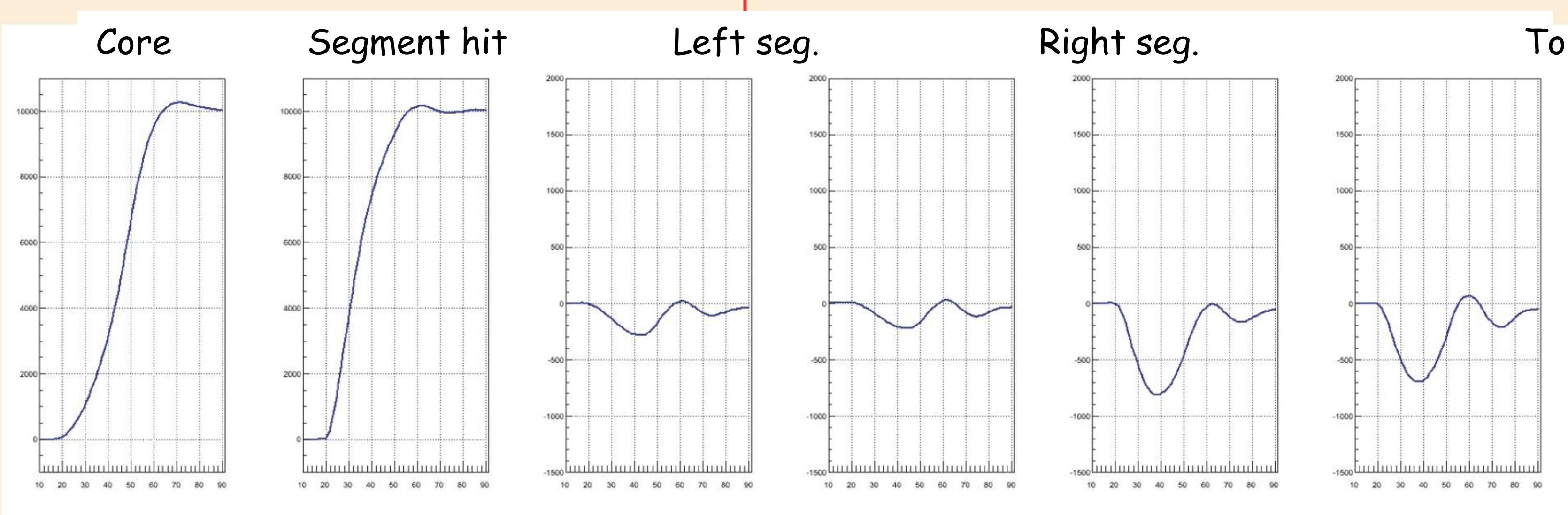


3D partial PSCS

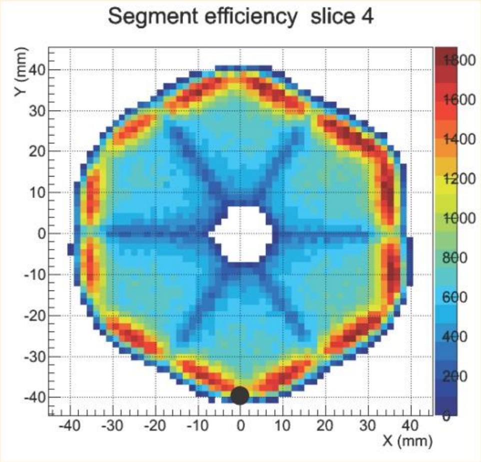


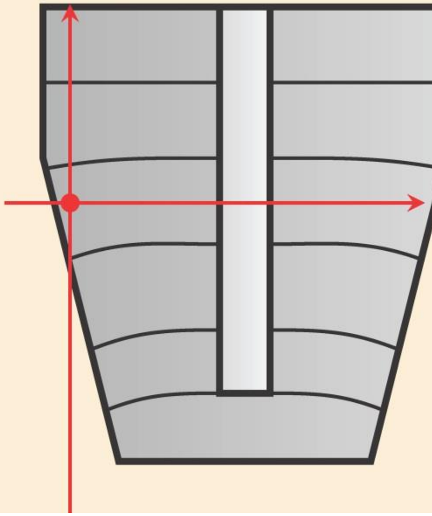


(0 ; -36.5 ; 50)

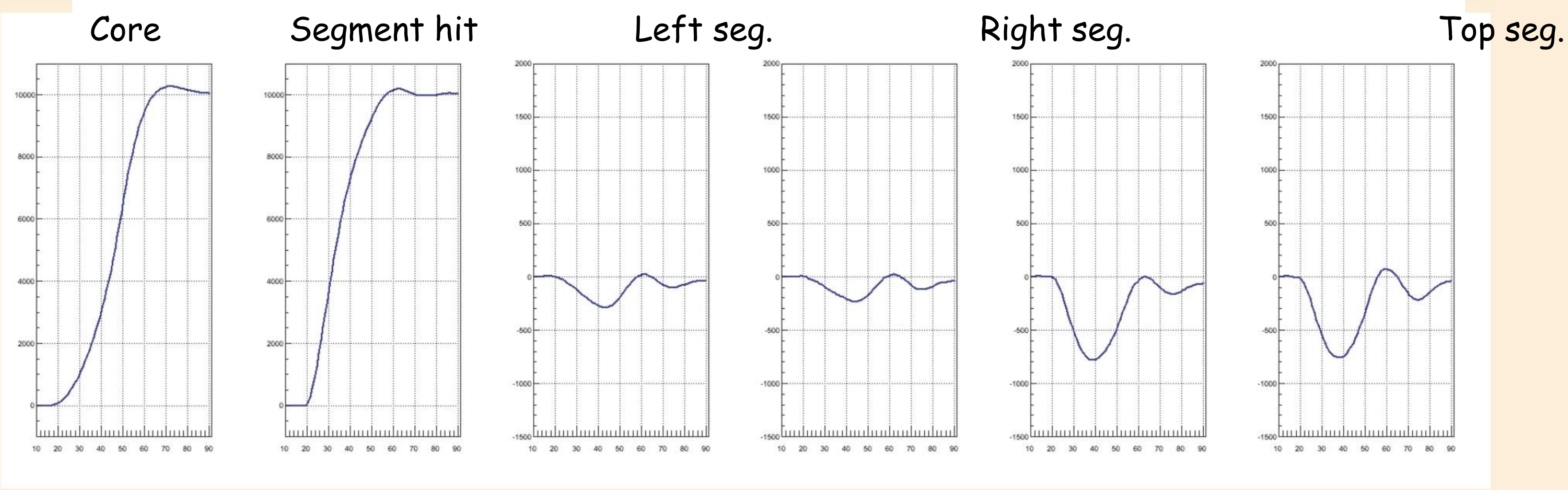


3D partial PSCS

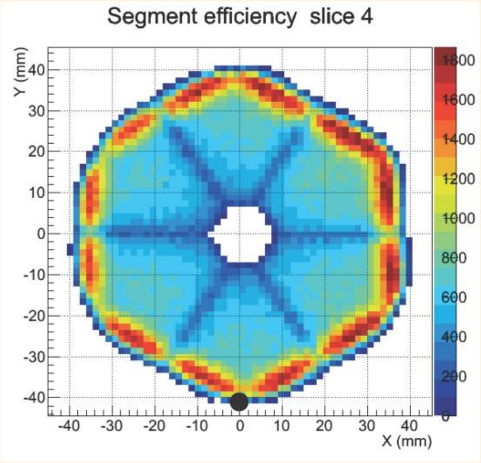


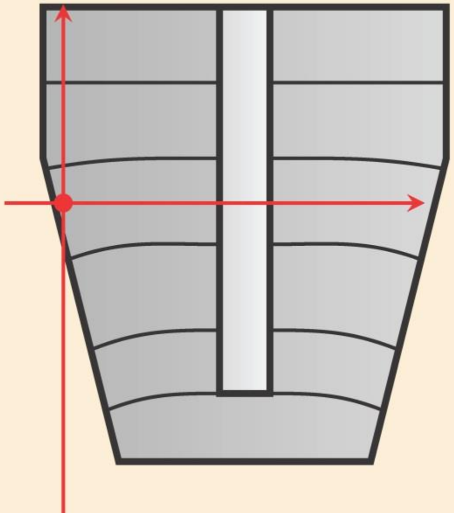


(0 ; -38.0 ; 50)

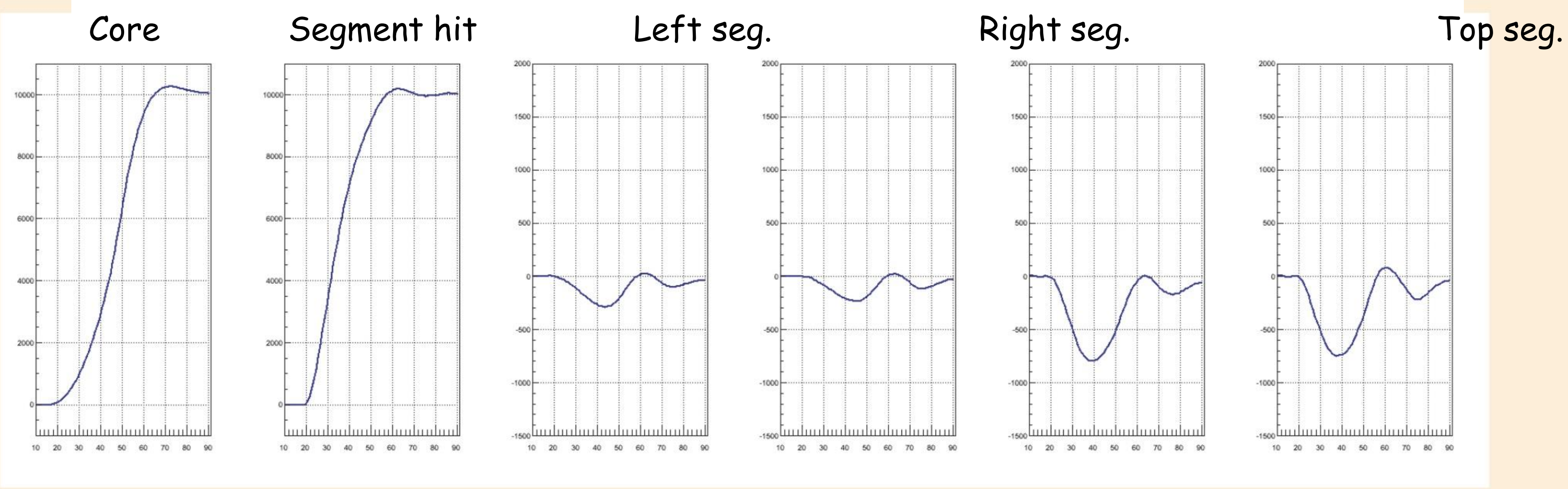


3D partial PSCS

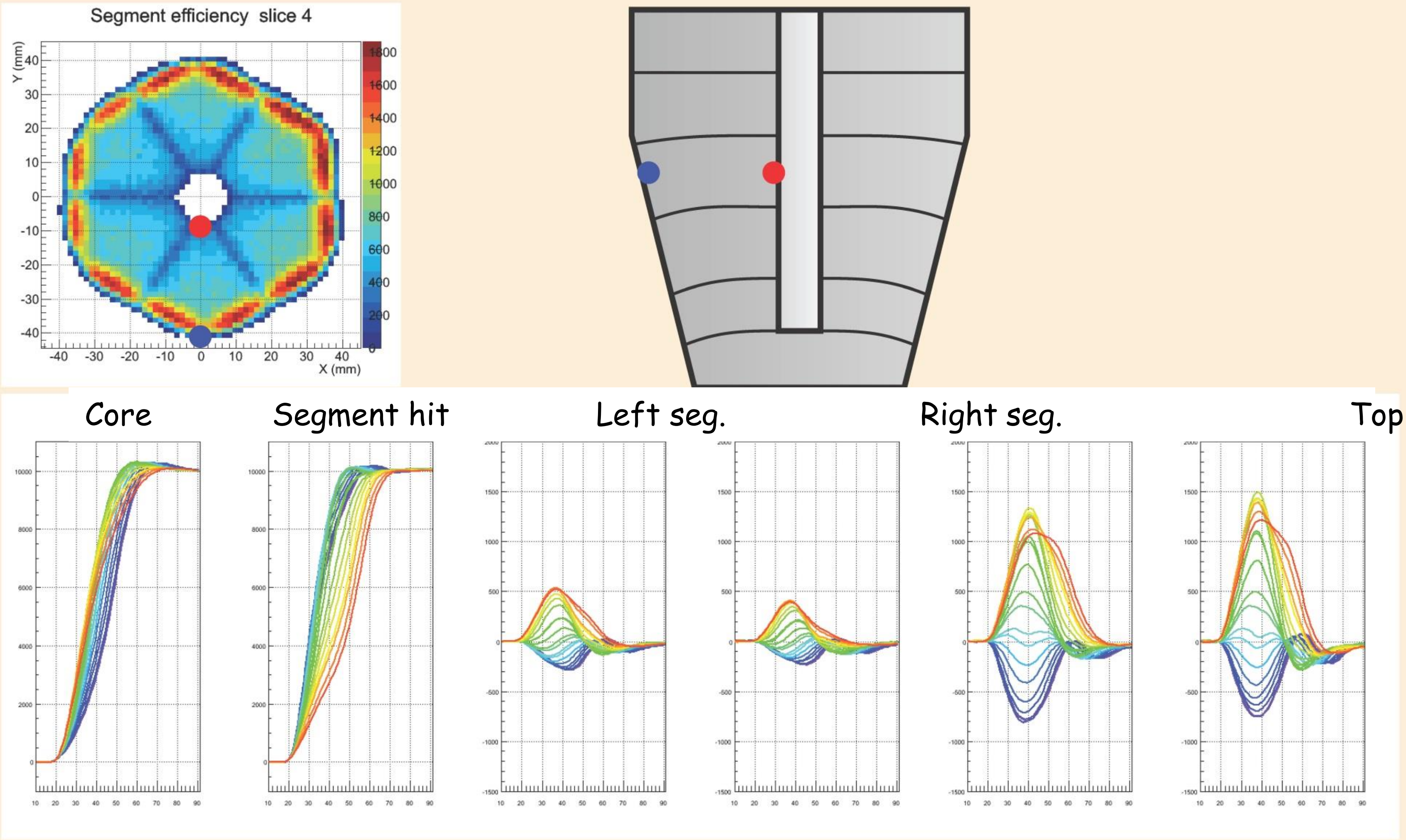




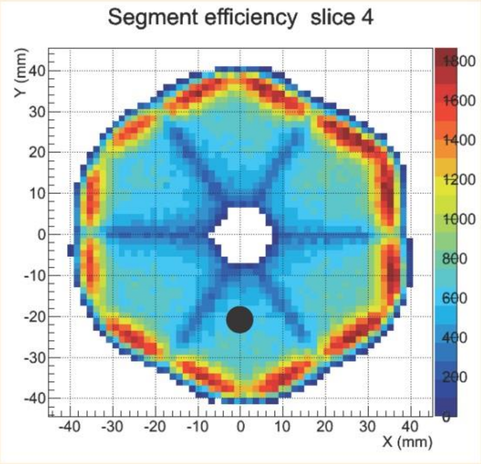
(0 ; -39.5 ; 50)

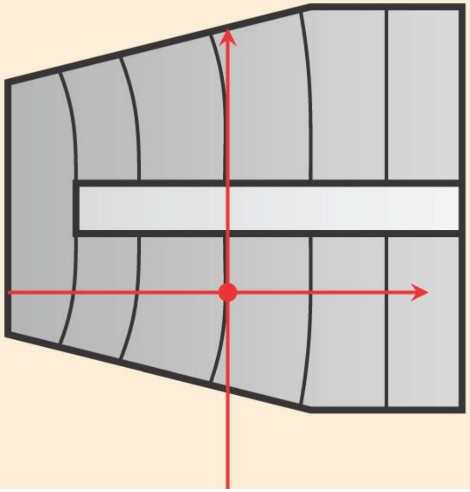


3D partial PSCS

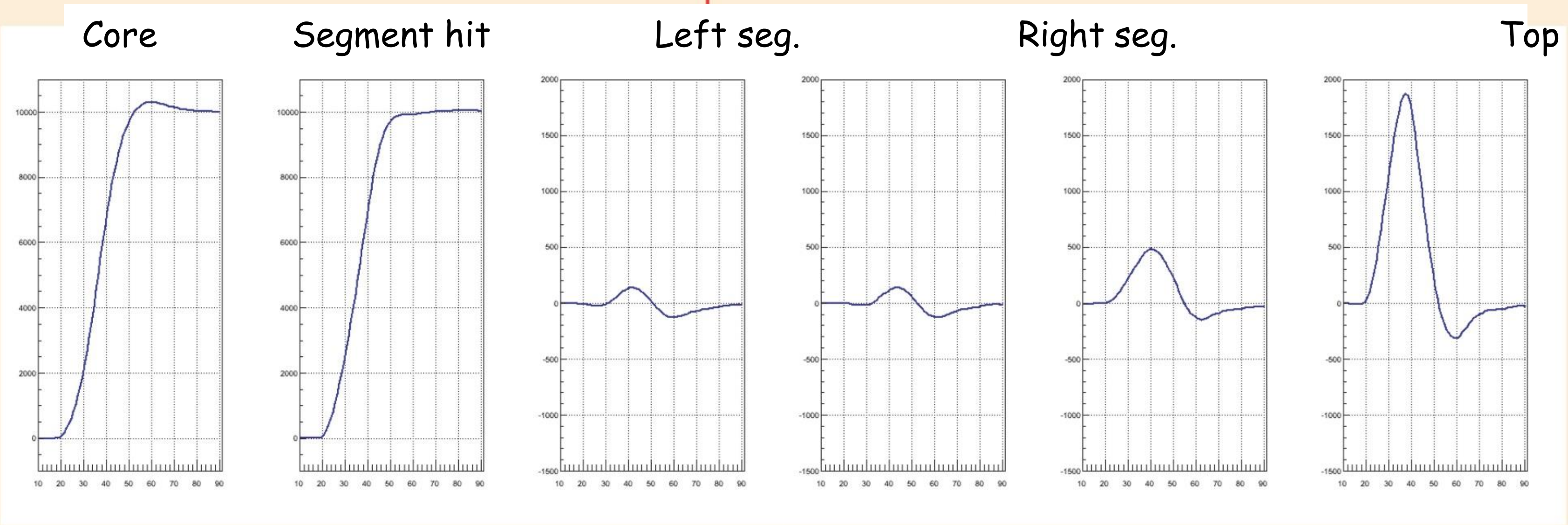


3D partial PSCS

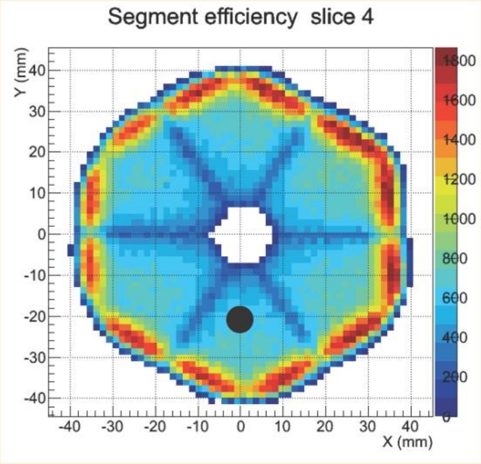


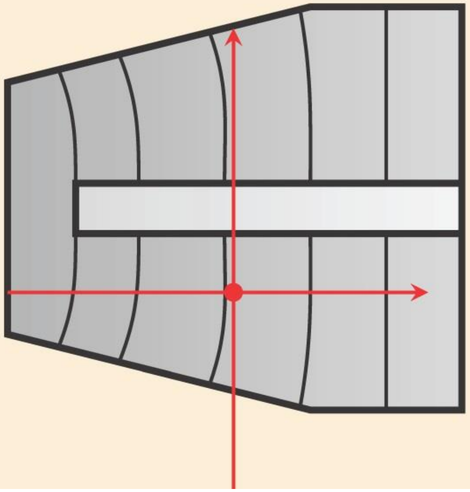


(0 ; -23 ; 43)

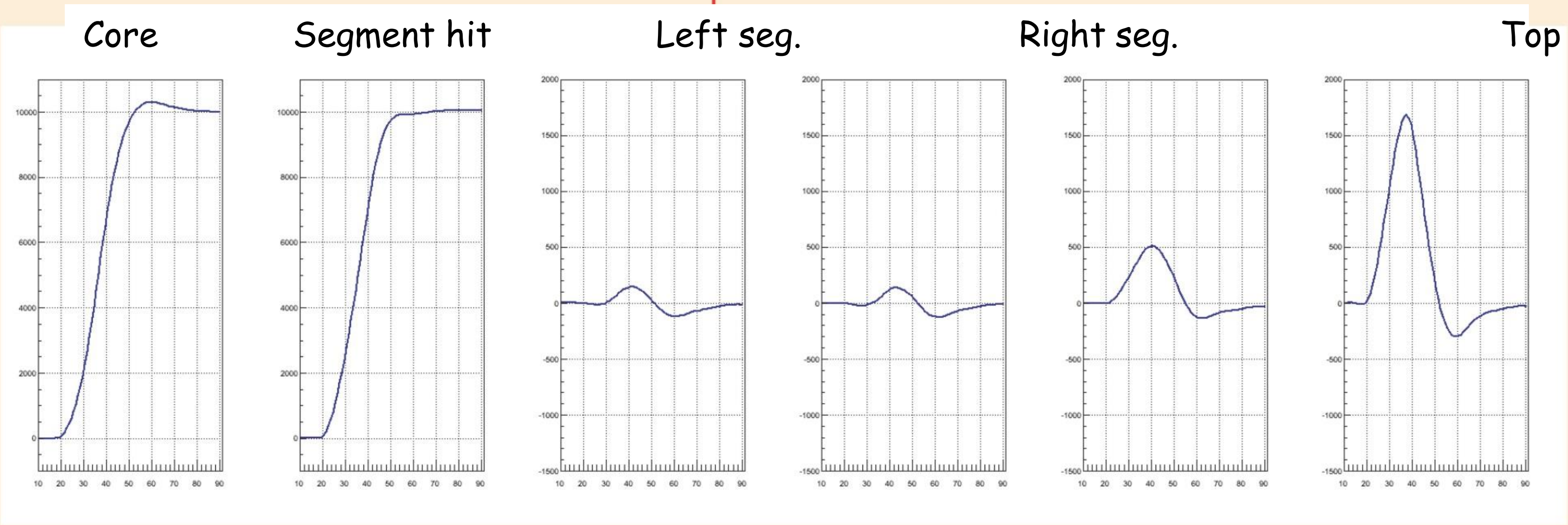


3D partial PSCS

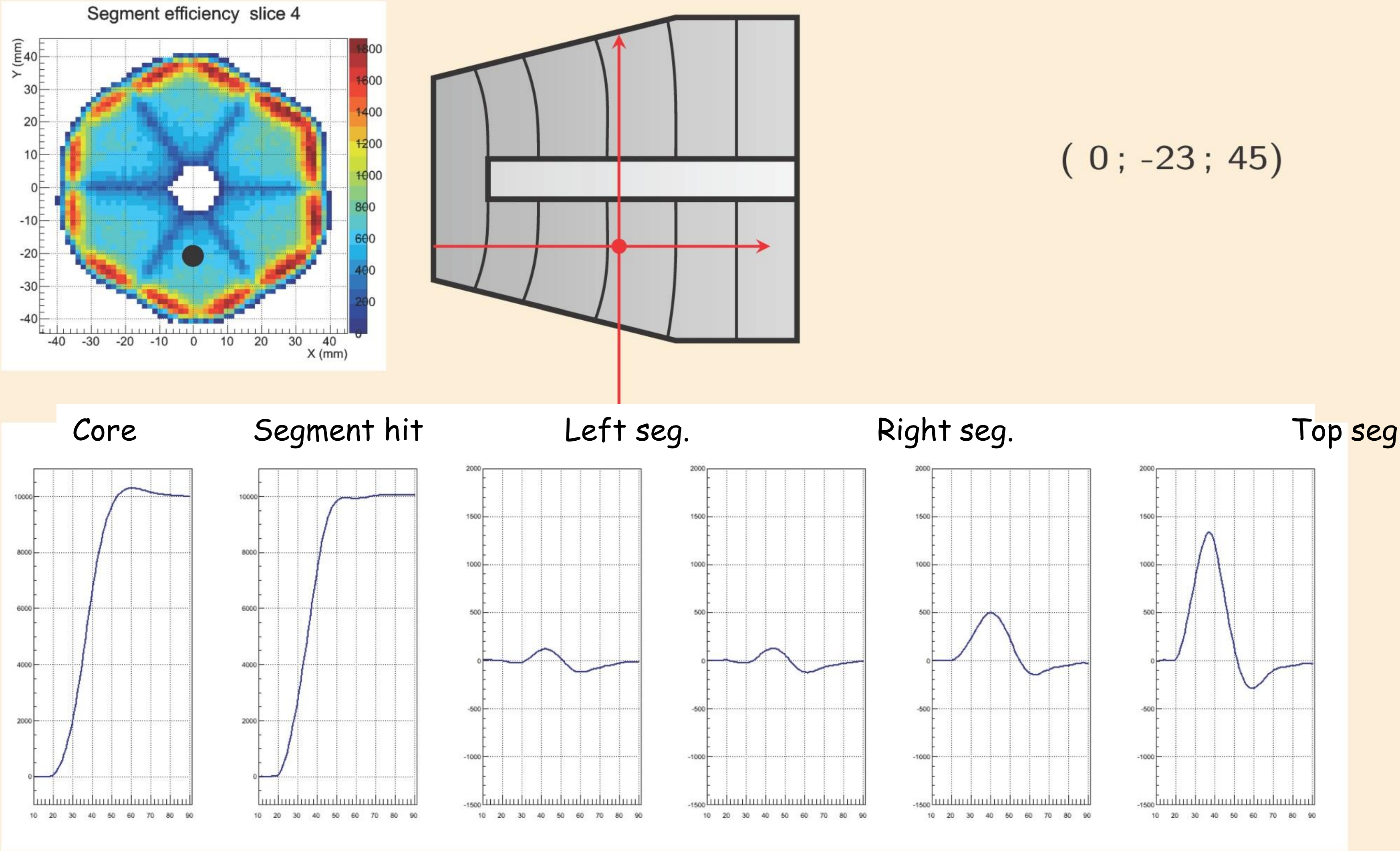




(0 ; -23 ; 44)

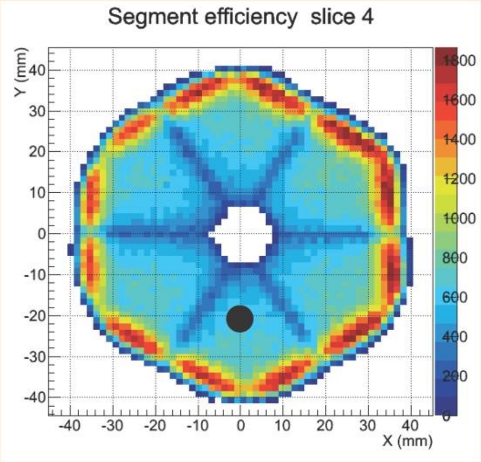


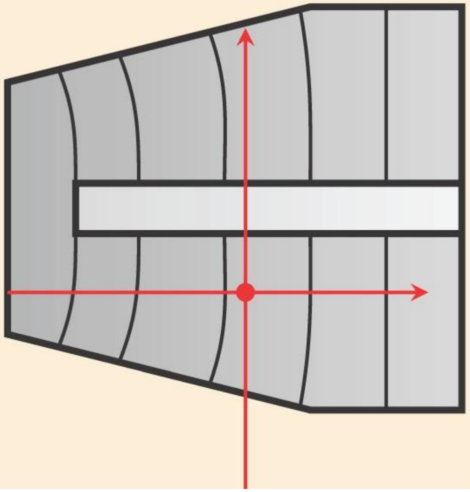
3D partial PSCS



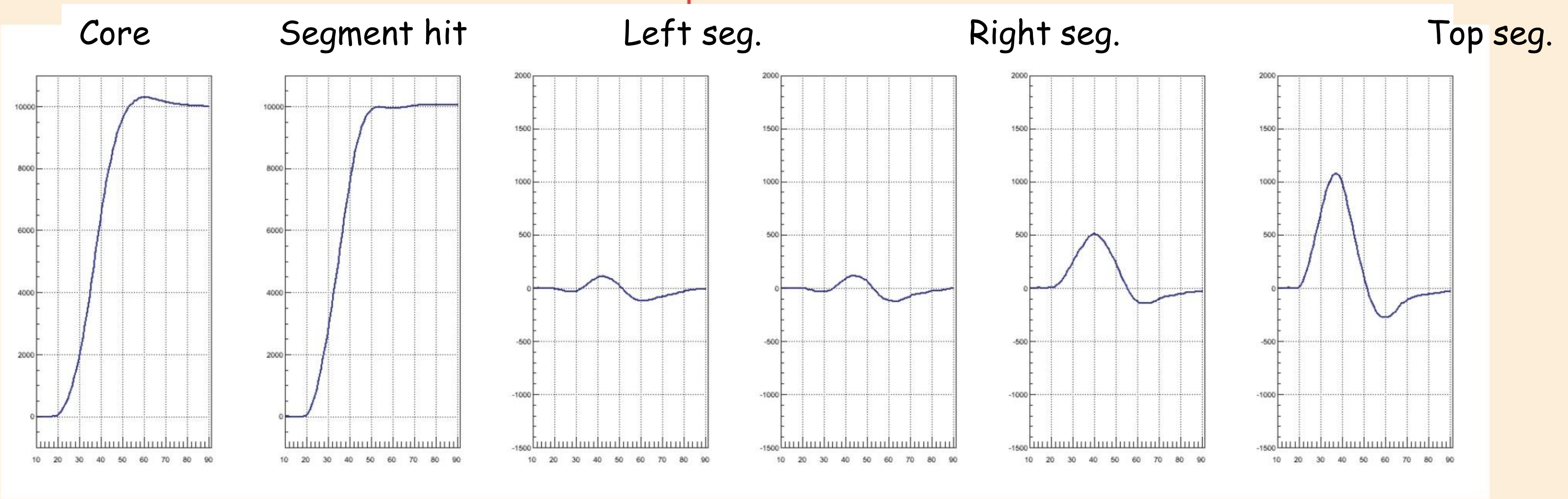
(0 ; -23 ; 45)

3D partial PSCS

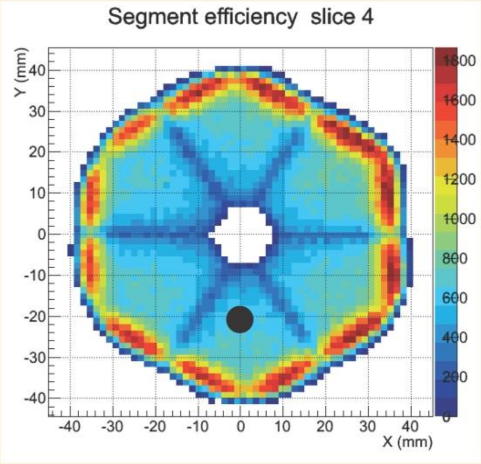


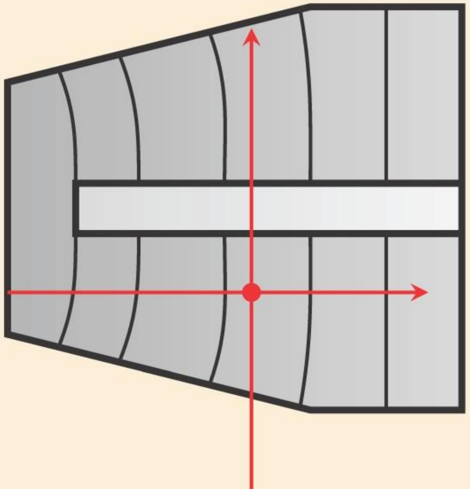


(0 ; -23 ; 46)

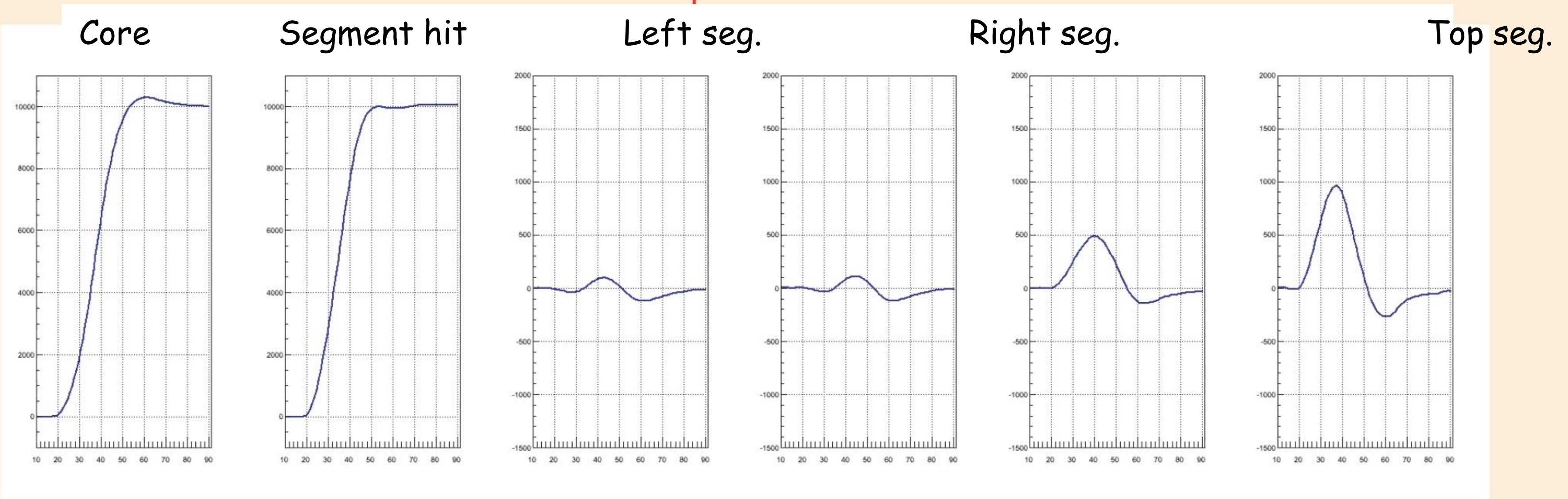


3D partial PSCS

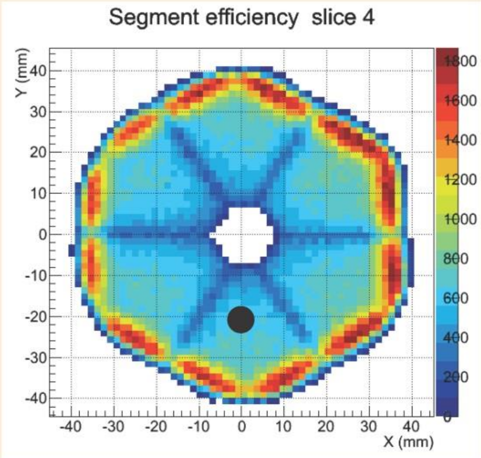


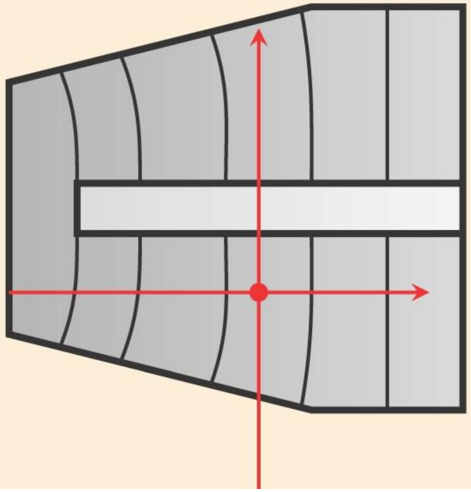


(0 ; -23 ; 47)

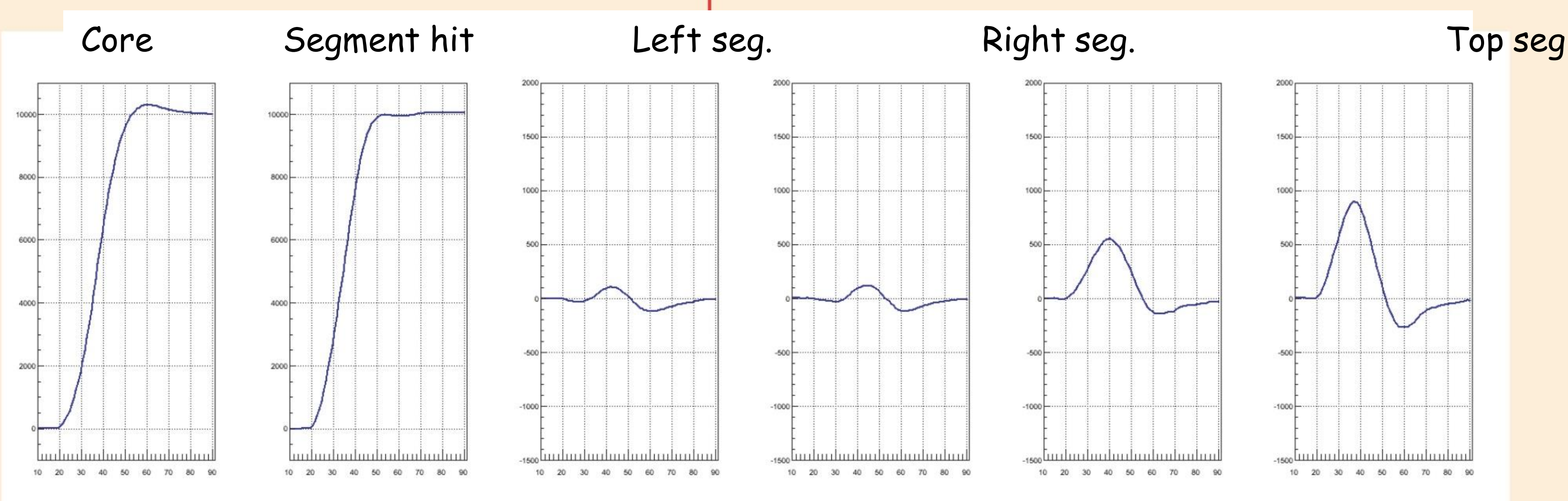


3D partial PSCS

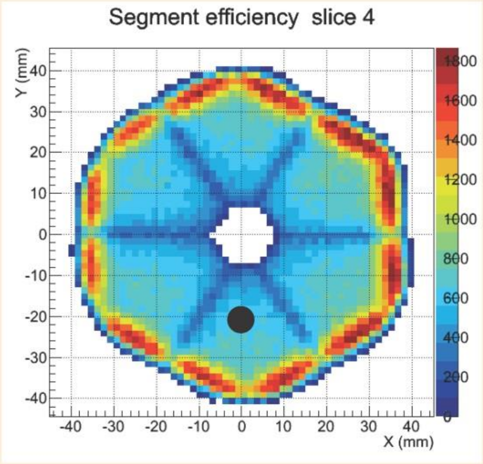


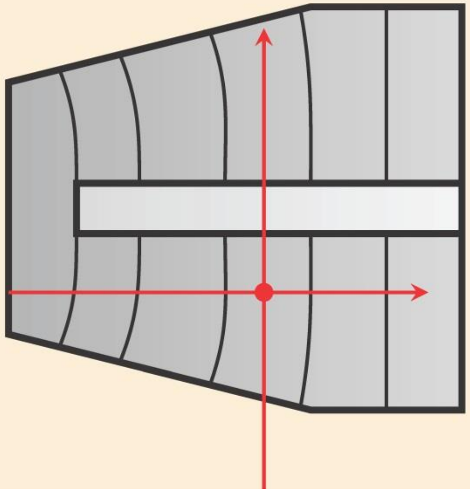


(0 ; -23 ; 48)

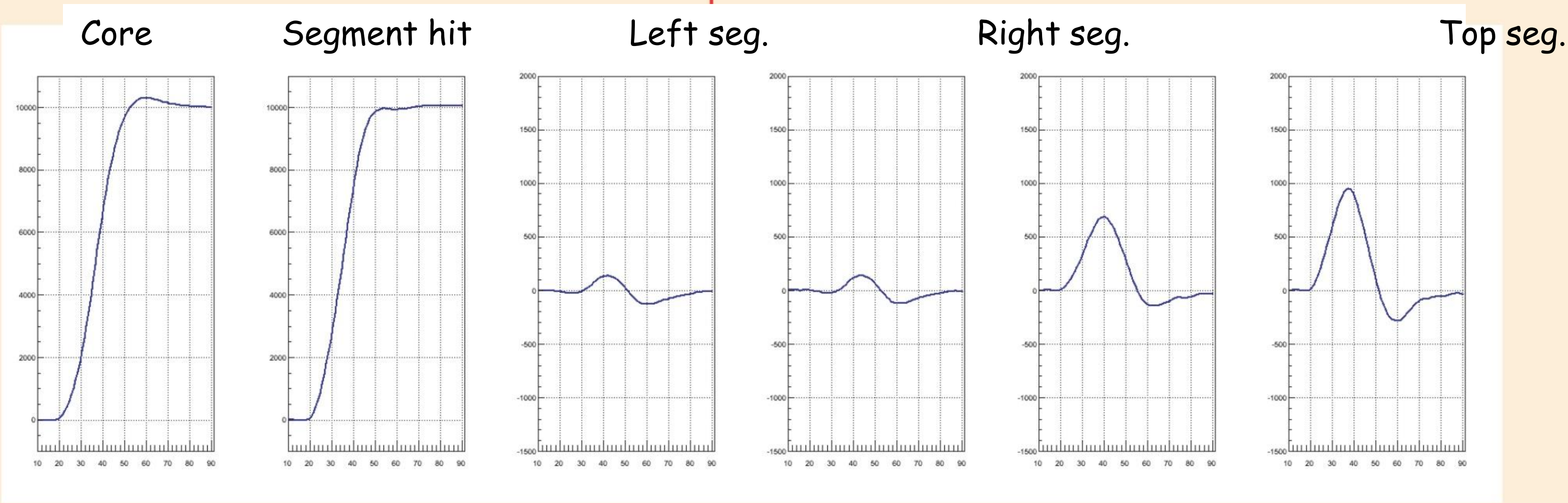


3D partial PSCS

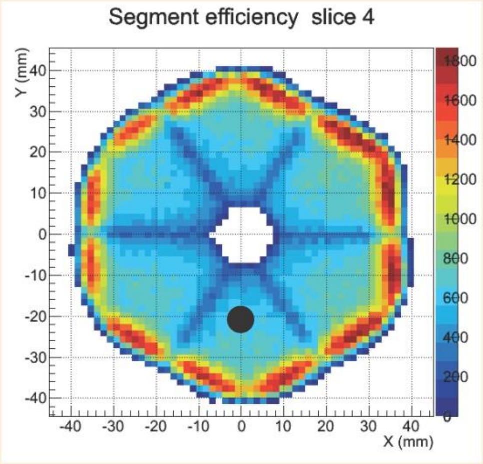


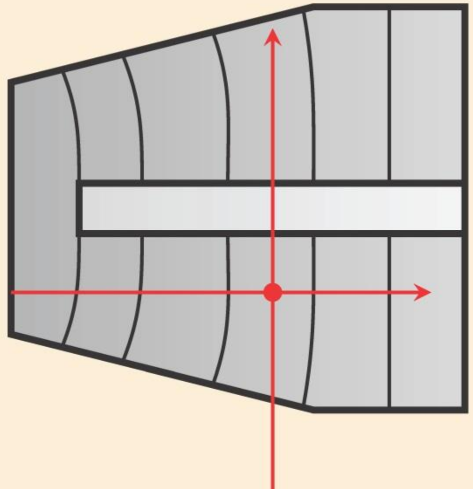


(0 ; -23 ; 49)

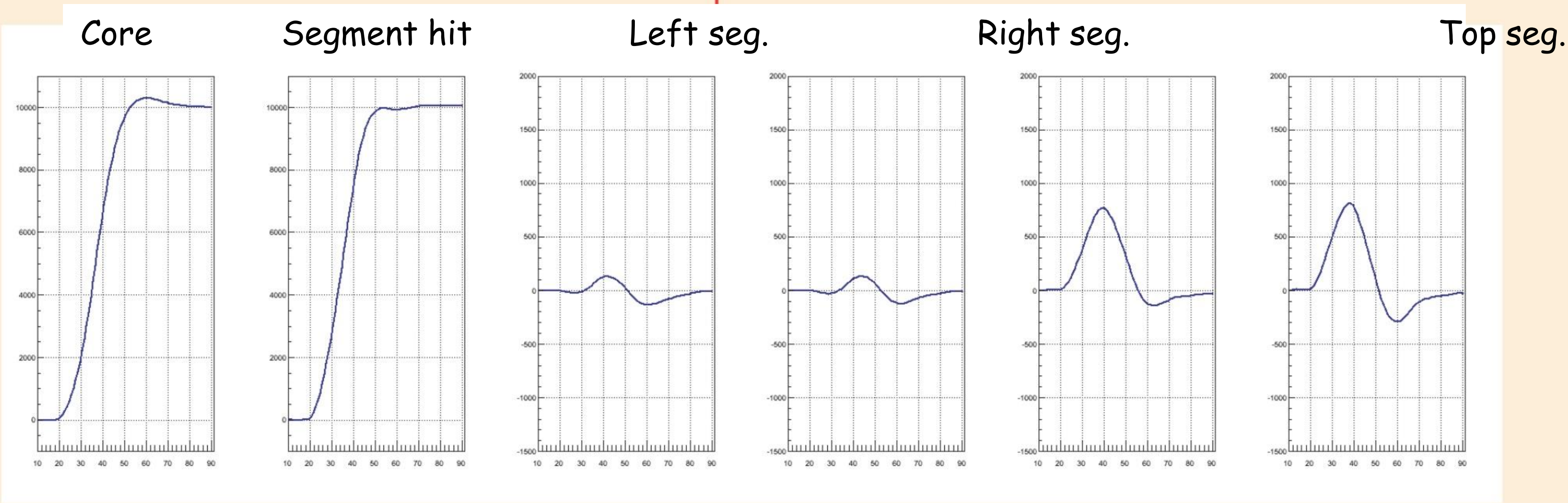


3D partial PSCS

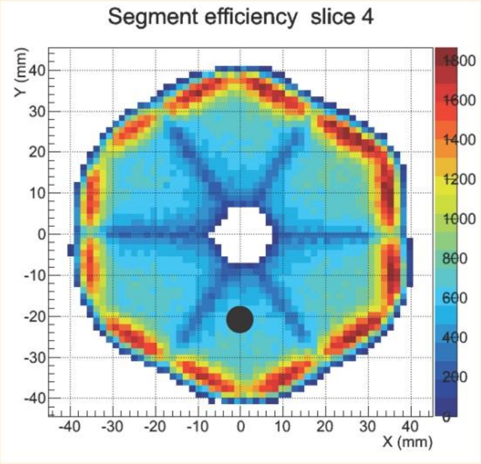


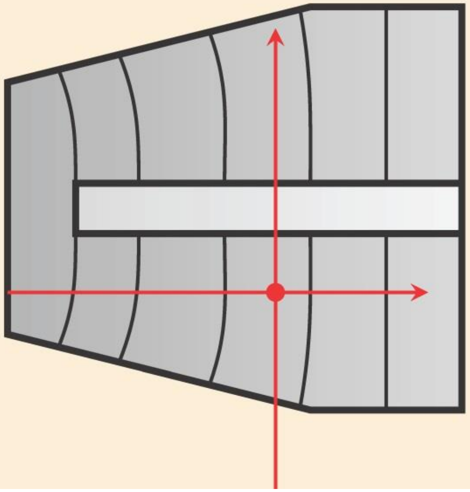


(0 ; -23 ; 50)

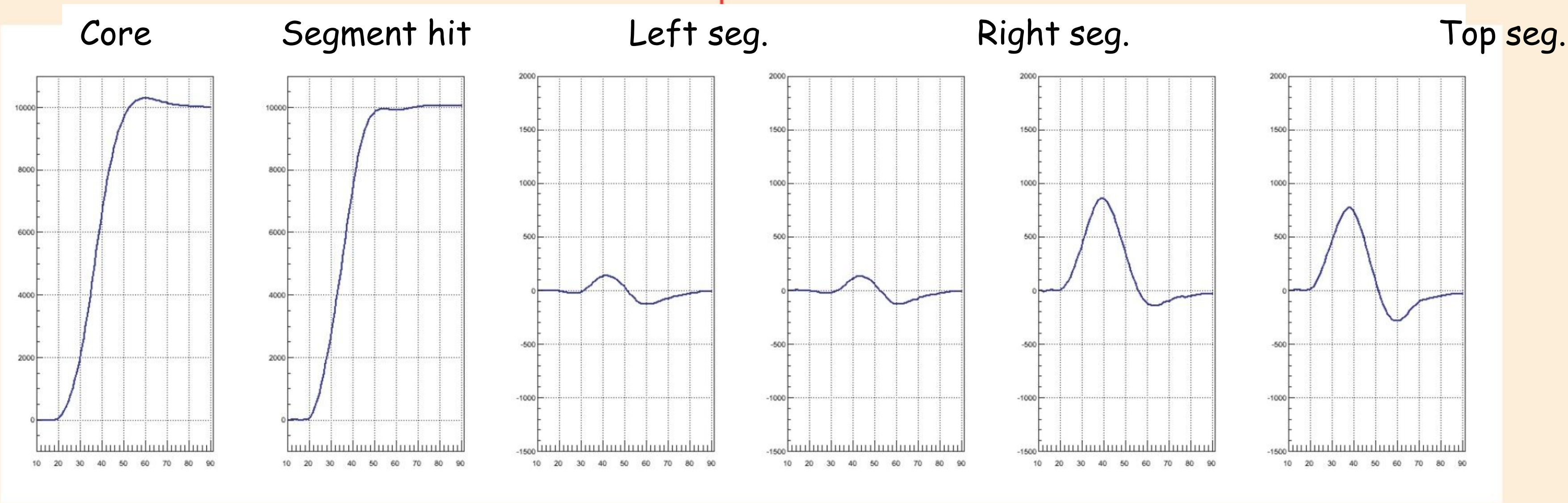


3D partial PSCS

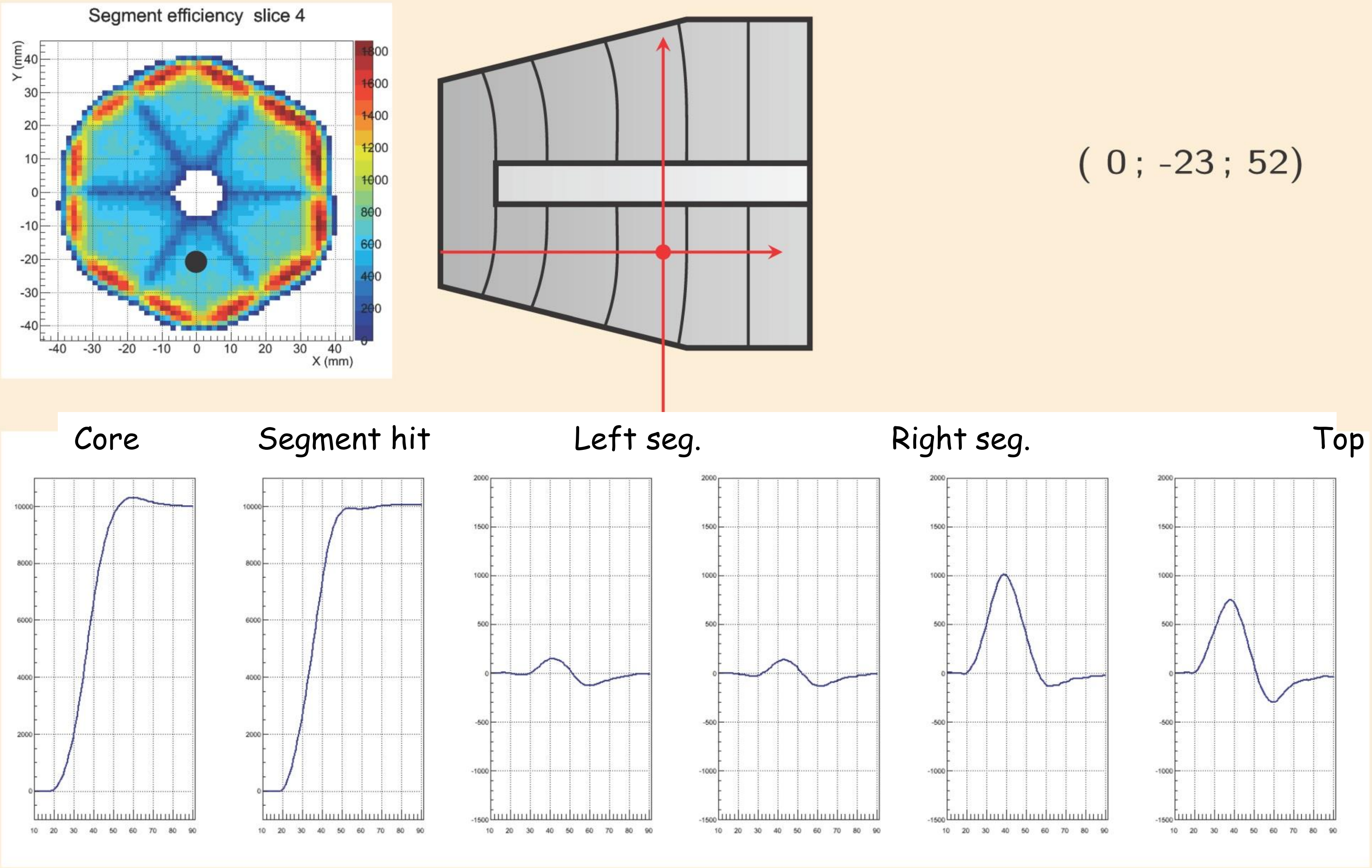




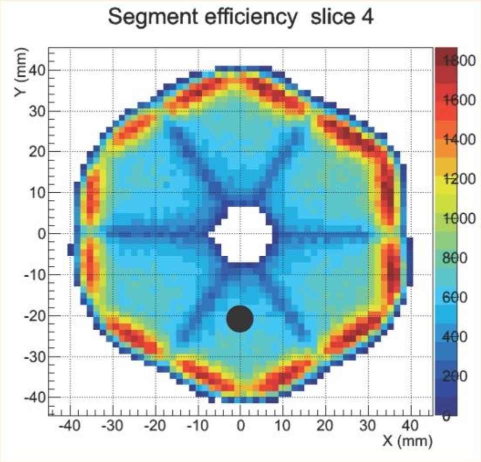
(0 ; -23 ; 51)

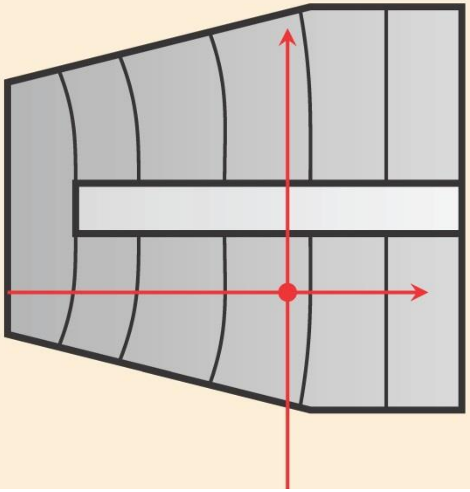


3D partial PSCS

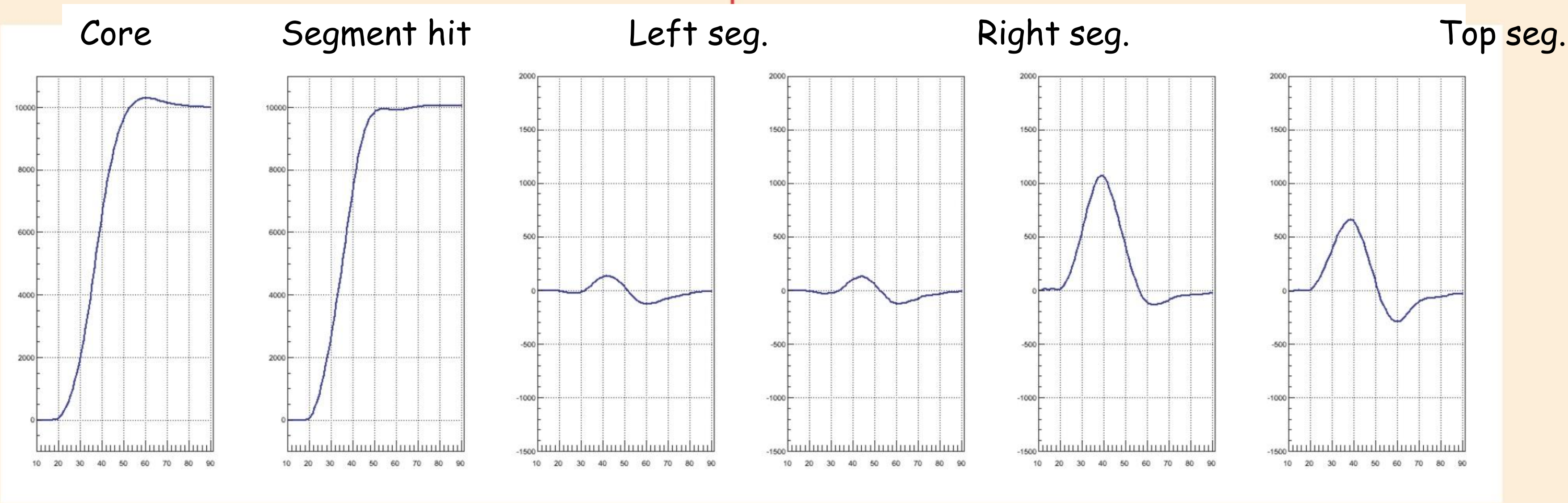


3D partial PSCS

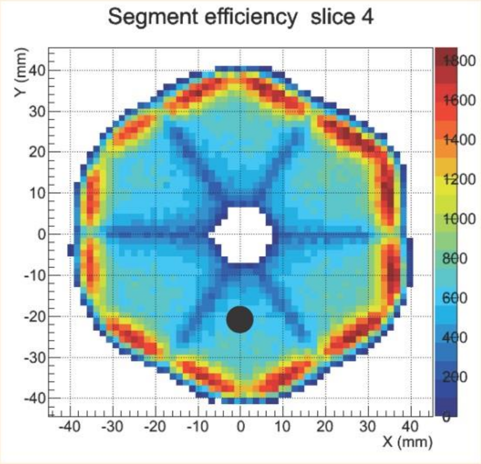


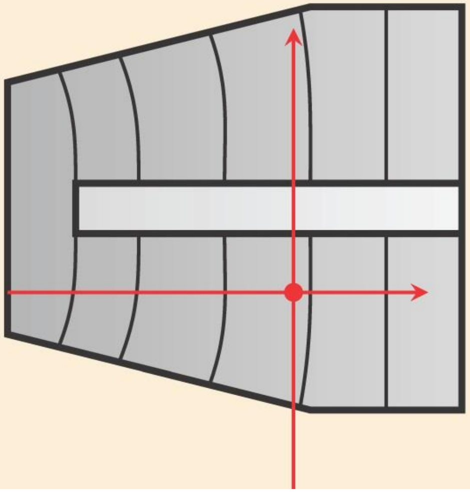


(0 ; -23 ; 53)

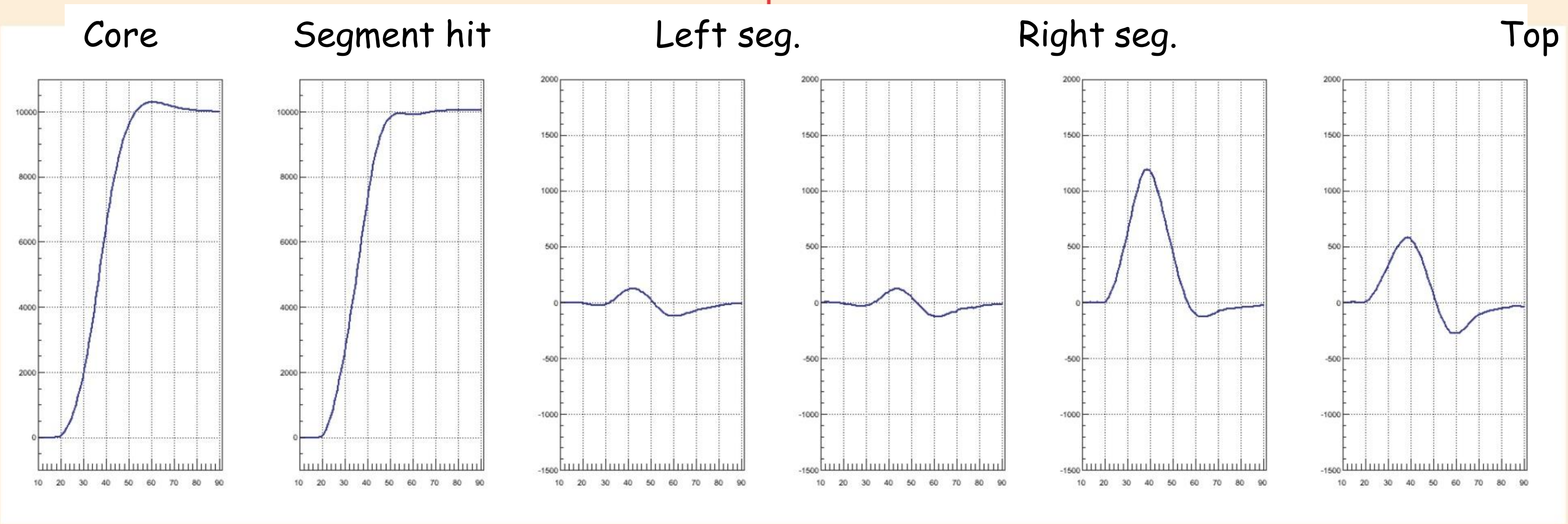


3D partial PSCS

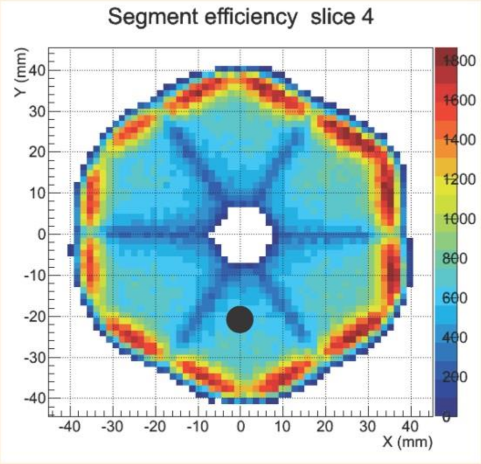


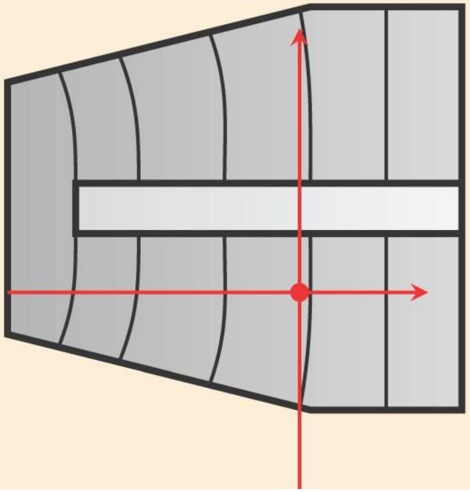


(0 ; -23 ; 54)

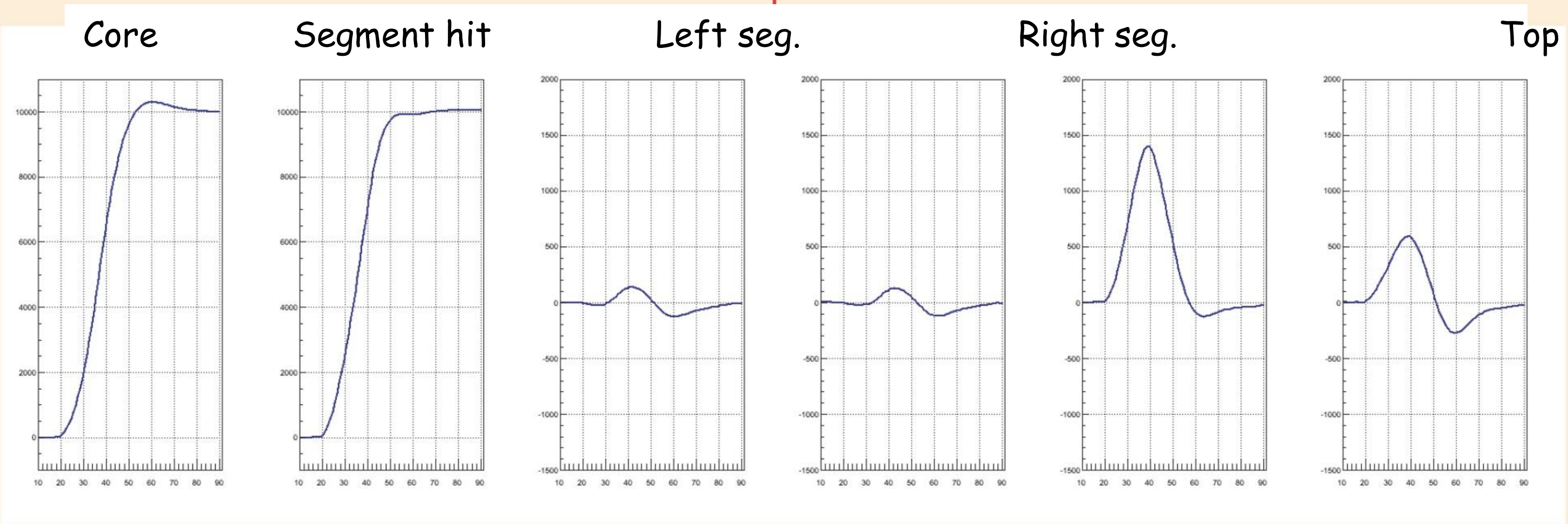


3D partial PSCS

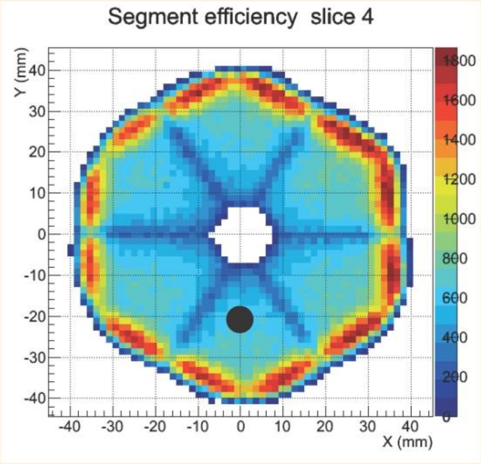


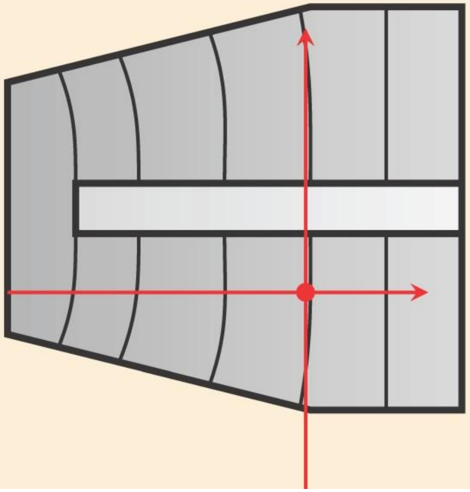


(0 ; -23 ; 55)

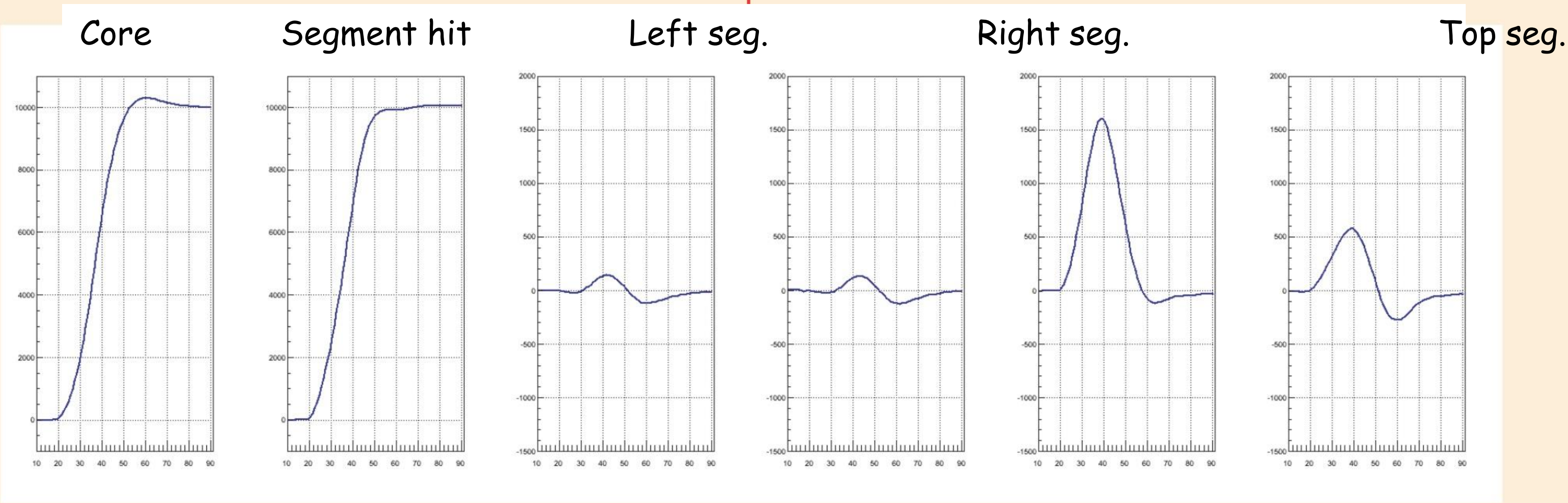


3D partial PSCS

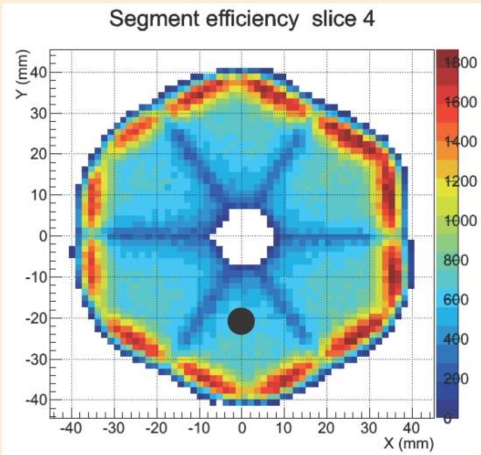


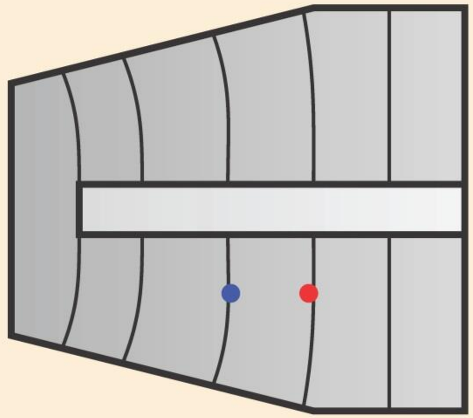


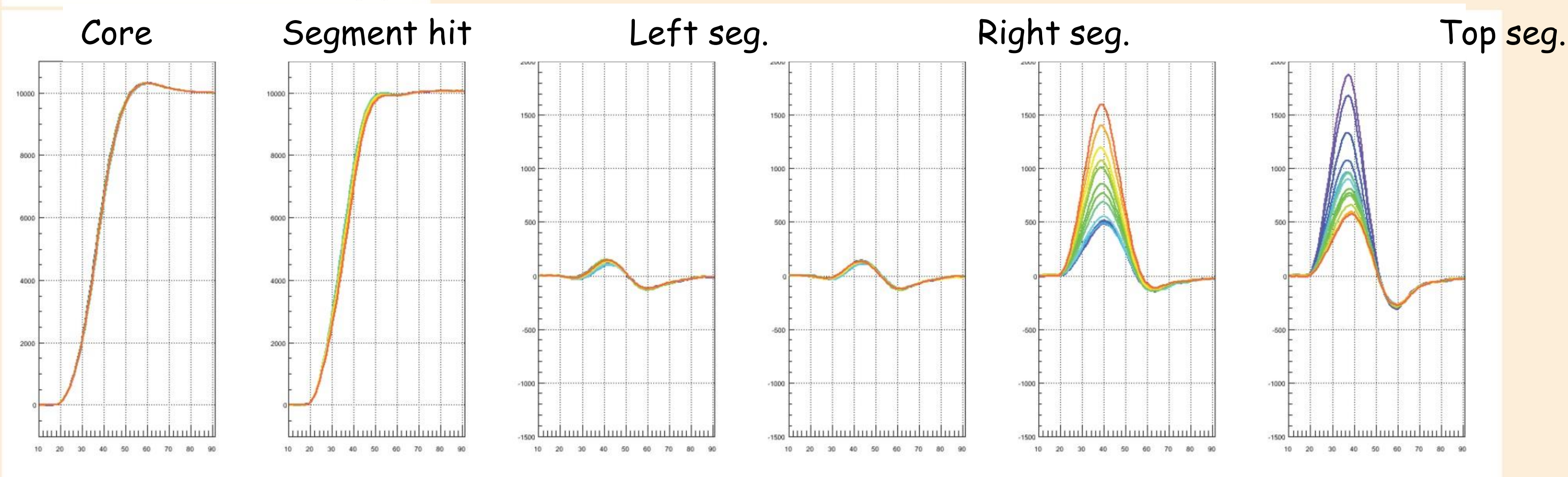
(0 ; -23 ; 56)



3D partial PSCS



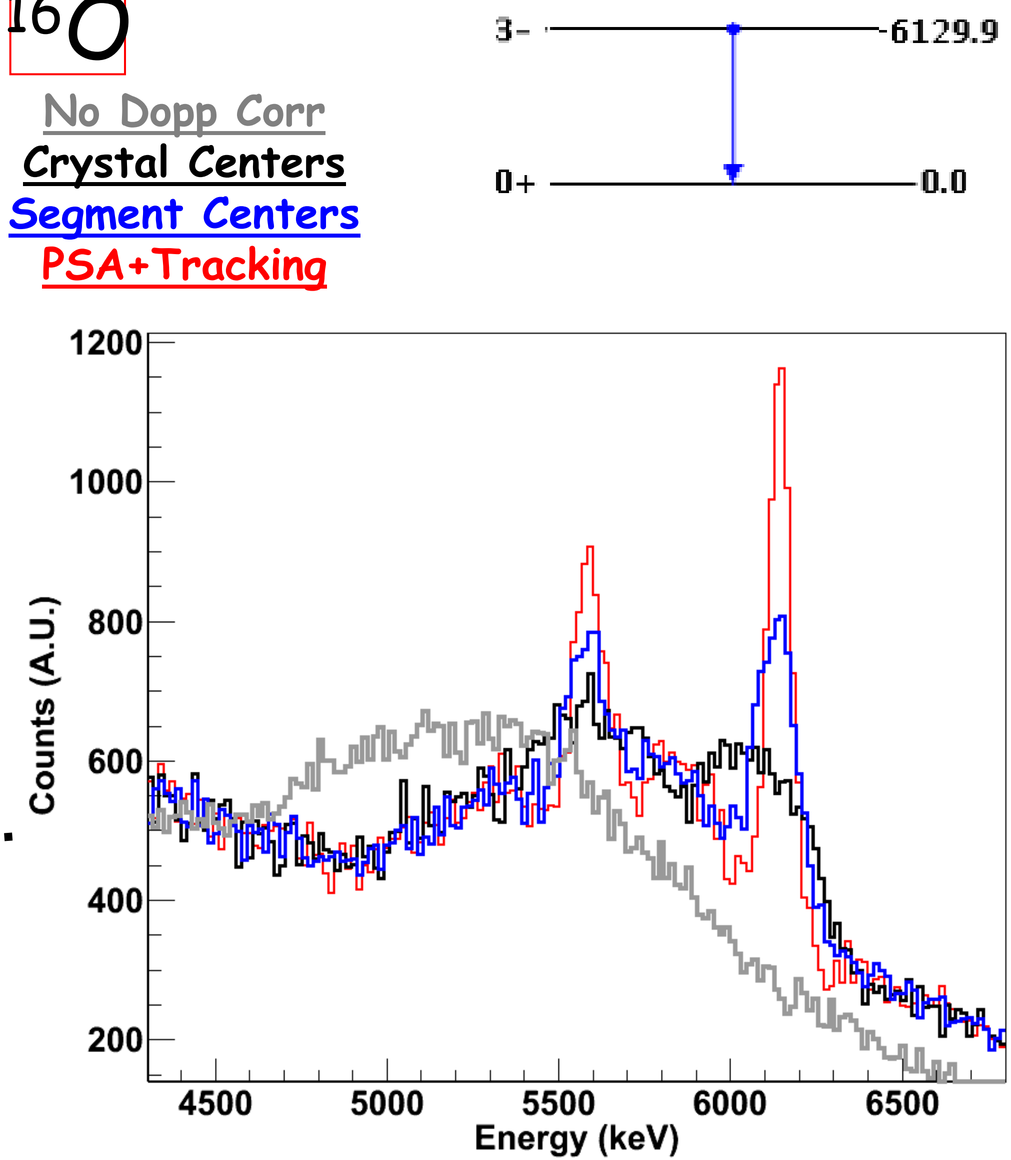




Multi-detector AGATA

^{16}O

No Dopp Corr
Crystal Centers
Segment Centers
PSA+Tracking



G. Duchêne

Lecture plan

1. Introduction
2. Radiation-matter interactions and detectors for charged particle and γ rays
3. **Nuclear reactions**
4. Nuclear structure and observables
5. Perspectives

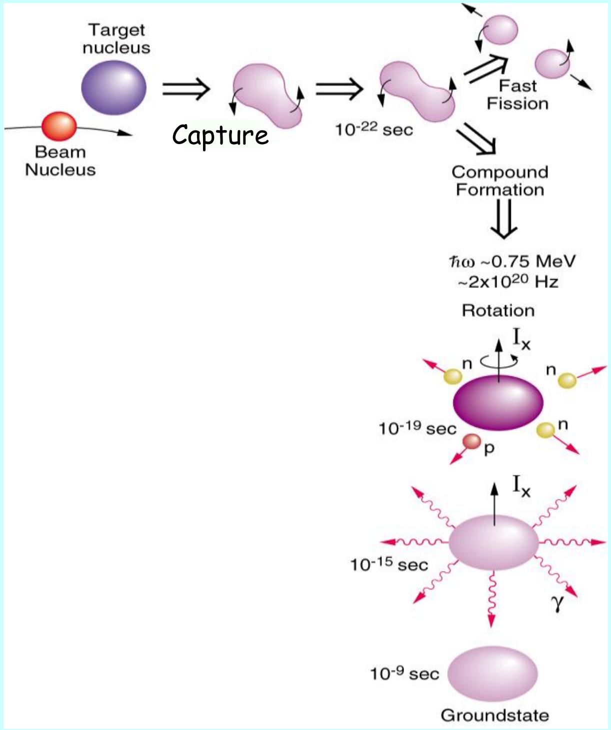
G. Duchêne

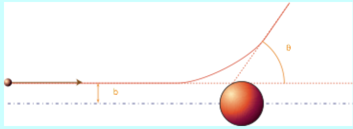
Nuclear reactions

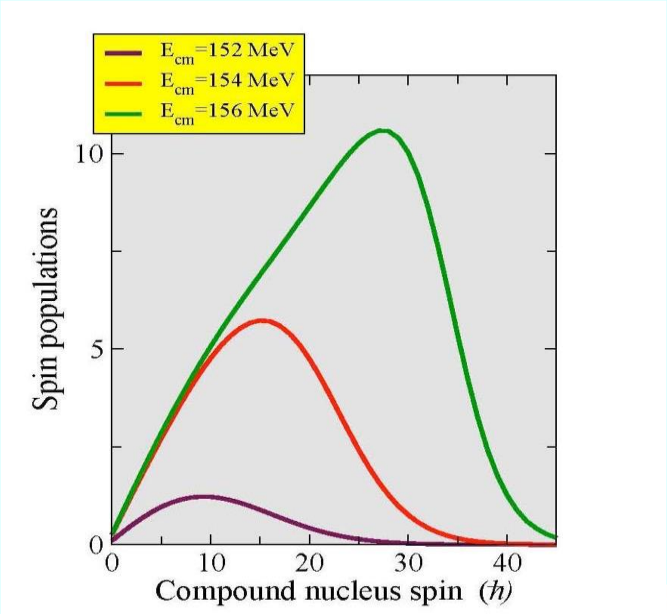
Fusion –evaporation

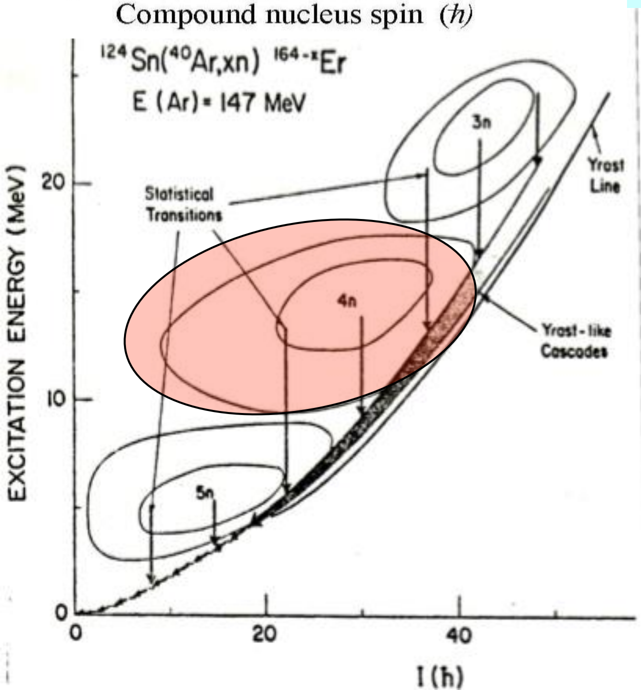
- Central collisions (E_{beam} ~ 6 MeV/u)

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







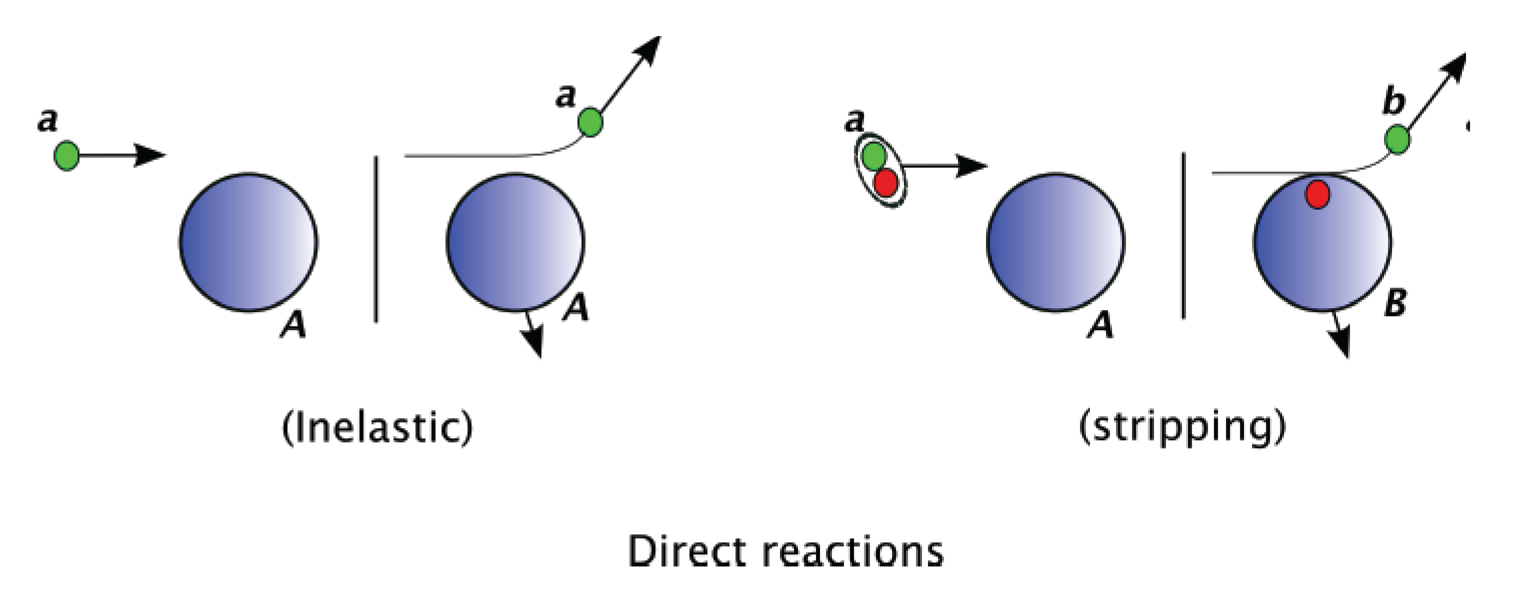


G. Duchêne

Nuclear reactions

Transfert of nucleon

- Peripheral collisions (direct reactions) with 10 – 25 MeV/u beam energy
- Energy exchange, internal excitation -> inelastic channel
- Energy exchange, internal excitation and transfer of few nucleons -> 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

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 (~20-30 $\hbar$)
- Inverse kinematics
  - Fast recoiling fission fragments
  - Forward focused fragments better entering in the magnet
- Systematic study of exotic-nuclei structure

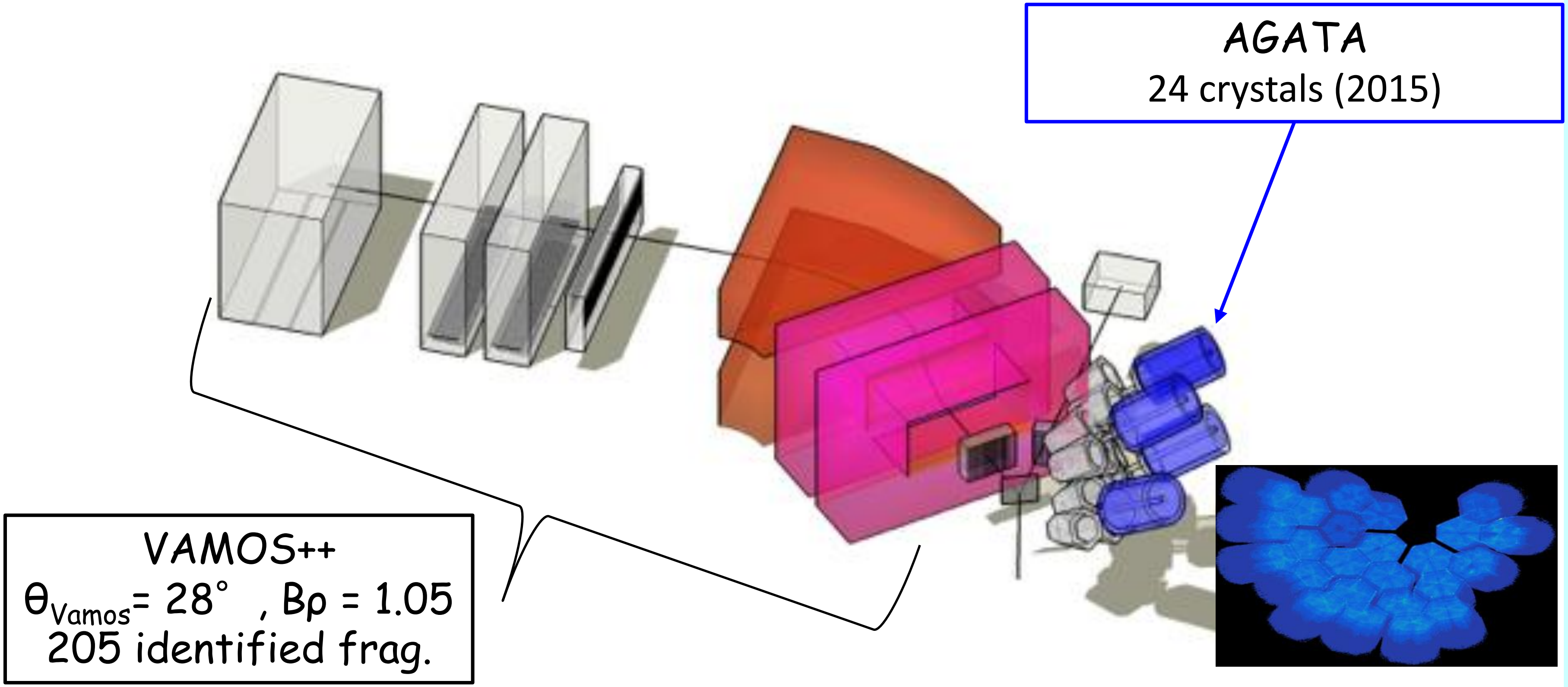
G. Duchêne

Case of an experiment @ GANIL

AGATA-VAMOS++ (exp at GANIL)

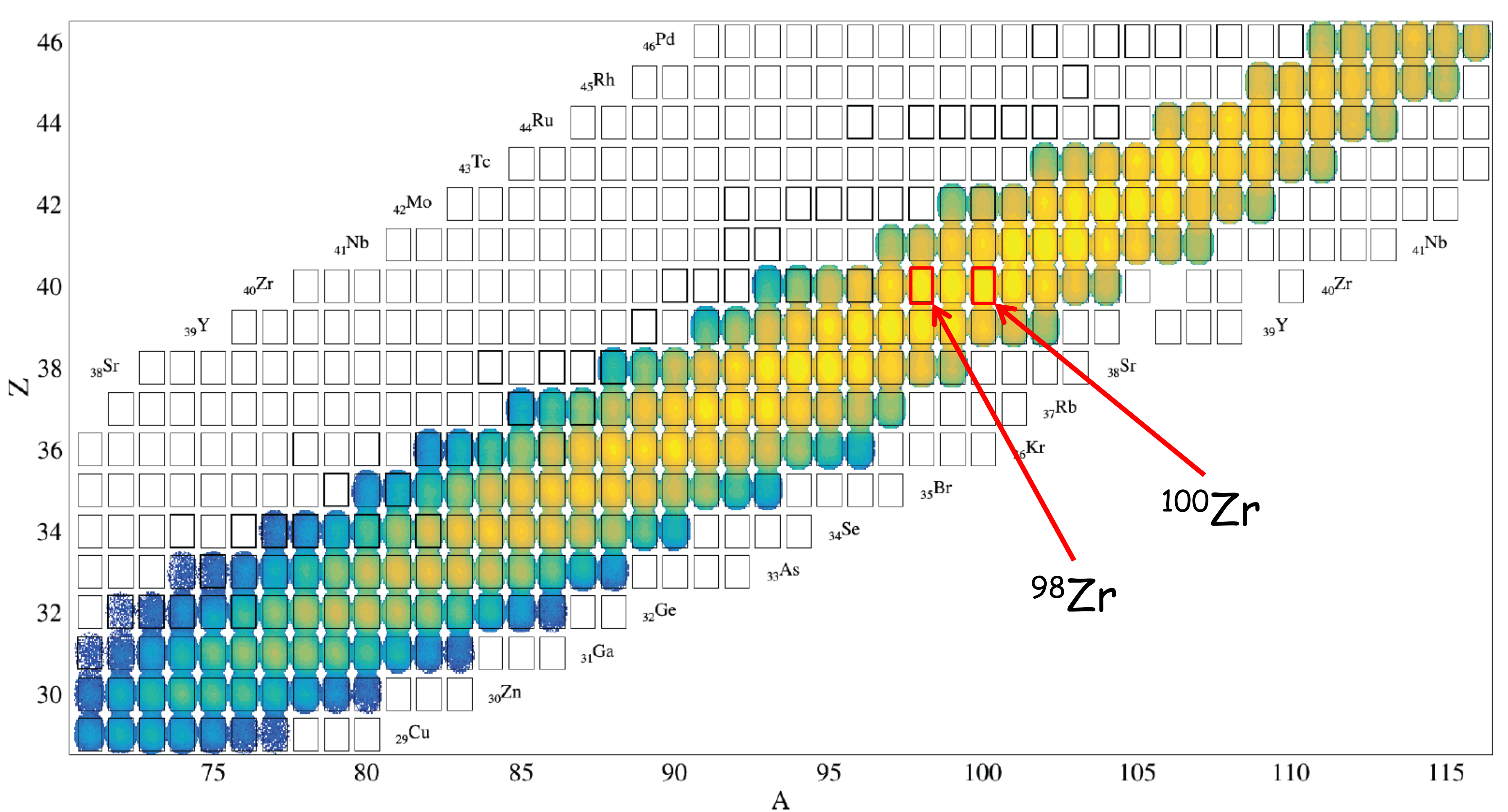
- Ge detector coupled to a spectrometer

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

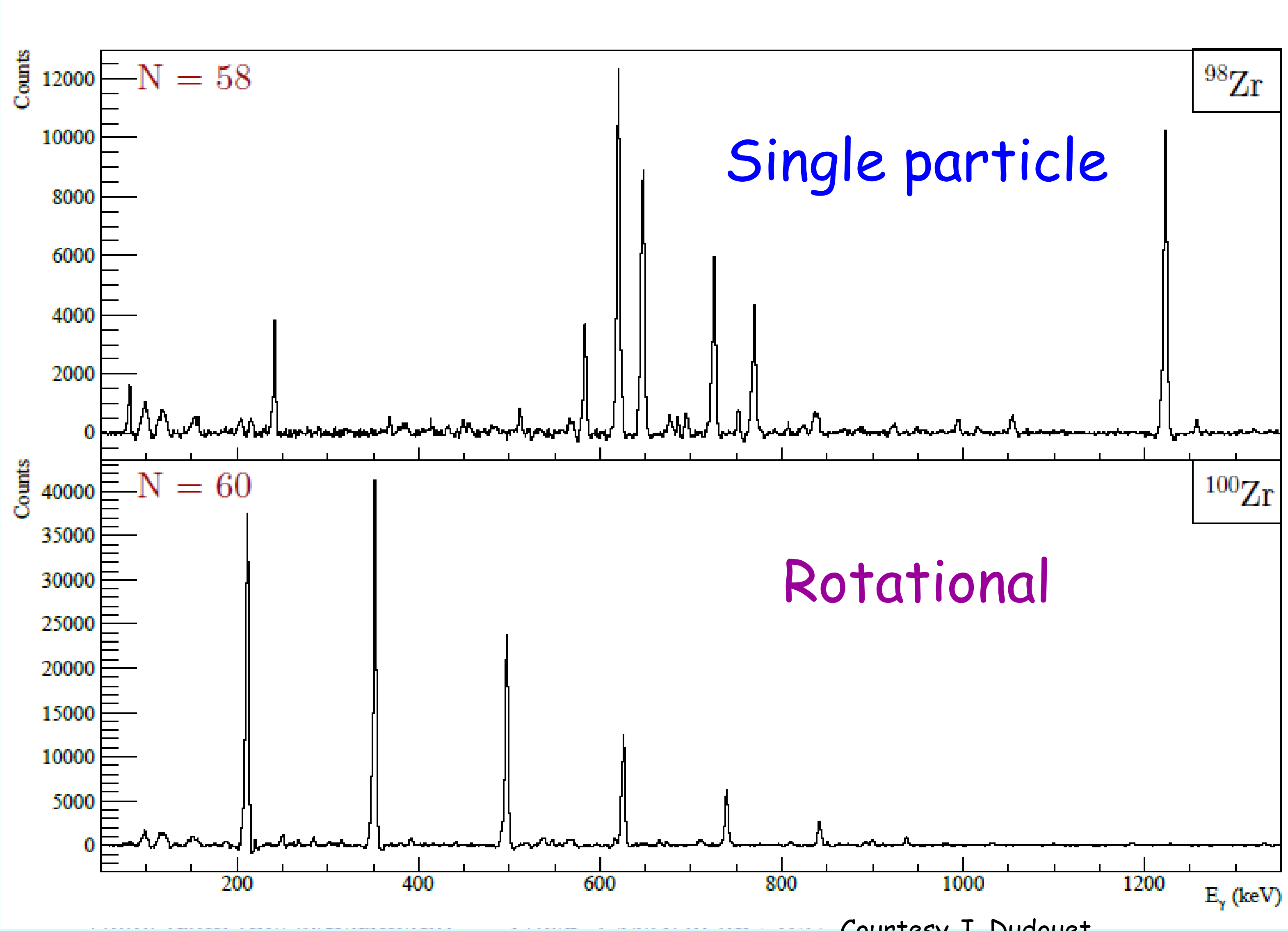


G. Duchêne

Case of an experiment @ GANIL



Selected nucleus in VAMOS - Prompt gamma-rays in AGATA



Courtesy J. Dudouet

G. Duchêne

Lecture plan

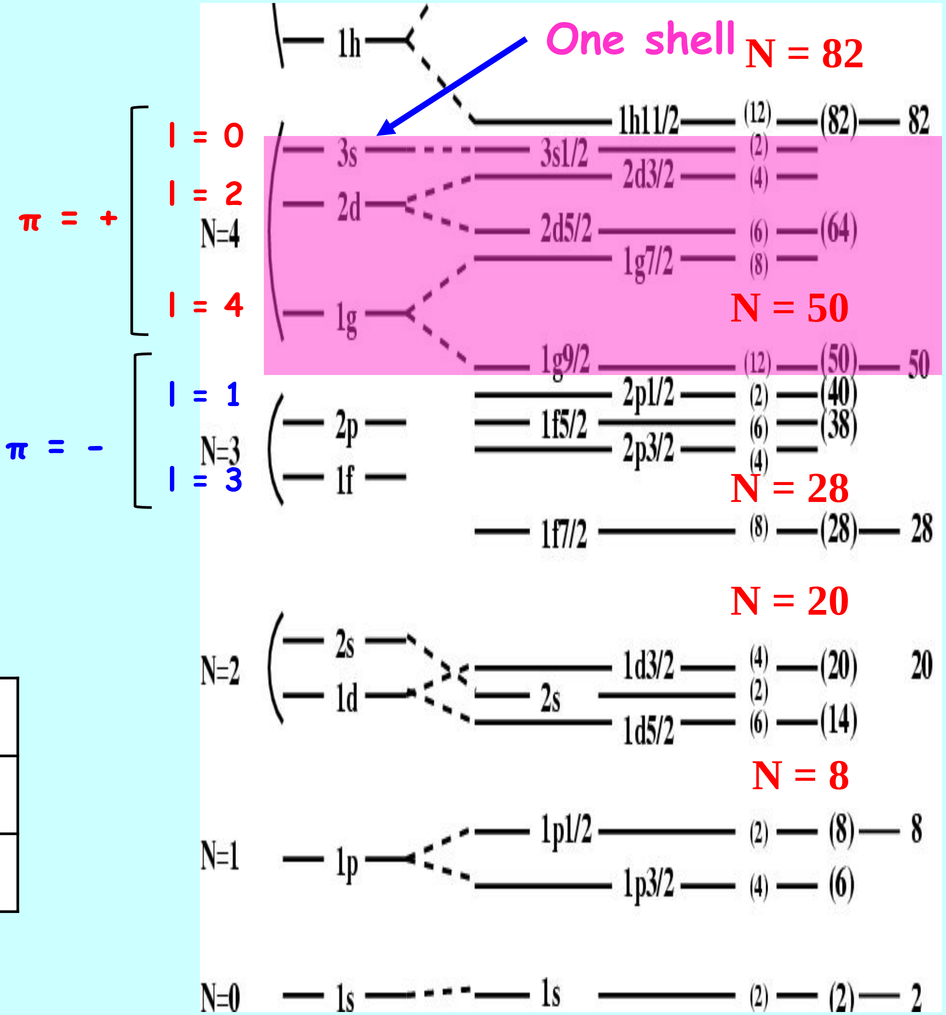
1. Introduction
2. Radiation-matter interactions and detectors for charged particle and γ rays
3. Nuclear reactions
4. **Nuclear structure and observables**
5. Perspectives

G. Duchêne

Basic rules

Spin coupling

- $\vec{J} = \vec{I1} + \vec{I2}$ $|I1-I2| \leq J \leq I1+I2$
- Nucleons are fermion: s=1/2
- On orbitals with momentum l
- Nucleon spin $\vec{j} = \vec{l} + \vec{s}$ $j = l+\frac{1}{2}$ or $l-\frac{1}{2}$

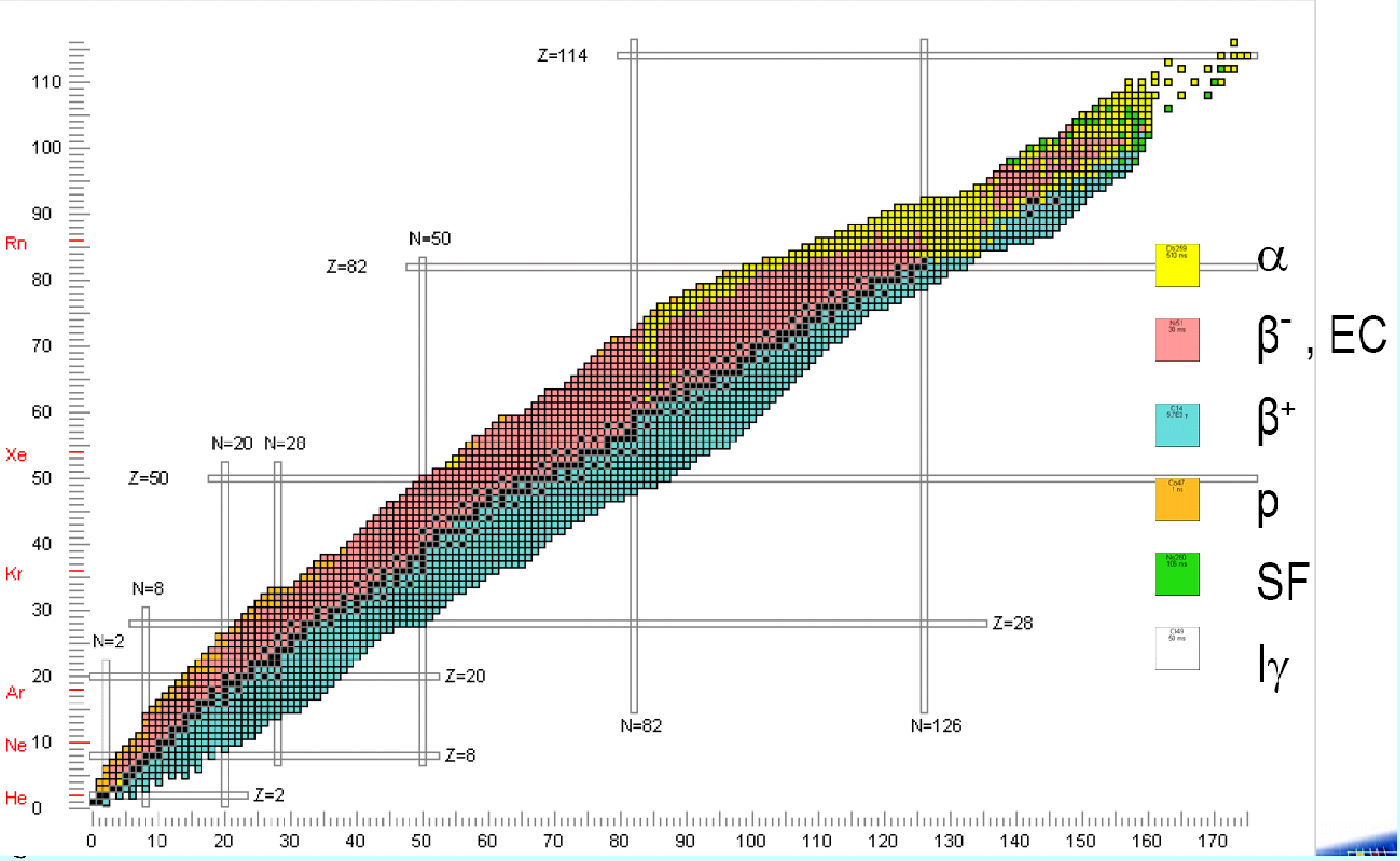


Orbital parity: $\pi = (-1)^l$

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

G. Duchêne

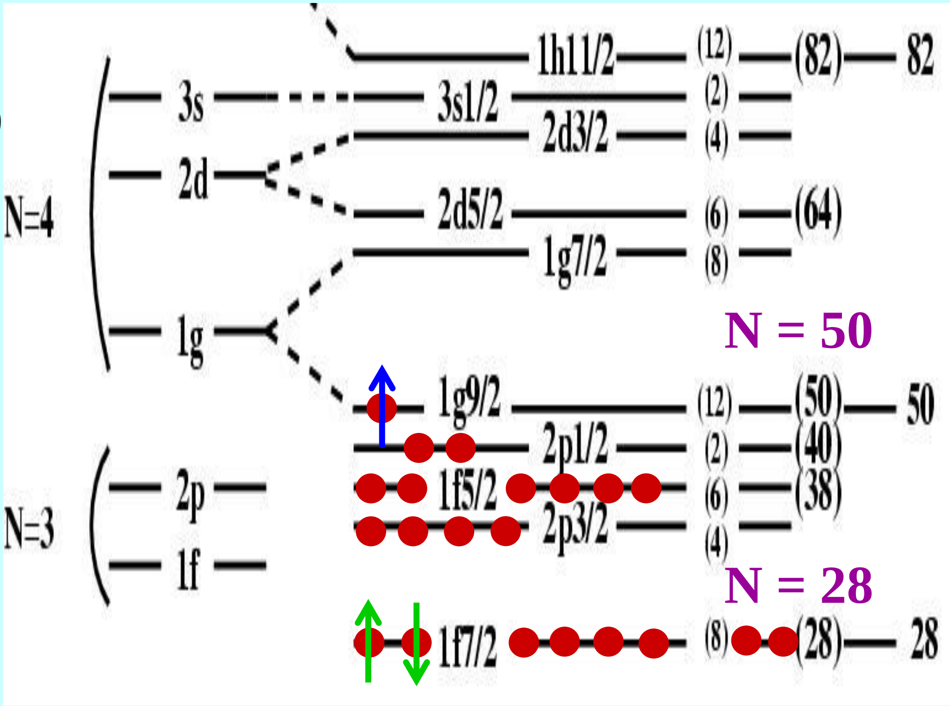
Magic numbers



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
  $J = \Sigma_i \, j_I$ with $-J \leq m \leq j$
- Parity of the nucleus
  $\pi_{nucleus} = \Pi_i \, \pi_i$
- 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: $J = j_{single\ nucleon}$



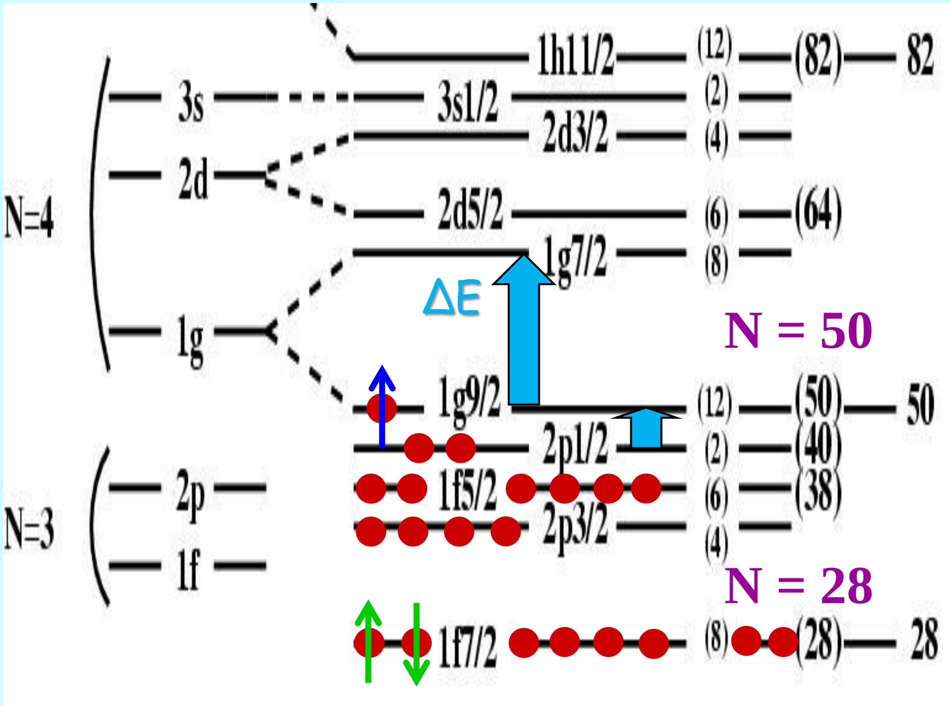
Protons (π) or neutrons (ν)

G. Duchêne

Basic rules

Nucleus

- Nucleon excitations within a shell need moderate energy
- Nucleon excitations across a shell gap need large energy
- Nucleus level scheme
  $\Delta E = E_{gap} + E_{pairing} + E_{correlations}$



First excited state

J

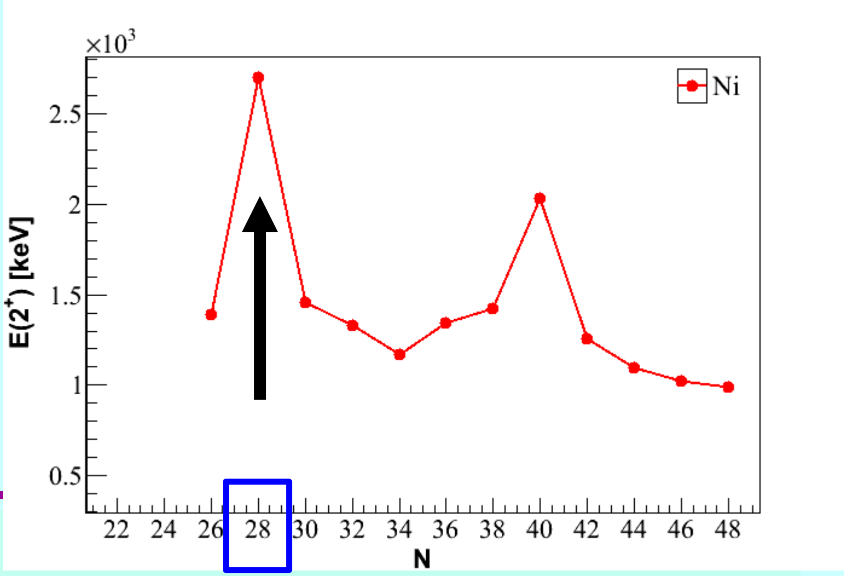
ΔE

E_γ

Ground state

0

Observable: E_γ

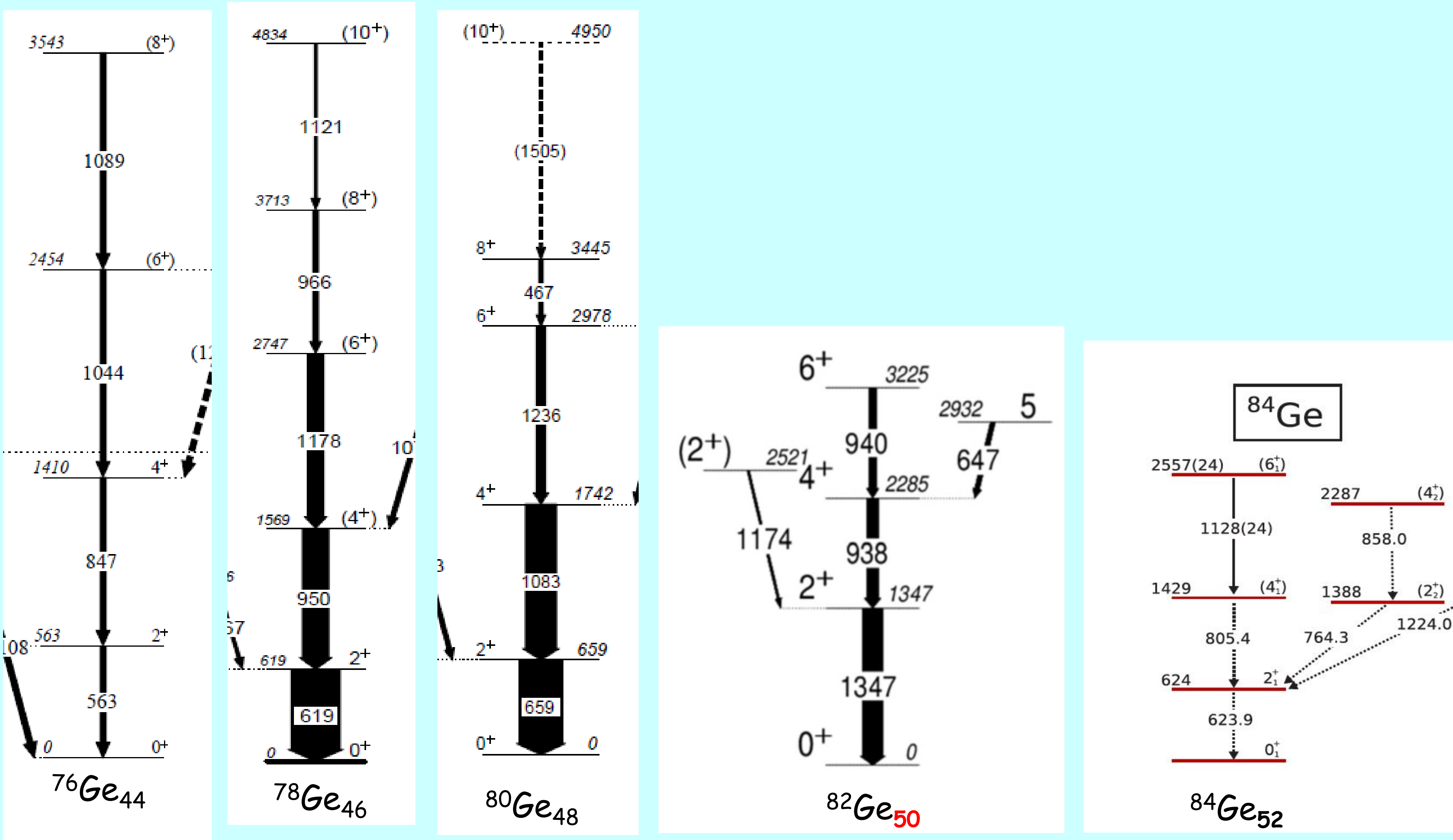


G. Duchêne

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

First 2+ excitation energy E*(2+)

Even Ge isotopes: Z=32

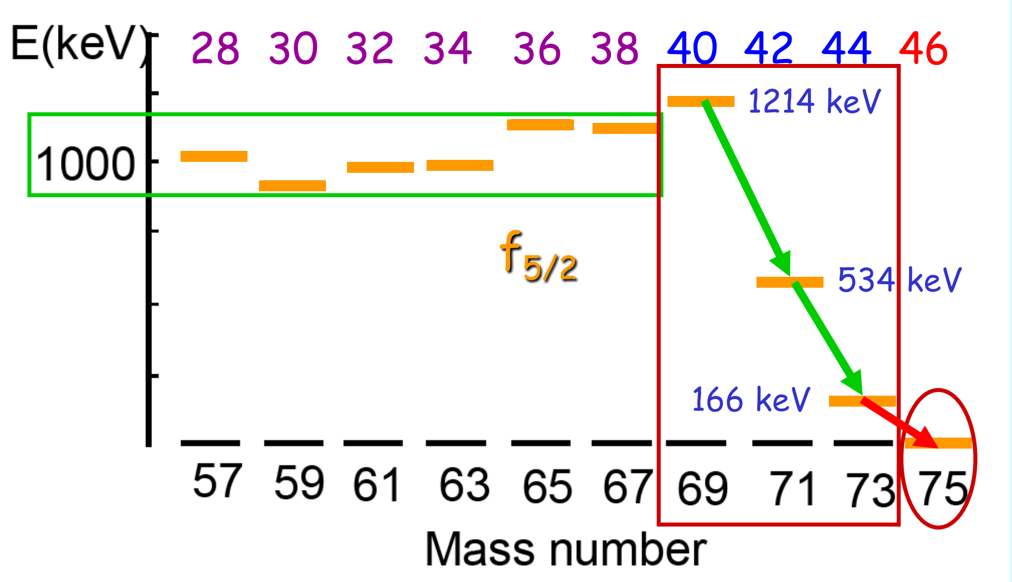


G. Duchêne

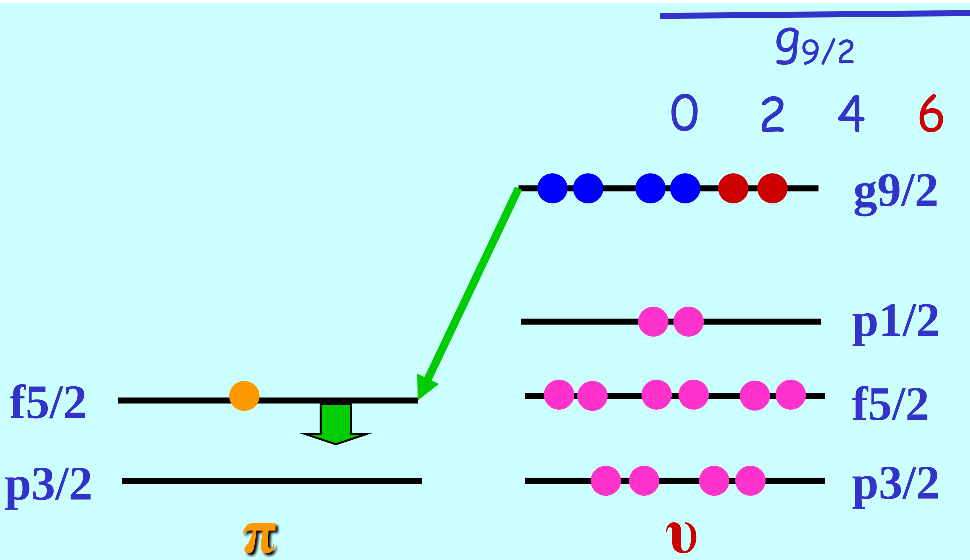
Odd Cu case

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*~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 $f_{5/2}$ – neutron $g_{9/2}$ interaction

G. Duchêne

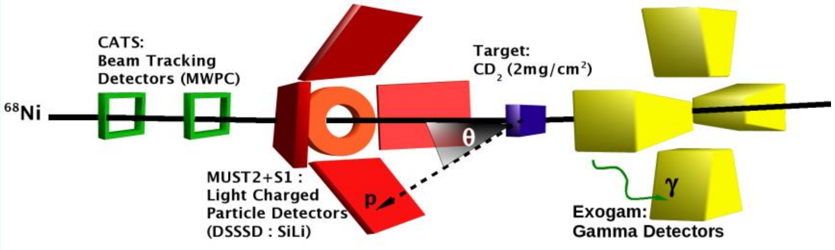
Orbital momentum assignment

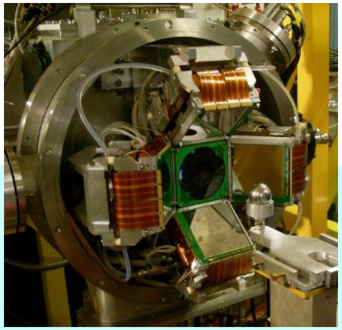
Direct reaction

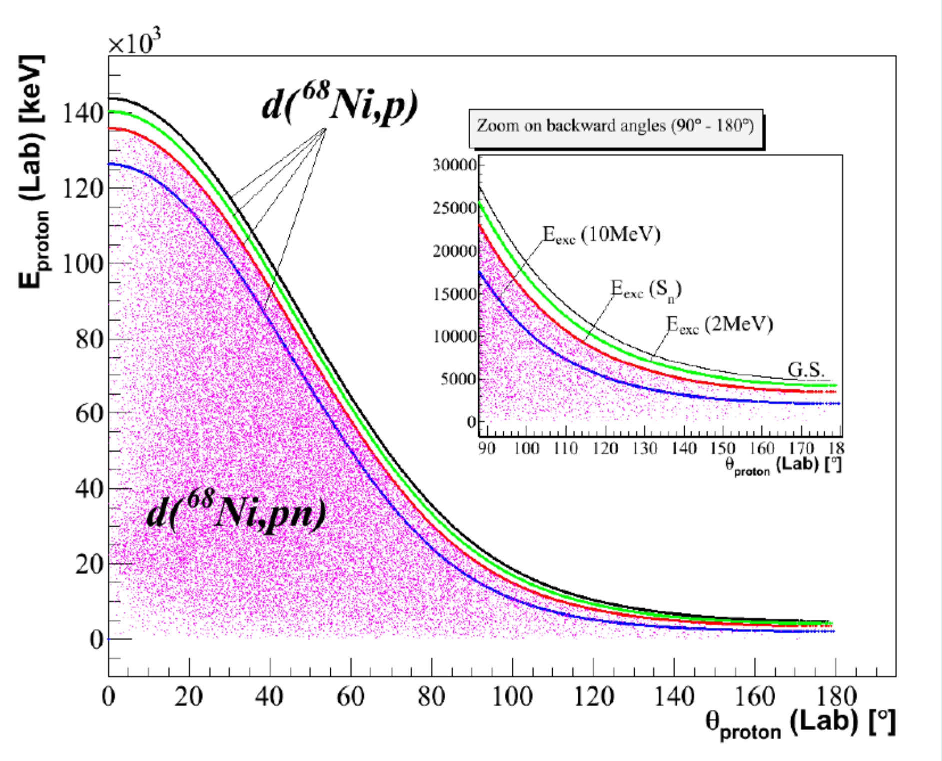
- ^{68}Ni + d -> ^{69}Ni + p
- Orbital populated by the neutron with momentum l
- Proton energy and angular distribution is affected by the neutron destination

Observables

- p energy -> excitation energy of the level populated
- p angular distribution -> l



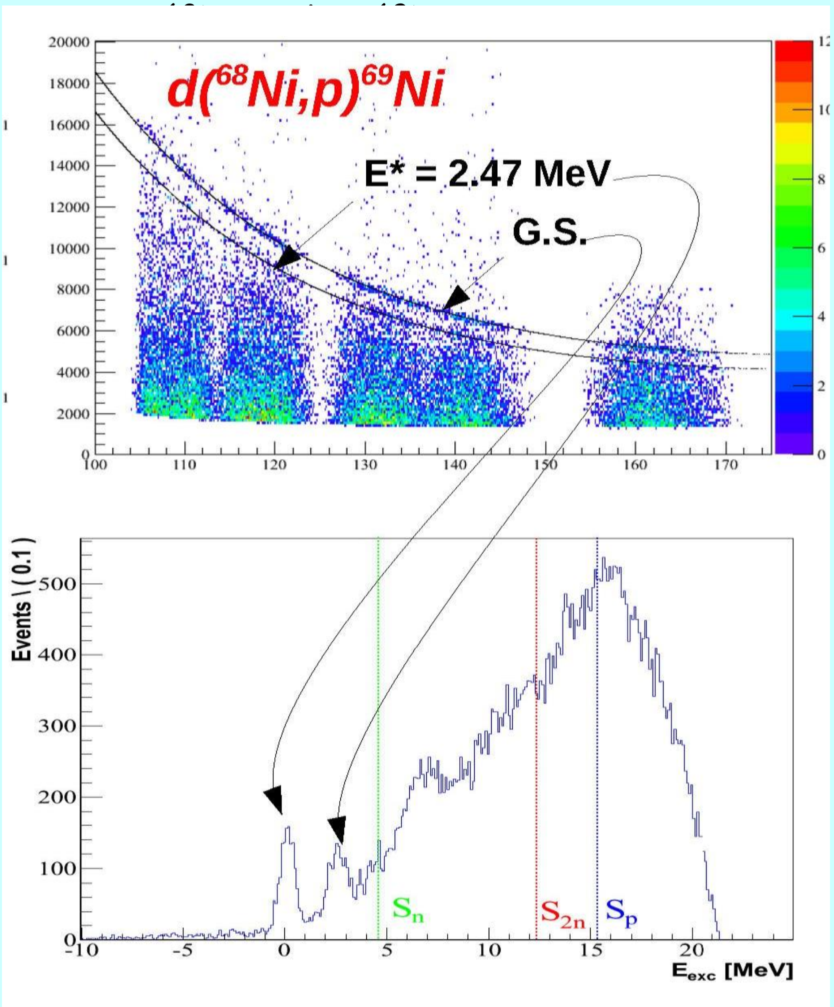


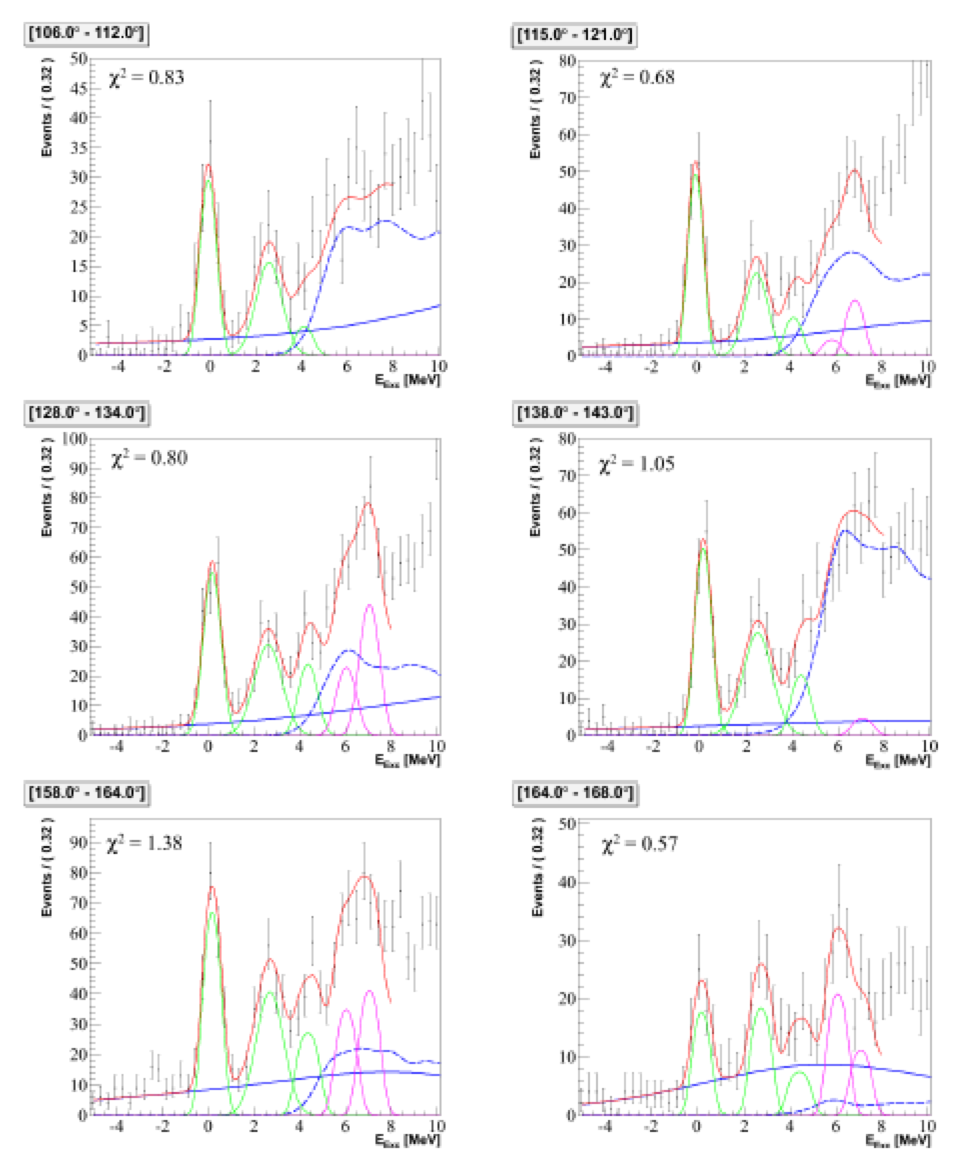


G. Duchêne

Orbital momentum assignment

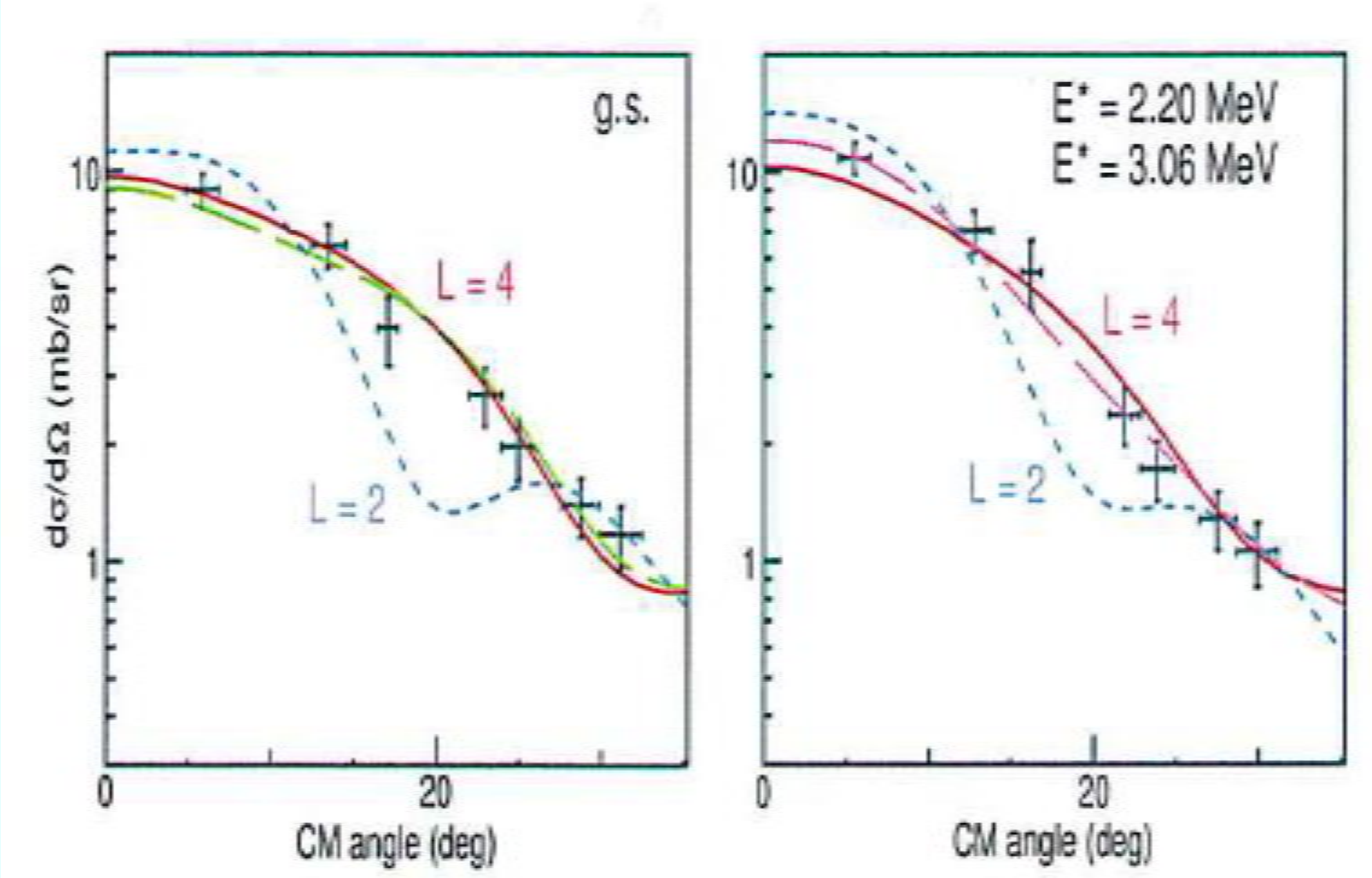
Direct reaction





G. Duchêne

Orbital momentum assignment



Direct reaction

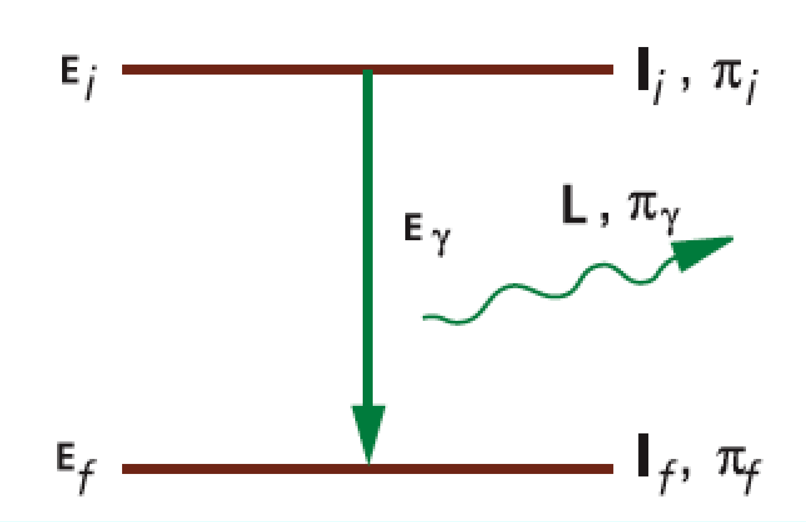
- With polarised d -> j = l ± ½

G. Duchêne

Spin - parity

γ-ray transition

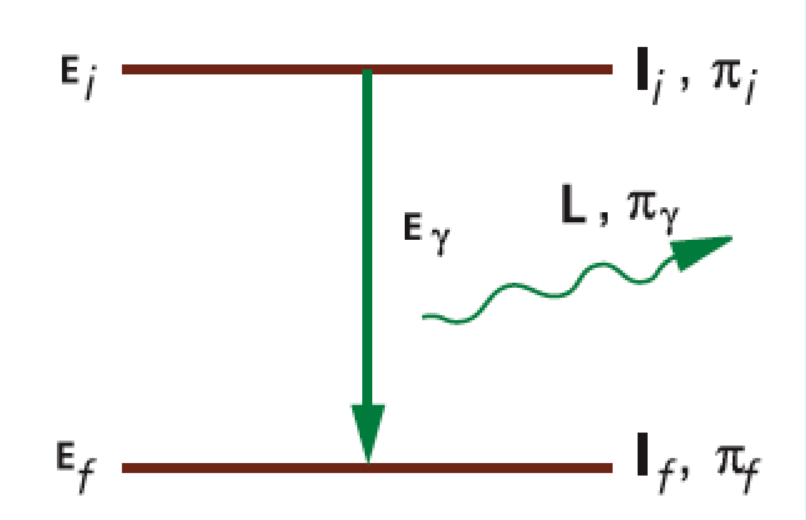
- Energy conservation: $E_f = E_i - E_\gamma$
  i = initial; f = final
- Parity conservation: $\pi_\gamma = \pi_i . \pi_f$
  - $\pi_\gamma = (-1)^l$ for an electric transition E
  - $\pi_\gamma = (-1)^{l+1}$ for a magnetic transition M
- Spin: $|I_i - I_f| \leq l \leq I_i + I_f$



Transition	Désignation	Lγ	πγ
Dipolaire électrique	E1	1	-1
Dipolaire magnétique	M1	1	+1
Quadripolaire électrique	E2	2	+1
Quadripolaire magnétique	M2	2	-1
Octupolaire électrique	E3	3	-1

Spin - parity

γ-ray transition



Examples:

-> 2^+ -> 0^+ transition:

$2-0 \leq l \leq 2+0$; $l=2$; $\pi_\gamma = +1$

electric transition E2

-> 4^+ -> 2^+ transition:

$4-2 \leq l \leq 4+2$; l= 2, 3, 4, 5, 6

E2,M3,E4,M5,E6

π_γ = (+1).(+1) = +1

E2 favored vs M3

electric transition E2

-> 4^+ -> 2^- transition:

$2 \leq l \leq 6$; l= 2, 3, 4, 5, 6

M2,E3,M4,E5,M6

π_γ = (+1).(-1) = -1

M2 unfavored vs E3

E3 or mixed M2+E3 transition

-> 3^+ -> 2^+ transition:

$1 \leq l \leq 5$; l= 1, 2, 3, 4, 5

M1,E2,M3,E4,M5

π_γ = (+1).(+1) = +1

M1 unfavored vs E2

2mixed M1+E2 transition

G. Duchêne

Transition probabilities

Charge distribution of the nucleus

- Electric or magnetic dipole described in l order $r^{\lambda} . Y_{\lambda\mu}(\theta,\varphi)$
- Lowest orders are most likely

- Reduced matrix element for a transition from J_i to J_f with projections m_i and m_f

$$B(\sigma,\lambda;J_i \to J_f) = \sum_{m_f \, \mu} \left| \langle \alpha_f; J_f m_f | \mathrm{M}(\sigma,\lambda\mu) | \alpha_i; J_i m_i \rangle \right|^2$$ with $m_f = m_i + \lambda$

Following Wigner-Eckart

$$B(\sigma,\lambda;J_i \to J_f) = \frac{1}{2J_i+1} \left| \langle \alpha_f \| \mathrm{M}(\sigma,\lambda) \| \alpha_i \rangle \right|^2$$

where the multipolar electric moment writes

$$\mathrm{M}(E\lambda\mu) = \int_{noyau} \rho(r).r^{\lambda} Y_{\lambda\mu}(\hat{r}).dv$$

and the multipolar magnetic moment writes

$$\mathrm{M}(M\lambda\mu) = \frac{-1}{c(\lambda+1)} \int_{noyau} j(r).(r \times \nabla) r^{\lambda} Y_{\lambda\mu}(\hat{r}).dv$$

G. Duchêne

Transition probabilities

Amplitude of transition probability

$$\Gamma_{if}\left(\{EL\,ou\,ML\};J_i \rightarrow J_f\right) = \frac{2(L+1)}{L\left[(2L+1)!!\right]^2}\frac{1}{\hbar}\left(\frac{\hbar\omega}{\hbar c}\right)^{2L+1} B\left(\{EL\,ou\,ML\};J_i \rightarrow J_f\right)$$

where $\hbar = 6.58211899(16)\ 10^{-19} keV.s$ $\quad B(EL)$ en unité de $e^2 fm^{2L}$

$\hbar c = 197{,}3269631(49)\ 10^3 keV.fm$ $\quad B(ML)$ en unité de $\left(e\hbar/2Mc\right)^2 fm^{2L-2}$

$$\Gamma_w(E1) = 1.59\times10^{15}.E^3.B(E1) \qquad \Gamma_w(M1) = 1.76\times10^{13}.E^3.B(M1)$$
$$\Gamma_w(E2) = 1.22\times10^{9}.E^5.B(E2) \qquad \Gamma_w(M2) = 1.35\times10^{7}.E^5.B(M2)$$
$$\Gamma_w(E3) = 5.67\times10^{2}.E^7.B(E3) \qquad \Gamma_w(M3) = 6.28\times10^{0}.E^7.B(M3)$$
$$\Gamma_w(E4) = 1.69\times10^{-4}.E^9.B(E4) \qquad \Gamma_w(M4) = 1.87\times10^{-6}.E^9.B(M4)$$

in Weisskopf unit

Transitions of smallest l predominate
Electric transitions predominate on magnetic transitions

G. Duchêne

Transition probability and half life

Half life of a state

$$\Gamma_{if}\left(\{EL\,ou\,ML\};J_i \to J_f\right) = \frac{2(L+1)}{L\left[(2L+1)!!\right]^2}\frac{1}{\hbar}\left(\frac{\hbar\omega}{\hbar c}\right)^{2L+1} B\left(\{EL\,ou\,ML\};J_i \to J_f\right)$$

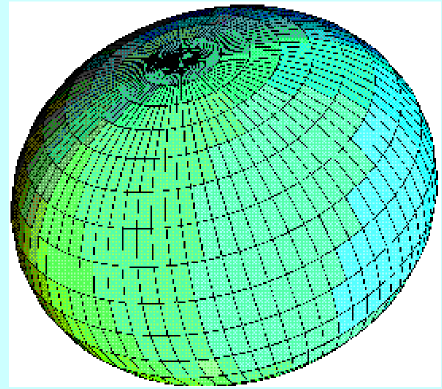
- The transition-probability amplitude Γ_{if} is related to the half life of state "i"
- Heisenberg: $\hbar = \tau_i . \Gamma_i$ with $\Gamma_i = \sum_f \Gamma_{if}(\sigma\lambda)$ including all decay paths
- Half life is deduced $T_{1/2} = \tau . \ln(2) = \frac{\hbar . \ln(2)}{\Gamma}$

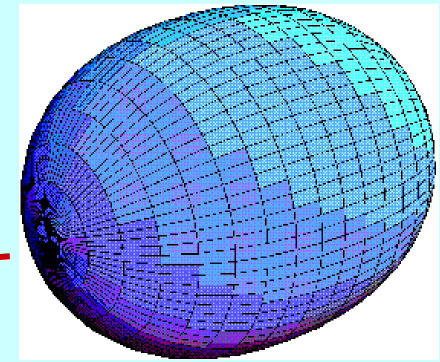
State half life depend on
- initial and final spins
- single-particle configuration of the initial and final states

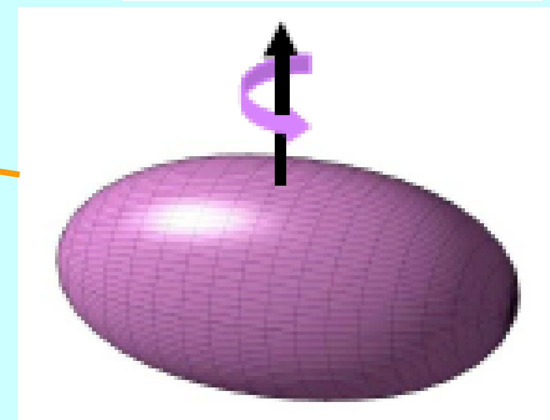
G. Duchêne

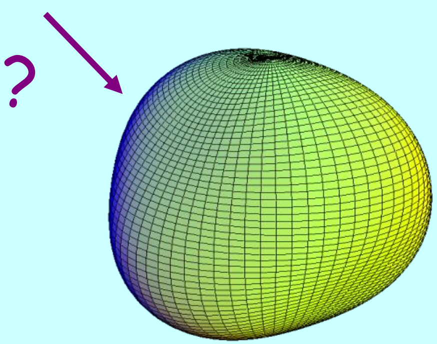
Nuclear shapes

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





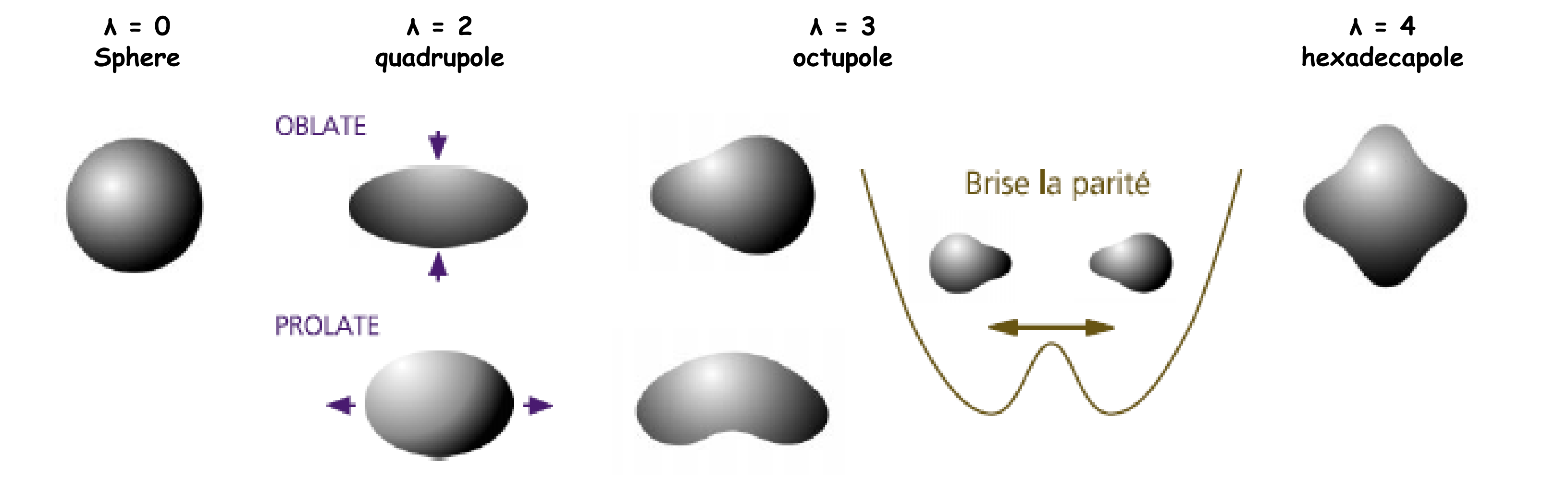




G. Duchêne

Nuclear shape parametrisation

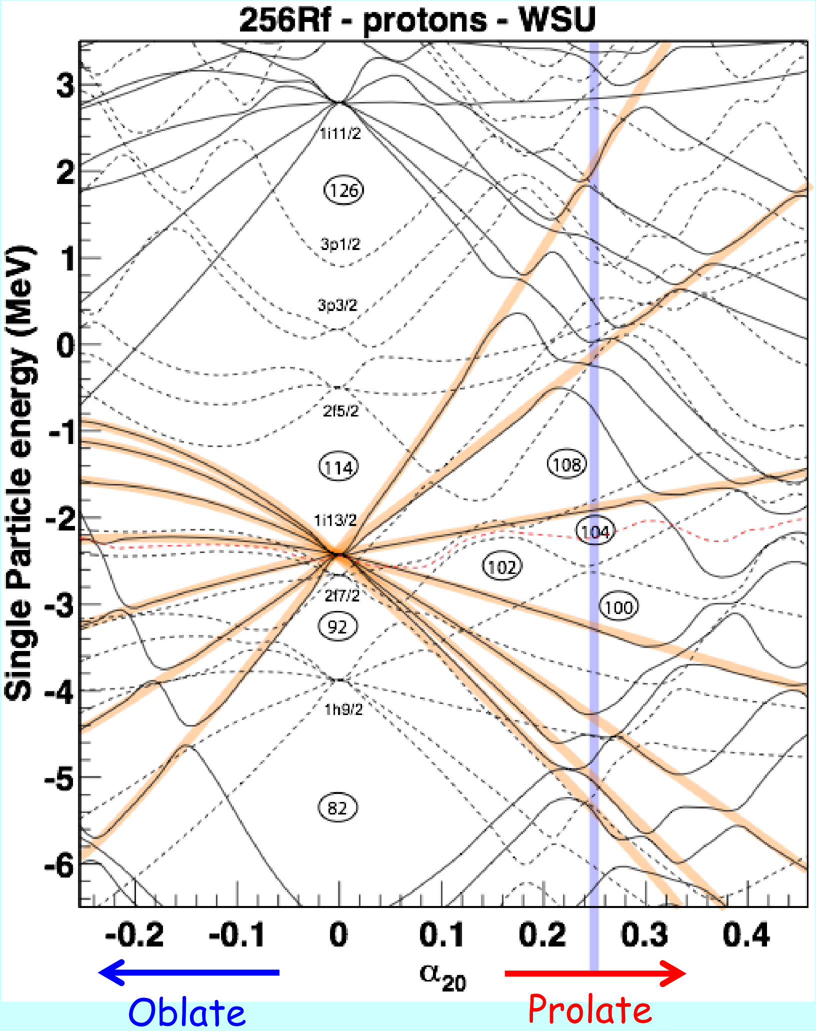
$$R(\theta,\phi) = R_0\left[1 + \sum_{\lambda=2}^{\infty}\sum_{\mu=-\lambda}^{\lambda} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi)\right].$$

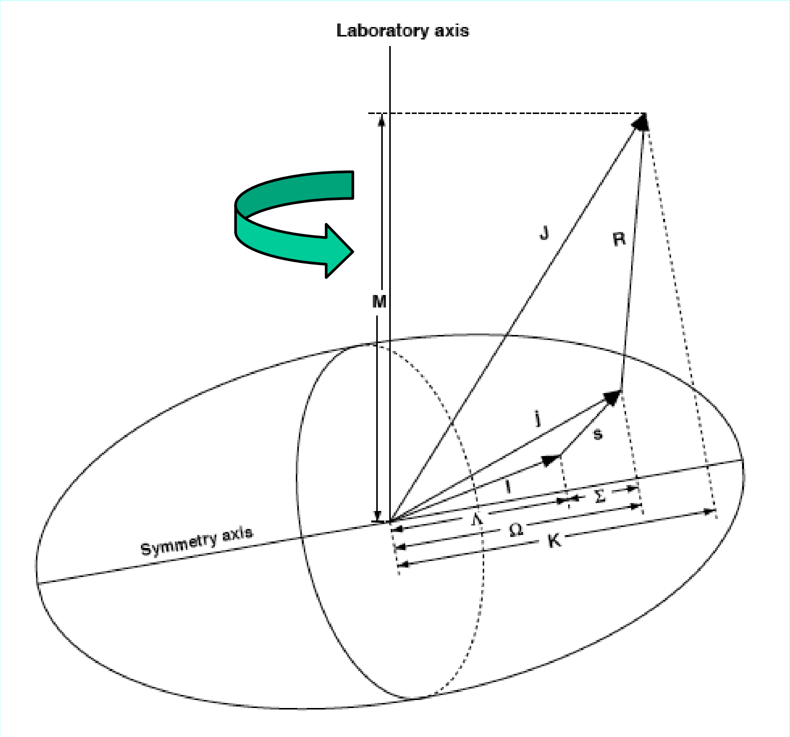


[Currently observed nuclear shapes.]

G. Duchêne

Nuclear shapes





G. Duchêne

Rotational bands

Excitation energy

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

γ-ray transition energy

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

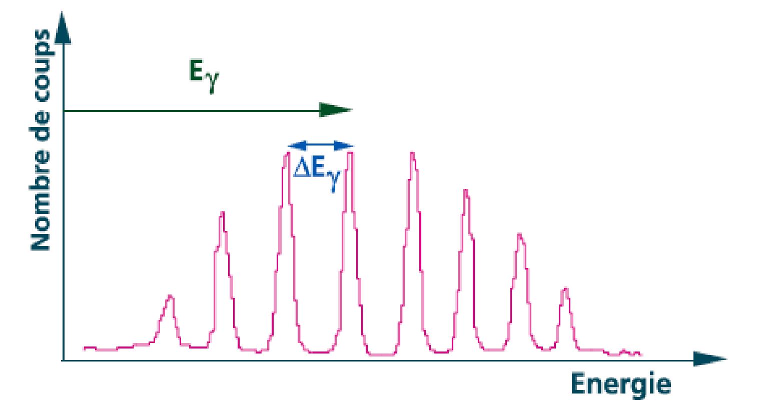
$$E_\gamma(I \to I-2) = \frac{\hbar^2\left[I(I+1)-(I-2)(I-1)\right]}{2\Im} = \frac{\hbar^2[4I-2]}{2\Im}$$

Difference between two consecutive transitions

$$\Delta E_\gamma(I, I-2) = \frac{\hbar^2[4I-2]}{2\Im} - \frac{\hbar^2\left[4(I-2)-2\right]}{2\Im} = \frac{4\hbar^2\left[I-(I-2)\right]}{2\Im} = \frac{4\hbar^2}{\Im}$$

Constant !!

Regular spacing of γ rays



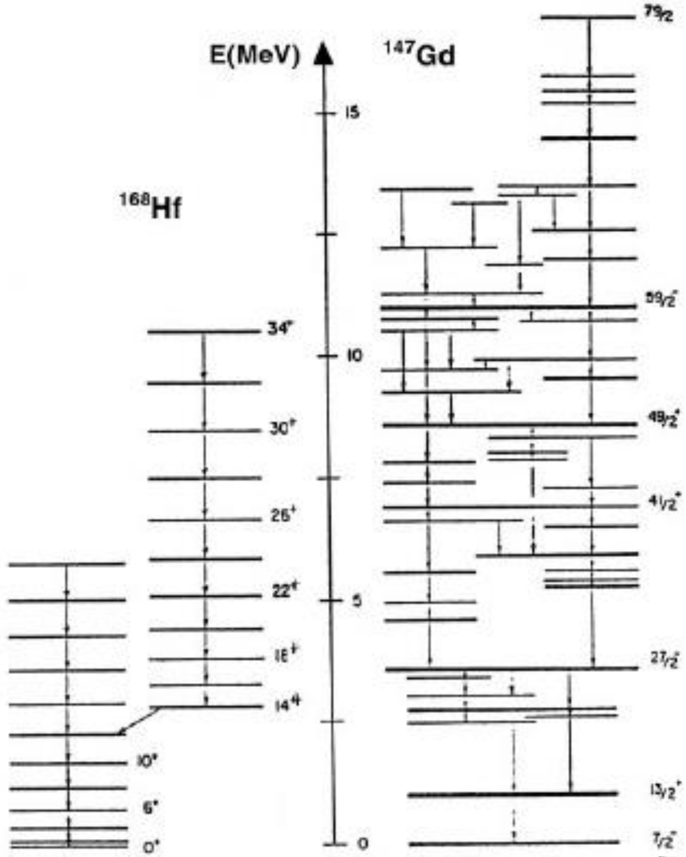
Nuclear shapes

Collective

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

Γ ~ 100 Wu
τ ~ 100 fs

Regular
level scheme

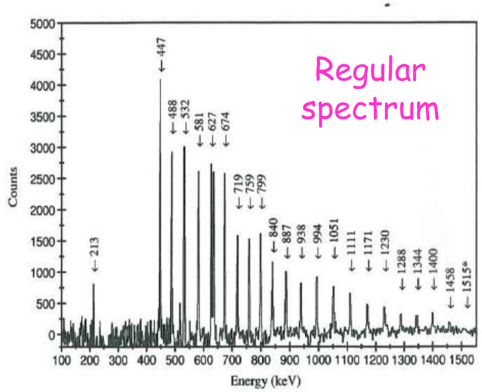


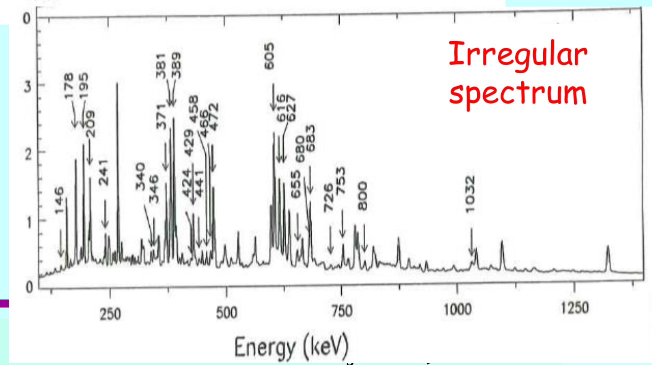
Individual

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

Γ ~ few Wu
τ > 10 ps

Irregular
level scheme

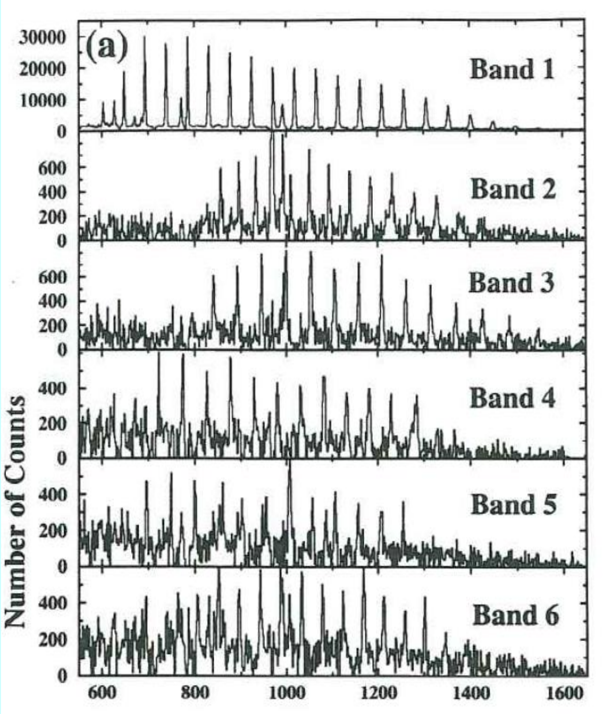


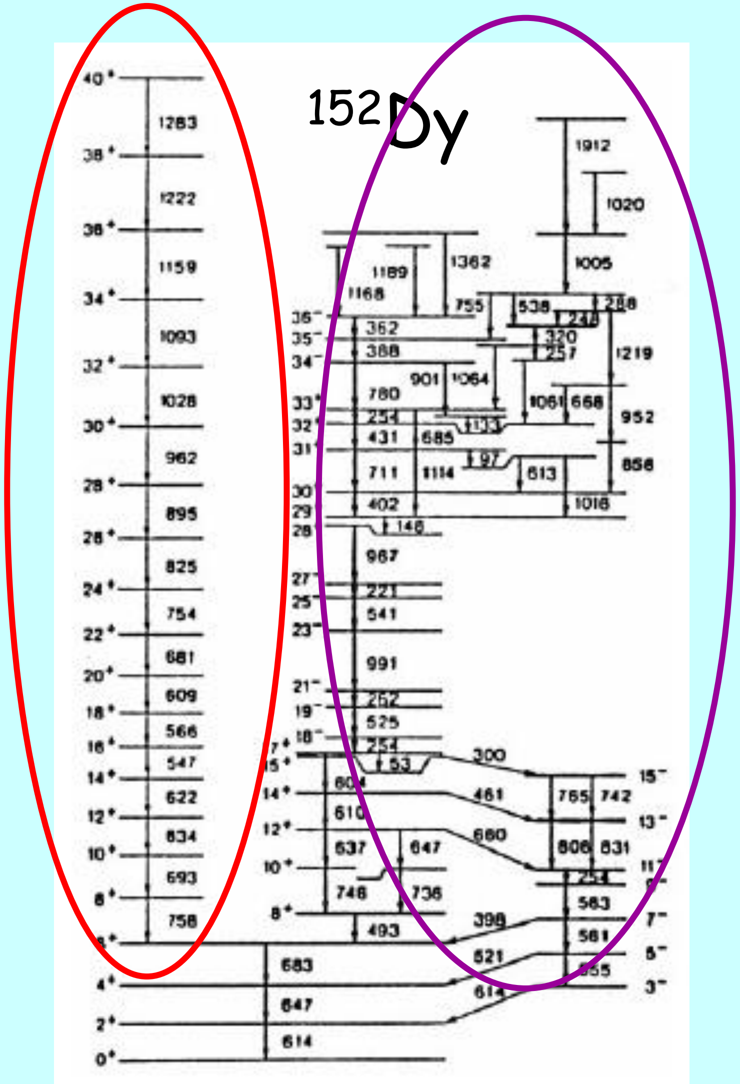


Nuclear shapes

Super deformed prolate shape

- Γ ~ 2000 Wu
- τ ~ 10 fs





- **Shape coexistence** with normal deformed, single particle states

G. Duchêne

Nuclear lifetime measurements

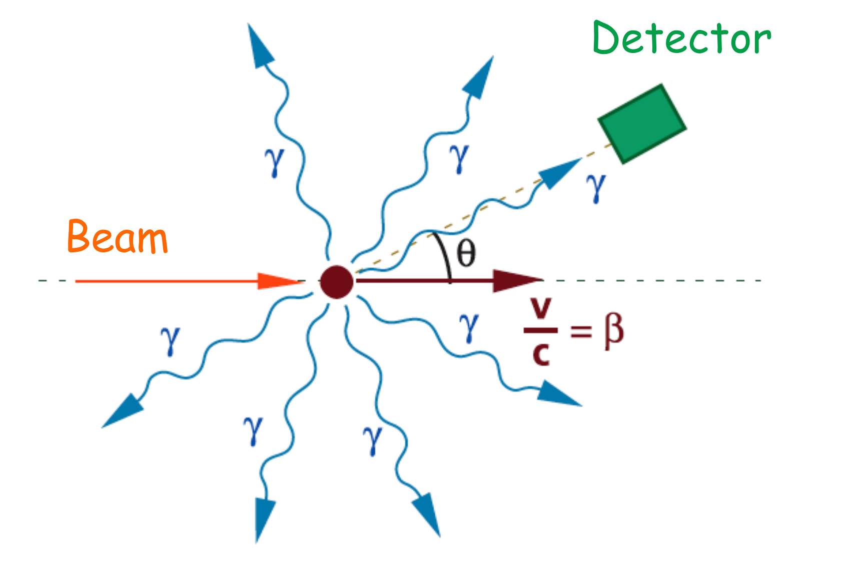
Many techniques

- DSAM (Doppler Shift Attenuation Method) -> below ps
- Plunger -> ps to ns
- Fast scintillators ($LaBr_3$) -> ps to ns
- ToF -> > μs

Doppler effect

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

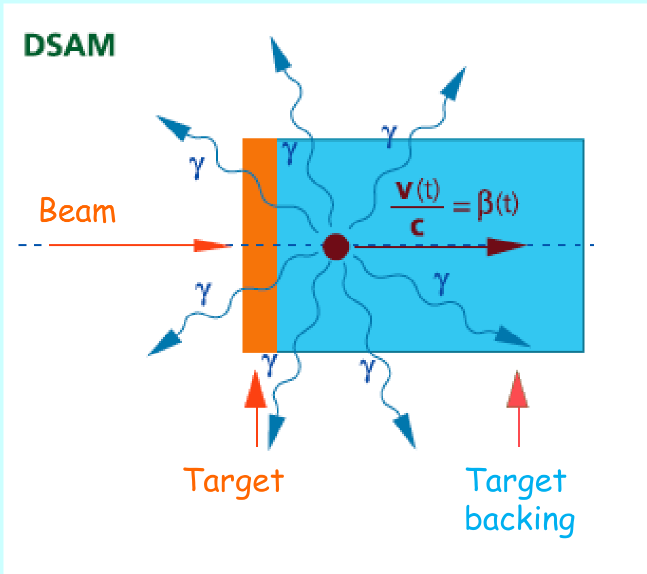
$$\Delta E_\gamma(\theta, E_\gamma) = E_\gamma \frac{v}{c} \cos(\theta).$$



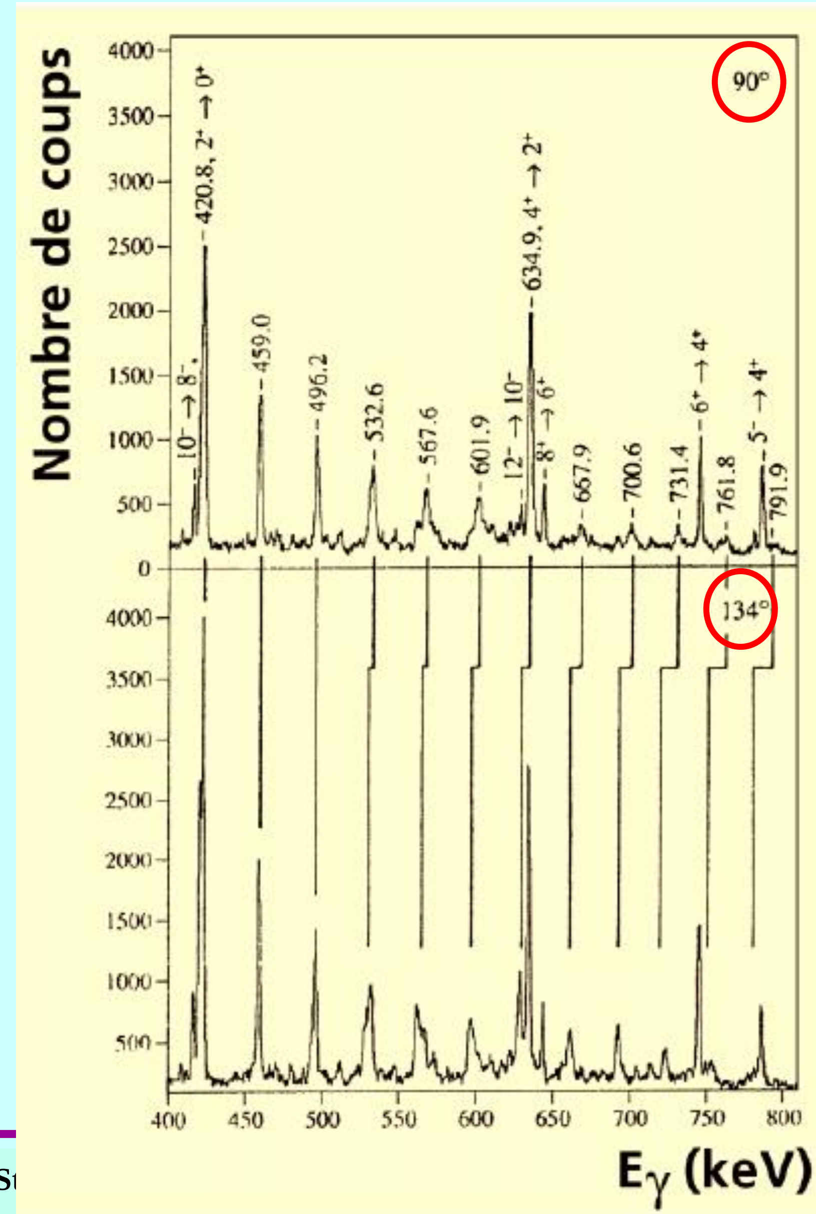
G. Duchêne

Nuclear lifetime measurements

DSAM



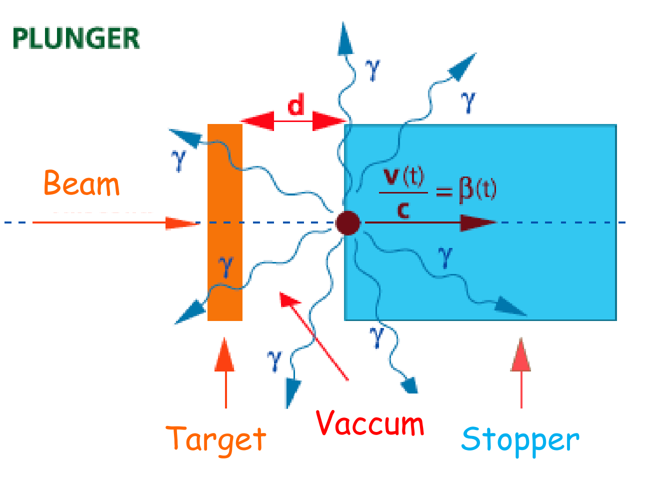
- Nucleus de-excitation during the slowing down in the backing of the target
- Varying velocity -> different Doppler shift
- Depend on the stopping power of the target and backing
- Lifetimes from 10 fs to few 100 fs

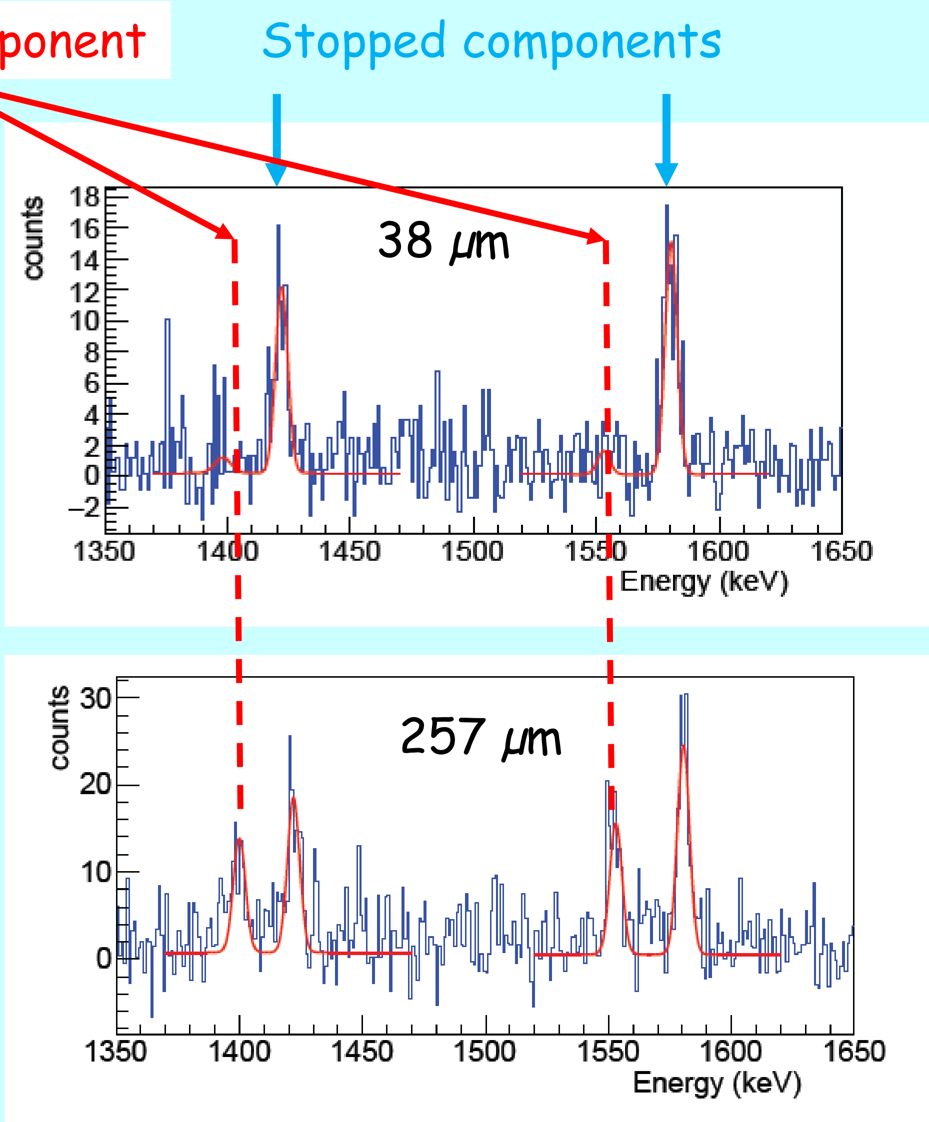


G. Duchêne

Nuclear lifetime measurements

Plunger





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

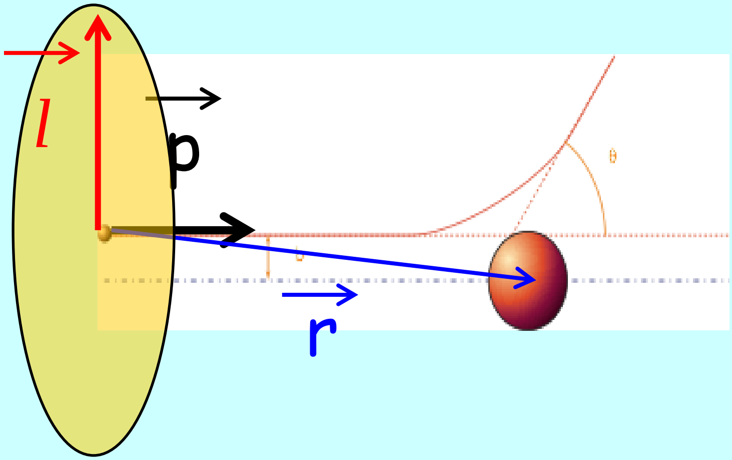
G. Duchêne

Angular distributions

Spin alignment

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

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



Angular distribution

- Distribution of normalised intensity

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

where

- θ = angle between γ ray (detector) and beam axis
- Pi (cos θ) = Legendre polynomials

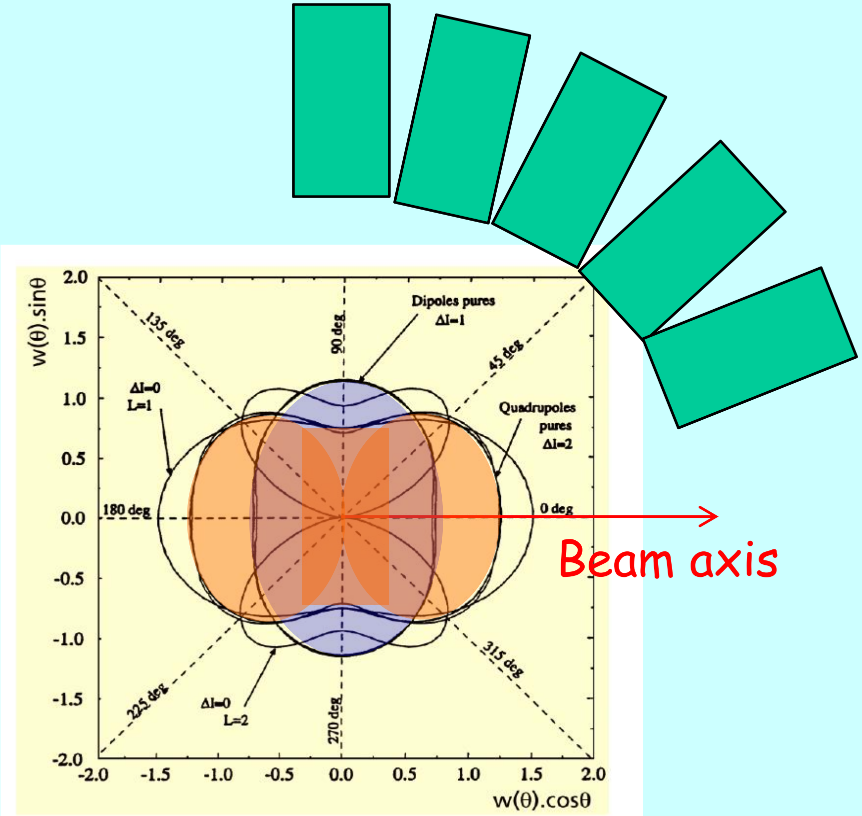
- Pure dipole (l=1): a_2 negative and a_4=0
- Stretched quadripole (l=2): a_2 positive and a_4 < 0 and small

G. Duchêne

Angular distributions

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 ($\Delta I=2$) quadripole transitions
  - max at ~45°
  - Important at 0°
  - Smallest at 90°

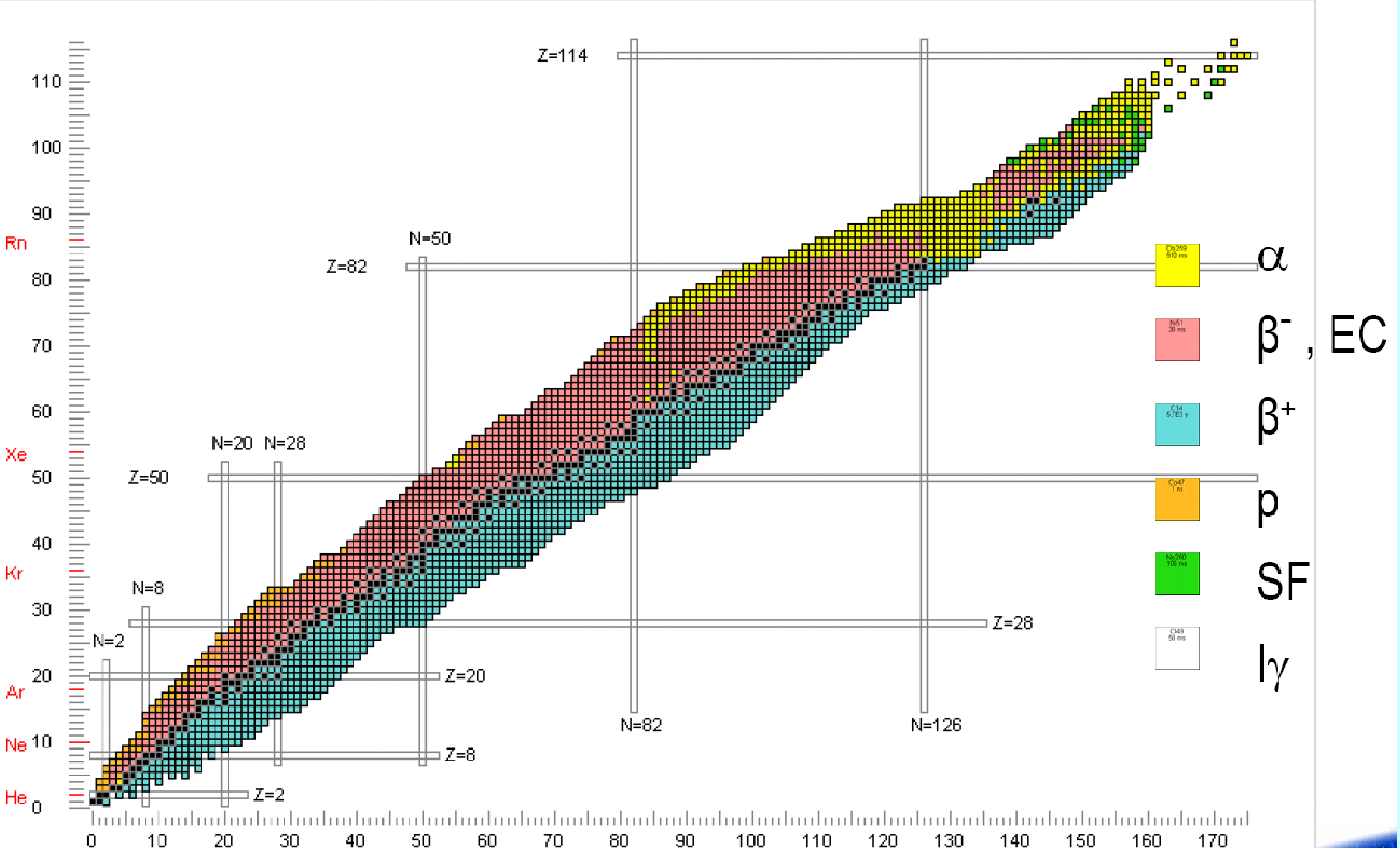


G. Duchêne

Lecture plan

1. Introduction
2. Radiation-matter interactions and detectors for charged particle and γ rays
3. Nuclear reactions
4. Nuclear structure and observables
5. **Perspectives**

Magic numbers



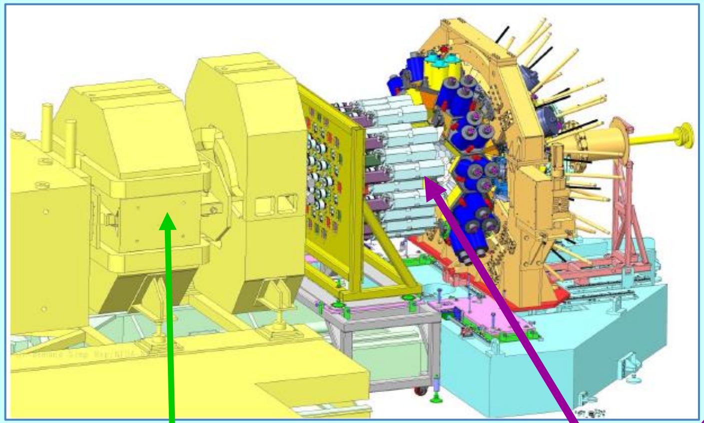
Perspectives

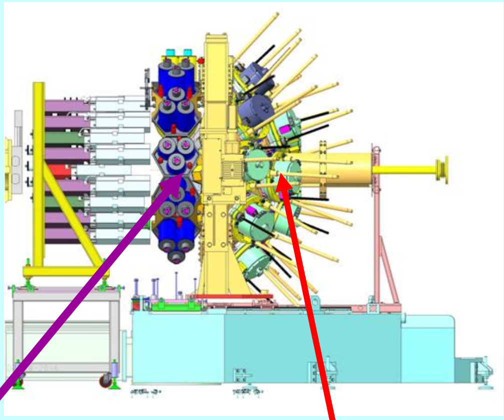
Coupling of different detectors to AGATA

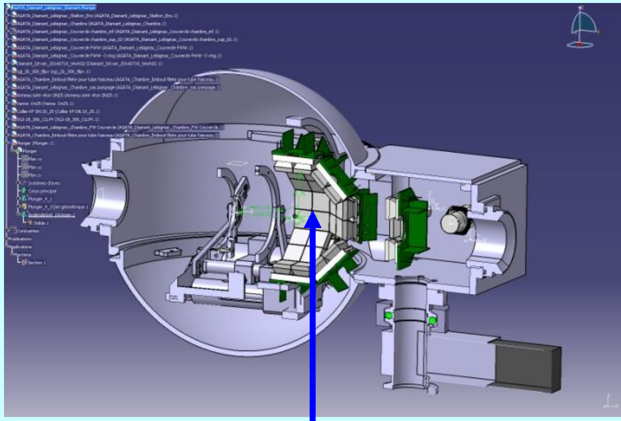
- GANIL physics campaigns

  2018

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







VAMOS++ spectrometer

NEDA + neutron-wall Neutron detector

AGATA for γ detection

DIAMANT for p,α detection

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

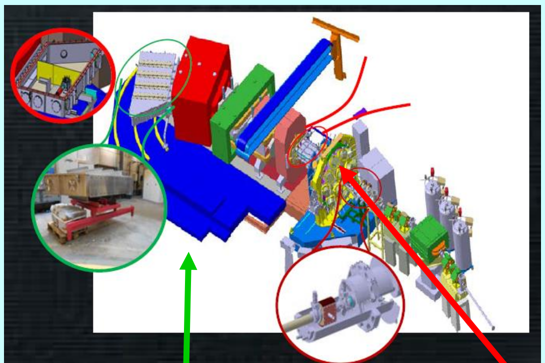
G. Duchène

Perspectives

Coupling of different detectors to AGATA

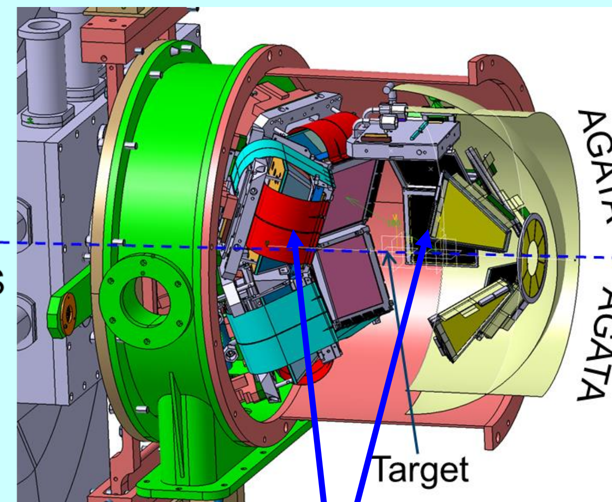
- GANIL physics campaigns
  2019 – (2020)

Nucleon transfer spectroscopy using **SPIRAL1 ISOL** beams



VAMOS spectrometer in Gas Filled Mode (GFM)

AGATA for γ detection



MUGAST for p,α detection

Structure study of superheavy elements

G. Duchêne

Perspectives

New accelerators for exotic beam

- SPES in 2022 (Legnaro, Italy) -> radioactive beams up to 10^8 particule per sec
- HIE-ISOLDE in 2020 (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 exotic nuclei

- GANIL SPIRAL2 (Caen, France) -> very intense stable beam (2018)
  -> very intense exotic beams (ISOL technique) ??

Structure study of exotic nuclei

G. Duchêne