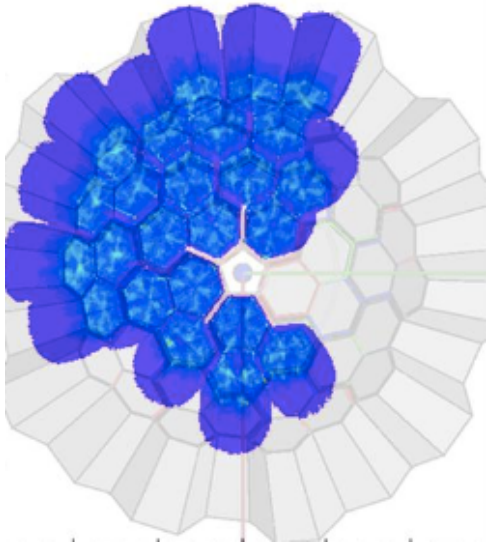
PARIS : A versatile detection array for low and high energy gamma-rays



Olivier Dorvaux, IPHC/University of Strasbourg
for the PARIS collaboration

PARIS (*P*hoton *A*rray for studies with *R*adioactive *I*ons and *S*table beams) is devoted to studies on both nuclear structure and reaction dynamics (exotic collective phenomena including giant resonances and rapid shape transitions, discrete gamma, ...).

To contend with the variety of physics cases (16 @ SPIRAL2), the PARIS array needs to be:

- **as efficient as possible in a wide energy range (from 50 keV to 40 MeV),**
- **with the best possible energy resolution for low energy gamma rays (~4% @ 662 keV),**
- **with a sub-nanosecond time resolution to discriminate gamma-rays against neutrons, (i.e. ~500 ps @ 511 keV**
- **with a high granularity (gamma-ray multiplicity, gamma-ray coincidence, Doppler correction),**
- **able to accept a high counting rate (50 kHz)**
- **modular and position sensitive**
- **transportable (experiments @ different facilities : GANIL/SPIRAL2, IPNO, HIL Warsaw, CCB Krakow, SPES/LNL, HIE-ISOLDE, TIFR Mumbai,…)**
- **as cheap as possible**

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- **as cheap as possible**

First presentation of the PARIS project : Zakopane 2008 by Adam MAJ

(see A. Maj et al., the PARIS project, Acta Physica Polonica B, 40 (2009) 565-575)

the PARIS collaboration

Institutions actively working for PARIS

POLAND (coord.: A. Maj): IFJ PAN Krakow, HIL Warsaw

FRANCE (coord.: I. Matea): INP3: IPN Orsay, IPHC Strasbourg, IPN Lyon, GANIL

INDIA (coord.: V. Nanal): TIFR Mumbai, BARC Mumbai, VECC Kolkata

ITALY (coord.: F. Camera): U. and INFN Milano, LNL Legnaro, LNS Catania

UK (coord.: D. Jenkins): U. York, U. Surrey, STFC Daresbury, U. Manchester

TURKEY (coord.: S. Ertürk): U. Istanbul, U. Nigde, U. Kayseri, U. Akteniz

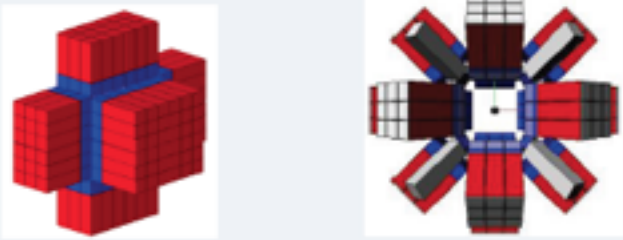
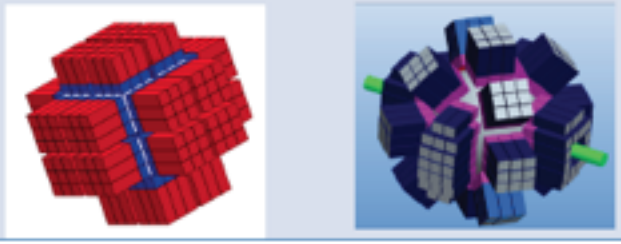
ROMANIA (coord.: F. Negoita) IFIN-HH Bucharest

Courtesy of A. Maj

PARIS Demonstrator MoU and PARIS phases

MoU on PARIS Demonstrator (Phase 2) was prepared and agreed to be signed by IN2P3 (France), COPIN (Poland), GANIL/SPIRAL2 (France), TIFR/BARC/VECC (India), IFIN HH (Romania), INFN (Italy), UK, Turkey

PARIS phases and cost estimates

Phase 1 **2011/2012** PARIS cluster	1 cluster: 9 phoswiches		250 k€	**Decided** Funds: SP2PP, ANR, Orsay, Strasbourg, Kraków, Mumbai Tests in-beam and with sources
Phase 2 2018 PARIS Demonstrator	5 clusters: 45 phoswiches		1100 k€	**Only if Phase1 validated** Funds: MoU Ph1Day1 exp@S3
2020 PARIS 2π	12 clusters: 108 phoswiches		≈ 2 M€	**Only if Phase2 validated** Funds: MoU, PARIS consortium Ph2Day1 exp. with AGATA and GASPARD Other exp.
Phase 4 2022? PARIS 4π	≥24 clusters: ≥216 phoswiches		≈ 4 M€	**Only if Phase3 validated** Funds: PARIS consortium Regular experiments in various labs

IPN Orsay

AGATA@GANIL

S3@GANIL

CCB Krakow

LNL/SPES

SPIRAL2 phase2

Courtesy of A. Maj

the PARIS collaboration

Since 2012 (after MoU was signed)
New organization of PARIS

PARIS Steering Committee
(by nominations of the MoU partners):

- **IN2P3 France: F. Azaiez**
- **GANIL France: M. Lewitowicz**
- **COPIN Poland: B. Fornal (dep.chair)**
- **India: V. Nanal (chair)**
- **Italy: A. Bracco**
- **Romania: F. Negoita**
- **UK: D. Jenkins**
- **Turkey: S. Erturk**
- **Bulgaria: D. Balabanski**

PARIS Project Manager
(nominated by PSC)
A. Maj (Poland)

Courtesy of A. Maj

Working Groups and their Coordinators
(proposed by PPM and aproved by PSC):

Geant4 simulation: **O. Stezowski** (Lyon)
Detectors: **O. Dorvaux** (Strasbourg)
Electronics and DAQ: **P. Bednarczyk** (Krakow)
Mechanical integrations: **I. Matea** (Orsay)
Data analysis: **S. Leoni** (Milano)
New materials: **F. Camera** (Milano)
New Physics case: **I. Mazumdar** (Mumbai)

PARIS Management Board:
PARIS Project Manager + WG coordinators

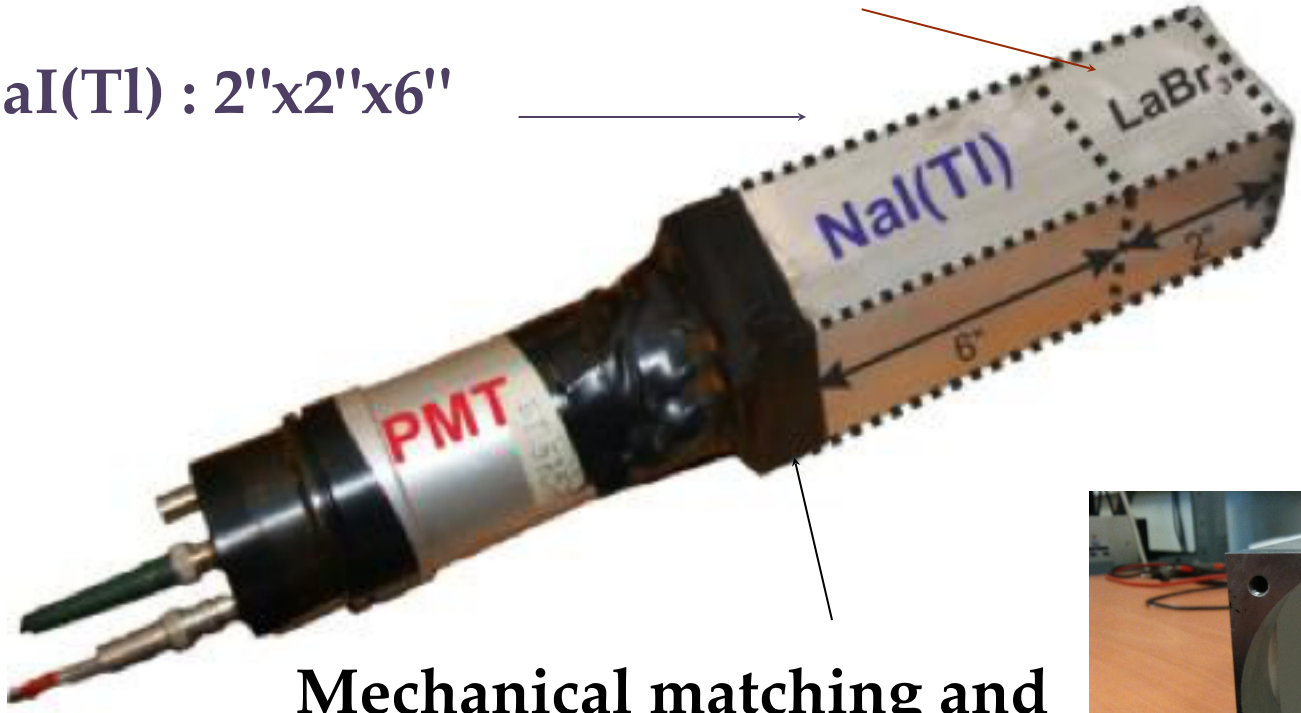
Campaign Spokesperson
(nominated by lab directors):
GANIL: C. Schmitt
IPN Orsay: I. Matea

the PARIS design

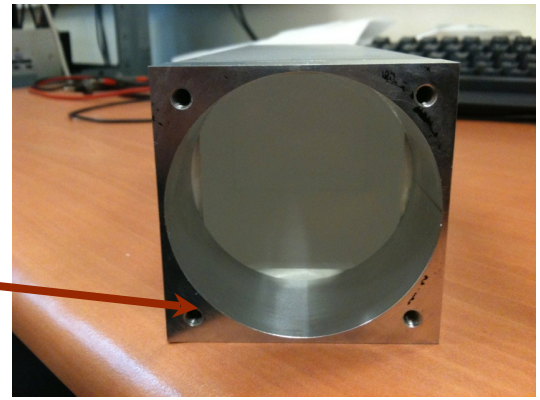
Choice is based on a « Phoswich » solution manufactured by Saint-Gobain Crystals encapsulated in 0,5 or 1 mm Al cap (+coating 0,3mm) and composed by two shells :

LaBr3(Ce) : 2''x2''x2''

NaI(Tl) : 2''x2''x6''



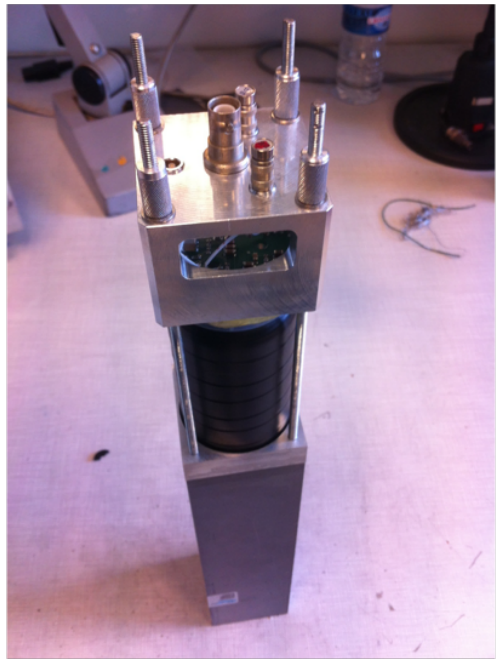
Mechanical matching and PM tube fixing



the PM tube

the PM tube

- Coupling with a R7723-100 Hamamatsu PM tube (high QE, good linearity, low gain, …) fixation with rods for a better stability
- Home made IPHC Voltage divider
  - design based on the Hamamatsu one (E5859-15MOD D Type Socket)
  - new PCB
  - Anode and 2 dynodes (between 6,7 and 8) outputs



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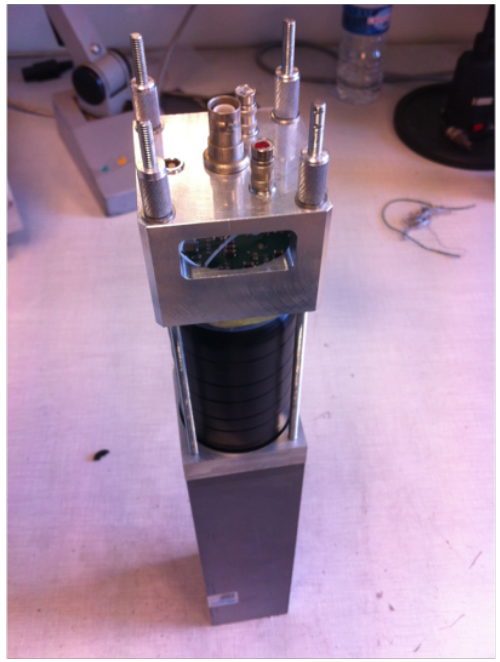
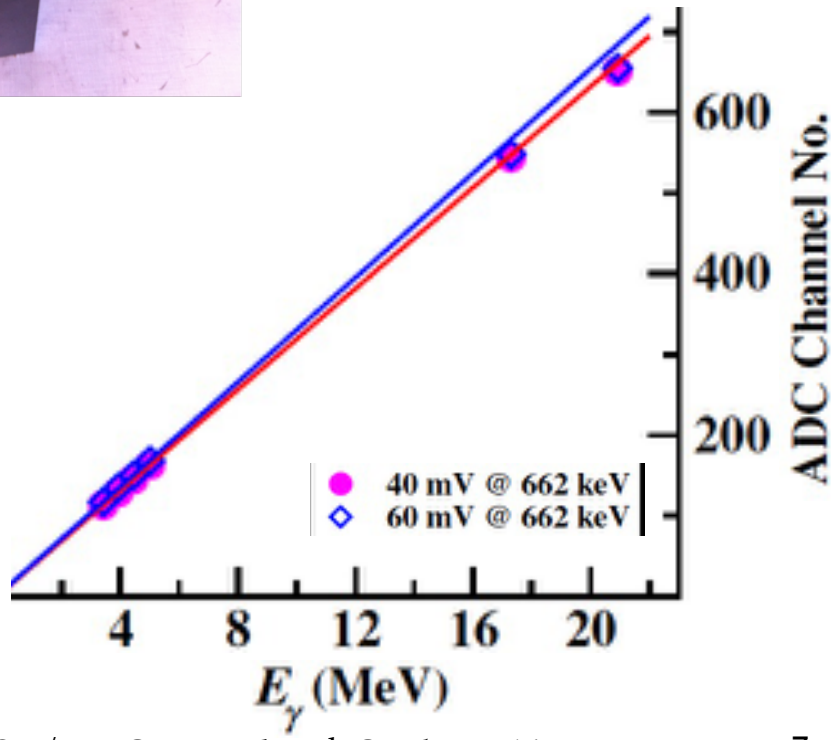
    - **and has shown a remarkable linearity up to 22 MeV γ-rays**

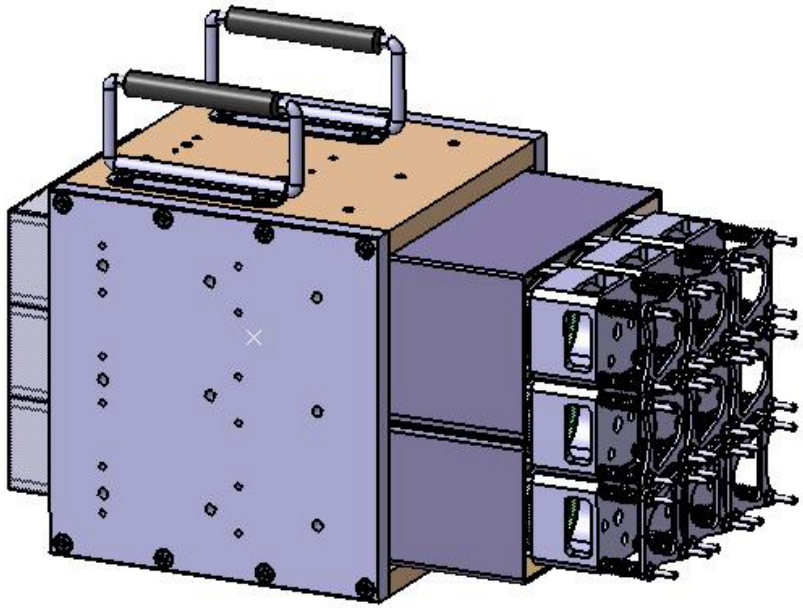
(see C. Ghosh et al., JINST 11 P05023 (2016))



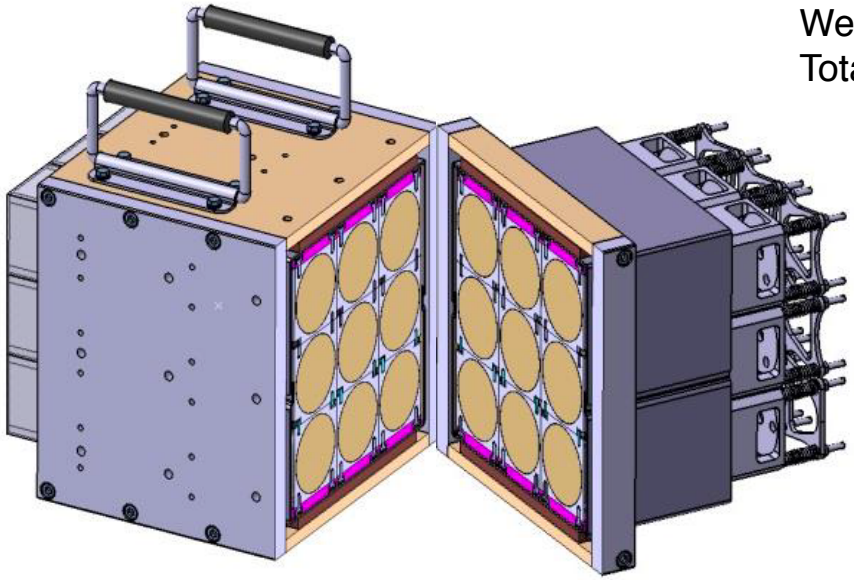


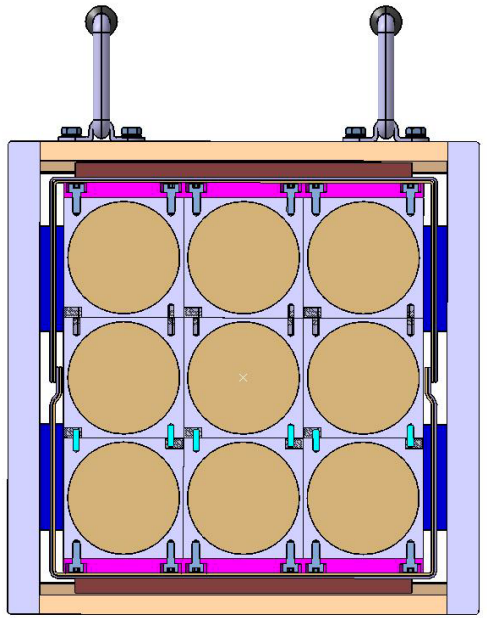
the mechanical design

- **Special mechanical design to ensure the optical coupling and compatible with the assembly in a "cluster" configuration of 9 phoswiches**



Weight 9 cristal LaBr3+NaI ~ 23 kg
Weight cluster ~ 11 kg
Total ~ 34 kg

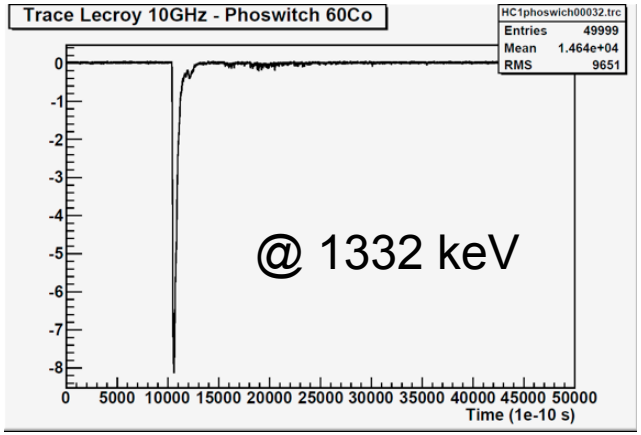




Courtesy of G. Minier, IPN Orsay

the Paris performances : 2 crystals - 1 output signal

γ interaction in $LaBr_3$ only



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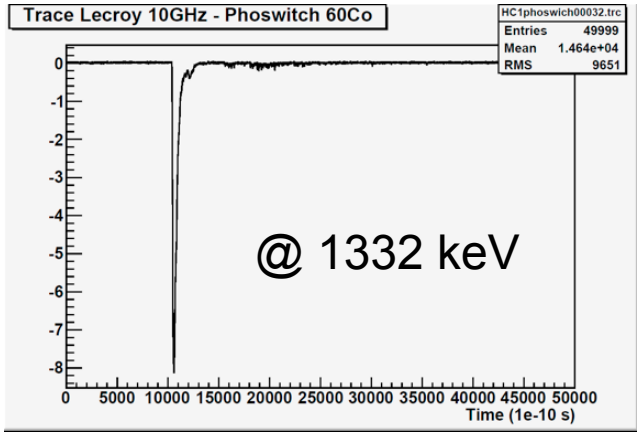
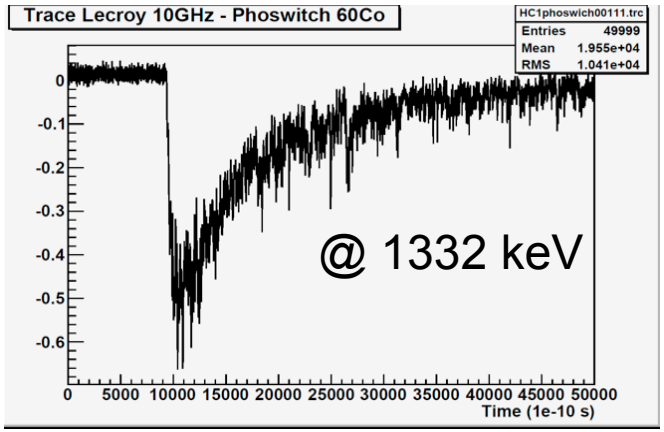


γ interaction in NaI only



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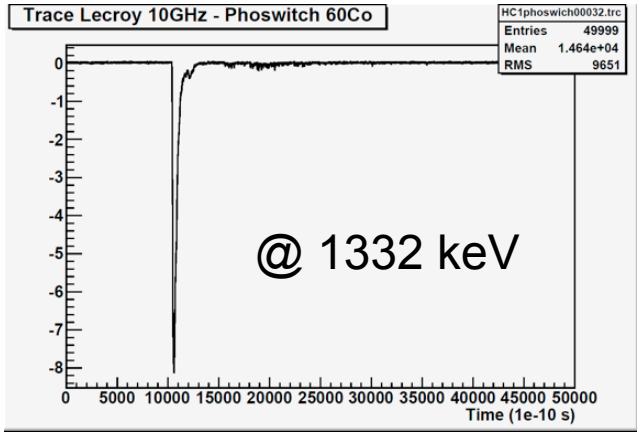

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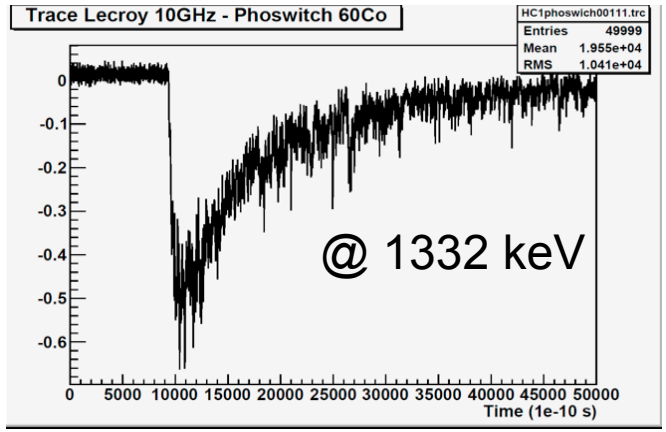
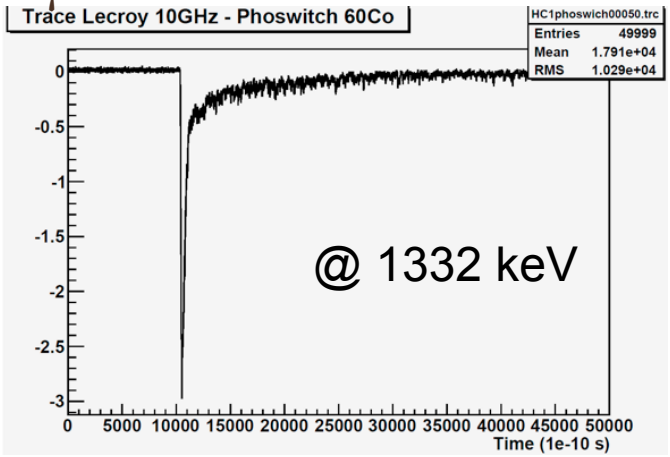


γ interaction in both shells



the Paris performances : 2 crystals - 1 output signal

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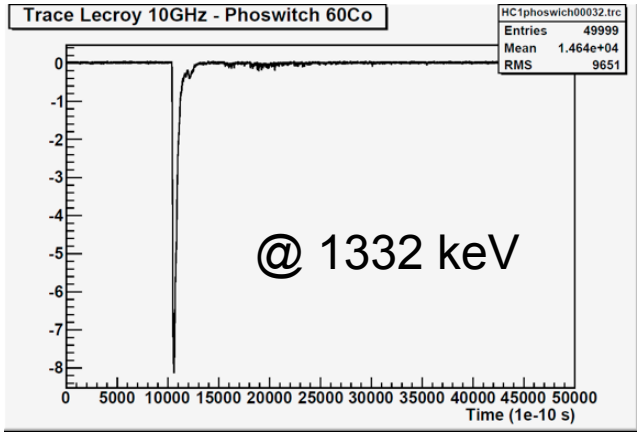

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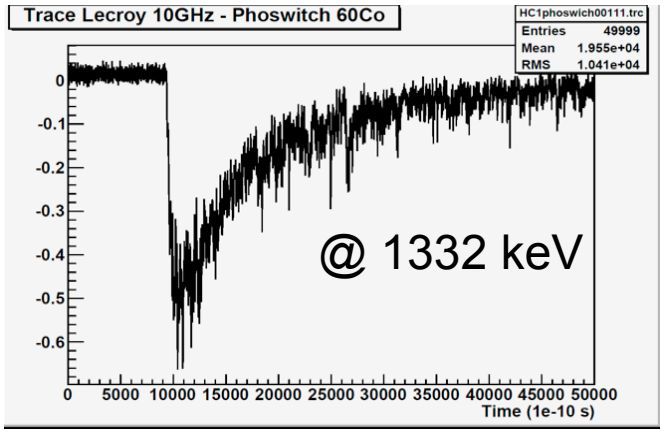

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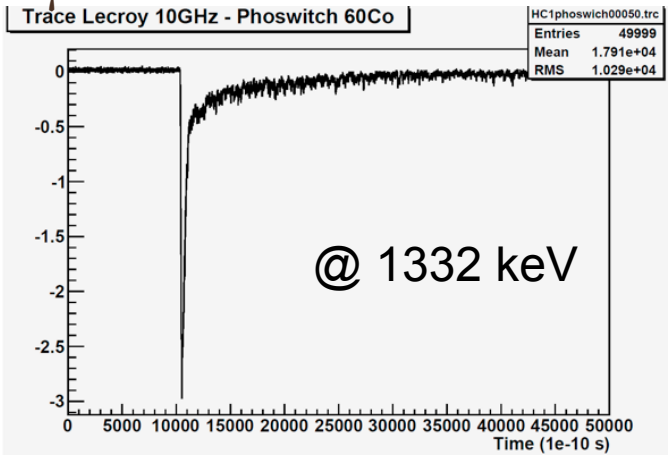
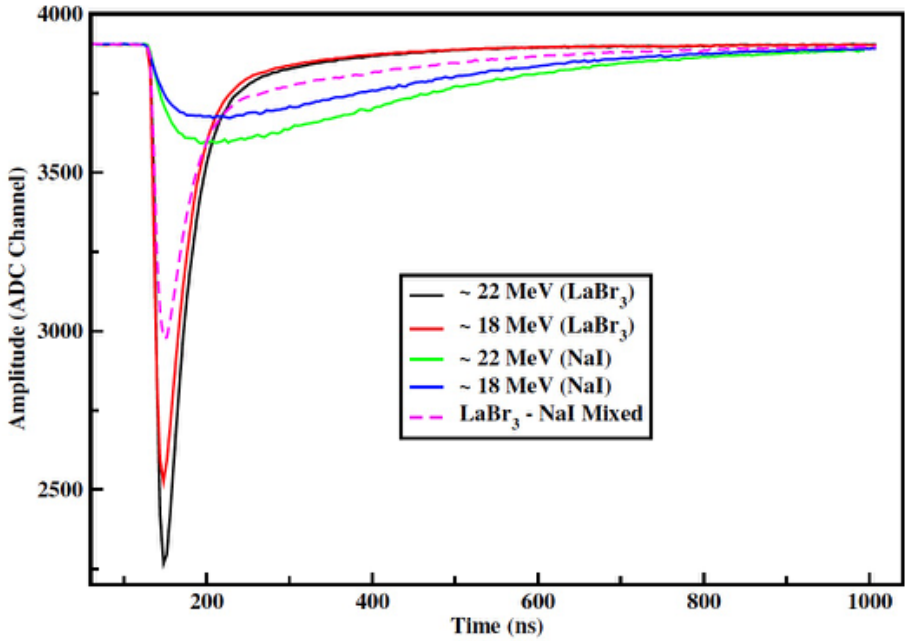
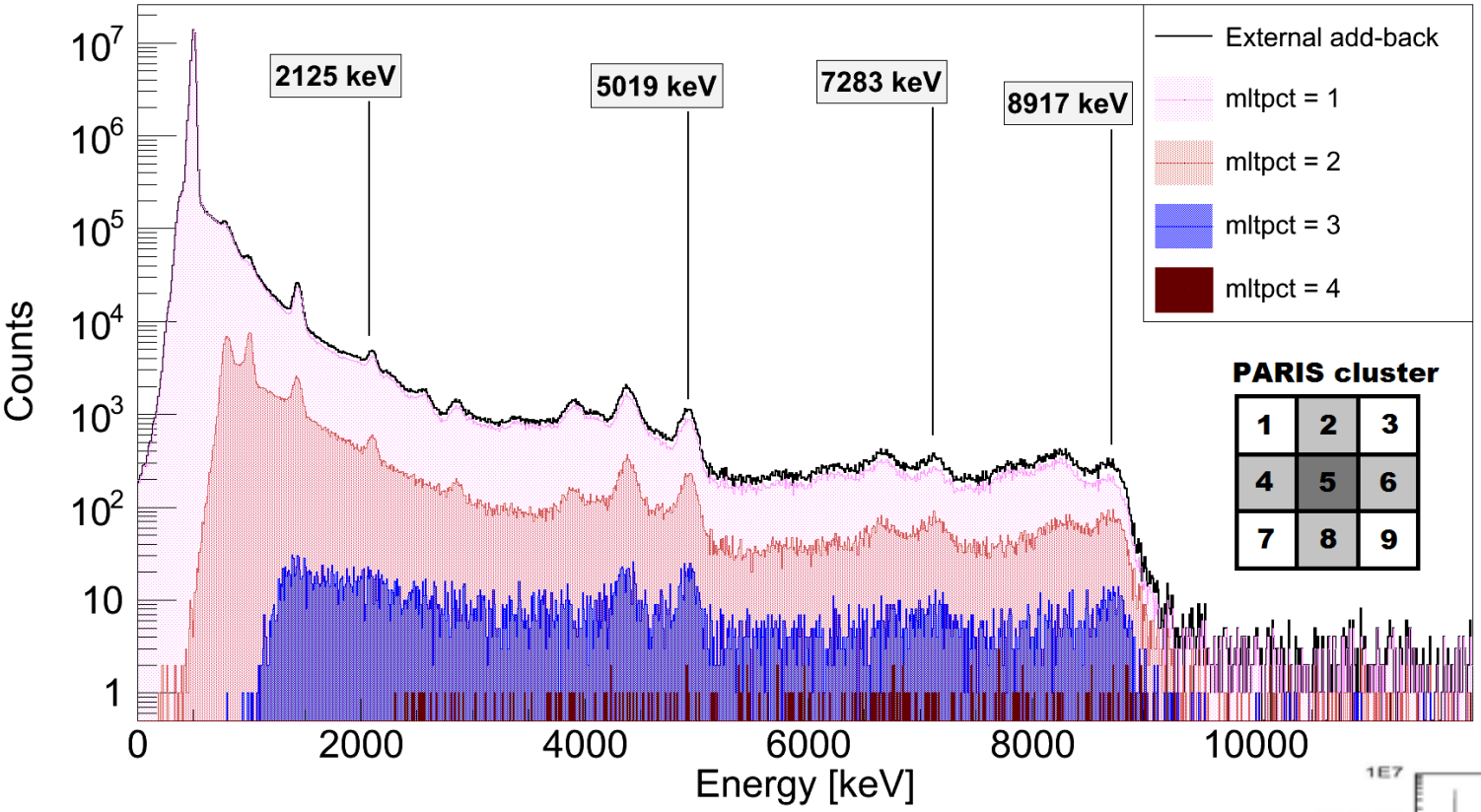




@ 18 and 22 MeV

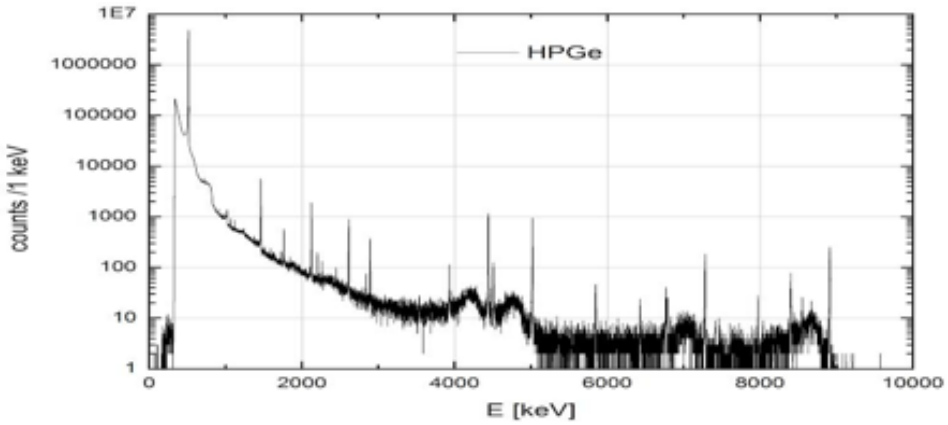
(see C. Ghosh et al., JINST 11 P05023 (2016))

the Paris performances : using analog electronics (BaFPro module from MILANO)



ELBE facility, Dresden 10-12 December, 2013
Nuclear Resonance Fluorescence experiment (Mazumdar, Maj, Schwengner)

Electron beam converted into Bremsstrahlung (γ energy up to 15.6 MeV)



(see B. Wasilewska and al. in: O. Roberts, L. Hanlon, S. McBreen (Eds.) Applications of Novel Scintillators for Research and Industry, Iop Publishing Ltd, Bristol, 2015

the Paris performances : using digital electronics

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^{60}Co+^{137}Cs sources placed in front @ 7-40 kHz

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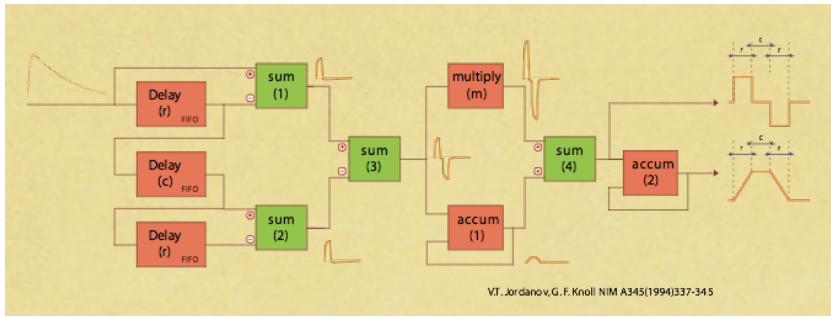
- **Triggerless digital 100 MHz electronics TNT2 using an algorithm based on the Jordanov trapezoïdal method**



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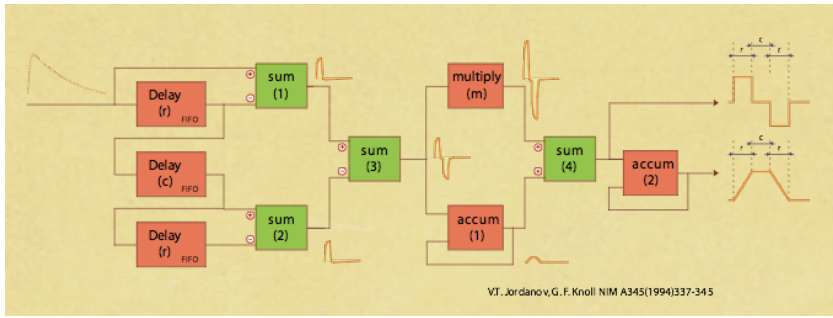

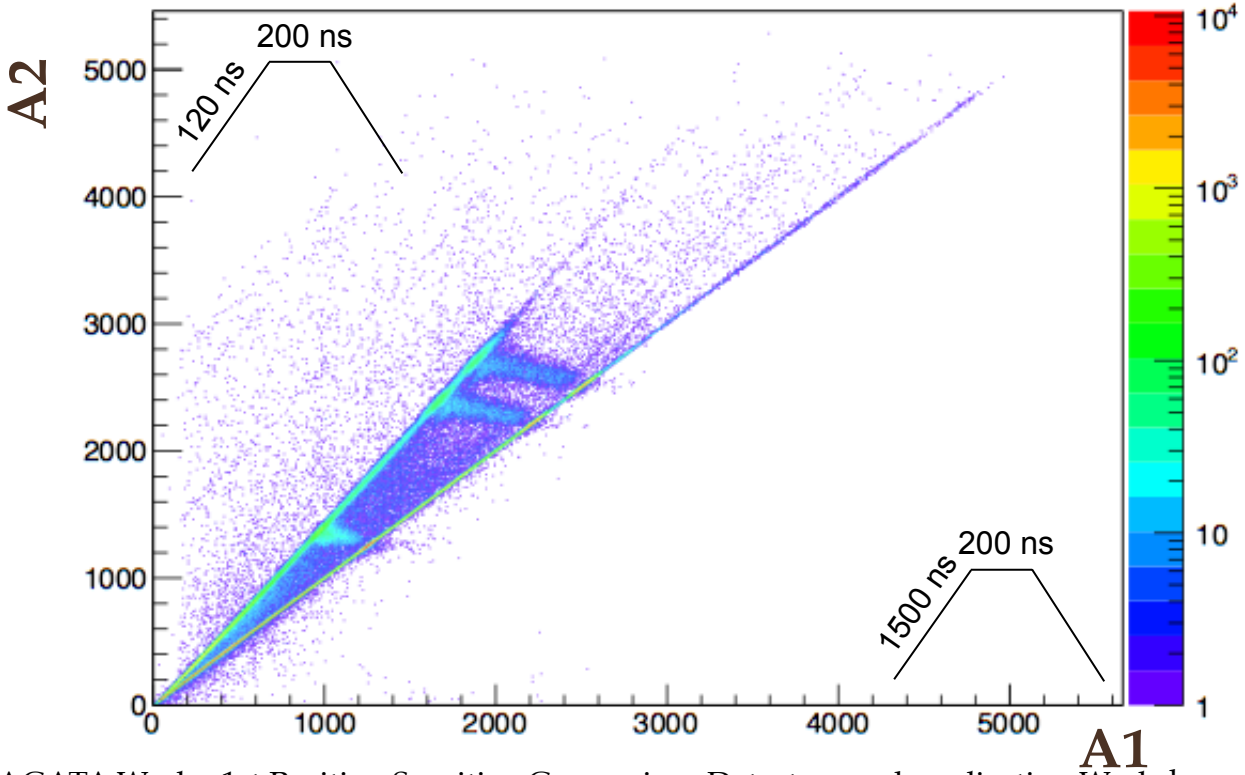

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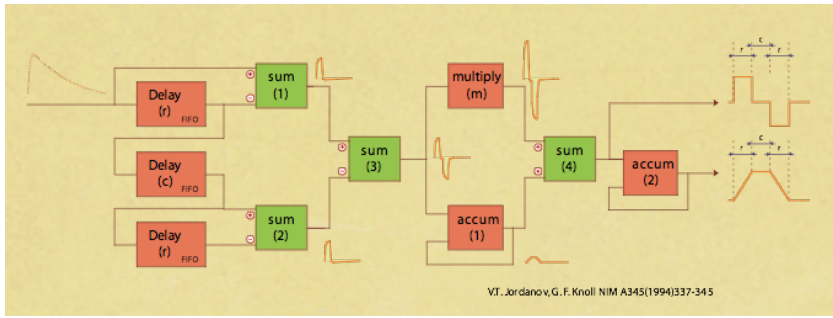
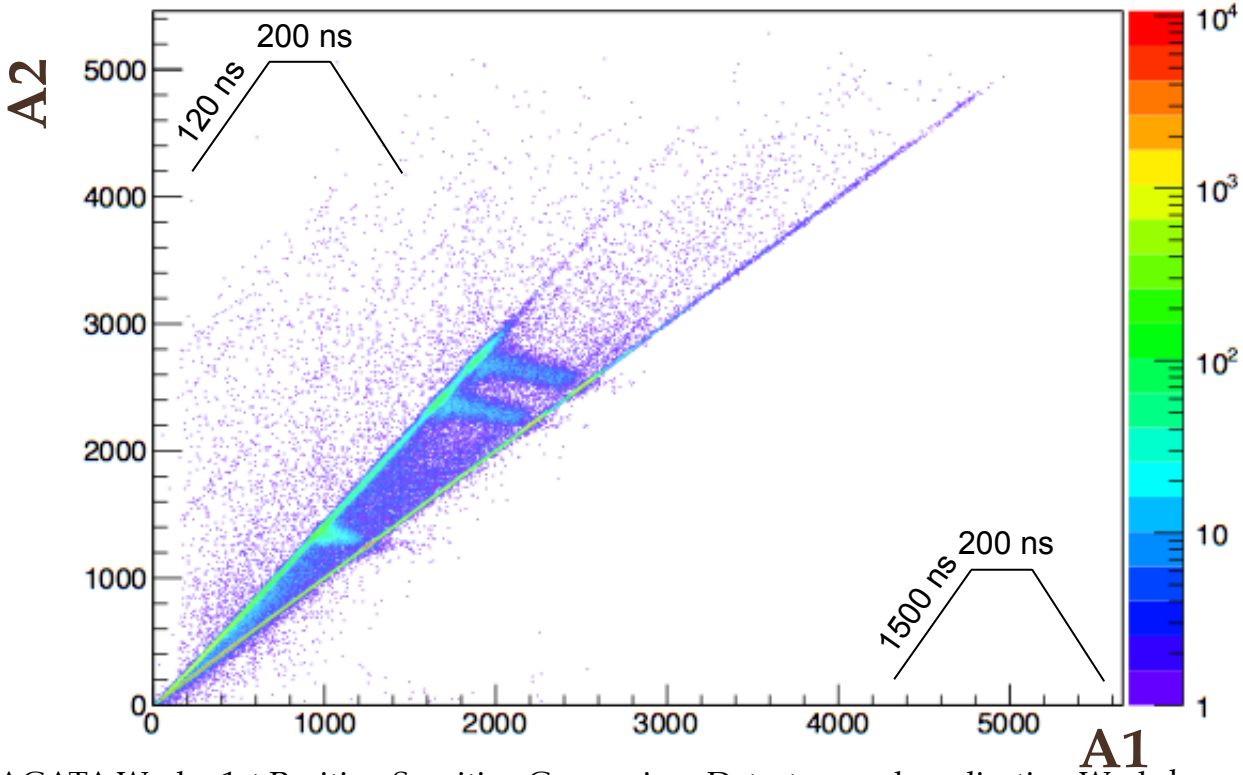
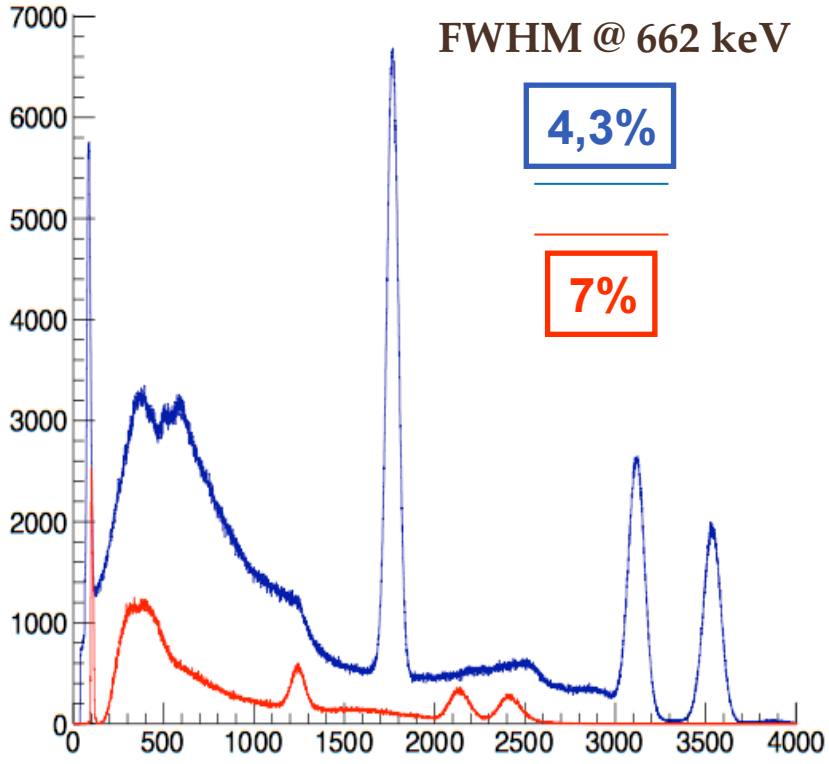
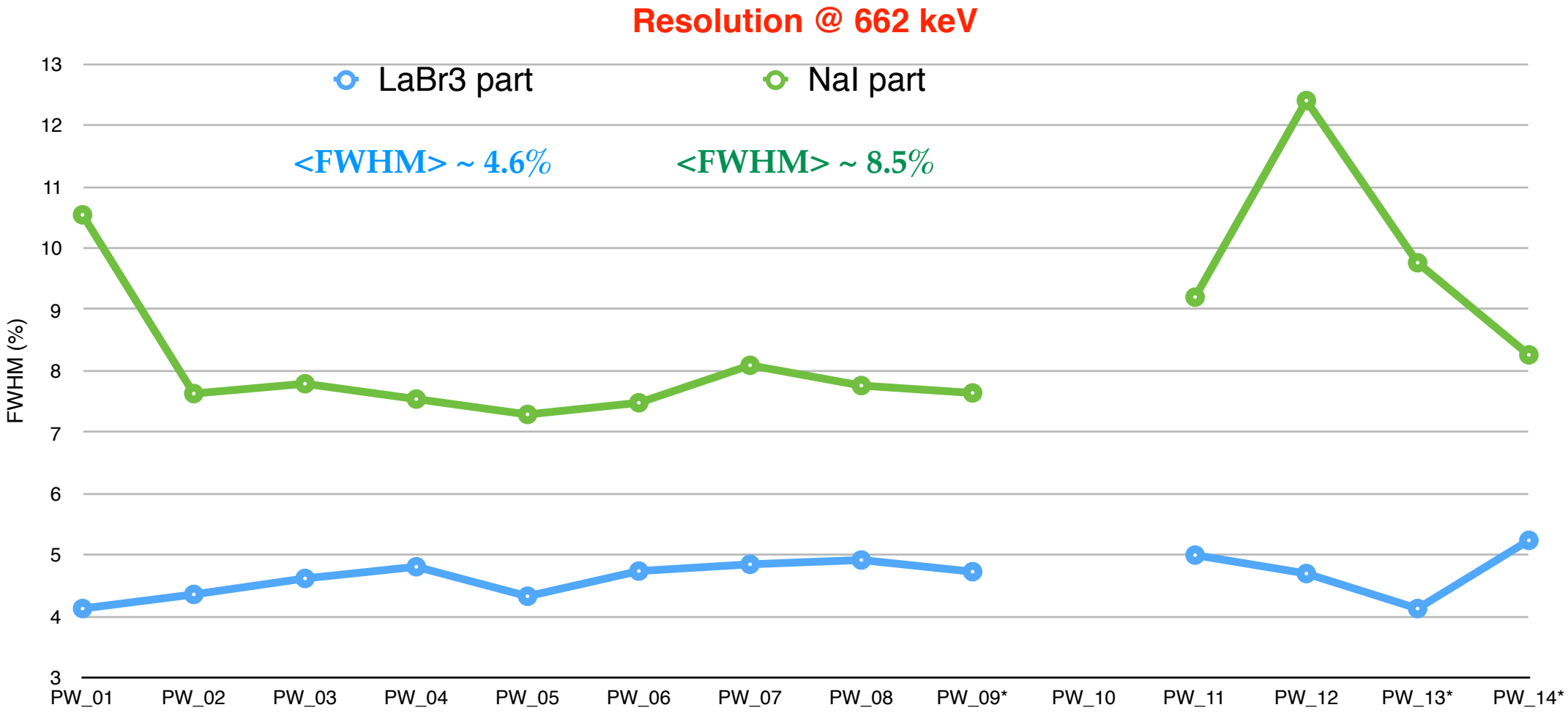




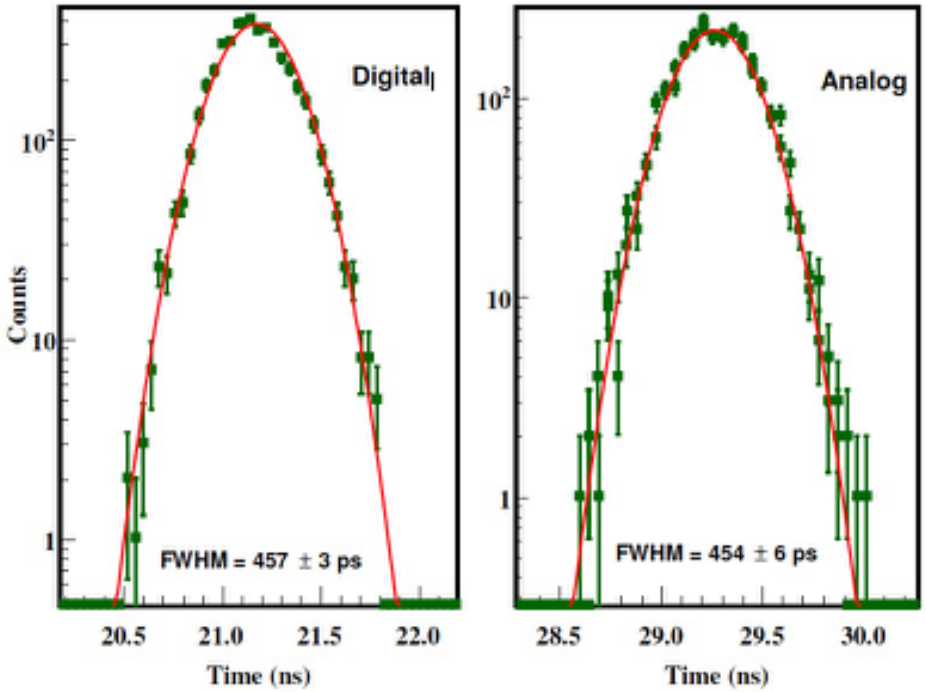


the Paris performances : energy resolution



the Paris performances : time resolution

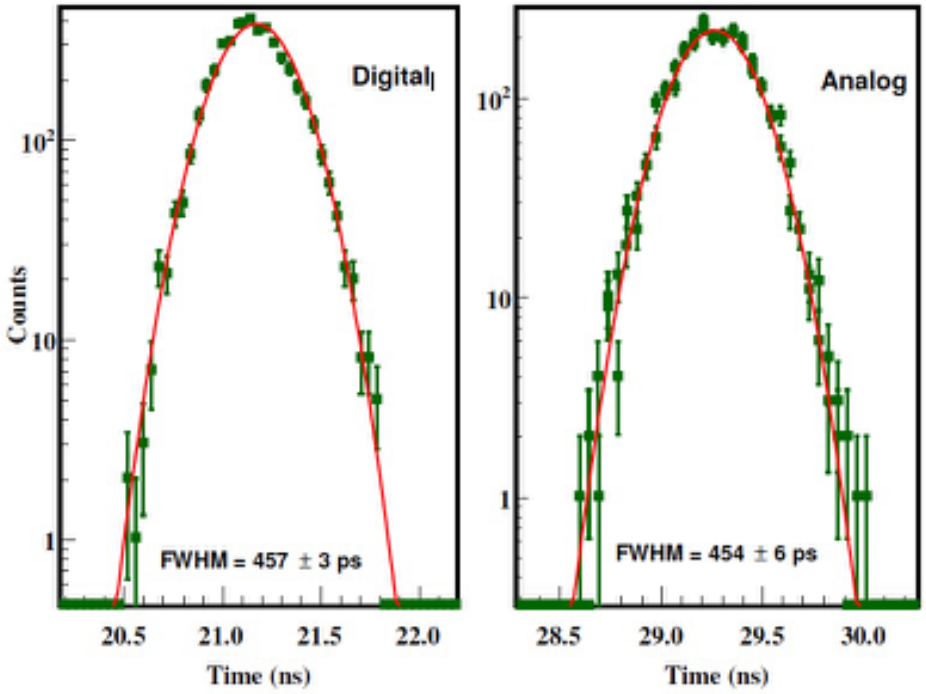
(see C. Ghosh et al., JINST 11 P05023 (2016))



done with V1751 CAEN digitizer 10 bits/1GHz

the Paris performances : time resolution

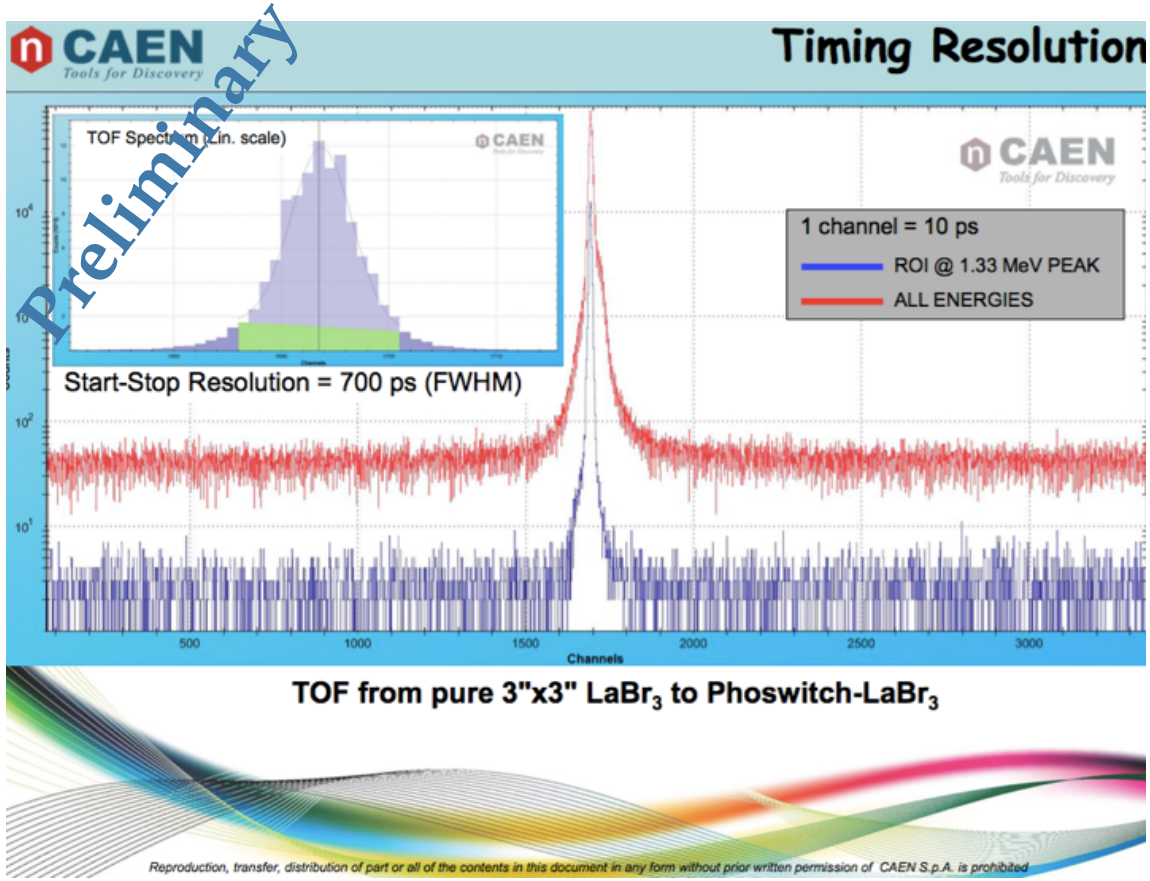
(see C. Ghosh et al., JINST 11 P05023 (2016))



done with V1751 CAEN digitizer 10 bits/1GHz

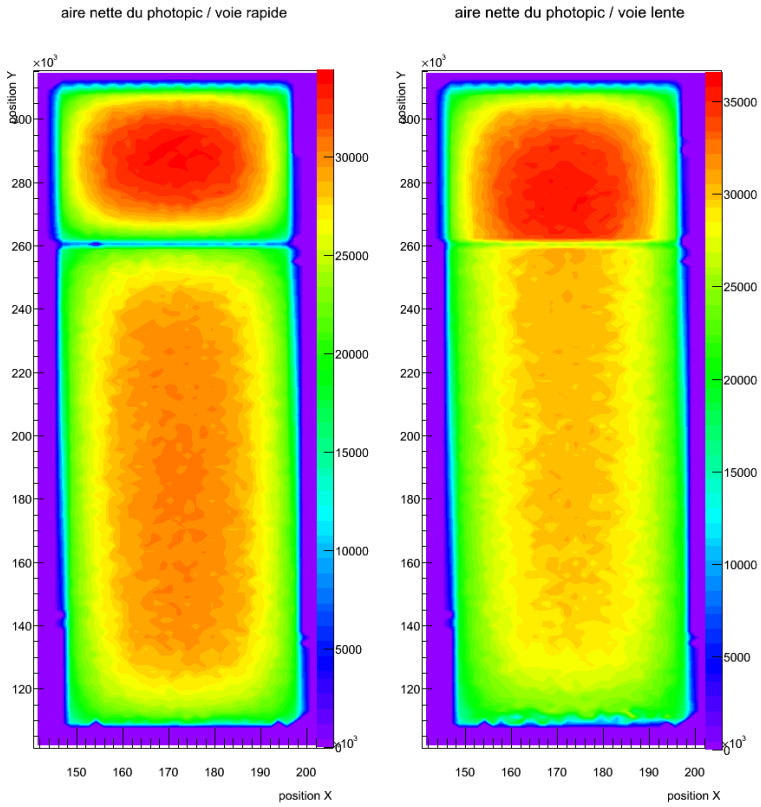
KRAKOW/MILANO/CAEN Collaboration

V1730 digitizer 14 bits/ 250 MHz



the scan of phoswiches : 1500 points

thanks to the AGATA collaboration for the scanning table@IPHC



~efficiency

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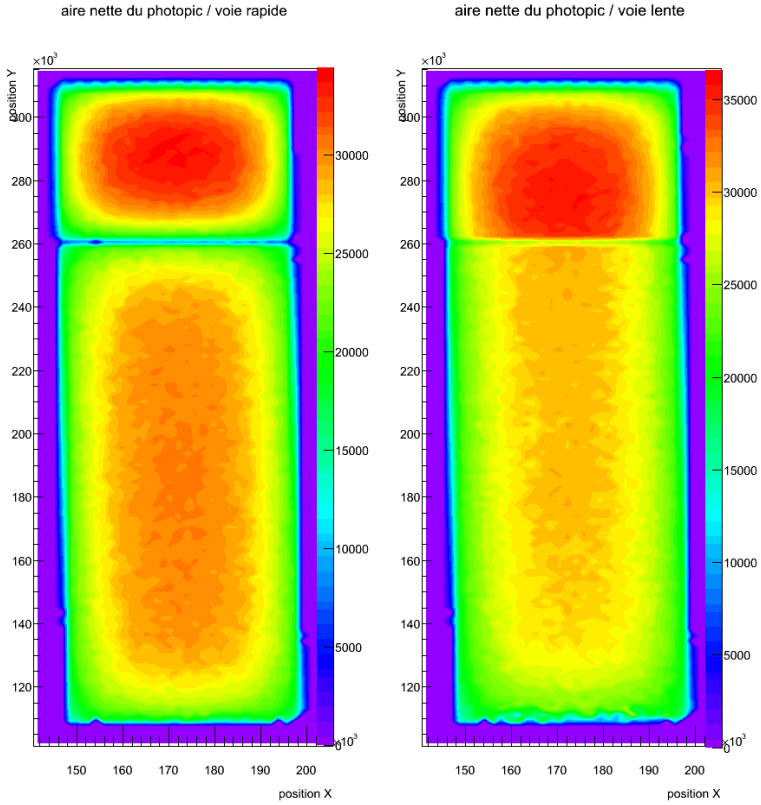
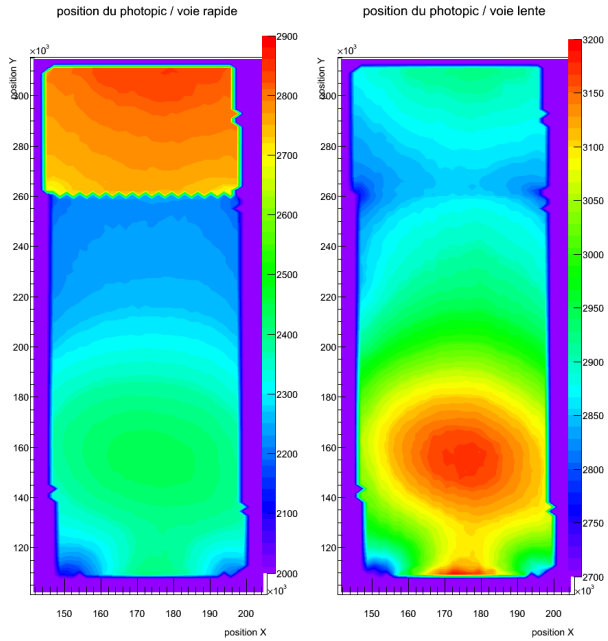


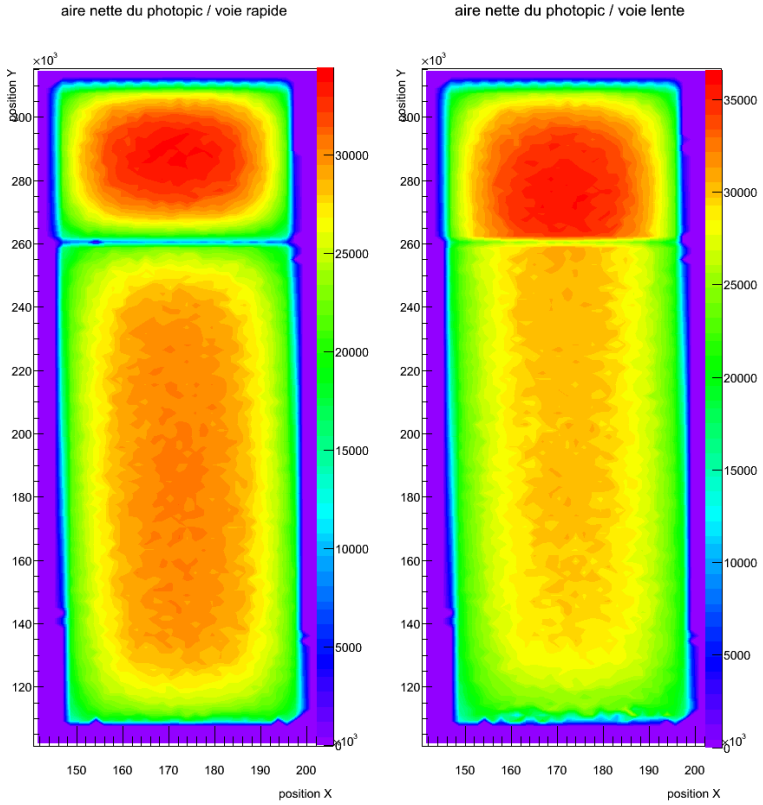
~efficiency



~light collection

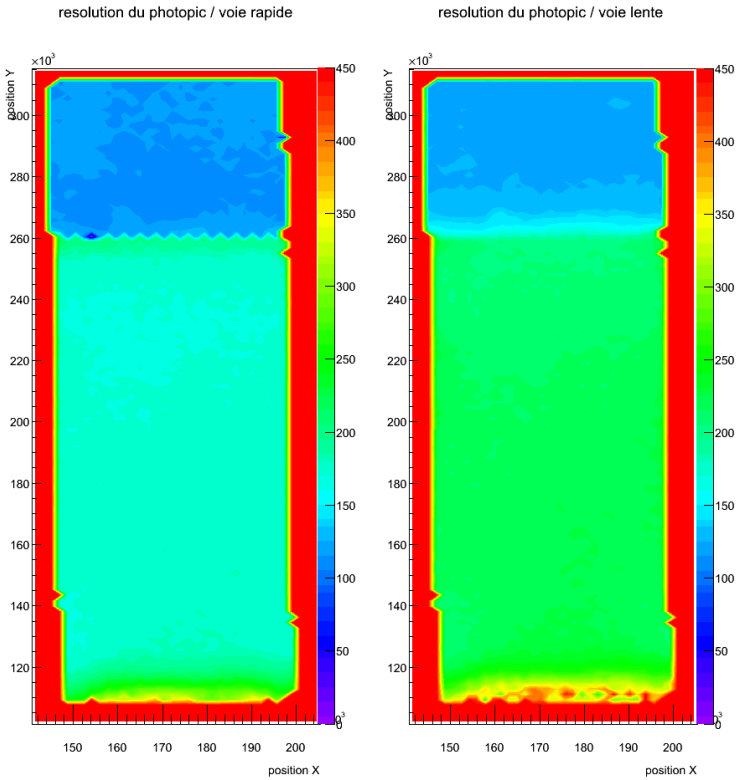
the scan of phoswiches : 1500 points

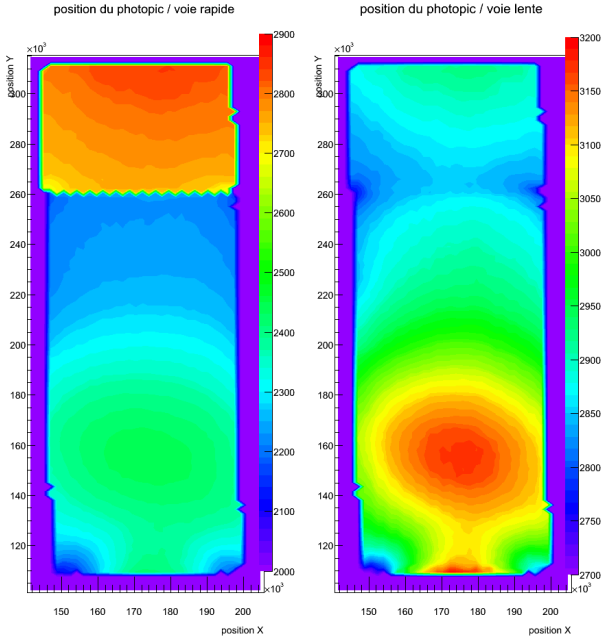
thanks to the AGATA collaboration for the scanning table@IPHC



~efficiency

~resolution

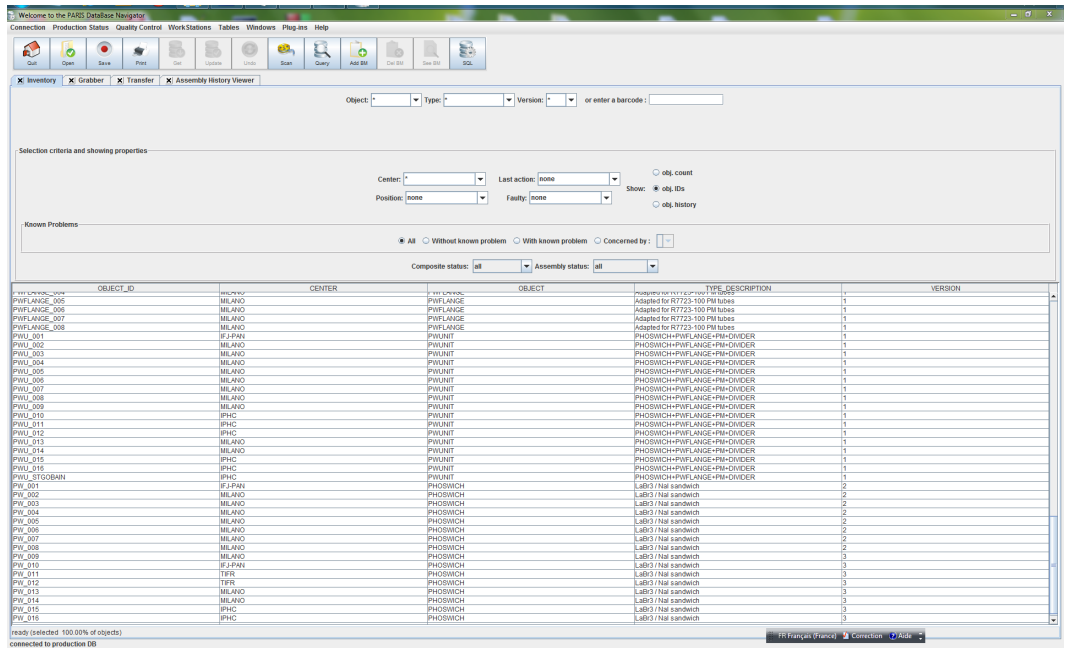




~light collection

the database @ IPHC

- we use the same R7723-100 PM and the same home-made voltage divider on a bench test to:
  - measure the LaBr3 and NaI energy resolution @ 662 keV
  - scan the full length of the PW unit to check the linearity @ 662 keV (thanks to the AGATA collaboration using the scanning table)
  - all informations are stored in a « AGATA-like » database (contact S.Kihel@IPHC)



PARIS tests

- Beam test in Krakow (GANAS detectors tests : PW LaBr3/LaCl3 + PARIS PW + large LaBr3 from Milano) from 13th to 28th of March 2013
- ORSAY experiment test in April 1st-8th 2013 @ Tandem ALTO : one cluster
- ELBE Rosendorf test in November 2013 : one cluster
- Many tests @ MILANO to optimize the PARISPro module

  @ KRAKOW to define a new digital electronics

  @ STRASBOURG with AmBe source and DT5730 digitizer

  @ VAMOS to see the effect of VAMOS magnetic field

PARIS experiments @ Tandem/ALTO IPN Orsay campaign manager : I. Matea

Two experiments recently performed

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- One cluster : experiment with neutrons @ LICORNE (april 2016)

  M. Lebois - **Prompt gamma and neutron emission for ^{238}U fast neutron induced fission as a function of incident neutron energy (see J. Wilson talk)**

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  E Kozulin - **Prompt γ-rays as a probe of nuclear dynamics**

4 other accepted proposals requiring 2-4 clusters

- B. Blank - **Measurement of the super-allowed branching ratio of ^{10}C**
- O. Kirsebom - **A new probe of alpha-cluster structure in ^{12}C**
- M. Wiedeking - **Coulomb Excitation of ^{14}C**
- P.J. Napiorkowski - **Coulomb excitation of super-deformed band in ^{40}Ca**

PARIS experiments @ GANIL/AGATA-VAMOS

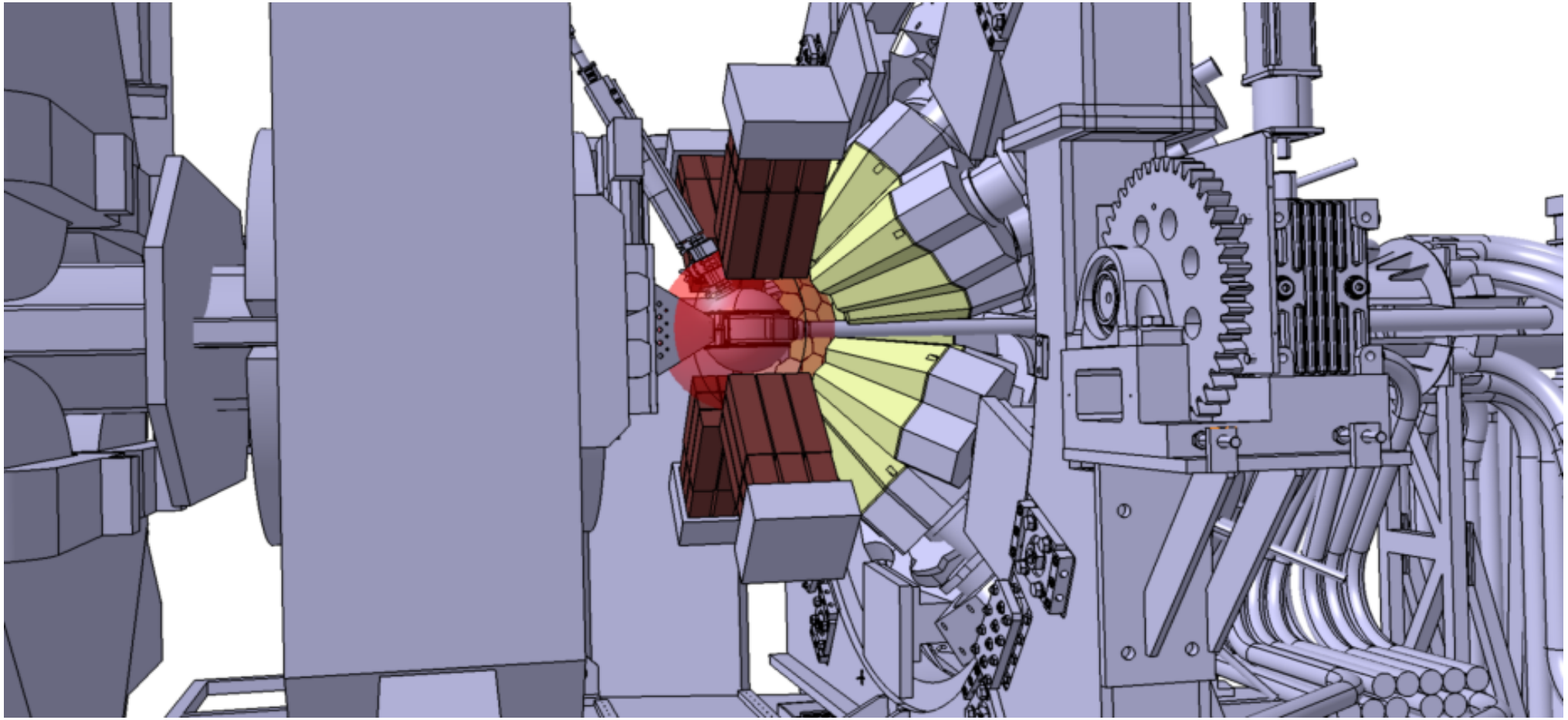
3 accepted proposals by the GANIL PAC requesting 2-4 PARIS clusters (mid 2017)

- S. Leoni, B. Fornal, M. Ciemala, **Lifetime measurements of excited states in neutron-rich C and O isotopes: a stringent test of the three body forces with the AGATA+PARIS** (at least 2 clusters)**+VAMOS setup**,

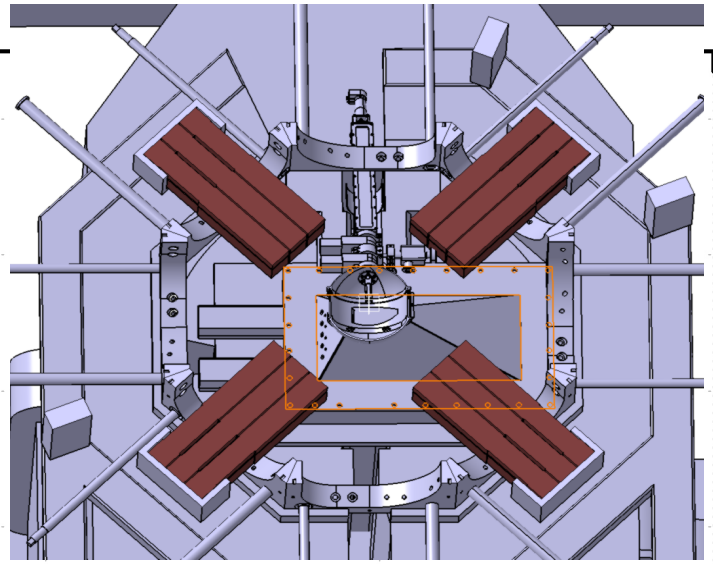
- P. Bednarczyk, A. Maj**, Investigation of a high spin structure in ^{44}Ti via discrete and continuum γ-spectroscopy** with *AGATA, PARIS* (4 clusters) and *DIAMANT,*

- B. Fornal, S. Leoni, M. Ciemala, „**Gamma decay from near-threshold states in ^{14}C: a probe of clusterization phenomena in open quantum systems", AGATA , PARIS** (4 clusters)**, NEDA, DIAMANT, DSSD**

PARIS and VAMOS and AGATA @GANIL



Standard geometry:
4 PARIS clusters at 23 cm from the target



PARIS photopeak efficiency

Simulation by M. Ciemala

8 clusters @ 23 cm

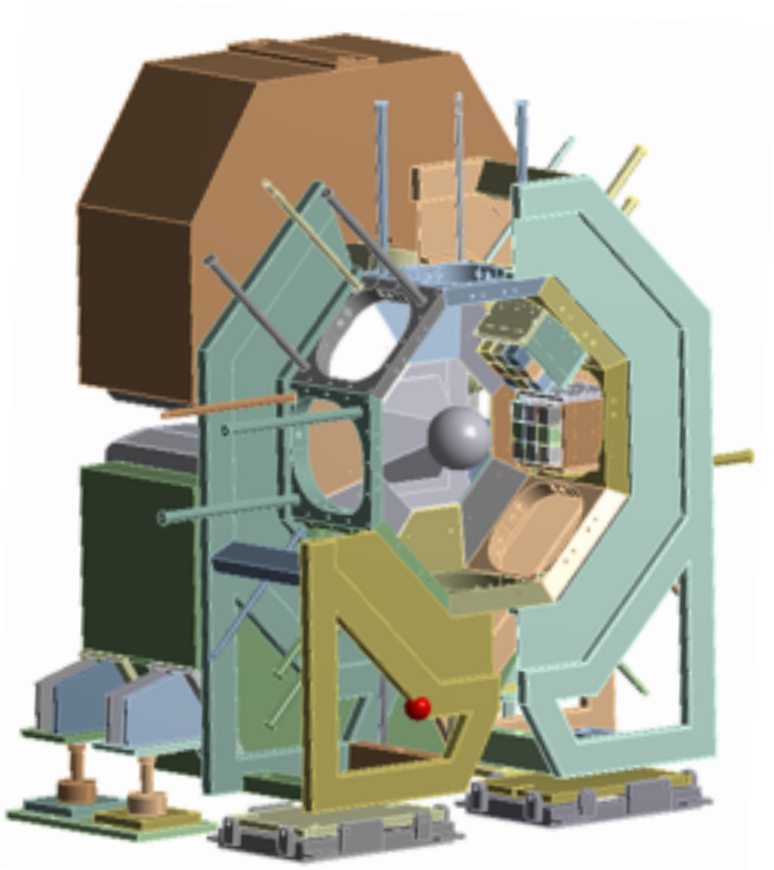
4 clusters @ 23 cm

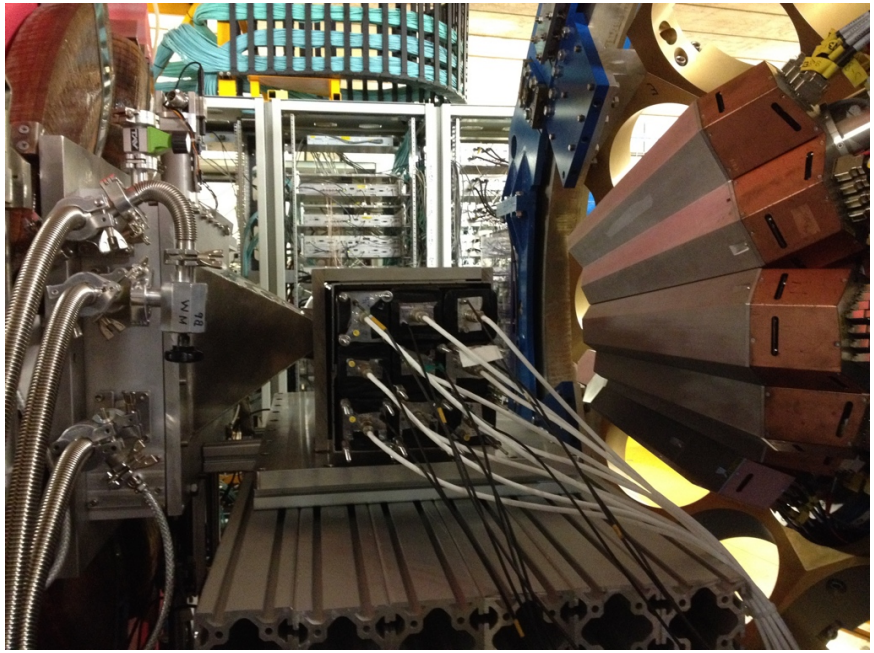
Photopeak efficiency [%]

E [MeV]

PARIS experiments @ GANIL/VAMOS & AGATA

Needs of test @ VAMOS to see the effect of VAMOS magnetic field





*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

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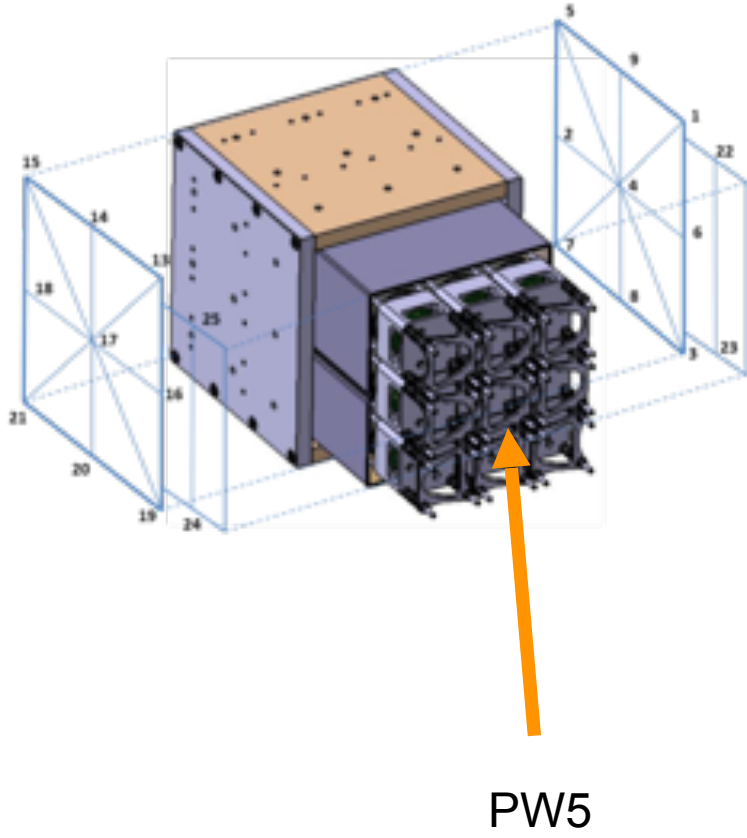
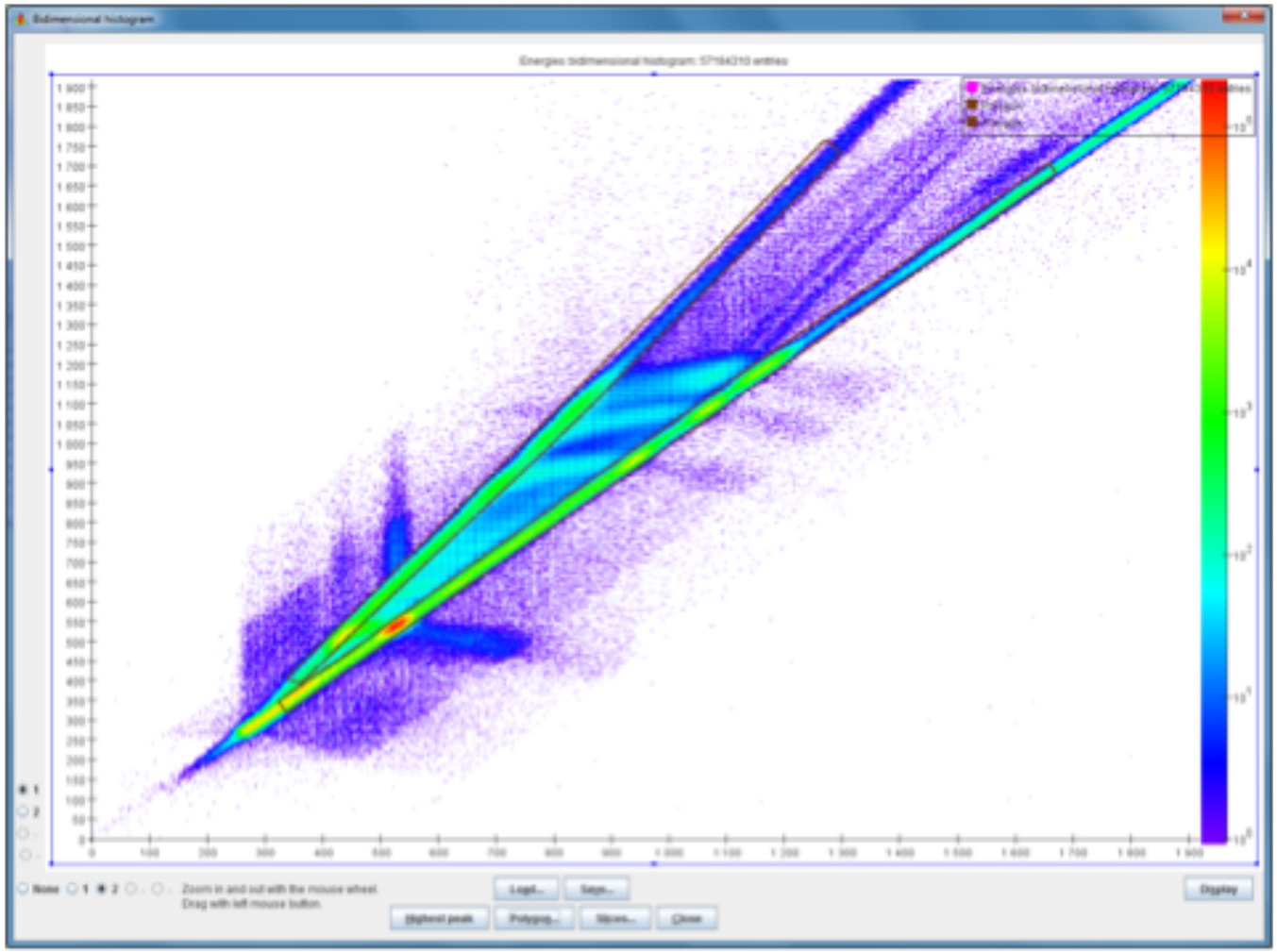
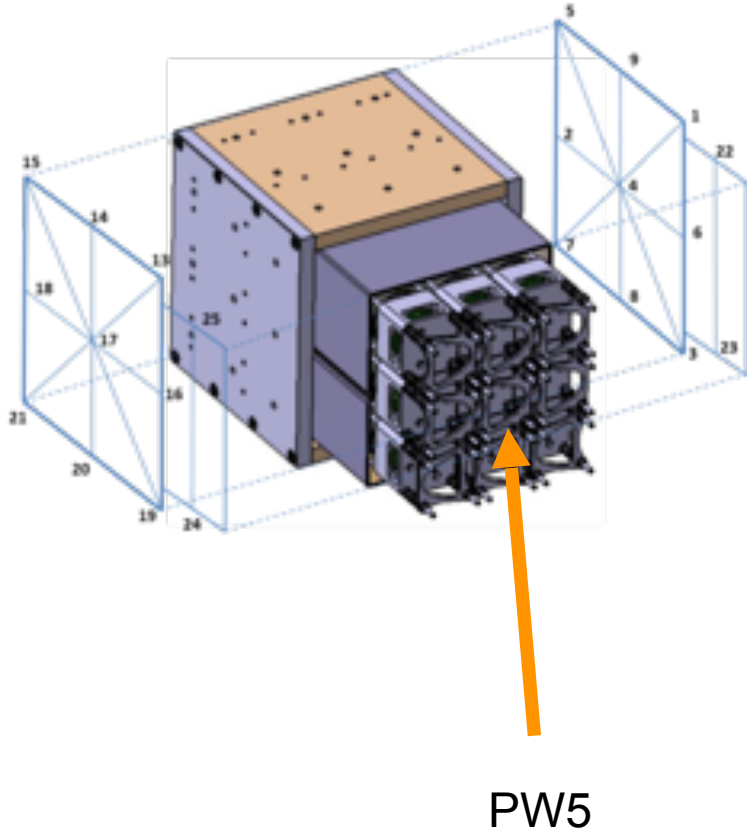


*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

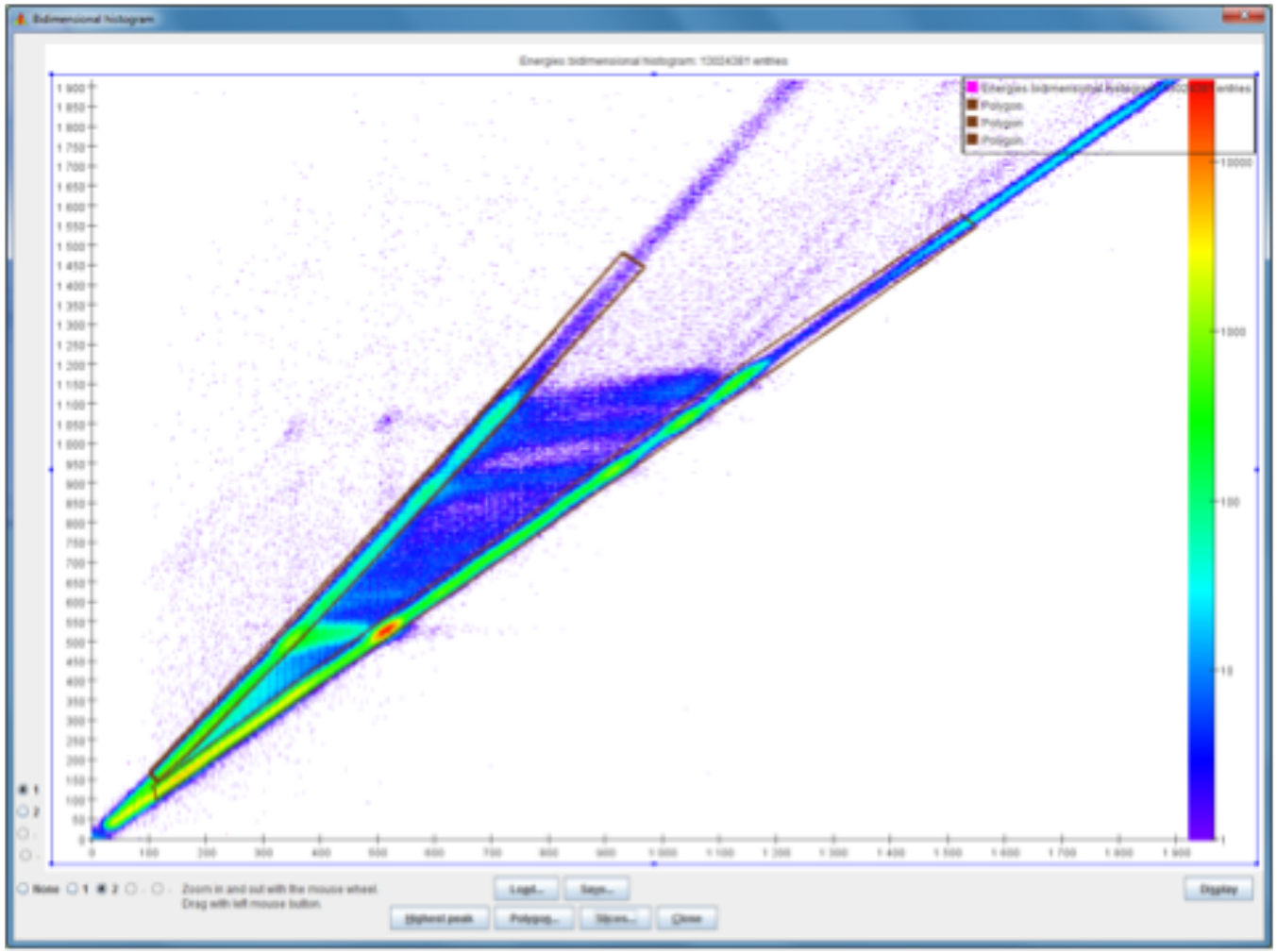
PW5 – 0 A , 662 keV @ -60 mV

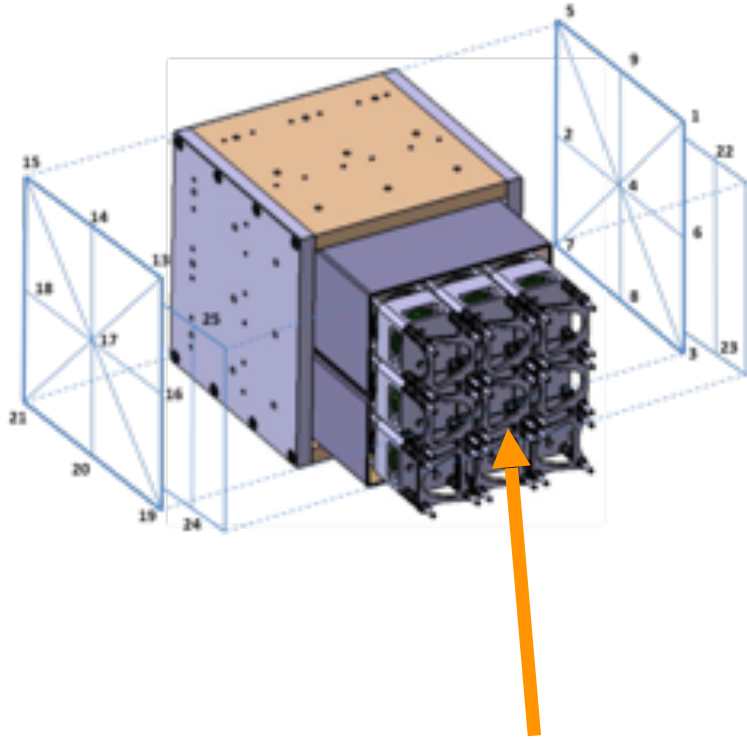




*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

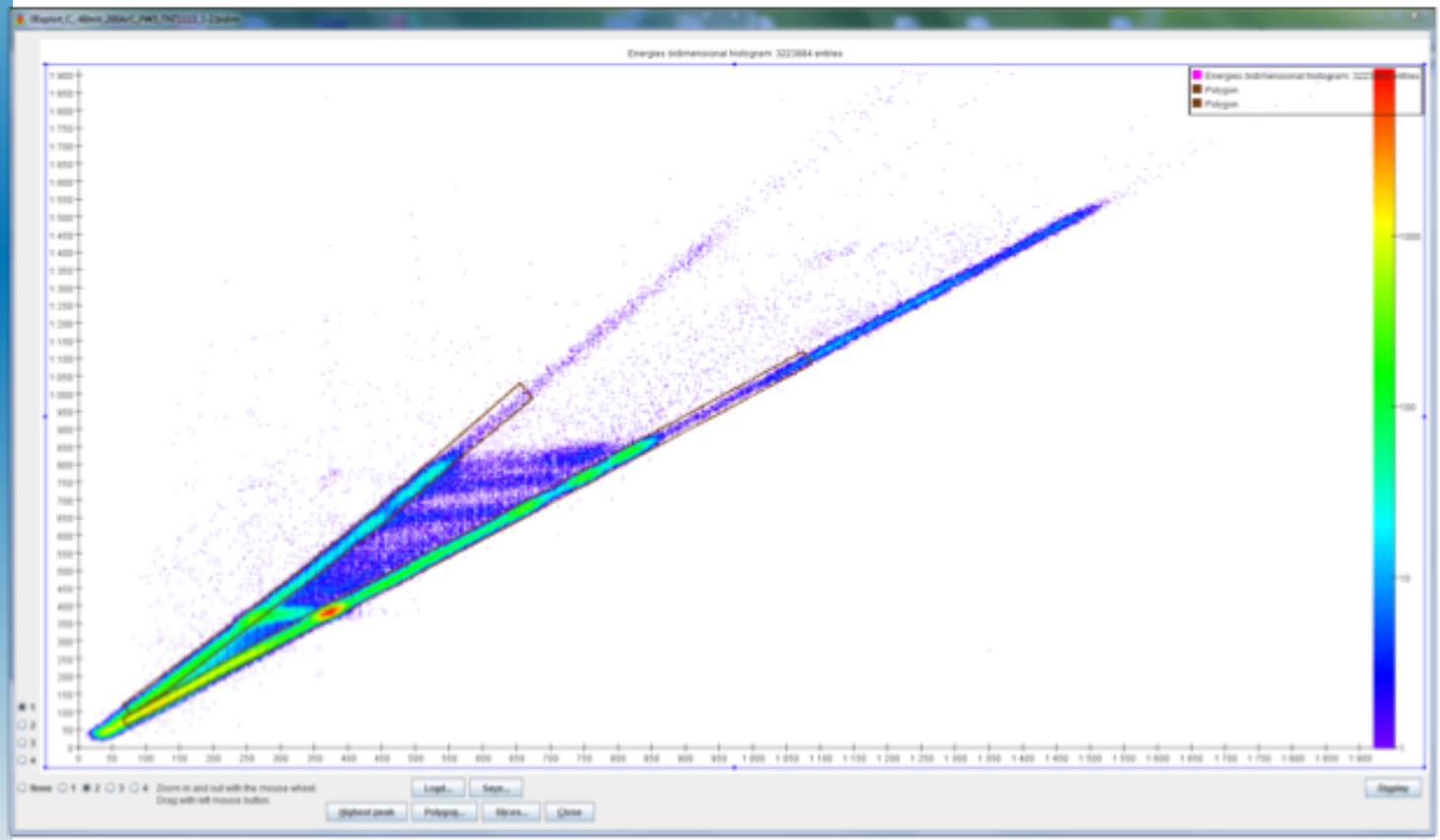
PW5 – 100 A , 662 keV @ -60 mV

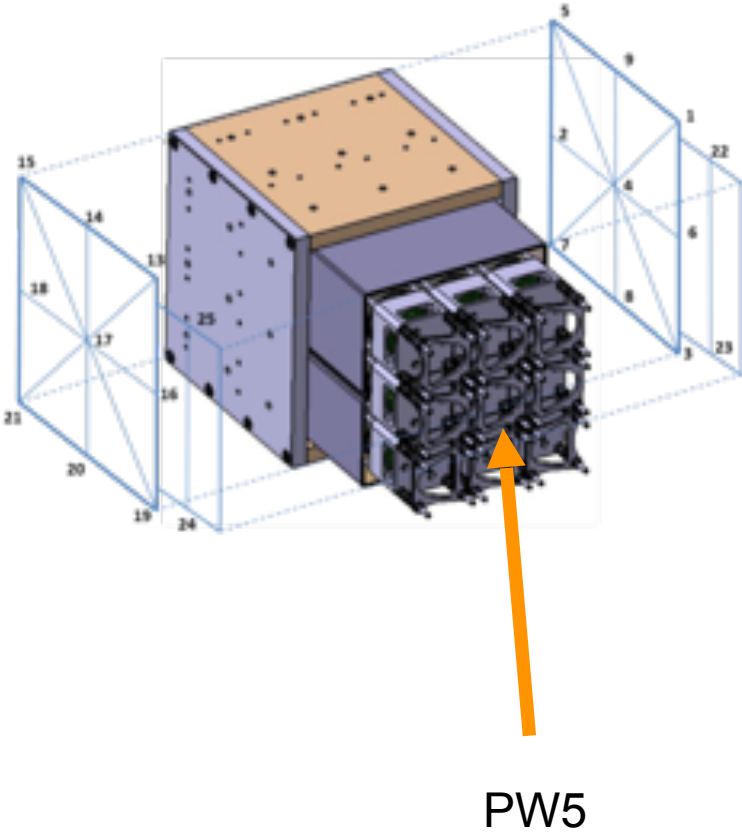




*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

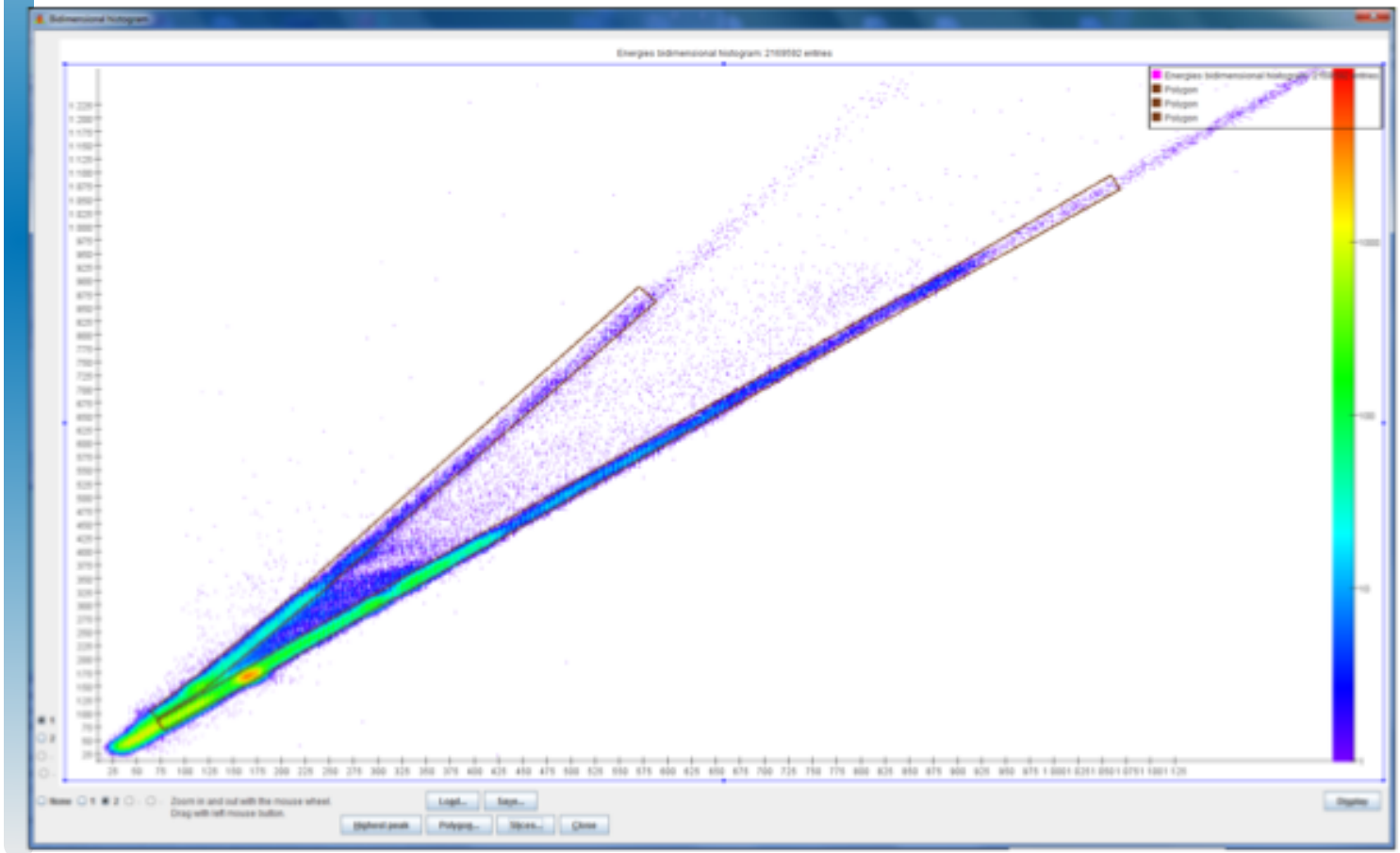
PW5 – 200 A , 662 keV @ -60 mV

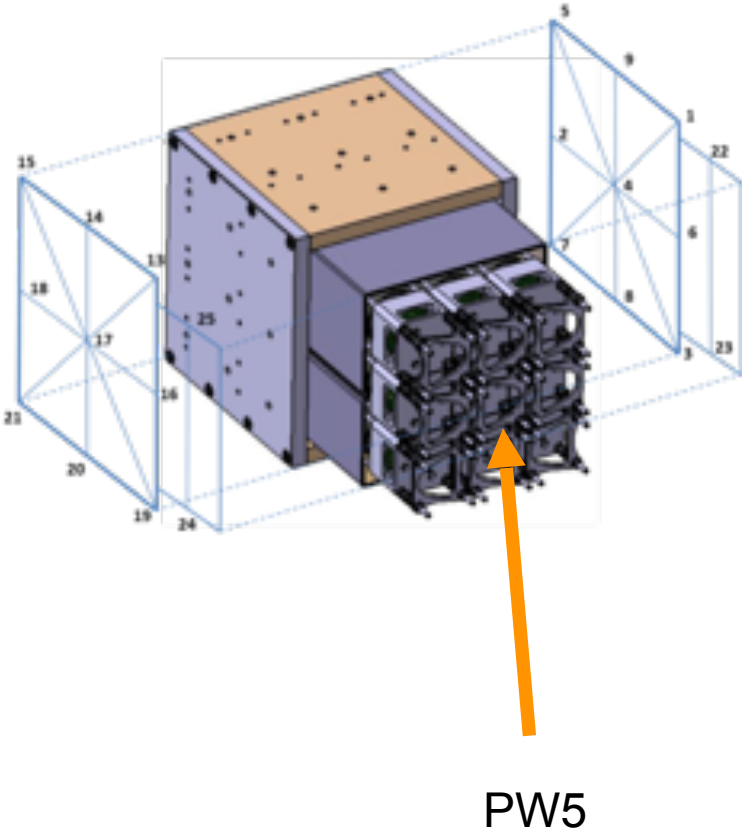




*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

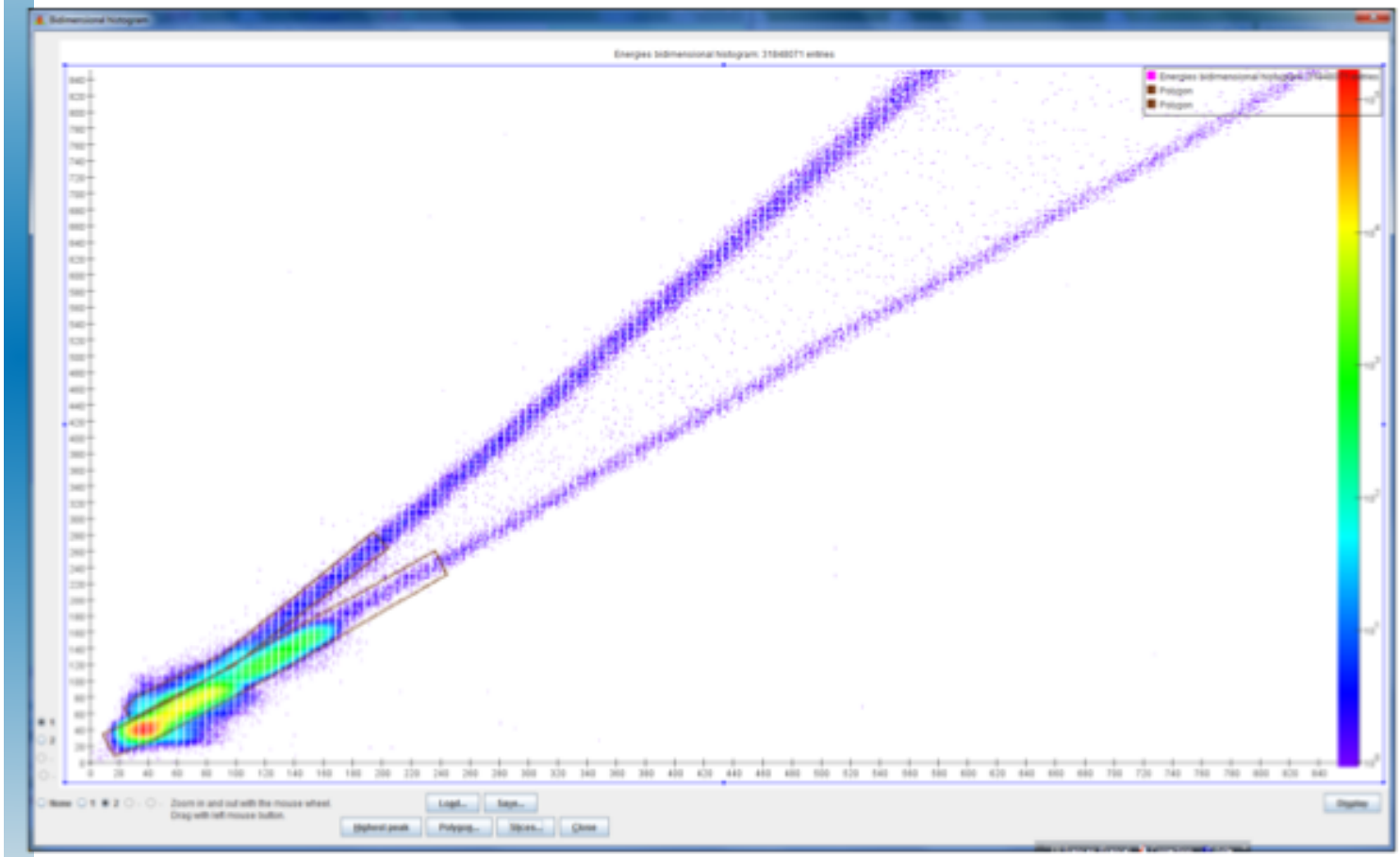
PW5 – 300 A , 662 keV @ -60 mV

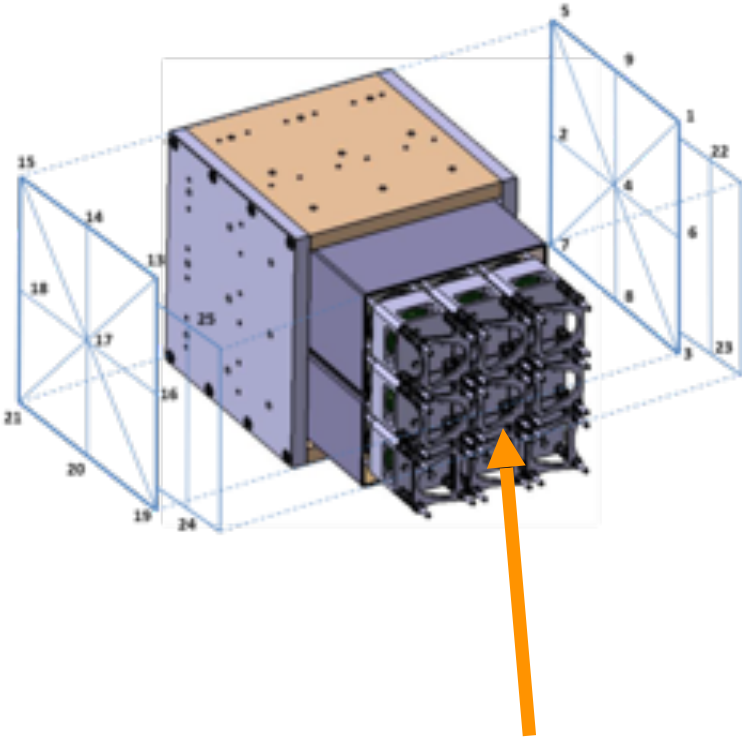




*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

PW5 – 400 A , 662 keV @ -60 mV





PW5

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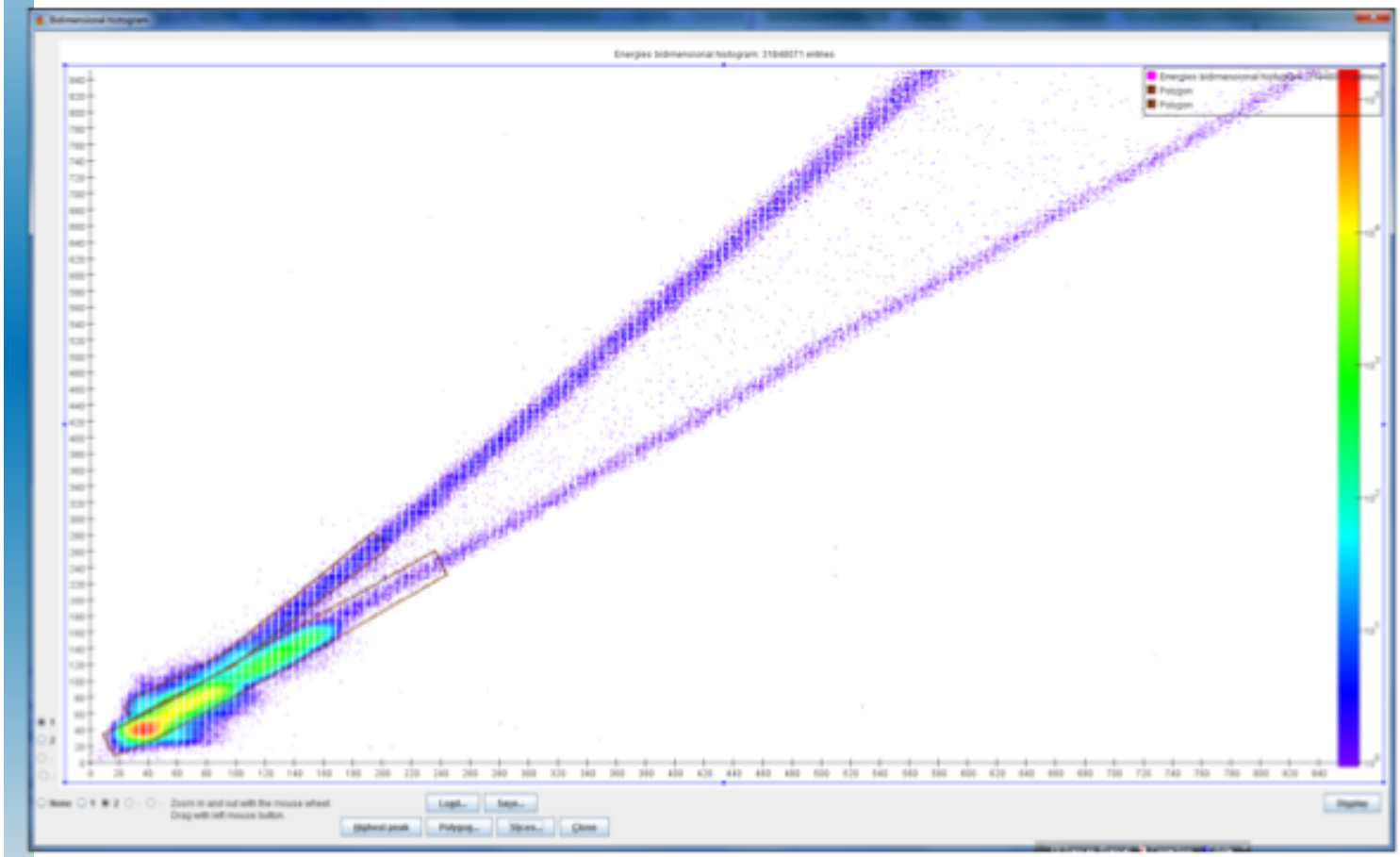
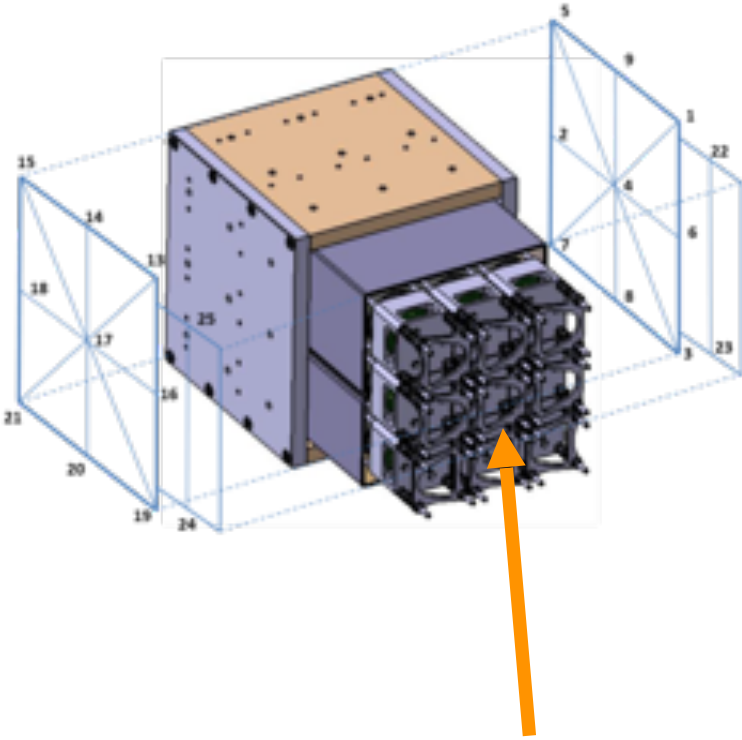
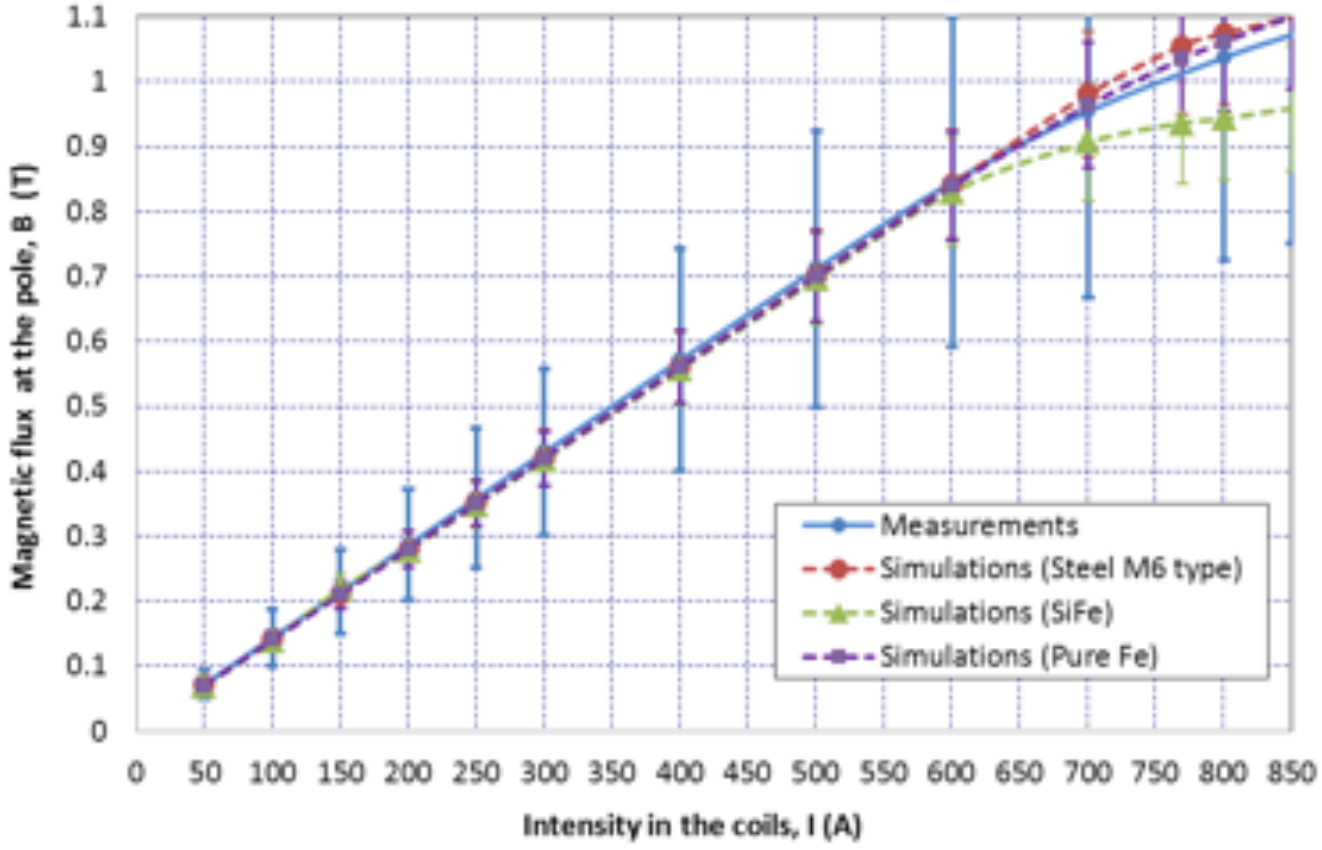


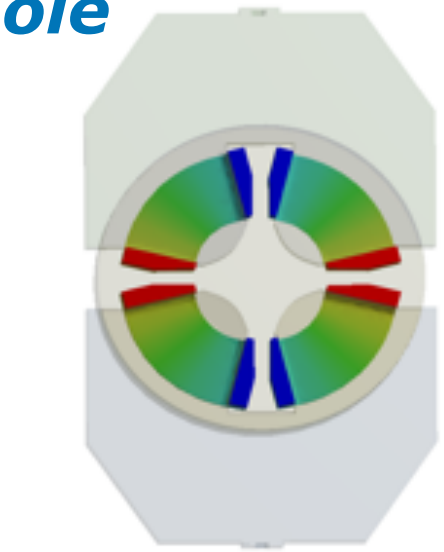


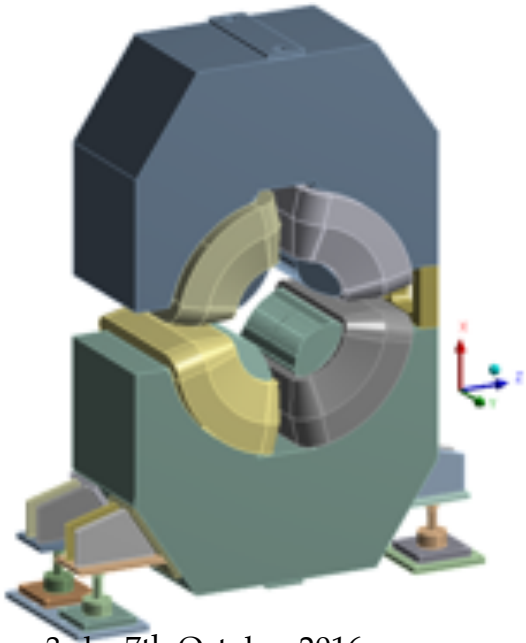
PW5

Needed an upgrade of the shield to be simulated

Excellent agreement between ANSYS simulations and magnetic field measurement @ VAMOS dipole

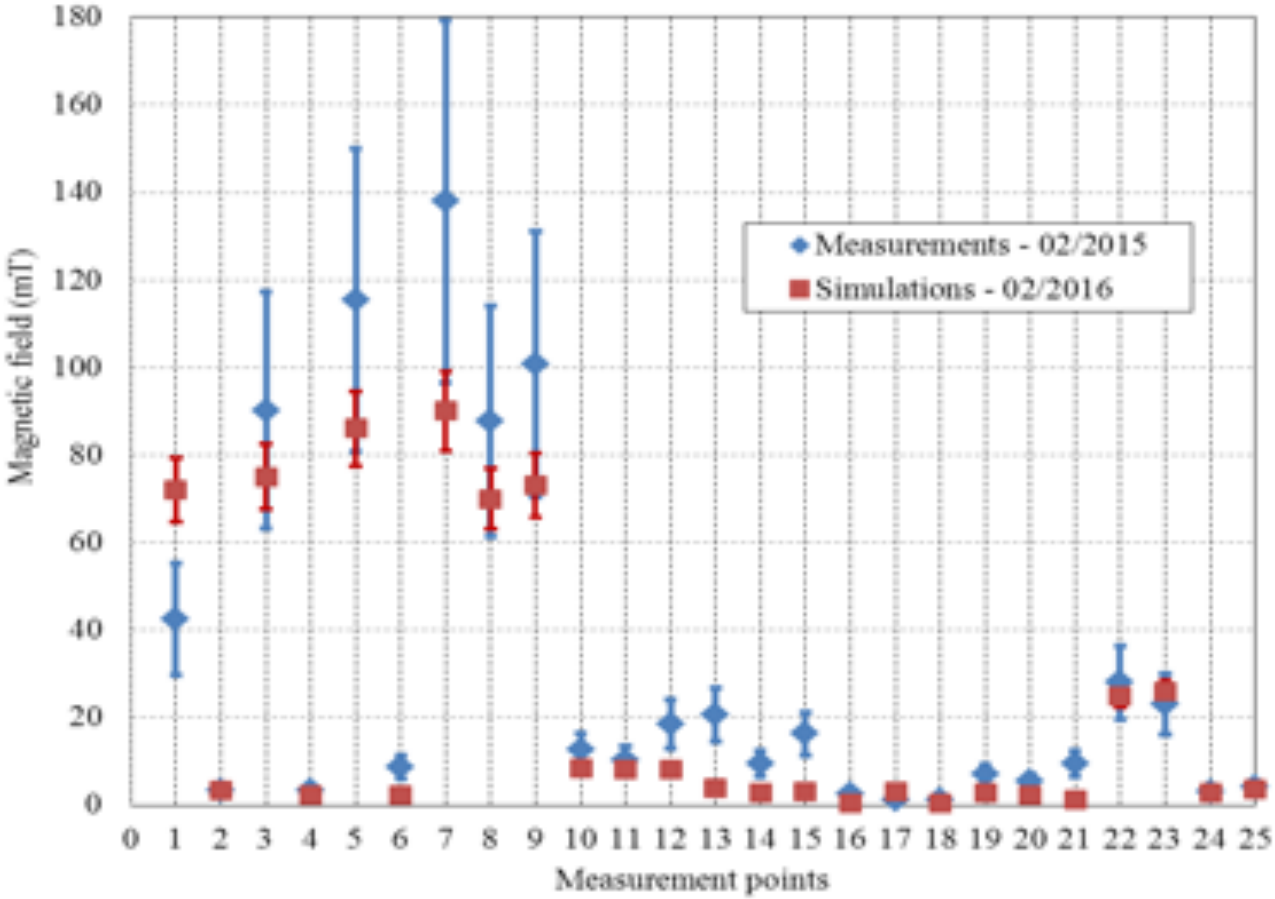


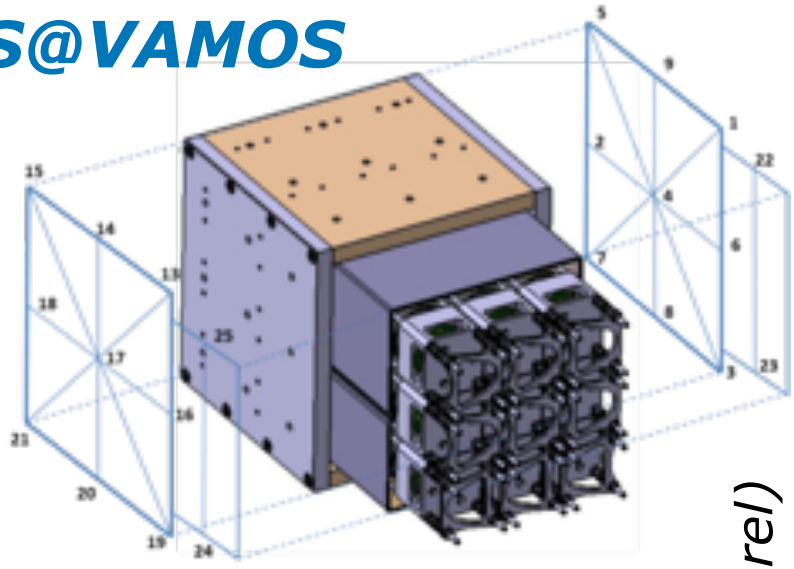


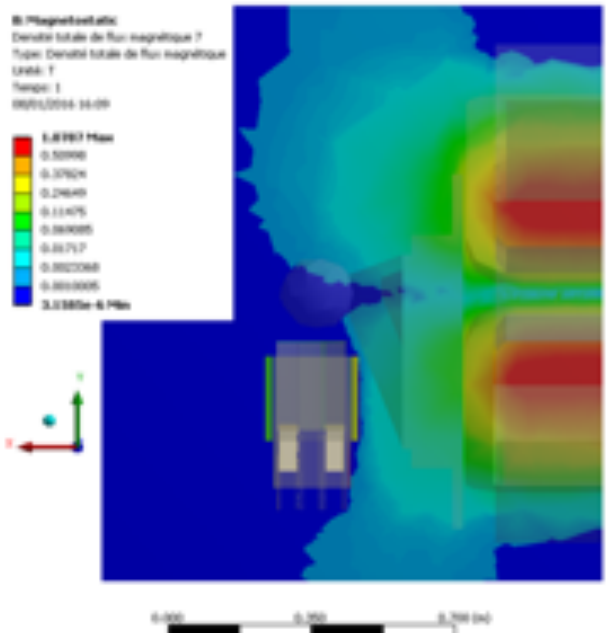


(Courtesy of E. Bouquerel)

Excellent agreement between ANSYS simulations and magnetic field measurement on PARIS@VAMOS

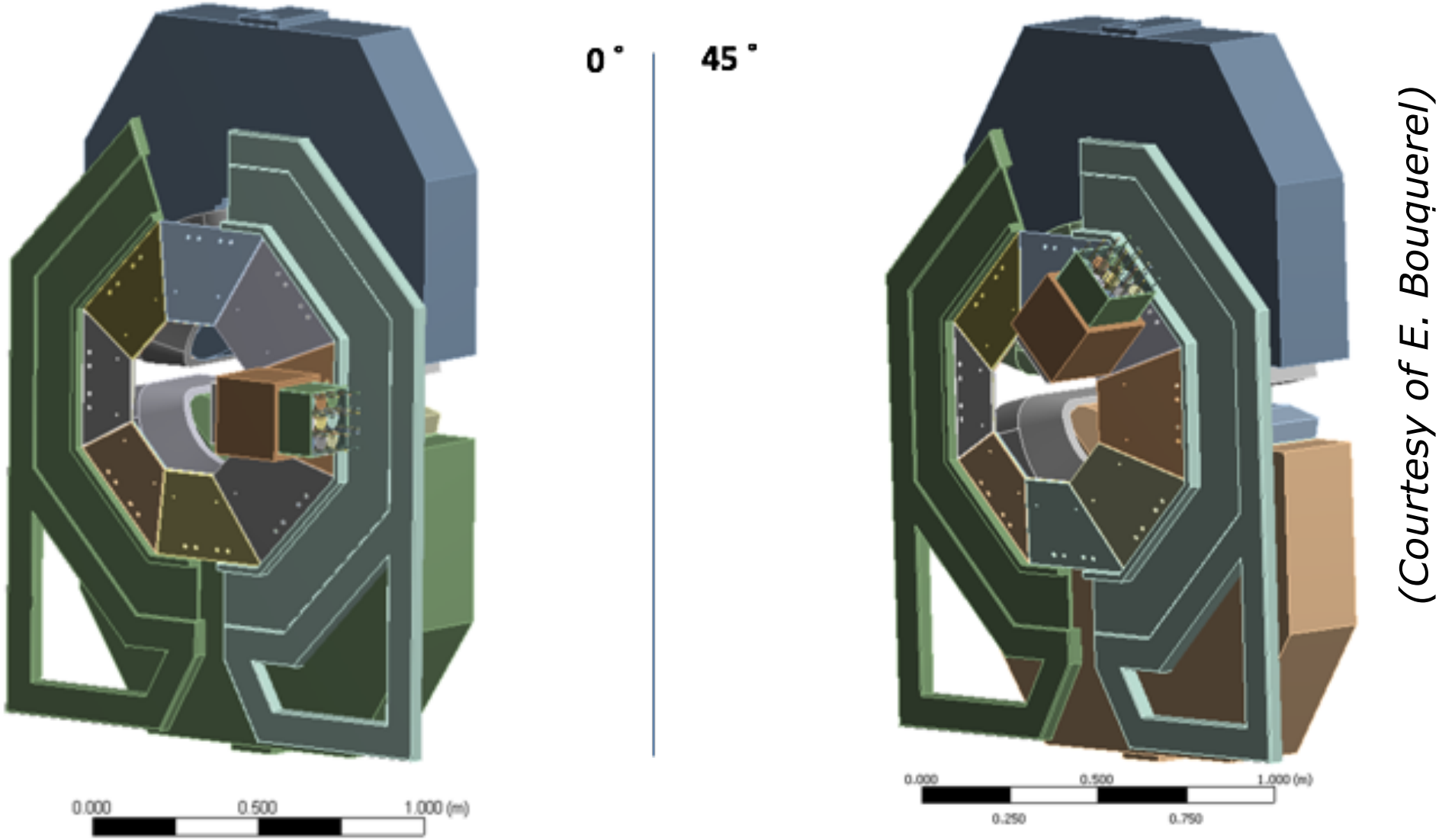






(Courtesy of E. Bouquerel)

- **Simulations at different angles with the actual PW shield and EXOGAM shield**



(Courtesy of E. Bouquerel)

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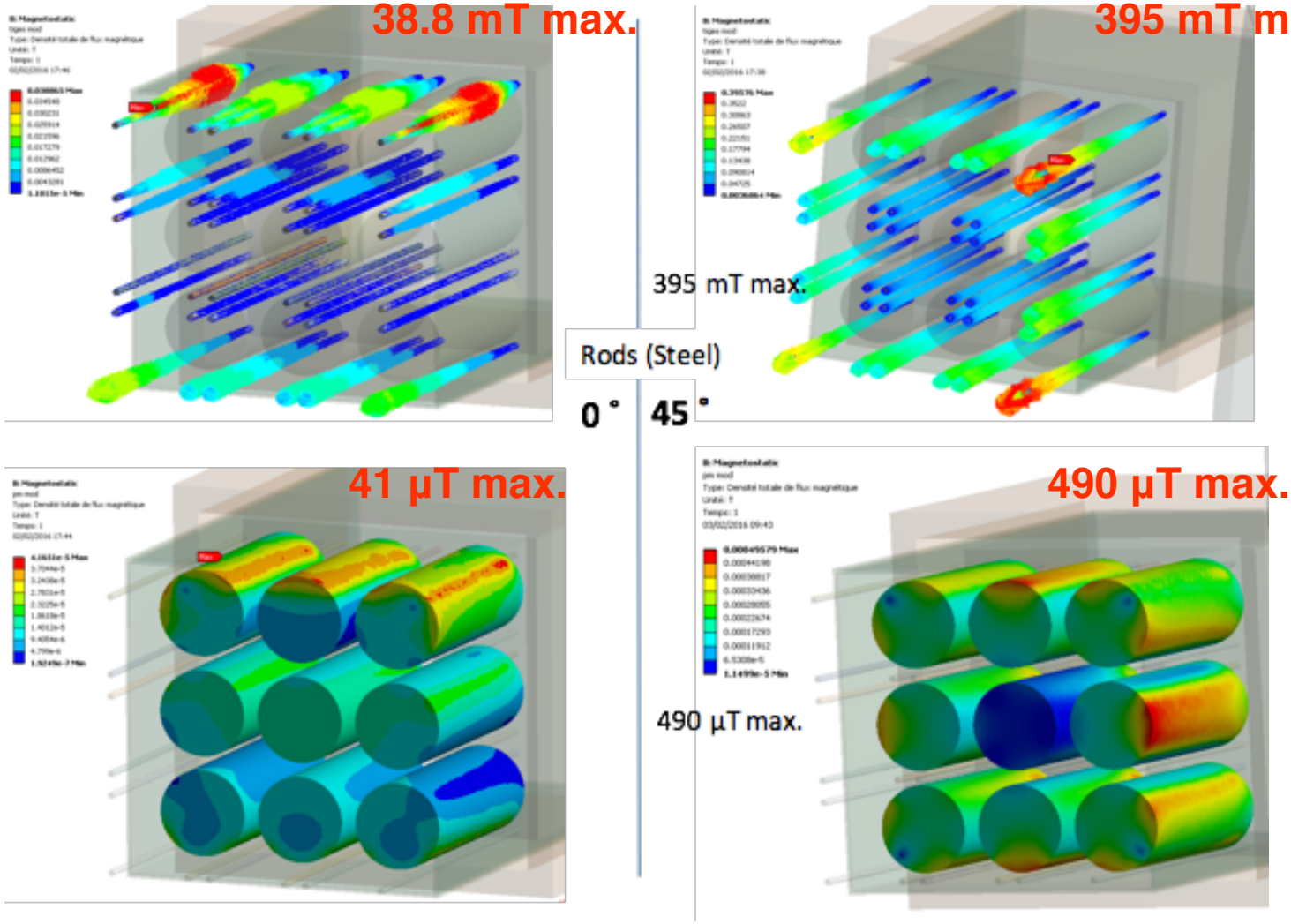
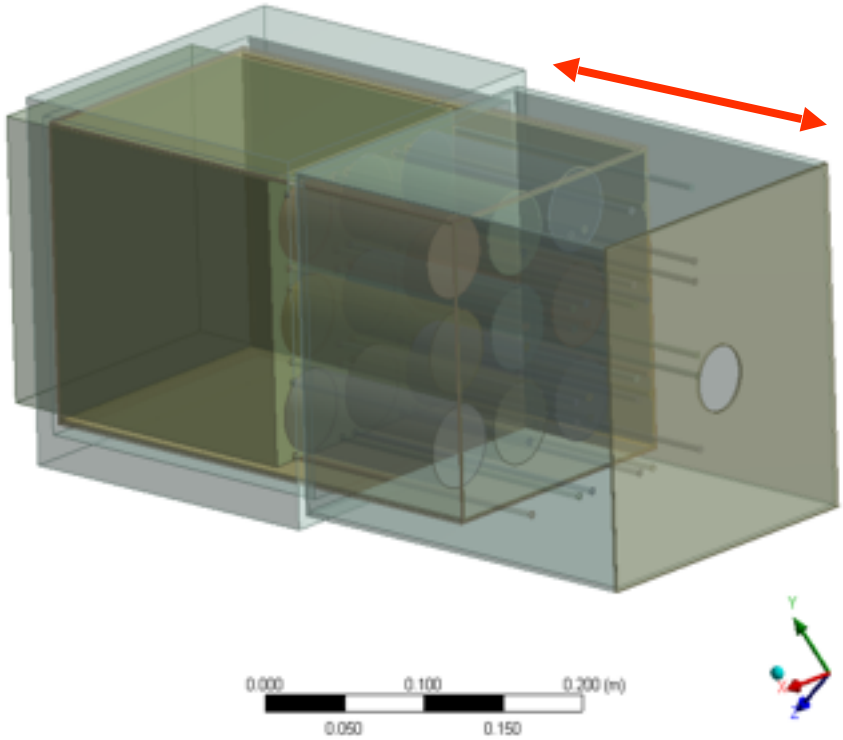


- Field at 45° is ~10 times higher than at 0° !!!

(Courtesy of E. Bouquerel)

- **Simulations modifying the actual shielding adding a second part with different thicknesses)**



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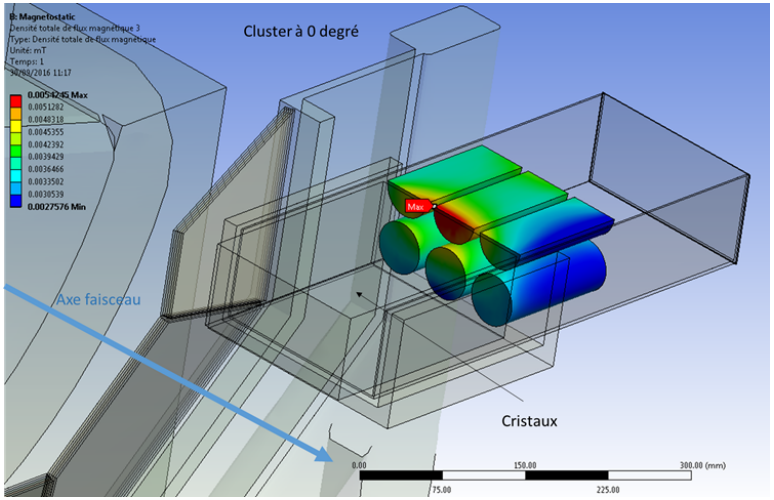
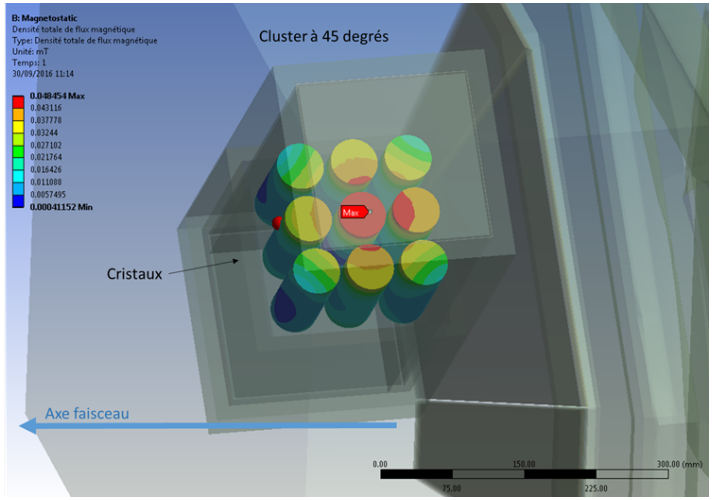


0 ° 45 °



With 2mm thick additional shield part :
Max. values obtained ~ **Earth magnetic field**
5,4 (0°) < 48 (45°) ~ 47 μT

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- **the phoswich concept of PARIS works and looks promising after a multitude of tests and two experiments,**

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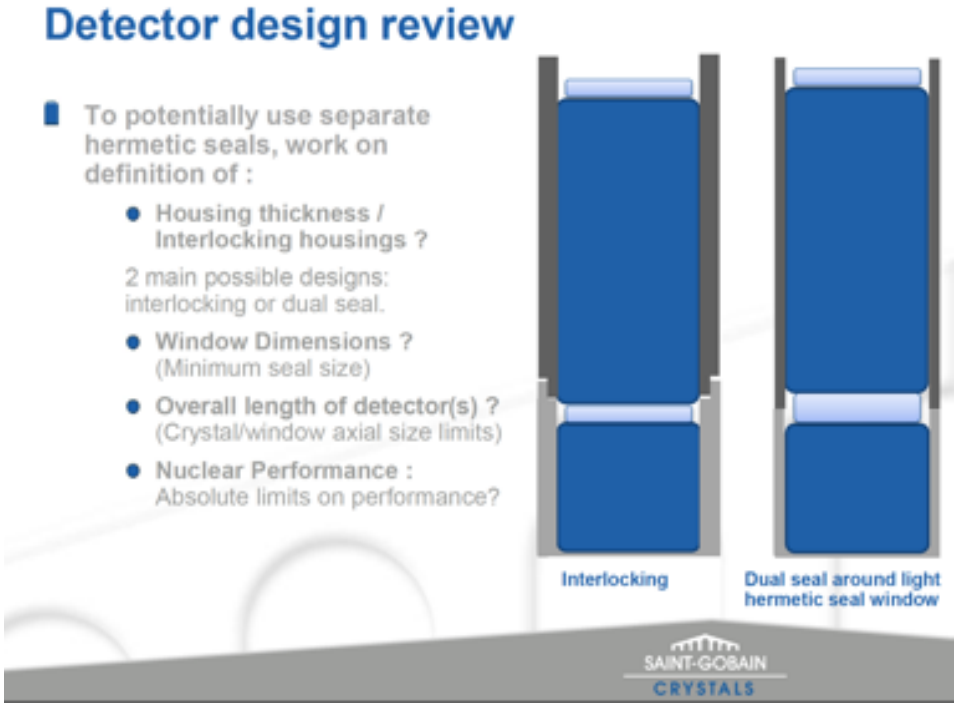
… but

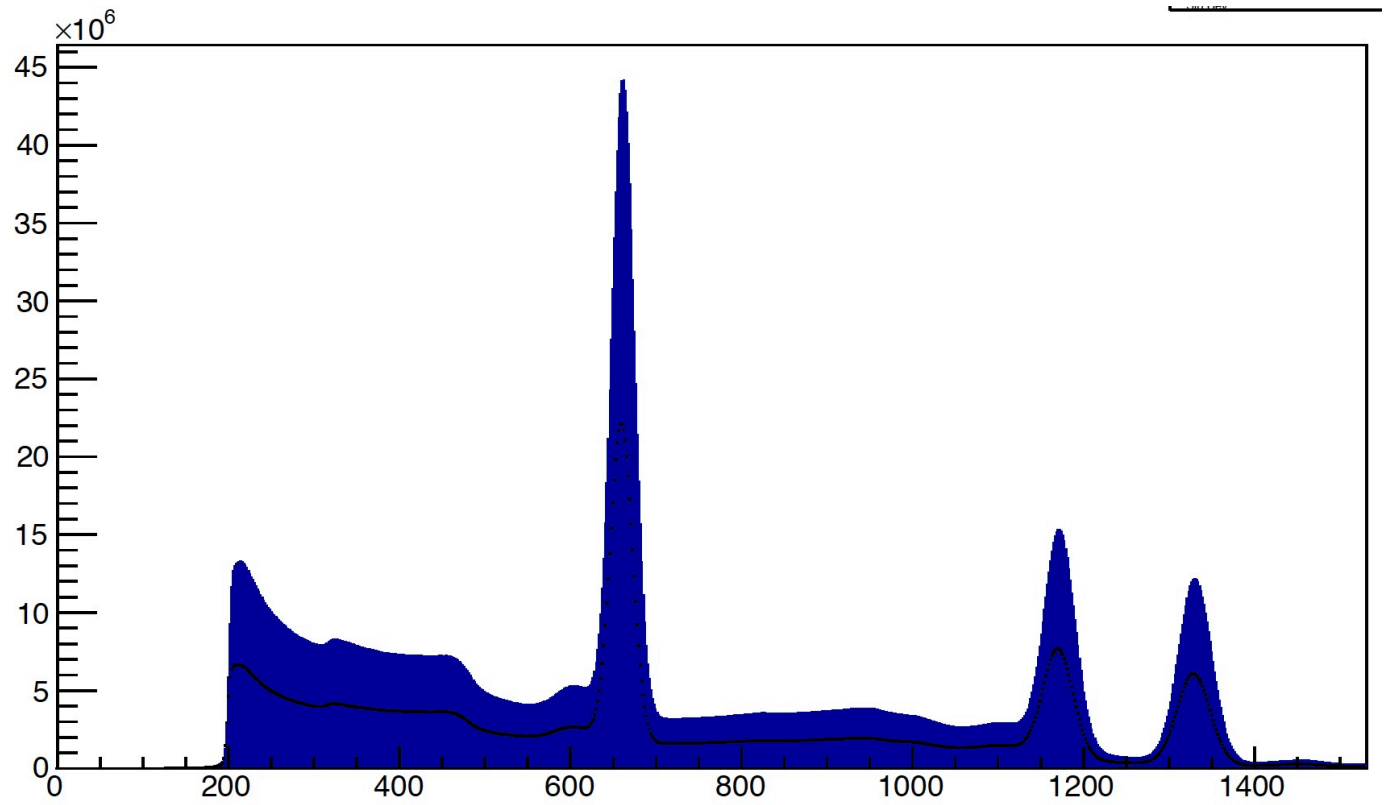
… we have only 1,5 cluster since Saint-Gobain was not able to produce anymore valuable phoswiches from ~2 years

- **12 pieces are still in backlog (6 returned to SG for repair/exchange and 6 new orders)**
- **one proposition is to modify the actual design by adding a quartz window between the two crystals**



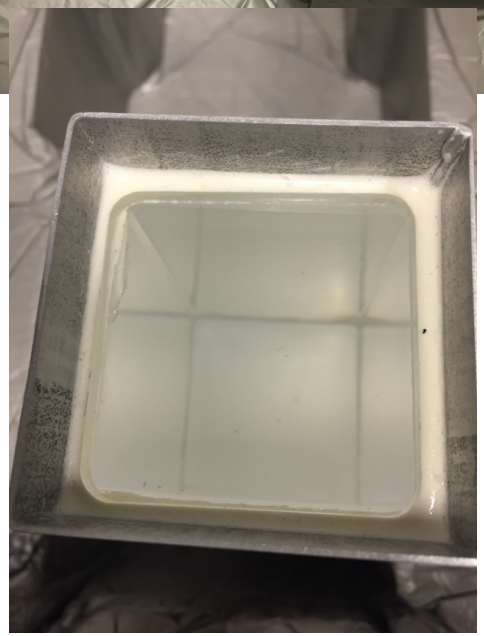
- **two prototypes have been manufactured in US and have been delivered @ IPHC in September…**

Very preliminary results with the last St-Gobain design (delivered in September 2016)

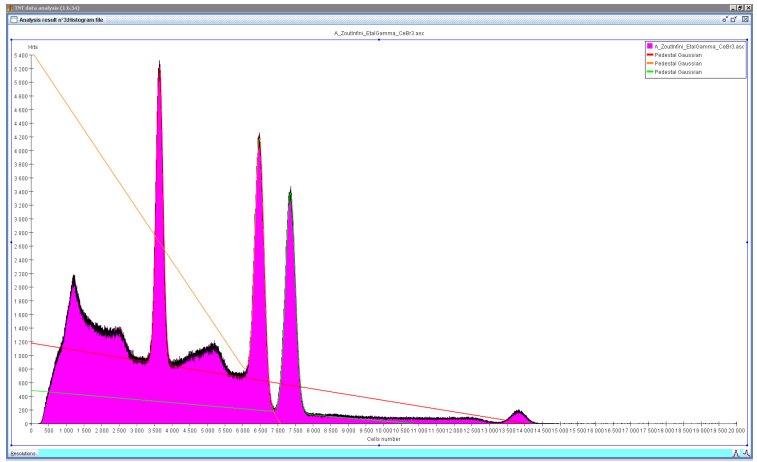


FWHM @ 662 keV ~ 5 keV - further tests under progress

Meanwhile the PARIS collaboration have bought a CeBr3/NaI @ SCIONIX - delivered in July 2016



Very preliminary resolution of ~5.5% sounds really promising and CeBr3/NaI phoswich is a valuable solution for PARIS concept
Further tests under progress



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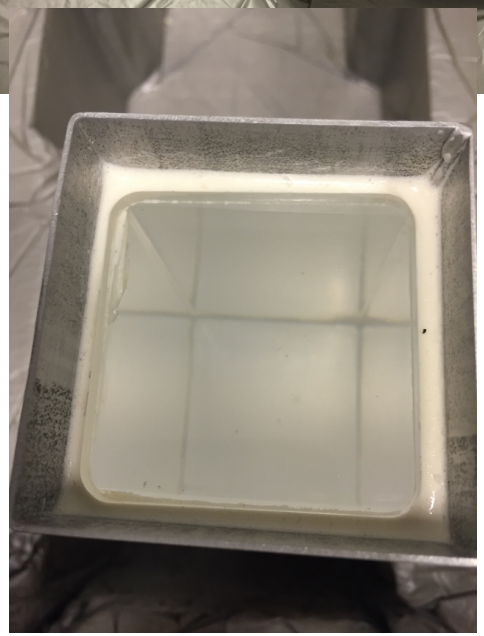

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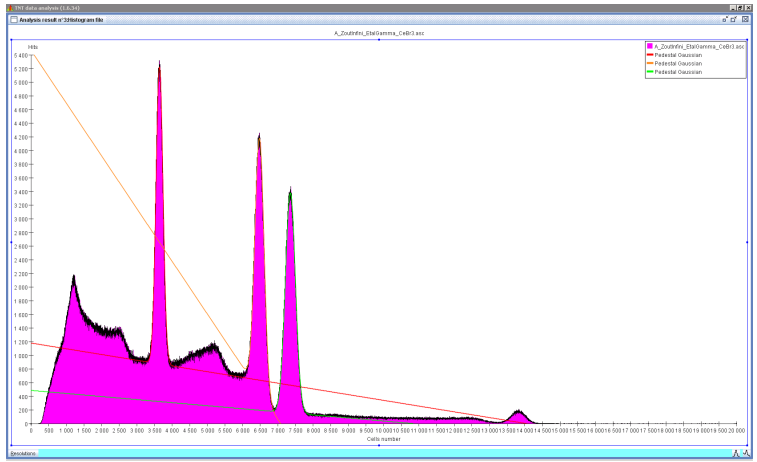
Further tests under progress

PARIS Management Board decided to purchase 8 additional CeBr3/NaI phoswiches to make one full cluster



- *in conclusion, if the phoswich production with a new design starts end of 2016 (either LaBr3/NaI and/or CeBr3/NaI) the PARIS collaboration should have at least 3 clusters by mid-2017, maybe 4.*

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then PARIS demonstrator should be ready for future experiments (starting @ AGATA-VAMOS/GANIL, ALTO/ ORSAY, SPES/LNL, CBB Krakow,…)

Thank you for your attention

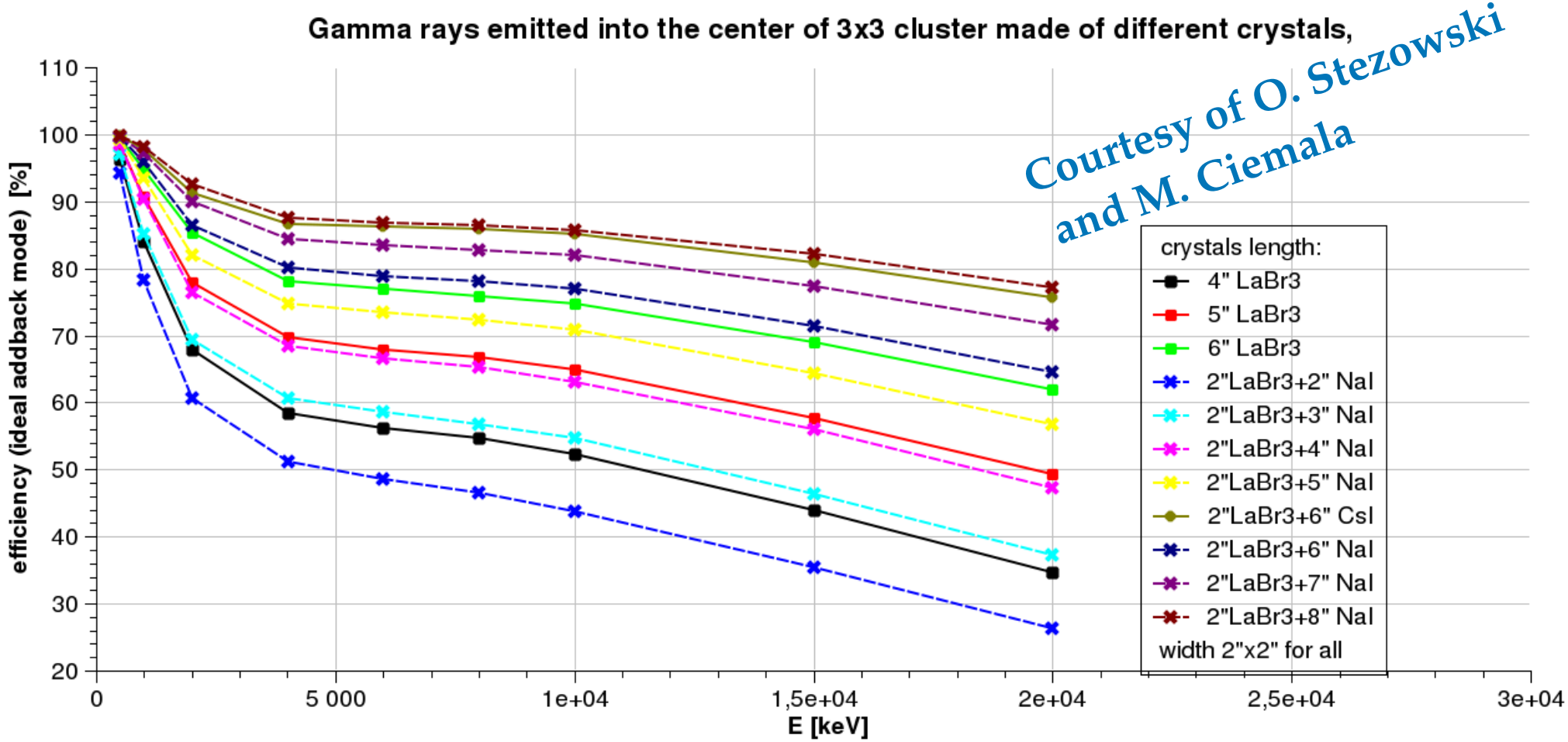
and thanks to

F. Azaiez, P. Bednarczyk, J. Bettane, ***E. Bouquerel****, C. Bonnin, A. Bracco,* ***S. Brambilla****, F. Camera, L. Charles,* ***M. Ciemała****, A. Czermak,* ***O. Dorvaux****, B. Fornal, A. Giaz, G. Hull, M. Jastrząb, D. Jenkins,* ***S. Kihel****, M. Kmiecik, M. Krauth, S. Kumar, S. Leoni, M. Lewitowicz,* ***A. Maj****, I. Matea, C. Mathieu, I. Mazumdar, K. Mazurek, A. Mentana, B. Million,* ***V. Nanal****, P. Napiorkowski, Ph. Peaupardin, Ch. Schmitt, O. Stezowski,* ***B. Wasilewska****, O. Wieland and M. Ziębliński*

on behalf of the PARIS collaboration

IFJ PAN Krakow, Poland
IPHC Strasbourg, France
IPN Orsay, France
GANIL Caen, France
IPN Lyon, France
INFN - University of Milano, Italy
TIFR Mumbai, India
York University, UK
HIL Warsaw, Poland

- **Simulations PW detectors compared to full LaBr3 detectors for different lengths**



Courtesy of O. Stezowski and M. Ciemala

PARIS physics cases for SPIRAL2

a) **Jacobi and Poincare shape transitions (+AGATA) ***
$^{130\text{-}142}Ba$, $^{116\text{-}120}Cd$, $^{88\text{-}98}Mo$, ^{71}Zn
(A. Maj, J. Dudek, K. Mazurek et al.)

b) **Studies of shape phase diagrams of hot nuclei – GDR differential methods**
$^{186\text{-}193}Os$, $^{190\text{-}197}Pt$
(I. Mazumdar, **A. Maj** et al.)

c) **Hot GDR studies in neutron rich nuclei ***
(D.R. Chakrabarty, **M. Kmiecik** et al.)

d) **Isospin mixing at finite temperature**
^{68}Se, ^{80}Zr, ^{84}Mo, ^{96}Cd, ^{112}Ba
(M. Kicińska-Habior, F. Camera et al.)

e) **Onset of the multifragmentation and the GDR (+FAZIA)**
$120<A<140$, $180<A<200$
(J.P. Wieleczko, D. Santonocito et al.)

f) **Reaction dynamics by means of γ-ray measurements**
$^{214\text{-}222}Ra$, $^{118\text{-}226}Th$, $^{229\text{-}234}U$
(Ch. Schmitt, O. Dorvaux et al.)

g) **Heavy ion radiative capture ***
^{24}Mg, ^{28}Si **(S. Courtin,** D.G. Jenkins et al.)

h) **Multiple Coulex of SD bands**
$36<A<50$
(P. Napiorkowski, F, Azaiez, A. Maj)

i) **Relativistic Coulex (after postacceleration)**
$40<A<90$
(P. Bednarczyk et al.)

j) **Nuclear astrophysics (p,γ)**
e.g. ^{90}Zr
(S. Harissopulos al.)

k) **Shell structure at intermediate energies (SISSI/LISE)**
$20<A<40$
(Z. Dombradi et al.)

l) **Shell structure at low energies (separator part of S³) ***
$30<A<150$
(F. Azaiez, I. Stefan, B. Fornal et al.)

m) **PDR studied with GASPARD+PARIS**
D. Beaumel et al.

n) **PDR in proton-rich nuclei with NEDA+PARIS**
G. De Angelis et al.

o) **Onset of chaotic regime: PARI+AGATA**
S. Leoni et al.

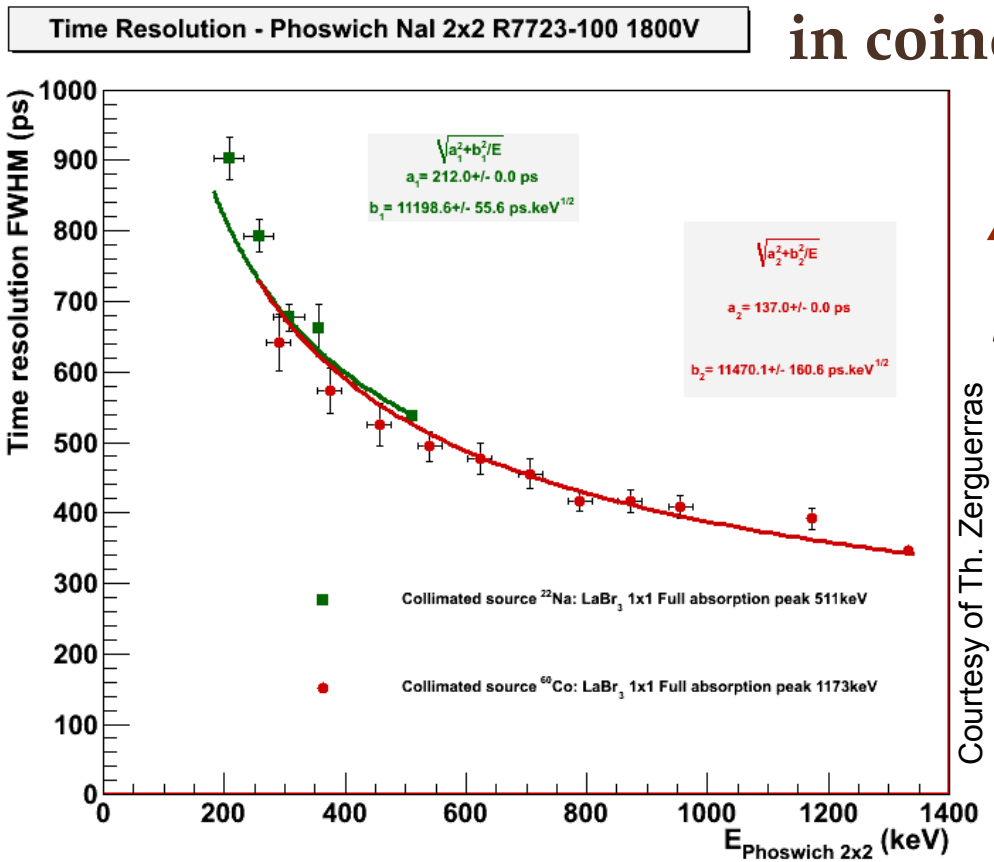
p) **Evolution of nuclear structure of ^{78}Ni and ^{132}Sn with ACTAR+PARIS**
C.E. Grinyer et al.

Courtesy of A. Maj

the Paris performances : time resolution

in coincidence with a small 1"x1"x2" $LaBr_3$:Ce

the Paris performances : time resolution



Courtesy of Th. Zerguerras

in coincidence with a small 1"x1"x2" $LaBr_3$:Ce

Analog electronics

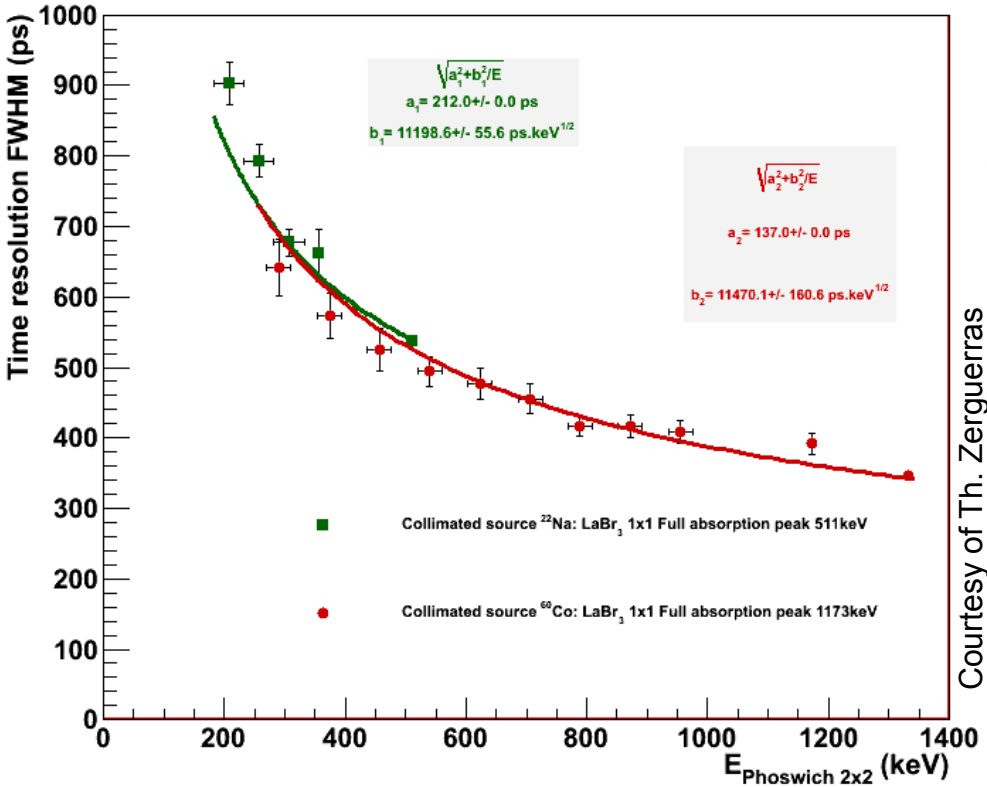
FWHM = 500 ps @ 551 keV

360 ps @ 1 MeV

the Paris performances : time resolution

Time Resolution - Phoswich NaI 2x2 R7723-100 1800V

in coincidence with a small 1"x1"x2" $LaBr_3$:Ce

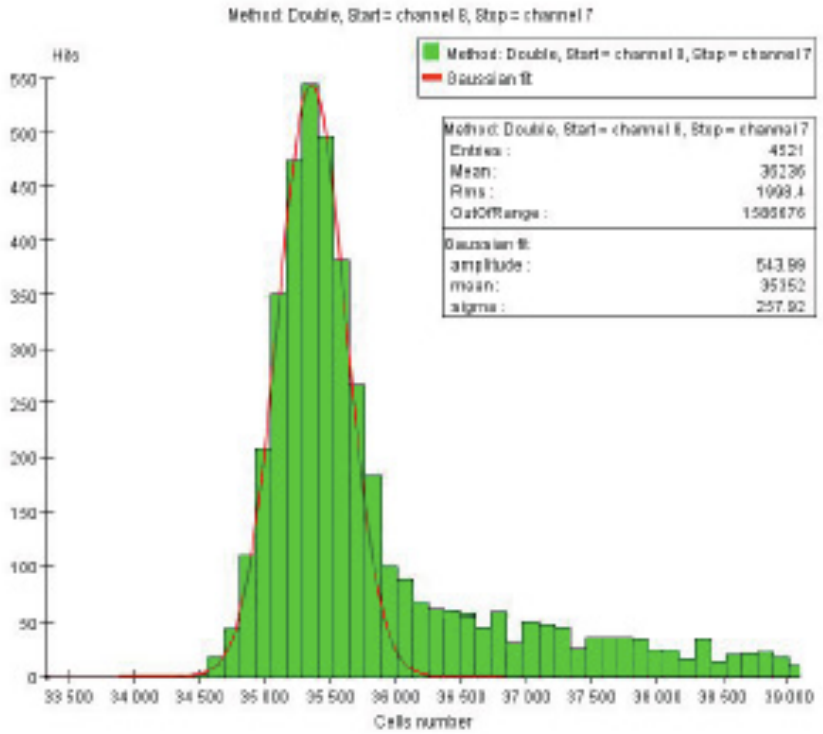


Courtesy of Th. Zerguerras

Analog electronics

FWHM = 500 ps @ 551 keV

360 ps @ 1 MeV



Courtesy of Ch. Bonnin

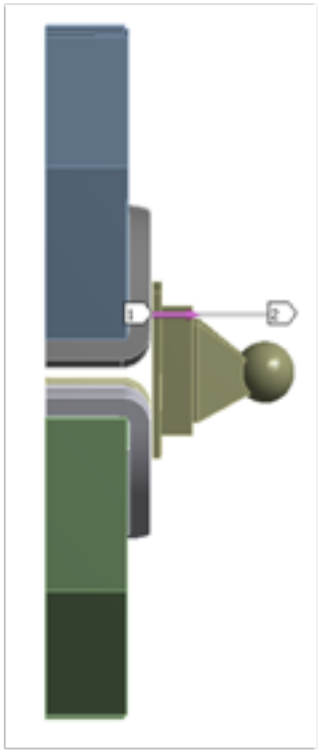
Digital 250 MHz electronics

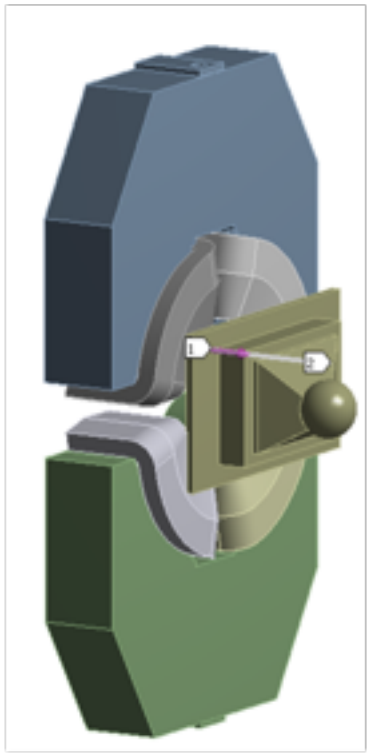
FWHM = 590 ps @ 1,33 MeV

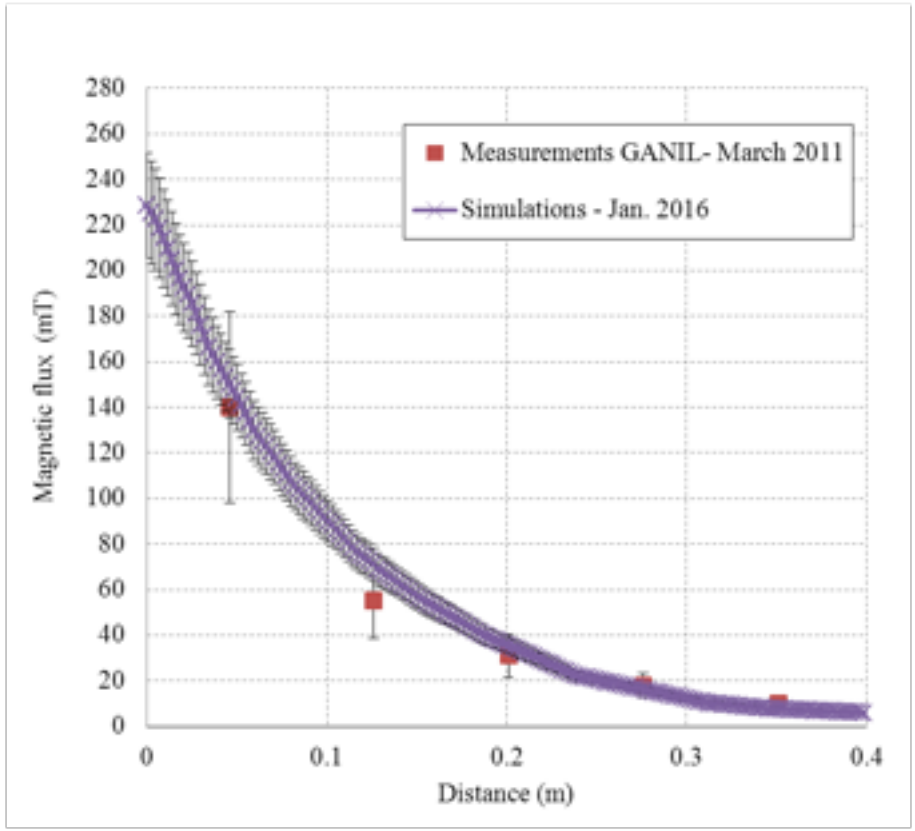
*(Courtesy of **E. Bouquerel**, S. Kihel, Ph. Peaupardin, M. Krauth and M. Ciemala)*

Fringe fields

- Intensity in the coils: 500 A
- Modelling the chamber (Al)







Comparison between simulations and measurements.

Uncertainties assumed: 10% on the simulations, 30% on the measurements

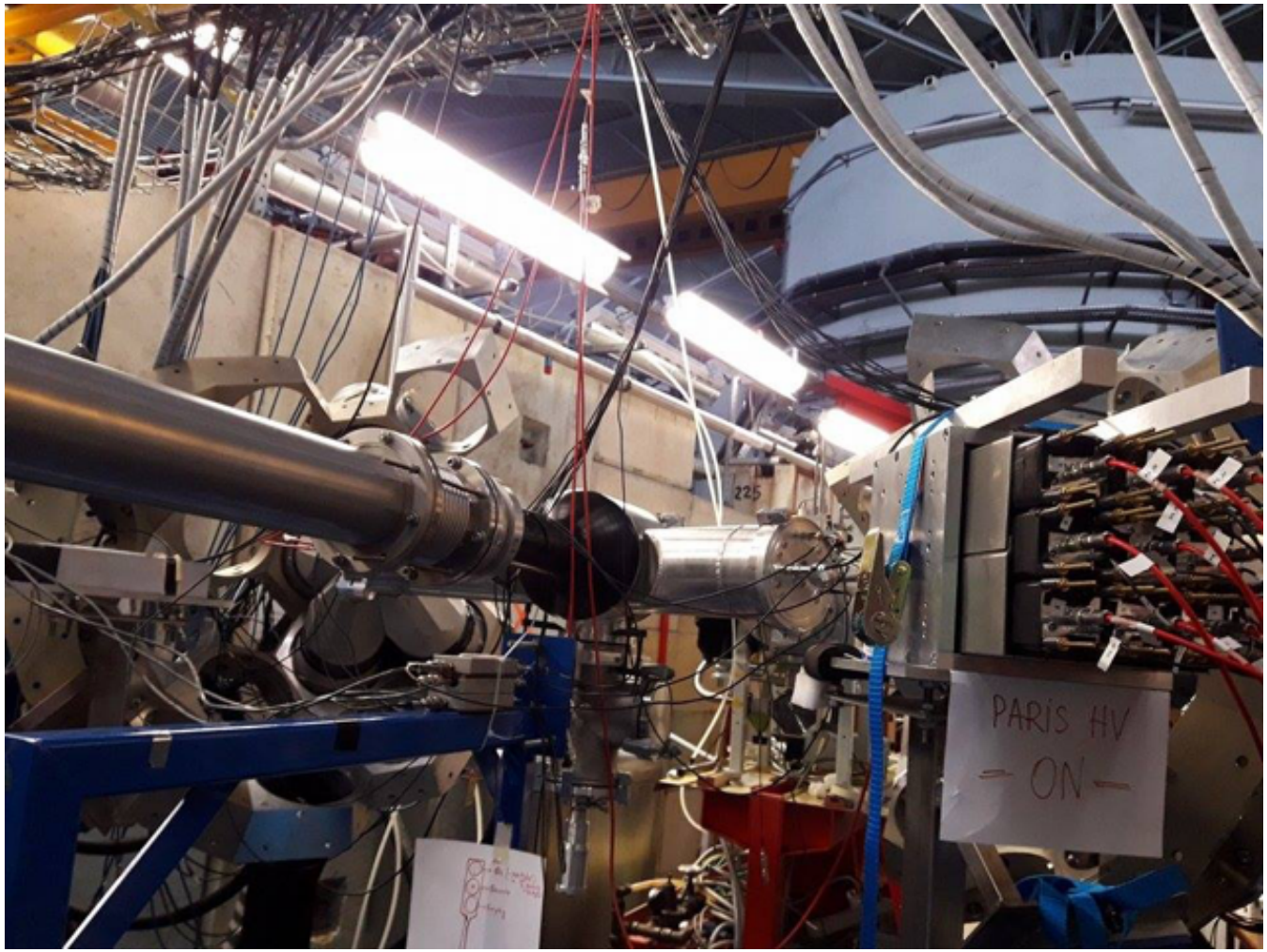
- Values from the simulations crosscheck the measurements performed at GANIL.

Preliminary results from « Prompt γ-rays as a probe of nuclear dynamics »

Aim of the experiment :

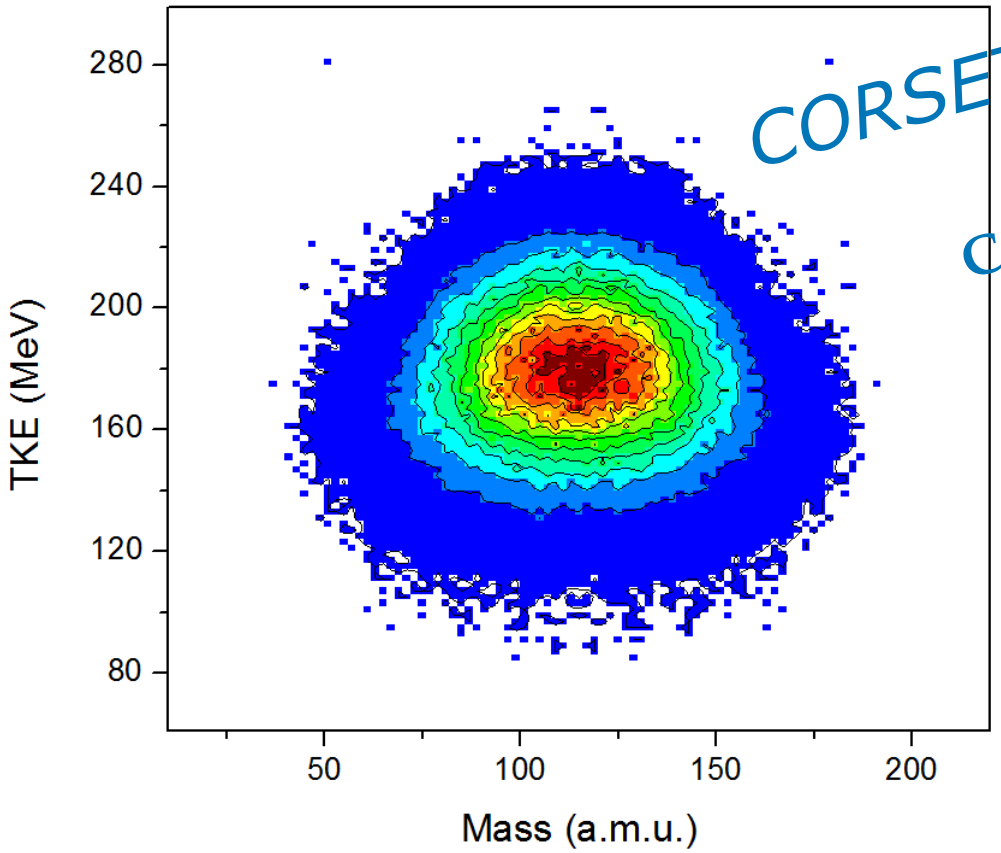
- Coupling *CORSET* with *ORGAM* and *PARIS* setups offers the unique opportunity of extracting details on the shell effects characterizing the two competitive processes, fusion-fission and quasifission, and which are deduced from the two-body kinematic method alone.
- Discrete γ-ray transitions to identify fragment (A,Z) and spin regions
- Gamma energy sum, multiplicity and angular distribution would give insight into entry point in E* and J

Preliminary results from « Prompt γ-rays as a probe of nuclear dynamics »



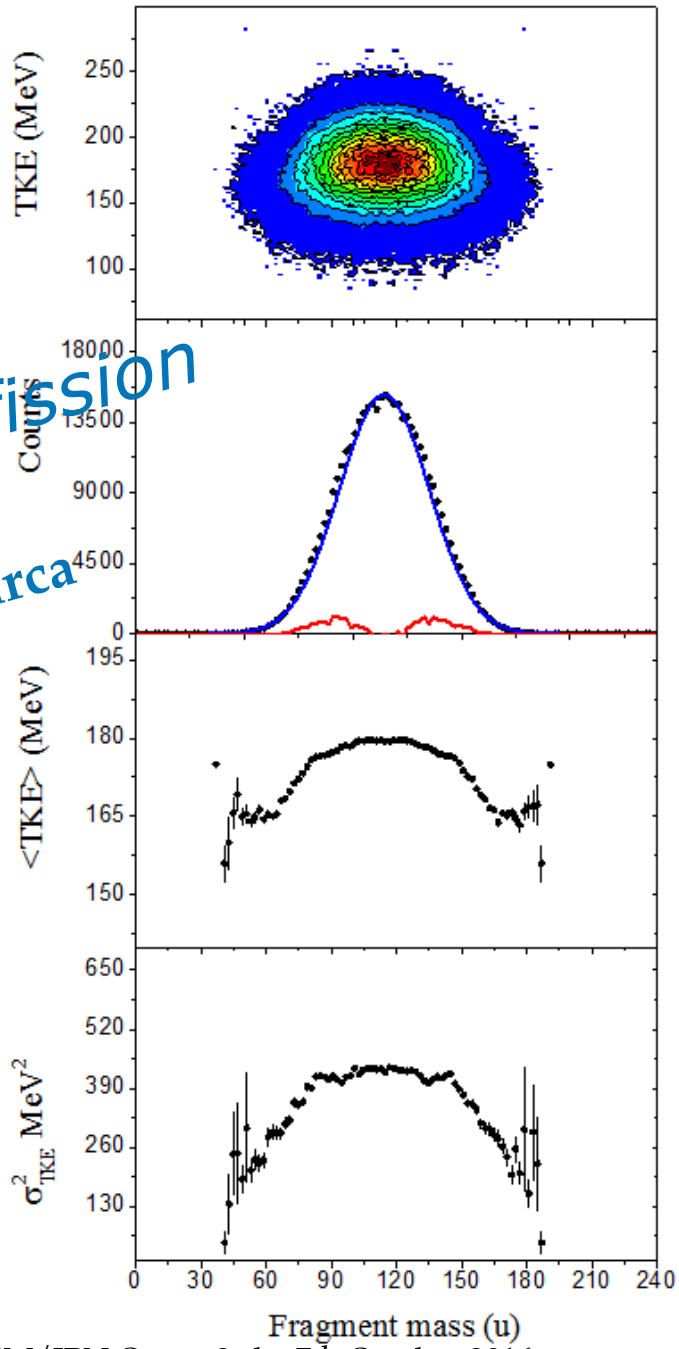
Preliminary results from « Prompt γ-rays as a probe of nuclear dynamics »

$^{32}S + ^{192}Os \rightarrow ^{224}U^*$



CORSET data for fission fragments

Courtesy of I. Harca



Preliminary results from « Prompt γ-rays as a probe of nuclear dynamics »