AGATA

GANIL laboratoire commun CEA/DRF — spiral2 — CNRS/IN2P3

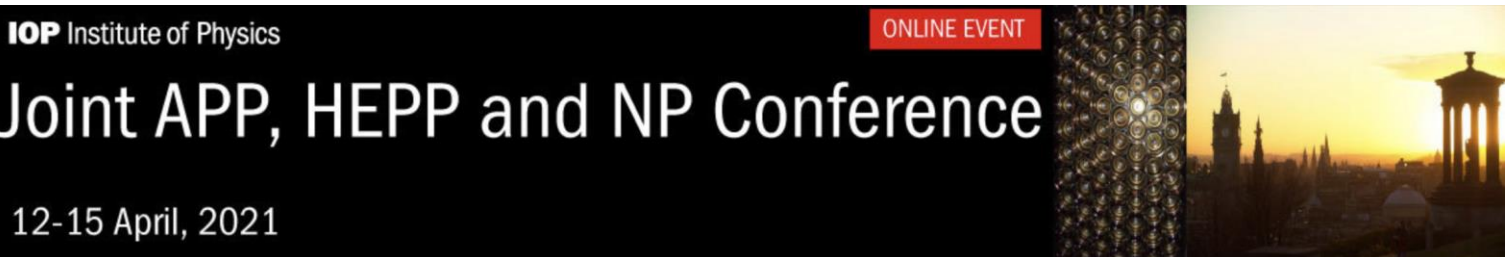
INFN Istituto Nazionale di Fisica Nucleare — Laboratori Nazionali di Legnaro

SPES Project

FAIR Facility for Antiproton and Ion Research in Europe GmbH

- What is AGATA?
- Recent physics highlights from AGATA
- AGATA technology in the UK

Precision Spectroscopy of Exotic Nuclei using AGATA



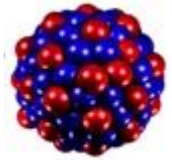
Mike Bentley & UK AGATA Collaboration

University of York

AGATA ADVANCED GAMMA TRACKING ARRAY

Gamma-ray spectroscopy

Precision spectroscopy of nuclear states



- Gamma-ray (hence level) energies
- Complex level schemes (γ^n coincidences)

(high resolution essential – i.e. Ge)



Precision probes of the nuclear wave function:

- Lifetimes (transition matrix elements)
- Electromagnetic moments
- Cross-sections for direct reactions

AGATA
ADVANCED GAMMA TRACKING ARRAY

The need for AGATA

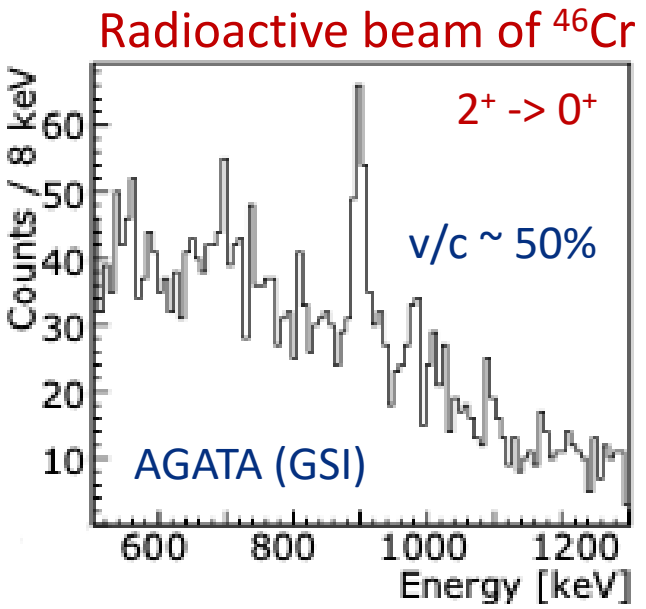
The challenge of the new generation of radioactive beam facilities

FAIR (Germany)
SPIRAL (France)
SPES (Italy)
HIE-ISOLDE (CERN)

- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High gamma-ray multiplicities

The ideal γ-ray spectrometer

- High efficiency
- Distinguish gammas from b/g
- Highly position sensitive
- High data throughput
- Can distinguish multiple gammas

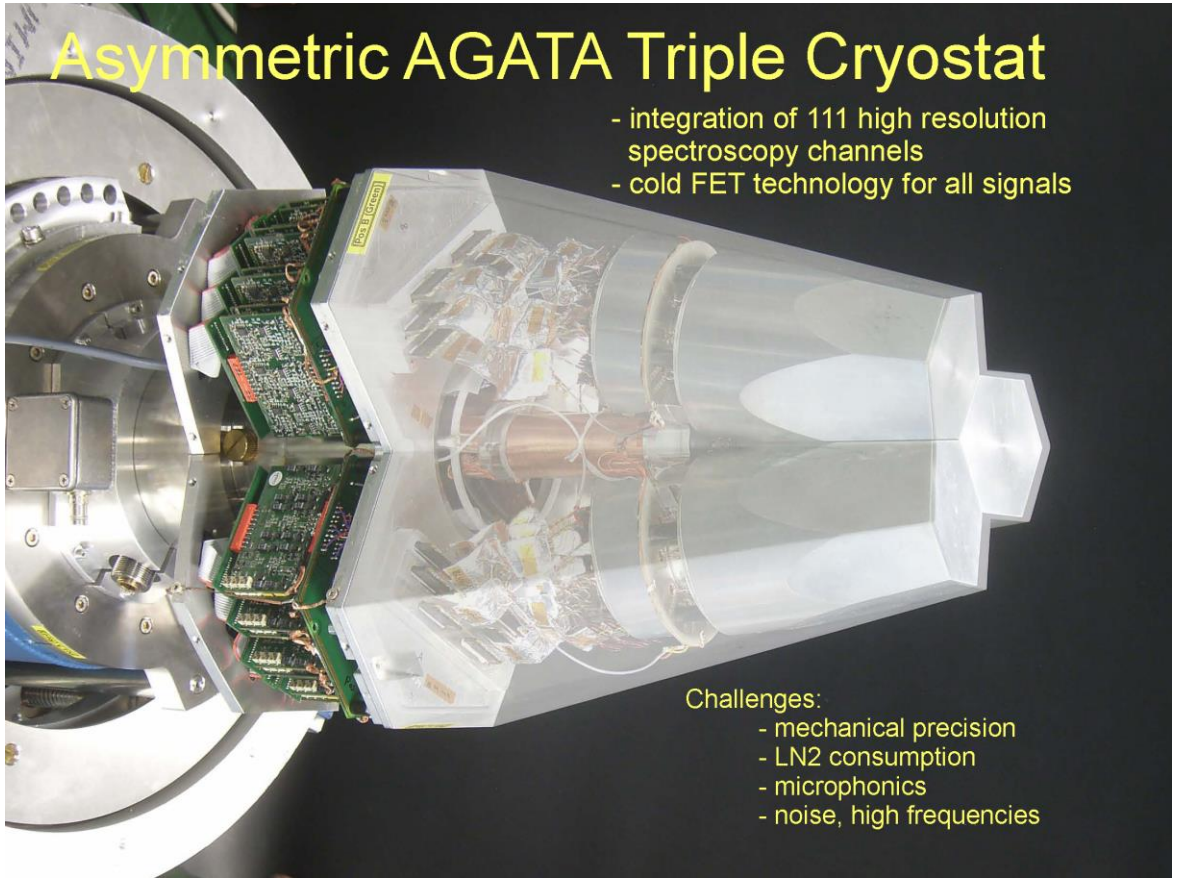


AGATA
ADVANCED GAMMA TRACKING ARRAY

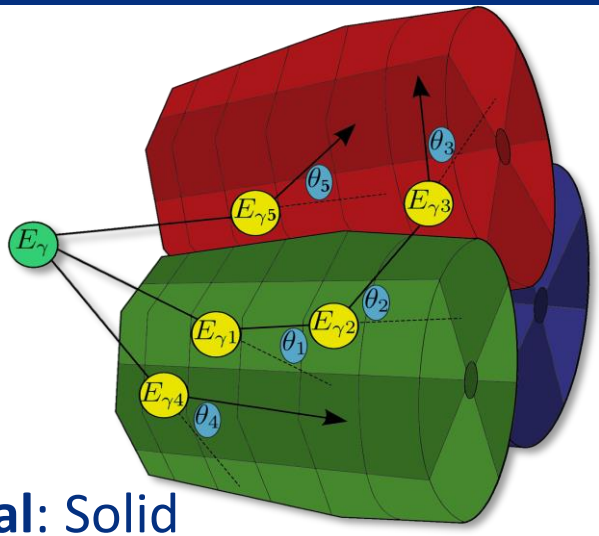
What is AGATA?



13 Countries, >40 Institutions



AGATA Definition: NIM A 668 (2012) 26



- Solid **Sphere of Ge material**: Solid angle coverage ~ 82 %
- 36-fold **segmentation** of crystal
- **Track** each gamma interaction through the crystal
- **Reconstruct** and **disentangle** gammas

180 hexagonal crystals:	3 shapes
3 fold clusters (cold FET):	60 all equal
Inner radius (Ge):	23.5 cm
Amount of germanium:	362 kg
36-fold segmentation	6480 segments

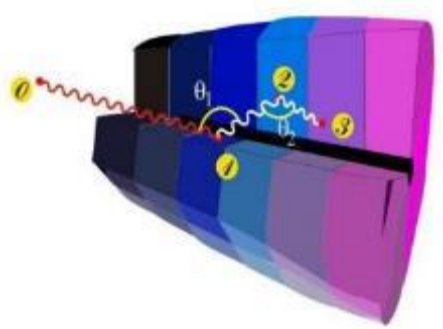
AGATA
ADVANCED GAMMA TRACKING ARRAY

The concept of γ-ray tracking

1

Highly segmented HPGe detectors

γ



2

Digital electronics to record and process signals

3



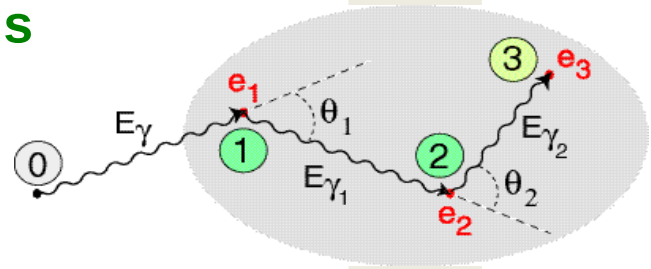
Identified interaction points

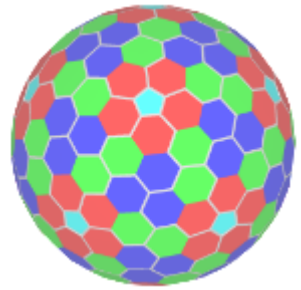
$(x,y,z,E,t)_i$

Pulse Shape Analysis to decompose recorded waves

4

Evaluation of permutations of interaction points

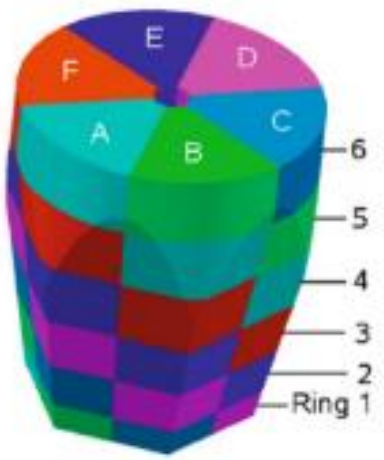


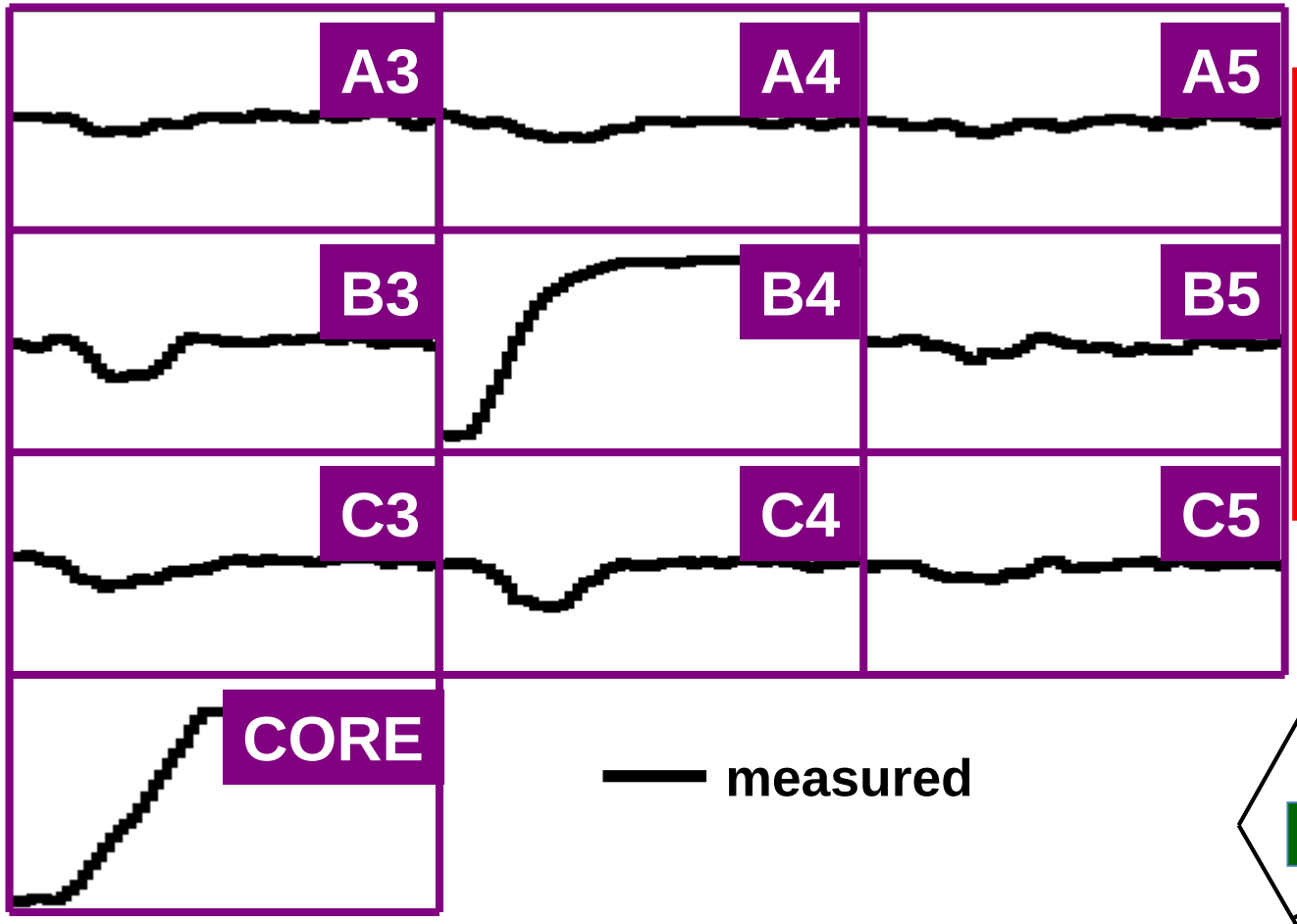


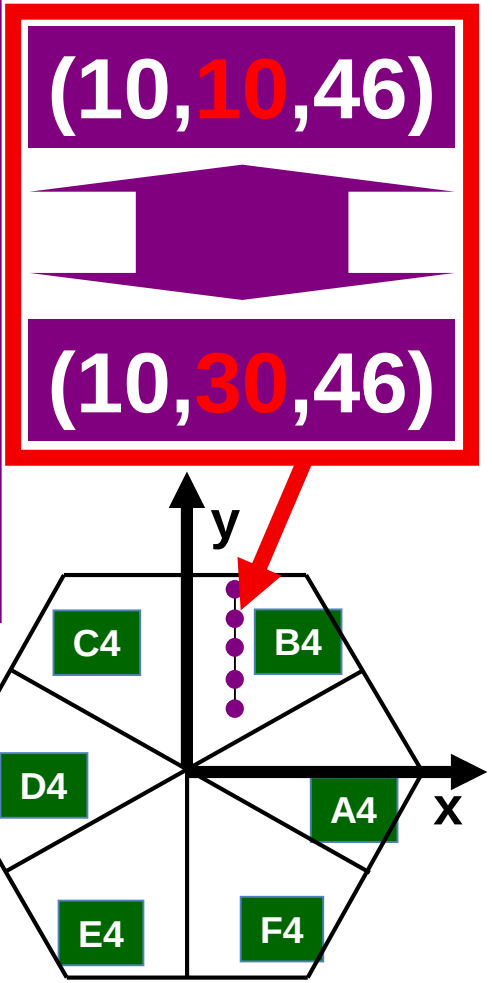
Reconstructed γ rays

AGATA
ADVANCED GAMMA TRACKING ARRAY

Pulse Shape Analysis concept



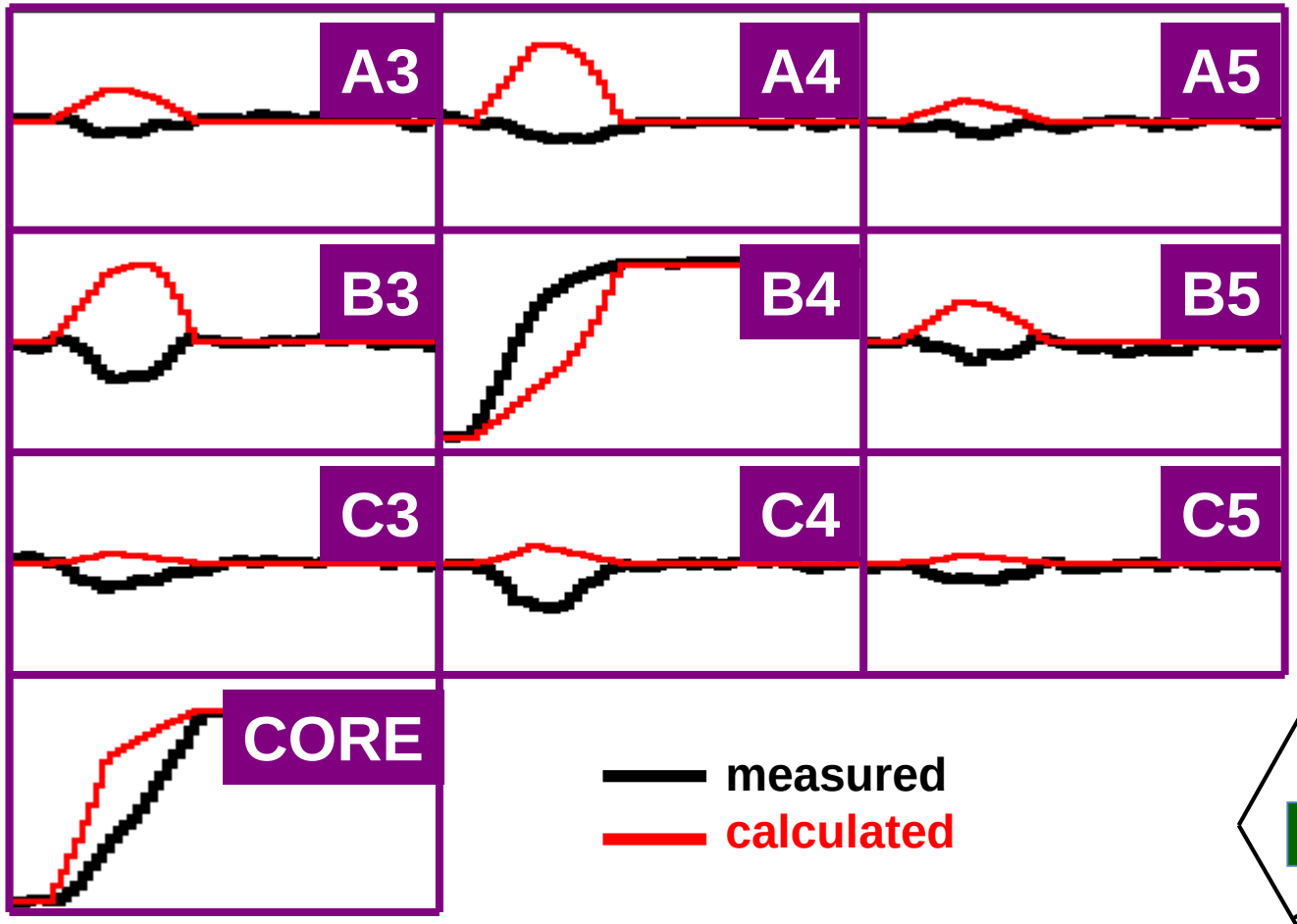




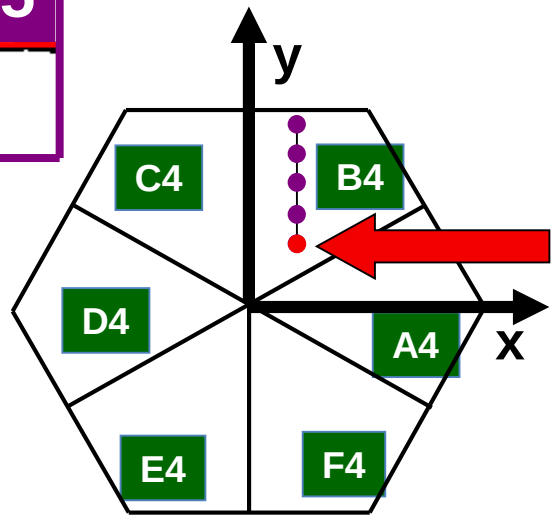
791 keV deposited in segment B4

z = 46 mm

Pulse Shape Analysis concept



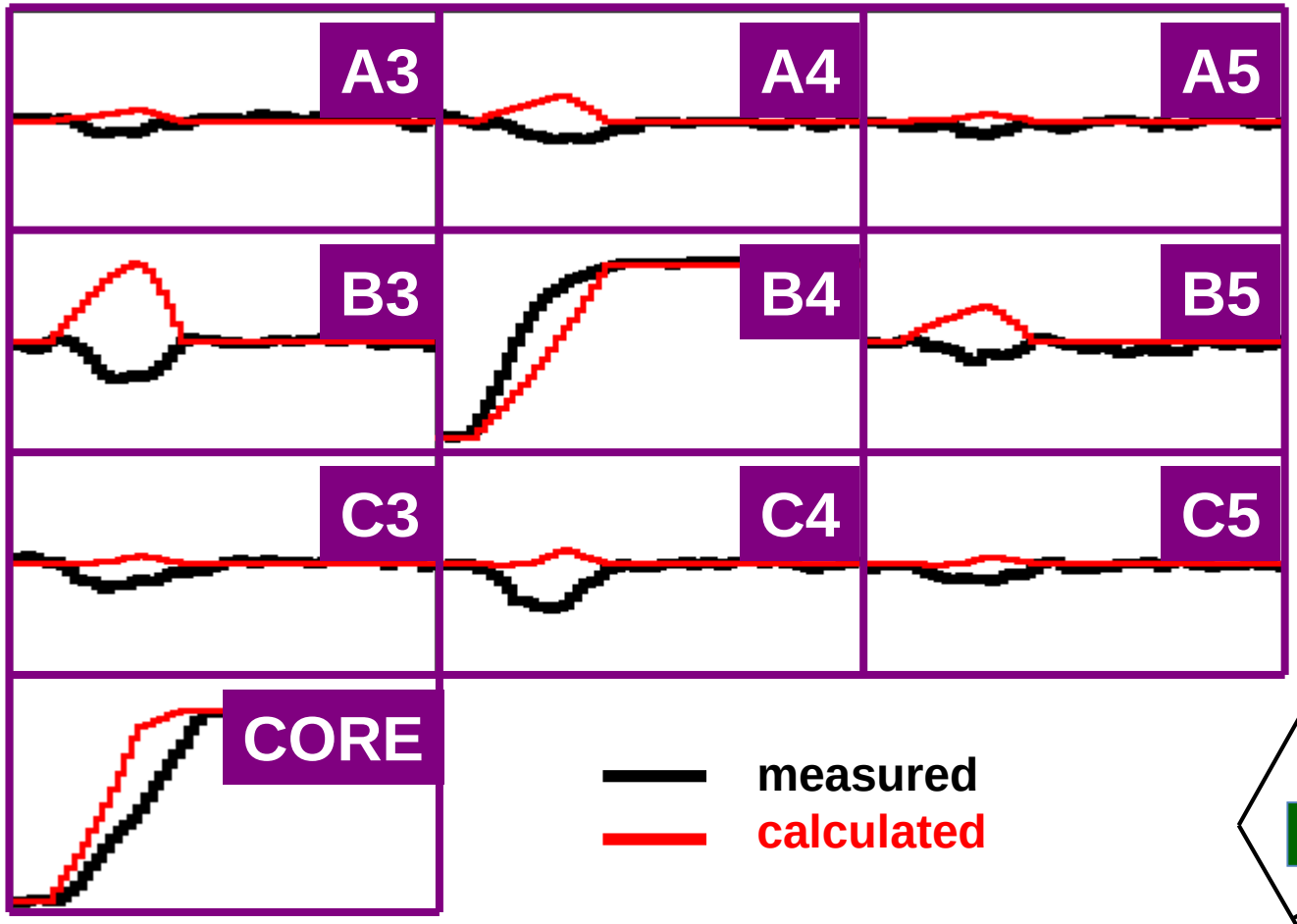
(10,10,46)



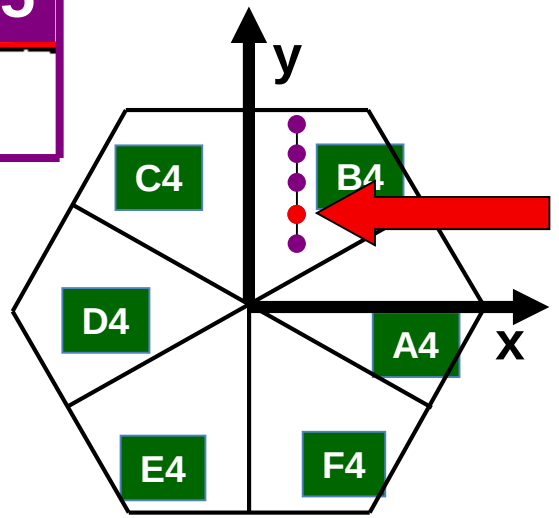
z = 46 mm

791 keV deposited in segment B4

Pulse Shape Analysis concept



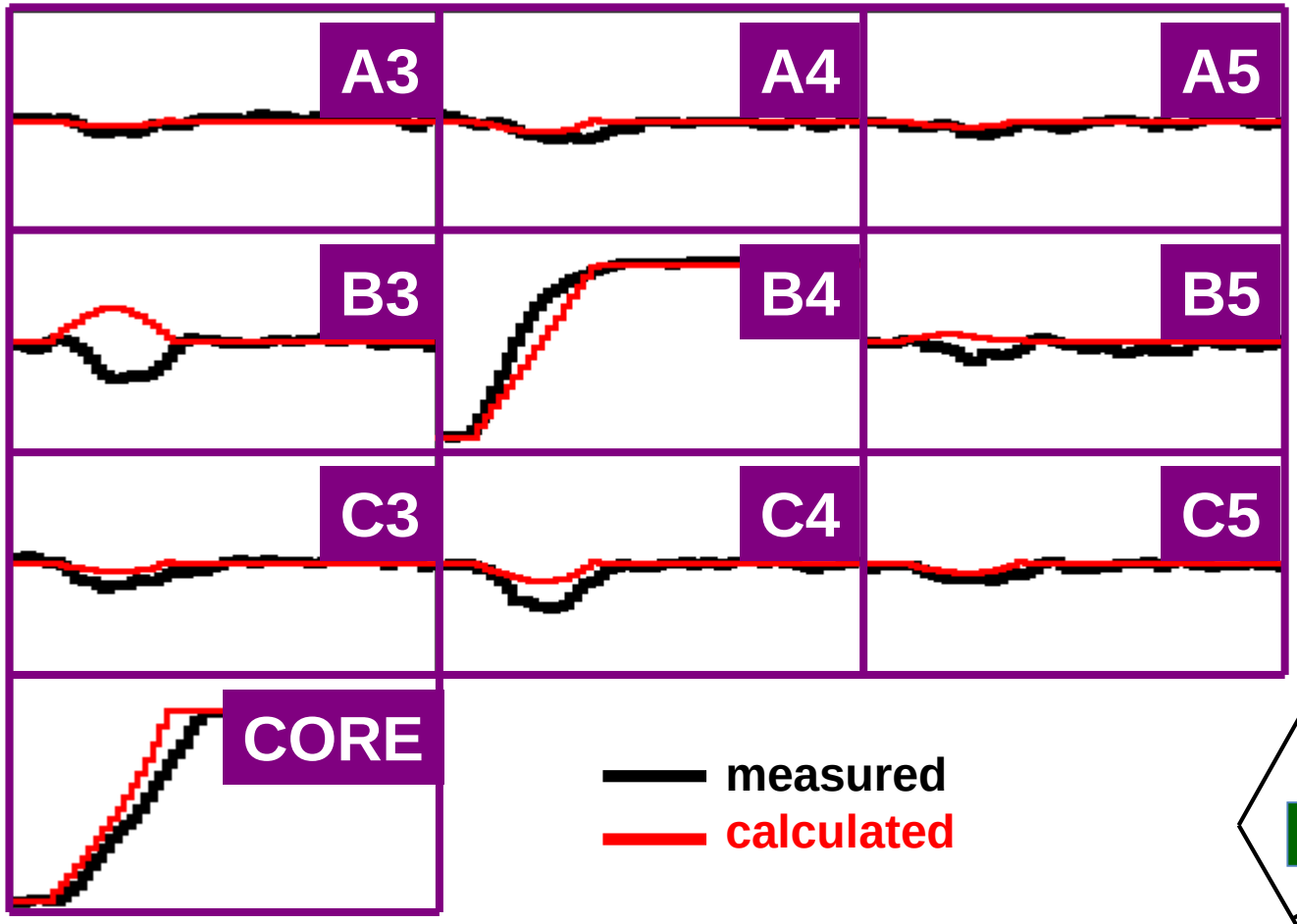
(10,15,46)



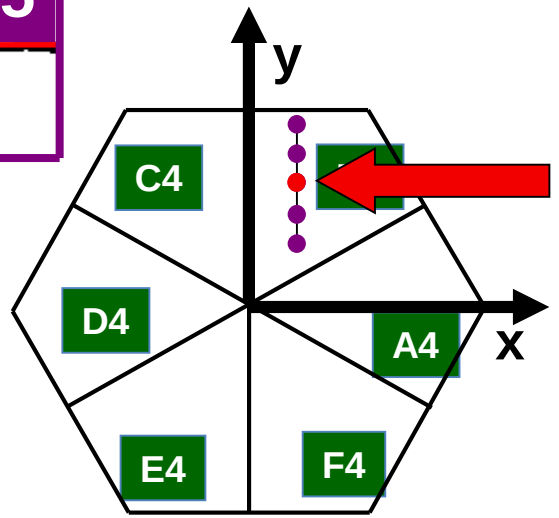
z = 46 mm

791 keV deposited in segment B4

Pulse Shape Analysis concept



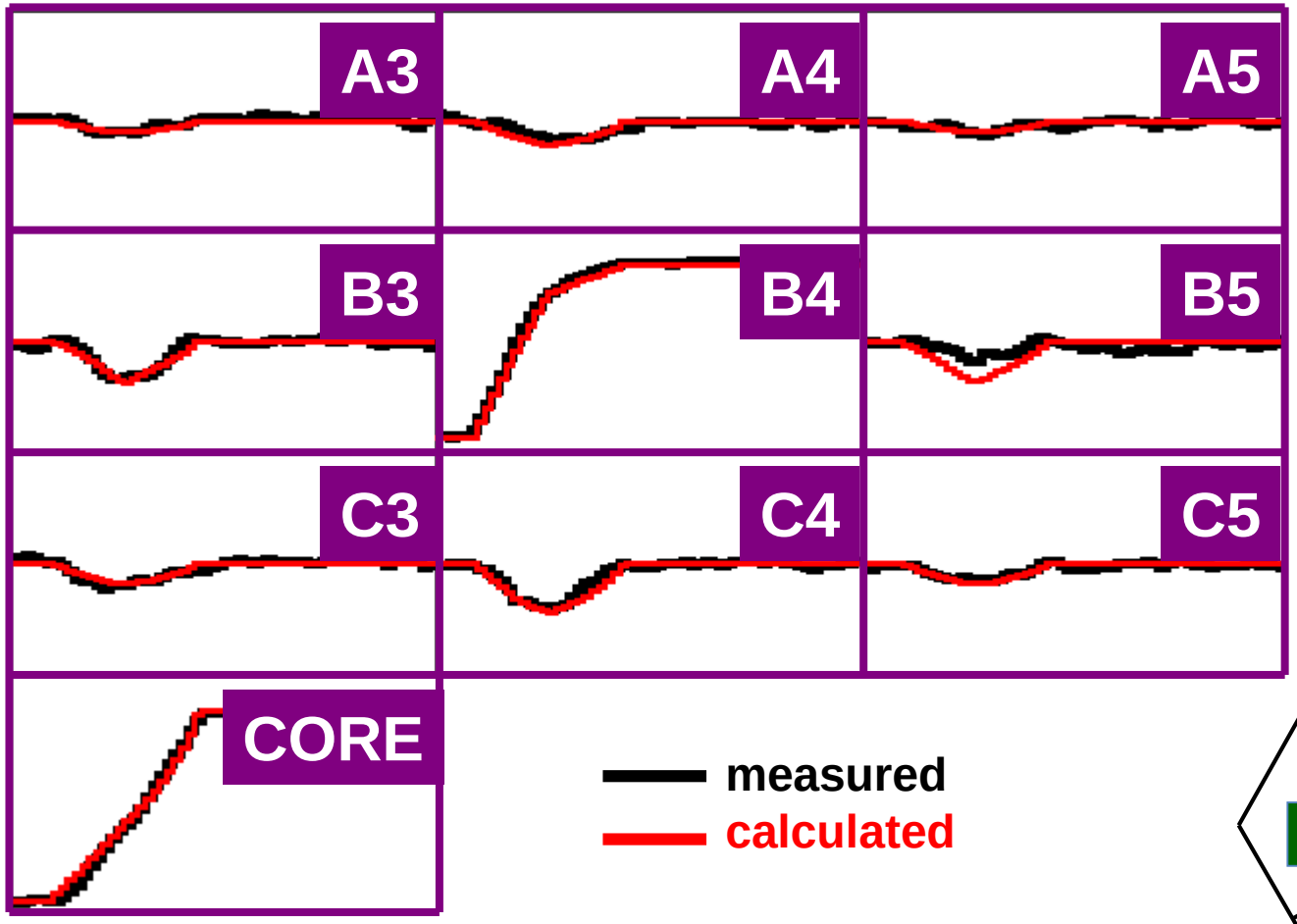
(10,20,46)



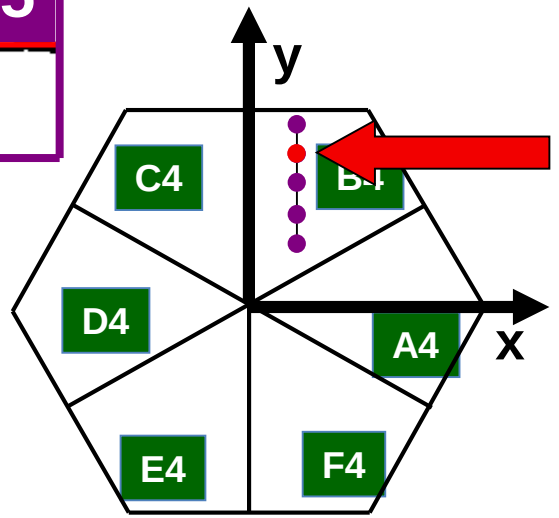
z = 46 mm

791 keV deposited in segment B4

Pulse Shape Analysis concept



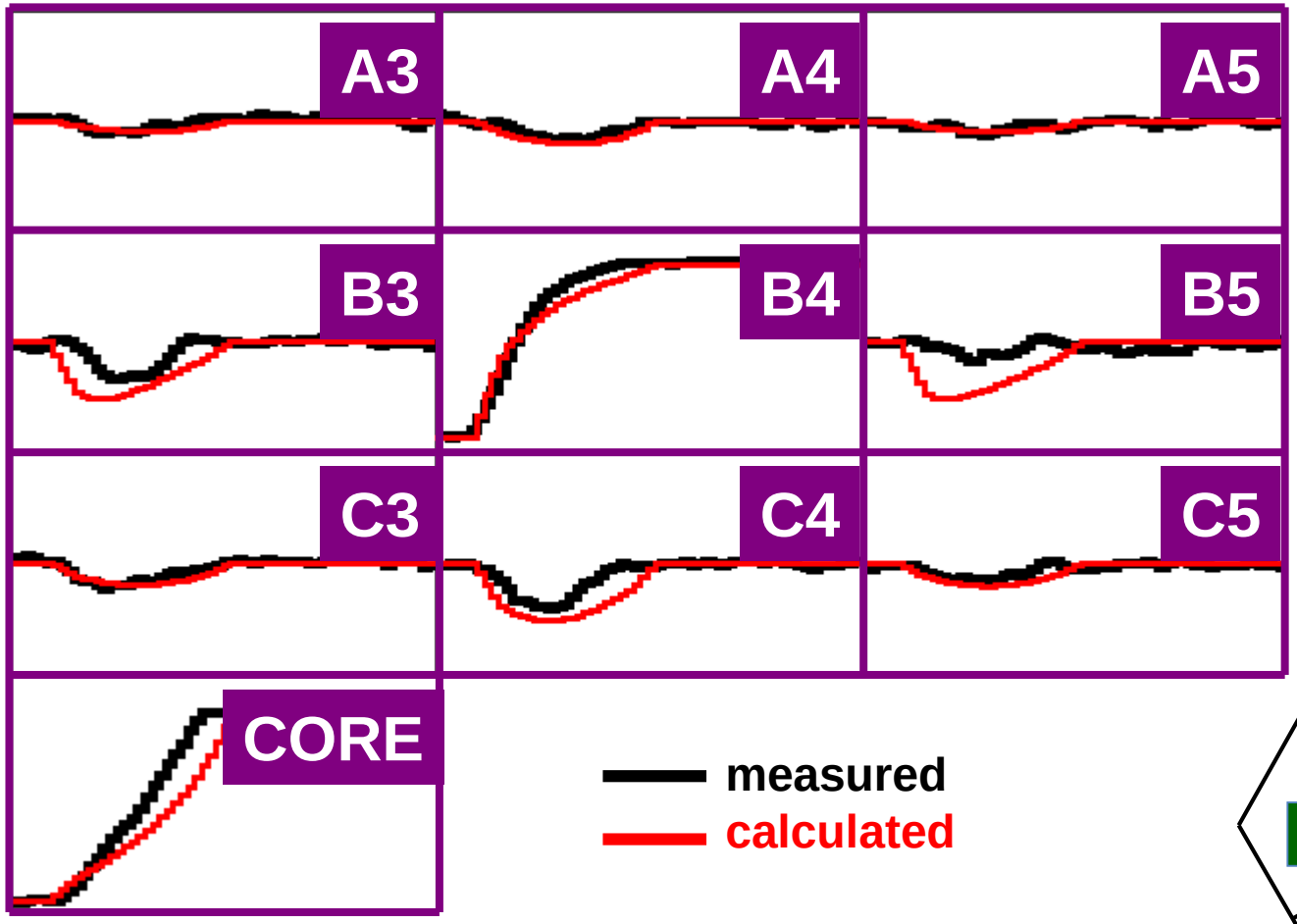
(10,25,46)



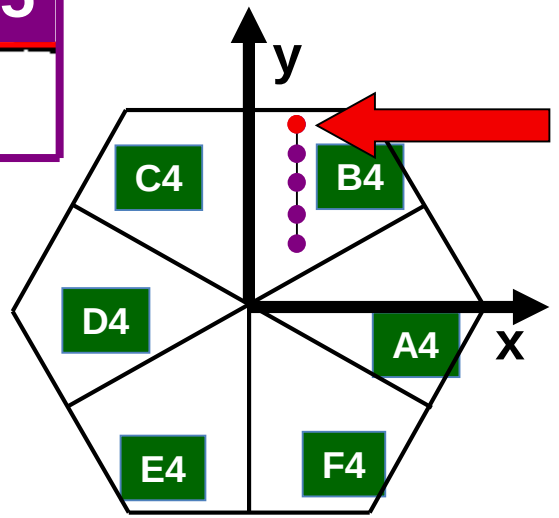
z = 46 mm

791 keV deposited in segment B4

Pulse Shape Analysis concept



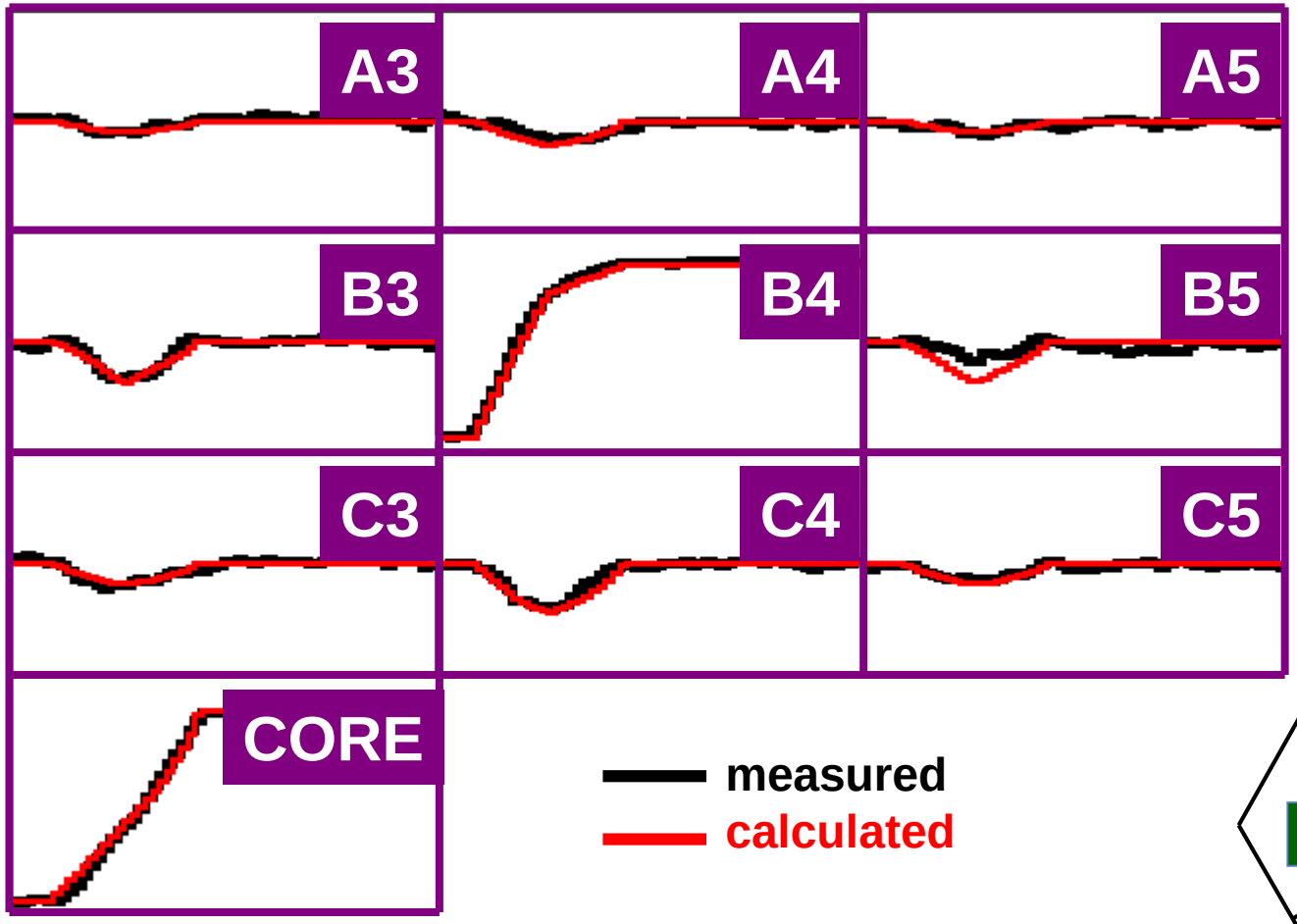
(10,30,46)



z = 46 mm

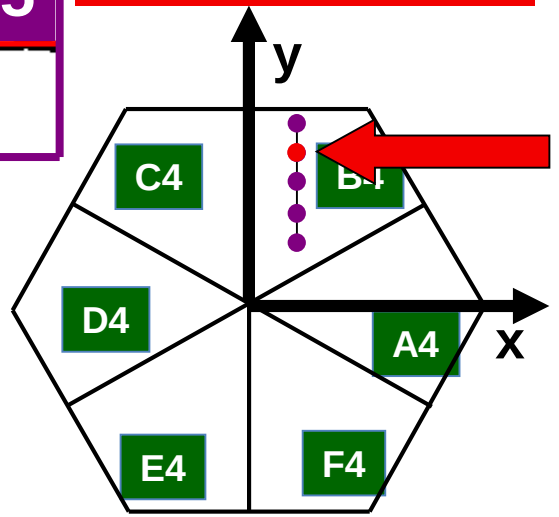
791 keV deposited in segment B4

Pulse Shape Analysis concept



Result of *Grid Search* algorithm

(10,25,46)

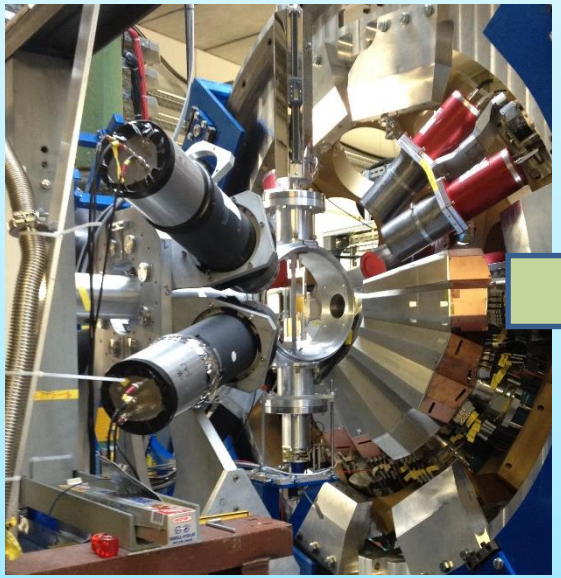


z = 46 mm

791 keV deposited in segment B4

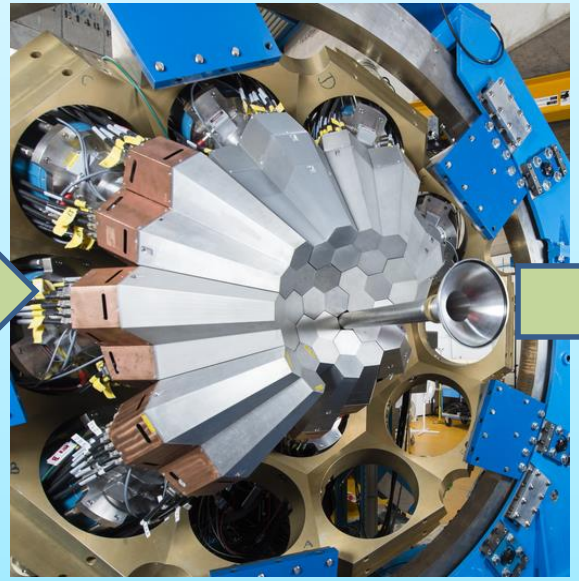
The AGATA journey…

2012-2014
GSI, Germany
~25 detectors



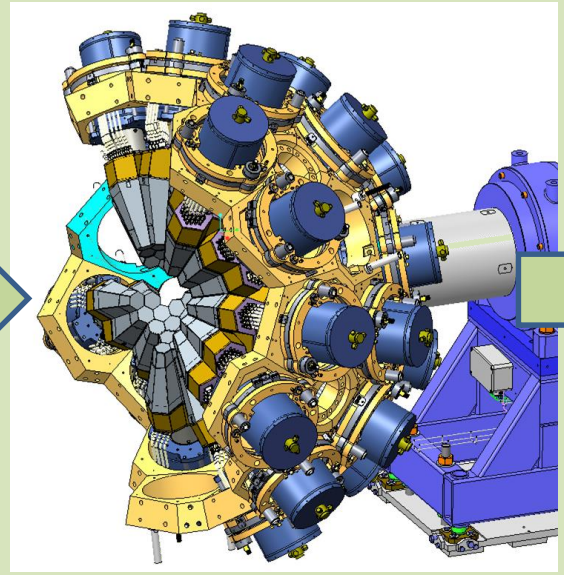
AGATA at GSI

2014-2021
GANIL, France
45 -> detectors



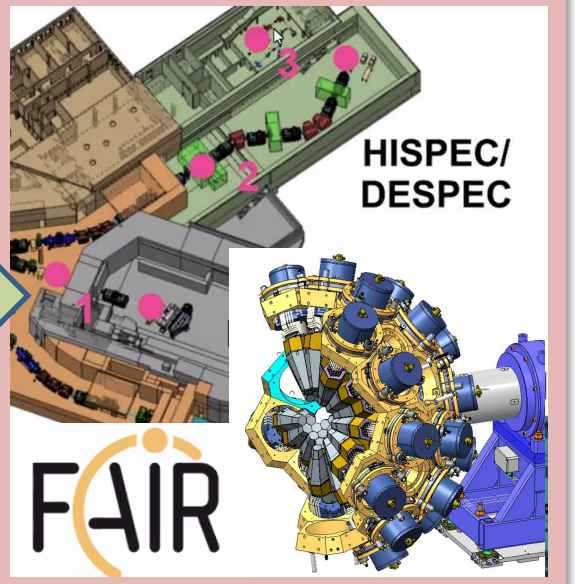
AGATA at GANIL

2021-2024
Legnaro, Italy
60 -> detectors



AGATA at LNL

2025 ->
FAIR, Germany
80-90 detectors



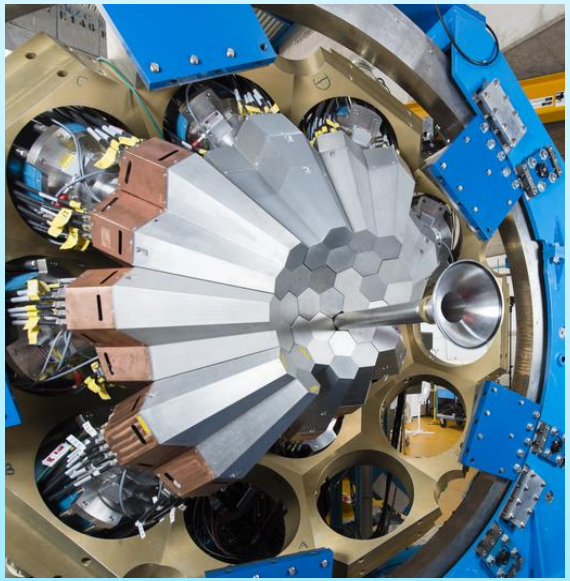
AGATA at NUSTAR

Reaccelerated RIBs:
- Coulomb Excitation, Direct Reactions, MNT, Deep Inelastic, Fusion
- **Direct and inverse kinematics β ~ 10%**

In-flight RIBs:
- Relativistic Coulomb Excitation, Knockout, Fragmentation.
- **β ~ 50%**

Recent Highlights at GANIL

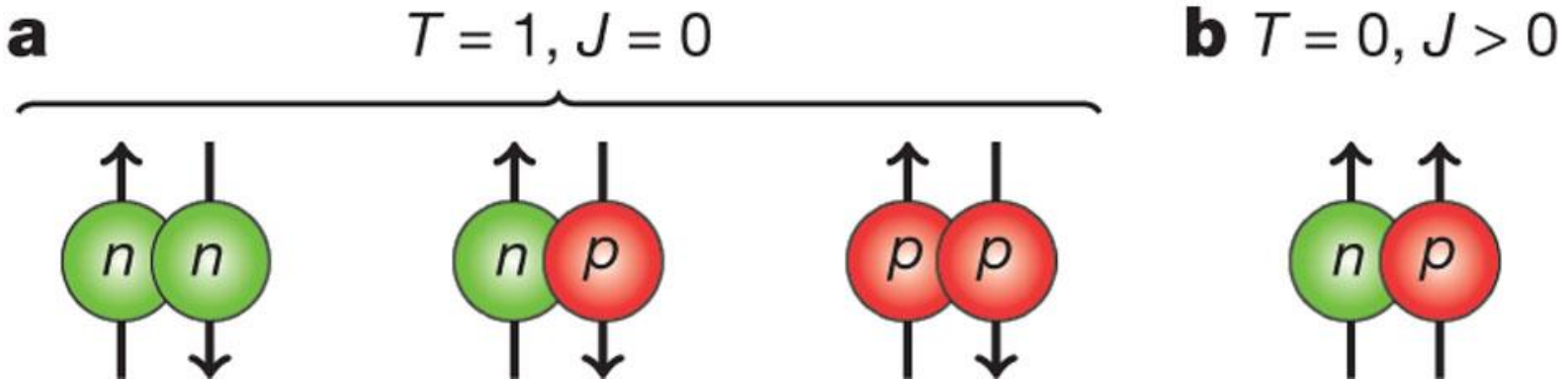
2014-2021
GANIL, France
45 -> detectors

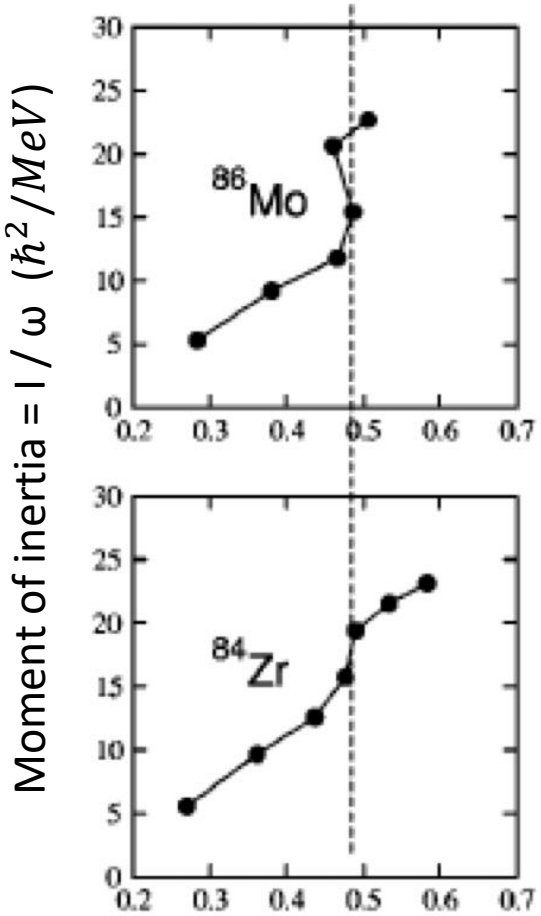


AGATA at GANIL

Neutron-proton pairing in N = Z nuclei

ISOVECTOR **ISOSCALAR**





- Search for np T=0 pairing in N=Z nuclei, **evidence is elusive**
- **Is there a "fluid" of T=0 np pairs along with "normal" T=1 pairs?**
- T=0 pairing may respond differently to rotational motion
- Look for delayed rotational alignments **in heavy N=Z nuclei**

S. Frauendorf, A.O. Macchiavelli, Prog. in Particle and Nuclear Physics 78, 24 (2014)

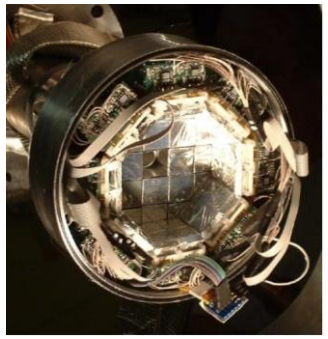
N=Z ^{88}Ru studied using AGATA

Bo Cederwall, KTH Stockholm
Bob Wadsworth, University of York
et al.

B. Cederwall et al., Phys. Rev. Lett. 124, 062501 (2020)

Fusion Reaction: ^{36}Ar + ^{54}Fe → **^{88}Ru + 2n + γ**

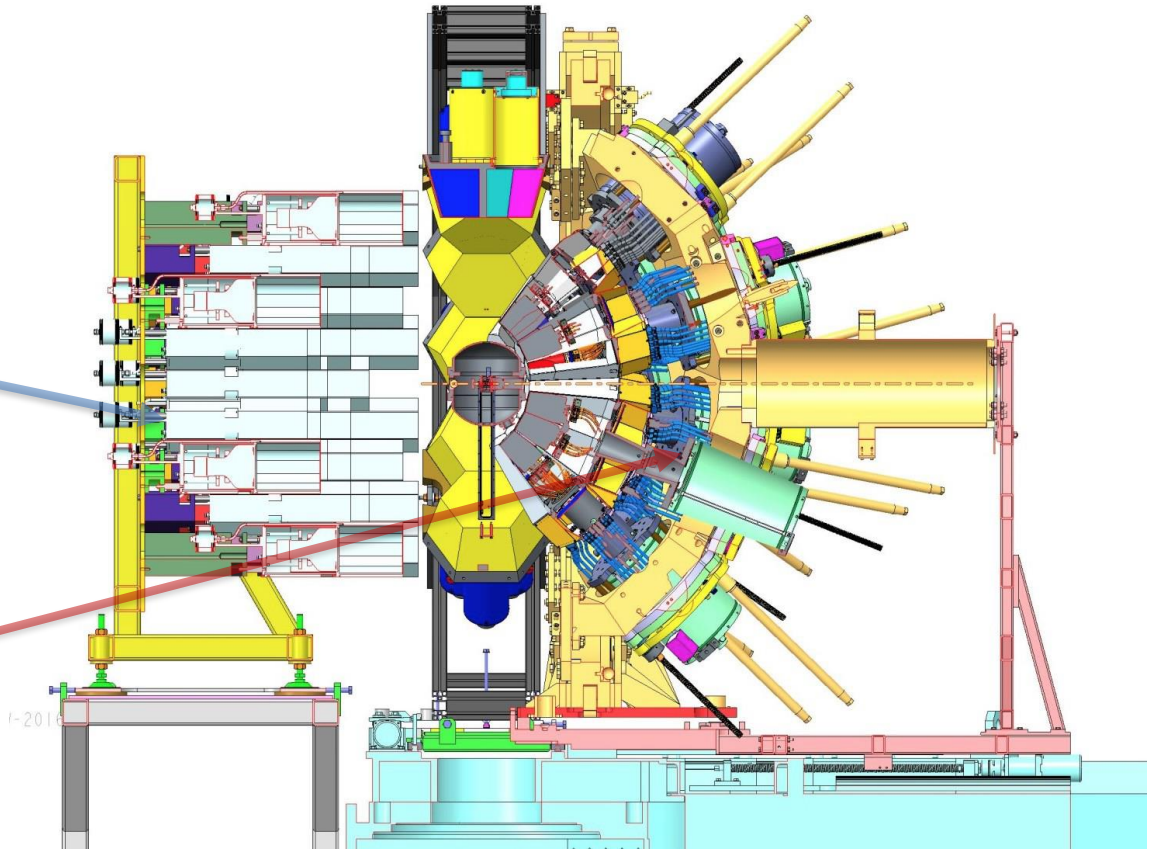
Cross section σ ~ few μb



NEDA (neutron detectors)
Select two-neutron events

DIAMANT (CsI)
Reject charged-particle events

AGATA
Record multiple gamma rays

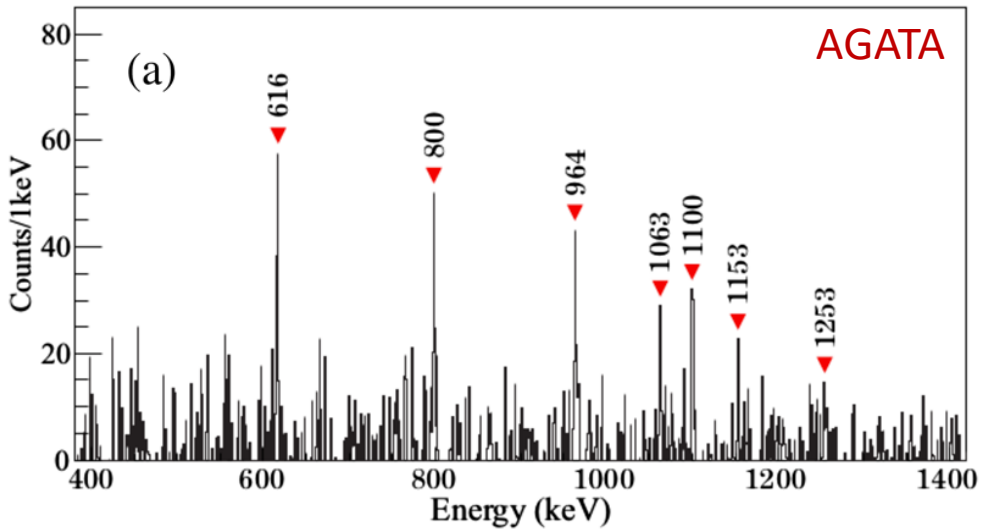


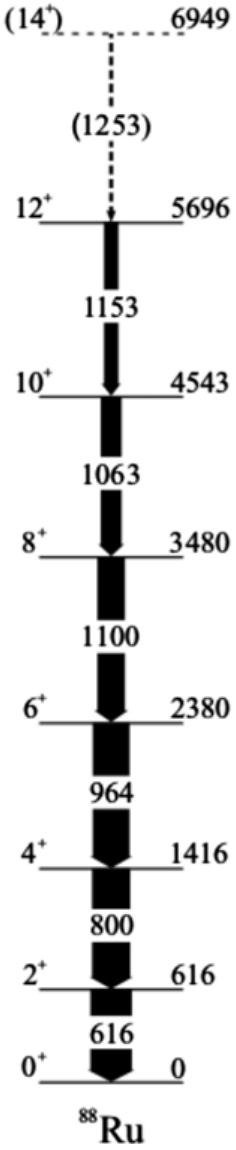
Power of AGATA:
- High Efficiency
- Multiple simultaneous γ rays

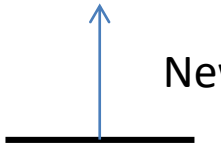
N=Z ^{88}Ru studied using AGATA

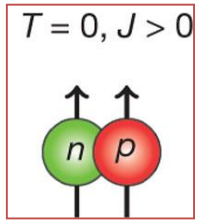
Bo Cederwall, KTH Stockholm

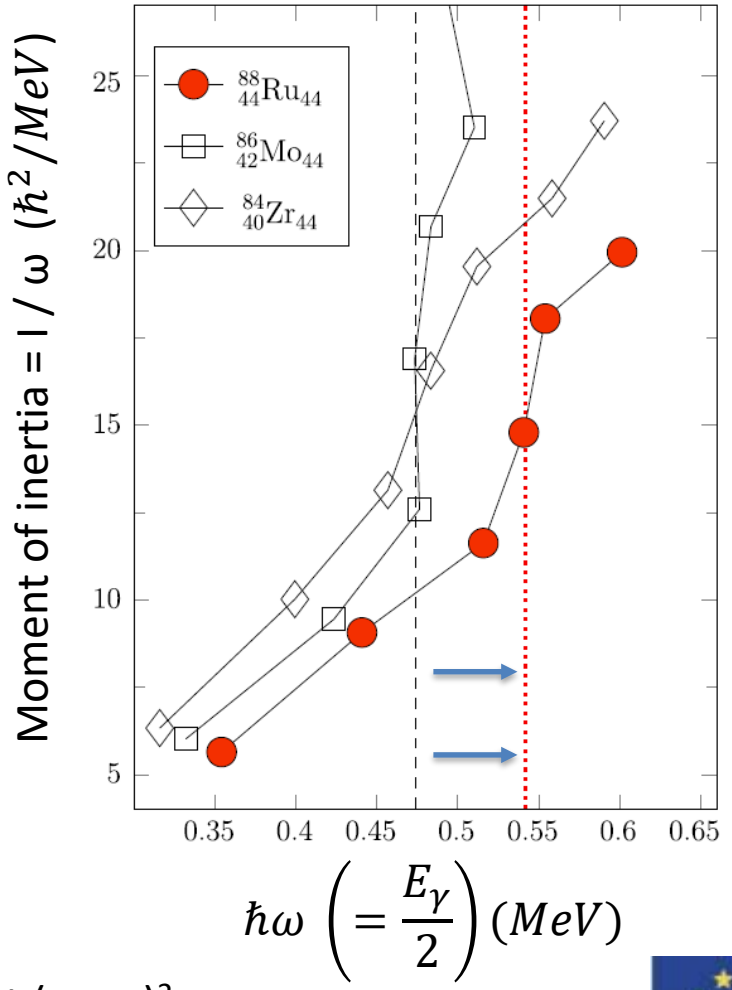
Summed two-neutron γ-γ spectrum









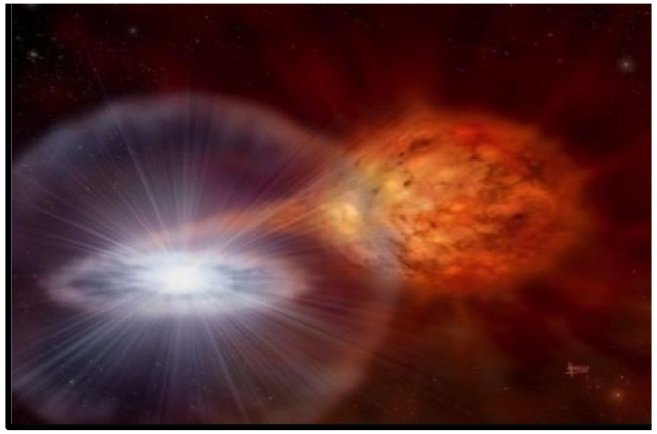


Delayed alignment $(\pi g_{9/2})^2$
…in **N=Z system**

B. Cederwall et al., Phys. Rev. Lett. 124, 062501 (2020)

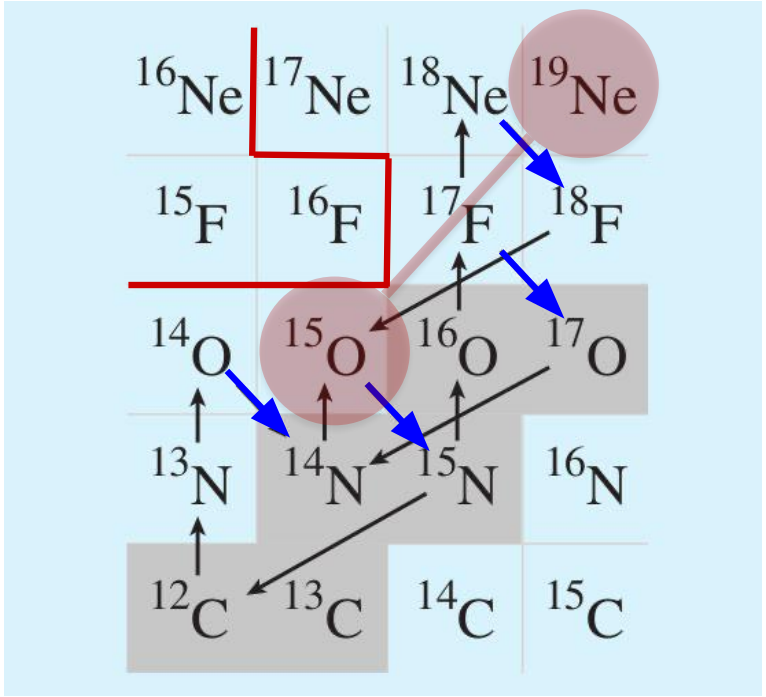
$^{15}O + \alpha$ studied using AGATA: A crucial reaction in astrophysics

Jennifer Sanchez Rojo, Christian Diget, University of York



Neutron stars in **binary** systems: **accrete** matter from companion

- Thermonuclear runaway producing flashes**: X-ray bursts**
- Site of the **rp-process** creating heavier elements up to A~100



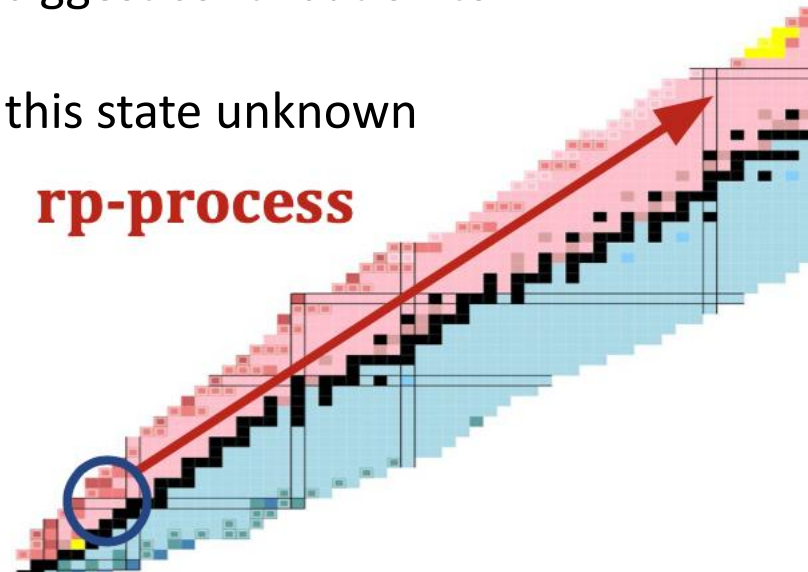
Hot CNO cycle(s)

↑ = p-capture

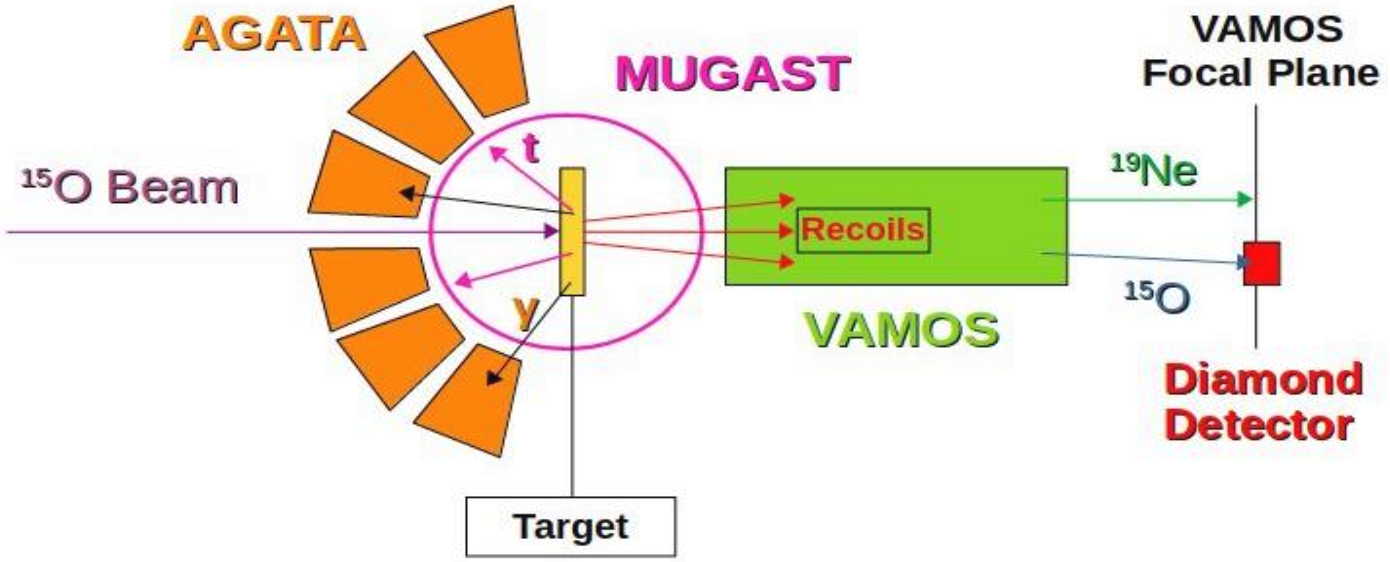
↘ = β decay

^{15}O captures alpha particle $^{15}O(\alpha,\gamma)^{19}Ne$

- Regulates flow between HCNO cycle and rp-process
- ^{19}Ne **4.033 MeV** state biggest contribution to reaction rate
- Reaction rate through this state unknown (upper limit)



^{15}O + α studied using AGATA at GANIL



$$^{15}O + ^{7}Li = t + ^{19}Ne^{*}$$

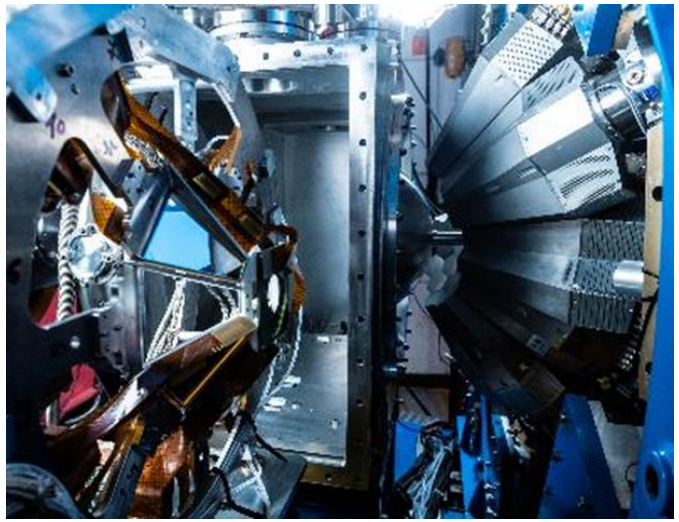
★ ^{19}Ne prompt-γ: **AGATA**

★ Triton ejectile: **MUGAST**

★ ^{19}Ne recoil: **VAMOS**

- **^{15}O** radioactive beam
- Cross section ~ **few µb**
- **Very challenging!**

Power of AGATA:
- High Efficiency (4 MeV γ ray)
- Position sensitivity (Doppler, v/c ≥ 10%)

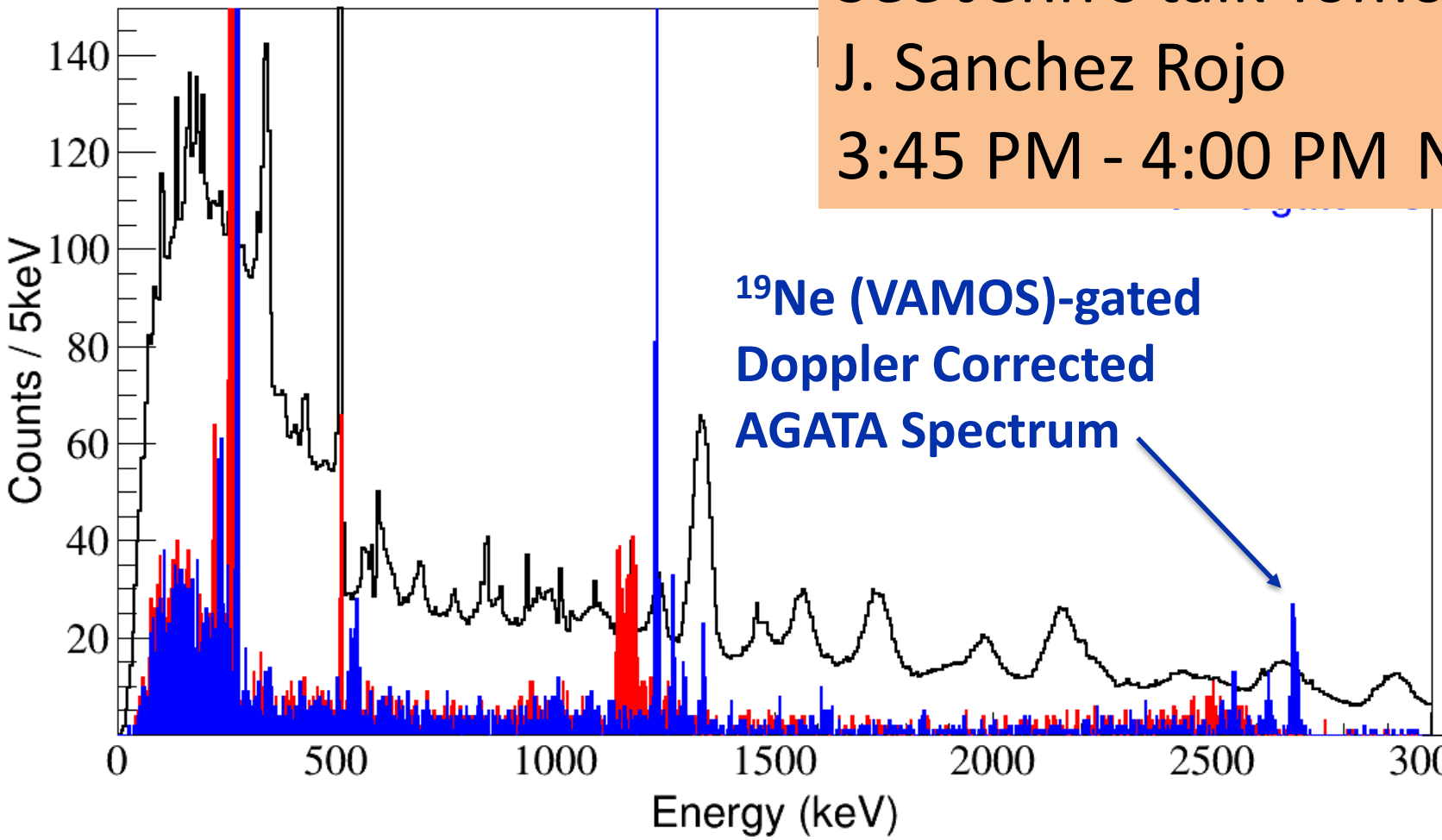


Jennifer Sanchez Rojo, Christian Diget, University of York

$^{15}O + \alpha$ studied using AGATA at GANIL

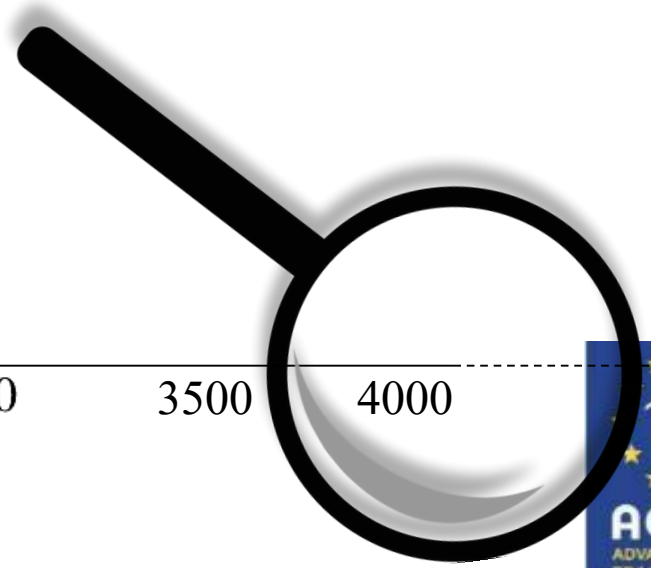
Jennifer Sanchez Rojo, Christian Diget, University of York

See Jenn's talk Tomorrow (Tuesday)
J. Sanchez Rojo
3:45 PM - 4:00 PM Nuclear Astrophysics 1



^{19}Ne (VAMOS)-gated Doppler Corrected AGATA Spectrum

4.033 MeV gamma-ray
Few (10?) counts expected



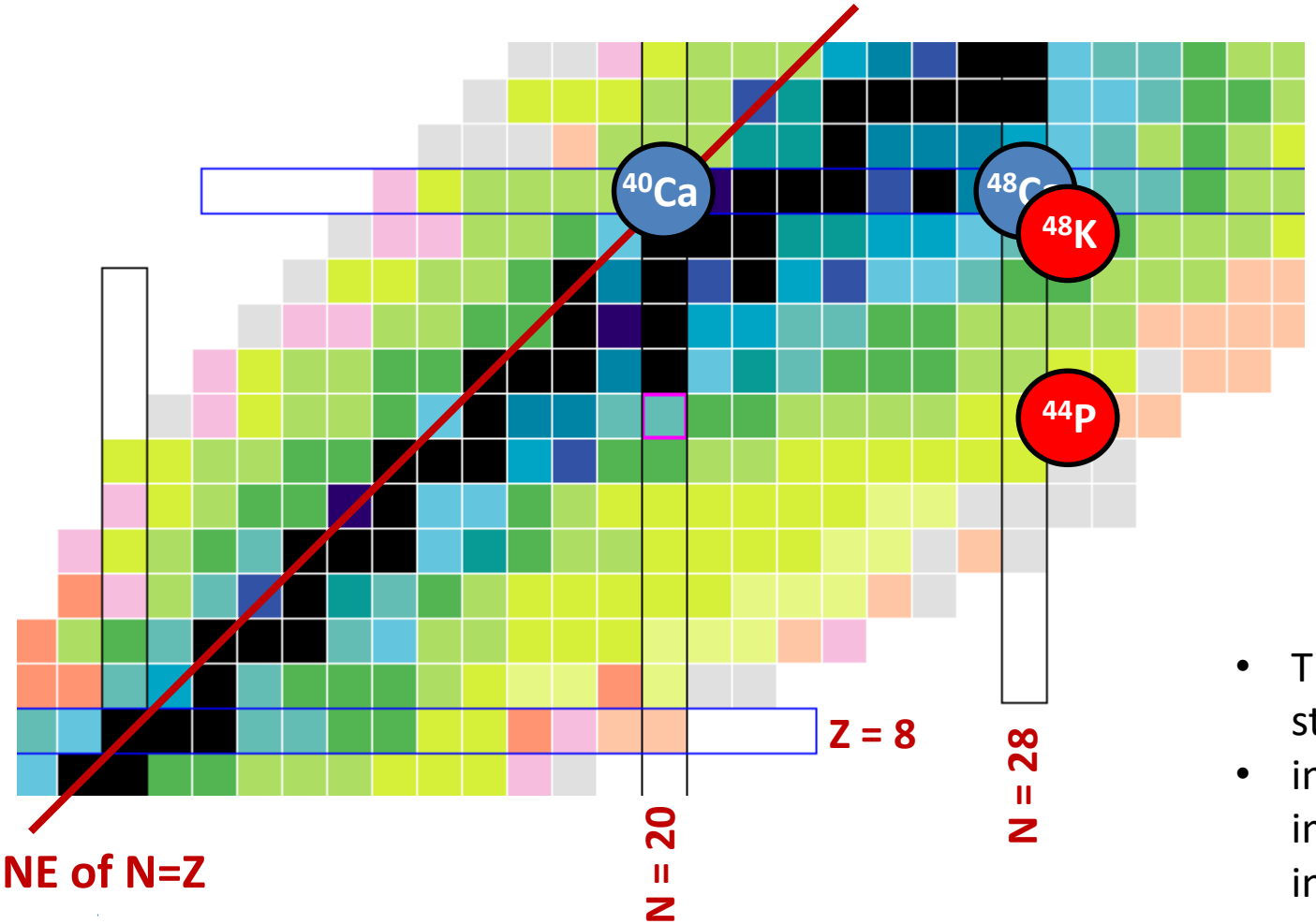
^{48}K as a window into shell structure near ^{44}P

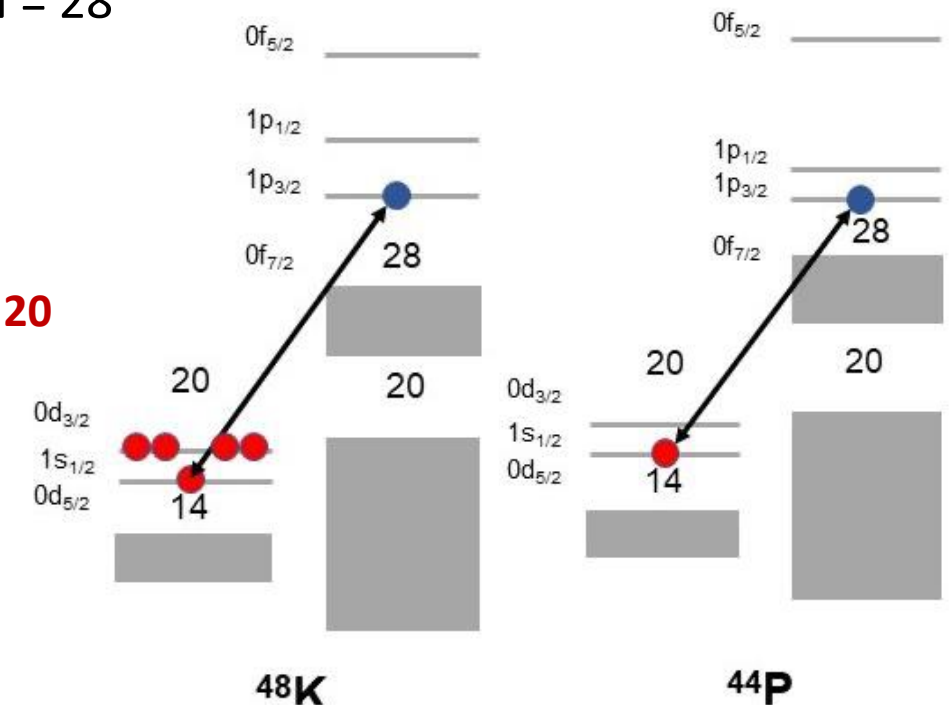
Wilton Catford & Adrien Matta

UNIVERSITY OF SURREY

lpc caen

Evolution of shell structure near N = 28





proton population inversion

- The single-particle structure of ^{48}K
- insights into the important valence interactions
- **$\pi(s_{1/2})$ - $\nu(f_{5/2})$** etc

AGATA ADVANCED GAMMA TRACKING ARRAY

d(^{47}K,p)^{48}K at SPIRAL1+ A few weeks ago!

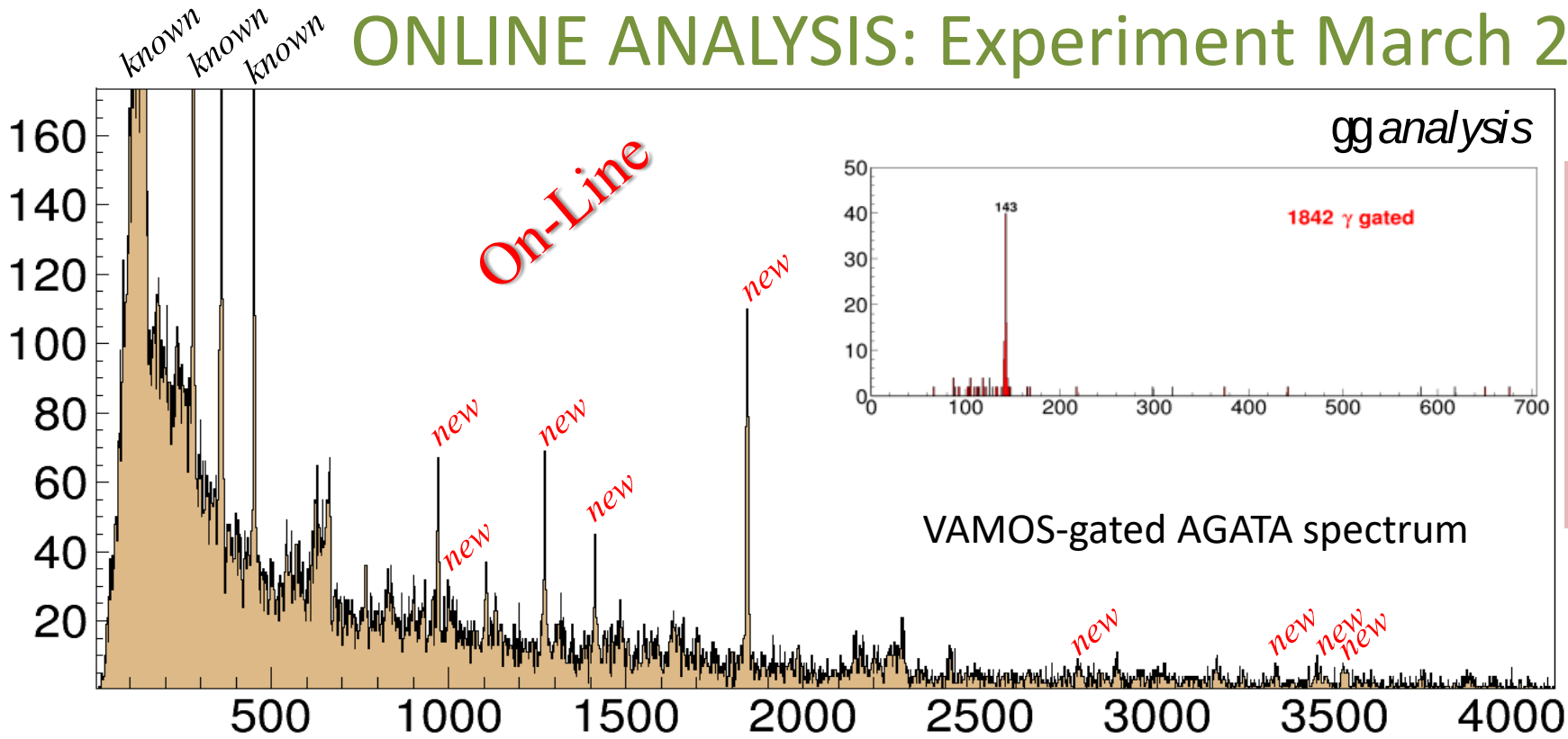
Wilton Catford & Adrien Matta

UNIVERSITY OF SURREY

lpc caen

- AGATA, MUGAST and VAMOS
- 10^6 pps, >99.99% pure **radioactive** ^{47}K beam
- Looking for new excited states in ^{48}K
- $\pi(0s_{1/2}) \otimes \nu(0f_{5/2})$ interaction

ONLINE ANALYSIS: Experiment March 2021 (E793s)



Power of AGATA:

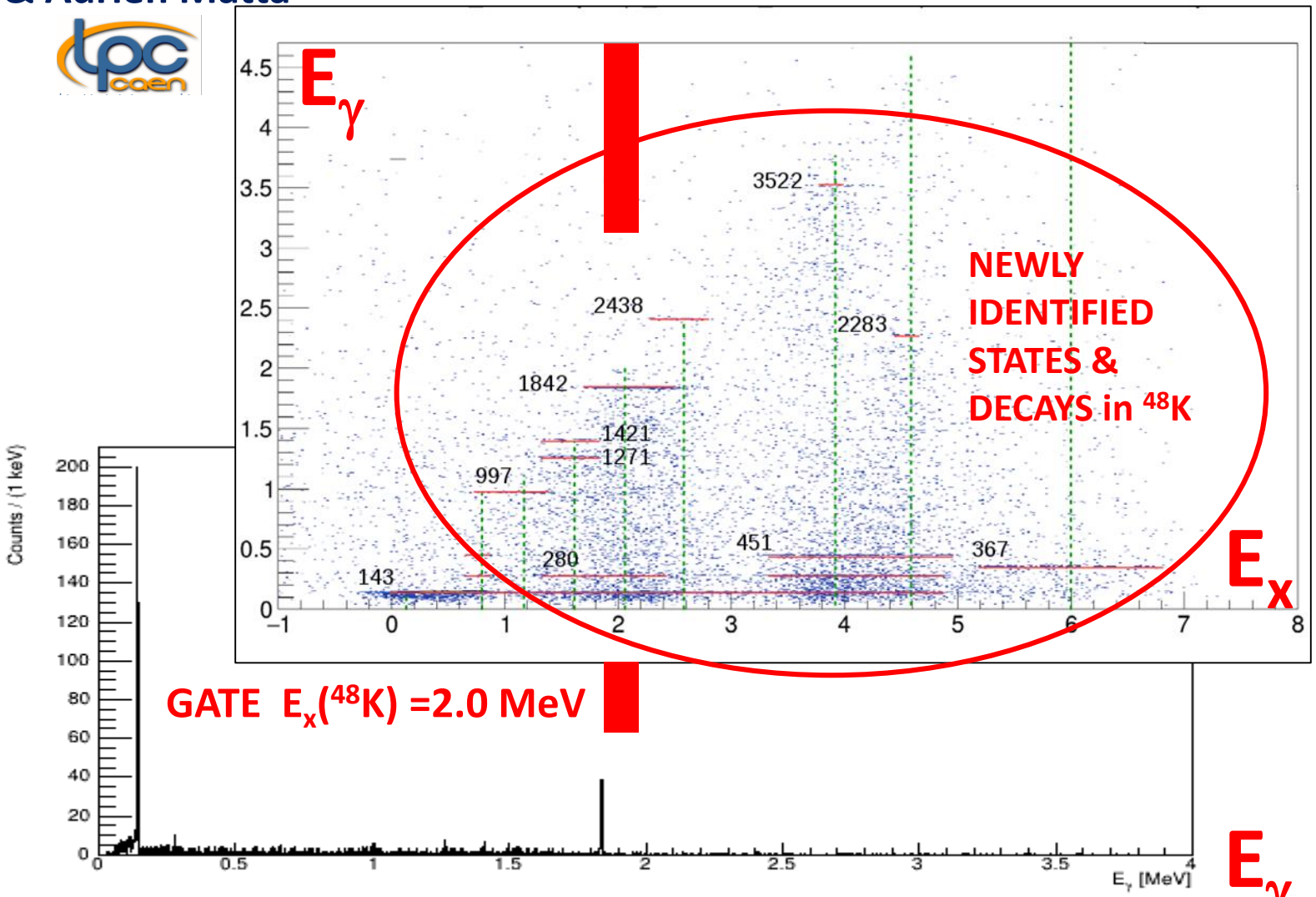
- High Efficiency (high-energy γ rays, γ-γ analysis)
- Position sensitivity (Doppler, v/c ≥ 10%)

AGATA ADVANCED GAMMA TRACKING ARRAY

d(^{47}K,p)^{48}K at SPIRAL1+ A few weeks ago!

Wilton Catford & Adrien Matta

UNIVERSITY OF SURREY

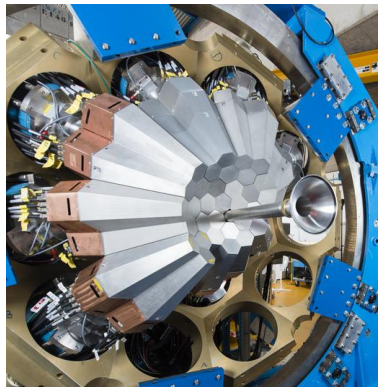


Thanks to **Wilton Catford** (Surrey) for the analysis and spectra !

PRELIMINARY ANALYSIS: Experiment March 2021 (E793s)

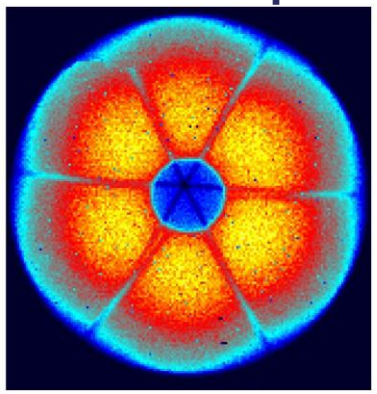
UK AGATA Project (STFC): 2020-24

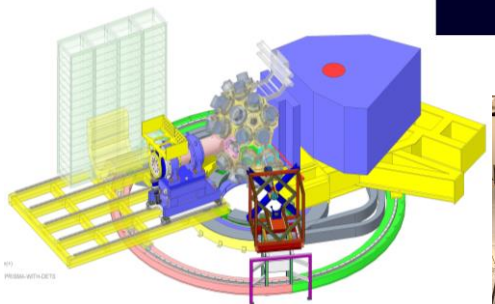
- Next phases of AGATA (SPES and FAIR)
- AGATA triple-cluster modules
- Detector prototyping and characterisation
- Mechanical support structure
- Electronics and Firmware
- **Pulse-Shape Analysis**
- Simulation



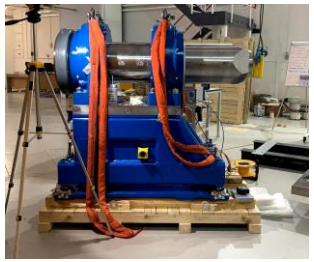
GANIL

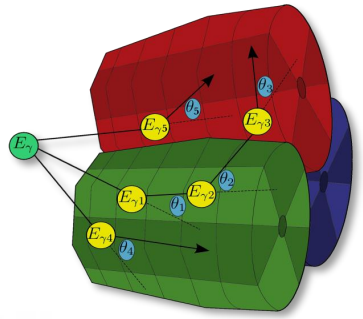
γ-interaction heat map





Support structure at LNL





University of York

University of the West of Scotland UWS

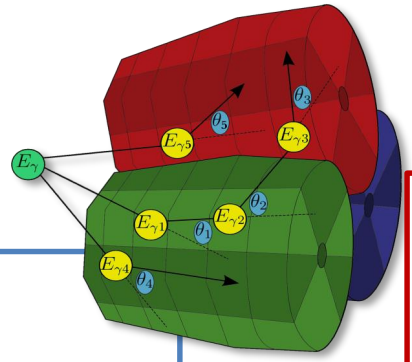
University of Liverpool

Science and Technology Facilities Council

AGATA Advanced Gamma Tracking Array

Challenges in pulse-shape analysis

signal basis generation

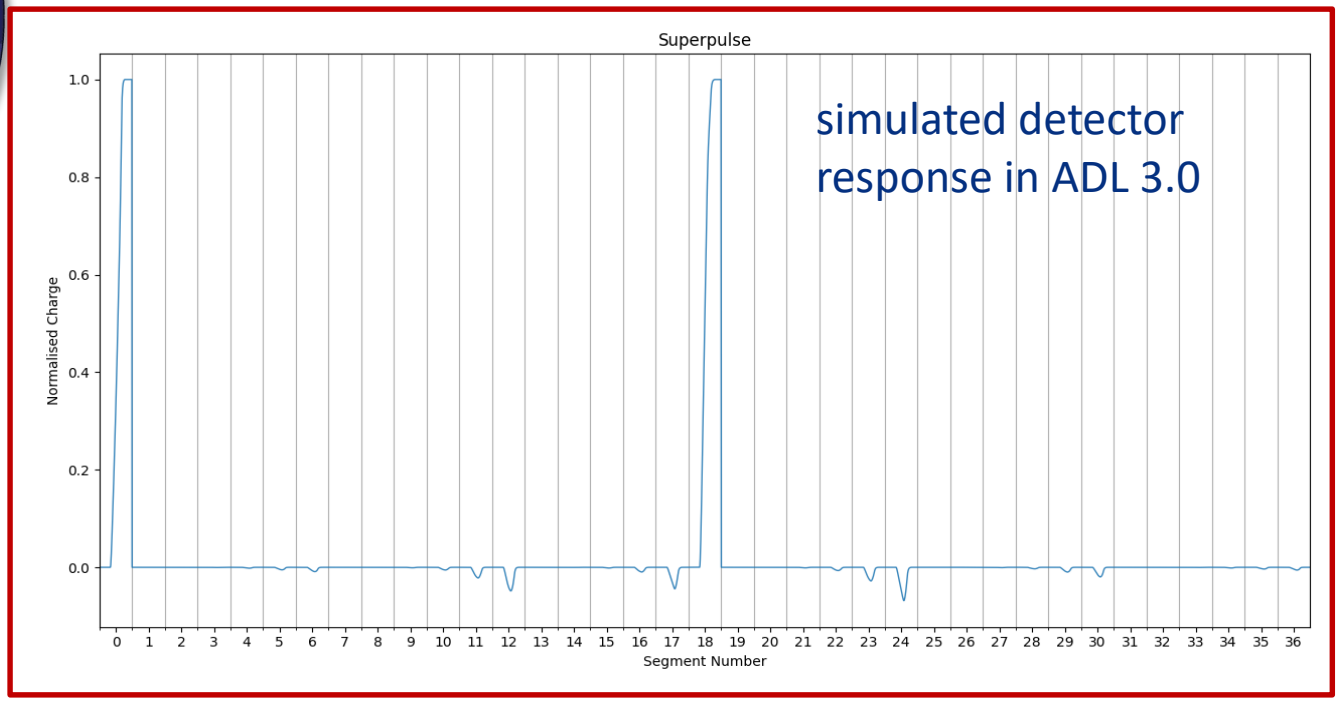


Experimental (scanning)

- long acquisition times
- experimental conditions change

Analytical (calculated)

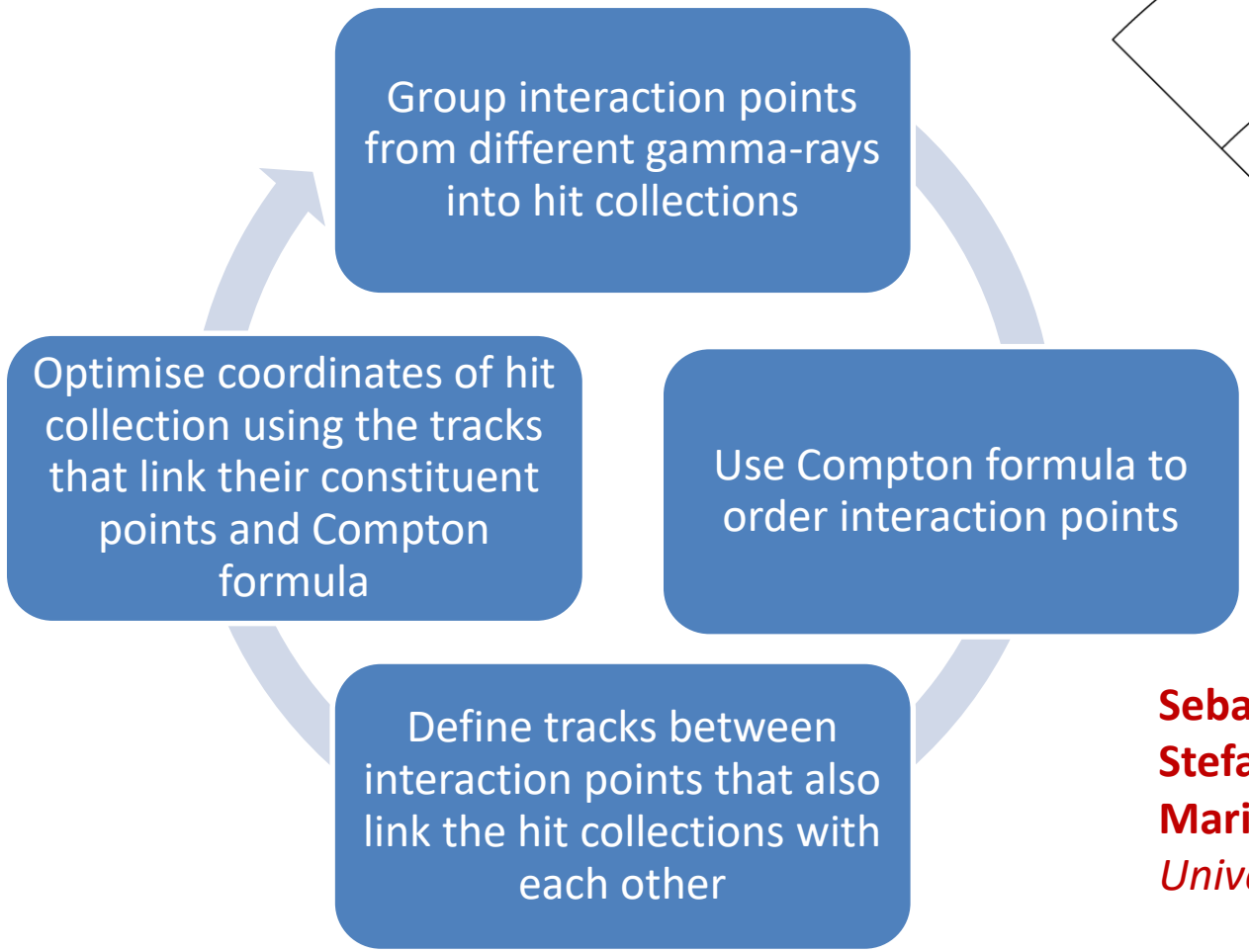
- Physics model, Complex Electric fields
- Impurity/n-damage
- electronics response
- temperature etc

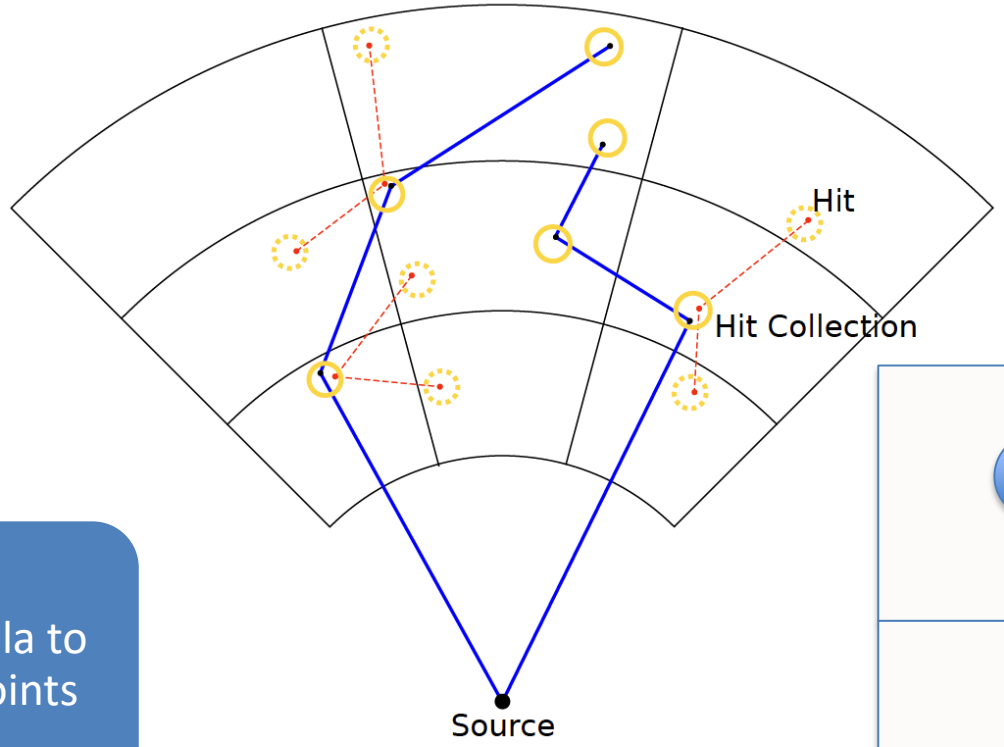


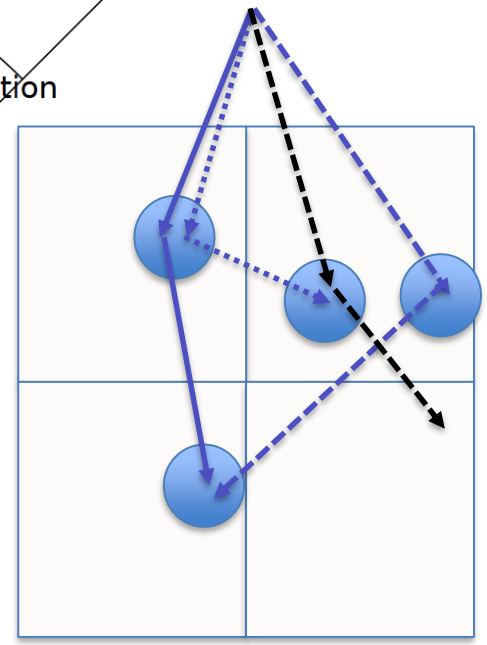
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ADVANCED GAMMA TRACKING ARRAY

PSA Self-calibration (experimental basis set)

- Generate an experimental set of position specific waveforms
- High-statistics source data
- **Iterative process** using Compton-tracking







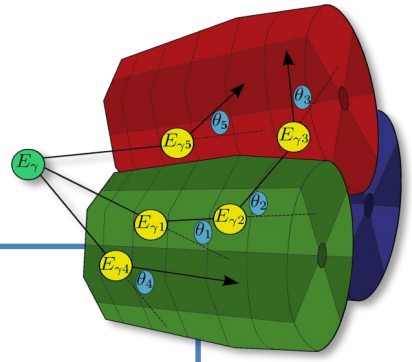
Sebastien Heil
Stefanos Paschalis
Marina Petri
University of York

S.Heil, S.Paschalis and M.Petri. Eur. Phys. J. A (2018) 54: 172

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ADVANCED GAMMA TRACKING ARRAY

Challenges in pulse-shape analysis

signal basis generation



Experimental (scanning)

- long acquisition times
- experimental conditions change

Analytical (calculated)

- Physics model, Complex Electric fields
- Impurity/n-damage
- electronics response
- temperature etc

Signal matching (grid search)

Grid Search

- Require positions at resolution $\leq$ 5mm
- Dataset is ~ 50,000 points (37x121)
- PSA-grid search needs to be very fast (~ ms)

University of Liverpool:

- Experimental validation of Simulation.
- **Machine Learning** for Advanced Signal Inference
- High resolution simulations of new detectors.
- Novel PSA techniques for **accelerated Grid Search**

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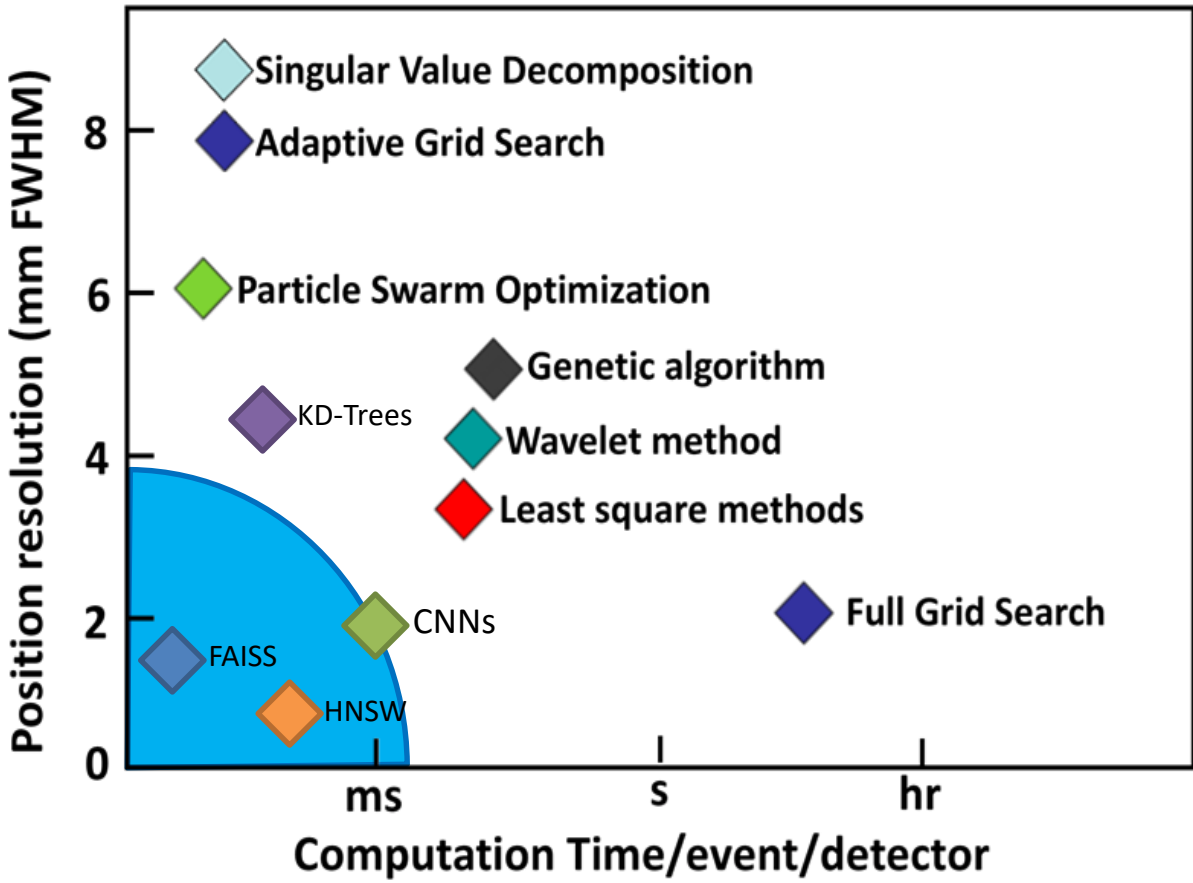
Novel Algorithm Development for PSA

Graph-accelerated techniques try to organize data and form efficient searches

- Search spaces can be Non-Euclidean, Embedded spaces.
- Searching n points can be $\mathcal{O}\log(n)$.
- Processing rates in region (12-400) kHz.

Machine Learning uses a simulated basis to learn trends via inference e.g. Position Regression, Autoencoding & Fold tagging

- No searching is performed whatsoever.
- Simulated basis only needed for training.
- Needs an appropriate model & good data.
- Can be used for hyper-efficient signal compression.
- Useful for determining Fold accurately.

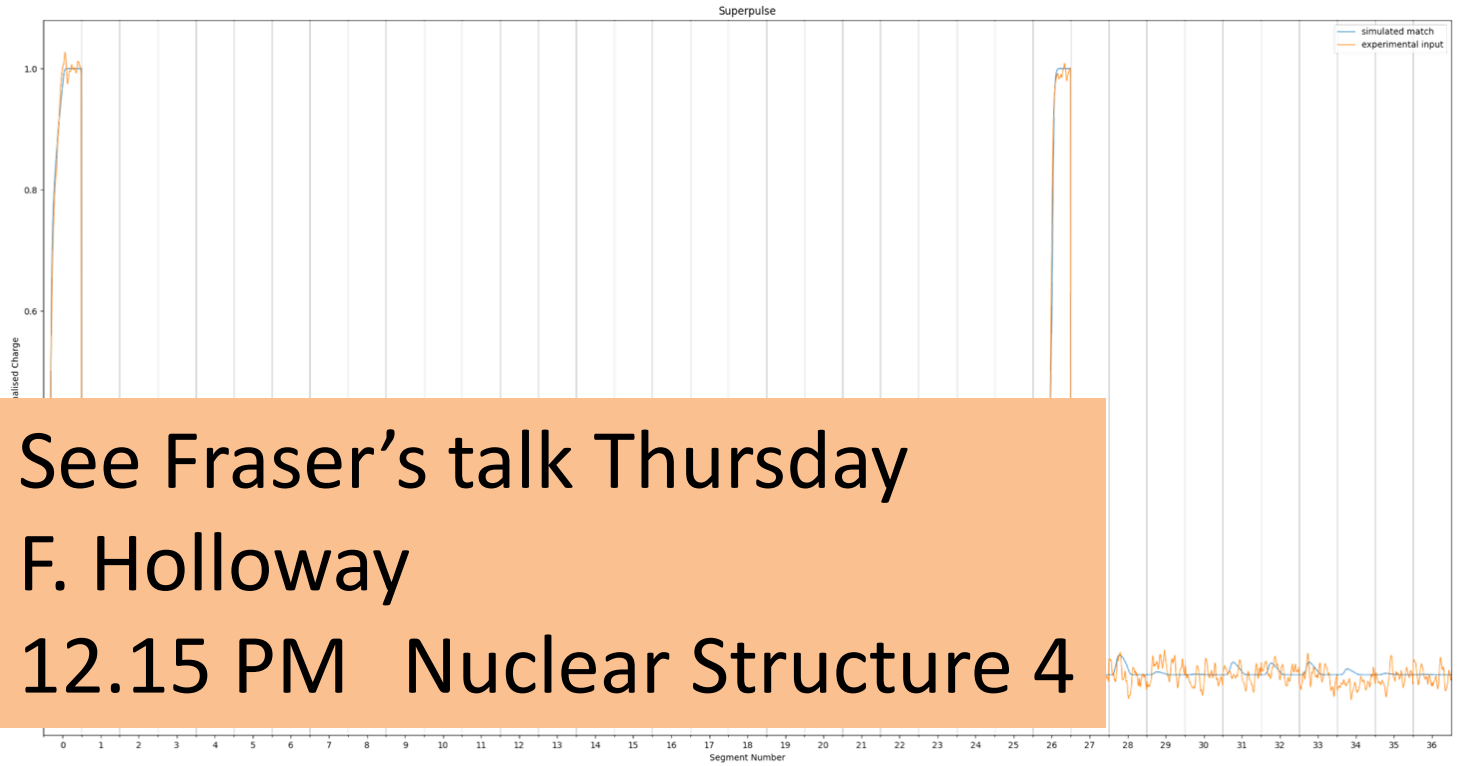


Courtesy of **Fraser Holloway**, University of Liverpool
F.Holloway@liverpool.ac.uk

Novel Algorithm Development for PSA

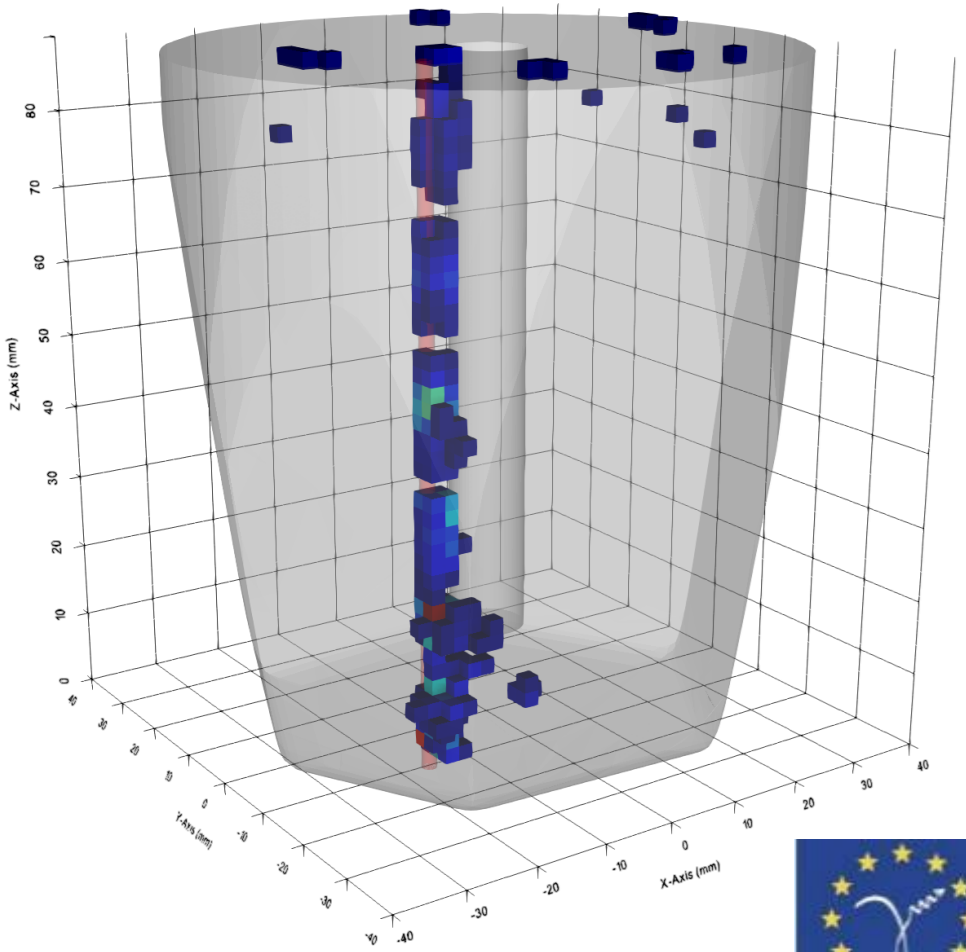
Experimental Results:

Example Optimum Solution for k-NN Method



See Fraser's talk Thursday
F. Holloway
12.15 PM Nuclear Structure 4

Pencil Beam Reconstruction



Courtesy of **Fraser Holloway**, University of Liverpool
F.Holloway@liverpool.ac.uk

Societal Impact of AGATA technology



Scientific Research Curiosity



See Laura Harkness Brennan's talk
Keynote talk
Thursday 10.00



State of the art detectors



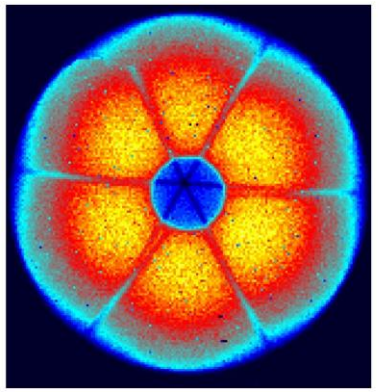


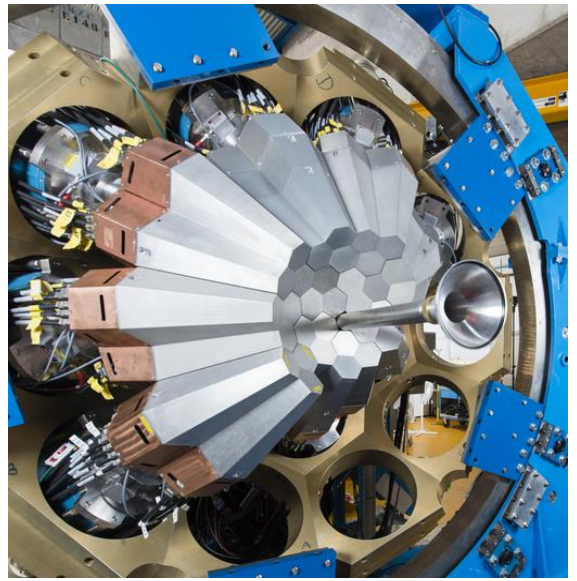
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ADVANCED GAMMA
TRACKING ARRAY

Conclusions and Thanks

AGATA:

- Key device for nuclear physics in Europe
- Capabilities enhance future RIB facilities
- Huge European technical effort





Thanks:

- UKRI-STFC support for AGATA
- Staff at GANIL
- Slides: **Jenn, Wilton, Fraser**
- AGATA collaboration


Thank you
AGATA
ADVANCED GAMMA
TRACKING ARRAY

Physics of AGATA

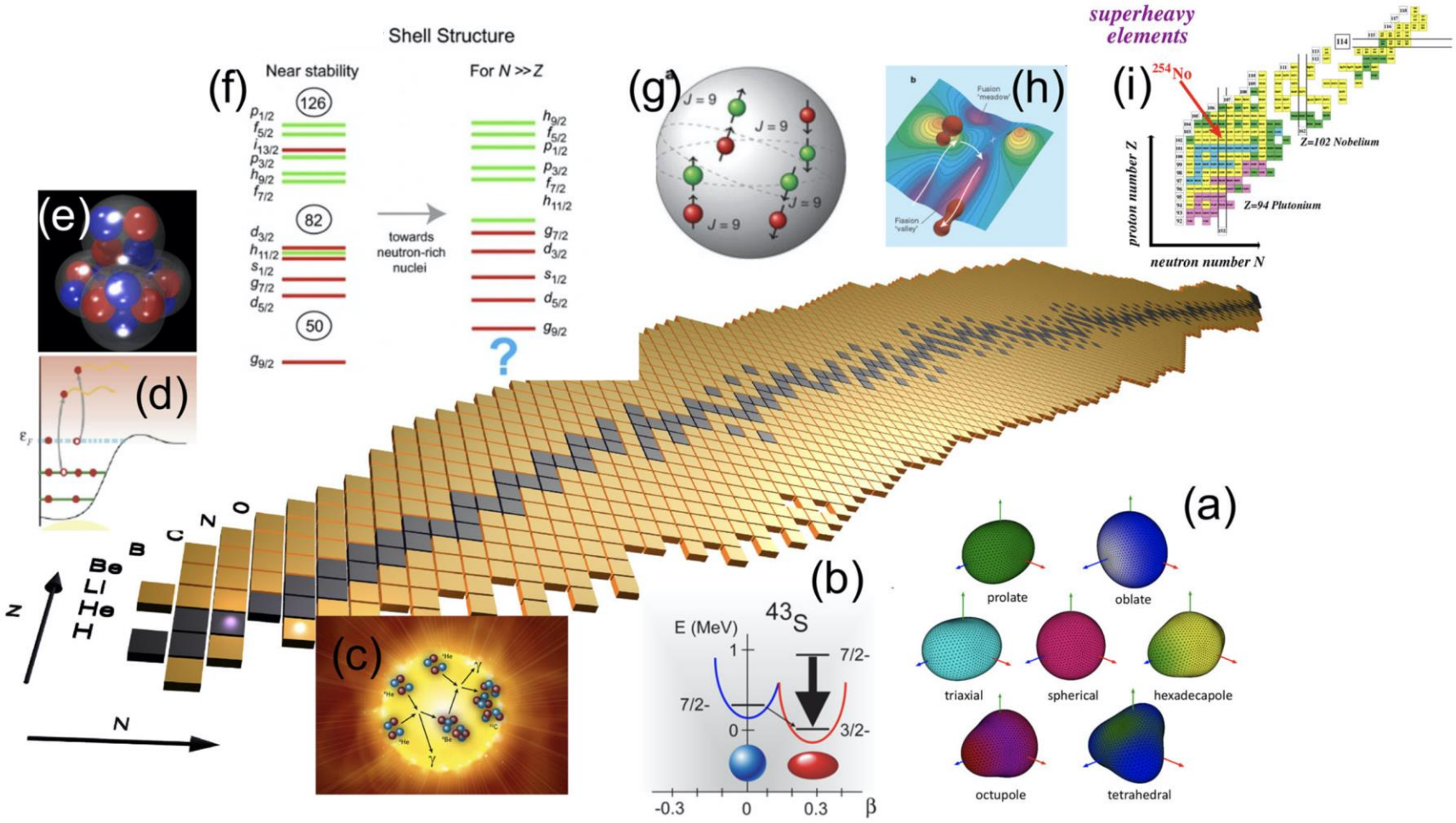
Eur. Phys. J. A (2020) 56:137
https://doi.org/10.1140/epja/s10050-020-00132-w

THE EUROPEAN PHYSICAL JOURNAL A

Review

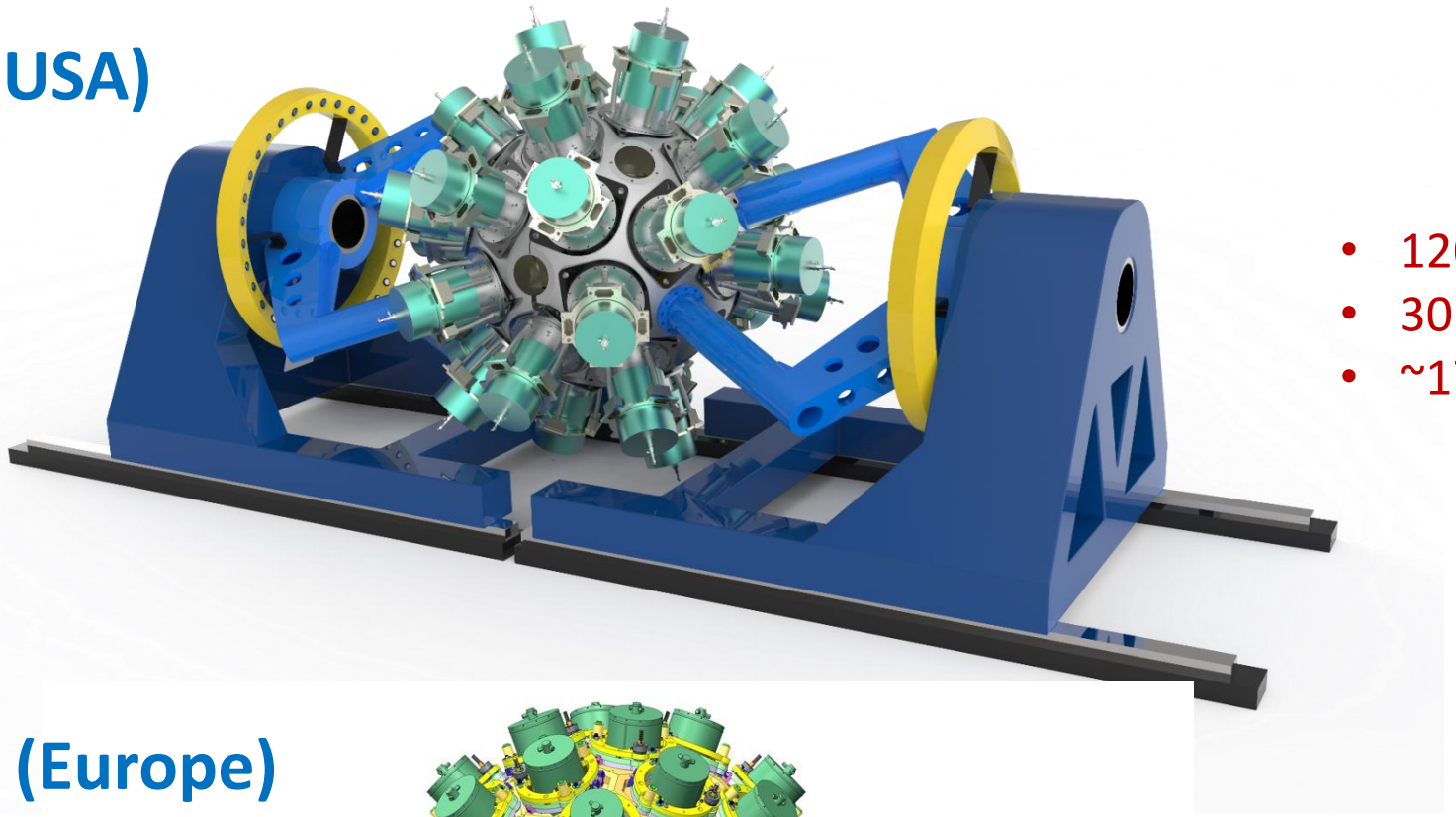
Physics opportunities with the Advanced Gamma Tracking Array: AGATA

W.Korten et al.,
Eur. Phys. J **A56**,
137 (2020)



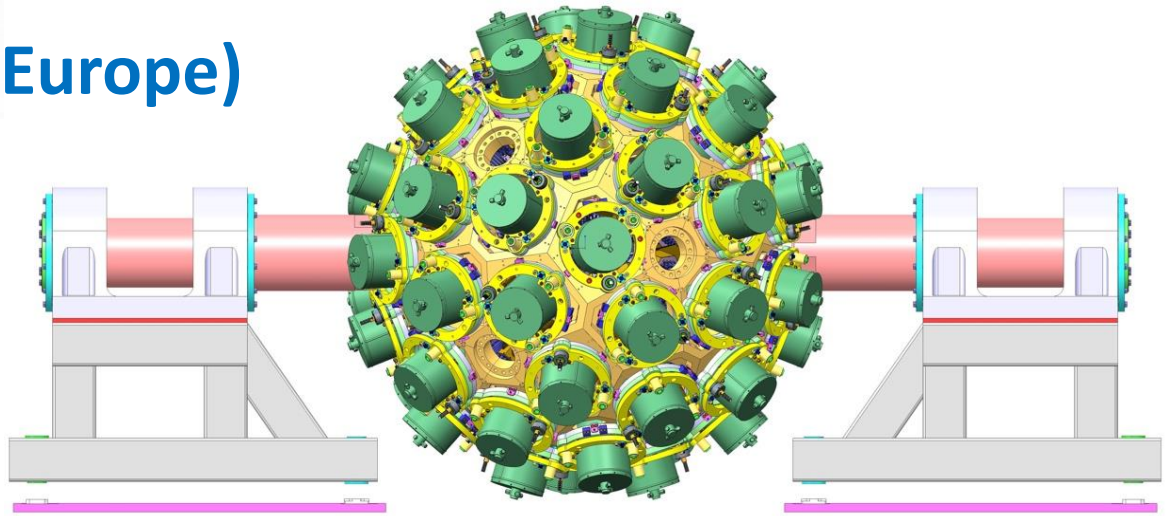
Gamma-Ray Energy Tracking Arrays Worldwide

GRETA (USA)



- 120 Ge crystals
- 30 Quad “modules”
- ~17 cm internal diameter

AGATA (Europe)



- 180 Ge crystals
- 60 Triple “clusters”
- ~23 cm internal diameter

AGATA
ADVANCED GAMMA TRACKING ARRAY

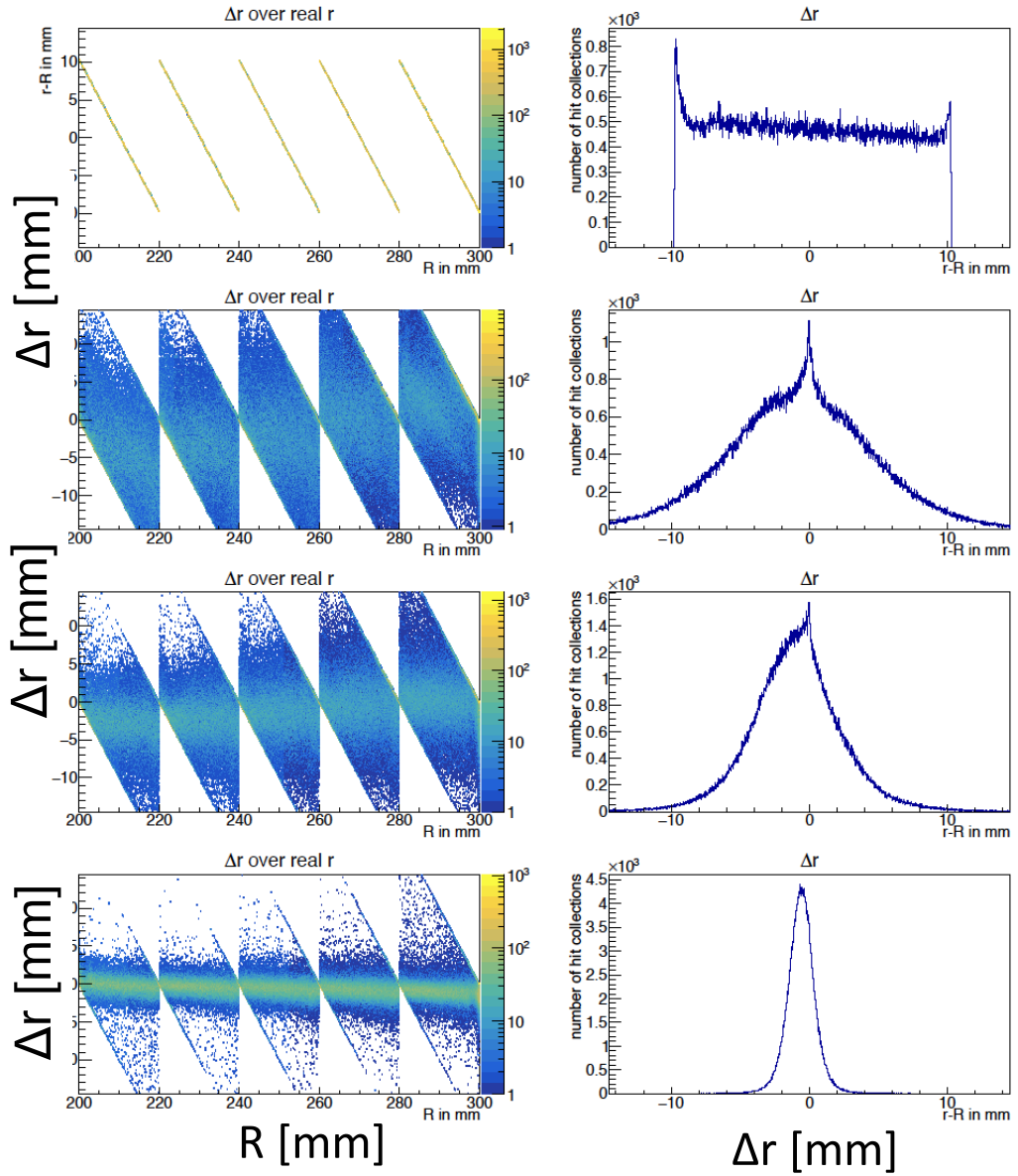
PSA Self-calibration (experimental basis set)

starting condition

after 1st iteration

after 2nd iteration

after 10th iteration



University of York:

- Demonstrated in simulation only
- Needs experimental validation
- Detailed analysis underway

Sebastien Heil
Stefanos Paschalis
Marina Petri
University of York

RMS = 1.2 mm

S.Heil, S.Paschalis and M.Petri.
Eur. Phys. J. A (2018) 54: 172

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ADVANCED GAMMA TRACKING ARRAY