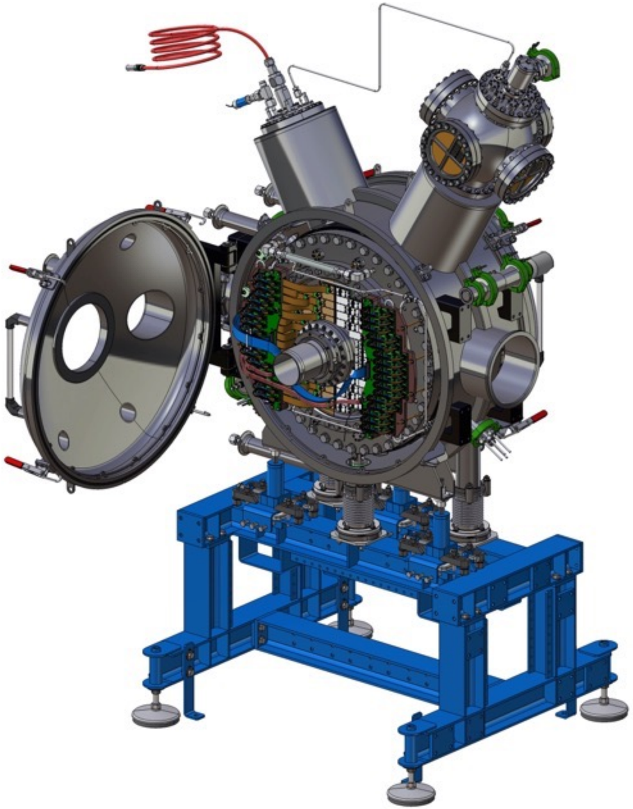
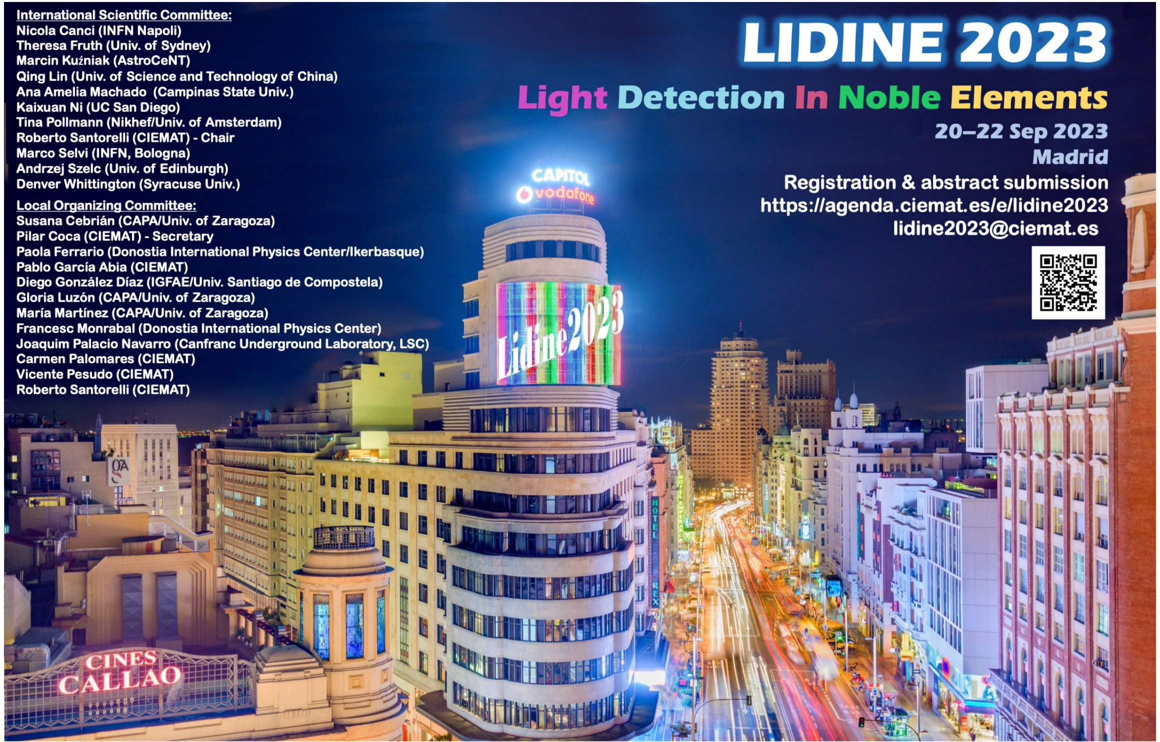
XEMIS2 : Status and Prospects

Dominique Thers (dominique.thers@subatech.in2p3.fr)
SUBATECH Laboratory

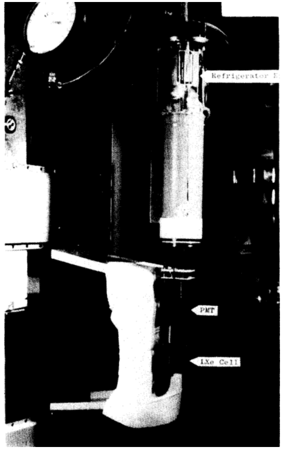




γ-medical imaging with LXe (1/3)

Big dream of the community for about 50 years, a very active field for R&D !

An impressive list (not exhaustive) of key contributions since 2 generations



1976 Louis Lavoie (University of Chicago)

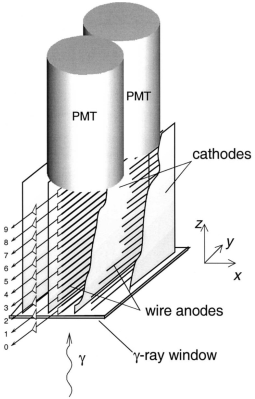
First time resolution expectation @ 511 keV, 160 ps

(with τ=10 ns, W=35 eV, QE=15% !!!)

2003 M. I. Lopes and V. Chepel et al. (LIP Coimbra)

Liquid xenon ionization chamber for PET

σ_x-σ_y-σ_z : 1 mm, σ_t = 500 ps @ 511 keV

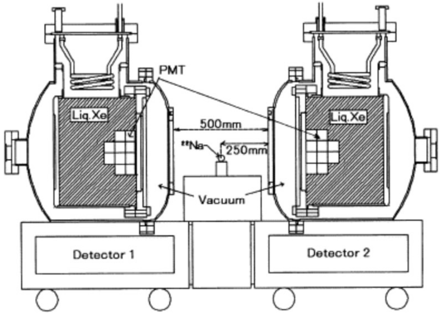


γ-medical imaging with LXe (2/3)

2006 Tadayoshi Doke et al. (Waseda University)

Monolithic liquid xenon scintillation calorimeter

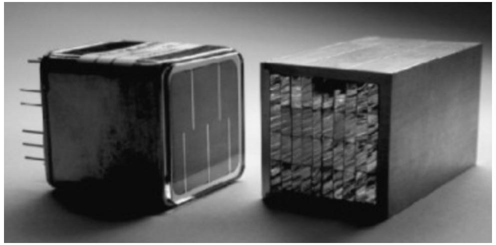
σ_x-σ_y-σ_z : 2-3,5 mm, σ_t = 260 ps @ 511 keV



2008 Philippe Martin et al. (LPSC Grenoble)

MgF_2-coated aluminum UV light guides

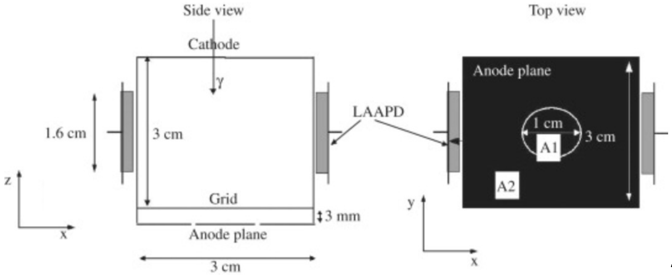
DOI : 2,5 mm, σ_E/E=10%, σ_t = 550 ps @ 511 keV



2009 P. Amaudruz, D. Bryman, F. Retiere et al. (Triumf)

Light and charge appearing

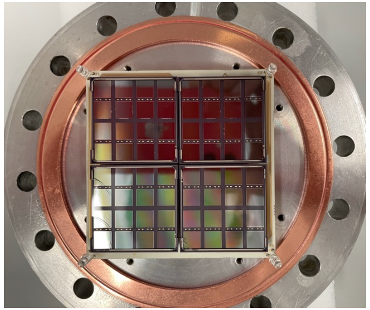
σ_E/E=4.1% @ 511 keV



γ-medical imaging with LXe (3/3)

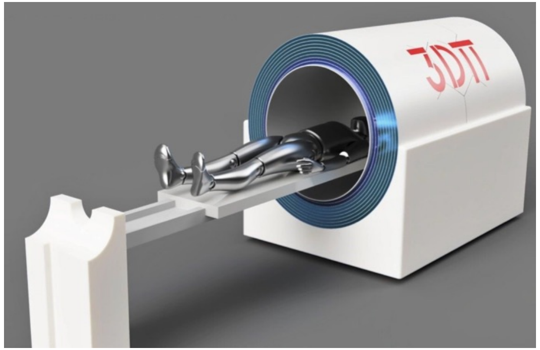
Petalo (IFIC Valencia)

Nerea's talk at 12:35 today
SiPMs TOF-PET with LXe



3DΠ (ASTROCENT, Warsaw)

Azam's talk today at 12:50
Total-Body TOF-PET with LAr+Xe
DarkSide spin-off



PET world race for personalized medicine

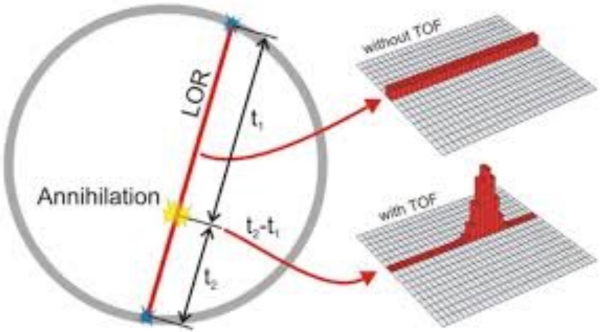
PET/Total body

- Increase FOV (Field Of View)
- Explorer: increase axial FOV of PET camera

2m axial FOV

PET/Time Of Flight

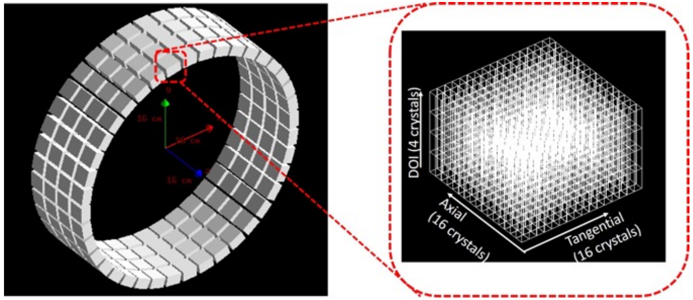
- Reduce Length of LOR (Line Of Response)
- Very good time resolution of detectors



10 ps challenge

PET/Depth Of Interaction

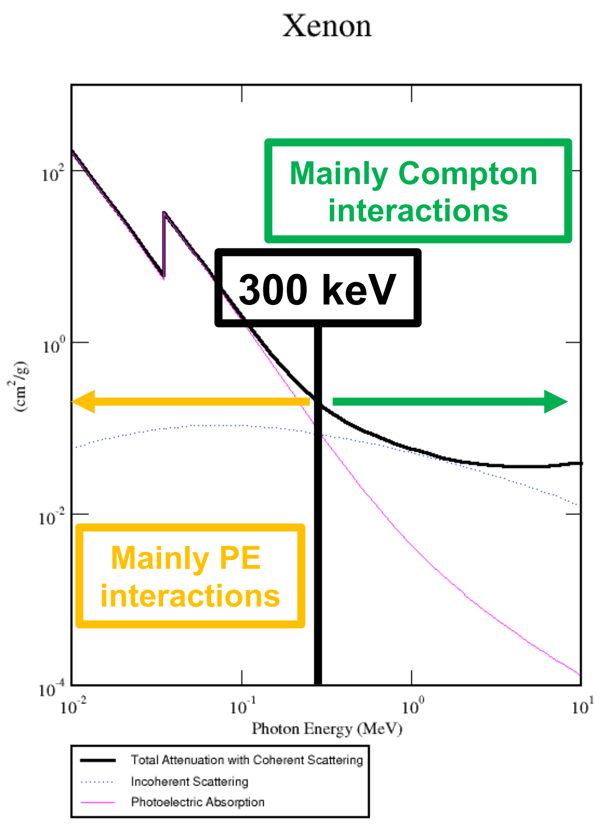
- Reduce Parallax effects on the whole FOV with precise DOI measurement
- Depth segmentation



DOI for parallaxe recovering

Smaller dose, faster exam, dynamical imaging
But only "photo-pic fraction" detection
Compton interactions in crystals not correctly taken into account

Compton interactions dominates HE γ-rays interaction



NIST:XCOM

Some basic considerations:

@ 511 keV: Compton/PE = 73/21
@ 1 MeV: Compton/PE = 90/8

γ-rays interaction length is also increasing more and more (max at 4 MeV thanks to pair production):

@ 511 keV: 3.4 cm
@ 1 MeV: 5.9 cm

Main drivers for HE Compton Cameras (and XEMIS future)

Efficient Compton camera should be monolithic and large enough

XEMIS (XENON MEDICAL IMAGING SYSTEM)

- Total Body, TOF like, parallax free 3γ medical imaging technique
- High Rate Single Phase LXe Time Projection Chamber
- XEMIS2 Compton telescope with LXe installed in Nantes Hospital

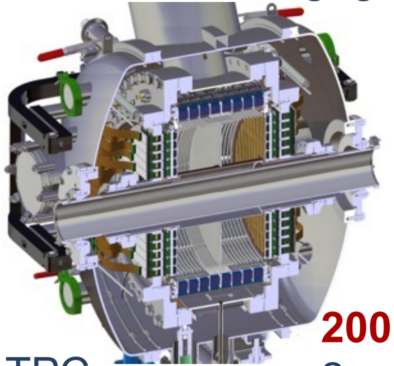
Done

XEMIS1
R&D Prototype

30 kg
6 (12) cm drift TPC

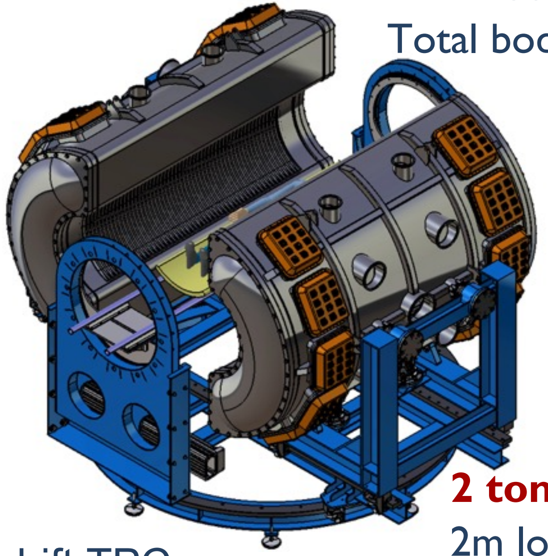
Under installation at Nantes CHU

XEMIS2
Small animal imaging



200 kg
2 × 12 cm drift TPC

XEMIS3
Total body imaging



2 tons
2m long
12 cm drift TPC

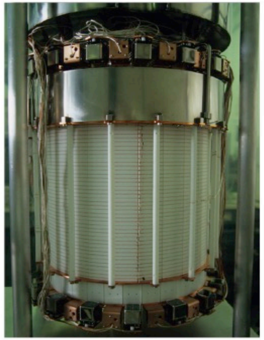
2010 — **2023** — **Final goal**

Monolithic LXe TPC scalabilty

Demonstrated by XENON International collaboration for DDM Searches

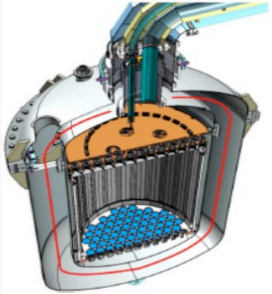
Time

XENON10



XENON100

XENON1T



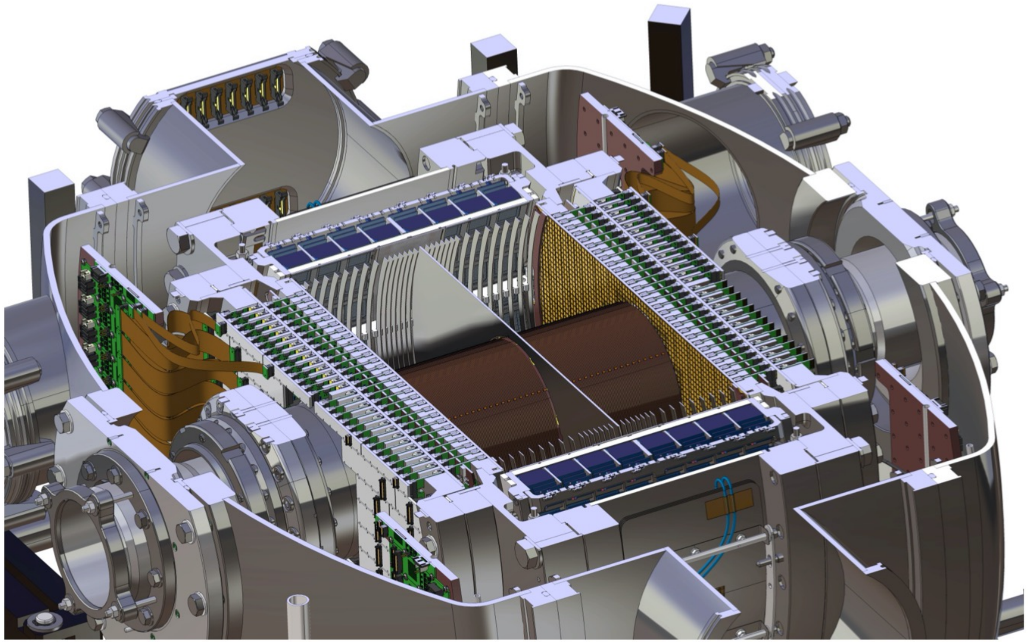
XENONnT

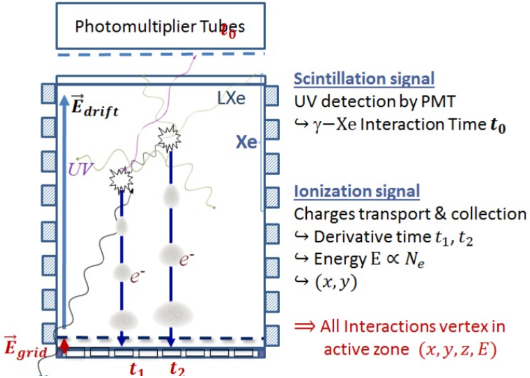
XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

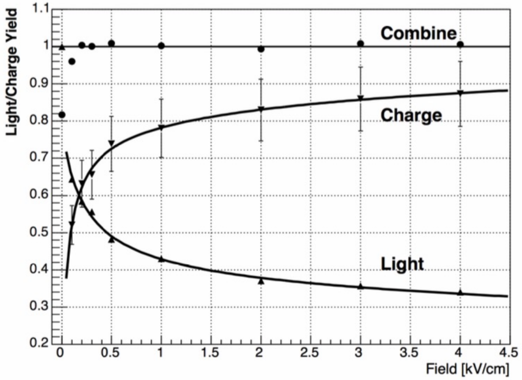
Best technology for direct detection WIMP searches (at masses above 6 GeV)

Very promising for camera market with LXe

Parallax free with LXe TPC used as ionization chamber for 3γ Compton imaging



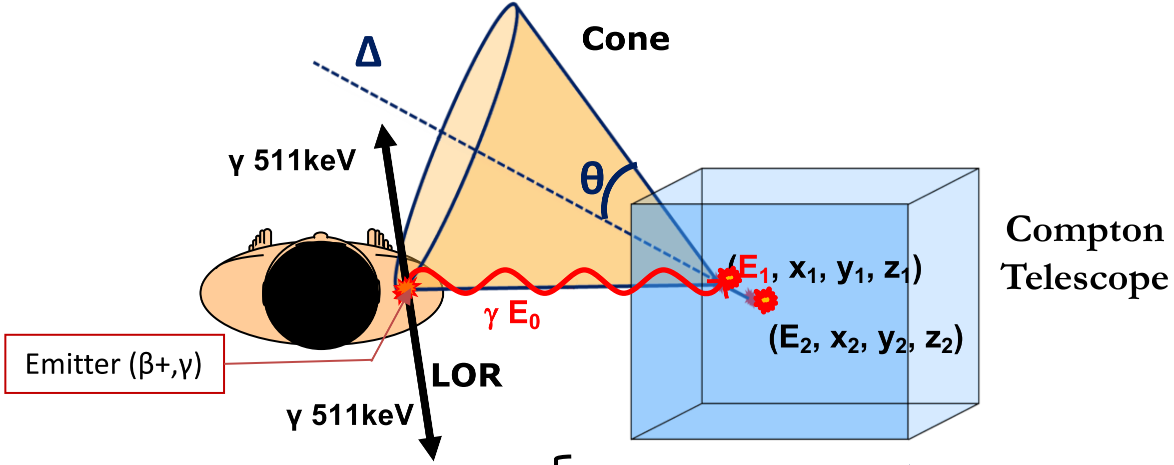




From E. Aprile et al., "Observation of Anti-correlation between Scintillation and Ionization for MeV Gamma-Rays in Liquid Xenon," Physical Review B, vol. 76, 2007.

No parallax effect with monolithic 70 kg active LXe TPC
Goal : 100 μm X,Y and Z spatial resolution on electronic recoil positions

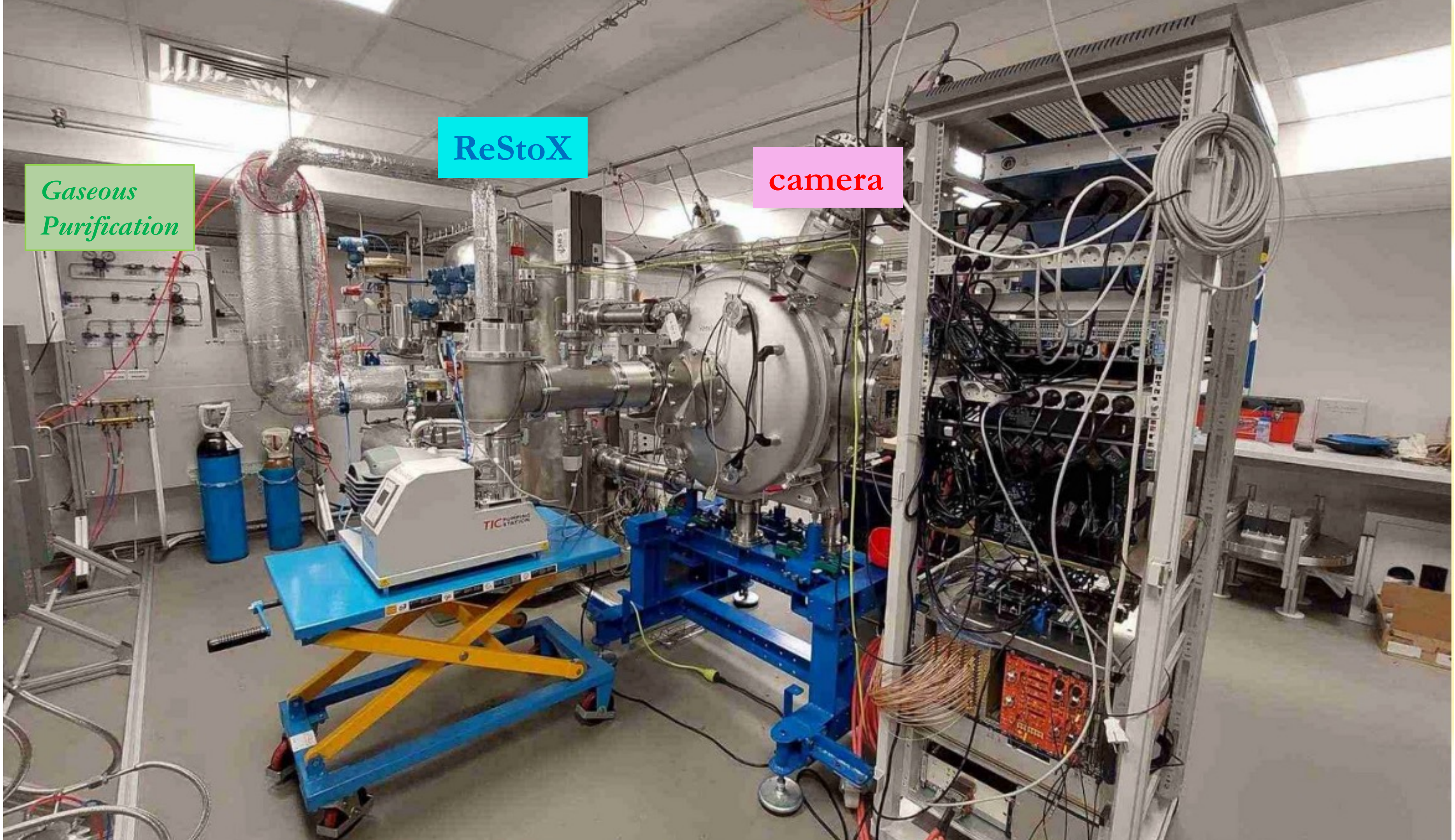
3γ imaging : Monolithic Compton telescope and 3γ emitter for “TOF-TEP like”



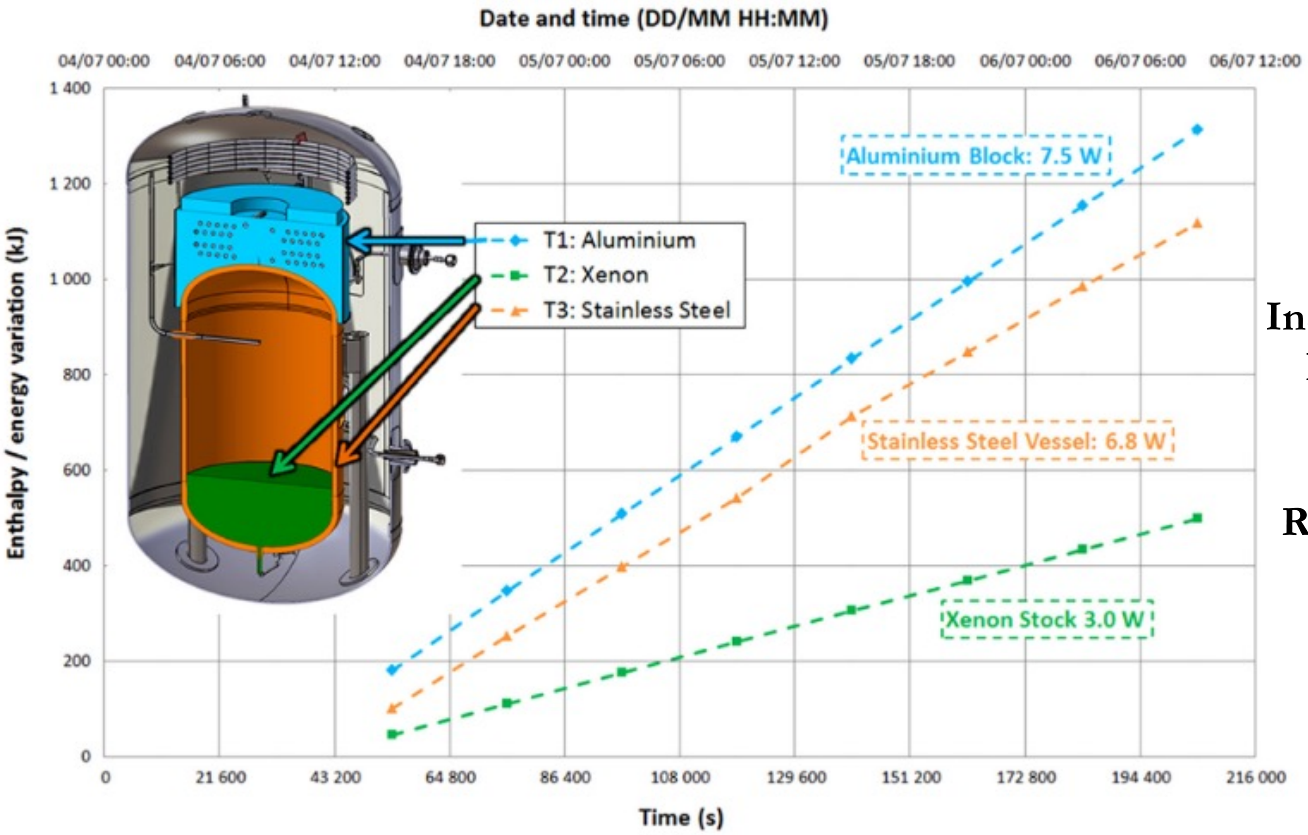
Reconstructed γ direction
- Spatial resolution ➡ cone axis (Δ)
- Energy resolution ➡ opening angle (θ)

Direct 3D location of the radioactive source: res. along LOR < 1 cm (FWHM) for small animal FOV

XEMIS2 goals:
50 ps “TOF like” with 5-10% global sensitivity
thanks to good spatial and energy resolution (only ns time resolution)


Gaseous Purification
ReStoX
camera

Warm up ReStoX test with LXe

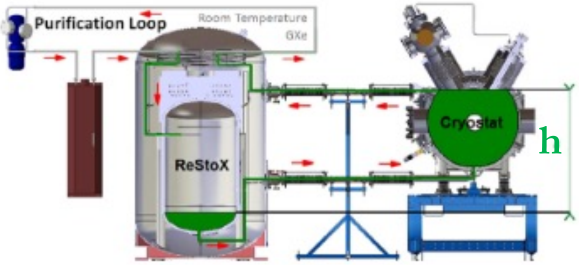


ReStoX

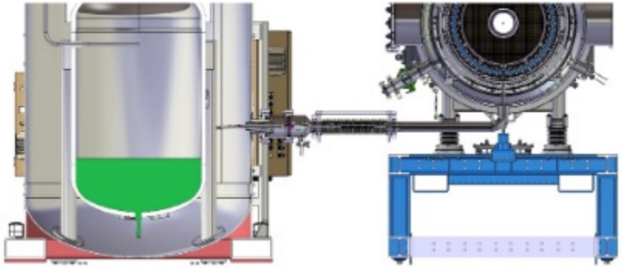
Insulation : vacuum and pearlite
Head load < 20 W with LXe
Cooling max: 5 kW

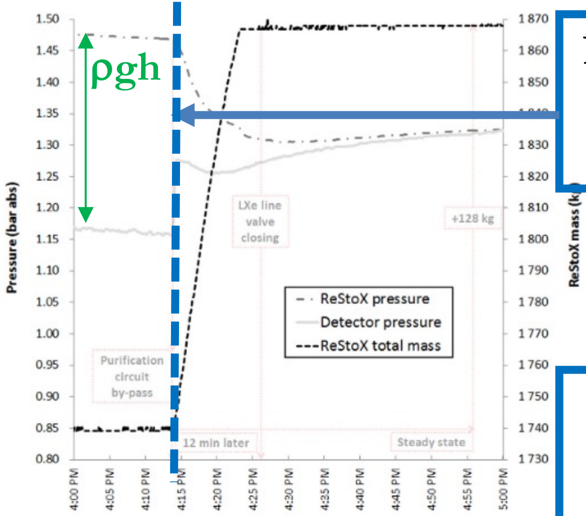
Regulation thanks to LN_2 flow and internal pressure

XEMIS2 cryogenics commissioning



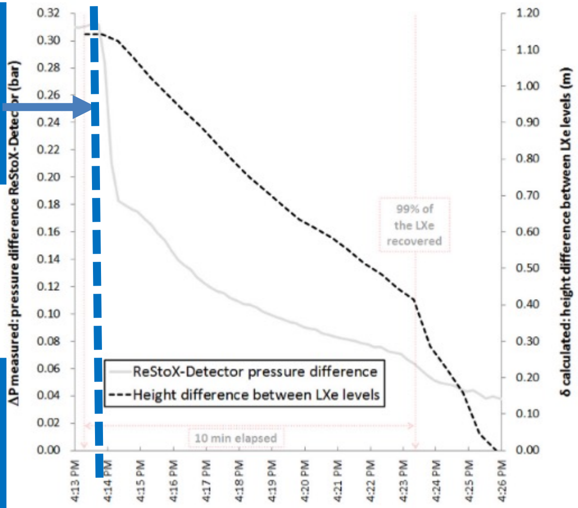
Gravity assisted recovery





Purification Circuit By-pass

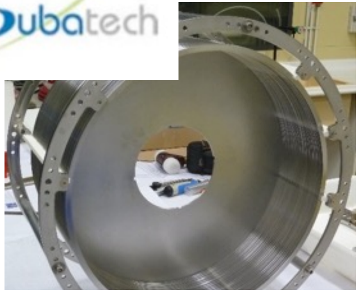
No more LXe in the camera
10 mn later



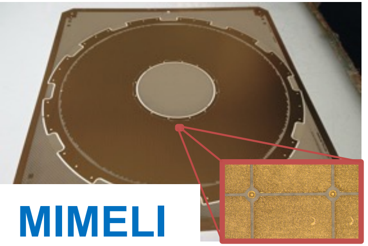
Very safe (subcooled LXe transfer) and Fast Xe mass flow rate: close to 1 ton·h−1 achieved in operation

Work automatically without human assistance

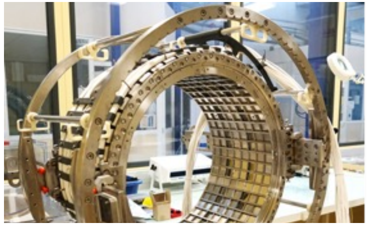
XEMIS2: High Purity LXe Compton Camera



Central cathode



MIMELI



PMTs & Support

LXe TPC

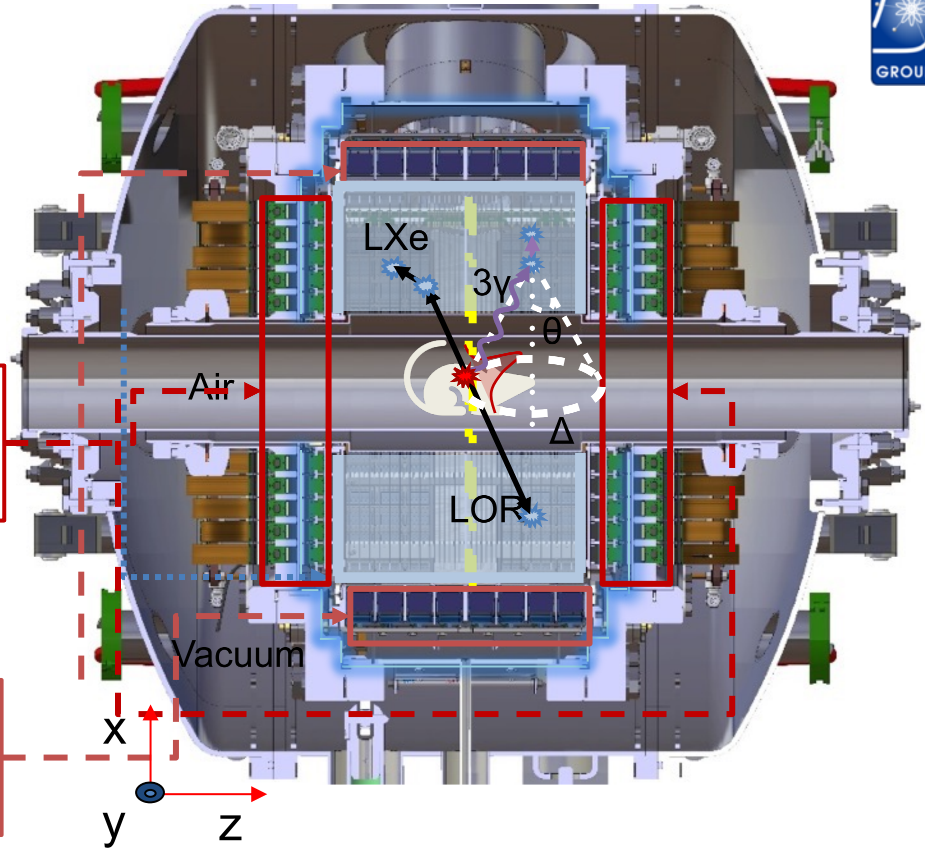
Active volume ~70 kg
- axial : 2 x 12 cm
- radius: 7 -> 19 cm

Charge readout

2×10^4 3.1×3.1 mm^2 pixels with ultra-low noise cold FEE

Light readout

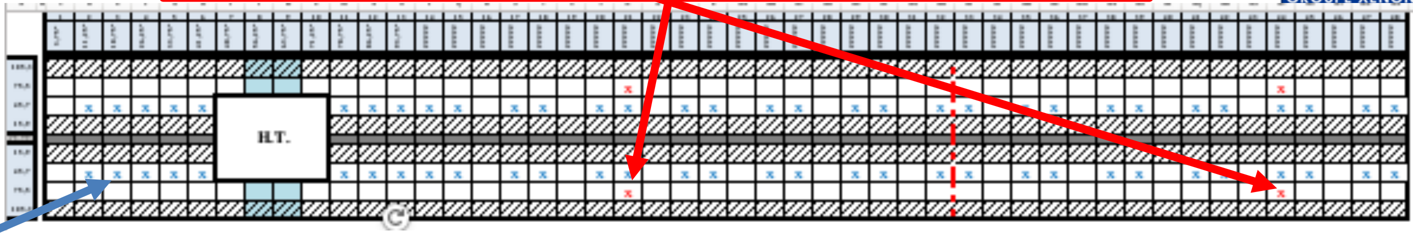
64 x 1'' Hamamatsu PMTs in LXe
Cover 32 sectors in ϕ



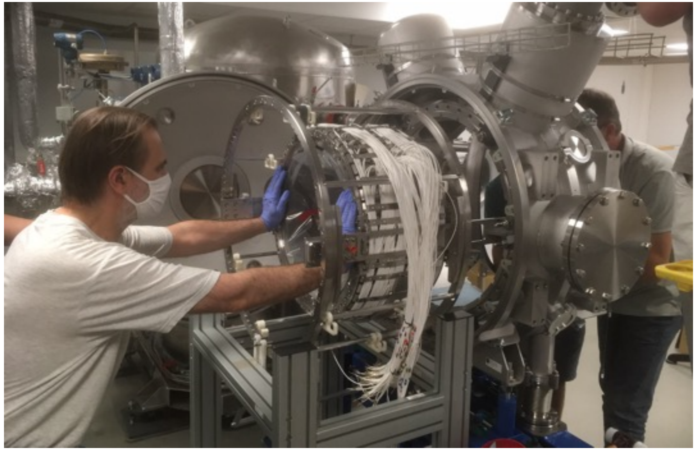
Full Gate/GEANT4 simulation
High sensitivity 3γ > 70 cts/kBq along the FOV

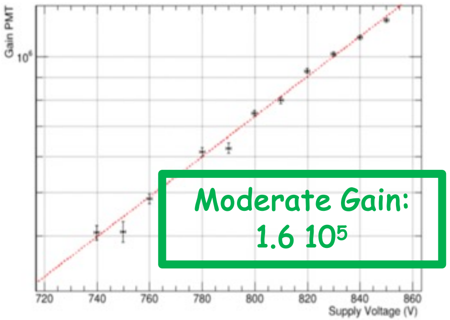
S1 Prompts scintillation light detection with 1 inch PMTs

Gain calibration with 4 photo diodes installed on the support



64 1" PMTs to cover ϕ acceptance
QE 32%

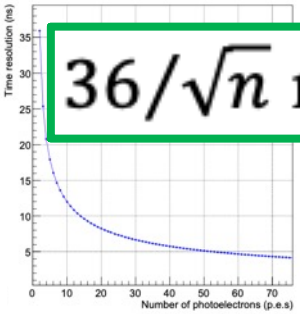




Moderate Gain: 1.6 10^5

Incident particle	τ_s (ns)	τ_t (ns)	τ_r (ns)	I_s/I_t
Electrons	2.2 ± 0.3	27.0 ± 1.0	~ 45	0.05

Time resolution dominated by LXe in XEMIS2



$36/\sqrt{n}$ ns

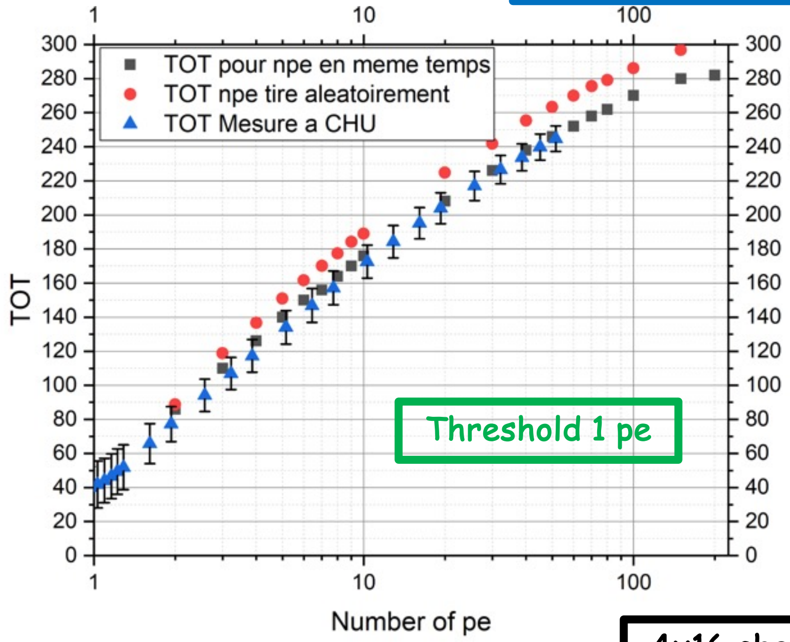
More than 15 fired PMTs with 3γ event
Mainly with a small number of photons
Between 1 and 10 pe/PMT expected
(reflection not considered)

Prompts scintillation XEMIS2 DAQ

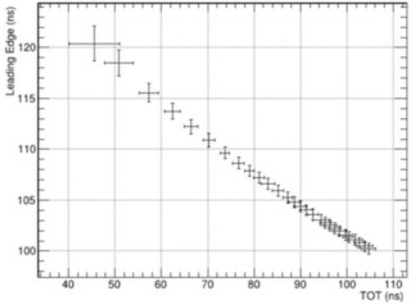
Each PMT is self-triggered, signal digitized with leading and trailing edge times measurement (200MHz)

Serial LVDS link up to SPARTAN FPGA, Continuous DAQ with max rate of 10^6 signals/s/PMTs

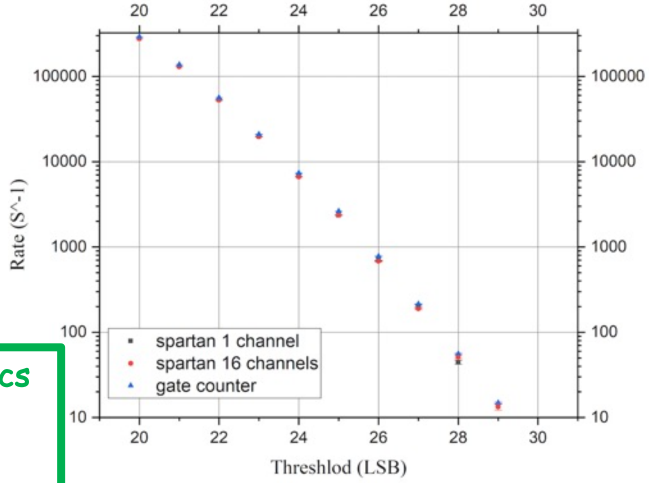
50 Go on disk for 20 mns image at 20 kBq



Threshold 1 pe



σ_t: 2-3 ns from electronics with l_{edge} and TOT correction
Dominated by LXe contribution



Up to 10^6 S1/s/PMT on disk

4x16 channels discrete cards "home made"

Light detection is "cheap" on XEMIS2: ns resolution/evt and 64 channels

Ionization measurement in XEMIS2

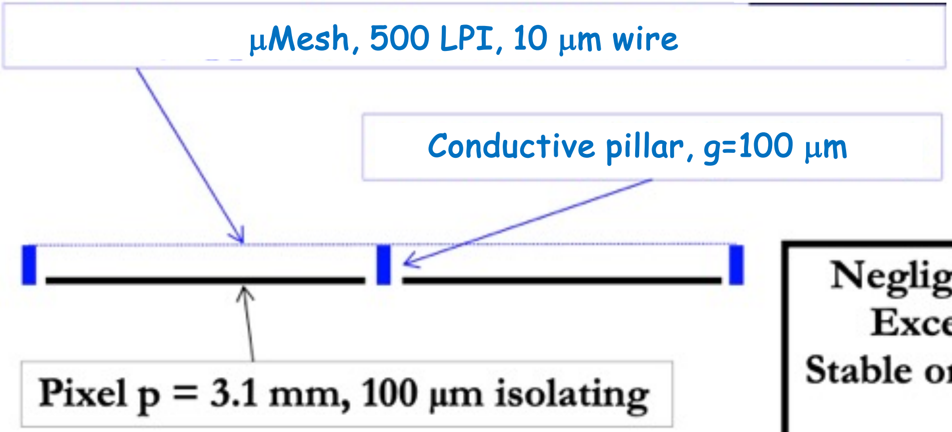
LXe ionization chamber properties very powerful (LXeGRIT, Exo, …) for 10 keV-MeV recoils electrons

Most of experiments use fast digitizers, not realistic for high rate and large number of pixels.

Technical option taken by XEMIS projects: just one sample for charge and one for time

Two main worries: Frish grid efficiency and induction on non-collecting electrodes

Development of new Micro-Pattern electrodes for electron collection



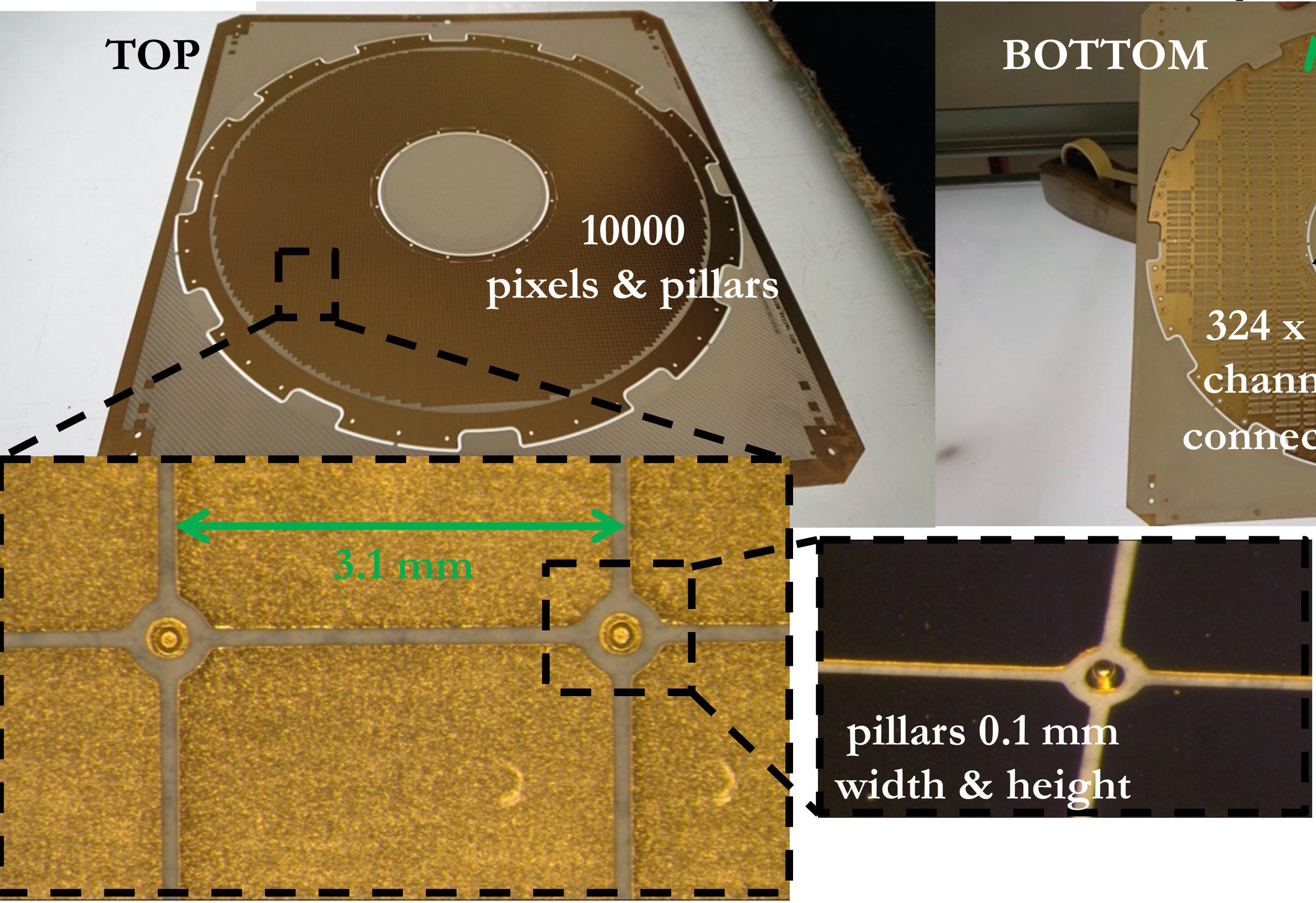
MIMELI

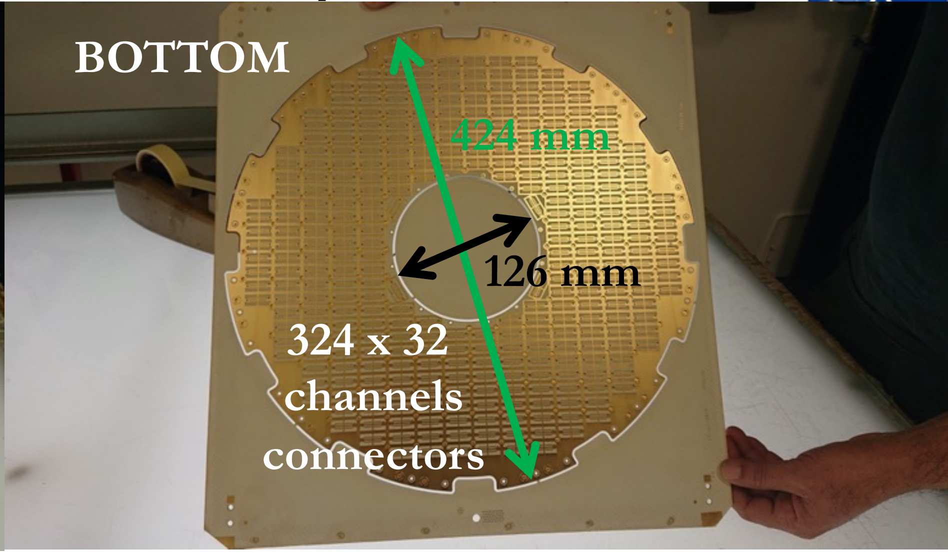
MIcro MEsh for Liquid Ionization chamber

microstructure to stabilize induced current

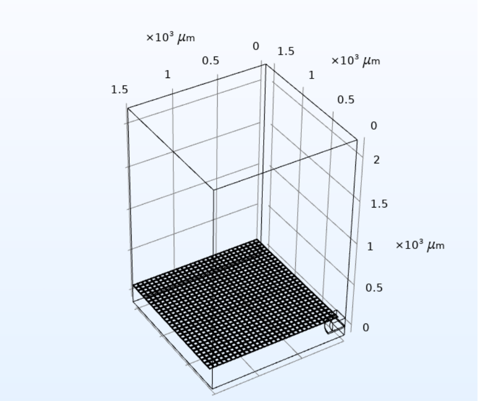
Negligible induction on neighbors pixels (g/p < 5%)
Excellent Frisch grid efficiency (500 LPI μMesh)
Stable on long term (more than 1 year accumulated test)
Scalable on large surface …

XEMIS2 MIMELI anodes fabricated by CERN
Gaseous μPattern detector dpt

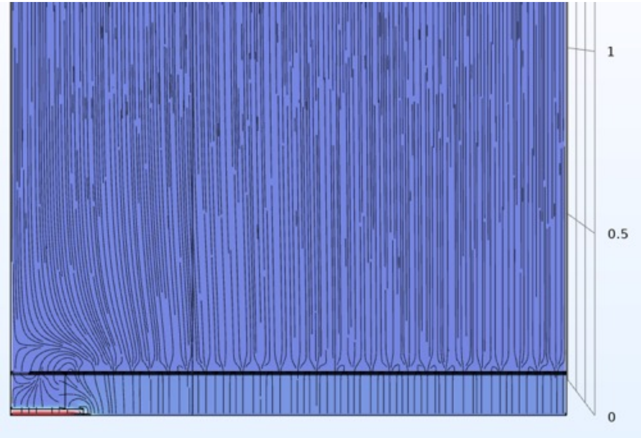


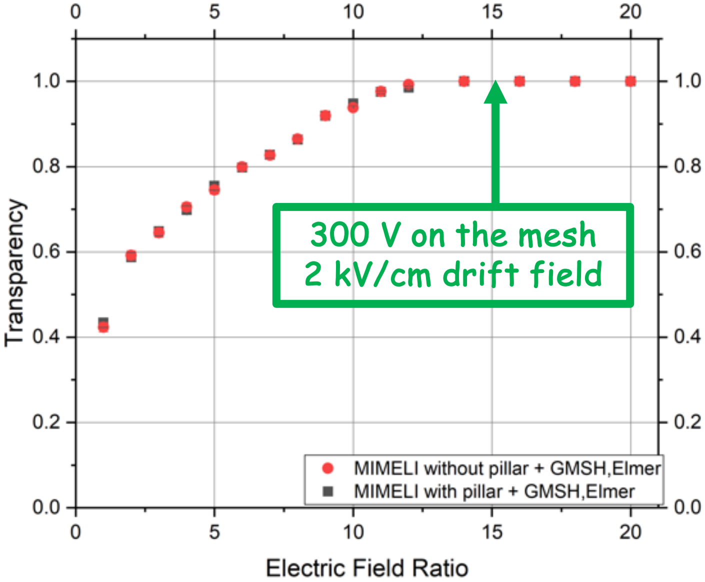


Ionization electrons collection with MIMELI



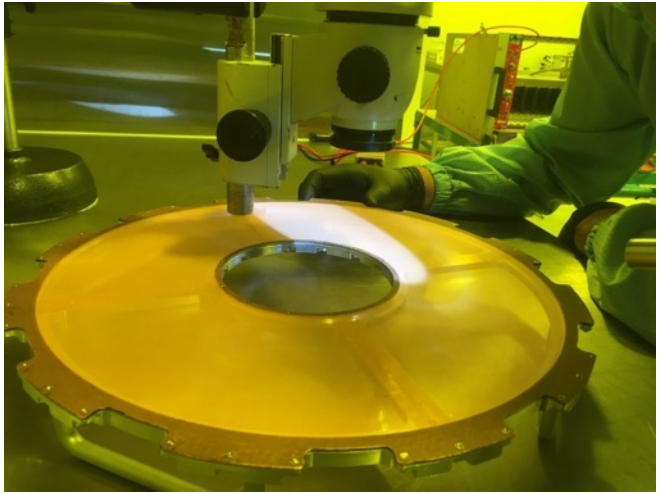
3D finite elements simulation with GMSH, Elmer and Garfield for the diffusion

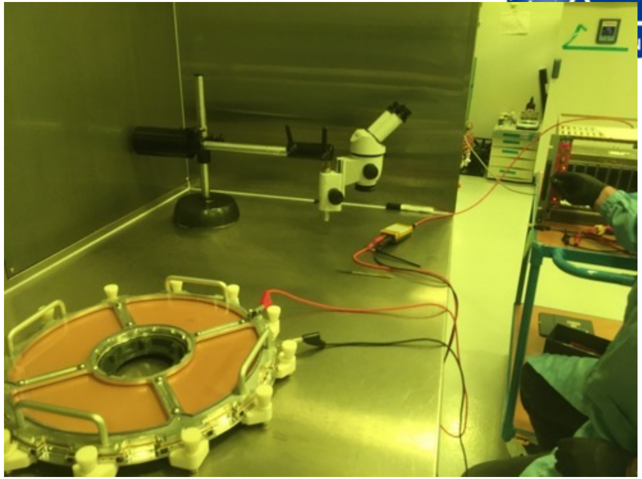




The conductive pillar is so small that it doesn't contribute to electron loss when field ratio is enough to focalize them in µMesh holes

MIMELI Micromesh assembling at CERN





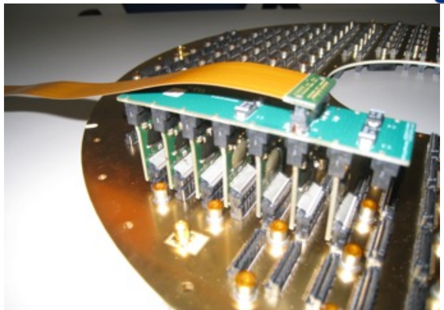
3 main steps:
- Anode and mesh washing with demineralized water
- Baking in high vacuum
- Assembling and HV test on dry air

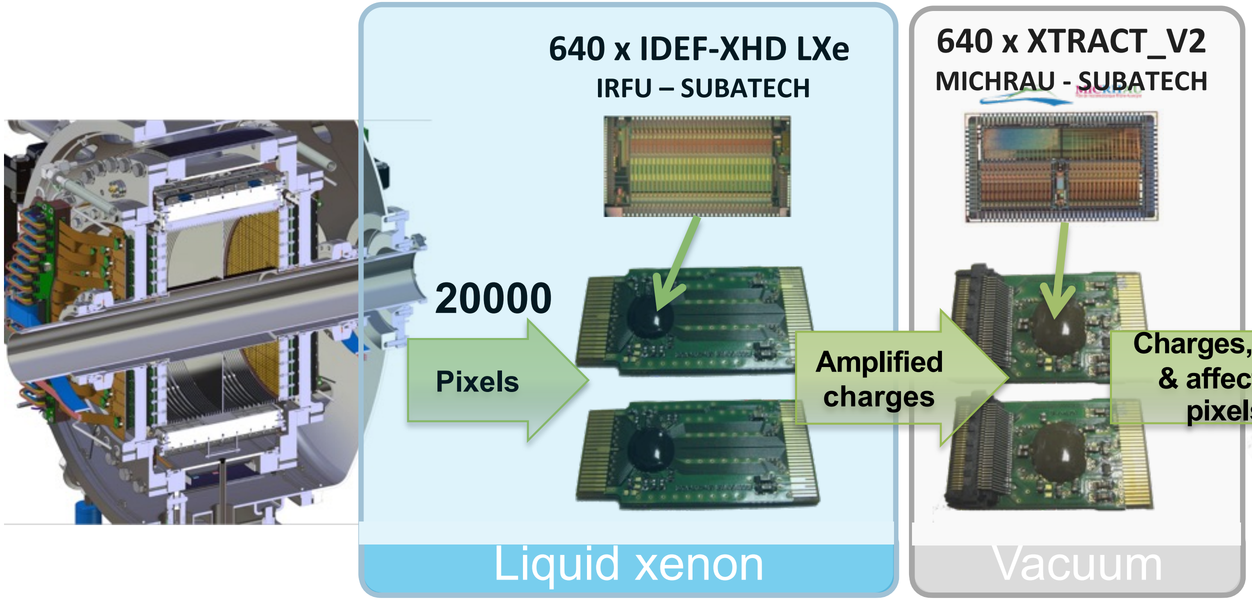
μMeshes with copper GEM-HD geometry also assembled

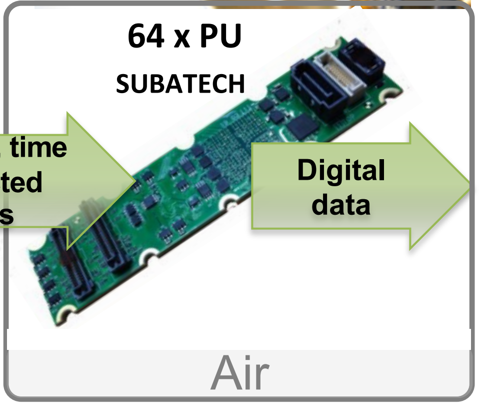
XEMIS2 charge read-out electronics

The known DAQ system cannot meet the requirements for use in LXe

Self-triggered high rate ionization signal readout architecture







Cold Front-end electronic to reduce the electronic noise

only 1 amplitude and 1 time per ionization pulse escape from the cryostat

only 2 data lines/PU escape the vacuum (to the air) for all the measured charges

XEMIS2 charge electronics test bench at Subatech

Test bench at RT with all the chain from Idef-XHD_LXe to storage disc

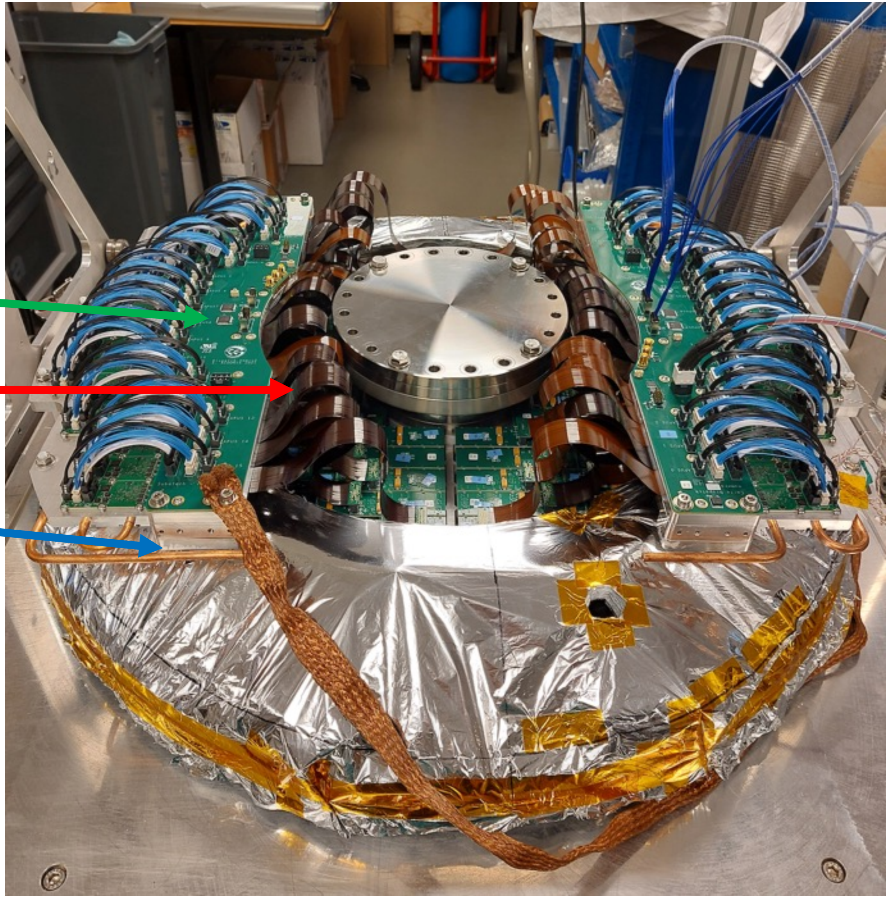
1 End-cap : Around 10 000 channels

32 PU cards in vacuum

Cold electronic to PU card with 32 Stripped Kapton flex

PU cards cooled with external cold water recirculation system (10W expected leak connected on LXe per endcap)

1 Spartan charge per ½ endcap outside the cryostat at RT

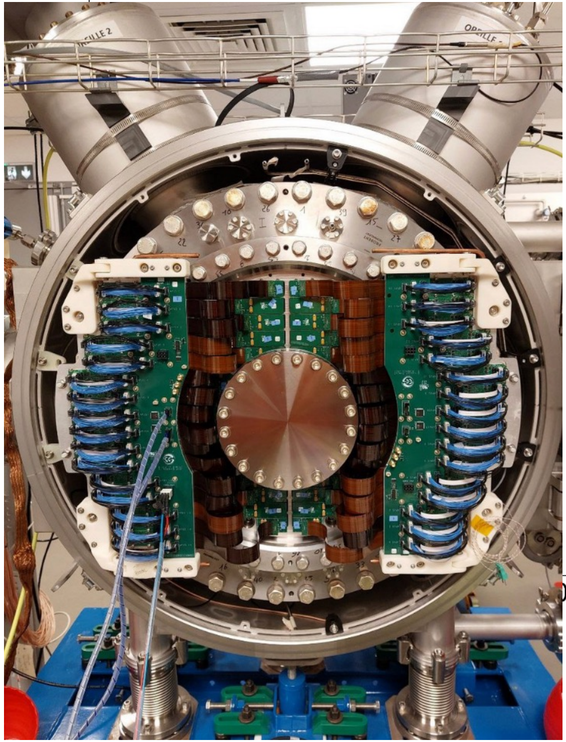


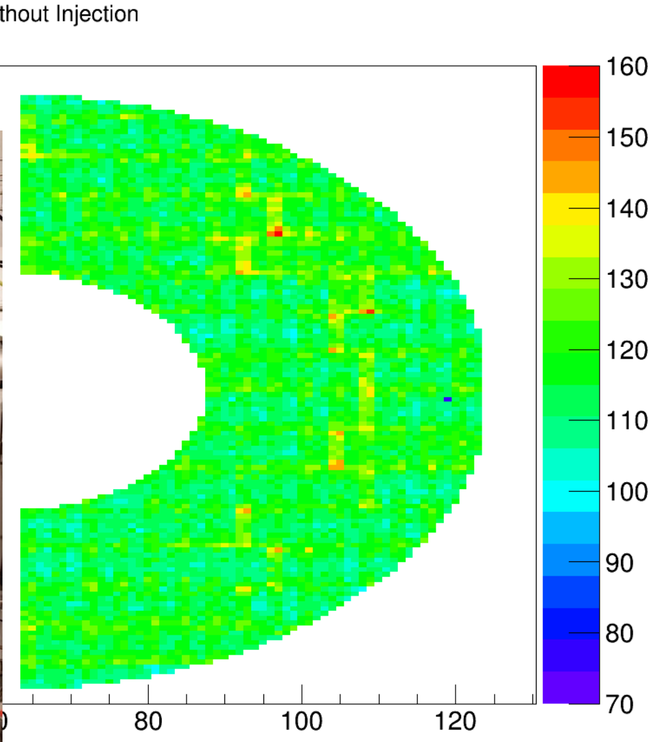
XEMIS2 noise measurement on charge electronics at RT

Used to:

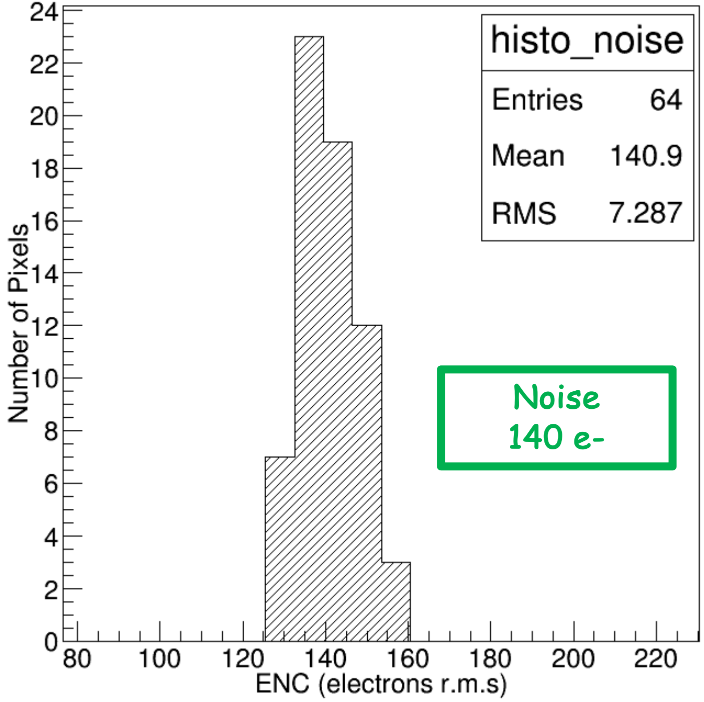
- identify Connectix problem
- identify pick-up
- validate each component before installation inside the cryostat
- test setting and calibration processes
- validate μmesh insulation with 50V DDP in nitrogen chamber

Second endcap currently in assembling

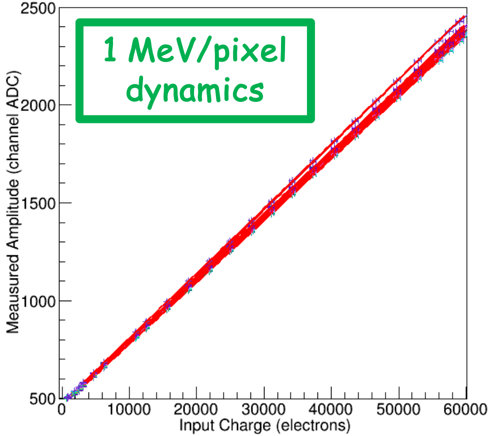


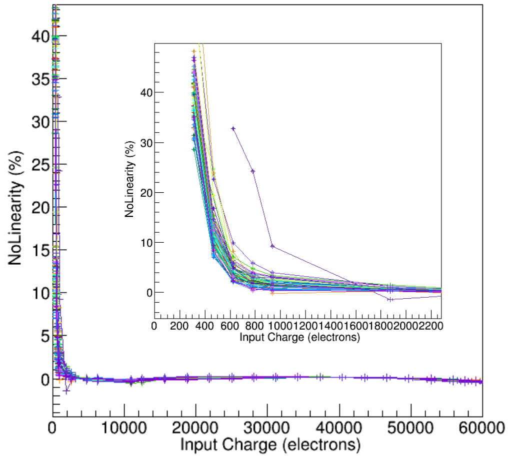


COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm



Charge measurement calibration

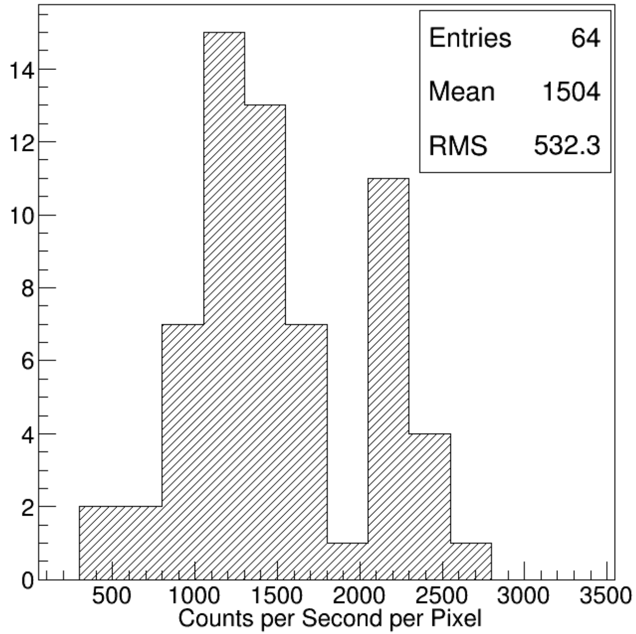


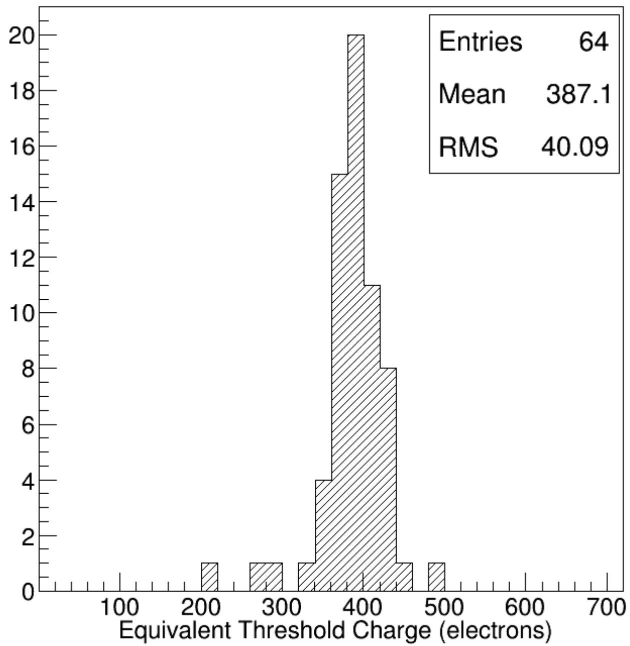


Noise : a little bit more than expected (100 e^-)
Linearity : impressive (less than 1 σ_{noise})

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Rate and self-triggered channels

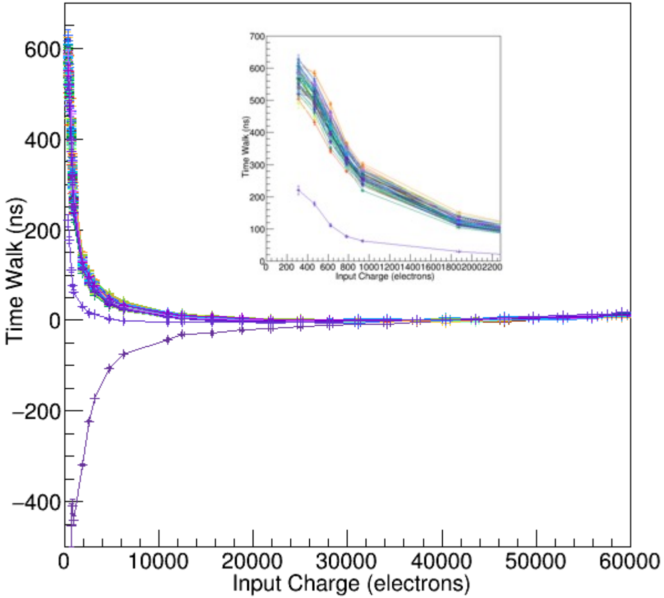




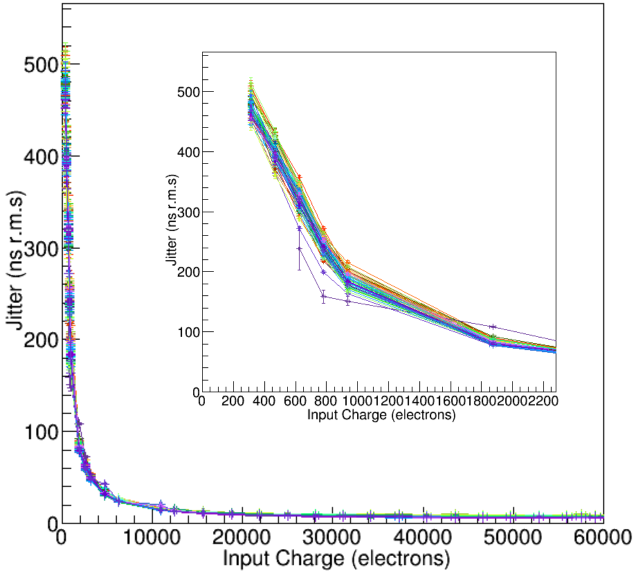
Threshold : close to 3 σ_{noise} on each channels
Counting rate : more than 10^3 ionization/s/p charge and time on disk

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Time measurement calibration

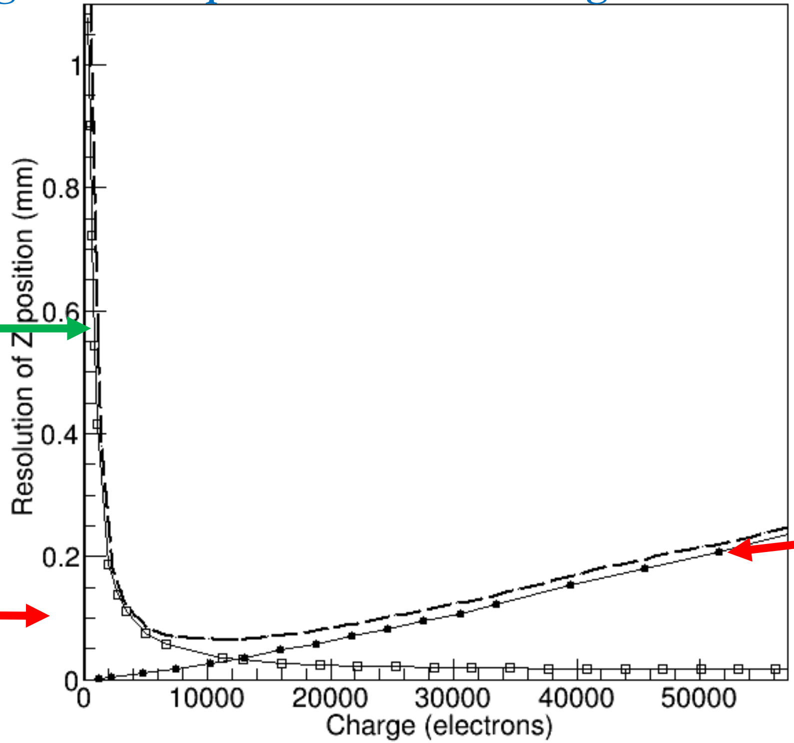


Walk: well understood
Time resolution on charge : up to 10 ns



COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Single scatter spatial resolution along drift direction

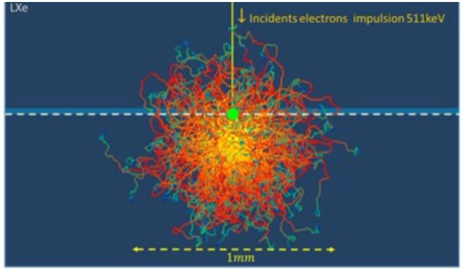


v_{drift} = 2,1 mm/µs
jitter on charge and light contributions

100 microns !

Electron Range contribution

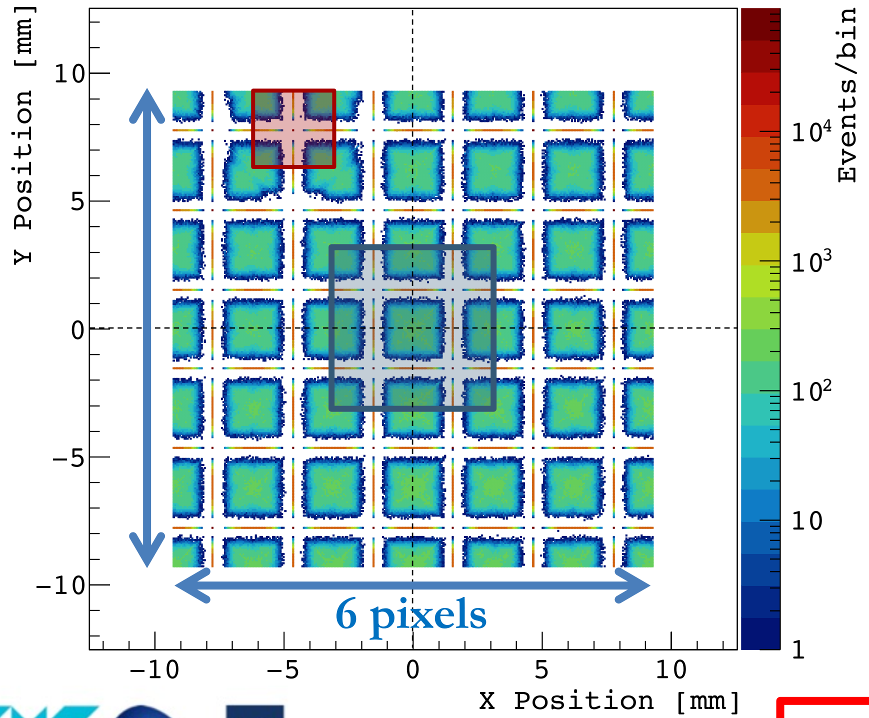
Geant4 v10.4
Electron recoils in LXe
T=511 keV

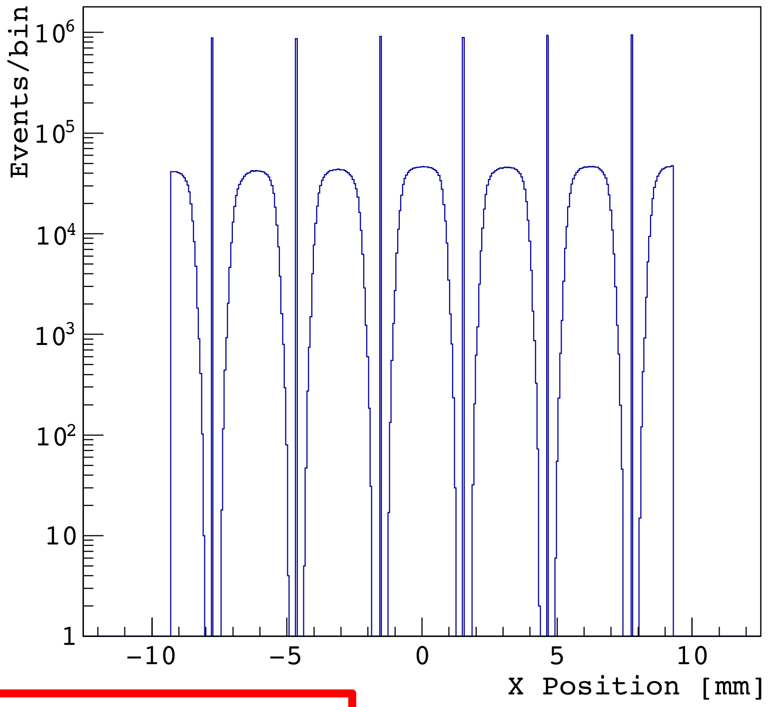


0,1 mm from 4000 to 30000 electrons, ie between 60 and 500 keV

COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

Spatial resolution transverse to the drift direction





100 microns @ 511 keV!

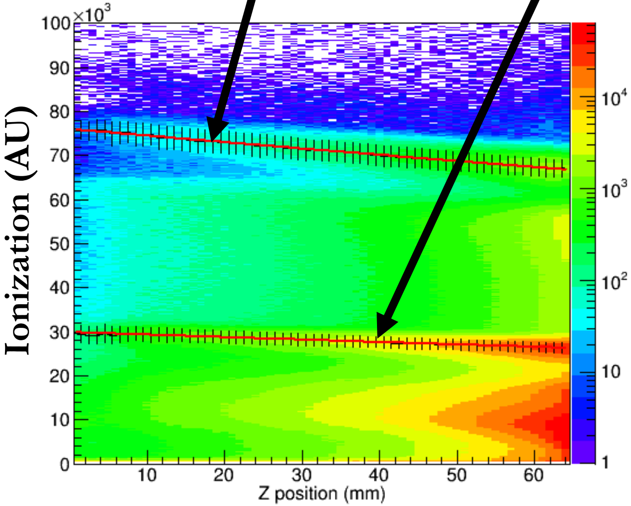
COLD Test with 64 pixels on XEMIS1
MIMELI+Idef-XHD_LXe+XTRACT+PU on XEMIS1 (64 channels)
2 kV/cm

1274 keV

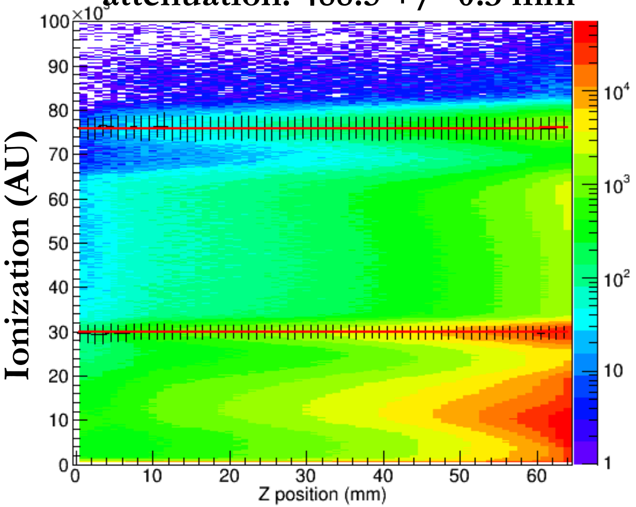
511 keV

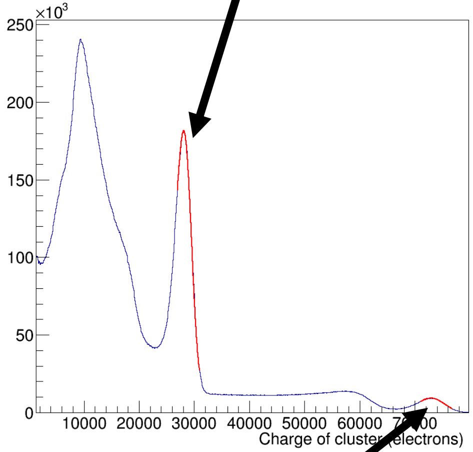
Energy resolution with single scatter and ^{22}Na source

4.78% @ 511 keV



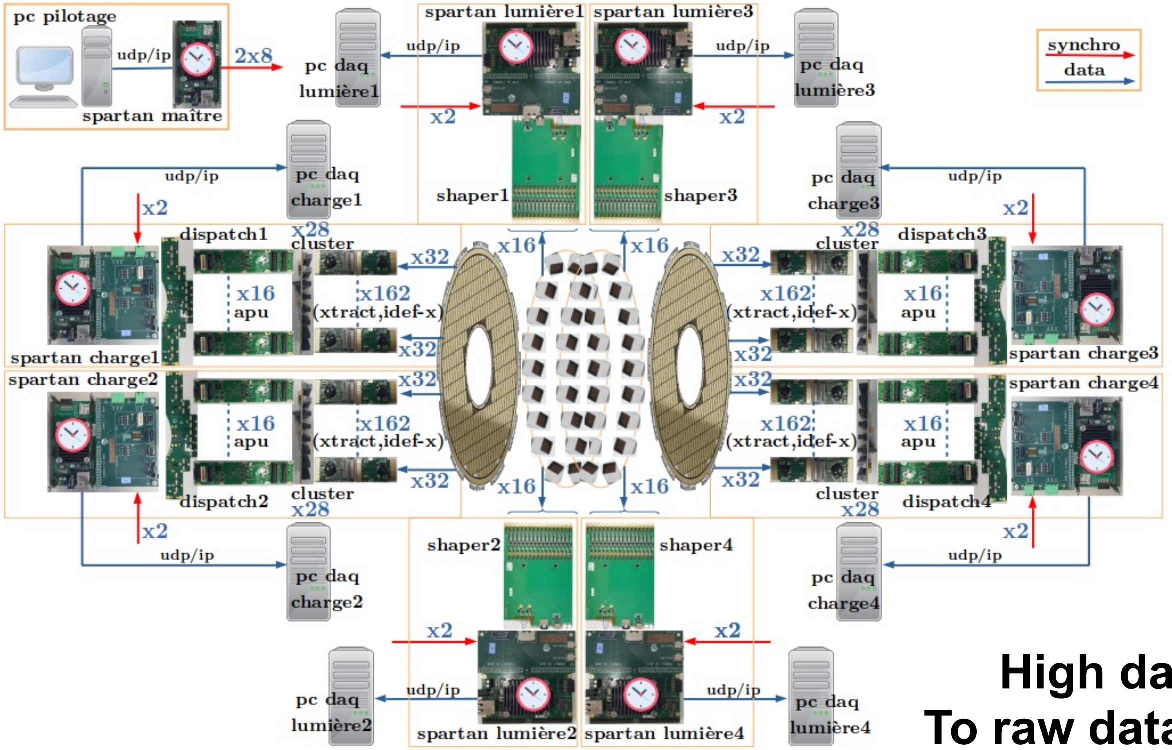
attenuation: 488.5 +/- 0.3 mm





2.81% @ 1274 keV

XEMIS2 DAQ
From detector to disk



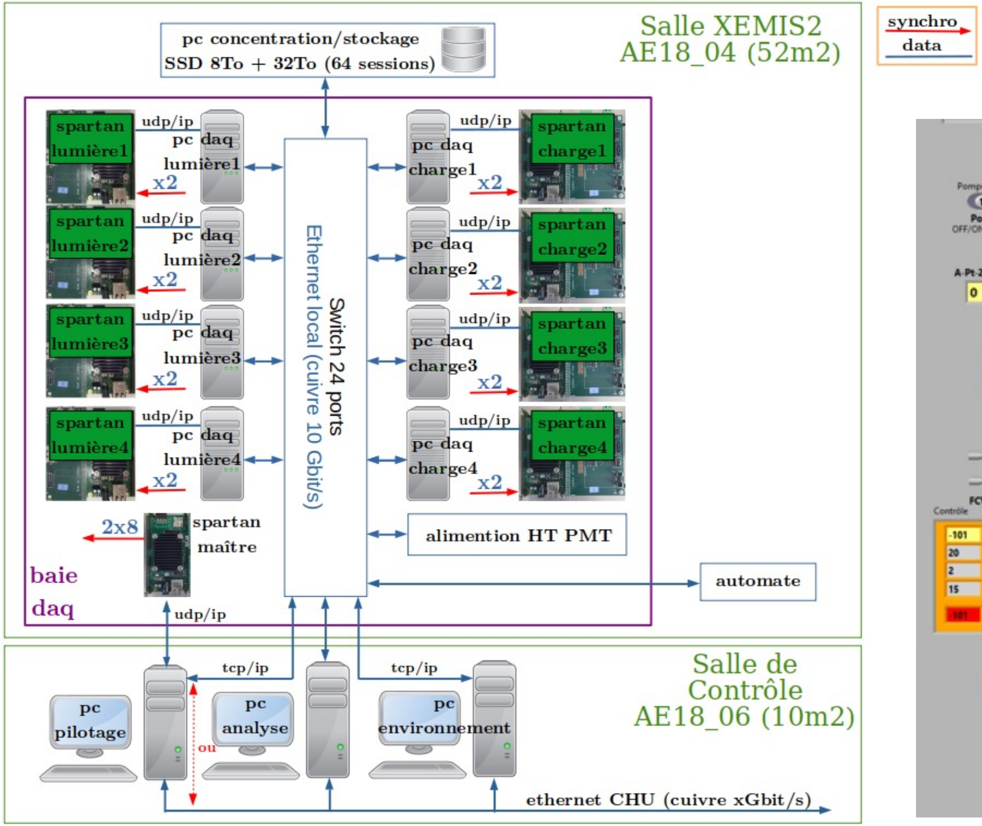
Synchronization with 200 MHz clock
No external trigger
Hardware synchronization
with 1 clock and 1 start signals

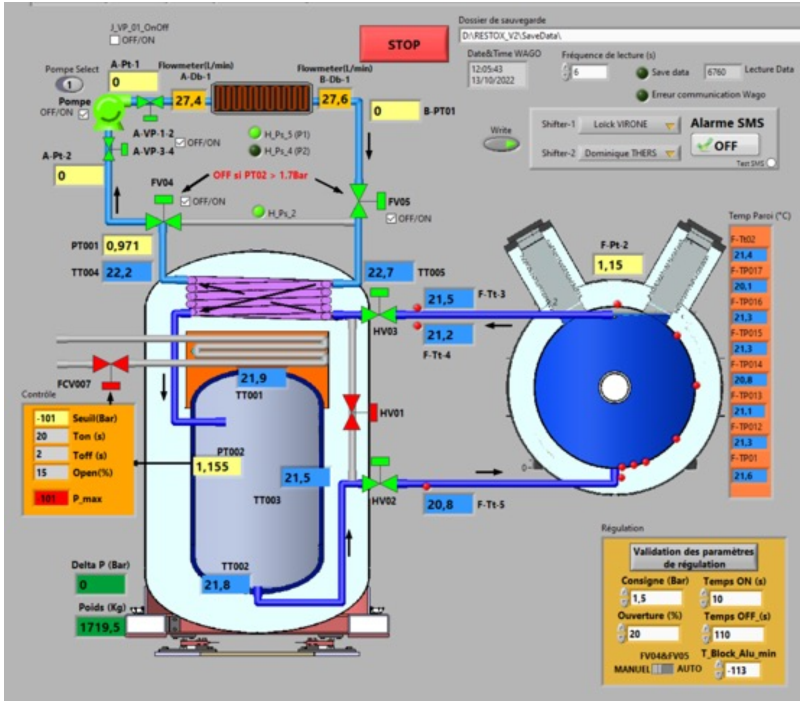
Light signal:
leading edge and TOT up to 1 Mevts/s per channel on 64 self triggered channels

Charge signal:
time and amplitude up to 3 kevts/s per channel on 20k self triggered channels

High data flow rate and transfer:
To raw data expected on disk in 20 mns

XEMIS2 DAQ infrastructure at CIMA



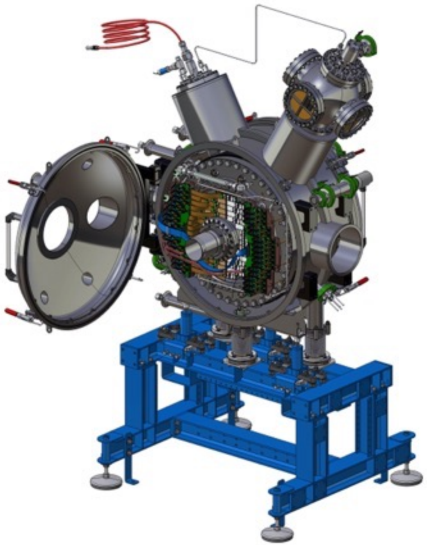


XEMIS2 DAQ is ready

XEMIS2 phase 1, research program

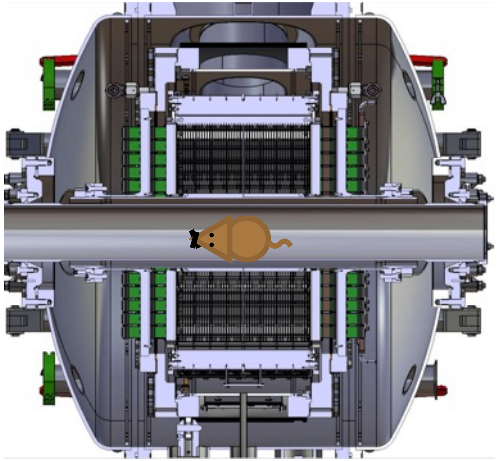
In collaboration with Air Liquide,
Nantes INSERM CRCINA and Nantes GIP ARRONAX

3γ image with 20 kBq of ^{44}Sc activity in the Field of View



XEMIS2 technology

First Monolithic Compton telescope dedicated to medical imaging



Timeline : camera closed for the end of 2023

XEMIS2 contains specific ASICS