Study of the n-γ During the De-excitation of ^{252}Cf(sf) Fission Fragments

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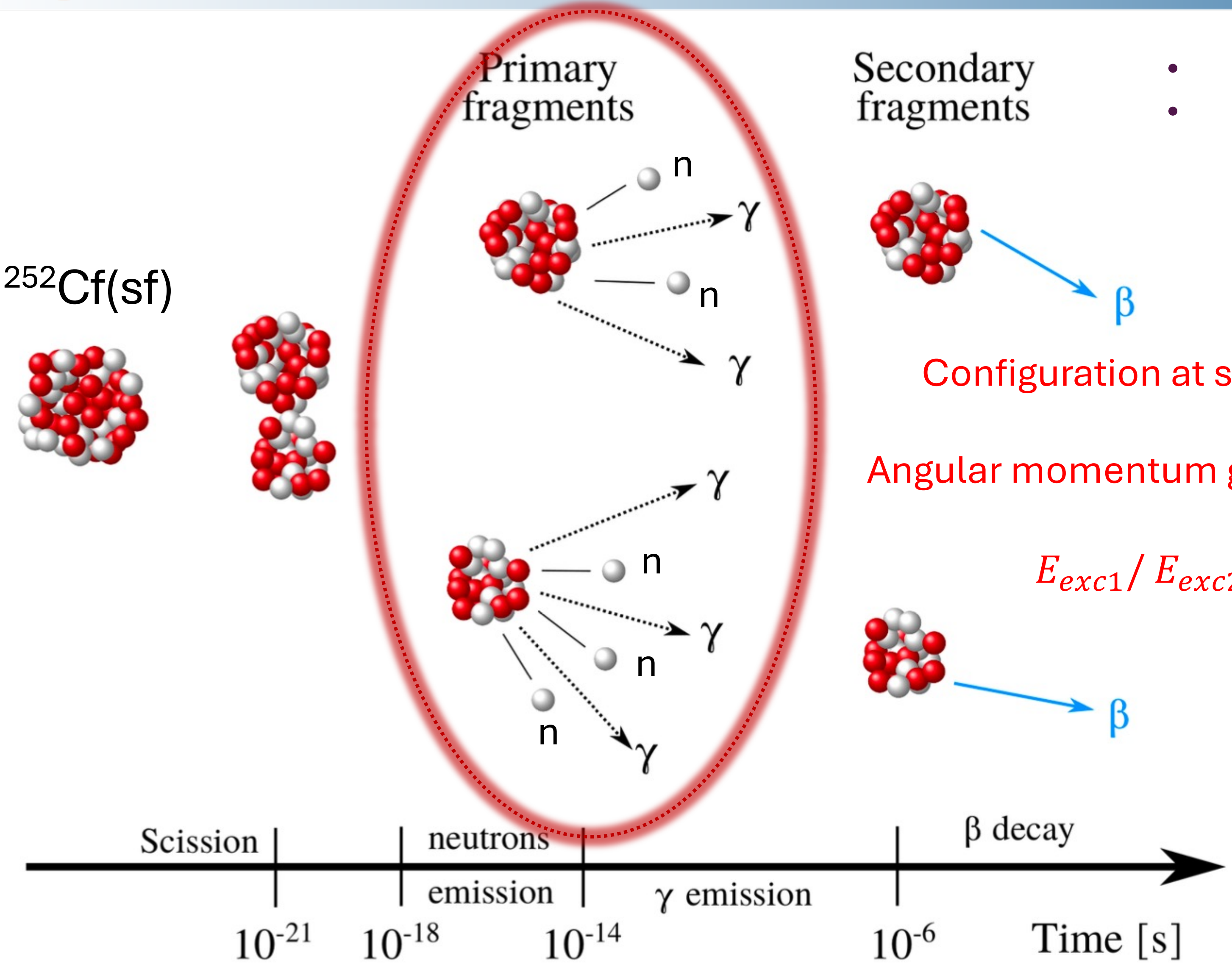
Supervisors: Matthieu Lebois & Gabriel Charles

Study of the De-excitation Process of $^{252}Cf(sf)$ Fission Fragments

- Average excitation energy TXE ~20 à 30MeV
- Average spin removed by fission fragments $J = 7{-}8\ \hbar$

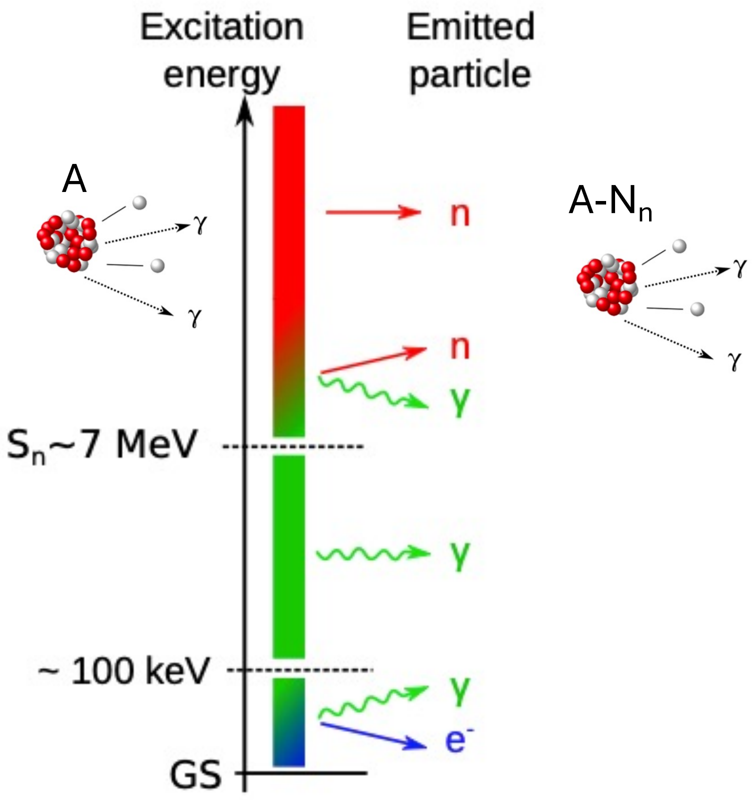


Configuration at scission?

Angular momentum generation?

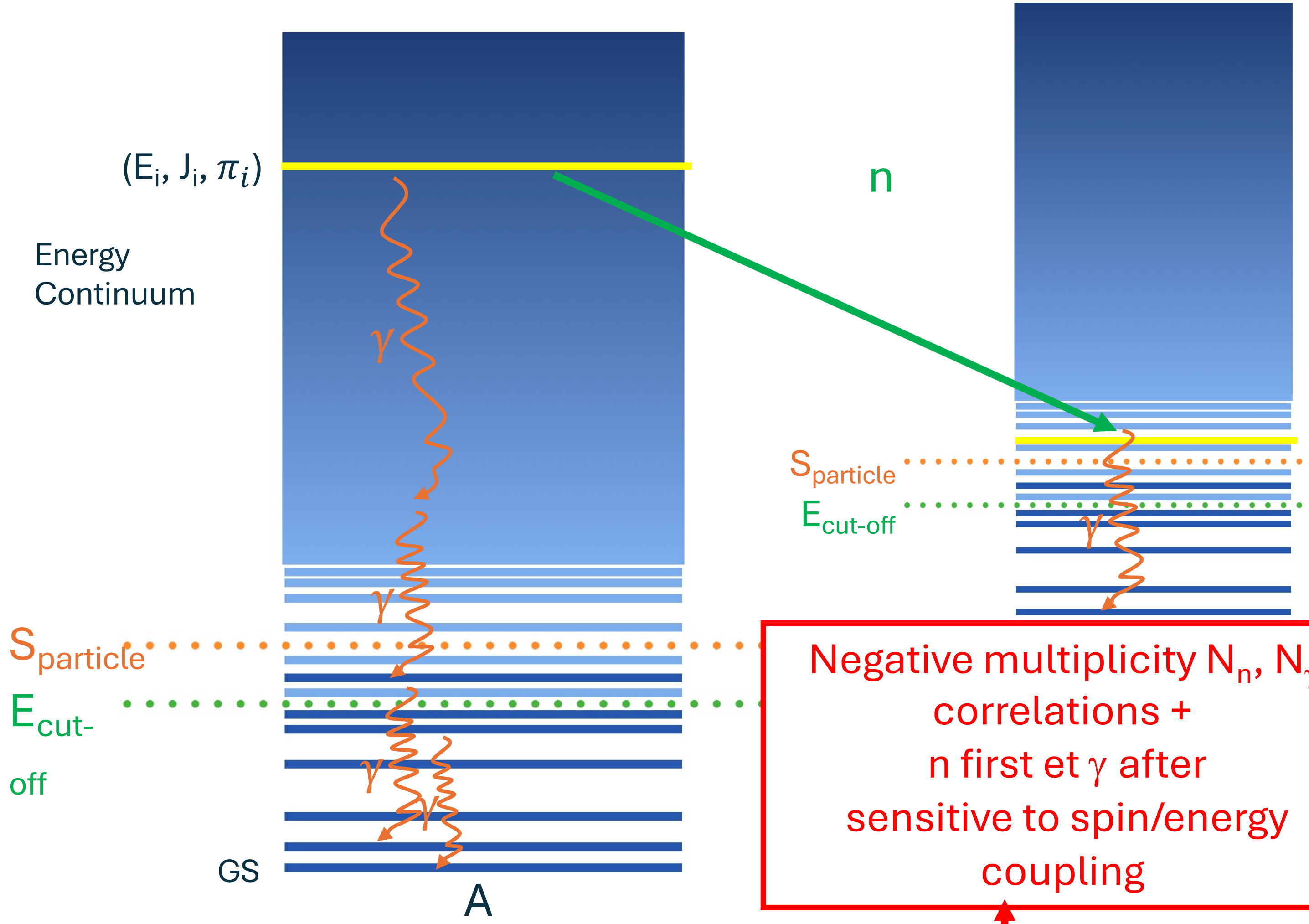
E_{exc1} / E_{exc2}?

A. Francheteau, PhD thesis (2023)



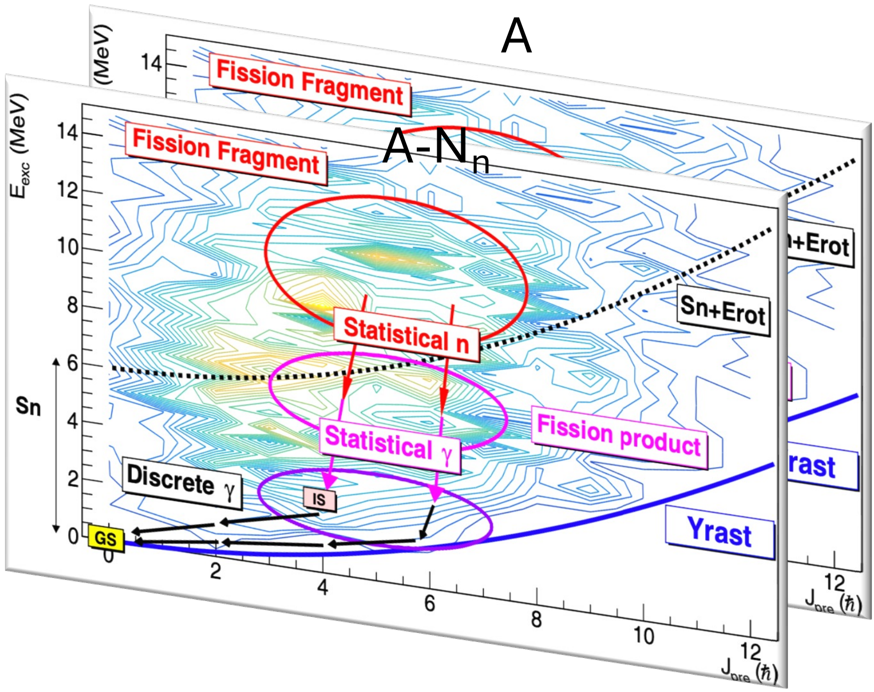
N. Schunck, D. Regnier, Prog.Part.Nucl.Phys. 125 (2022) 103963

Statistical Approach – Hauser-Feshbach FIFRELIN-style with n-γ coupling



Particle emisision energy threshold
Energy threshold above which level scheme is incomplete
Measured experimental levels
Model-calculated levels

Negative multiplicity N_n, N_γ correlations +
n first et γ after
sensitive to spin/energy coupling



Scheme of the de-excitation cascade according to FIFRELIN considering n-γ coupling
Readapted from O. Litaize et al. The Eur. Phy. J. Conf. (January 2018)

Prompt Neutron Angular Momentum Removal

PHYSICAL REVIEW LETTERS **127**, 222502 (2021)

CGMF Simulation

Angular Momentum Removal by Neutron and γ-Ray Emissions during Fission Fragment Decays

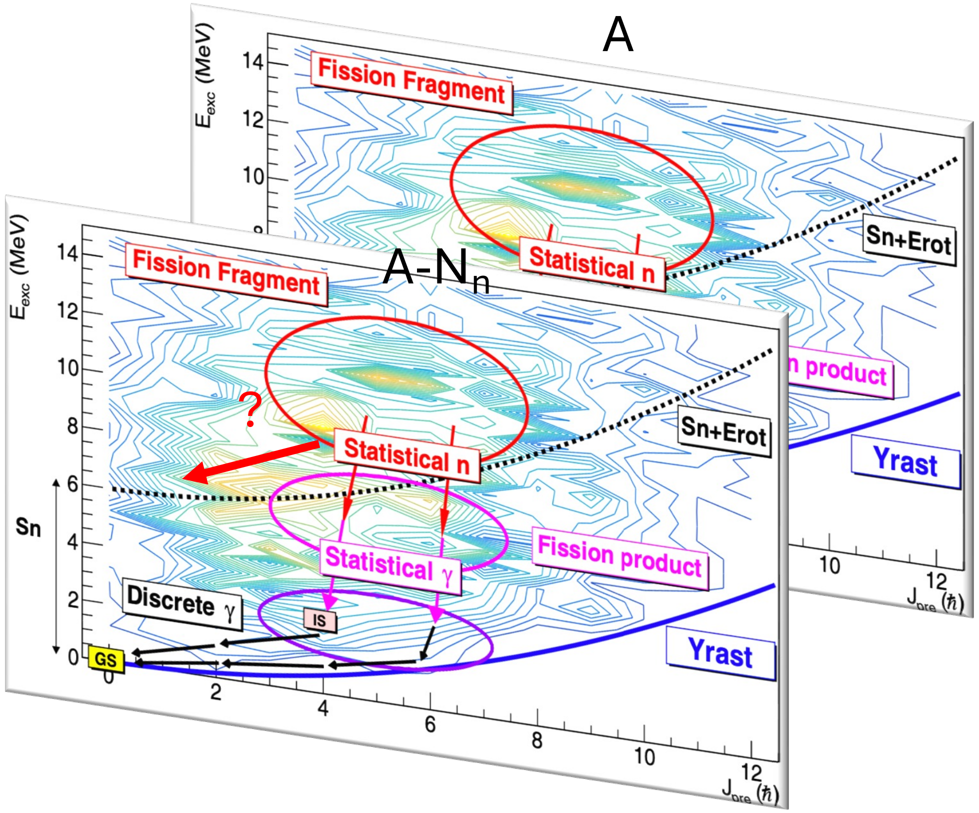
I. Stetcu,[1] A. E. Lovell,[1] P. Talou,[1] T. Kawano,[1] S. Marin,[2] S. A. Pozzi,[2] and A. Bulgac[3]
[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA*
[3]*Department of Physics, University of Washington, Seattle, Washington, D.C. 98195–1560, USA*

(Receiv... vember 2021)

We ... d γ-ray emiss... change in ang... usual assum... ge the spin ... Such

TABLE I. The average angular momentum $\langle j_{\rm rm}\rangle = j_{\rm ini} - j_{\rm fin}$ (in $\hbar$ units) removed by each prompt neutron, and its standard deviation, $\Delta j_{\rm rm}$, for ^{235}U$(n_{\rm th}, f)$ and ^{239}Pu$(n_{\rm th}, f)$, ^{238}U$(n_{1.9\ \rm MeV}, f)$, and ^{252}Cf(sf) reactions, and the percentage of neutrons that remove an angular momentum larger or equal to $\frac{3}{2}$ and $\frac{7}{2}$, respectively. Only about 25% of the neutrons remove $\frac{1}{2}$. "Removed" angular momentum smaller than zero means that the neutron emission increases the FF angular momentum, using the Koning-Delaroche optical potential [30].

			$j_{\rm rm}$		
Reaction	$\langle j_{\rm rm}\rangle$	$\Delta j_{\rm rm}$	< 0 (%)	≥ 1.5 (%)	≥ 3.5 (%)
^{235}U$(n_{\rm th}, f)$	1.33	1.97	22.2	51.7	14.5
^{238}U$(n_{1.9\ \rm MeV}, f)$	1.34	1.93	21.5	52.5	14.5
^{239}Pu$(n_{\rm th}, f)$	1.23	1.91	23.5	49.9	12.8
^{252}Cf(sf)	1.13	1.71	23.7	49.2	11.1



γ Multiplicity & Excitation Energy

PHYSICAL REVIEW LETTERS 127, 222502 (2021)

CGMF Simulation

Angular Momentum Removal by Neutron and γ-Ray Emissions during Fission Fragment Decays

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TABLE I. The average angular momentum $\langle j_{rm} \rangle = j_{ini} - j_{fin}$ (in $\hbar$ units) removed by each prompt neutron, and its standard deviation, Δj_{rm}, for $^{235}U(n_{th}, f)$ and $^{239}Pu(n_{th}, f)$, $^{238}U(n_{1.9\ MeV}, f)$, and $^{252}Cf(sf)$ reactions, and the percentage of neutrons that remove an angular momentum larger or equal to $\frac{3}{2}$ and $\frac{7}{2}$, respectively. Only about 25% of the neutrons remove $\frac{1}{2}$. "Removed" angular momentum smaller than zero means that the neutron emission increases the FF angular momentum, using the Koning-Delaroche optical potential [30].

Reaction	$\langle j_{rm} \rangle$	Δj_{rm}	j_{rm} < 0 (%)	j_{rm} ≥ 1.5 (%)	j_{rm} ≥ 3.5 (%)
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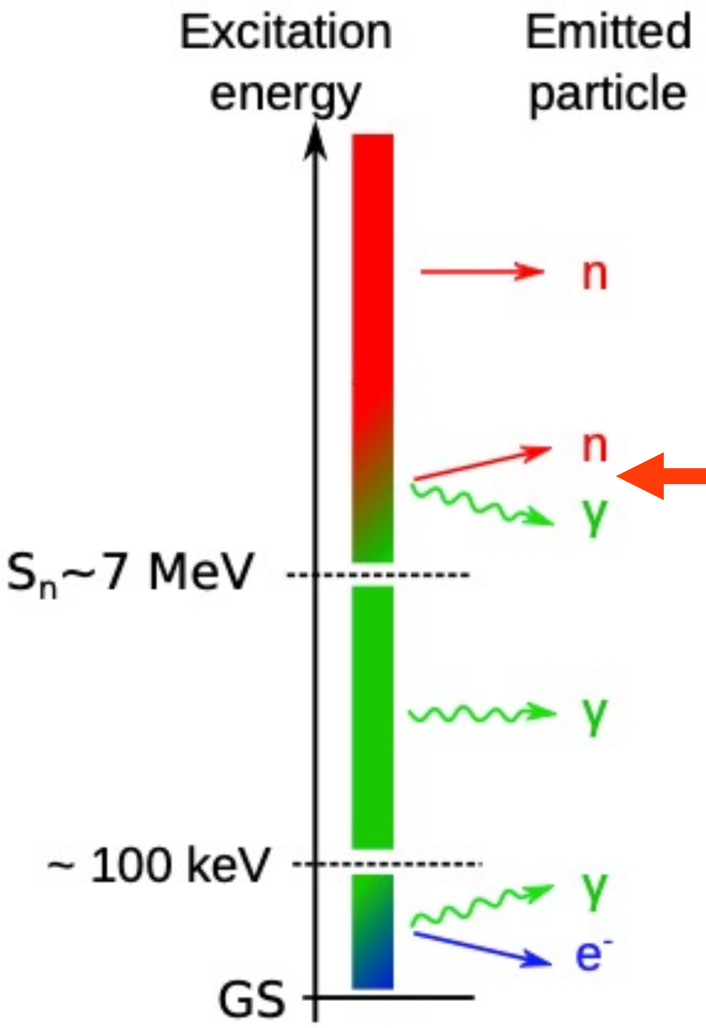

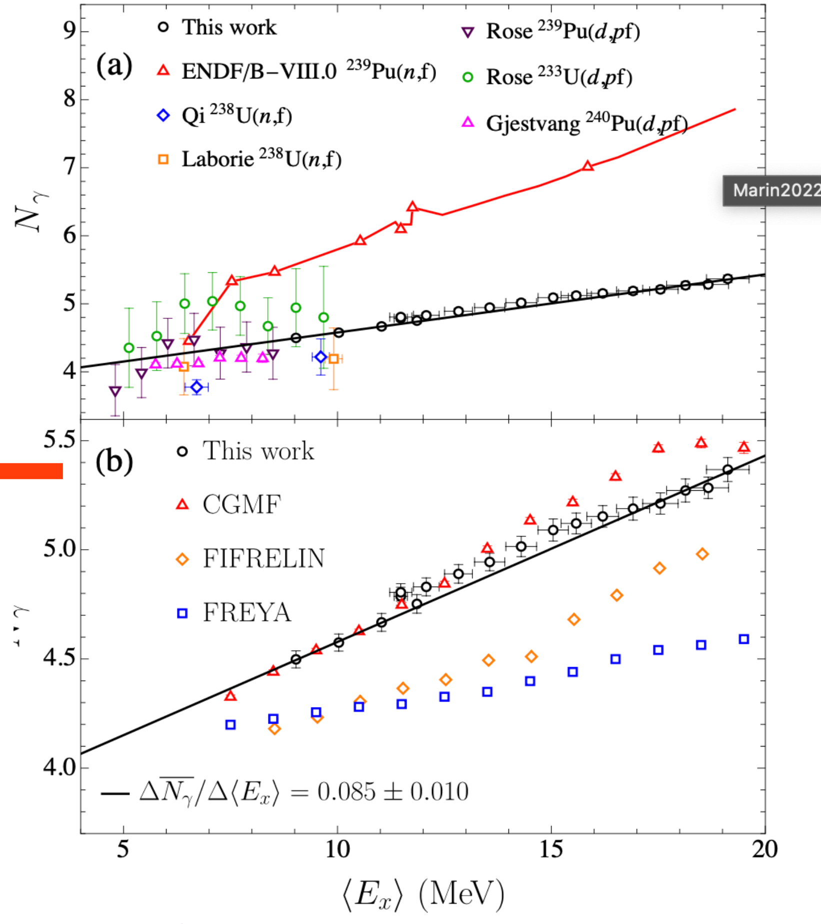

N.P. Giha, PhD thesis (2023)

N. Schunck, D. Regnier, Prog.Part.Nucl.Phys. 125 (2022) 103963

Previous Measurements of the n- γ Competition in ^{252}Cf(sf)

2.J: 3.A

Nuclear Physics A189 (1972) 285—304;

GAMMA-NEUTRON COMPETITION IN THE DE-EXCITATION MECHANISM OF THE FISSION FRAGMENTS OF ^{252}Cf

H. NIFENECKER, C. SIGNARBIEUX, M. RIBRAG, J. POITOU and J. MATUSZEK

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Received 23 September 1971
(Revised 3 February 1972)

Abstract: A multiparameter experiment in which the kinetic energies of the fragments, the number of prompt fission neutrons and the total γ-ray energy per fission were measured, has been performed. The neutron multiplicity and the γ-ray measurements were made with the same large scintillator. A method which corrects the γ-pulse for the proton recoils caused by the fission neutrons is described. The results show that the γ-energy decreases by about 0.1 MeV when the total kinetic energy of the fragments increases by 1 MeV. A linear relationship between the γ-ray energy emitted by a given fragment and the average number of neutrons emitted by the same fragment is suggested, namely:

$$E_\gamma(m, E_t) = 0.75\bar{\nu}(m, E_t)+2 \text{ (MeV)}.$$

These results are interpreted as caused by a linear increase of the average spin of the fragments with their excitation energy.

Experiment	Conclusion on the Cov(N_n, N_γ)
Nifenecker et al. (average over the fragments)	Positive linear correlation

Previous Measurements of the n- γ Competition in ^{252}Cf(sf)

Nuclear Physics A502 (1989) 315c-324c
North Holland, Amsterdam

^{252}Cf FISSION REVISITED — NEW INSIGHTS INTO THE FISSION PROCESS

P. Glässel, R. Schmid-Fabian*, D. Schwalm

Physikalisches Institut der Universität Heidelberg, FRG

D. Habs, H.U. v. Helmolt

Max-Planck-Institut für Kernphysik, Heidelberg, FRG

γ-ray energies and multiplicities and neutron multiplicities from Cf spontaneous fission were measured with NaI detectors in 4π at the Heidelberg-Darmstadt Crystal Ball together with the mass and kinetic energy of the fission fragments. The correlation of neutron multiplicity with fragment mass and kinetic energy is presented and discussed in the context of nascent fragment deformation. The γ-multiplicity unfolded for individual fragments is found to be rather independent of mass. A high-energy component in the γ-spectra is found in the vicinity of symmetric fission. The results are discussed in the framework of current fission models.

Experiment	Conclusion on the Cov(N_n, N_γ)
Nifenecker et al. (average over the fragments)	Positive linear correlation
Glässel et al. (event by event as a function of KE)	Weak,Linear, negative -0.35 $\pm$ 0.01

Previous Measurements of the n- γ Competition in ^{252}Cf(sf)

Nuclear Instruments and Methods in Physics Research A 624 (2010) 691–698

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Gamma-ray multiplicity measurement of the spontaneous fission of ^{252}Cf in a segmented HPGe/BGO detector array

D.L. Bleuel [a,*], L.A. Bernstein [a], J.T. Harke [a], J. Gibelin [b], M.D. Heffner [a], J. Mintz [c], E.B. Norman [a,b,c], L. Phair [b], N.D. Scielzo [a], S.A. Sheets [a], N.J. Snyderman [a], M.A. Stoyer [a], M. Wiedeking [a,b]

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[b] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States*
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Multiplicity
Gamma-ray
Neutron

A B S T R A C T

Coincident γ rays from a ^{252}Cf source were measured using an array of six segmented high-purity germanium (HPGe) Clover detectors each enclosed by 16 bismuth-germanate (BGO) detectors. The detectors were arranged in a cubic pattern around a 1 μCi ^{252}Cf source to cover a large solid angle for γ-ray measurement with a reasonable reconstruction of the multiplicity. Neutron multiplicity was determined in certain cases by identifying the prompt γ rays from individual fission fragment pairs. Multiplicity distributions from previous experiments and theoretical models were convolved with the response function of the array and compared to the present results. These results suggest a γ-ray multiplicity spectrum broader than previous measurements and models, and provide no evidence of correlation with neutron multiplicity.

Experiment	Conclusion on the Cov(N_n, N_γ)
Nifenecker et al. (average over the fragments)	Positive linear correlation
Glässel et al. (event by event as a function of KE)	Weak,Linear, negative -0.35 $\pm$ 0.01
Bleuel et al. (no direct neutron measurement)	No correlation 0

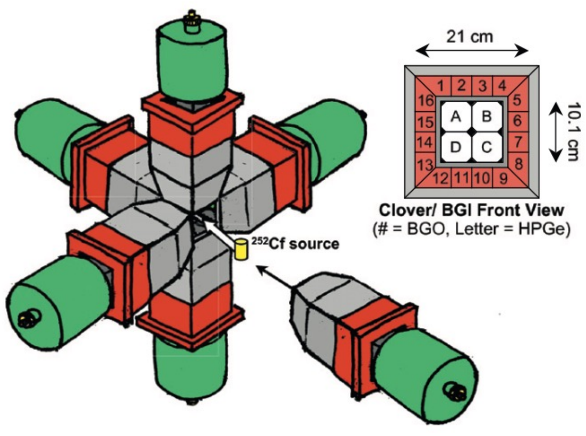

Fig. 3. Schematic representation (not to scale) of detector arrangement, with ^{252}Cf source about to be placed at the center.

Previous Measurements of the n- γ Competition in ^{252}Cf(sf)

PHYSICAL REVIEW C **97**, 044622 (2018)

Measured and simulated ^{252}Cf(sf) prompt neutron-photon competition

Matthew J. Marcath,[1,*] Robert C. Haight,[2] Ramona Vogt,[3,4] Matthew Devlin,[2] Patrick Talou,[2] Ionel Stetcu,[2] Jørgen Randrup,[5] Patricia F. Schuster,[1] Shaun D. Clarke,[1] and Sara A. Pozzi[1]

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Neutrons and photons are characteristically emitted during the nuclear fission process when a deformed, neutron-rich nucleus divides into two fragments that then deexcite. During deexcitation, neutrons are emitted first, followed by photons; this process gives rise to correlated emissions. Few data exist on event-by-event neutron-photon correlation. In this work, ^{252}Cf(sf) neutron and photon correlations were measured with an array of 45 liquid organic scintillation detectors and a fission chamber. The measured correlations are compared with `MCPNX-PoliMi` simulations using the built-in model and two event-by-event fission models, `CGMF` and `FREYA`, which predict correlations in prompt emissions from fission. Experimental results suggest weak neutron-photon competition during fragment deexcitation.

DOI: 10.1103/PhysRevC.97.044622

Experiment	Conclusion on the Cov(N_n, N_γ)
Nifenecker et al. (average over the fragments)	Positive linear correlation
Glässel et al. (event by event as a function of KE)	Weak, Linear, negative -0.35 $\pm$ 0.01
Bleuel et al. (no direct neutron measurement)	No correlation 0
Marcath et al. (event by event)	Very Weak negative -0.02 $\pm$ 0.12

FROZEN : Study of n- γ Competition in ^{252}Cf(sf)

2.J: 3.A
Nuclear Physics A189 (1972) 285—304; © *North-Holland Publishing Co., Amsterdam*

GAMMA-NEUTRON COMPETITION IN THE DE-EXCI
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ELSEVIER

Gamma-ray multiplicity meas...
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D.L. Bleuel[a,*], L.A. Bernstein[a], J.T. Har...
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[c] Nuclear Engineering Department, University of California, Berke...

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ABS...
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PHYSICAL ...VIE... C ...44622 (2018)

BIAS

Measured and simu...ed ^{25}...f(sf) prompt neutron-photon competition

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(Received 23 January 2018; published 30 April 2018; corrected 22 May 2018)

Neutrons and photons are characteristically emitted during the nuclear fission process when a deformed, neutron-rich nucleus divides into two fragments that then deexcite. During deexcitation, neutrons are emitted first, followed by photons; this process gives rise to correlated emissions. Few data exist on event-by-event neutron-photon correlation. In this work, ^{252}Cf(sf) neutron and photon correlations were measured with an array of 45 liquid organic scintillation detectors and a fission chamber. The measured correlations are compared with MCPNX-PoliMi simulations using the built-in model and two event-by-event fission models, CGMF and FREYA, which predict correlations in prompt emissions from fission. Experimental results suggest weak neutron-photon competition during fragment deexcitation.

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...-Darmstadt Crystal Ball together with
The correlation of neutron multiplicity
...nd discussed in the context of nascent
...for individual fragments is found to be
...t in the γ-spectra is found in the vicinity
framework of current fission models.

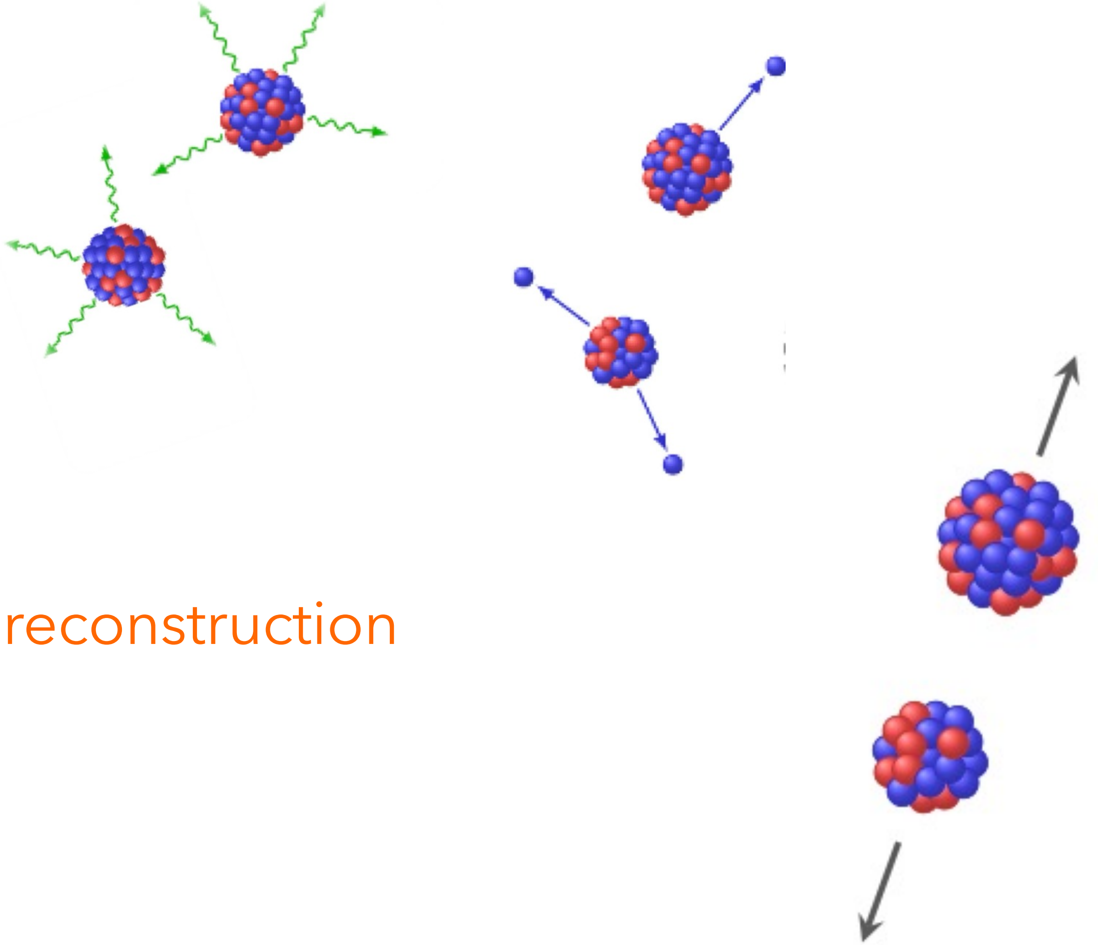
New Measurement Needed!

Goal:
γ spectroscopy & multiplicity measurement as a function of neutron multiplicity

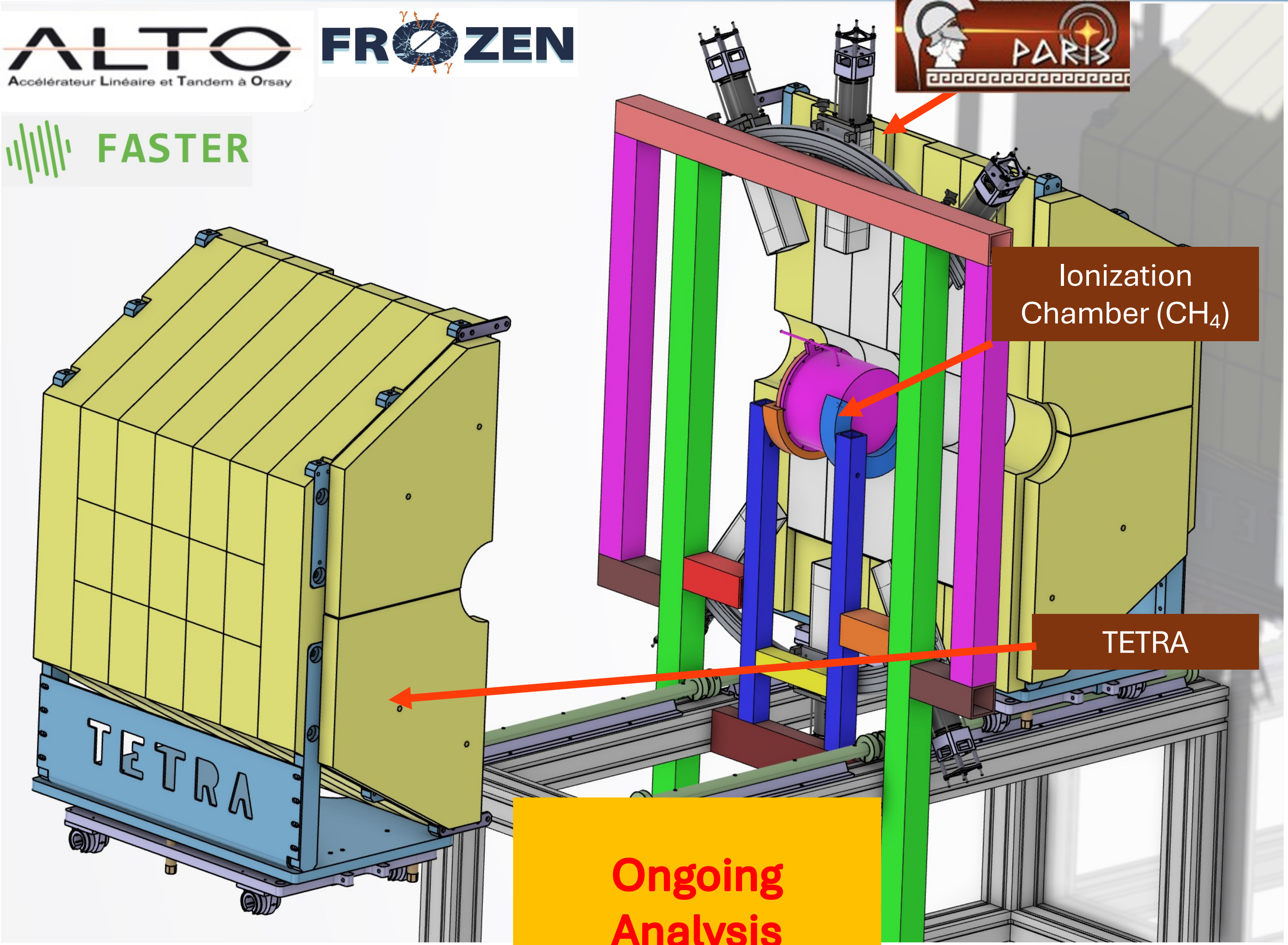
Fission Reaction at Orsay with Zero Emission of Neutrons

Experimental Features

- γ measurement
  - Spectroscopy with scintillators
- Neutron measurement
  - Neutron counters, scintillators
- Fission event ID/ Fission fragment kinematics reconstruction
  - Gaseous detector: ionization chamber

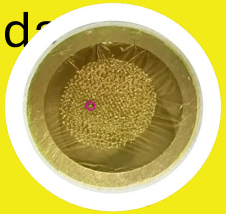


Experimental Setup



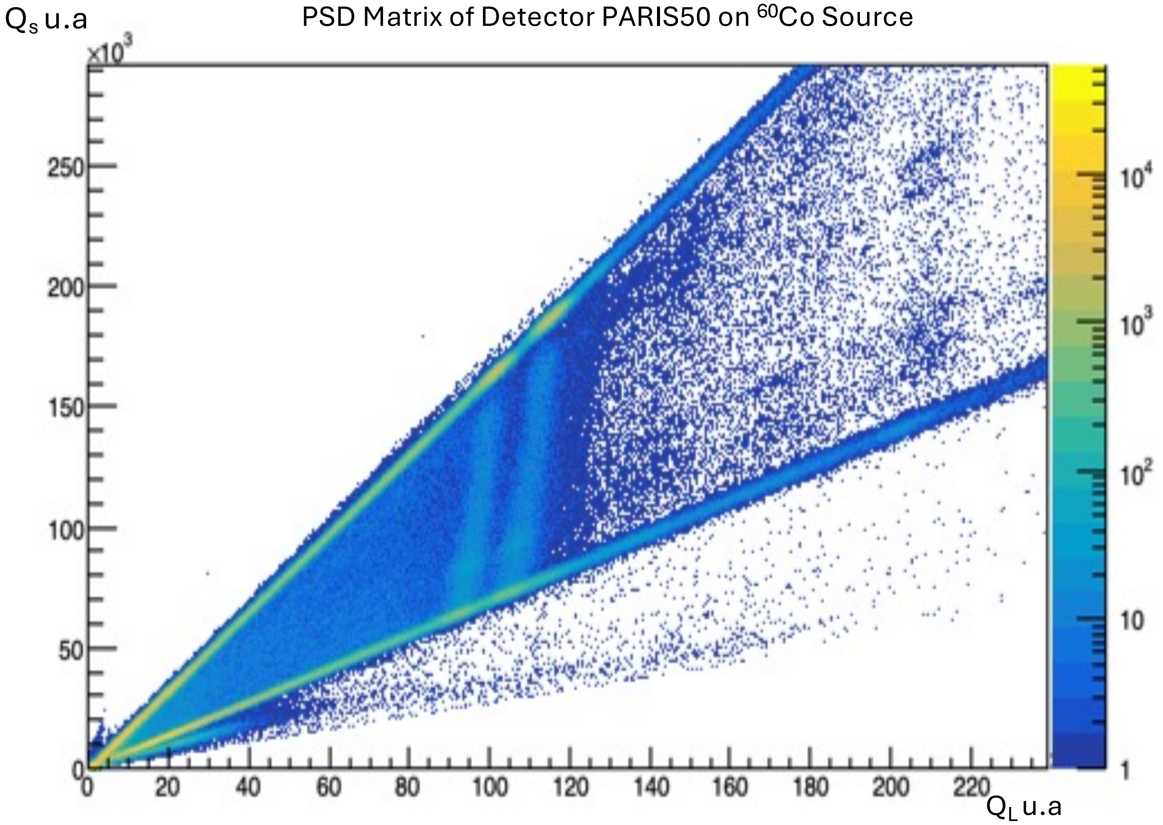
Ongoing Analysis

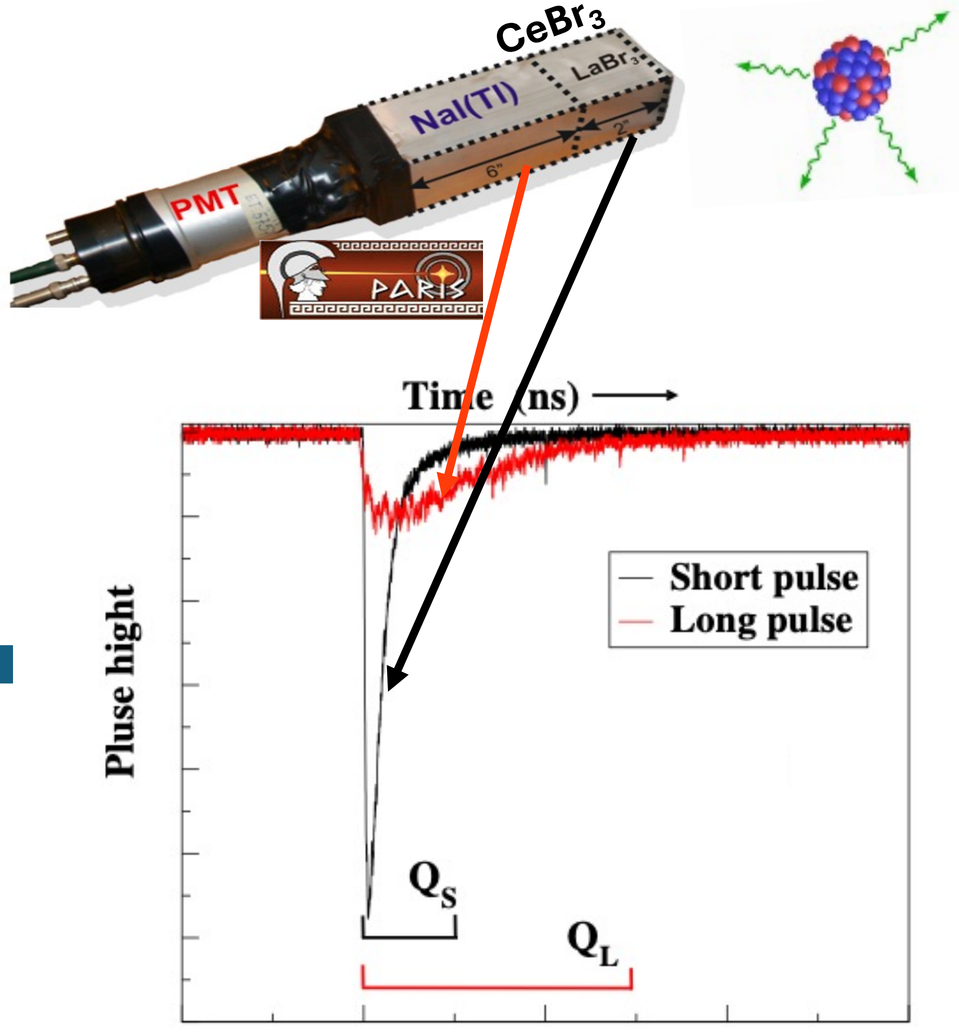
- 6 months in 2024 @ALTO (41Tb d
- ^{252}Cf(sf, 3%): ~200 f/s , ~97% α



- 9 PARIS CeBr3/NaI phoswiches
- Resolution (FWHM) ΔE/E (γ)~2.3%@ 662 keV
- PARIS timing resolution FWHM~750ps
- Total efficiency $\varepsilon_{\gamma tot}$ (E_{CeBr3}~1MeV)~0.5%
- TETRA neutron counter ε_n ~18%
- JRC Geel – Ionization chamber TFGIC
- Waveform storage TFGIC + FASTER

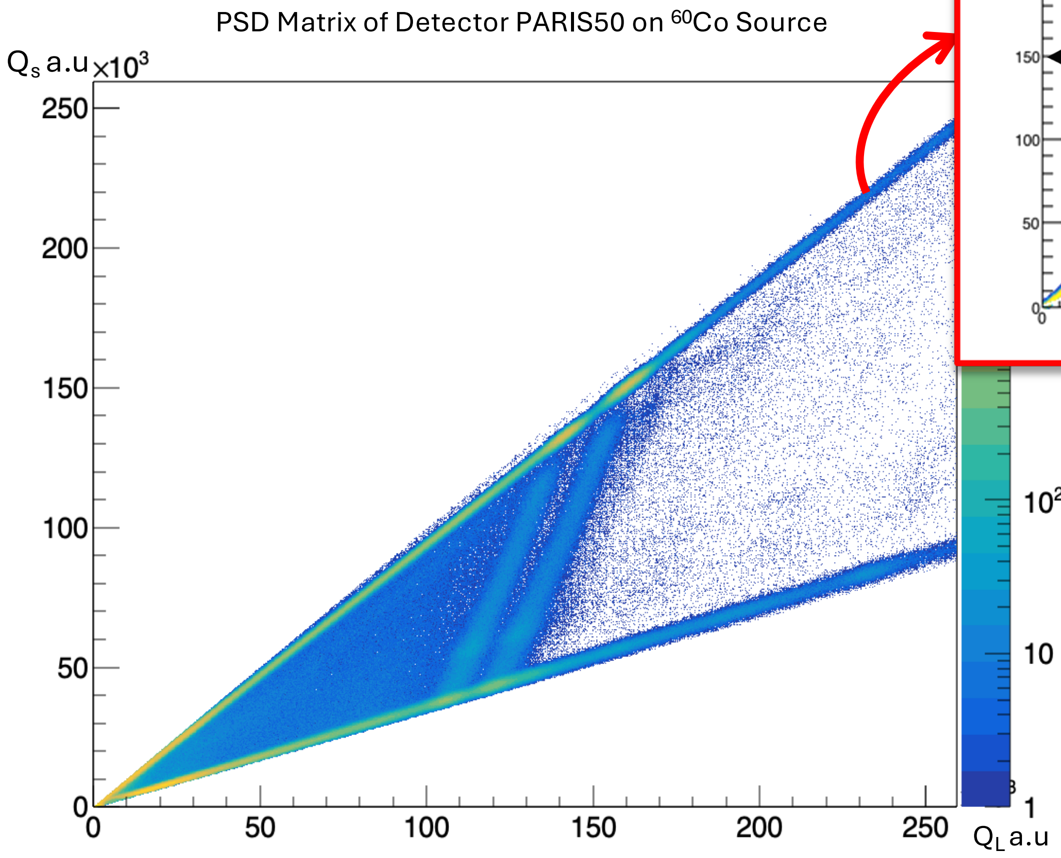
- γ measurement

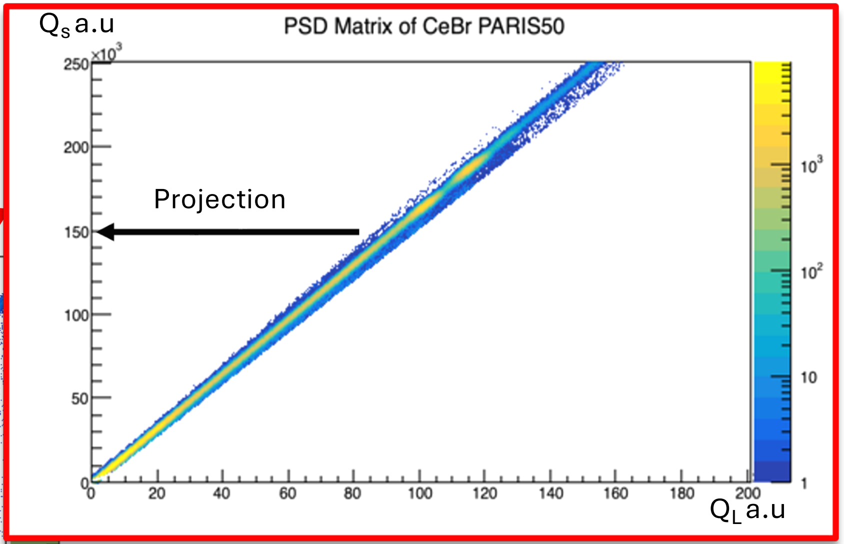




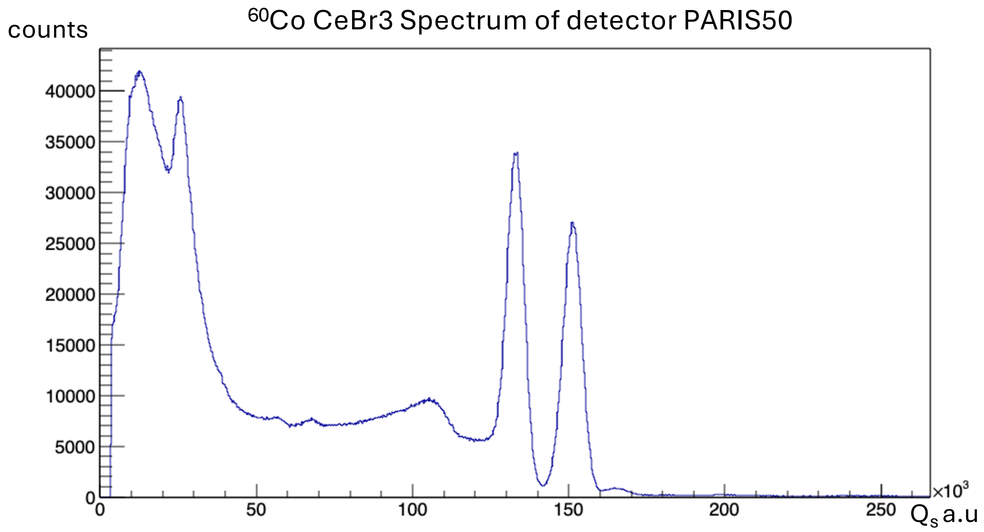
Signaux bruts

Pure $CeBr_3$ event selection

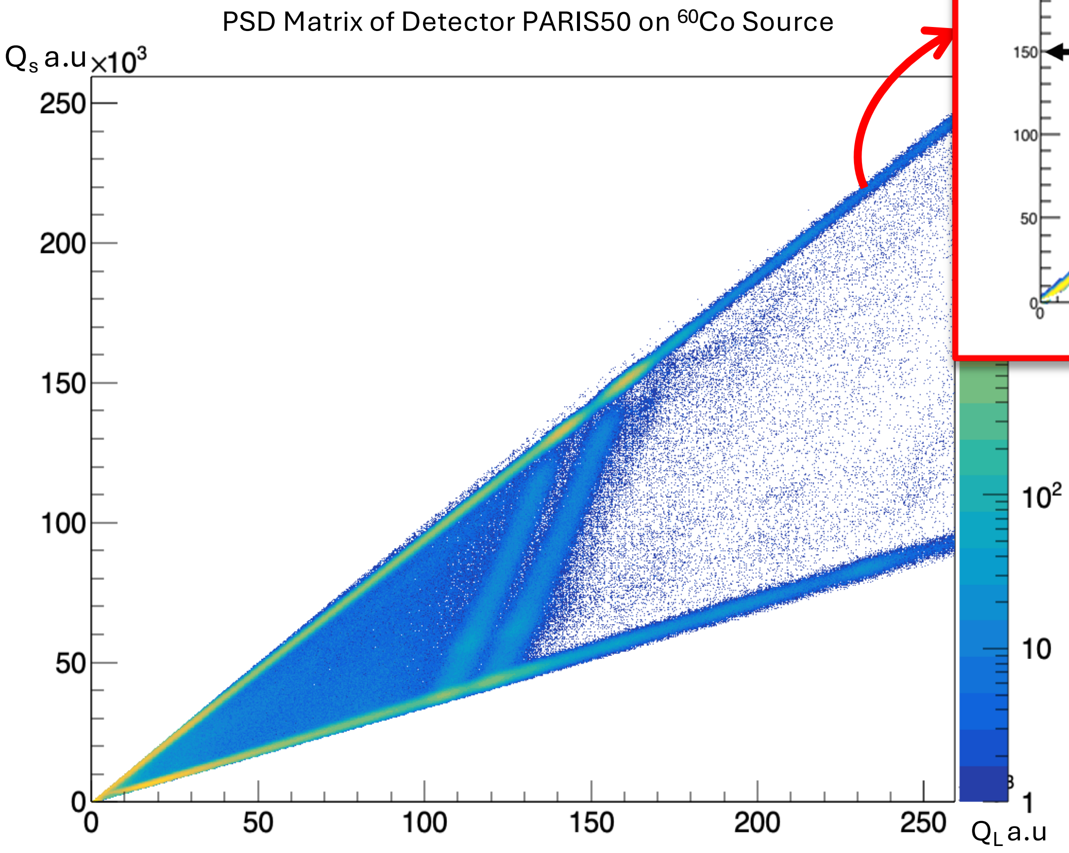


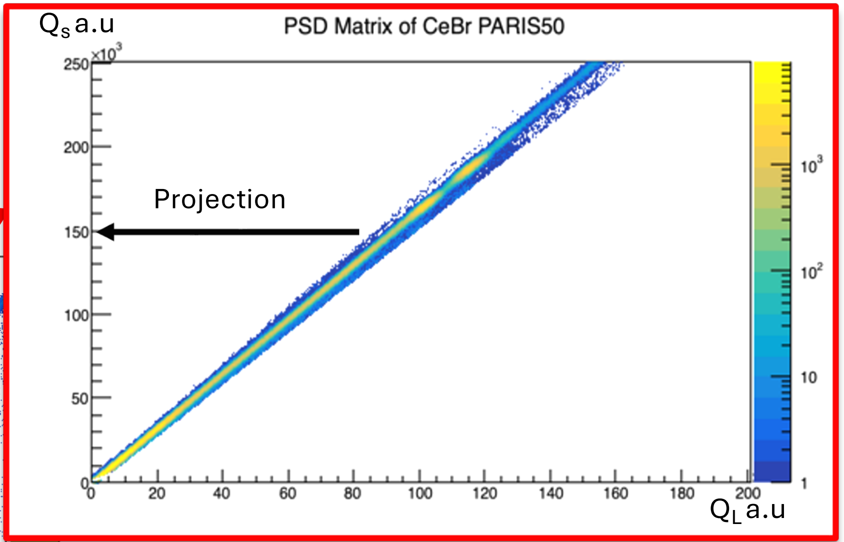


Raw spectrum

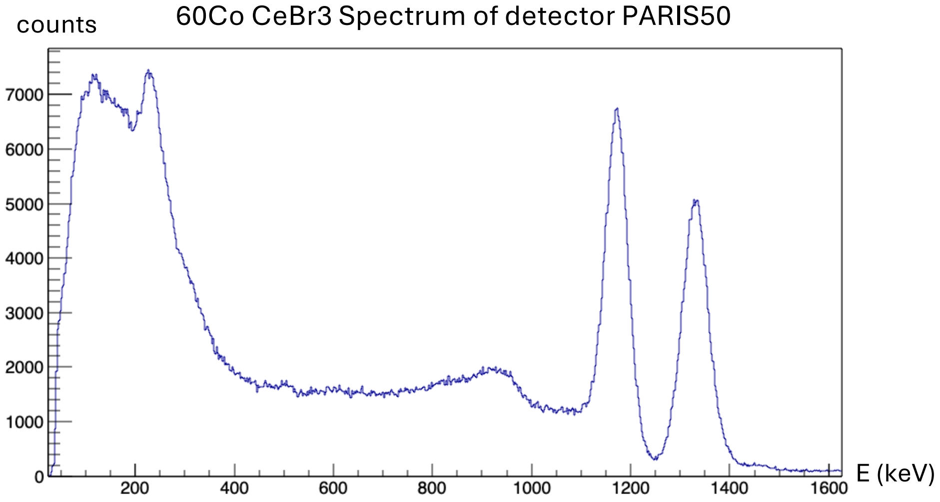


Energy Calibration of PARIS Detectors



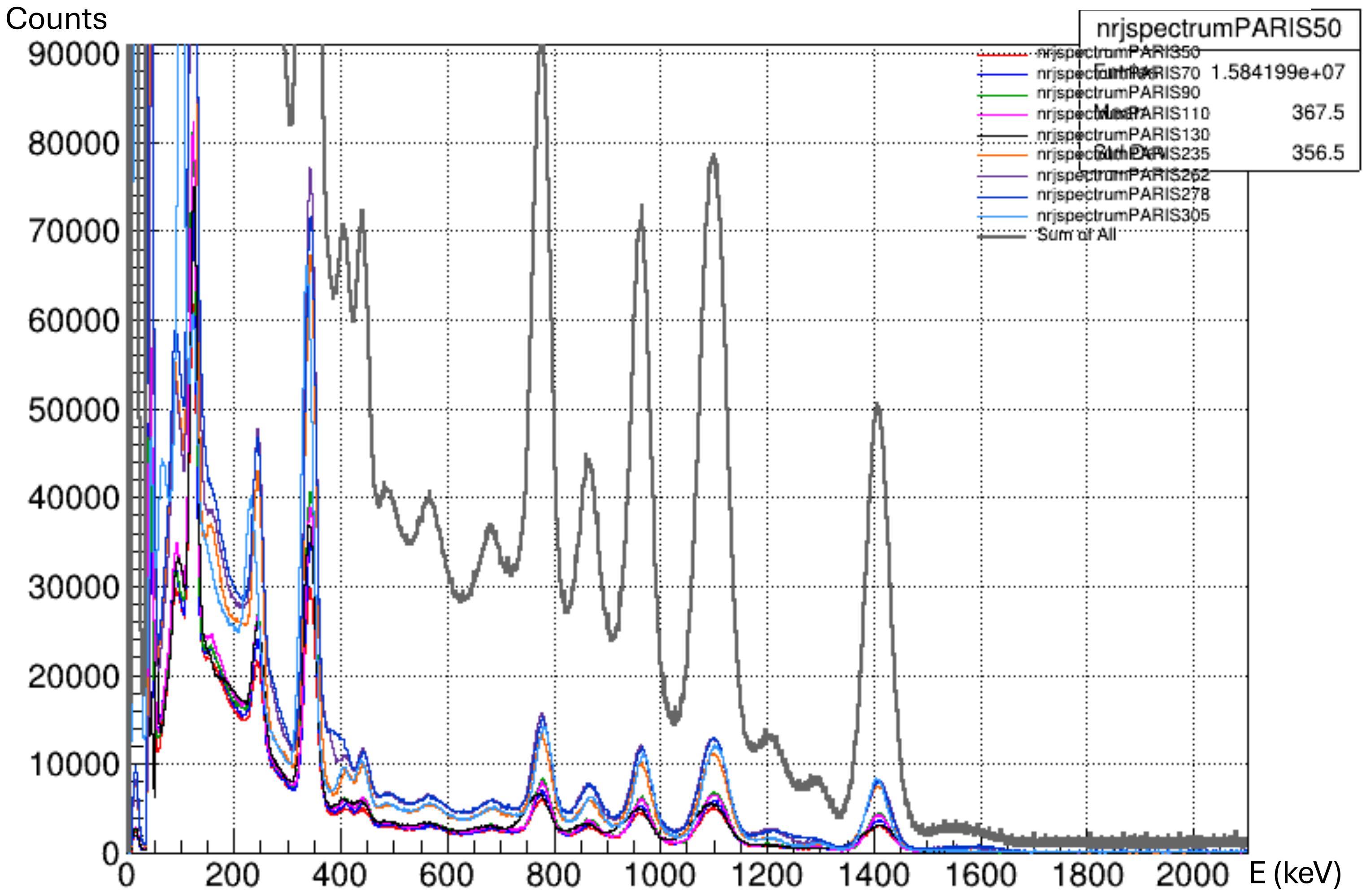


Isotop e	Eγ (keV)	Intensity
60Co	1173.228	0.99850
	1332.501	0.99985



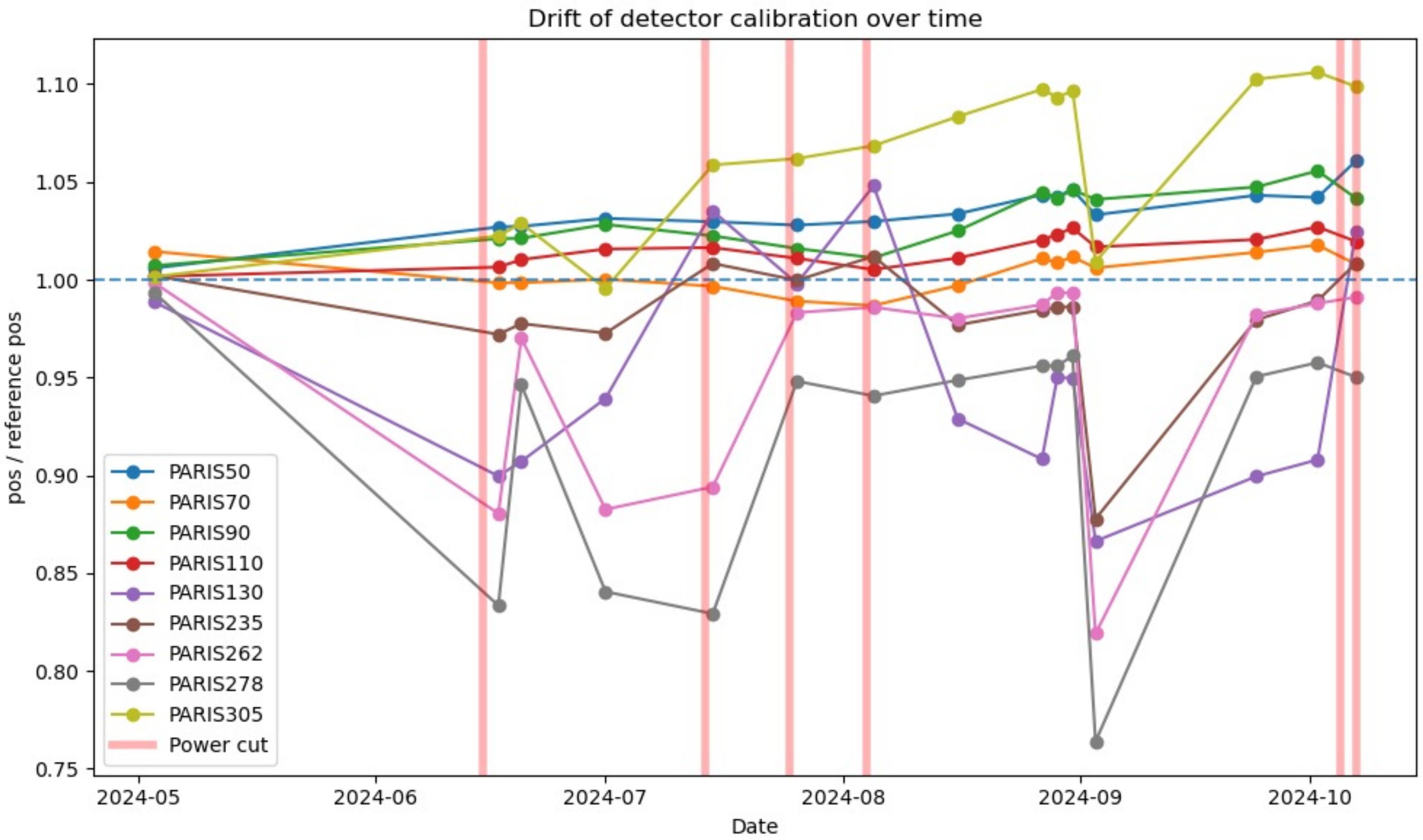
Energy Calibration of PARIS Detectors

^{152}Eu γ spectrum of all PARIS (pure $CeBr_3$ events only) and sum spectrum



Source	Eγ (keV)	Intensity
^{60}Co	1173.228	0.99850
	1332.501	0.99985
^{152}Eu	121.7817	0.2858
	244.6975	0.07583
	344.2785	0.265
	778.904	0.12942
	964.079	0.14605
	1408.006	0.21005
^{137}Cs	661.657	0.851
AmBe	4438.91	0.56

Energy Calibration Follow Up



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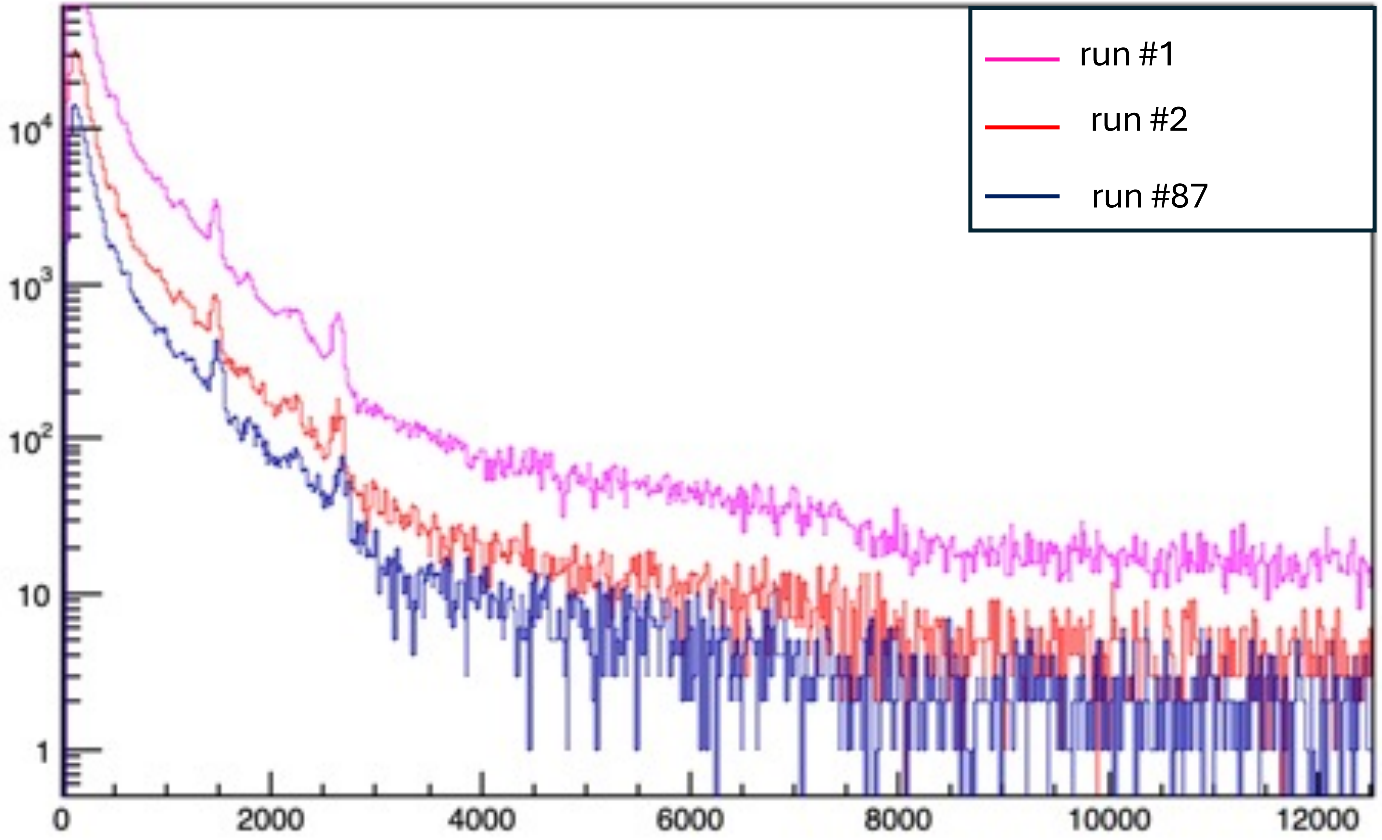
	964.079	0.14605
	1408.006	0.21005

Energy Calibration of PARIS Detectors

Counts

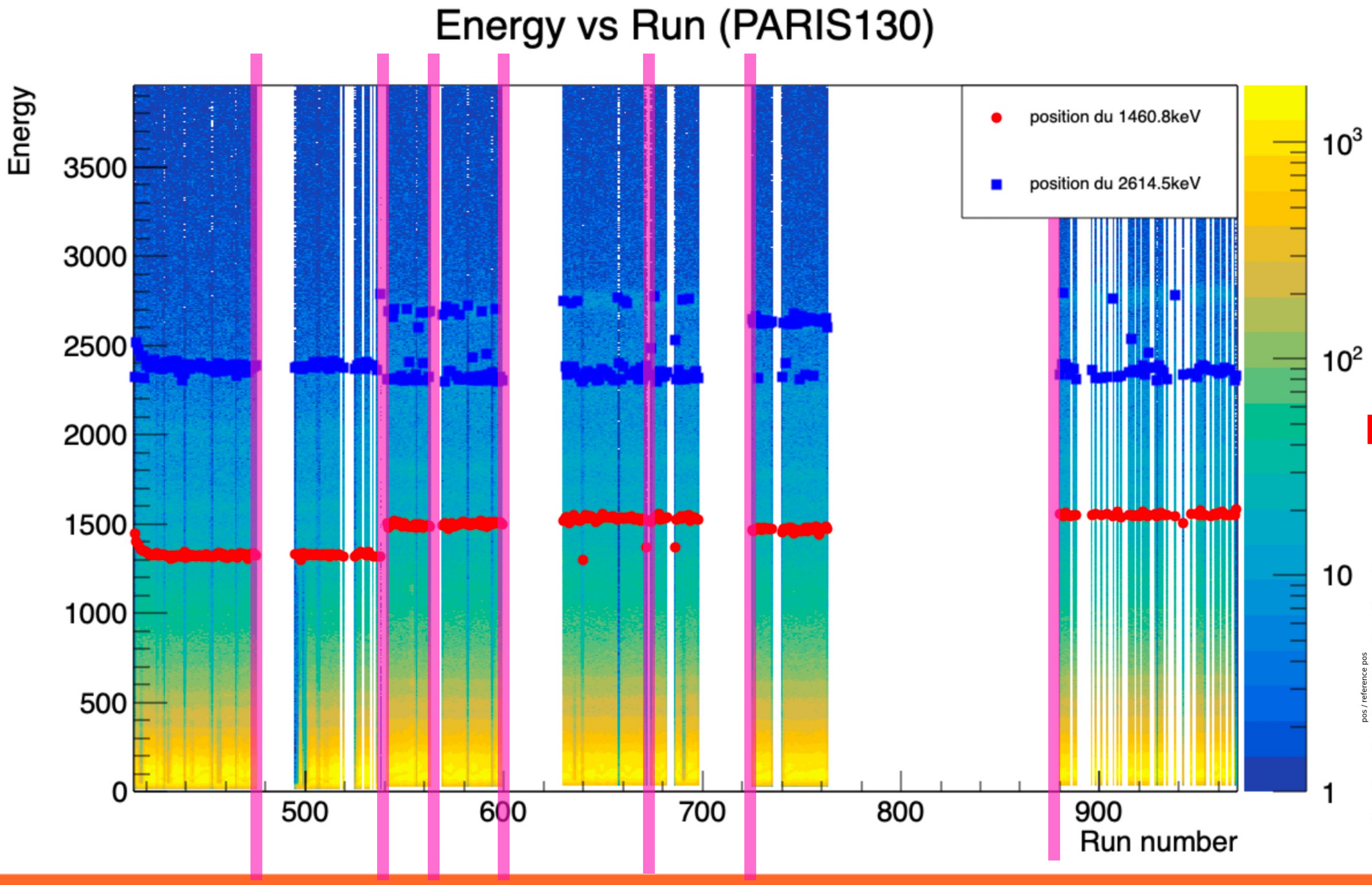
Prompt γ ^{252}Cf spectrum + background of one PARIS (CeBr3)

P



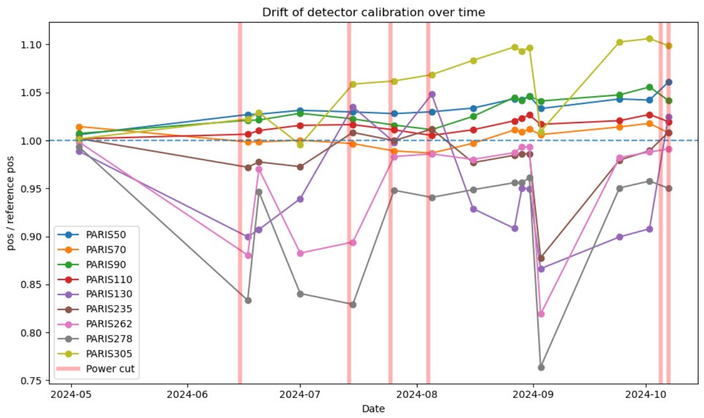
E (keV)

Energy Calibration Follow Up

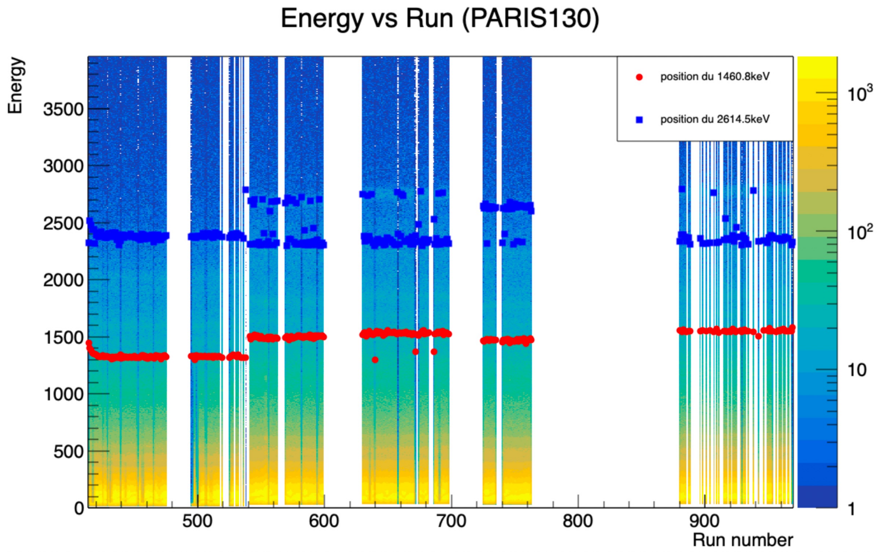


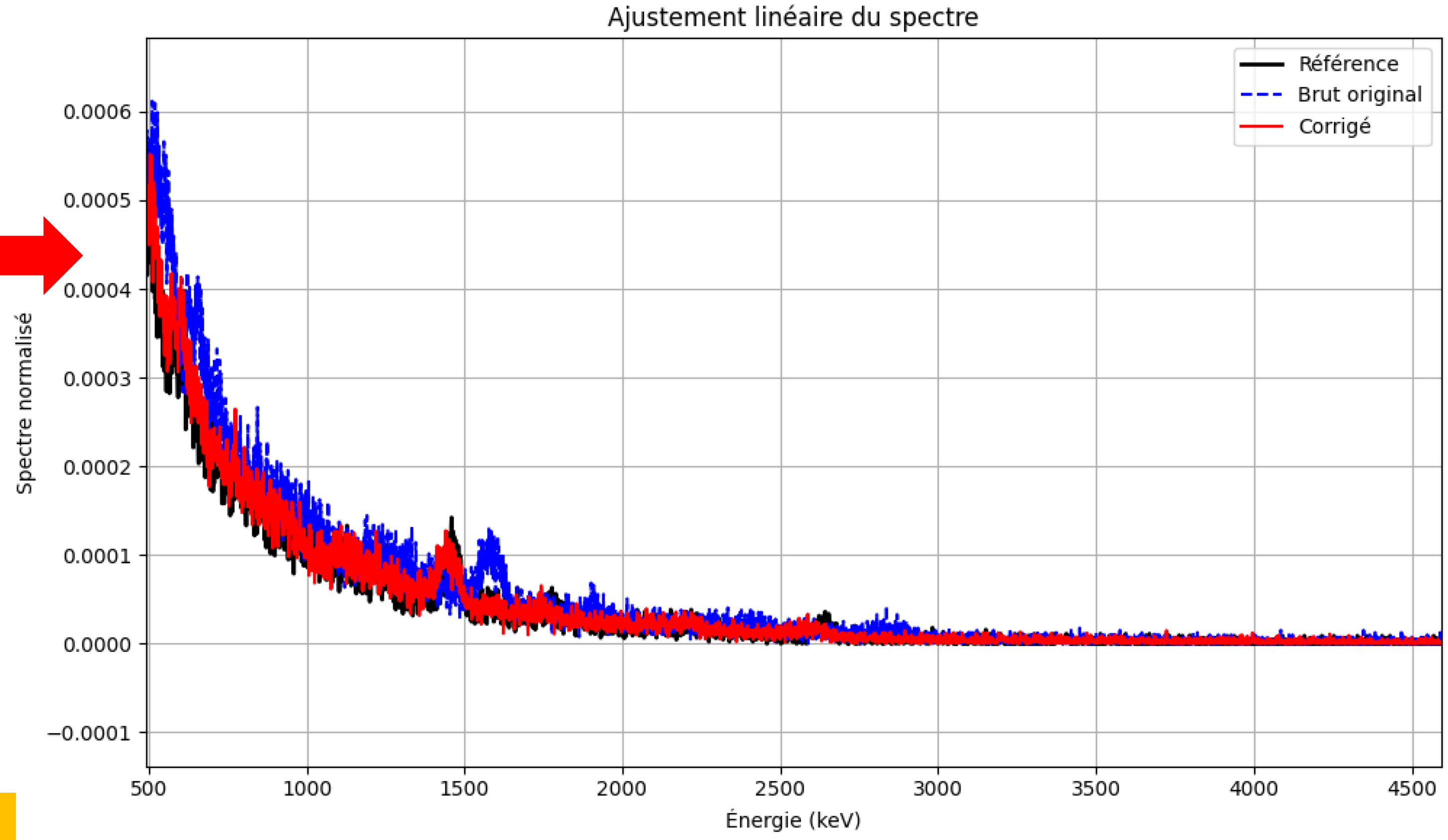
Source	Eγ (keV)
^{40}K	1460.8
^{208}Tl	2614.5

Correction!



Energy Calibration Follow Up



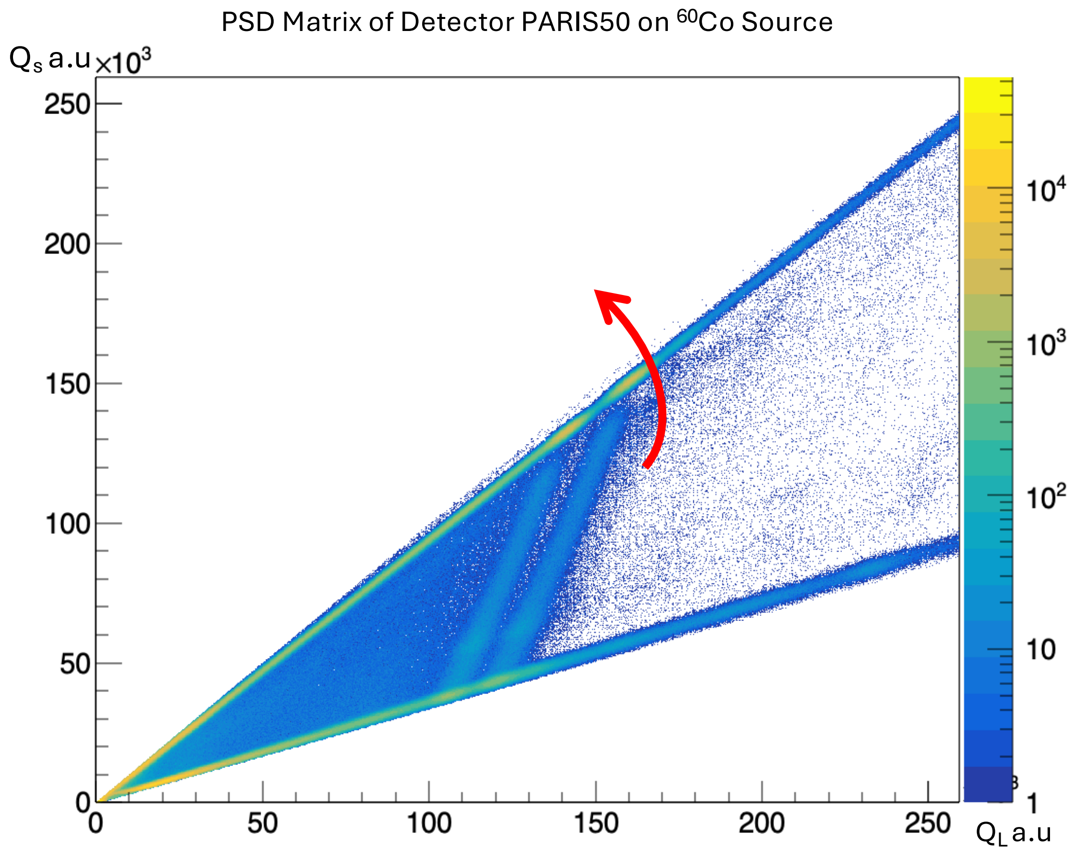


To be corrected & completed

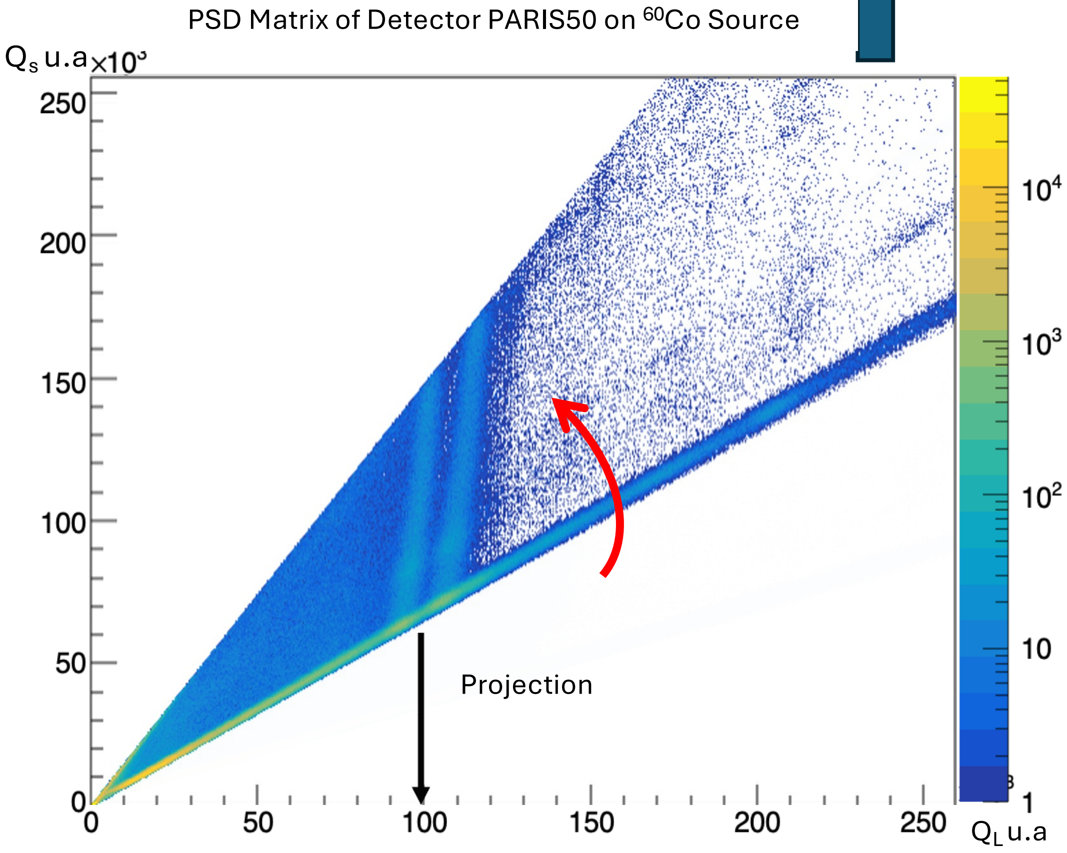
Source	Eγ (keV)
^{40}K	1460.8
^{208}Tl	2614.5

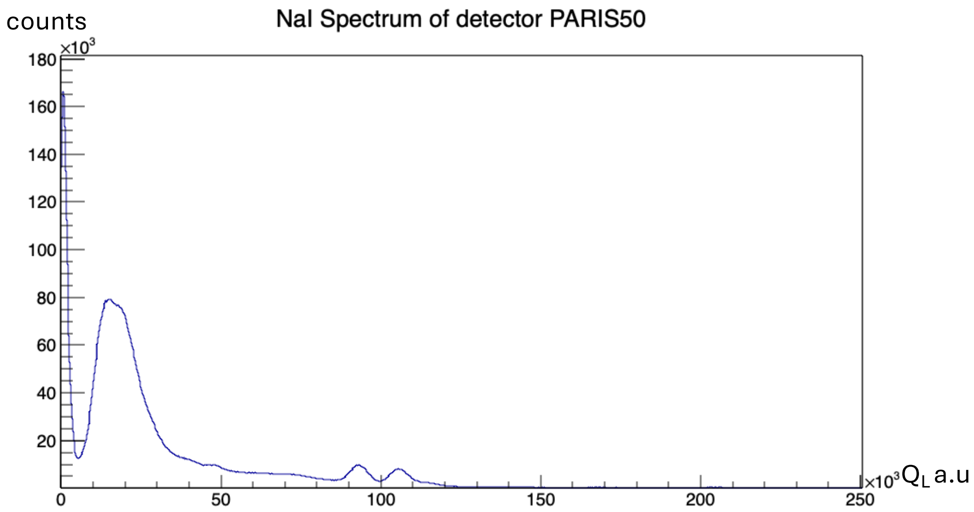
Work in progress

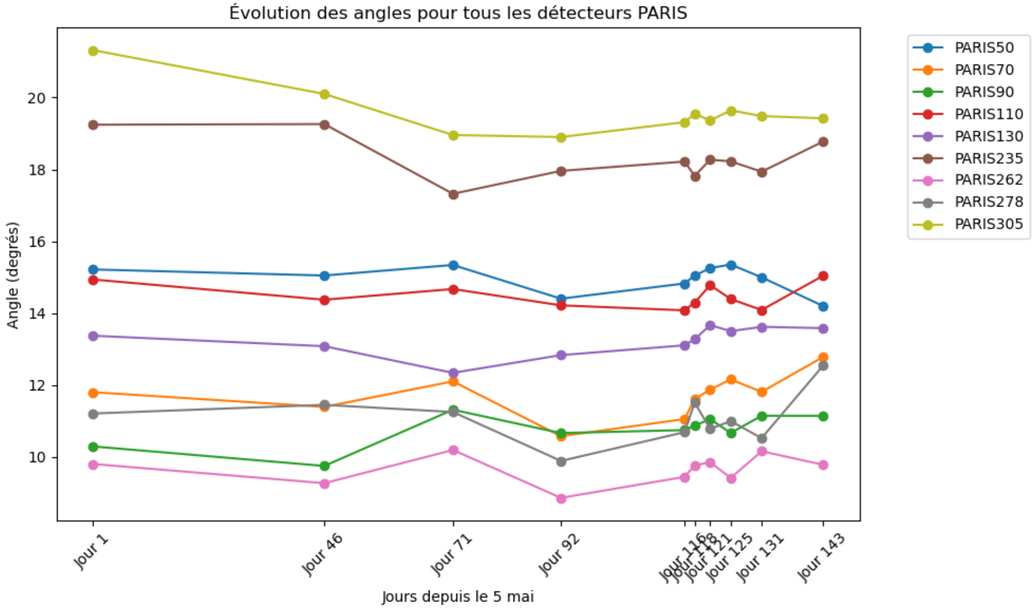
Selection of the pure NaI + crosstalk events



Selection of the pure NaI + crosstalk events



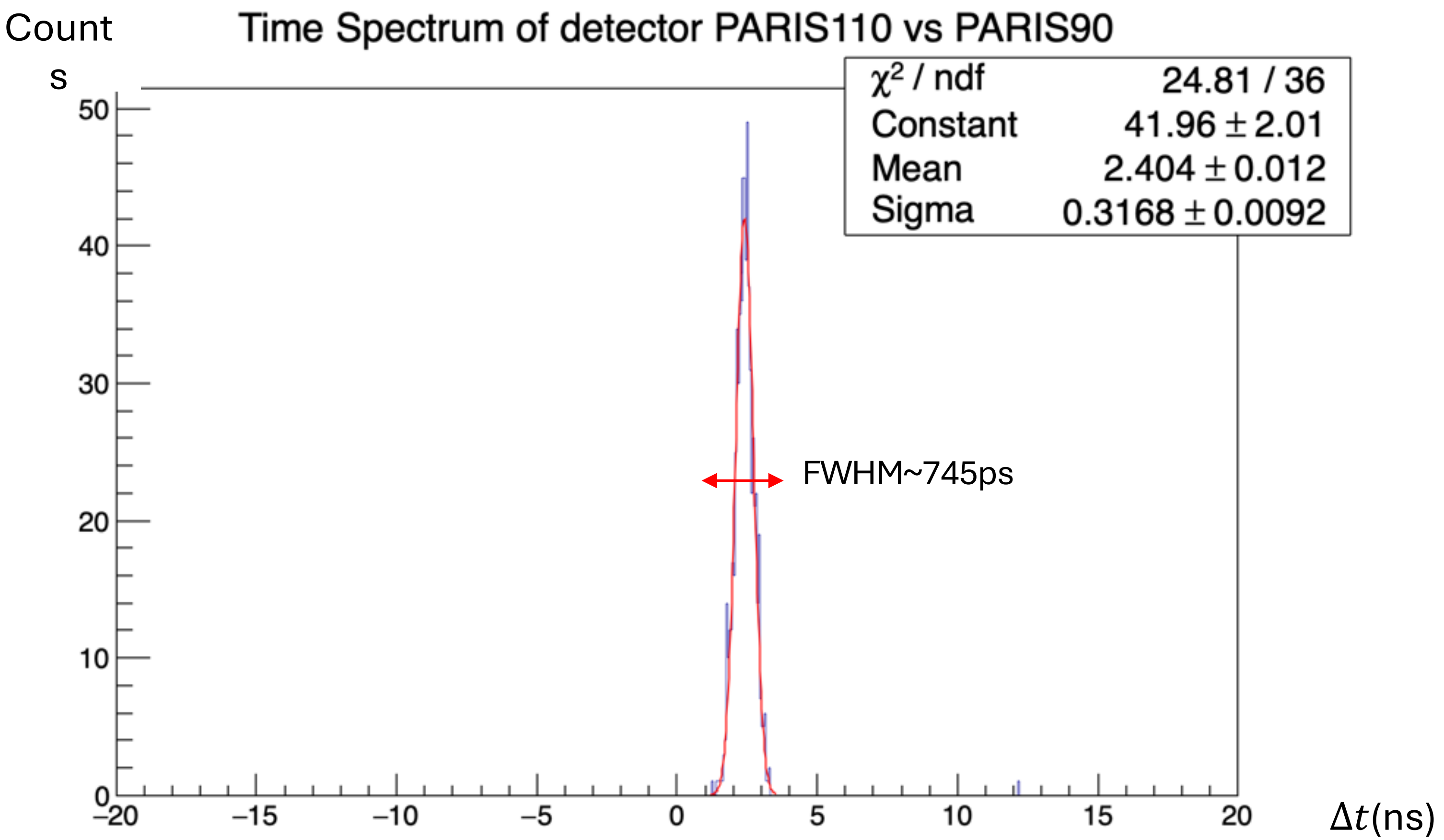


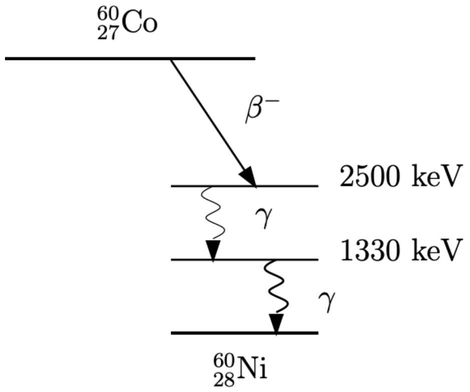


Time Alignment of PARIS Detectors

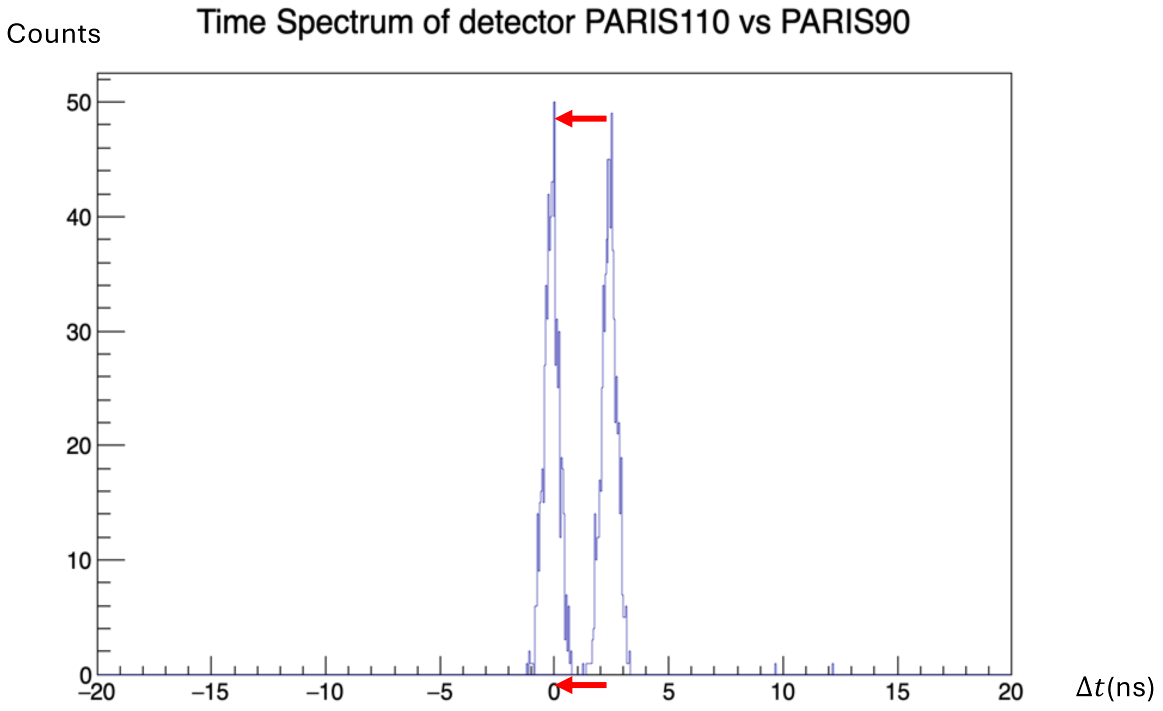
Reference detector: PARIS90

^{60}Co γ coincidence time differences

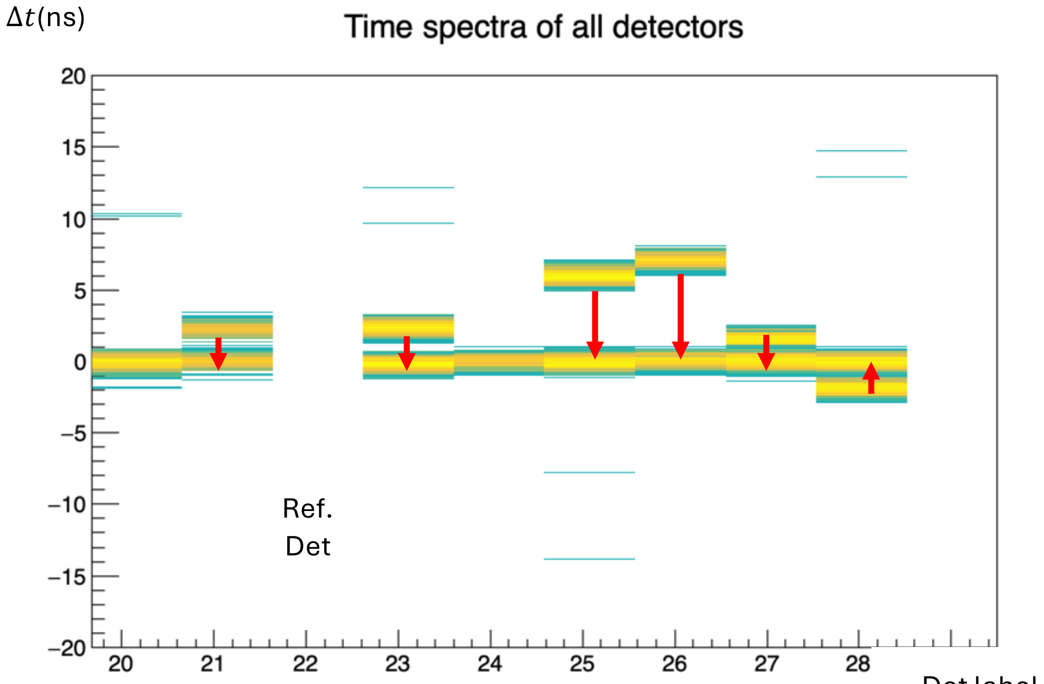




Time Alignment of PARIS Detectors



Alignment on reference detector



Example of time alignment of the 9 PARIS phoswiches

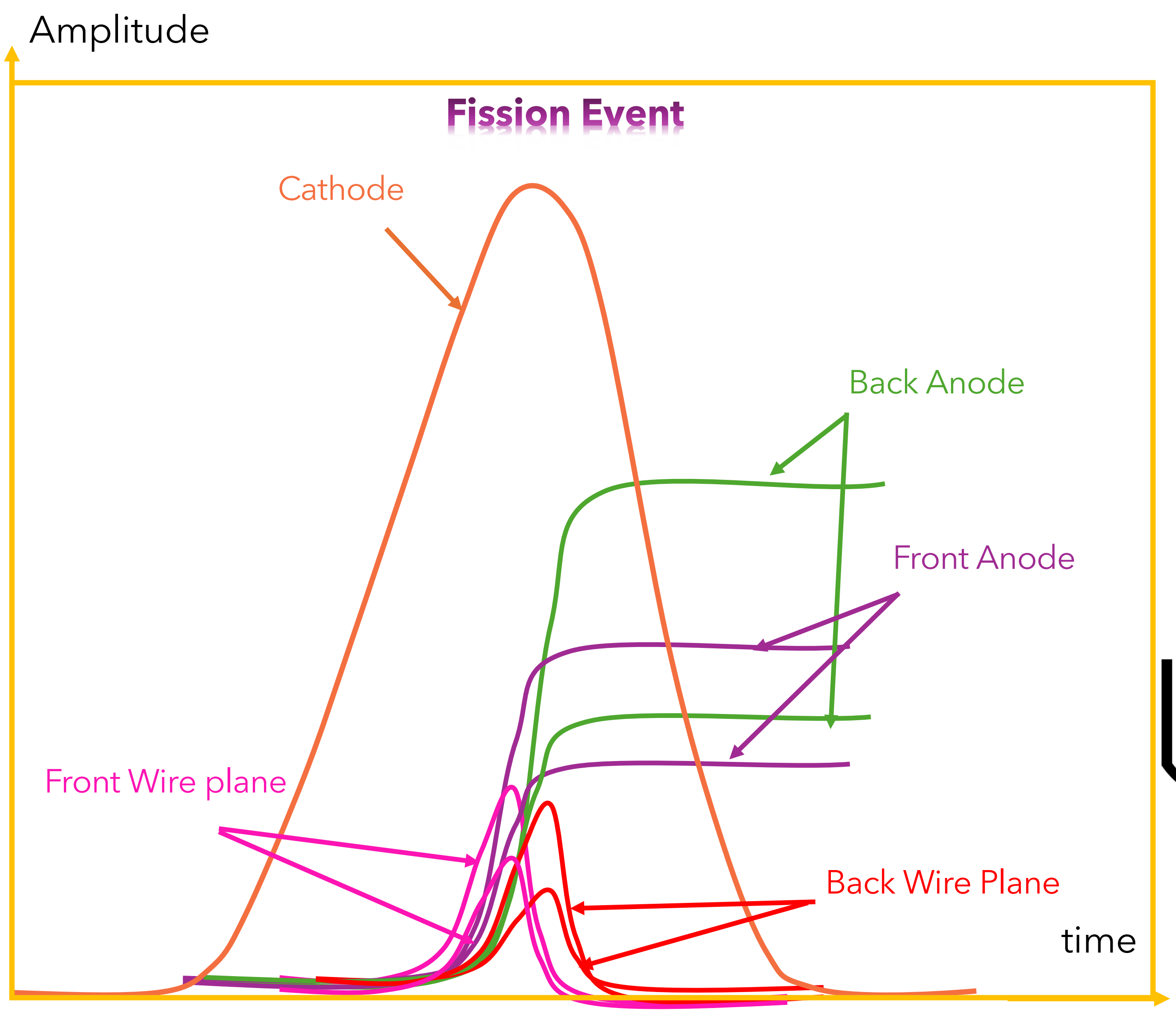
Reference detector : PARIS90

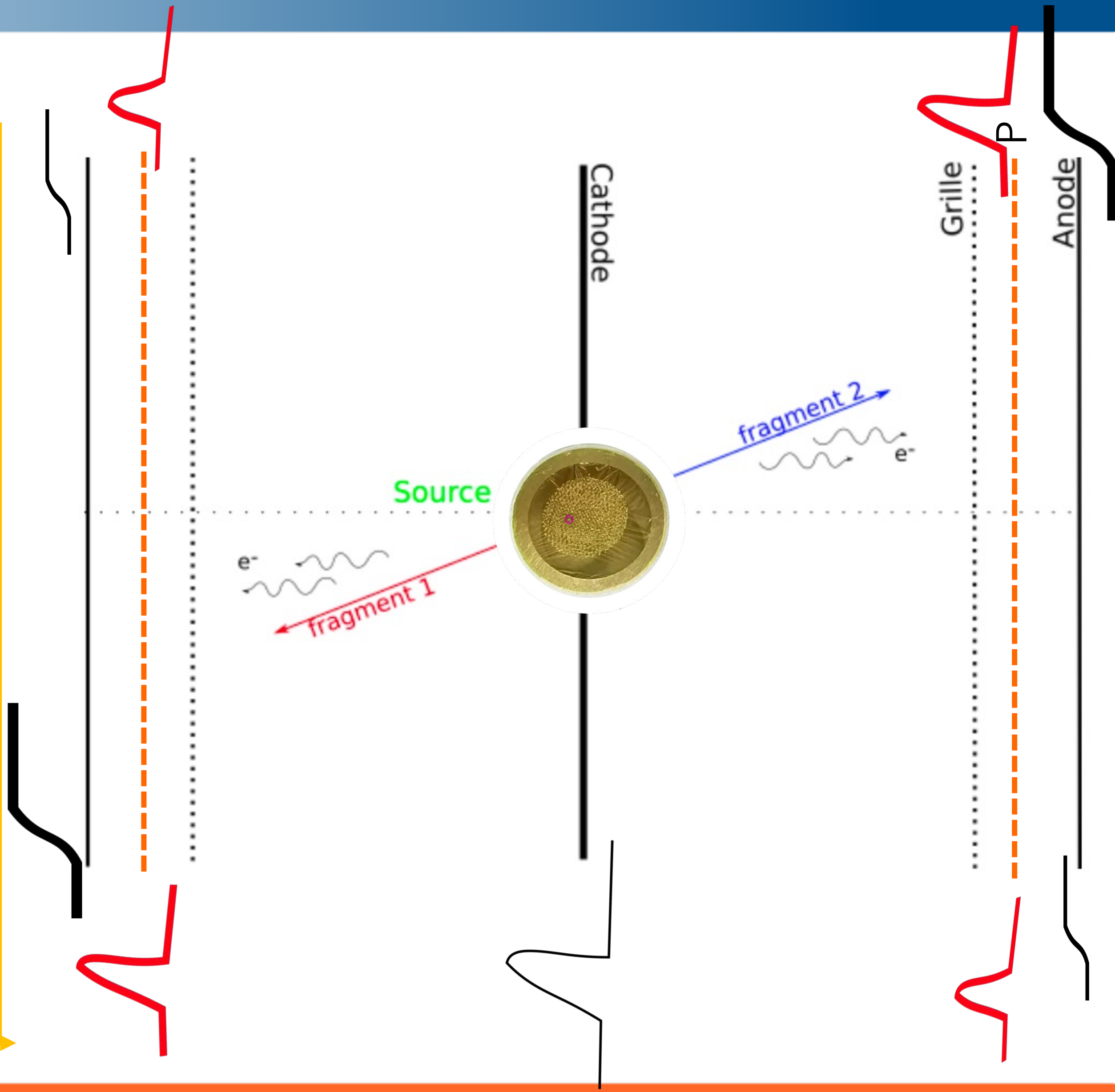
Time differences on ^{60}Co γ coincidences

Follow up over 6 months of data → To be adjusted on each run based on the prompt γ peak

Work in progress

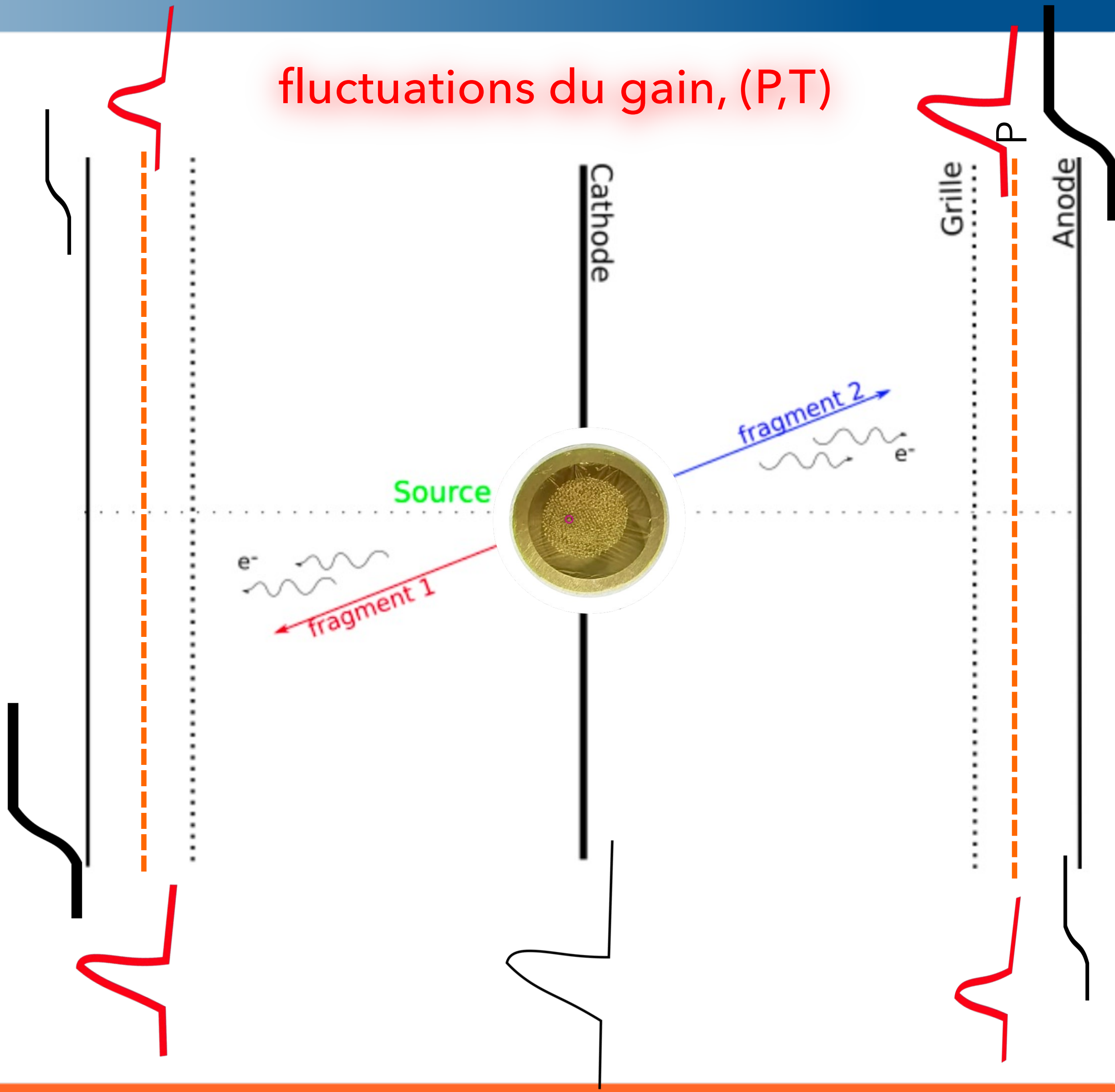
Twin Frisch-Grid Ionization Chamber



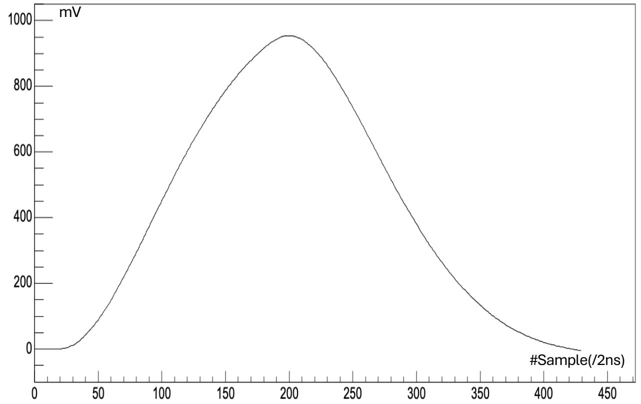


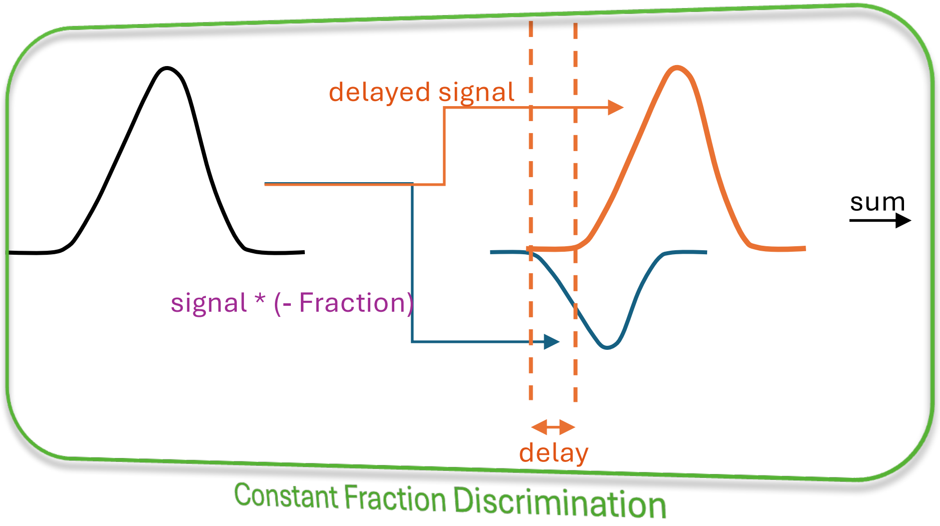
- Fission Event ID
  - $T_{Fission}$ fission fragment emission time to establish correlations with n-γ measurements

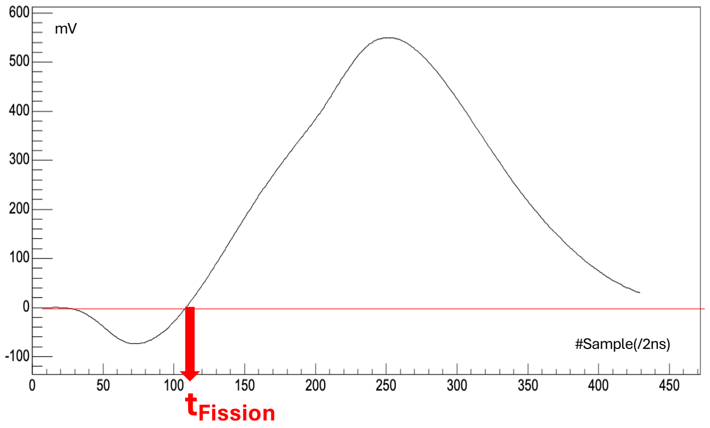
  - Fragment energy loss (kinetic energy~ 50MeV<E<105MeV) → fragment mass A
    2E Method



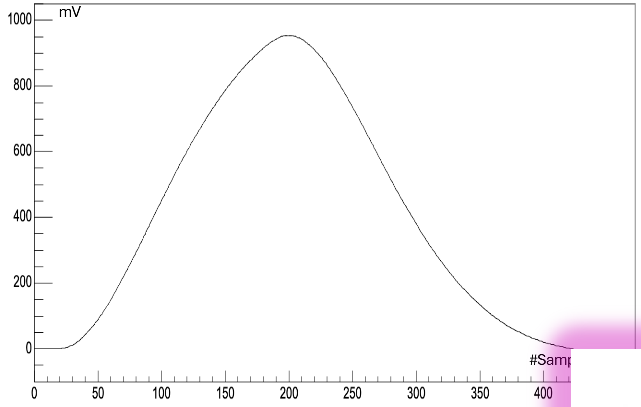
Twin Frisch-Grid ionization Chamber – Numerical Waveform analysis

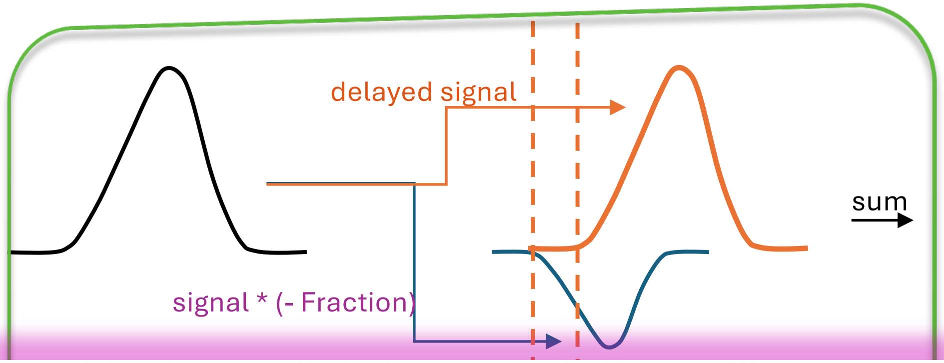


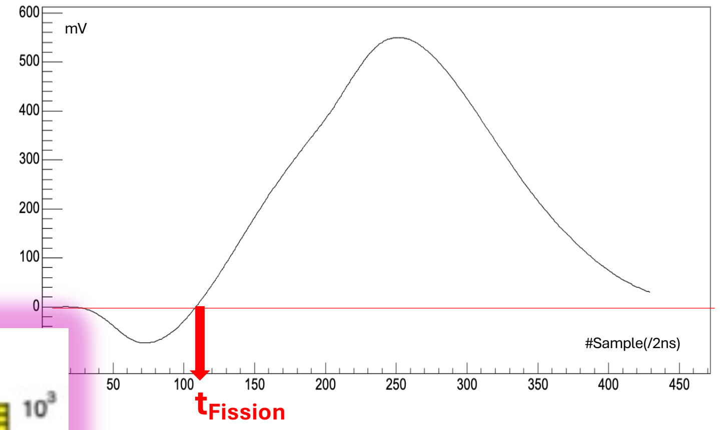


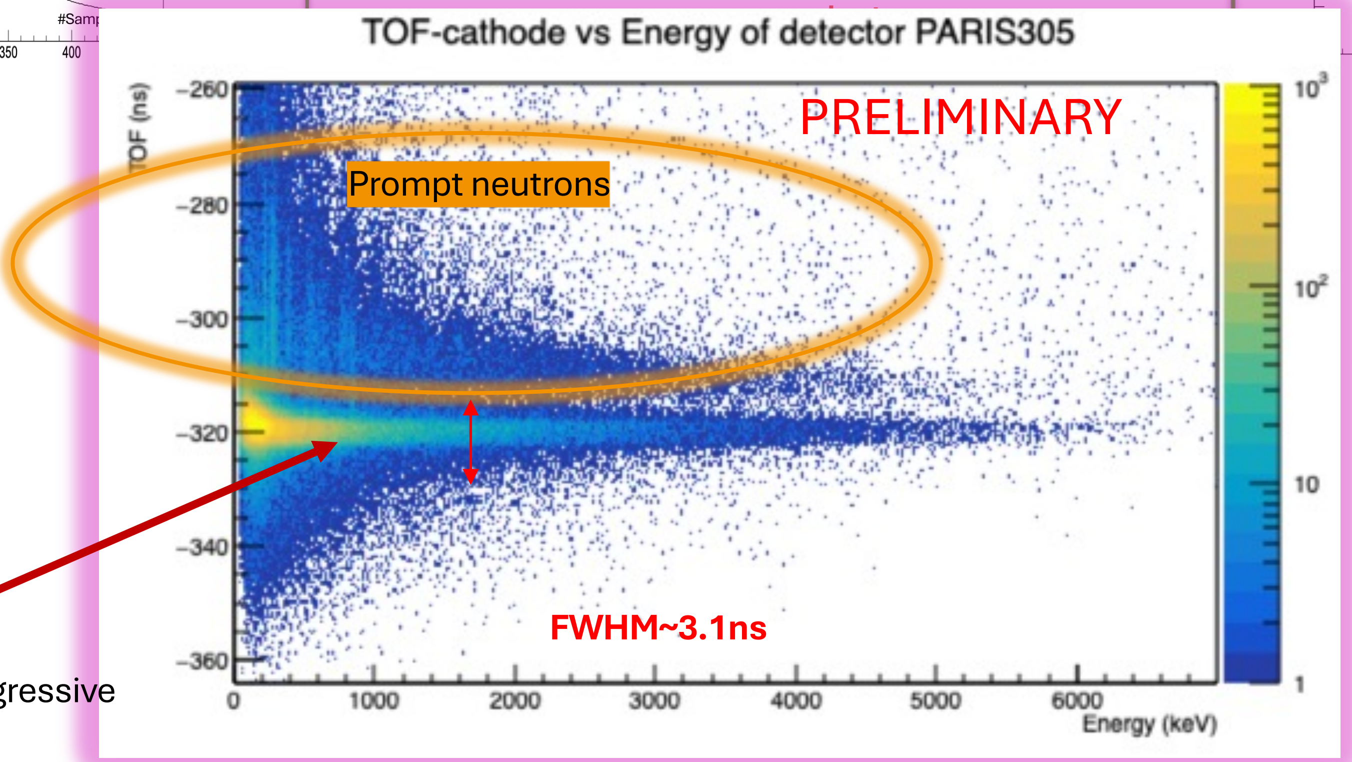


t_γ - $t_{Fission}$





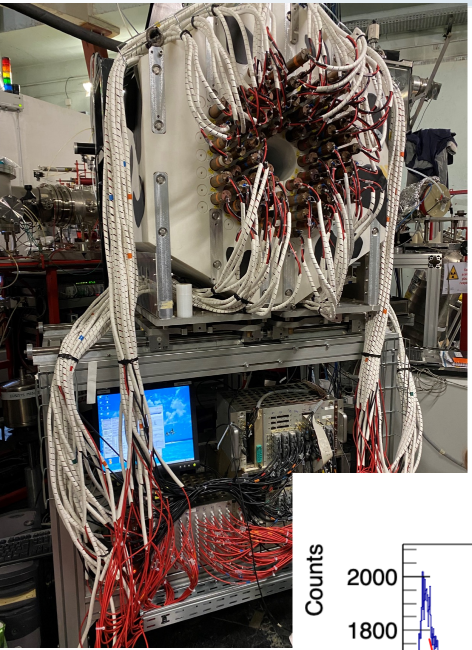


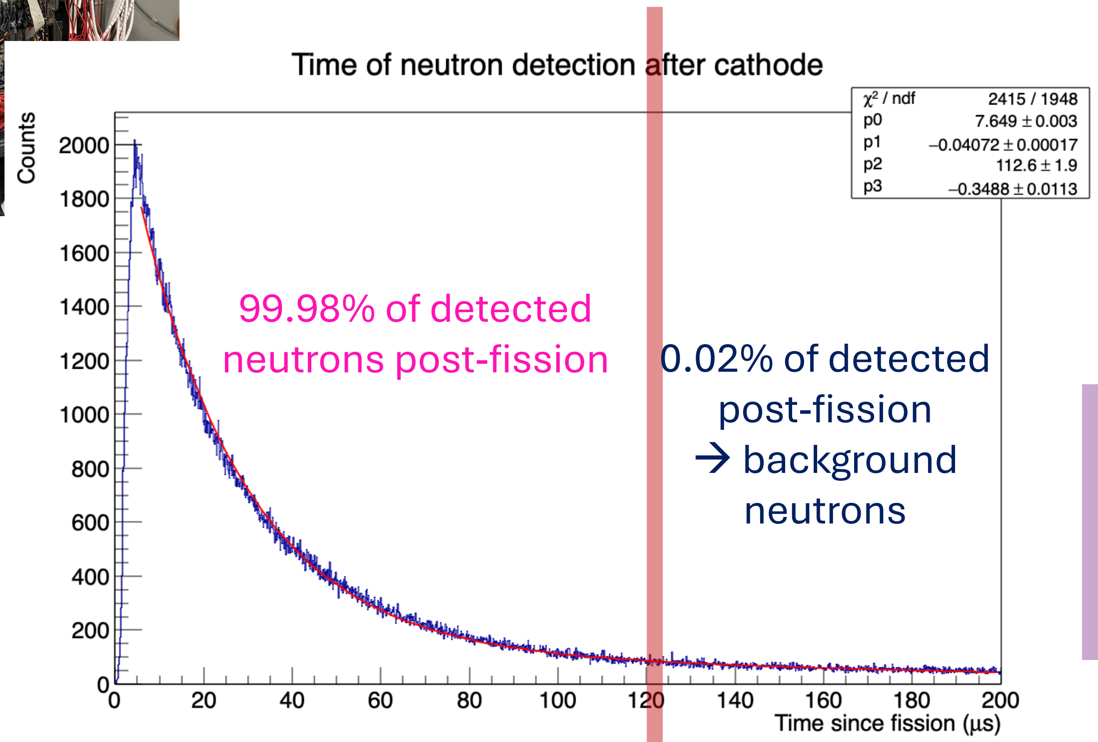


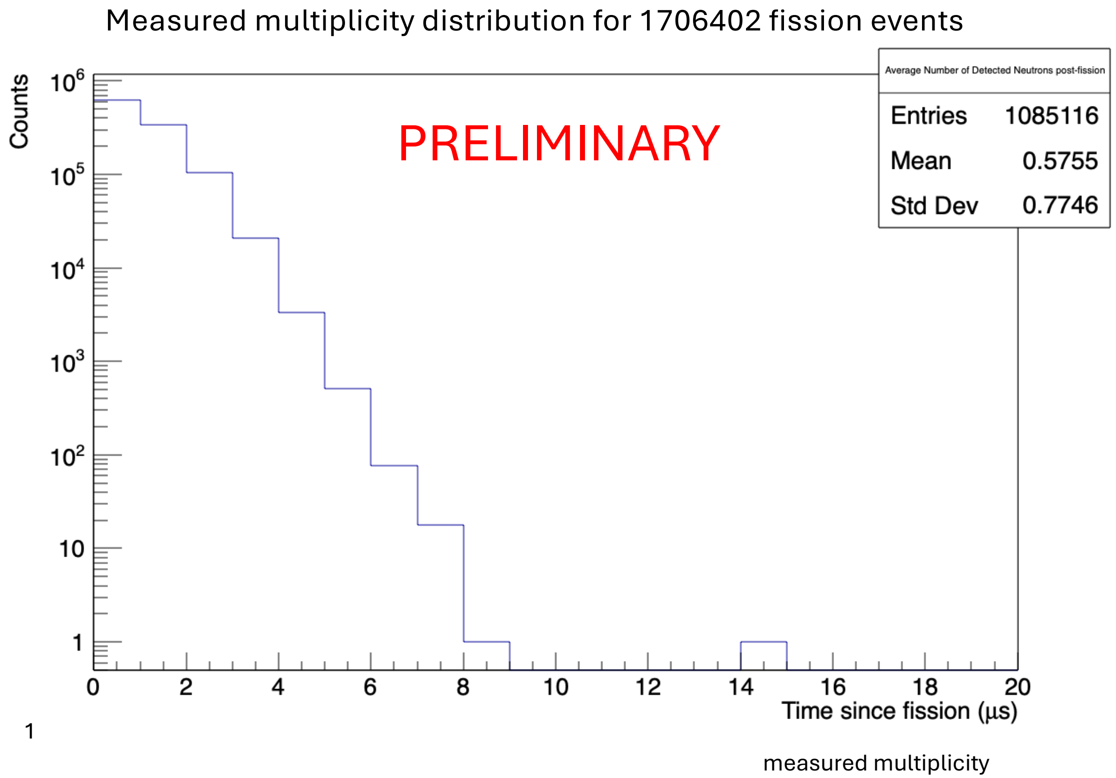
t_γ - $t_{Fission}$

Prompt gammas
also useful for progressive
time alignment

Neutron Counting with TETRA







- Raw measured prompt neutron multiplicity over 1 run (2h ~17M fissions)
- Average estimated efficency ~16%
- Ongoing Monte Carlo Simulation with Geant4 of the experiment

Mid-presentation Summary

- ✓ PARIS (gamma) calibration and time alignments
- ✓ Fission event tagging
- ✓ Neutron mutiplicity with TETRA
- o Fission fragments kinematics reconstruction and mass distribution
- o Monte-Carlo simulations and detectors response functions
- o n-γ correlations

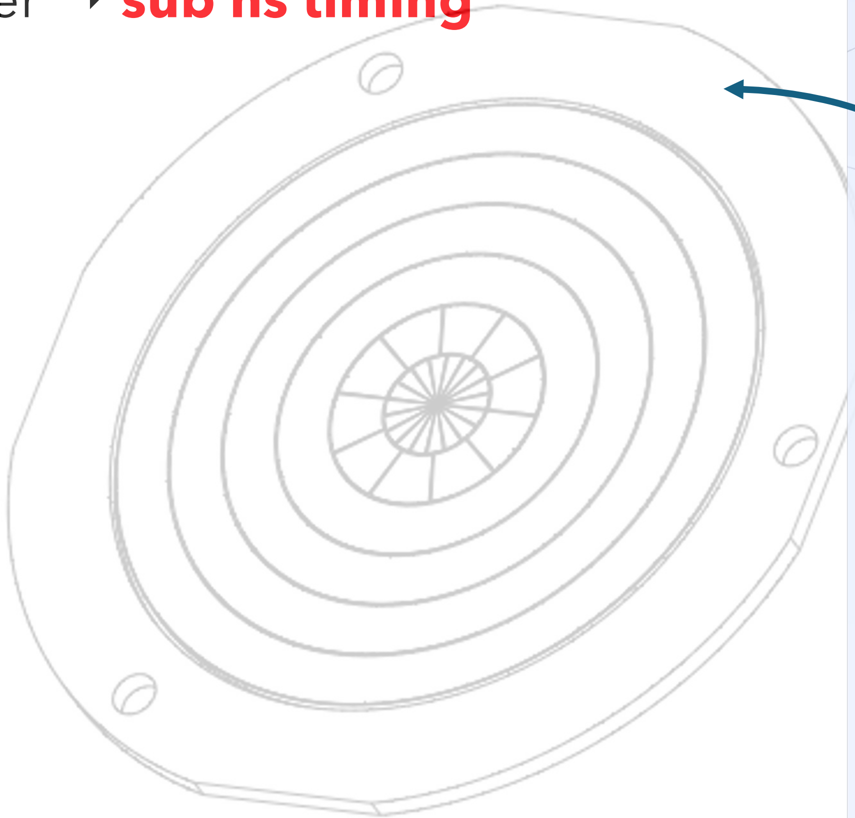
Please stay awake, we will have lunch very soon

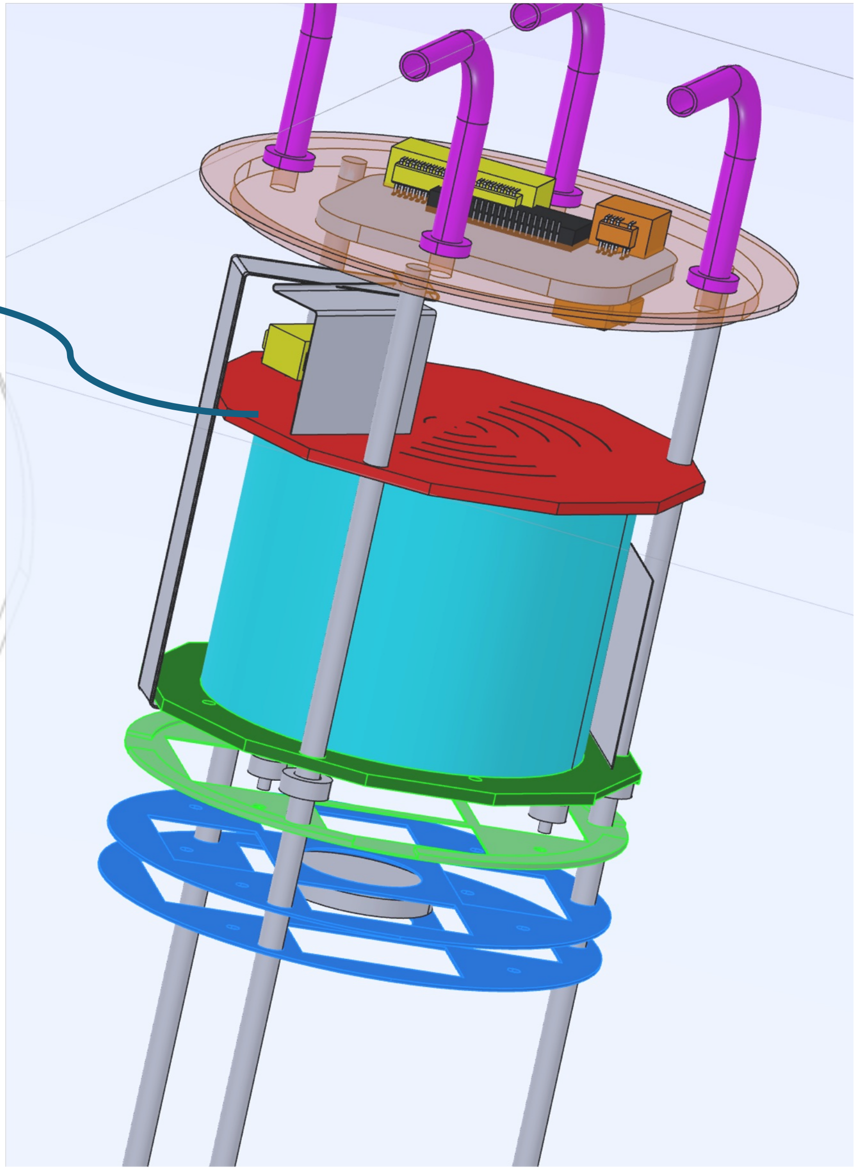
INSTRUMENTATION

ICETEA

ICETEA gaseous TPC targeted features

- Multiwire proportional chamber → **sub ns timing resolution** + ternary fission ID





ICETEA gaseous TPC targeted features

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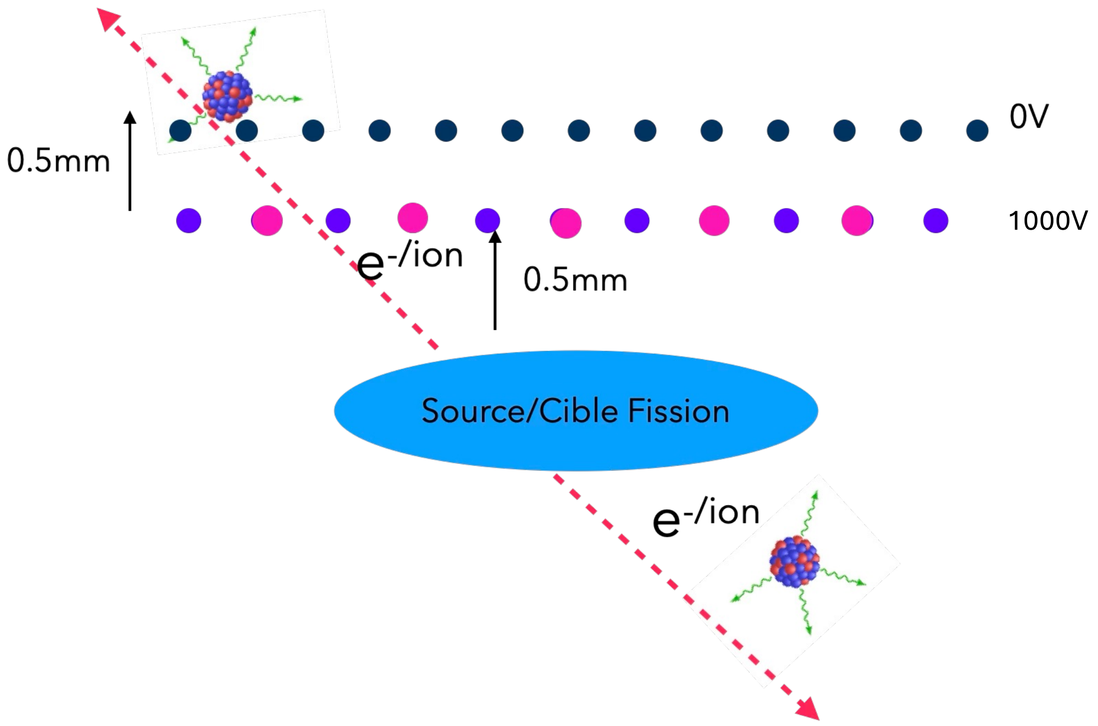

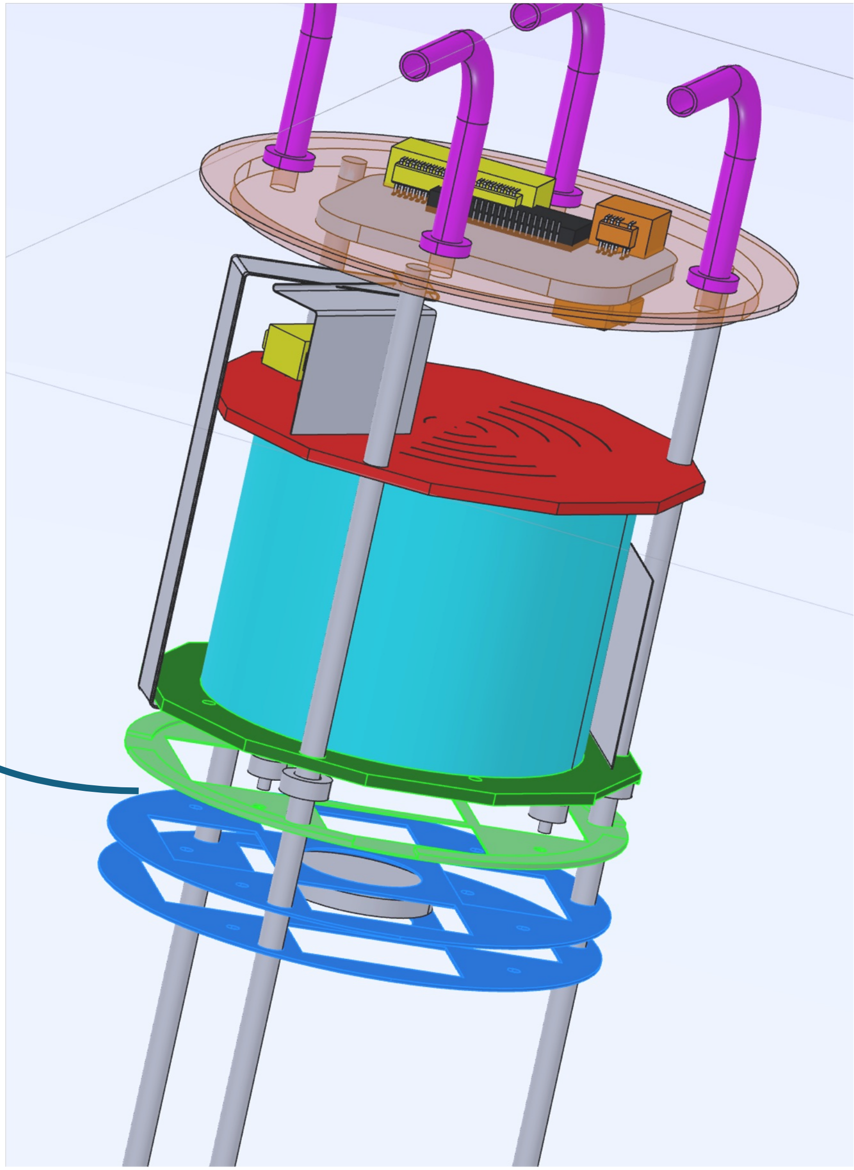

ICETEA gaseous TPC targeted features

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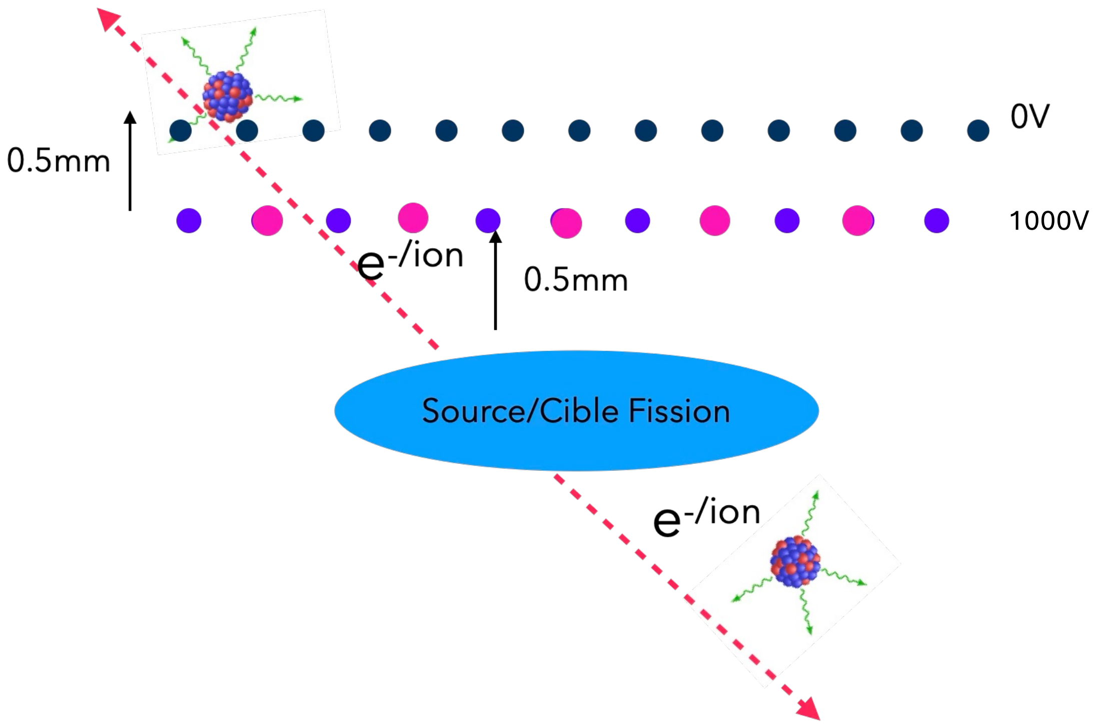
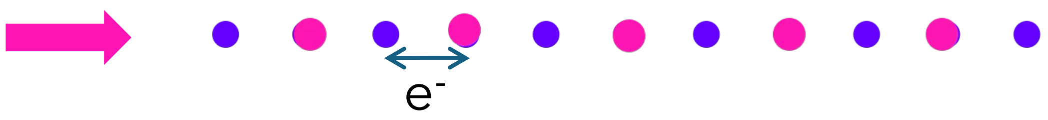


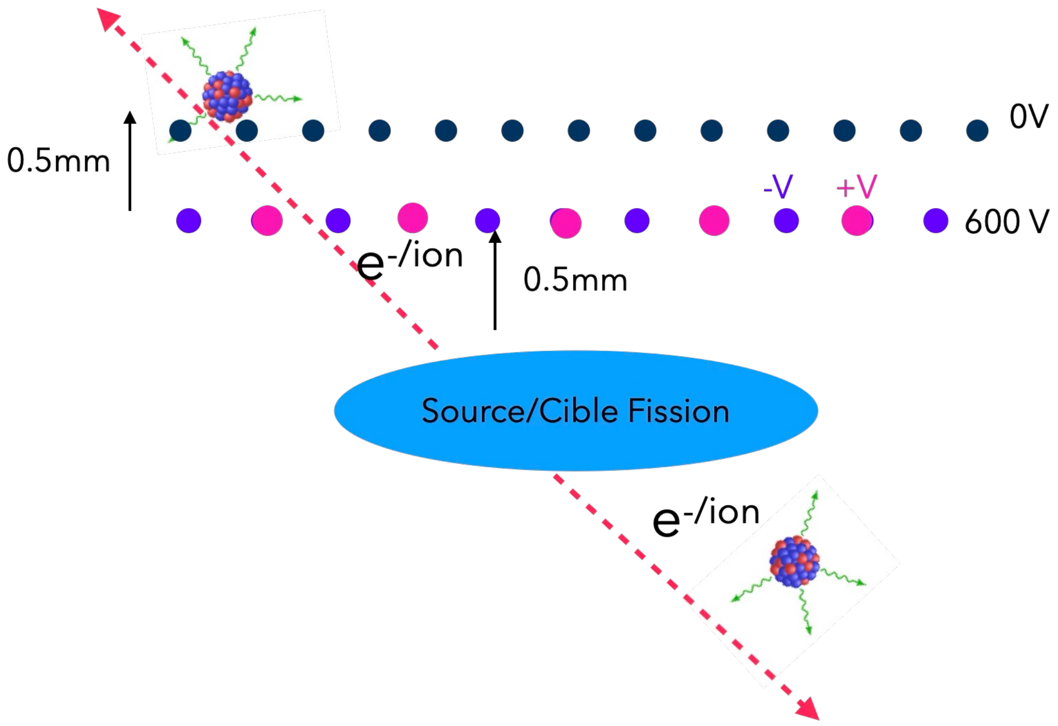
Simulation of e⁻ drift time with GARFIELD++/MAGBOLTZ



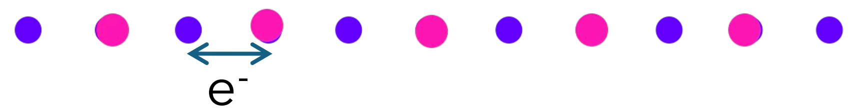
Gas	Pressure (bar)	$V_{polarisation}$ (V)	Gain	$\sigma_{\text{drift time (ns)}}$
CH_4	1	1000	30	~0.91

ICETEA gaseous TPC targeted features

- Multiwire proportional chamber → **sub ns timing resolution** + ternary fission ID



Simulation of e⁻ drift time with GARFIELD++/MAGBOLTZ



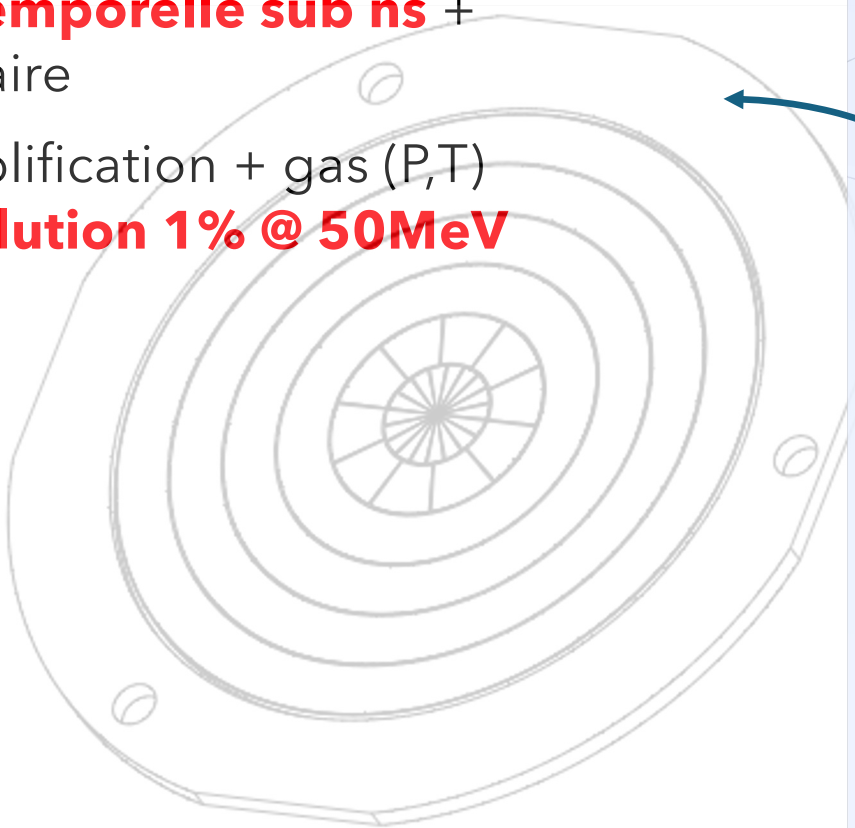
Gas	Pressure (bar)	$V_{polarisation}$ (V)	Gain	σ drift time (ns)
CH_4	1	+/- 600	40	~0.4
CH_4	1	1000	30	~0.91

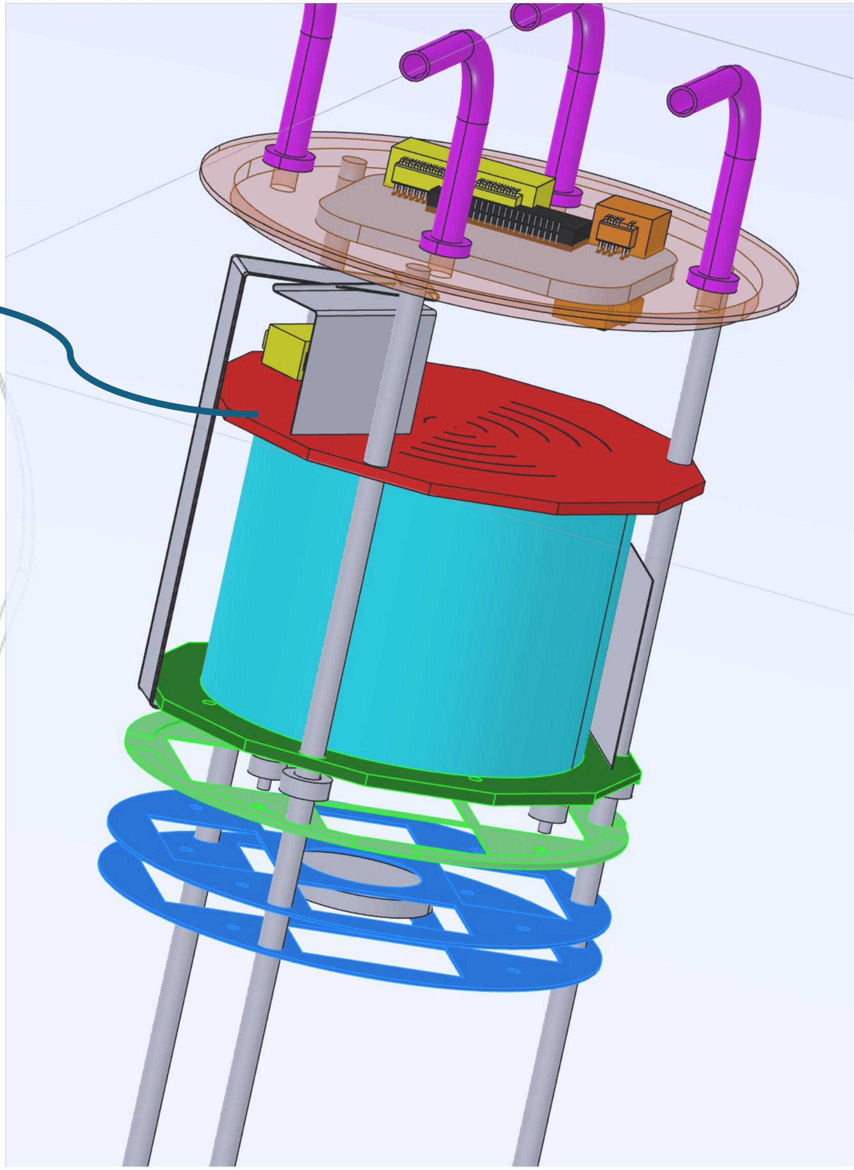
CH_4 best compromise up to now

ICETEA: Ionization Chamber with Enhanced Timing & Energy resolution without Amplification

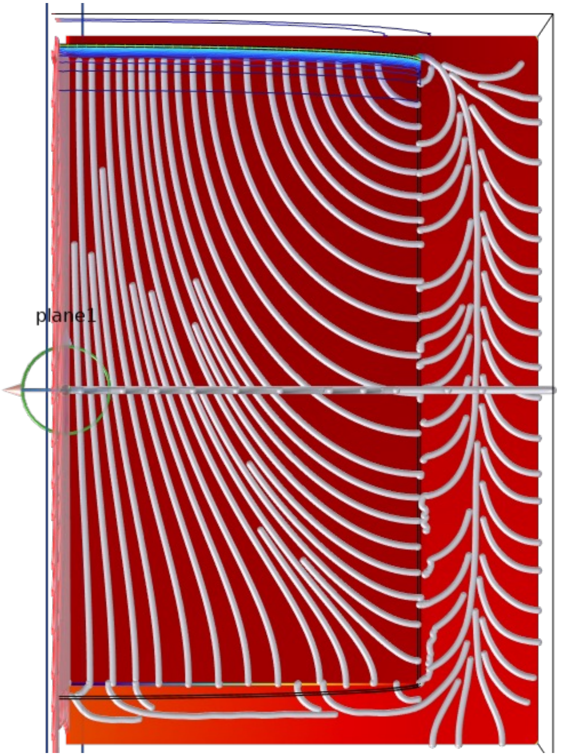
ICETEA gaseous TPC targeted features

- Chambre à fils→ **résolution temporelle sub ns** + identificaton de la fission ternaire
- Field degrader cage + no amplification + gas (P,T) control → **better energy resolution 1% @ 50MeV**

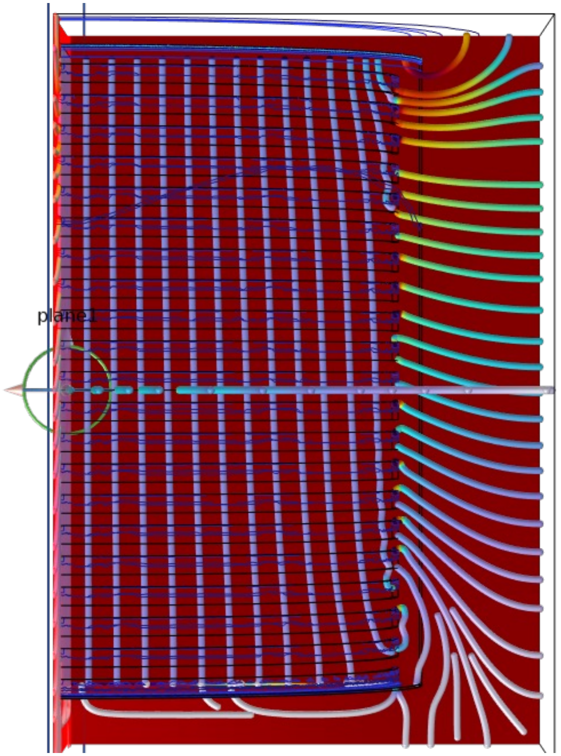




Simulations COMSOL – Field Cage



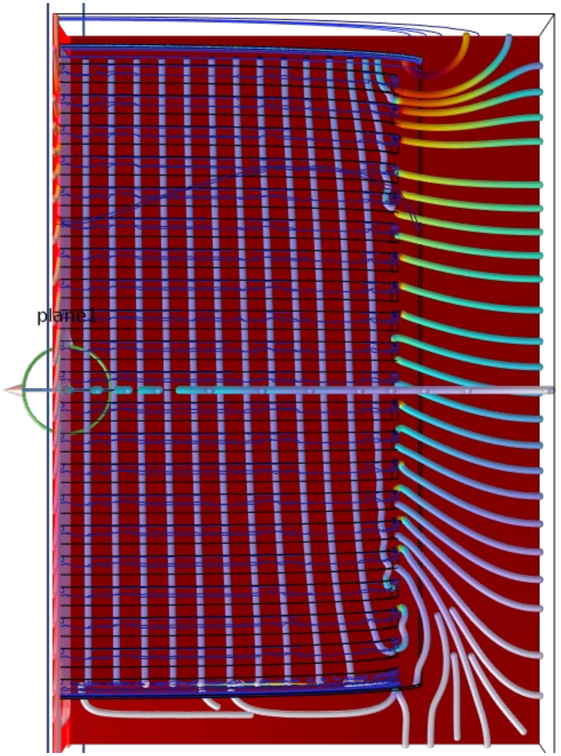
No field cage



Inner strips (classic) field cage on Kapton material

Inspired from the GADGET proton TPC

M. Friedman et al. ,Nuclear Inst. and Methods in Physics Research, A 940 (2019) 93–102

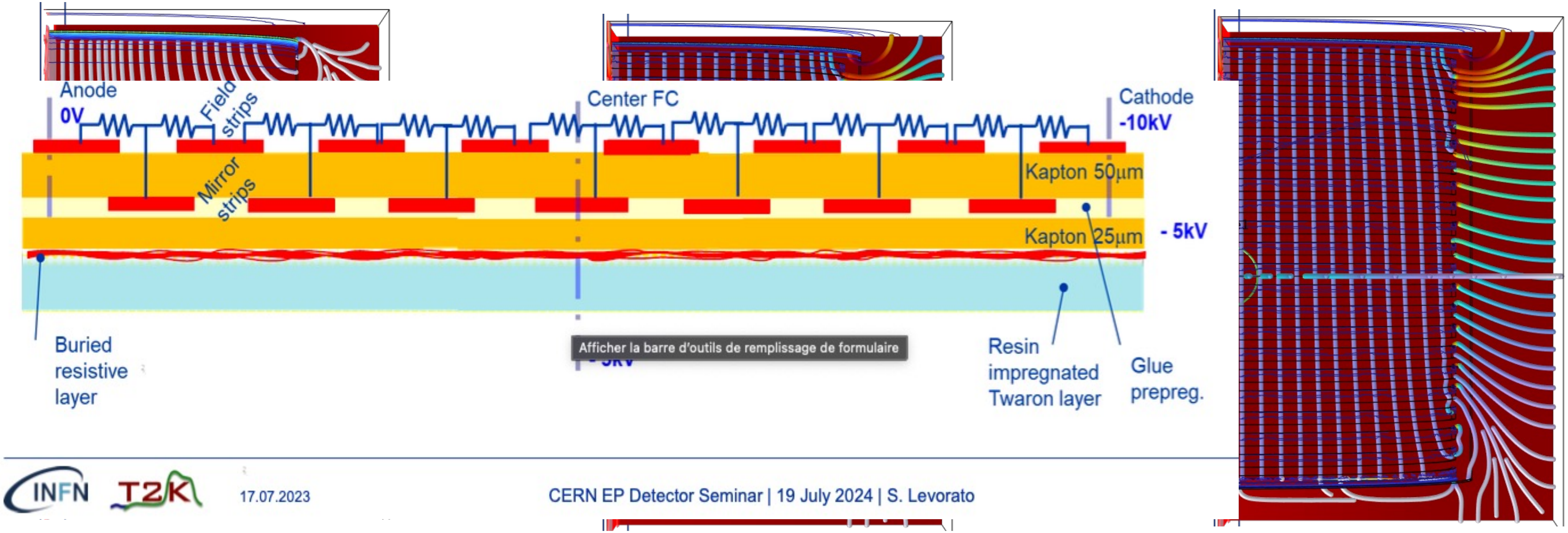


Inner & mirror (Kapton burried) strips

Inspired from the GADGET proton TPC & the T2K design

S. Levorato, CERN Seminar, July 19th, 2024

Simulations COMSOL – Cage de Champ



No field cage

Inner strips (classic) field cage on Kapton support

Inspired from the GADGET proton TPC

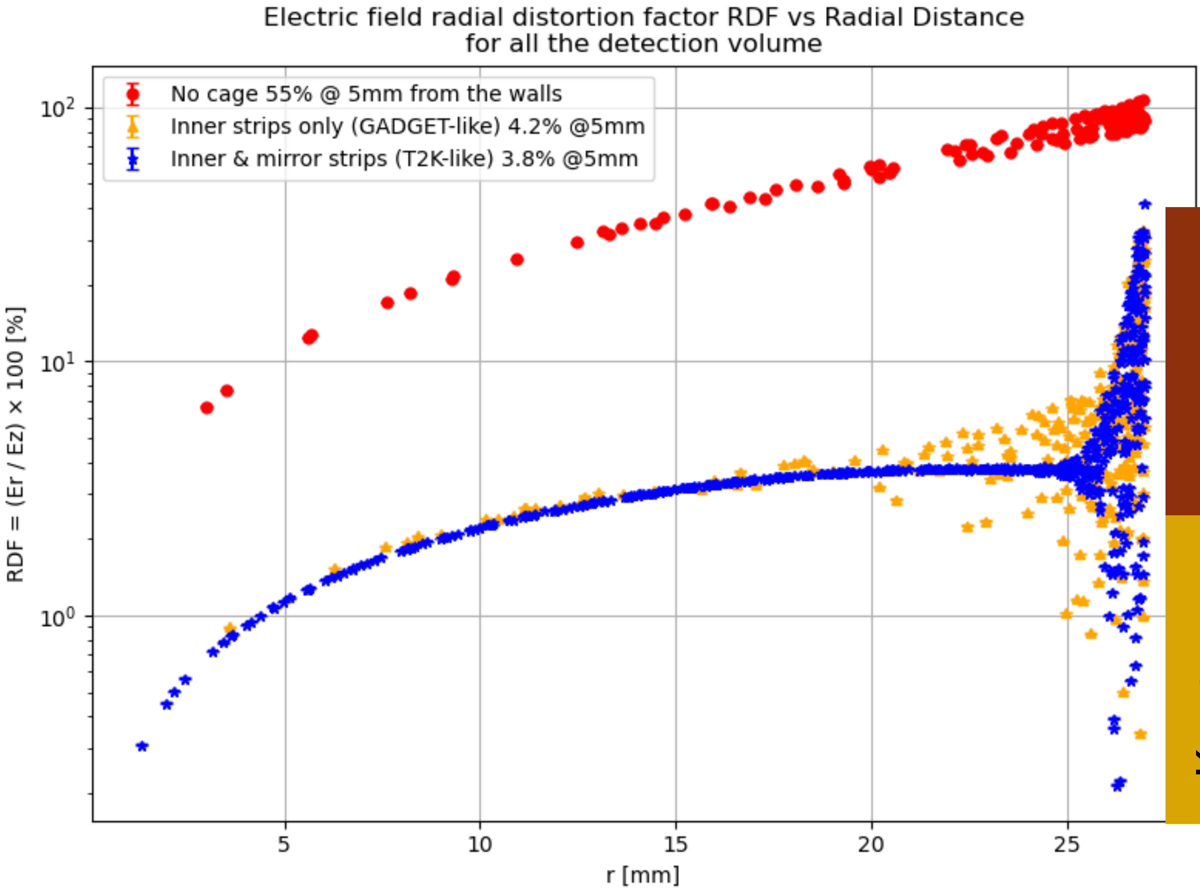
M. Friedman et al. ,Nuclear Inst. and Methods in Physics Research, A 940 (2019) 93–102

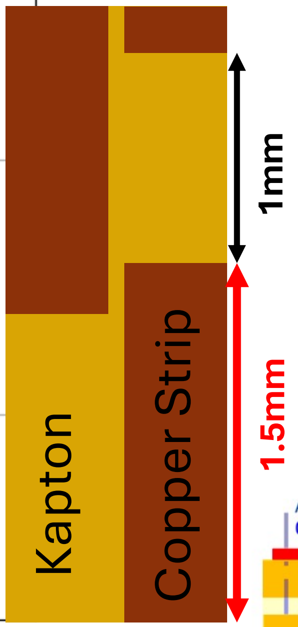
Inner & mirror strips (kapton burried) field cage

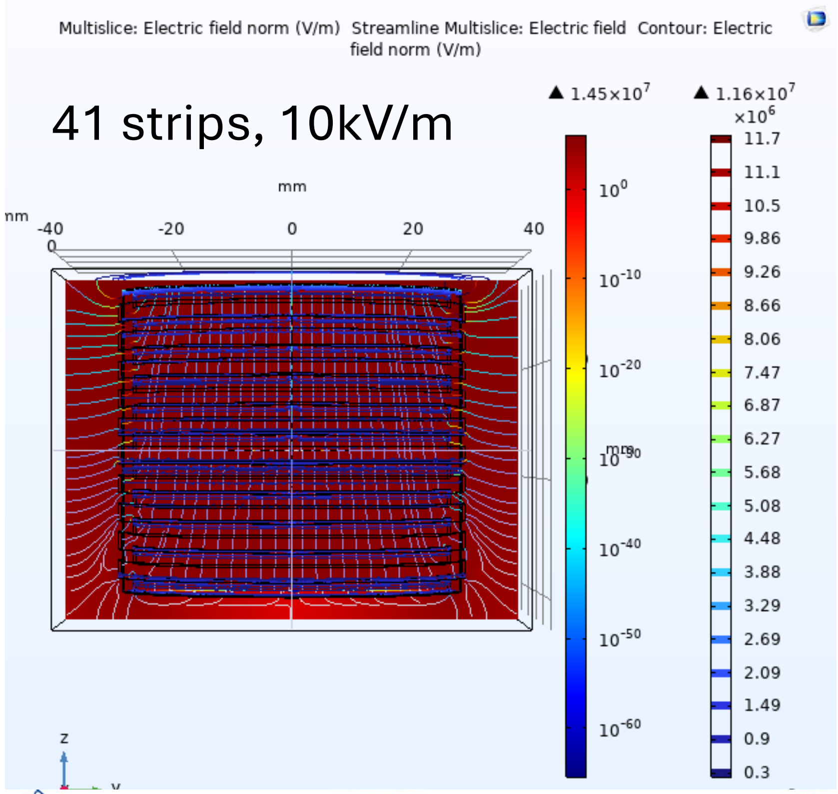
Inspired from the GADGET proton TPC & the T2K design

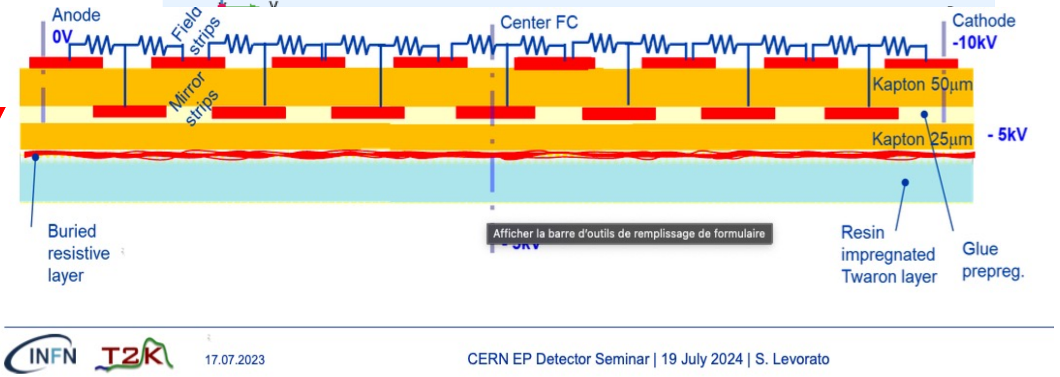
S. Levorato, CERN Seminar, July 19th, 2024

COMSOL Simulations – Field Cage





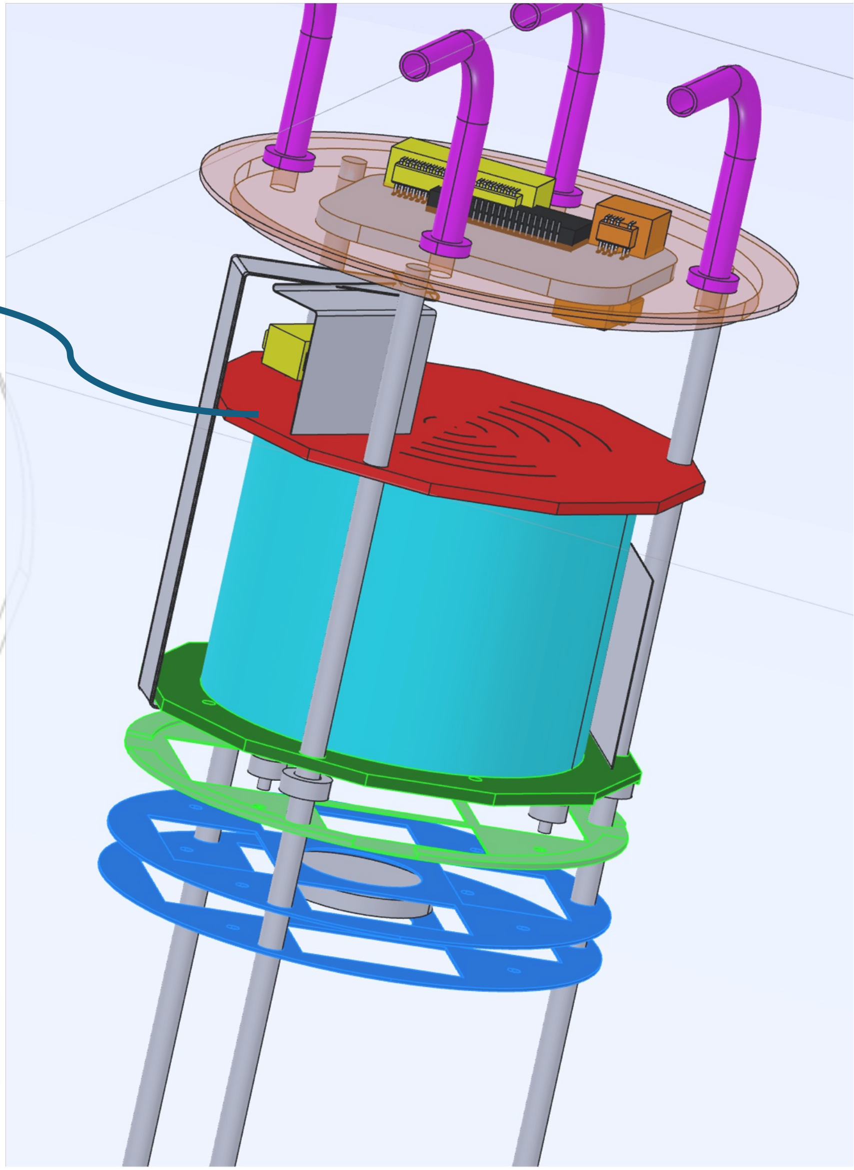




$$RDF = \frac{E_r}{E_z}\text{, ideally } RDF = 0$$

ICETEA gaseous TPC targeted features

- Multiwire proportional chamber → **sub ns timing resolution** + ternary fission ID
- Field degrader cage + no amplification + gas (P,T) control → **better energy resolution 1% @ 50MeV**
- Better polar angular AND **azimutal** reconstruction (wire chamber + padded energy plane (segmented anode) + field cage)
- **Compactness** to fit in different detection setups 182mm long & 100mm Ø

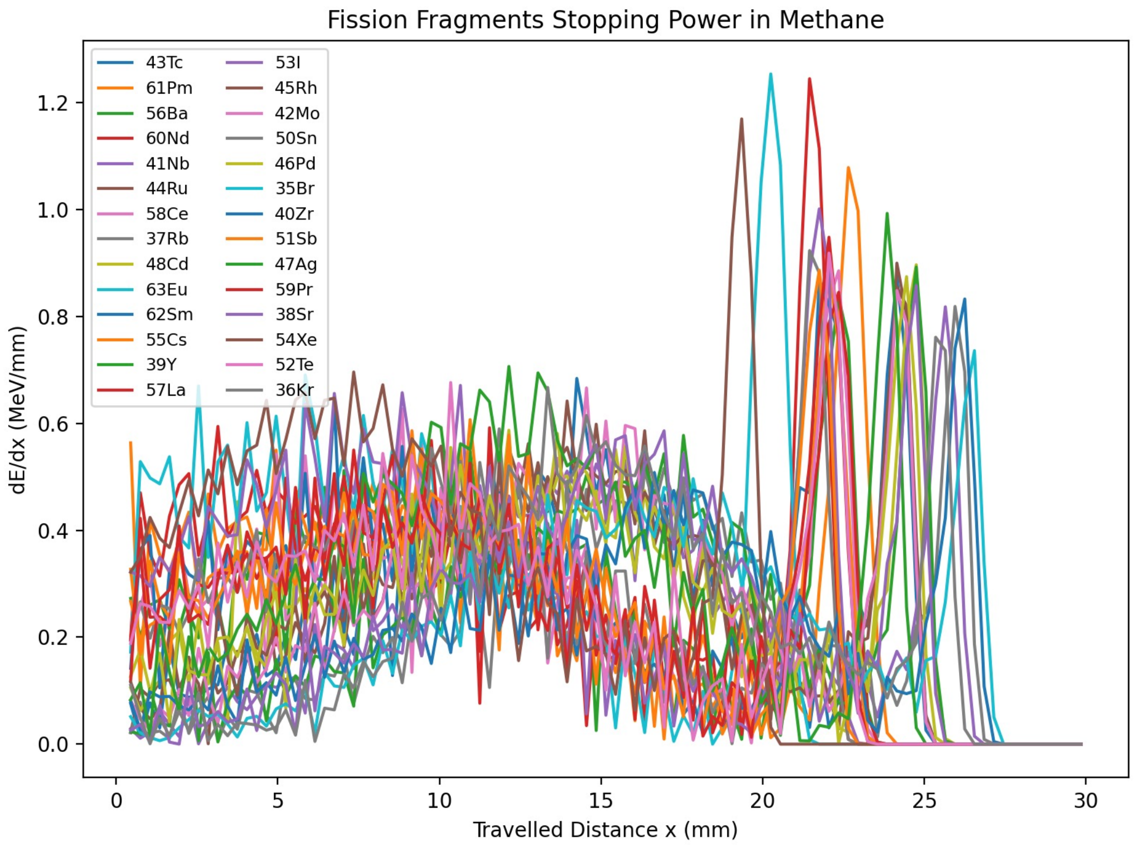


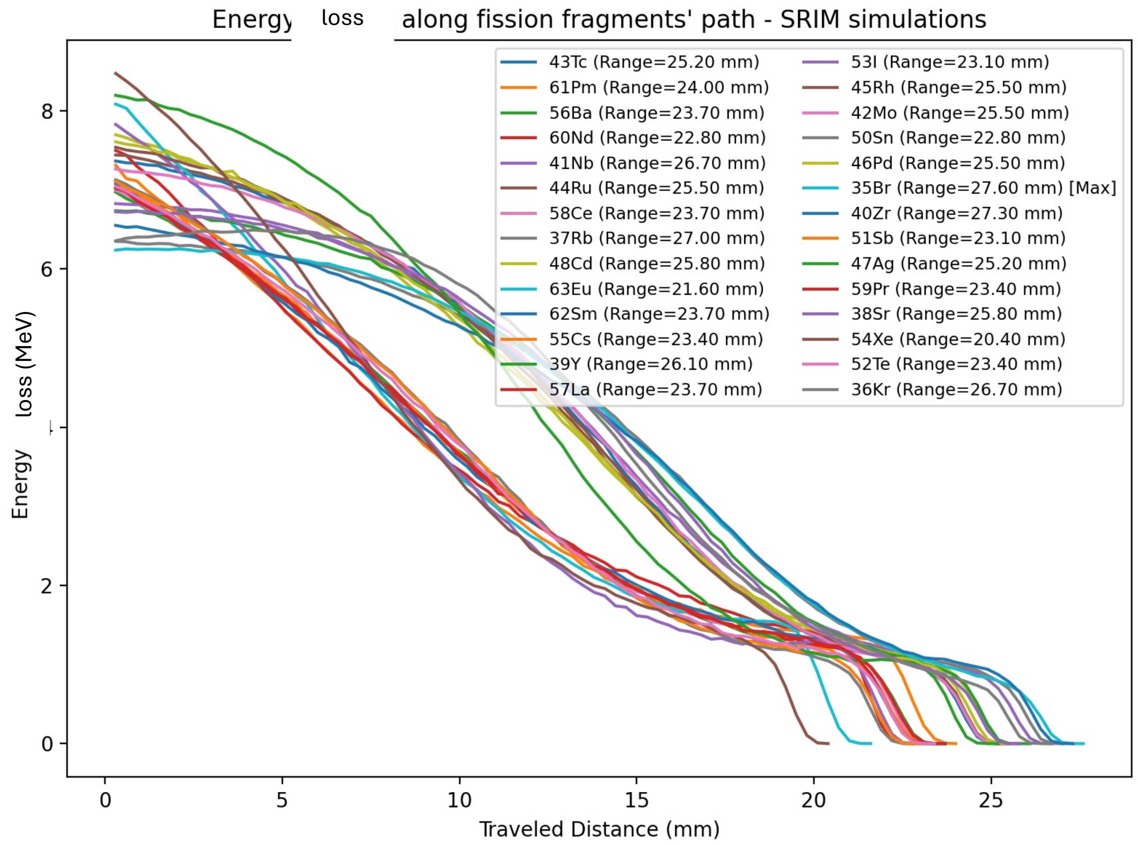
Innovative Rapid TPC for fission studies

Energy Plane Geometry – SRIM Simulations

- Max fragment range ~27mm
- Min size of detection volume element

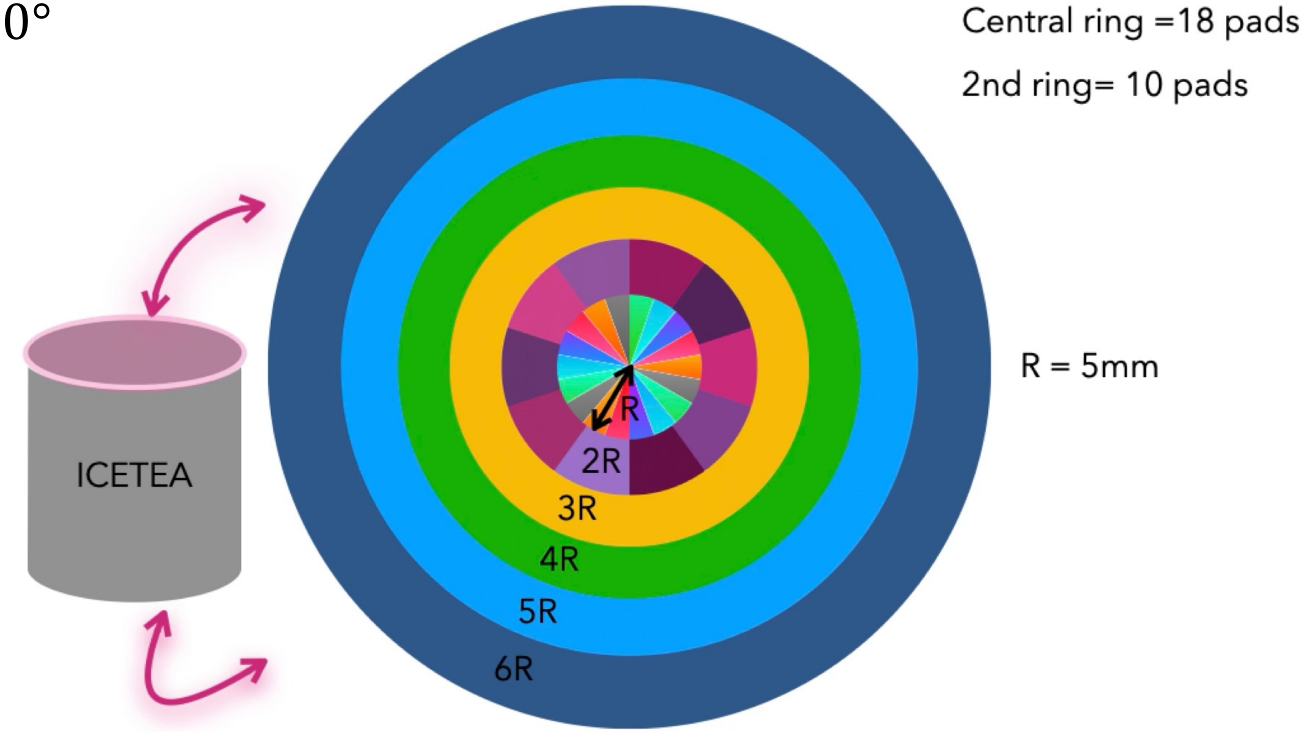
E_{HFF}=79.7MeV
E_{LFF}=104.9MeV





Energy Plane Geometry – SRIM Simulations

- Max FF ~27mm
- Min size of detection volume element
- Targeted angular resolution vis $\Delta\theta, \Delta\varphi \leq 10°$
- 32 pixel-pads per plane (64 in)



Assumptions:

- Negligeable electronic cloud dispersion

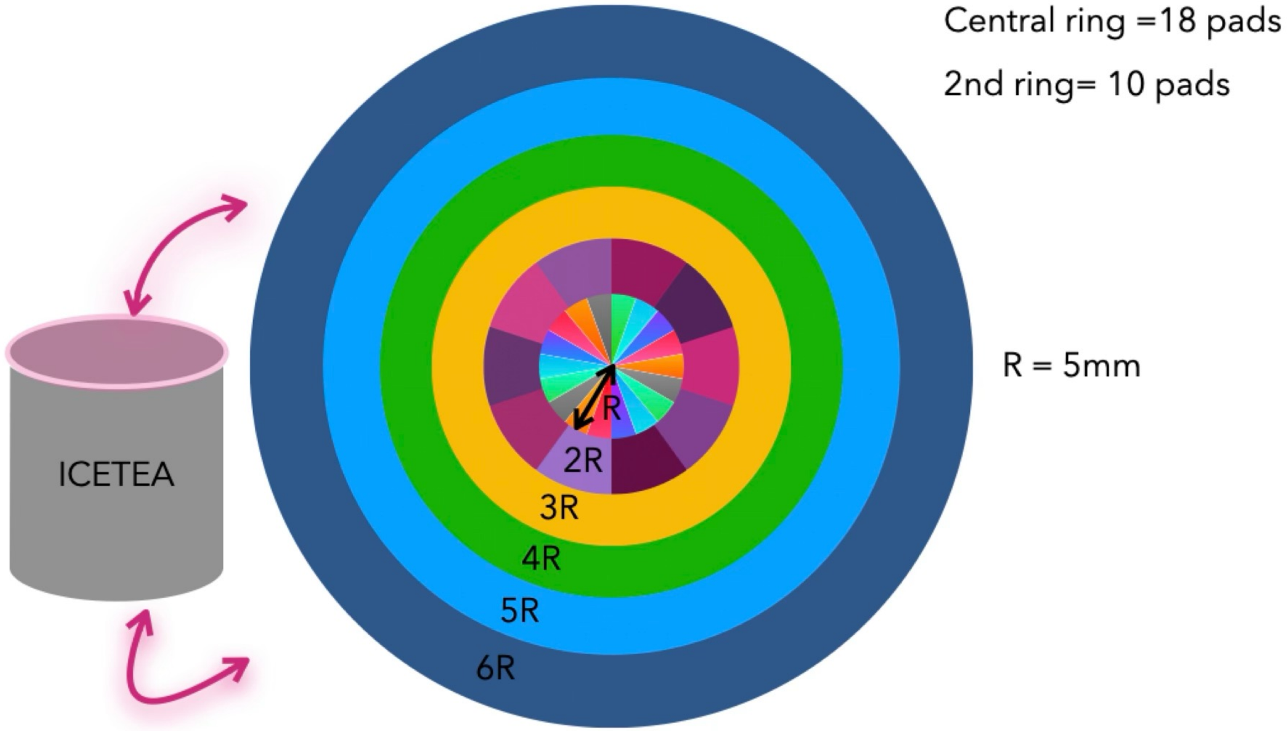
Electronic Readout

- 32 pixel-pads per plane (64 in total)
- 4 multi-wire proportional chamber readouts
- PAC-I preamplifiers (being tested)
- Modular data acquisition system FASTER

  ADC, QDC-TDC, SAMPLER, RF, decision

  (several available trigger modes)

https://faster.in2p3.fr/faster/



Conclusions and Perspectives

Instrumentation – ICETEA

- ✓ Simulations GARFIELD++ MAGBOLTZ for e- in gas
- ✓ COMSOL for field lines simulations
- ✓ SRIM simulations for fission fragments energy loss and track
- o Tests of PACI preamplifiers coupled to FASTER
- o ICETEA prototype assembling and comissionning

Thank you for your attention!

Data Analysis - FRØZEN

- ✓ PARIS (gamma) calibration and time alignments
- ✓ Fission event ID
- ✓ Neutron mutiplicity with TETRA
- o Fission fragments kinematics reconstruction and mass distribution
- o Monte-Carlo simulations and detectors response functions
- o n-γ correlations

Approche Théorique Statistique – Hauser-Feshbach

Hauser-Feshbach
Statistical method to describe the de-excitation process of a highly excited compound nucleus (exc. energy rotation, vibration, deformation)
Conditions:
Highly excited compound nucleus, high nuclear level density (NLD), uncorrelated input-output channels.
Inputs:
NLD, exp. data, strength functions, widths, particle emission probability
Outputs:
Partial probability of a de-excitation channel

FIFRELIN
Fission Fragments Evaporation Leading to Isotopic Nuclear data
(O. Litaize et al., CEA Cadarache)
-Hauser-Feshbach + RIPL-3 + calculated levels
-Detailed complete level scheme+ transition probabilities (microscopic approach)
Outputs :
Detailed gamma spectra, transition intensities, Spin-multiplicity correlations

CGMF
Cascade Gamma-ray Multiplicity and Fission
(P. Talou et al. @ LANL)
-Hauser-Feshbach + Monte Carlo + RIPL-3
-n-gamma correlations
-Spin-sensitive (spin dynamics)
Outputs :
n–γ–fission fragment correlations, angular distributions