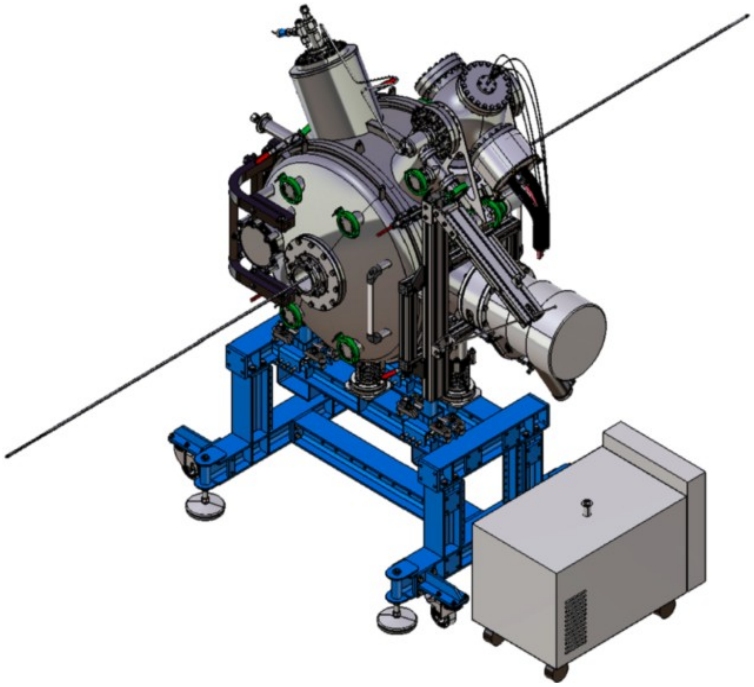
* Liquid **Xe**non **M**edical **I**maging **S**ystem



Talk by Eugene Semenov:

Feasibility evaluation of nuclear fuel homogeneity control with XEMIS2* camera

XeSAT2023

Nantes, France

6-8 June, 2023

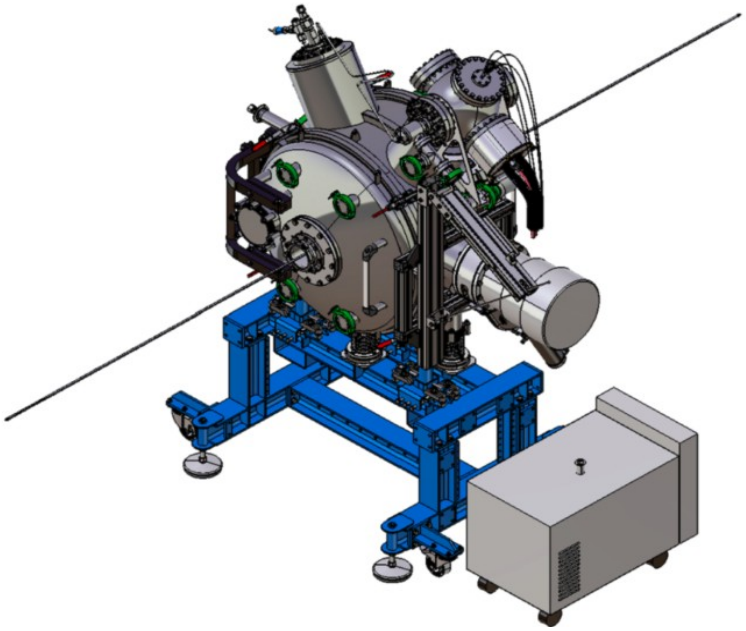
Collaboration

2 orano

1 IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom

1 cnrs

1 Nantes Université



Talk by Eugene Semenov:

Feasibility evaluation of nuclear fuel homogeneity control with XEMIS2 camera

XeSAT2023

Nantes, France

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Team

- Eugene Semenov[1]
- Nicolas Beaupere[1]
- Andre Charre[2]
- Abibatou **Ndiaye**[2]
- Amandine Spiteri[2]
- Dominique **Thers**[1]

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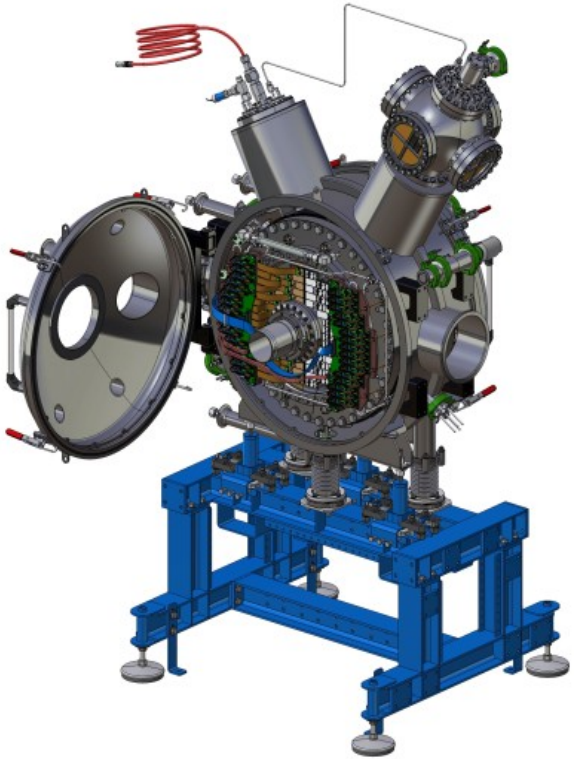
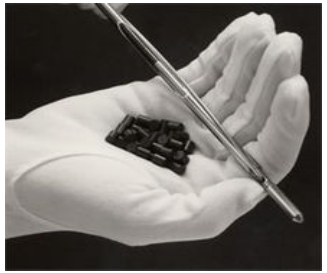
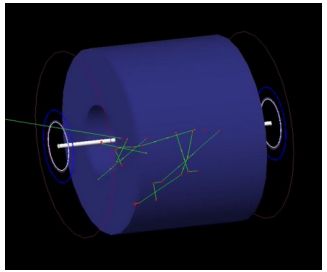
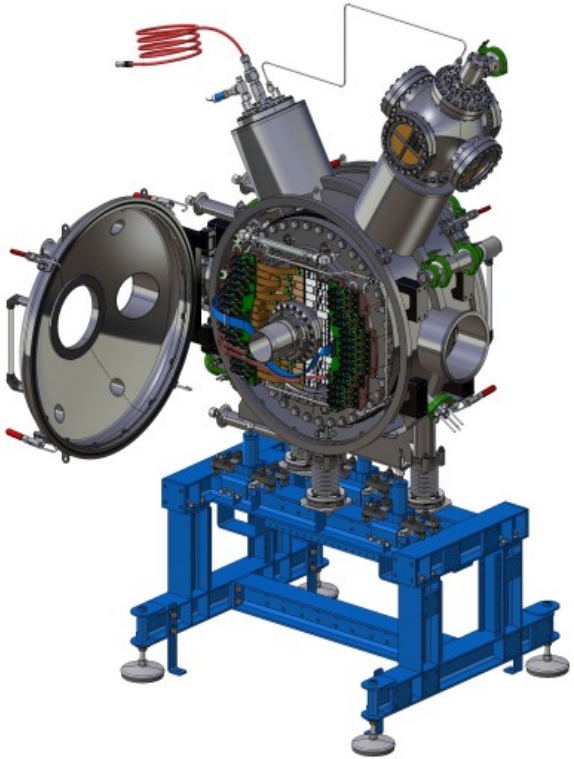


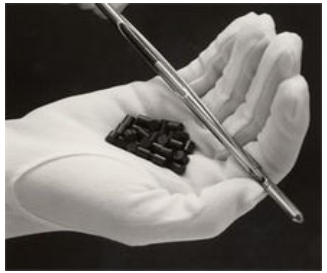


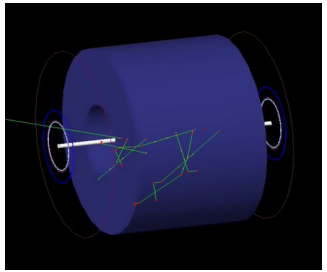


- XEMIS2 overview
- 3γ-imaging
- Object to image
- Control methods:
  - *Scanning & Counting*
  - *Compton tracking*
- Conclusions

CONTENT







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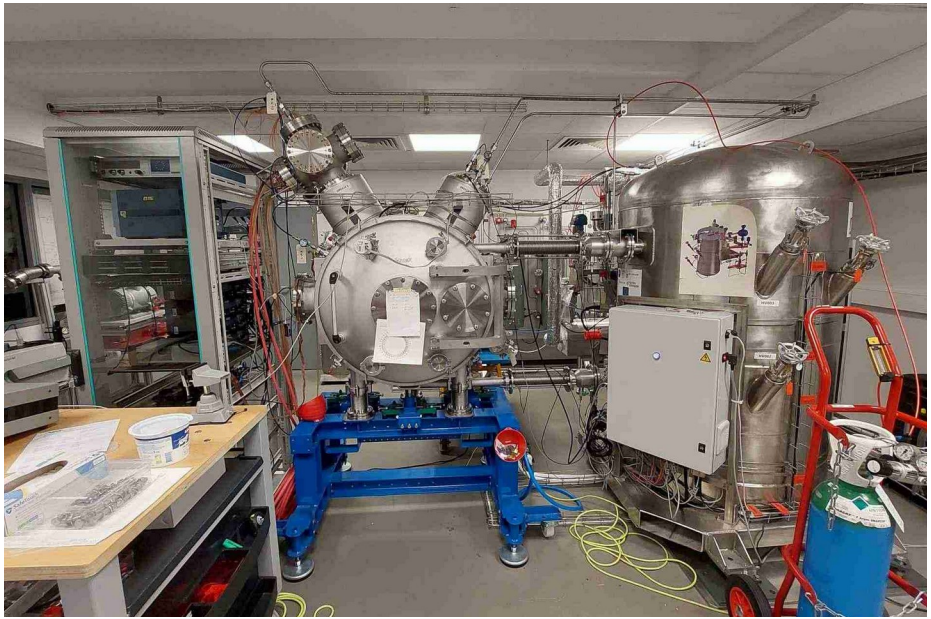
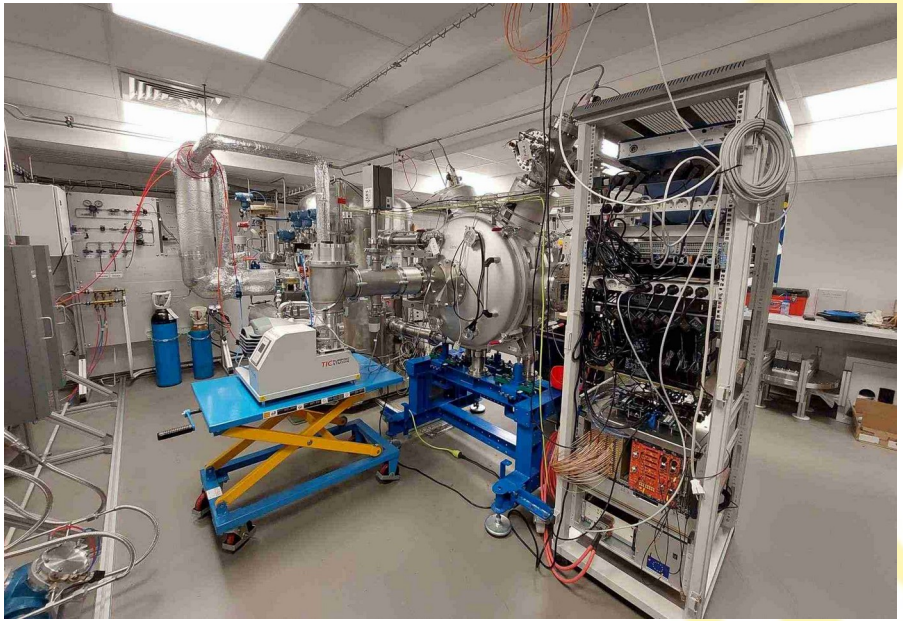
XEMIS2

General view [Nantes Hospital]



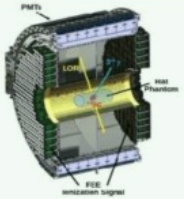


*Visit of **XEMIS2** at CHU Nantes proposed for XESAT2023 participants!*

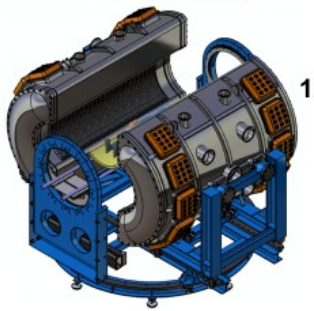
XEMIS2

THEN	NOW	FUTURE
XEMIS1 R&D	XEMIS2 Small animal imaging	XEMIS3 Whole body imaging

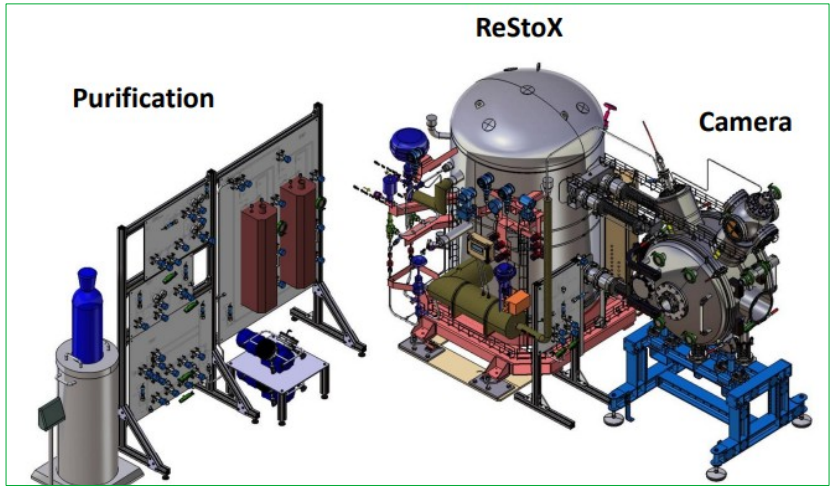
30 kg
12 cm drift TPC



200 kg
2 x 12 cm drift TPC



Toward 2 tons
2 m long
12 cm radial drift
TPC



XEMIS2

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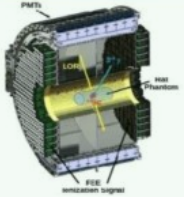

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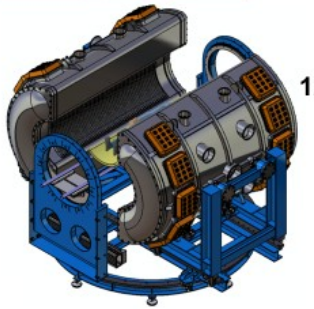

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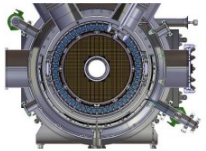
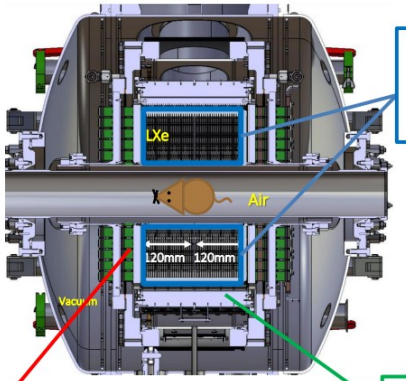
XEMIS2 CAMERA



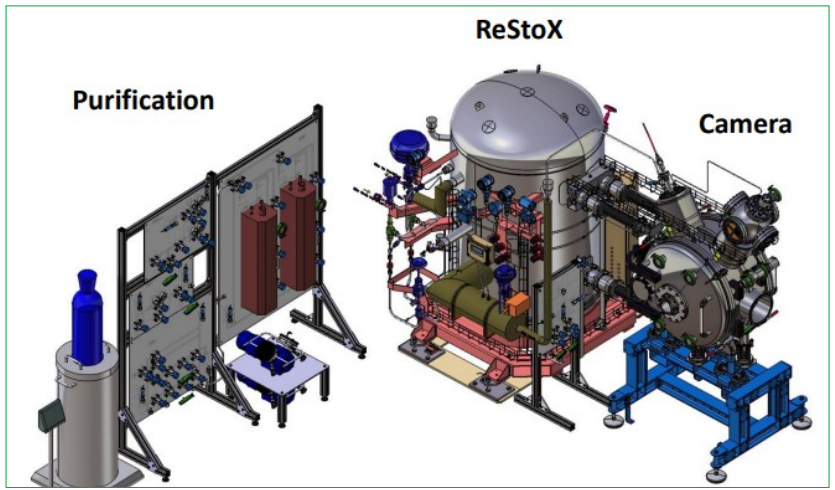


LXe TPC
X2 active volume
- axial : 2 x 12 cm
- depth : 12 cm
- r_{min} : 7 cm

Ionization
2 x 10^4 3.1x3.1 mm^2 pixels with ultra low noise cold FEE

Scintillation
64 x 1'' PMTs in LXE covering 8 sectors in ϕ

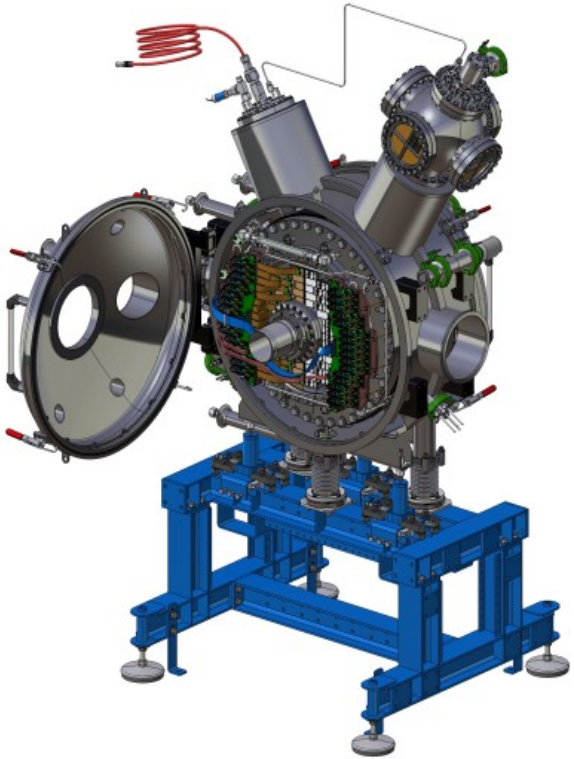
[380 PMT placements reserved]

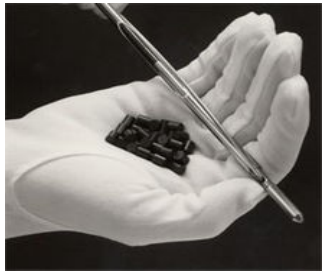


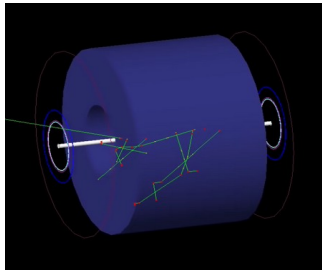
XEMIS2:

- *Nuclear Medical Imaging with **3γ technique** and **LXe***
- *High Rate Single Phase LXe Time Projection Chamber*

CONTENT







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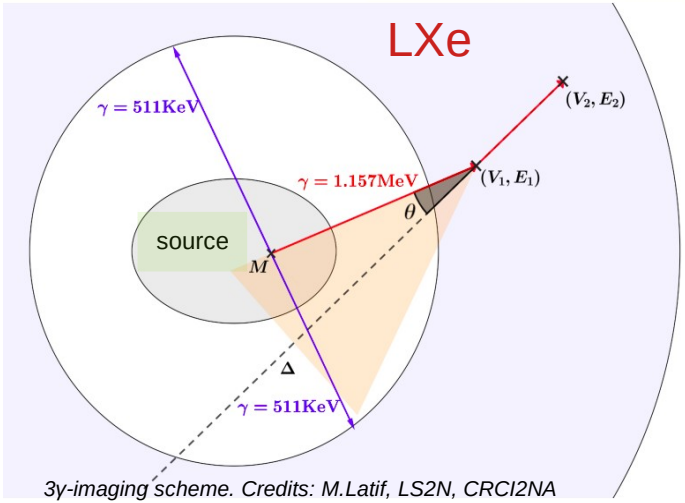
3γ-IMAGING

Classic way [medical application]



3γ-imaging scheme. Credits: M.Latif, LS2N, CRCI2NA

Source:

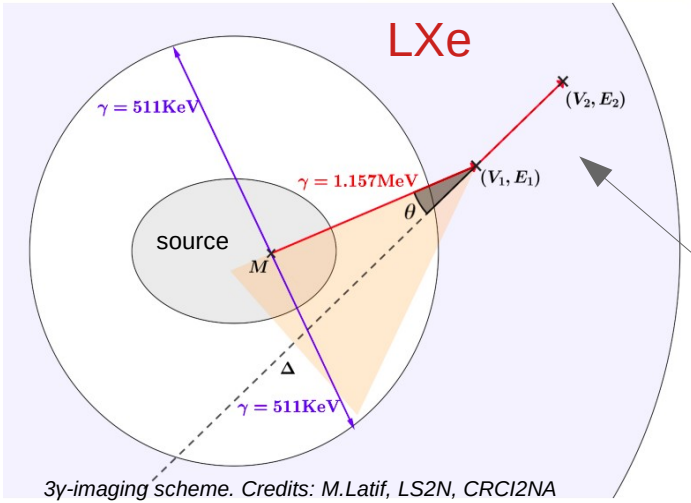
$$^{44}_{21}\mathrm{Sc} \xrightarrow{\beta^+} {}^{44}_{20}\mathrm{Ca}^{*} + \nu_e + e^+ \xrightarrow{\gamma} {}^{44}_{20}\mathrm{Ca} + \nu_e + e^+ + \gamma$$

Goal:

Direct 3D location of the radioactive source

3γ-IMAGING

Classic way [medical application]



3γ-imaging scheme. Credits: M.Latif, LS2N, CRCI2NA

Source:

$$^{44}_{21}\mathrm{Sc} \xrightarrow{\beta^+} {}^{44}_{20}\mathrm{Ca}^{*} + \nu_e + e^+ \xrightarrow{\gamma} {}^{44}_{20}\mathrm{Ca} + \nu_e + e^+ + \gamma$$

Measure:

V_1, V_2 – hits positions
E_1, E_2 – energy deposited

$$\Delta = \overrightarrow{V_2 V_1}\,;$$

$$\theta = \arccos\left(1 - \frac{m_e c^2 E_1}{E_0 (E_0 - E_1)}\right);$$

^{44}Sc-pharmaceutics:

Emission γ:
~100% of E_γ = 1.157 MeV
Fast emission [2.61 ps]

Emission β+
E_{max} = 1.474 MeV
$T_{1/2}$ = 4 h
effective range : 2.8 mm

Have:

LOR reconstruction [e^+]
+ *Compton telescope* [LXe]

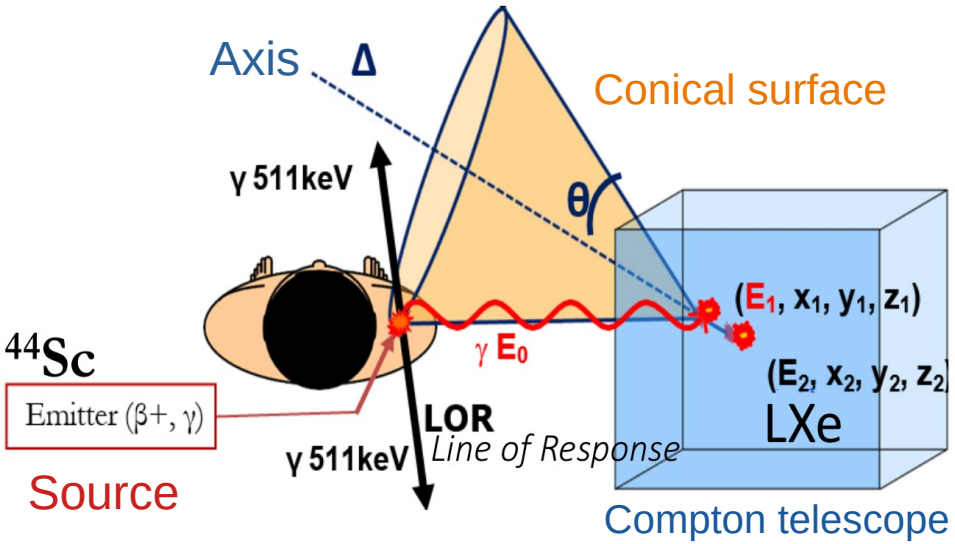
Resolution:

Spatial → axis **Δ** *of the cone*
Energy → opening angle ***θ***

Goal:

Direct 3D location of the radioactive source

3γ-IMAGING **Summarize** [medical application]



Looking for crossing points → emitter's position

XEMIS2:

*Low activity [~20 kBq] + good resolution**

Specificity:

Mono-energetic γ & e+ source

Research done:

*Events **selection** and **topology***

σ(**x,y**) = 100 µm σ(**z**) = 100 µm for single scatter

σ(**E**) = 3.5 %

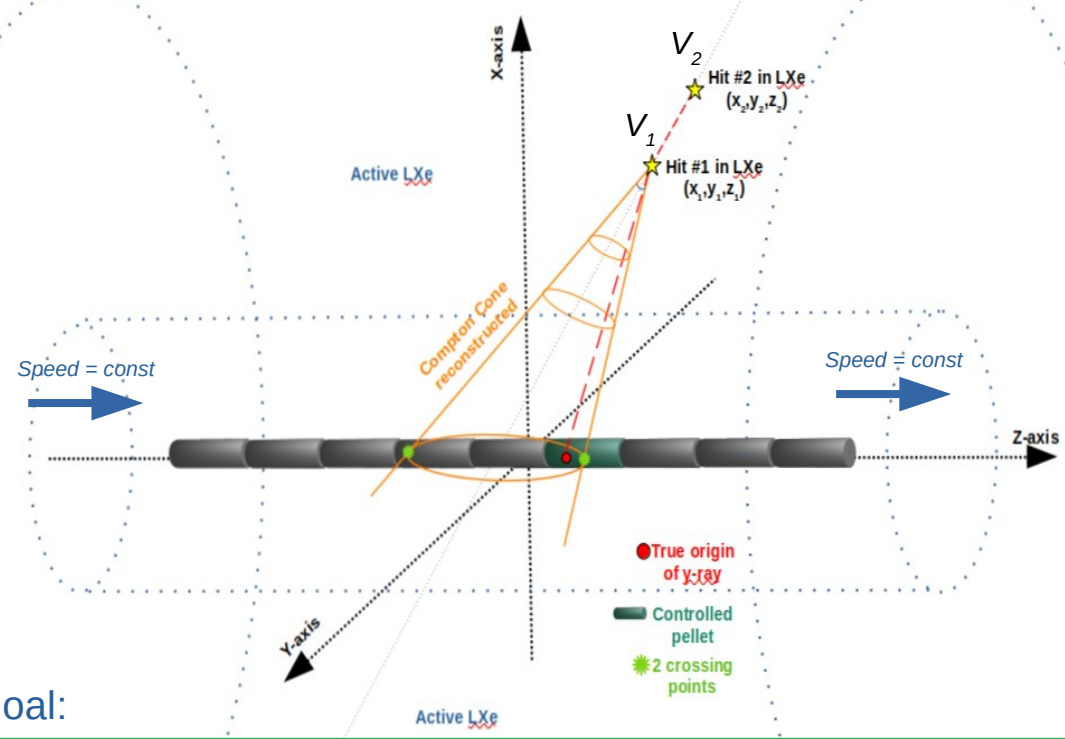
for ^{22}Na, single scatter, 2 kV.cm^{-1}

σ(**θ**) = 2°

**Y. Xing*, *"Studies and optimization of ionization signal measurement for the 3-gamma imaging XEMIS2 liquid xenon Compton camera",*
*PhD thesis @ **Subatech***

IMAGING

Fuel control application [this work]



Source:

- *Nuclear fuel pellets*
- *Moving along Z-axis*
- *Spectrum of γ-rays*

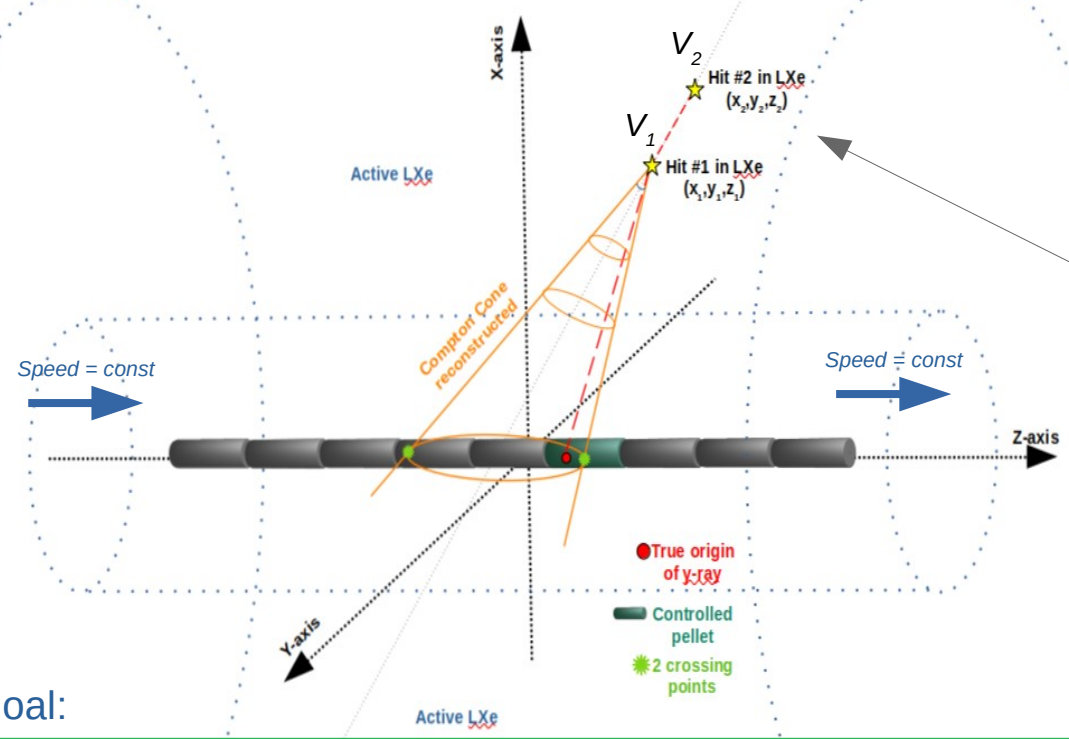
Goal:

Find **cone's crossing points** with **Z-axis** → image & control

First time probe such **source and geometry**!

IMAGING

Fuel control application [this work]



Source:

- *Nuclear fuel pellets*
- *Moving along Z-axis*
- *Spectrum of γ-rays*

Measure:

V_1, V_2 – hits positions
E_1, E_2 – energy deposited

Challenge [later]:

- *Emission spectrum*
- *Control parameters*
- *High activity [total γ]*
- *Low statistics [useful γ]*

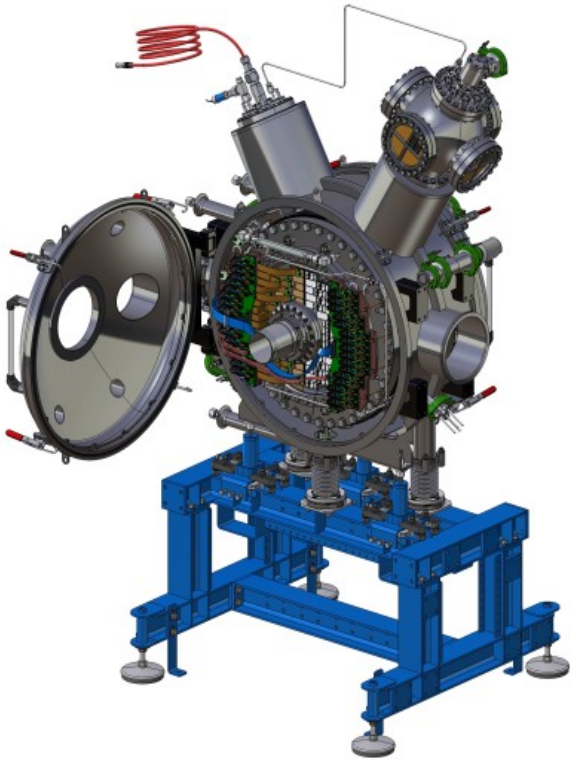
To be continued...

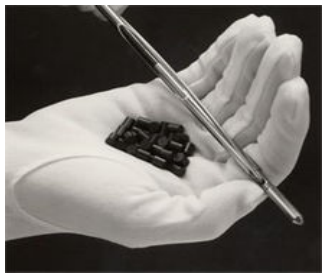
Goal:

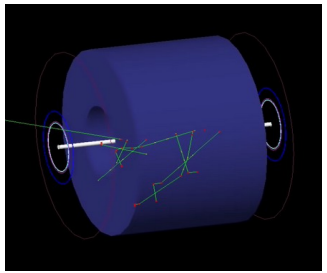
Find cone's crossing points with Z-axis → image & control

First time probe such **source and geometry**!

CONTENT







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OBJECT TO IMAGE

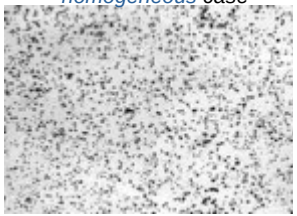
MOX [UO_2+PuO_2 pellets]

Goal:

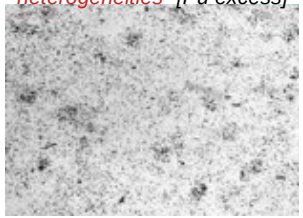
Detect heterogeneity of fixed* sizes, shape & PuO_2 concentration

*not in the scope

homogeneous case



"heterogeneities" [Pu excess]



*Uniform and non-uniform distributions of Pu in fuel**

***Example** of alpha-autoradiography results*

OBJECT TO IMAGE

MOX [UO_2+PuO_2 pellets]

Goal:

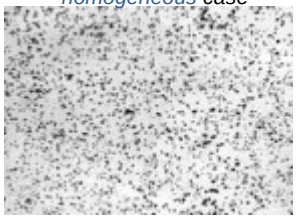
Detect heterogeneity of fixed* sizes, shape & PuO_2 concentration

*not in the scope

Specificity:

- ***ρ ~ 11 g/cm³***
- *U + Pu + daughters*
- *High γ activity*
- *Emission spectrum*
- *Moving in FOV*
- *Control parameters*

homogeneous case



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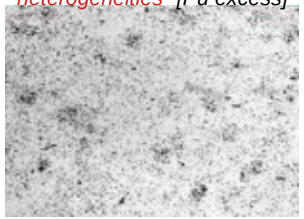
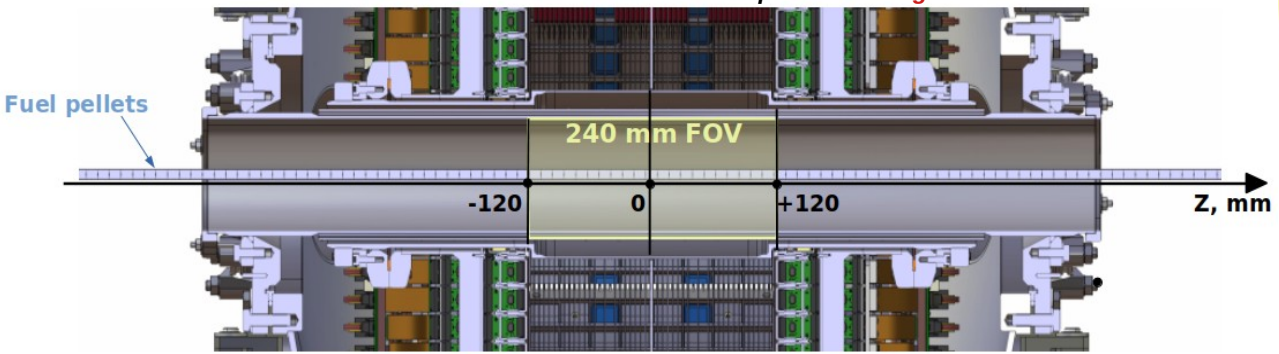


*Uniform and non-uniform distributions of Pu in fuel**

Fuel pellets moving in XEMIS2 FOV



***Example** of alpha-autoradiography results*

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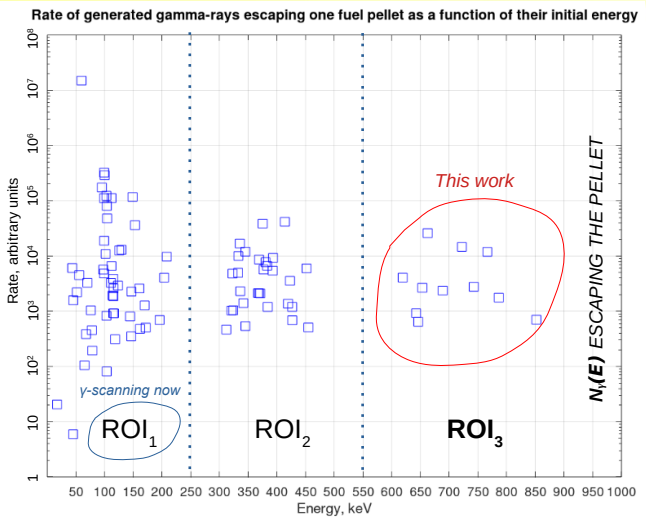
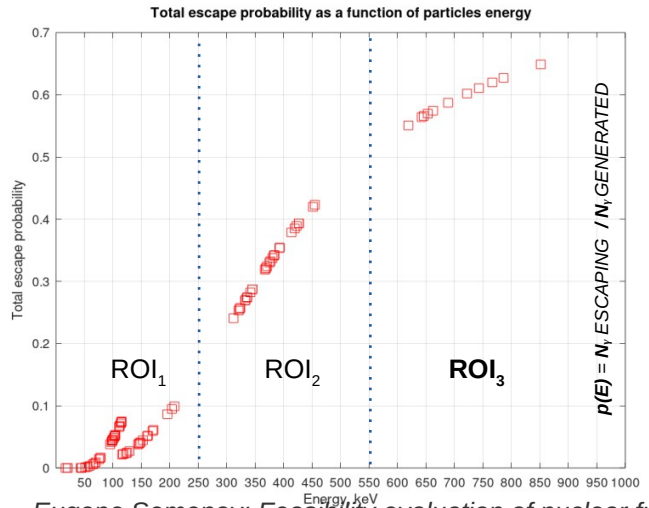




Systematic bias ~ absorption:

Strong : ROI_1 [E_γ < 250 keV]

Moderate : ROI_2 [250 keV < E_γ < 550 keV]

Small : ROI_3 [E_γ > 550 keV]

Challenge:

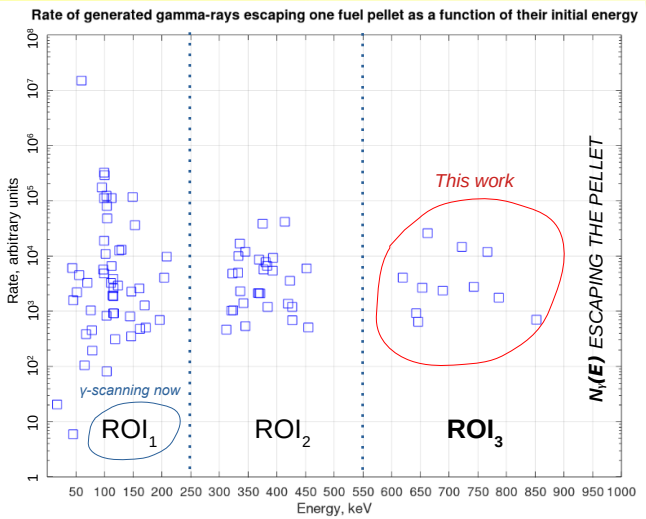
Statistics & attenuation are opposite!

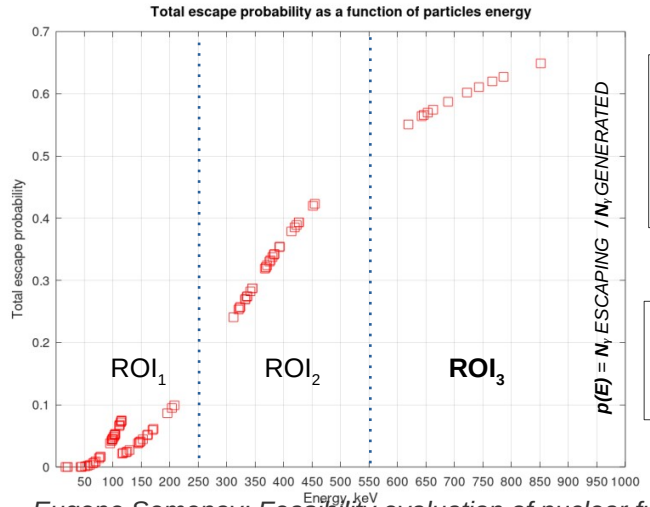
+ Noise study done: γ of UO_2 can be neglected

+ Noise study to be finalized: neutrons from ^{238}Pu

OBJECT TO IMAGE

MOX [UO_2+PuO_2 pellets]





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Strong : ROI_1 [E_γ < 250 keV]
Moderate : ROI_2 [250 keV < E_γ < 550 keV]
Small : ROI_3 [E_γ > 550 keV]

Challenge:

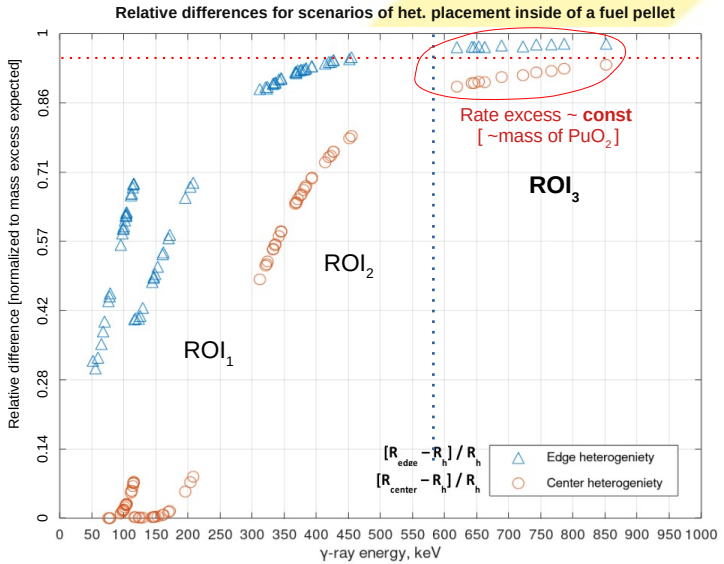
Statistics & attenuation are opposite!

Detection threshold:

Impossible : ROI_1 + any scenario
Better : ROI_2, but strong bias ~ scenarios
Ideal : ROI_3, but need good stats

Shielding study:

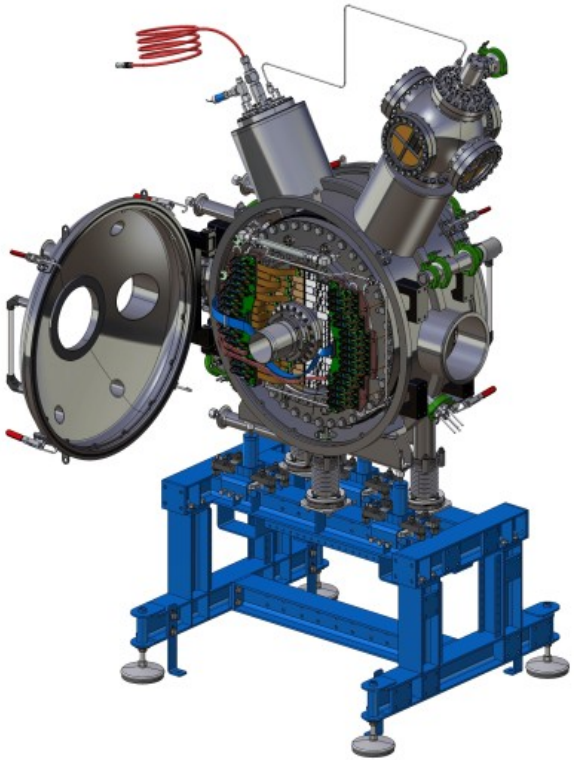
ROI_1 + ROI_2 γ – removed with 1mm thick W-cylinder

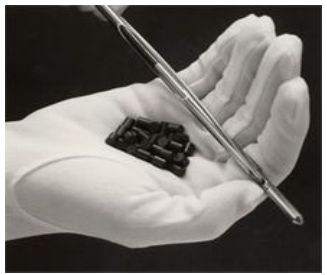


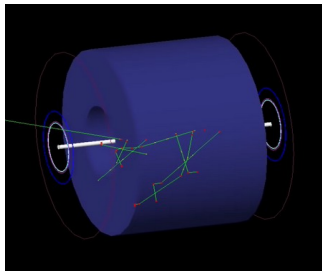
R_{edge} – *rate in LXe – case of "at the edge" placement of heterogeneity*
R_{center} – *rate in LXe – case of "at the center" placement of heterogeneity*
R_h – *rate in LXe – case of homogeneous pellet*

+ Noise study done: γ of UO_2 can be neglected
+ Noise study to be finalized: neutrons from ^{238}Pu

CONTENT







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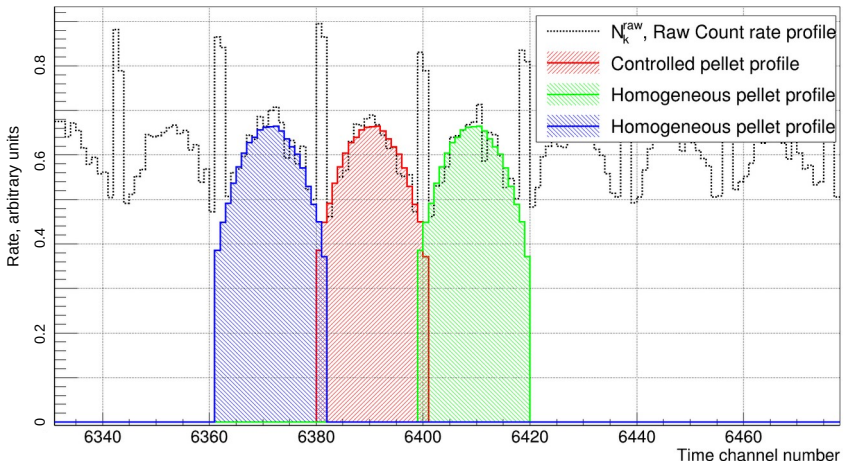
CONTROL METHODS

Scanning & Counting

I. Geant4 simulation: source + XEMIS2

II. Methods development

*Count rate profiles from **moving** pellets in FOV*



Ideas:

- *Find observables*
- *Bias: **fluctuations** from each pellet*
- *Compare with **excess expected***
- *Find **control efficiency***

Specificity:

- *Subtract BKG from non-controlled pellets*
- *Study inter-pellet distance*
- ***Is it enough?***

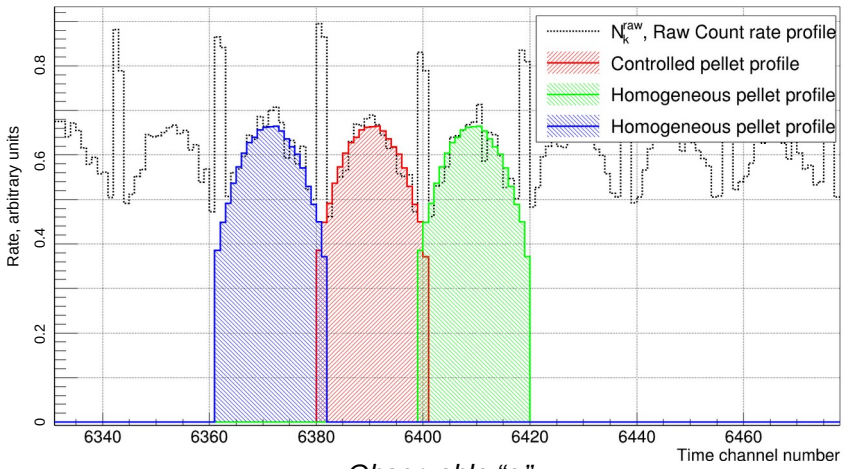
CONTROL METHODS

Scanning & Counting

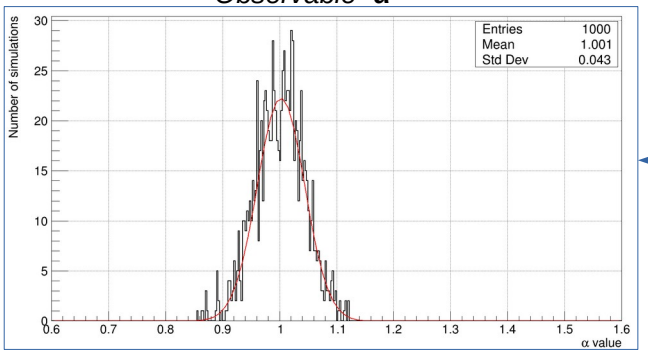
I. Geant4 simulation: source + XEMIS2

II. Methods development

*Count rate profiles from **moving** pellets in FOV*



*Observable "**α**"*



Ideas:

- *Find observables*
- *Bias: **fluctuations** from each pellet*
- *Compare with **excess expected***
- *Find **control efficiency***

Specificity:

- *Subtract BKG from non-controlled pellets*
- *Study inter-pellet distance*
- ***Is it enough?***

Example:

- *1000 simulations of **homogeneous** pellet*
- *inter-pellet distance of **0 mm***
- *To compare:*
  ***Uncertainty** vs **excess** expected*

CONTROL METHODS Scanning & Counting

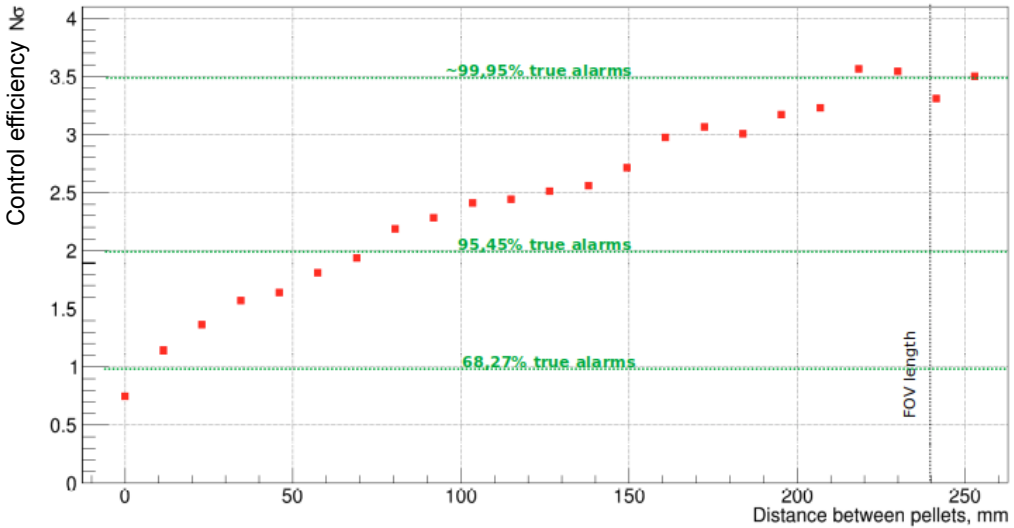
Done:

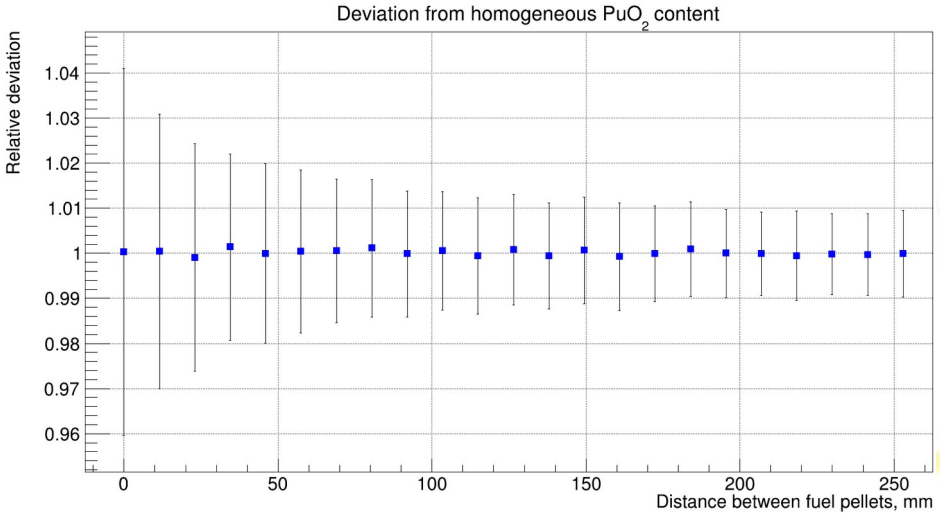
- *Inter-pellet distance study*
- *Defined true and false alarms**

To be defined:

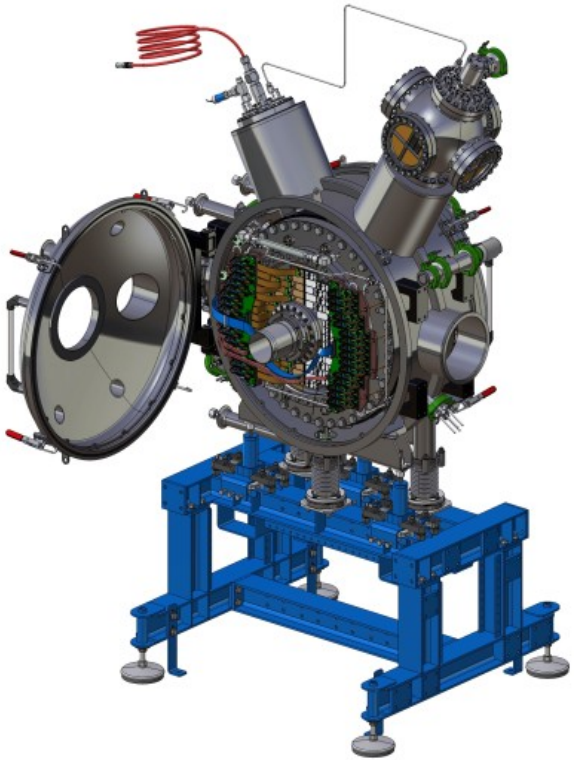
- *Target control efficiency*
- *Suitable for control?*

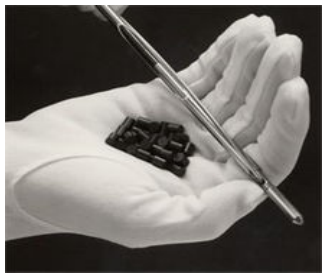
Example: One **heterogeneous** pellet in a sample

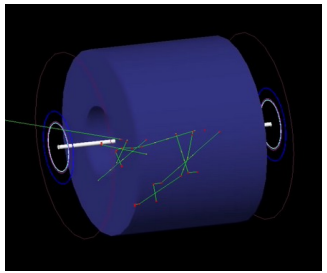




CONTENT

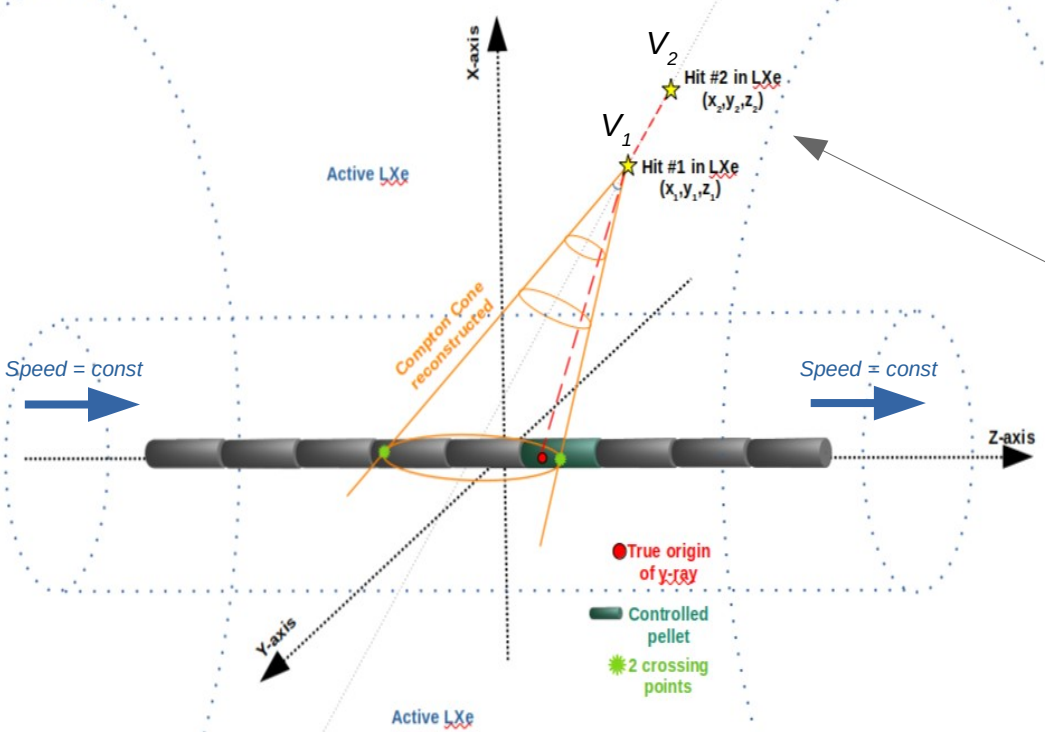






- XEMIS2 overview
- 3γ-imaging
- Object to image
- Control methods:
  - *Scanning & Counting*
  - *Compton tracking*
- Conclusions

CONTROL METHODS Compton tracking



Source:

- ***Nuclear fuel pellets***
- *Moving along Z-axis*
- *Spectrum of γ-rays*

Measure:

V_1, V_2 – *hits positions*
E_1, E_2 – *energy deposited*

Challenge:

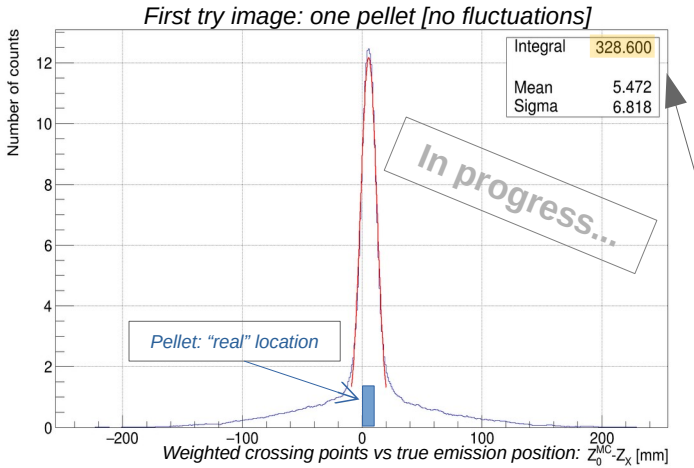
- *Emission spectrum*
- *Control parameters*
- *High activity [total γ]*
- *Low statistics [useful γ]*

Find cone's crossing points with Z-axis → image & control

First time probe such **source and geometry**!

CONTROL METHODS

Compton tracking



Strategy:

1. Image of controlled pellet
2. Image of all pellets in FOV
3. Detect the excess
4. Compare to fluctuations

Work in progress:

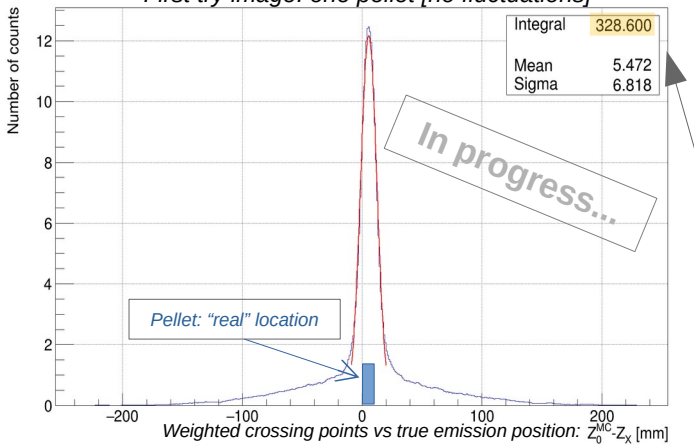
1. Improve events selection & cuts
   "*Integral*" → *increased step-by-step*
2. Compton Tracking in-depth
3. New topology? [3-hit events, cuts, ...]
4. Very **promising** and interesting to industry

Target: resolution ~ pellet size

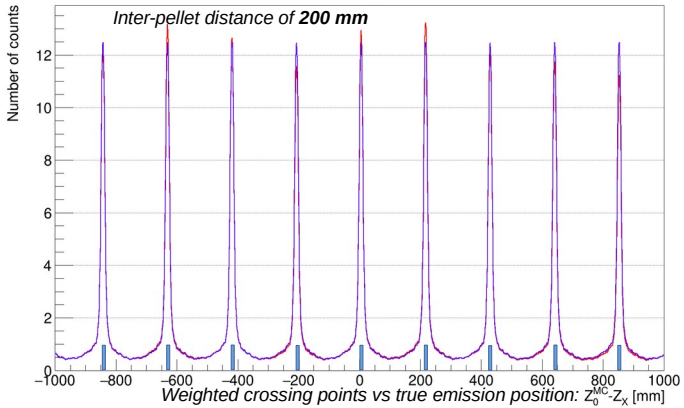
CONTROL METHODS

Compton tracking

First try image: one pellet [no fluctuations]



*First try image: all pellets in FOV [**with** & **without** fluctuations]*



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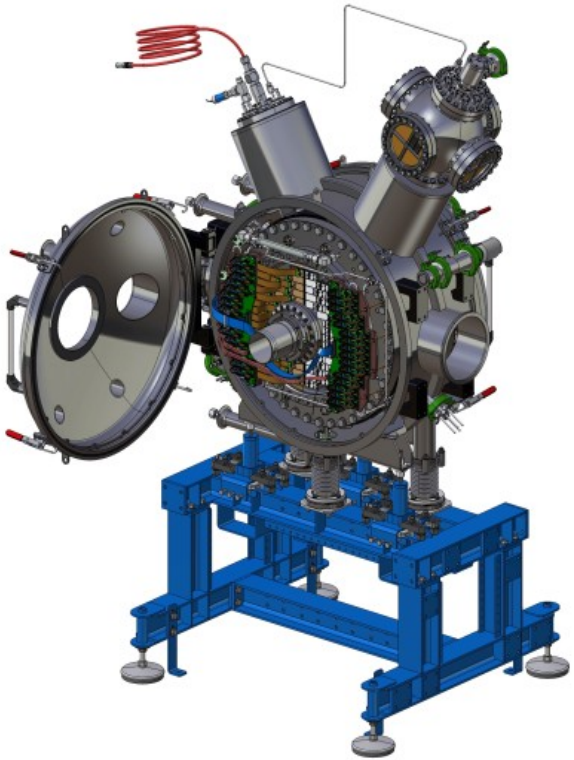

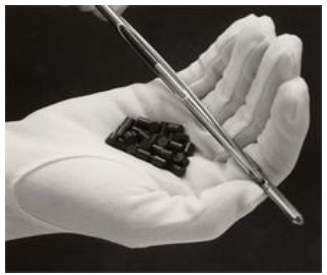

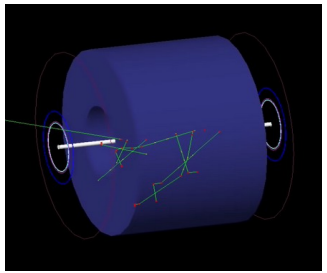

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CONCLUSIONS

- Feasibility not yet established...
- ...work is **in progress** right now!
- Very promising first results
- New application of imaging with LXe

- **Experiment** planned with XEMIS2 during the PhD
- Measure camera response with ^{137}Cs

- More **background** studies needed
- Step-by-step **improvement**: events selection, topology, cuts, etc...
- ...lead to better **resolution** and **control**

*Many thanks to the **ORANO** & **Subatech's XEMIS team** that make this work possible.*

*Thanks to **XeSAT** international advisor committee, organizing committee, institutes and participants.*