4th AGATA-GRETINA/GRETA
Tracking Arrays Collaboration Meeting

HPGe crystal research at LNL-INFN

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OUTLINE

- Introduction: HPGe gamma detectors
- Gamma detector state of the art
- *PLM (Pulse Laser Melting):* Next generation of segmented contact/junction on HPGe detectors
- PLM Planar gamma segmented detectors
- PLM Coxial gamma segmented detectors
- Neutron damage in PLM planar segmented detectors

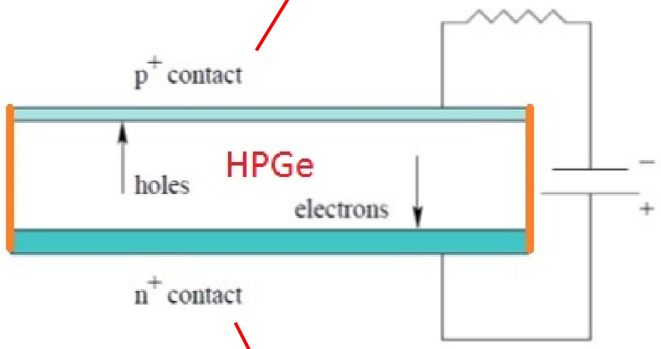
Schematic HPGe planar gamma detector

HPGe

Charge carrier density: 10^{10} cm^{-3}

Surface passivation:

B doped = **0.3 µm**
(implantation)

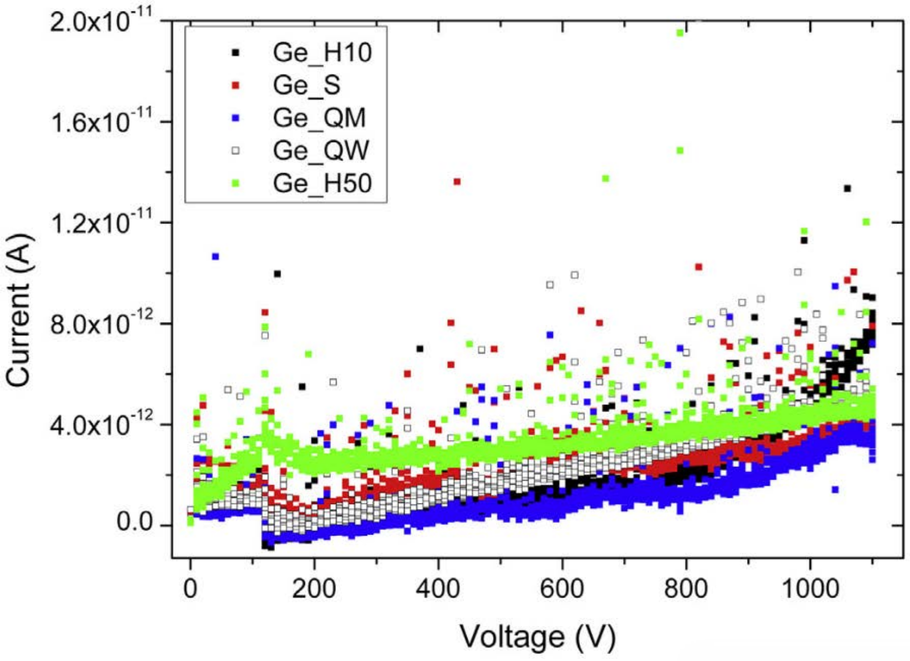


Li doped = **0.9 mm**
(diffusion)

Chemical passivation:

HNO_3/HF (3:1) etching and quenching bath:

- Water (Ge_W)
- Methanol (Ge_QM)
- Sulfide termination (Ge_S)
- Hydride termination (Ge_H10)



S. Carturan et al., **Mater. Chem. Phys.** 2015

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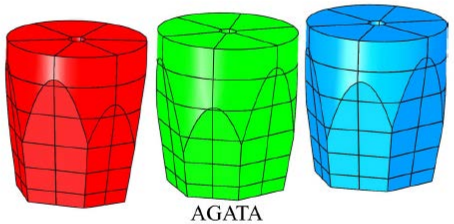
Gamma detector state of the art (AGATA and GRETA)

Encapsuleted coaxial HPGe n-type detectors

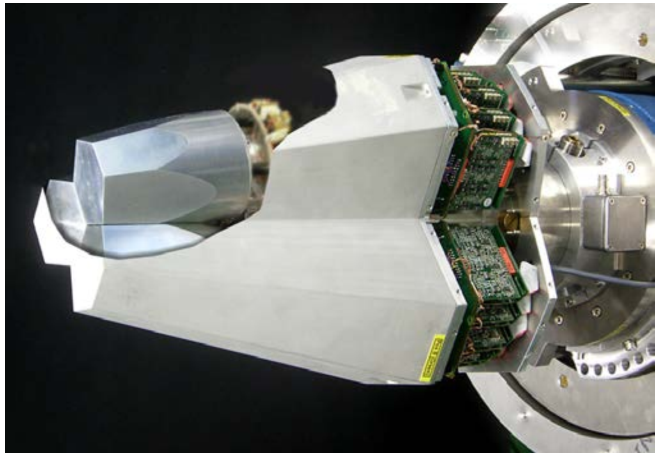
- 2Kg weight
- 80 mm diameter
- 90mm long
- 1 core inner contact
- 36 segments

3 asymmetrical HPGe detector (AGATA)

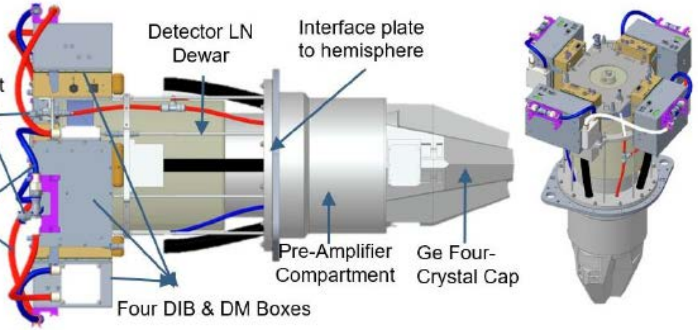


J. Eberth et al. **Eur. Phys. J. A** (2023) 59: 179

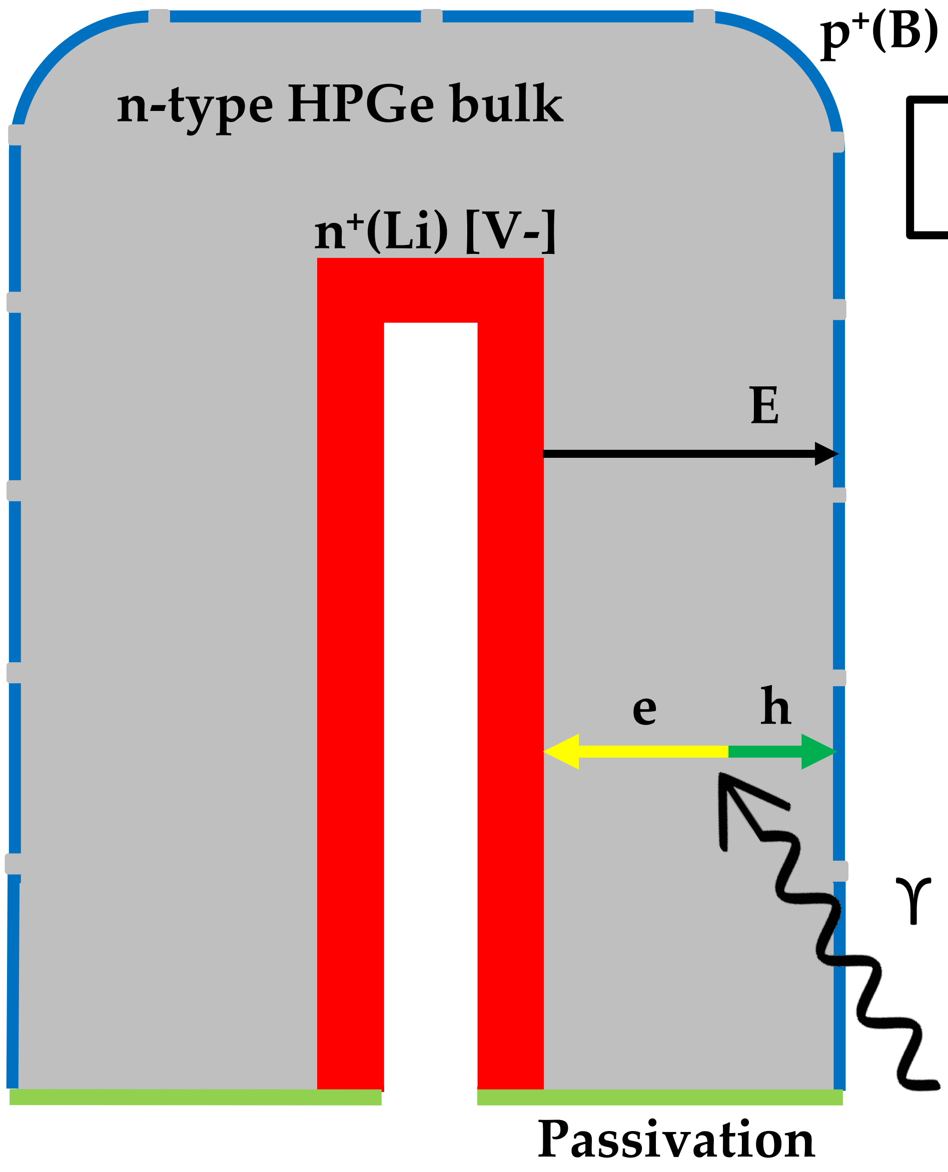
ATC (AGATA triple cluster detector)



GRETA (Quad Detector Module)

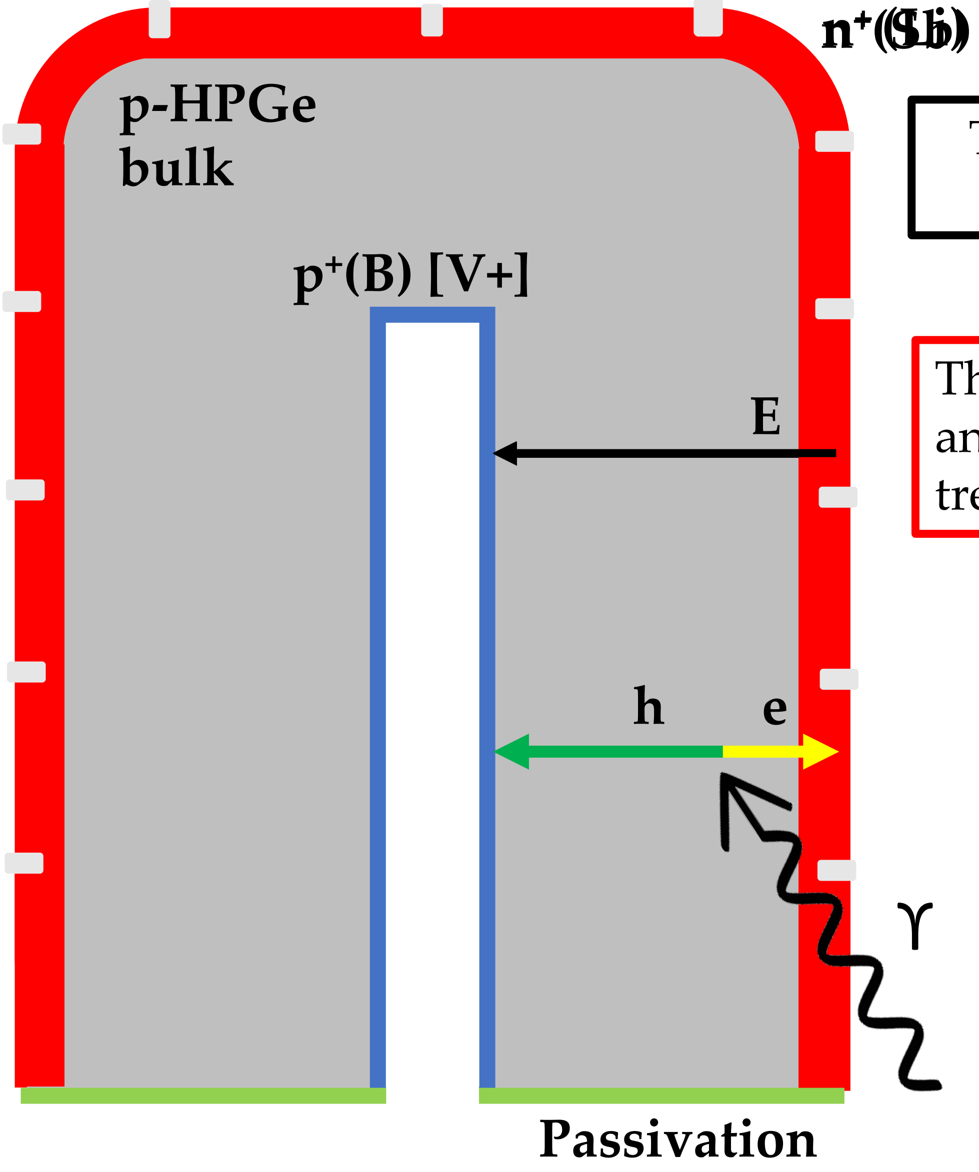


*Schematic coaxial segmented **n-type** detector*



The boron junction is thin,
and easily segmentable

*Schematic coaxial segmented **p-type** detector*



The boron junction is thin, and easily segmentable

Polarity inversion demanded to test higher damage resistivity (hole trapping by neutron damage)

The lithium junction is thick and not stable under annealing treatments

J. Eberth et al. **Eur. Phys. J. A** (2023) 59: 179

Thin and thermally stable n-type dopants (**Pulsed Laser Melting**).

p-HPGe with segmentable n+ junction collecting electrons.

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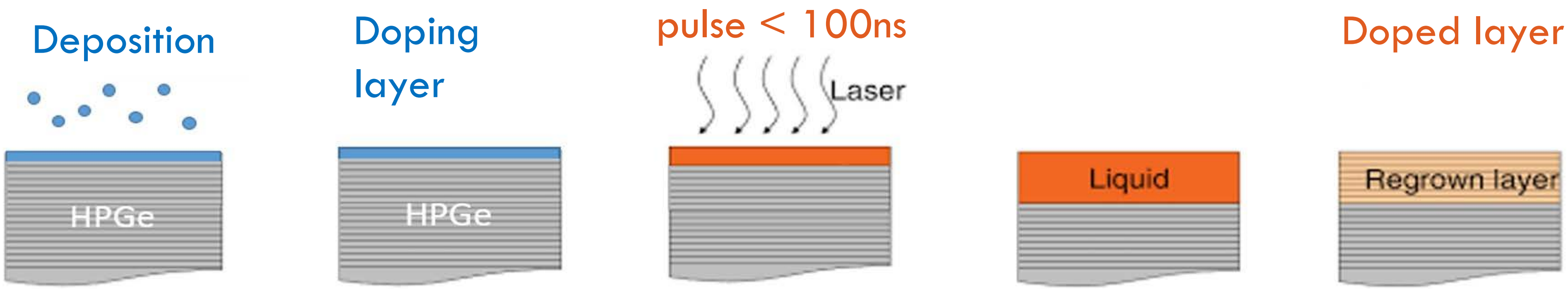
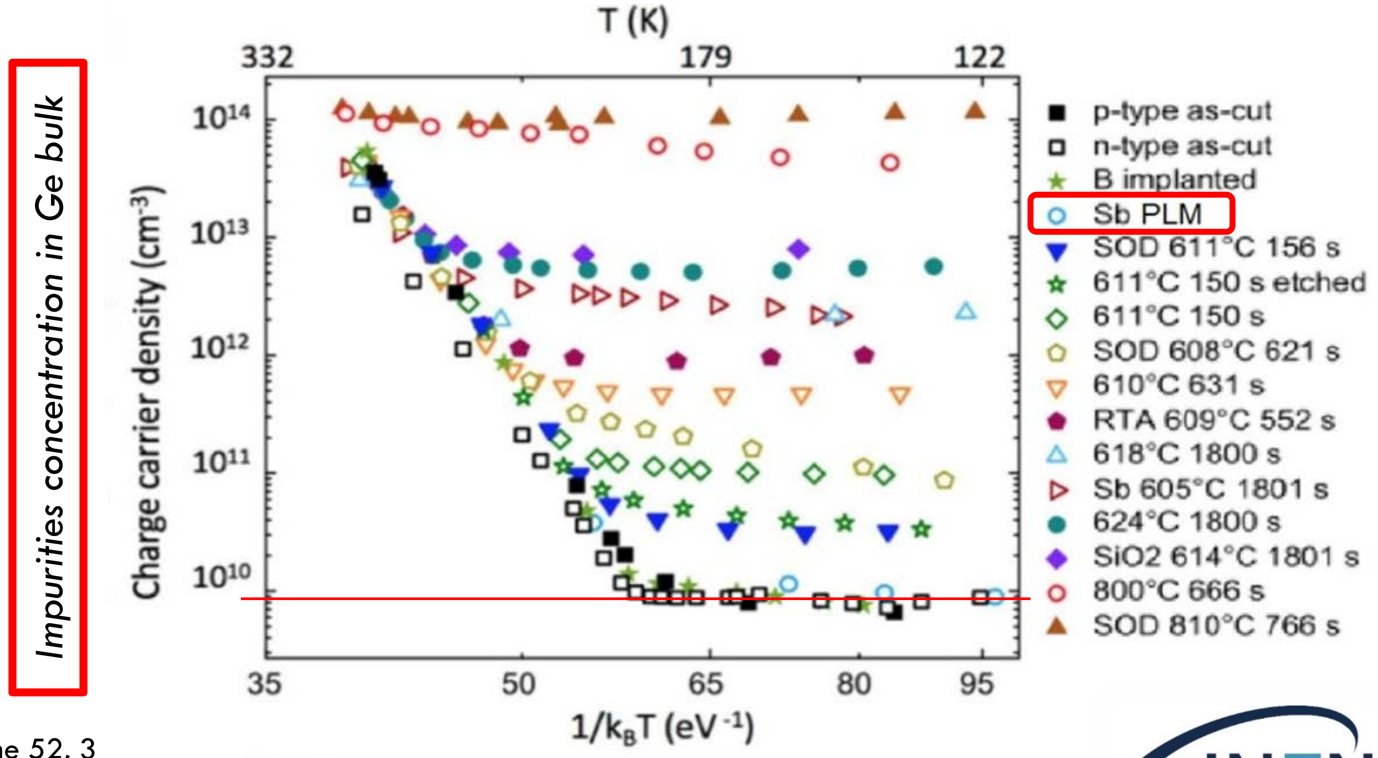
New contact/junction on HPGe: PLM (Pulse Laser Melting)



Advantages:
- Melting temperature is reached - short time (<100 ns)
- Only the surface (< 200 nm) is melted, the bulk is at room temperature
- High dopant concentrations with very sharp dopant profile
- Doping with heavy elements without crystal damage
- Very clean process suitable for preserving the Ge hyperpurity
- Suitable for complex contact geometries (**segmentation**)



V. Boldrini et al., **Journal of Physics D: Applied Physics** (2018) volume 52, 3

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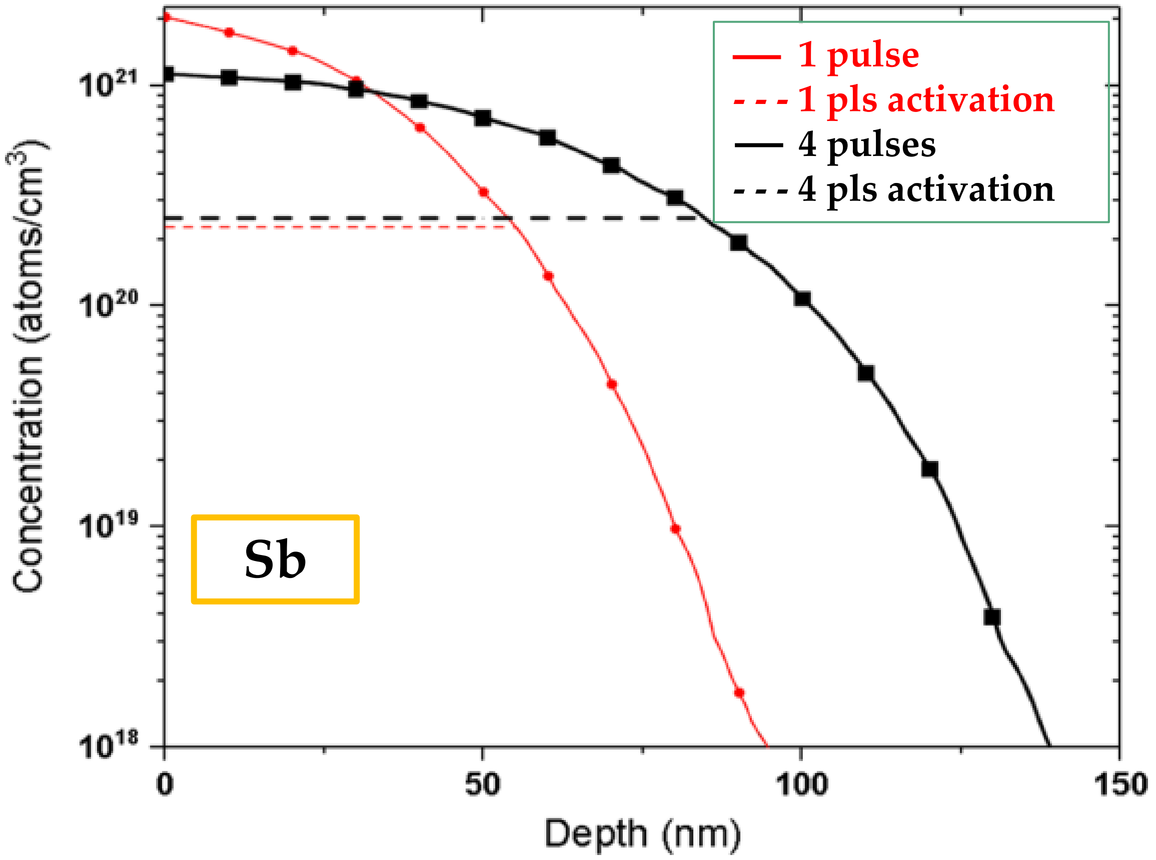
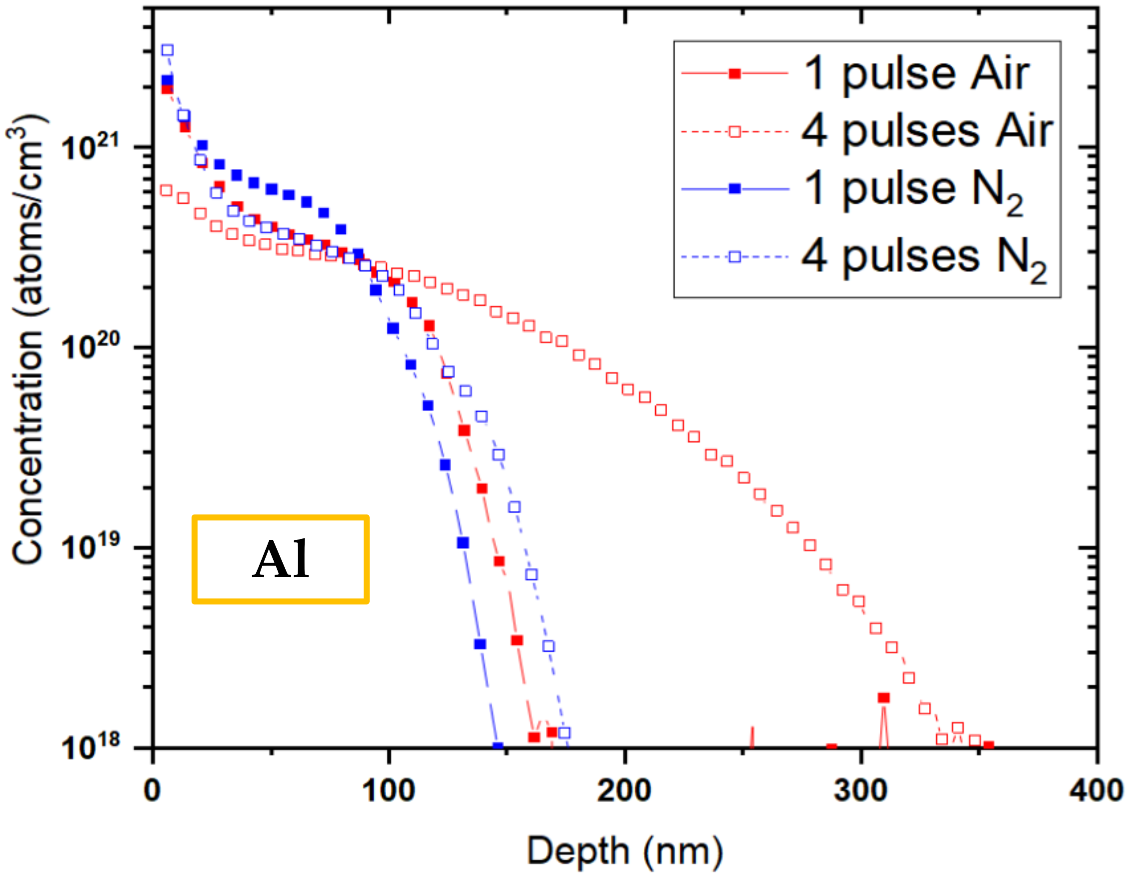
New contact/junction on HPGe: Chemical concentration profile

SIMS (Secondary Ions Mass Spectrometry)





S. Bertoldo et al., **Eur. Phys. J. A** (2021) 57:177
J. Eberth et al. **Eur. Phys. J. A** (2023) 59: 179

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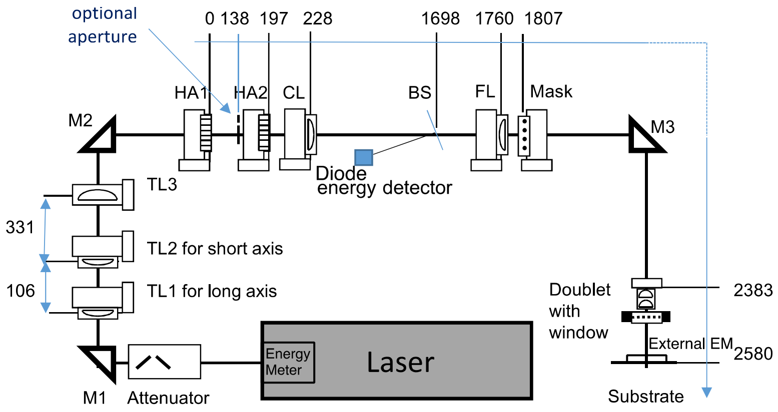
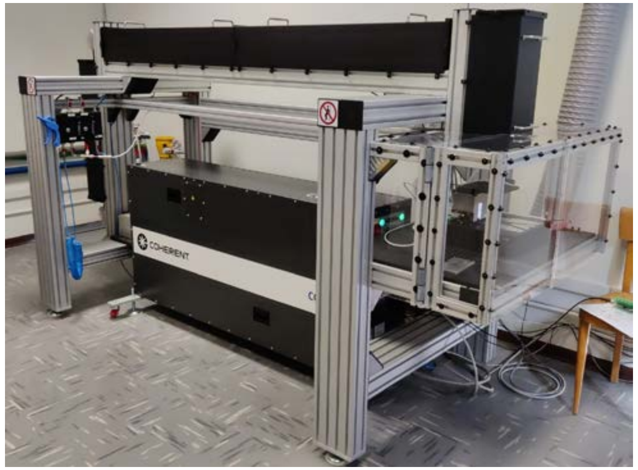
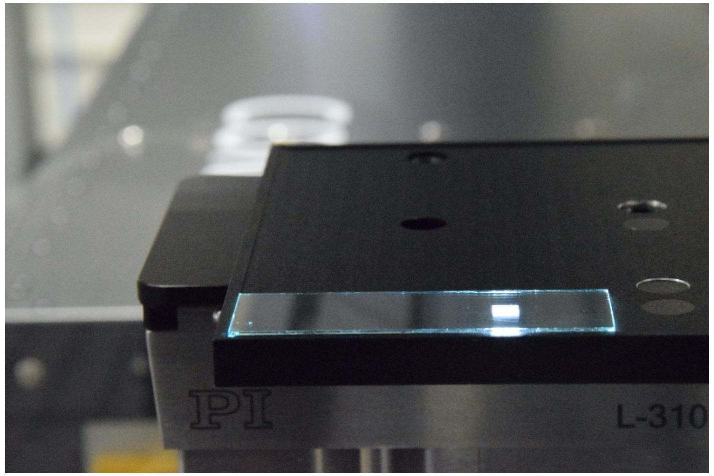
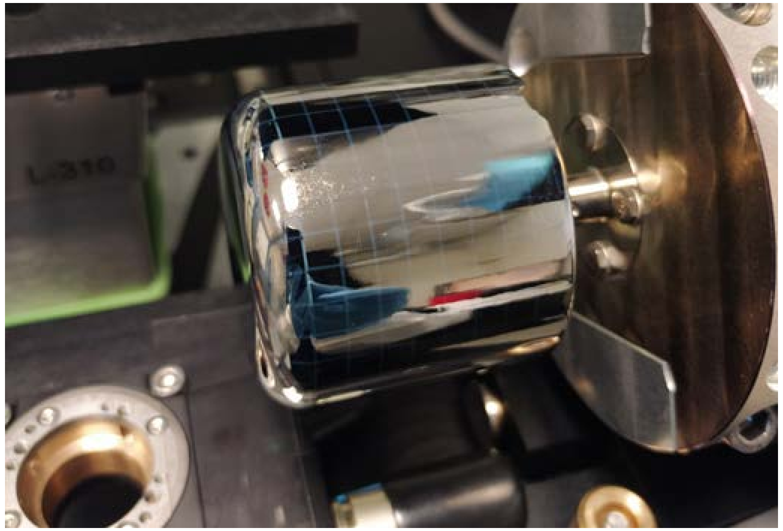
New contact/junction on HPGe: PLM Laser tecnology

Excimer KrF laser









- λ=248 nm, 22 ns
- Frequency: 1-10 Hz
- ED= 50-1300 mJ/cm^2
- Square 5x5mm^2 spot
- Homogeneity: < 2%
- lateral resolution <30 μm
- Motorized XYZ stage

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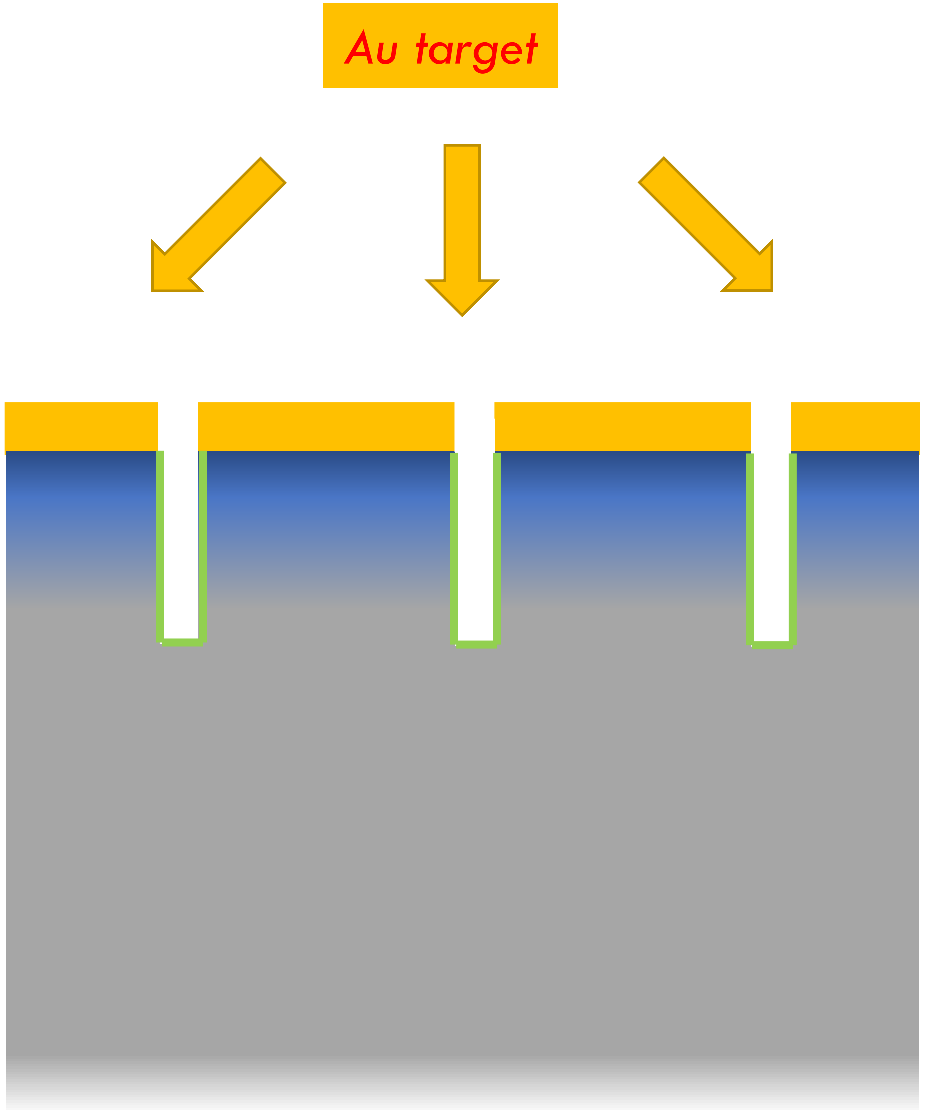
PLM contact/junction: 1° type Segmentation

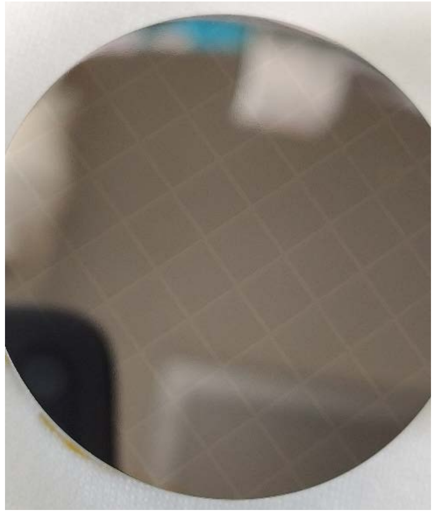


Full area ⇐ **PLM**

Au deposition
100 nm PVD deposition of Au in Ar plasma with ultrapure target in vacuum (10^{-6} mbar)

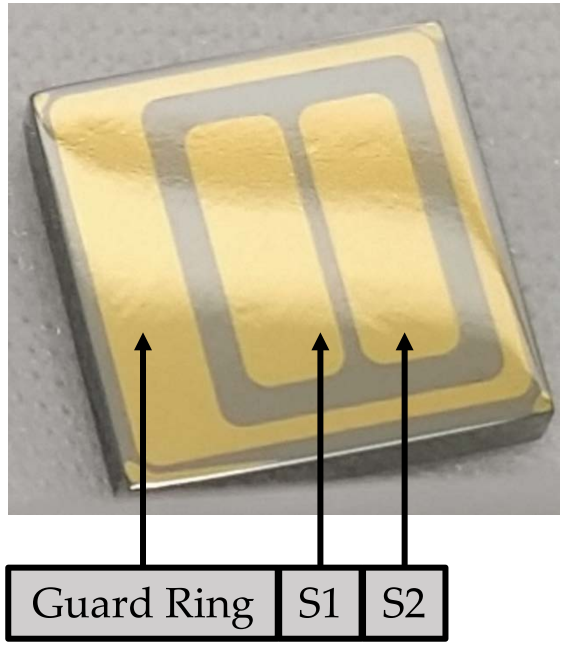
Photolithography
Photoresist deposition, baking, exposure and development, followed by Au stripping and resist removal.

Intercontact gaps passivation
(3:1) HNO_3 : HF etching followed by chemical quenching passivation.



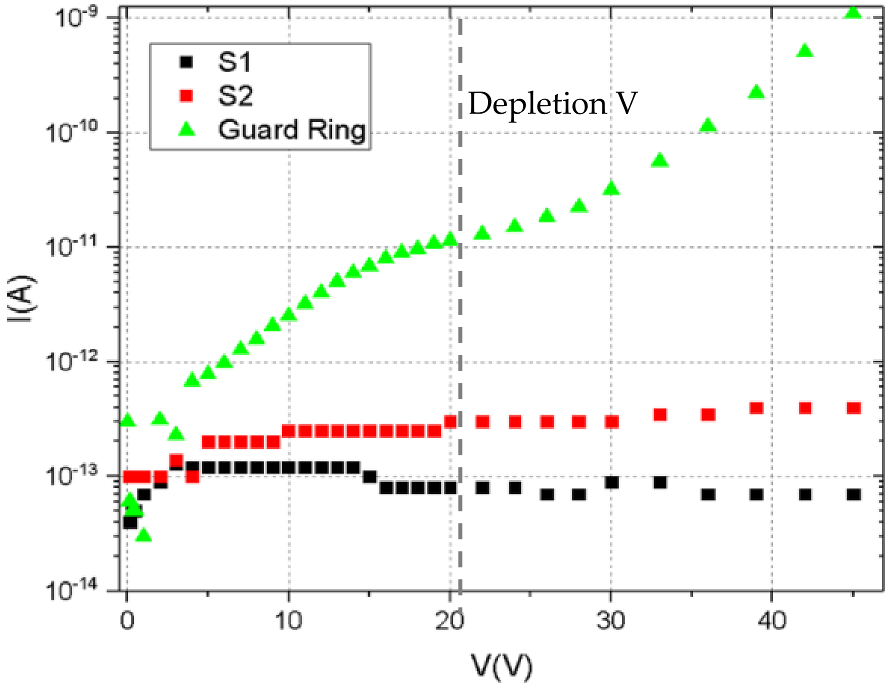
Thin planar HPGe detectors

Sb n^+ junction, p-type HPGe, B p^+ L=10mm, t=2mm



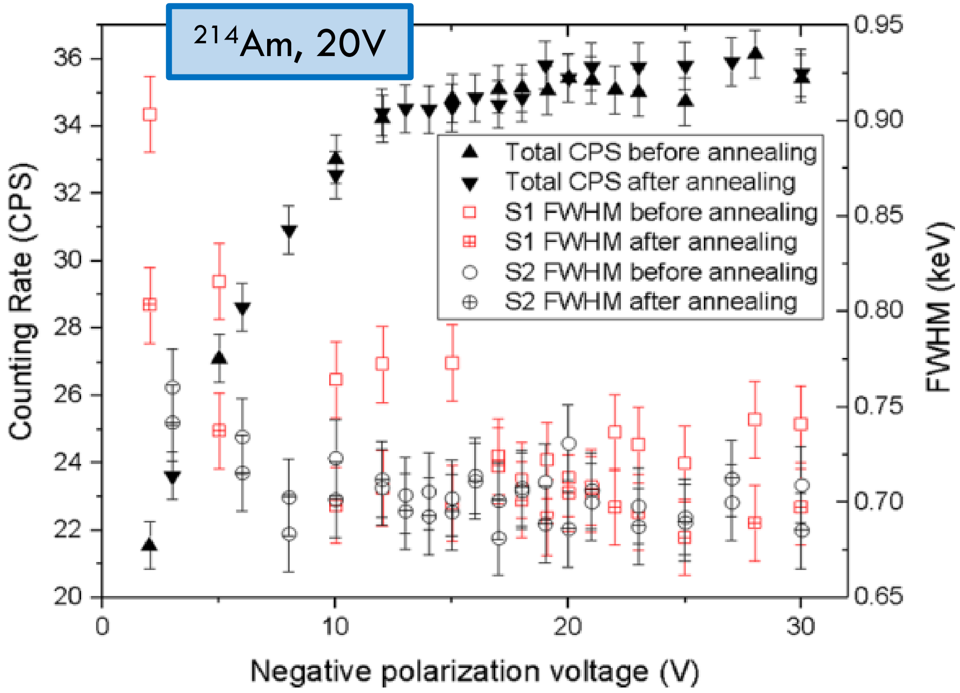
Measured before and after recovery annealing and re-passivation to test junction stability

Electrical test: reverse I-V characteristics



Gamma ray test: 241Am spectra acquisition

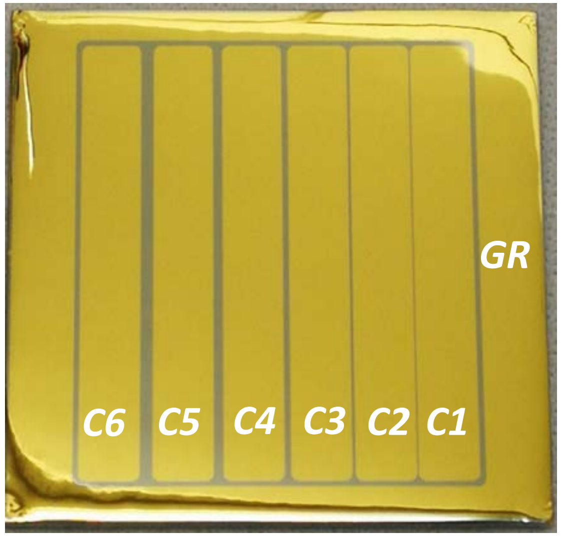
Annealing at 105°C



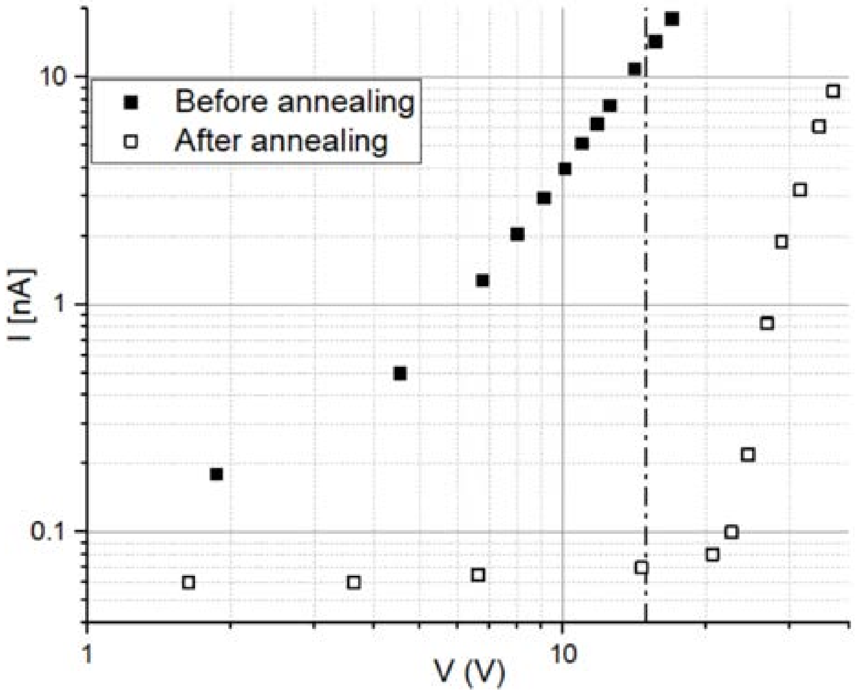
S. Bertoldo et al., **Eur. Phys. J. A** (2021) 57:177

Thin planar HPGe detectors

Sb/p-HPGE/Al, L=35mm, t=2mm



Minimum gap tested 0.1mm



^{133}Ba, 20V

E=80keV
FWHM=0.89keV

E=356keV
FWHM=1.19keV

Before annealing
After annealing

W. Raniero et al., **Il NUOVO CIMENTO 44 C** (2021) 154

PLM contact/junction: 2° type Segmentation

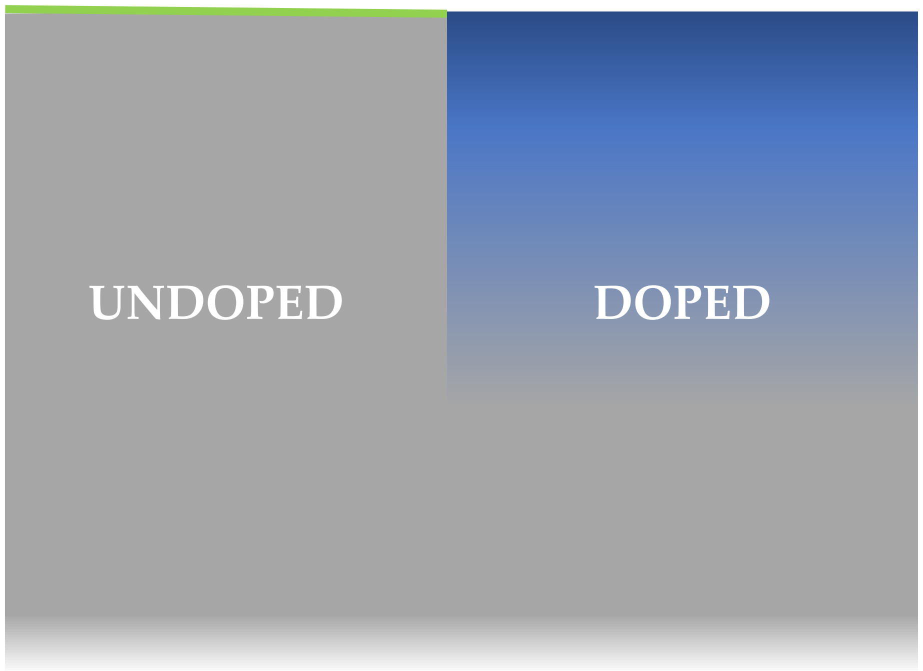
PLM ⇨ **Partial area**

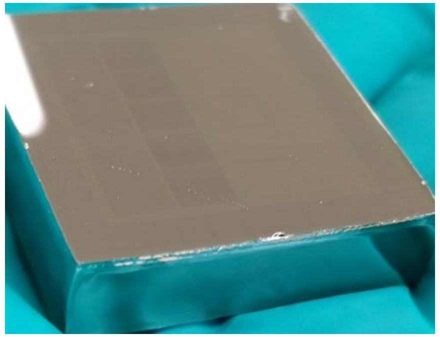
Selective etching
Removal of untreated dopant using selective etchants to protect the near junction.

Chemical passivation
Passivation of undoped surfaces with suitable solutions.

Lithographic process using selective etching solutions:

- Hot pure H_2SO_4 for Sb deposition (preserve Sb junction)
- H_2O_2 for GeP deposition (slowly etches everywhere)
- Kern solutions (H_2O_2, H_3PO_4, Ethanol) for Al-Ge deposition (preserve Al junction)



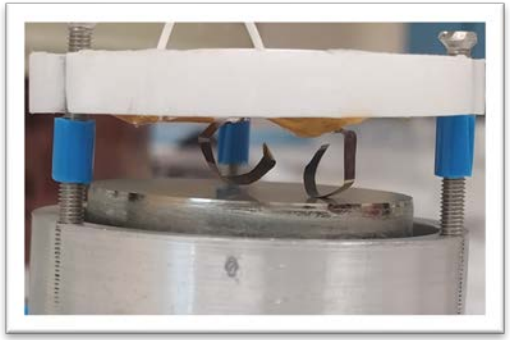


Thick planar HPGe detectors

Sb/p-HPGE/Al,
L=35mm, t=10mm

n+ junction
(*spring contact*)

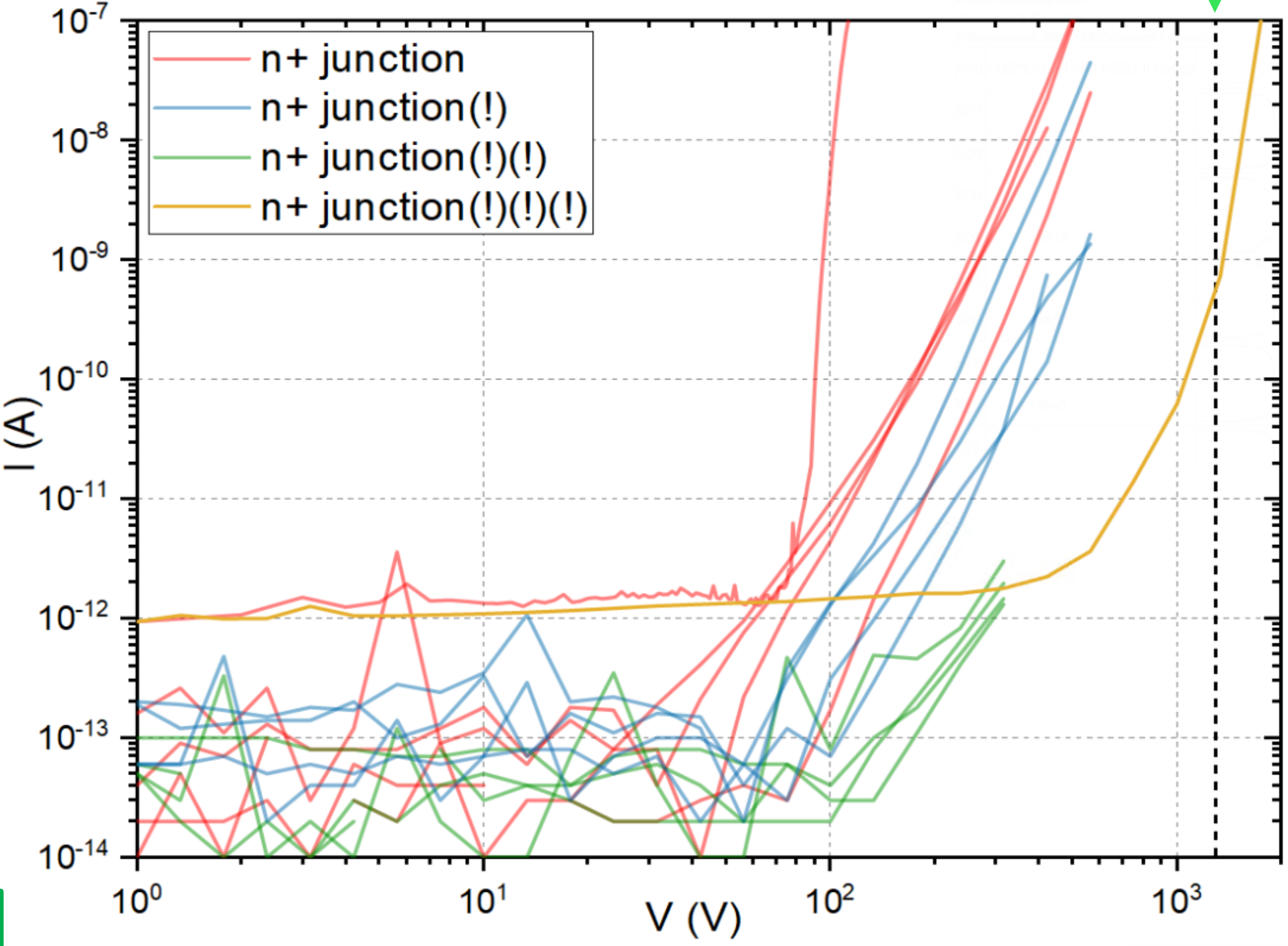
n+ junction (!) / (!)(!)
(*indium pad*)



n+ junction (!)(!)(!)
(*elastic tabs*)

Sb/p-HPGE/Al,
D=40mm, t=20mm

$V_{depl.}$: 1300V



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Coaxial Photolithography: Robot 3D

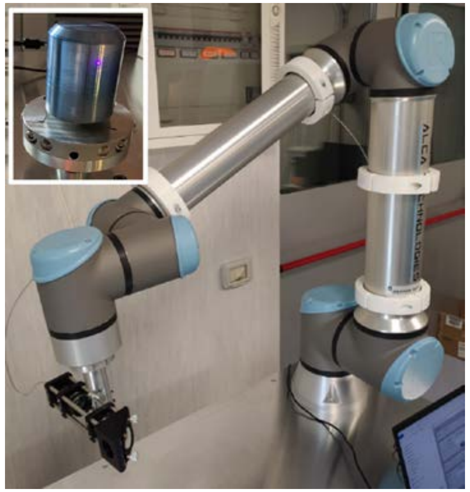
The laser micrometer measures the surface after a rotation of the coaxial detector while keeping the robot in the same position

Coaxial Dummy

Misalignment of the segmentation lines at the top of the sample

The error is non-reproducible and is caused by the gripping system of the coaxial detector and the hole in the crystal itself

3D mapping of the coaxial detector and obtaining its coordinates relative to the robot's coordinate system with an accuracy of less than 0.1mm



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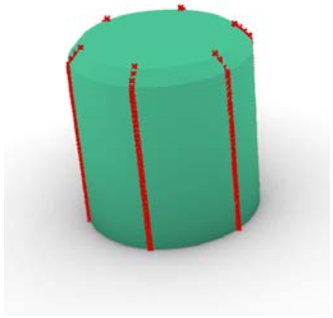
Coaxial Photolithography: Robot 3D

1

2



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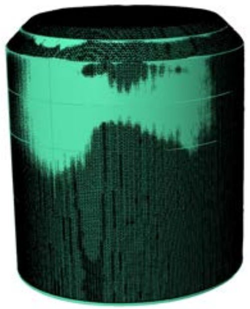

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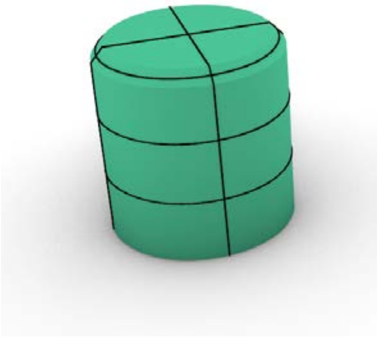

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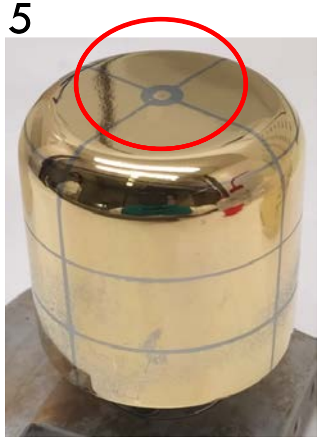


1. Mapping of the cylinder through vertical lines: line formed by a series of points
   Each point is determined by the robot's position + laser micrometer measures

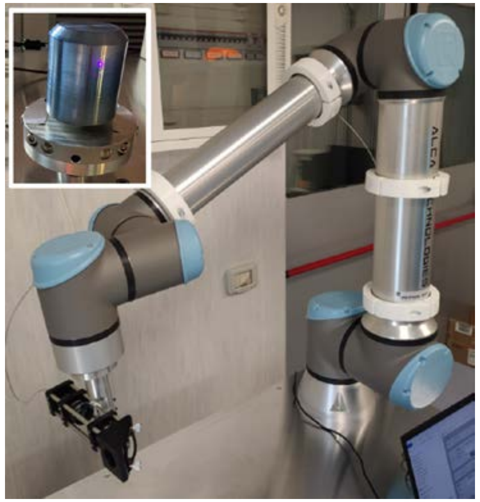
2. 3D reconstruction via lofting technique.

3. Comparison with a professional 3D scanner , Accuracy <0.1mm.

4. Construction of the pattern to be lithographed in the robot's coordinate system

5. Photolithography carried out by the robot

UV photolithography robot

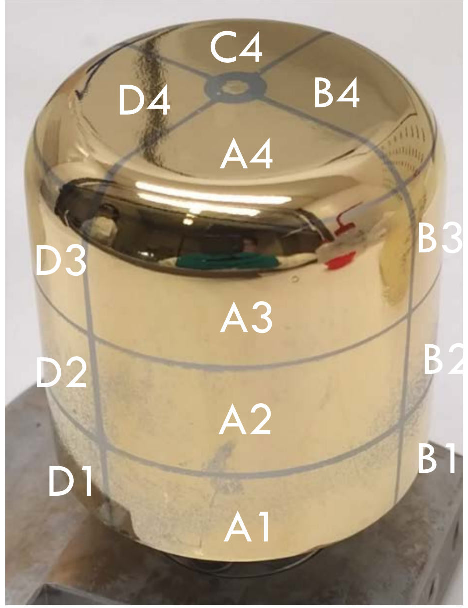


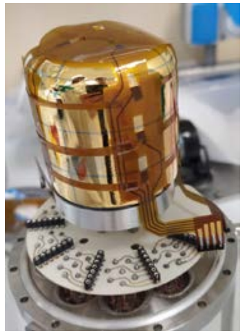
Segmentation Test of Coaxial detector

T= 25°C

Ω	A1		B1		C1		D1
A2	17.8	B2	16.6	C2	16.4	D2	22.1
A3	23.6	B3	21.3	C3	21.5	D3	27.3
A4	26.8	B4	23.8	C4	23.6	D4	30.5

Ω	A1		A2		A3		A4
B1	22.5	B2	18.0	B3	17.7	B4	18.0
C1	27.0	C2	19.8	C3	19.4	C4	20.1
D1	21.7	D2	16.3	D3	18.1	D4	17.4





T= 80°K

GΩ	C1	C3	D2	D4
Up	0.4	20	1.4	/
Down	/	0.6	7.5	3.0
Right	6.0	7.7	5.3	31.3
Left	4.3	25.0	0.1	12.8

GΩ	A1	B2	B4
Up	8.9	21.7	/
Down	/	3.1	27.8
Right	62.5	0.2	5.0
Left	62.5	11.4	12.5

High resistance between the segments is measured, exceeding 100 MΩ

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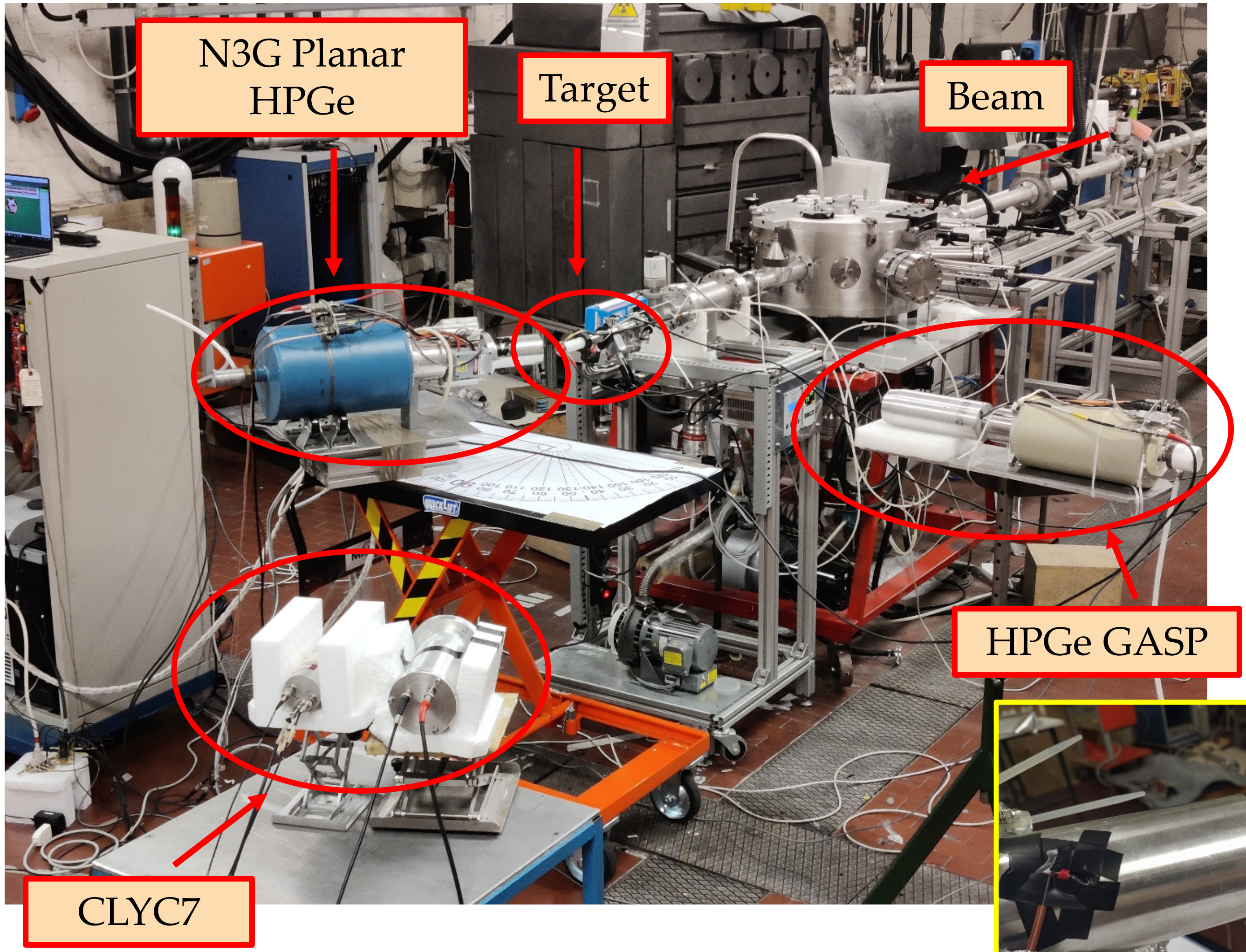
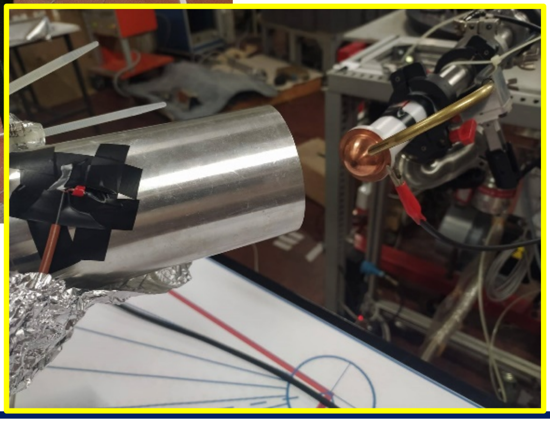
Neutrons damage on planar PLM segmented detector





380nA 4MeV proton beam
^{7}Li target, 100µm

Reaction: $^{7}Li\ (p,n)\ ^{7}Be$

Prototype detector is located at 30° 9.5 cm

Neutrons are directly measured with

- CLYC7 scintillators, 30° 2 m
- GASP HPGe γ detector, 90° 1 m

$^{7}Be + e^{-} \xrightarrow{53.3\ days} {}^{7}Li \rightsquigarrow 477.6\ keV$

R. Escudeiro at all. “**Neutron radiation damage on a planar segmented germanium detector**” proceeding Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, September 3-9, 2023

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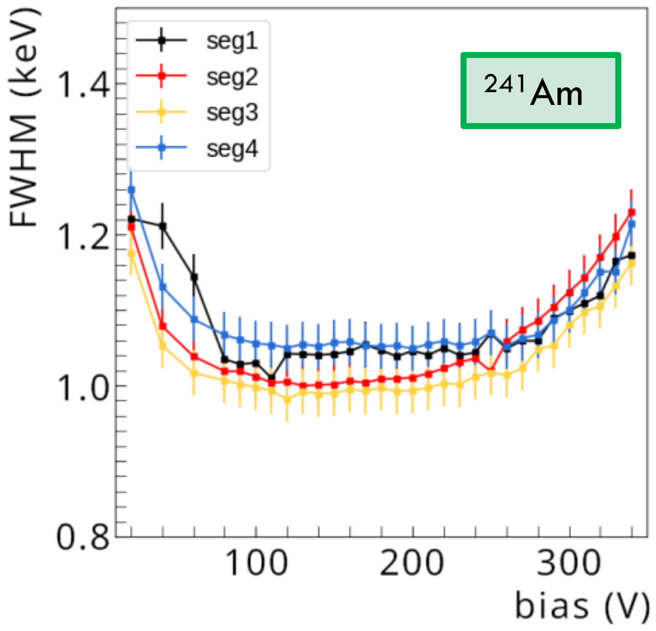
Neutrons damage on planar PLM segmented detector: before run

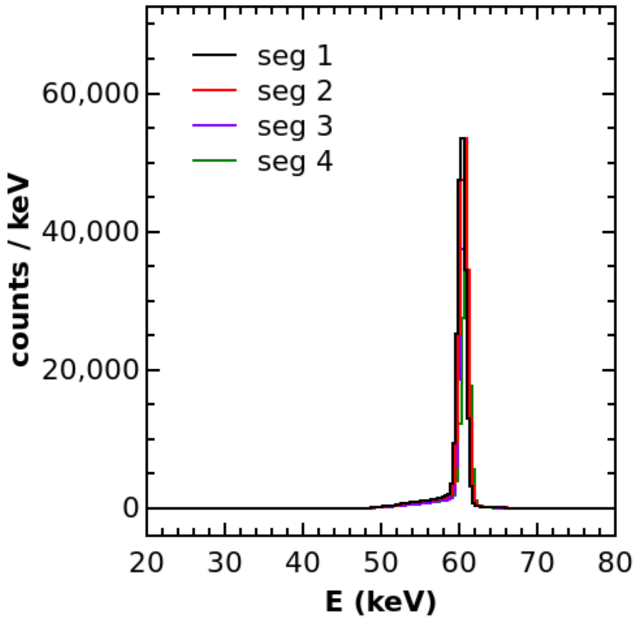
Detector prototype:
Sb/p-HPGE/Al, L= 32mm, t= 8.6mm
4 contacts + guard ring

Energy resolution in the lab

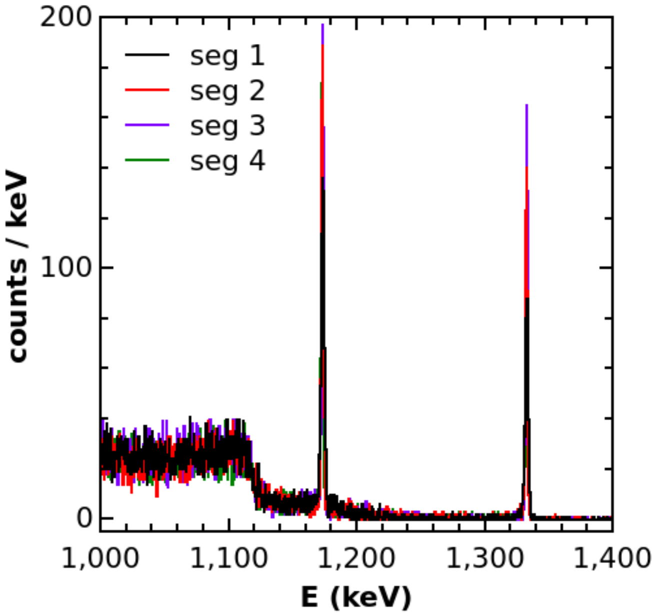


Starting resolution at **80V** operational bias before the neutron damage run

^{241}Am
E = 59,5 keV
FWHM < 1,1 keV



^{60}Co
E = 1332 keV
FWHM < 1,8 keV



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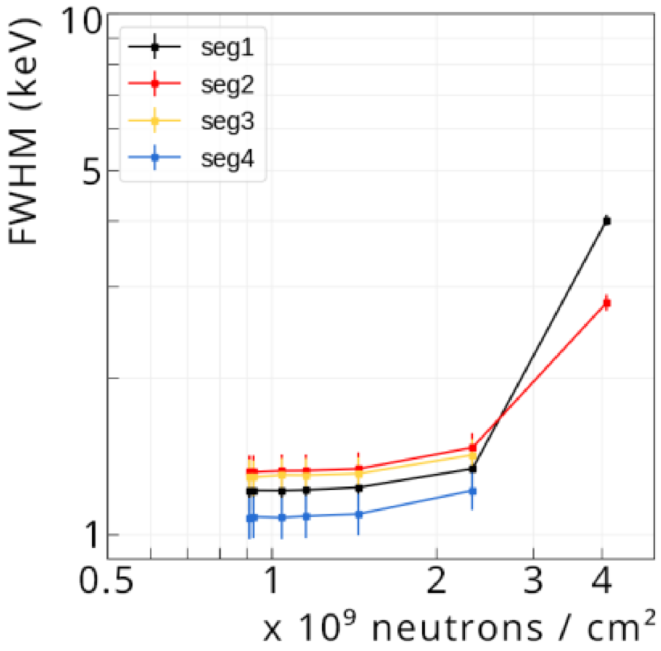
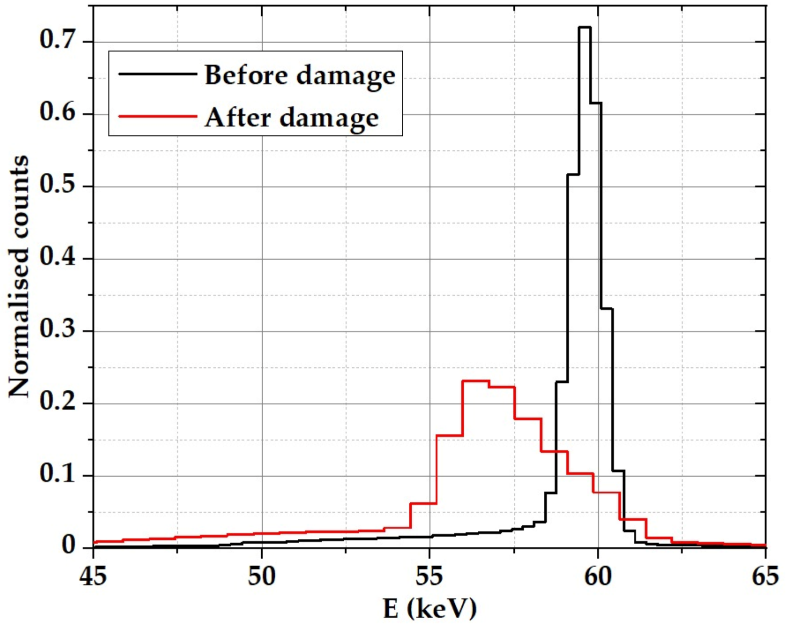
Neutrons damage on planar PLM segmented detector: after 1° run

Operational Voltage 80V
Neutron irradiation for increasing time intervals alternated to 5 min runs with ^{241}Am and ^{60}Co leads to increasing resolution worsening

^{241}Am
E = 59,5 keV
FWHM = 3,2 – 4,2 keV

After 4 hours of irradiation time,
≈ $4 \cdot 10^9$ neutrons/cm^2, detector is no longer operable



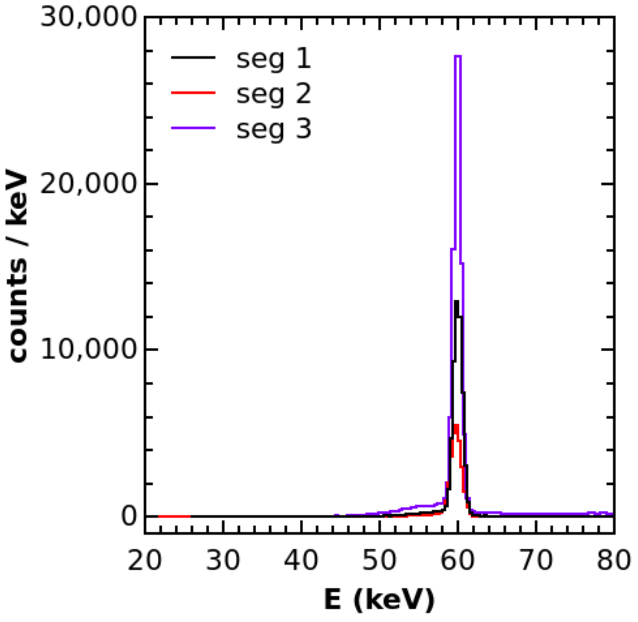


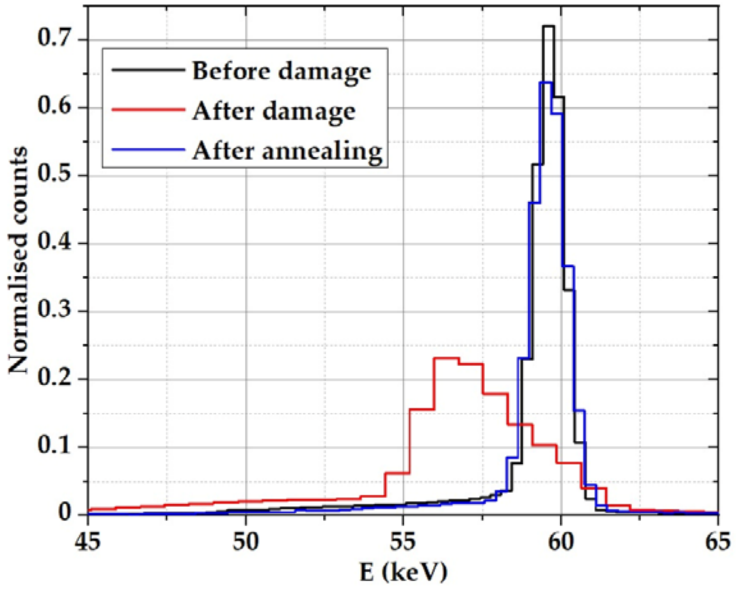
Neutrons damage on planar PLM segmented detector: After Recovery

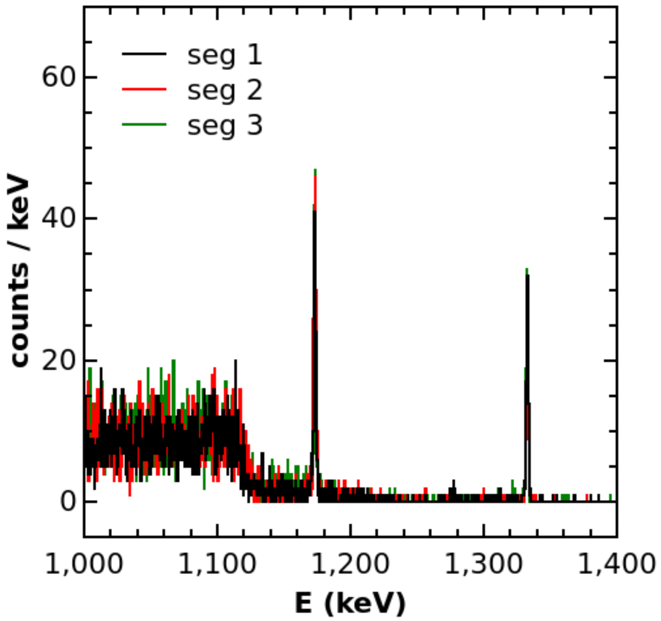
Annealing procedure: 7 days at 105°C continuously pumped inside the cryostat

^{241}Am
E = 59,5 keV
FWHM < 1,6 keV

^{60}Co
E = 1332 keV
FWHM < 2 keV





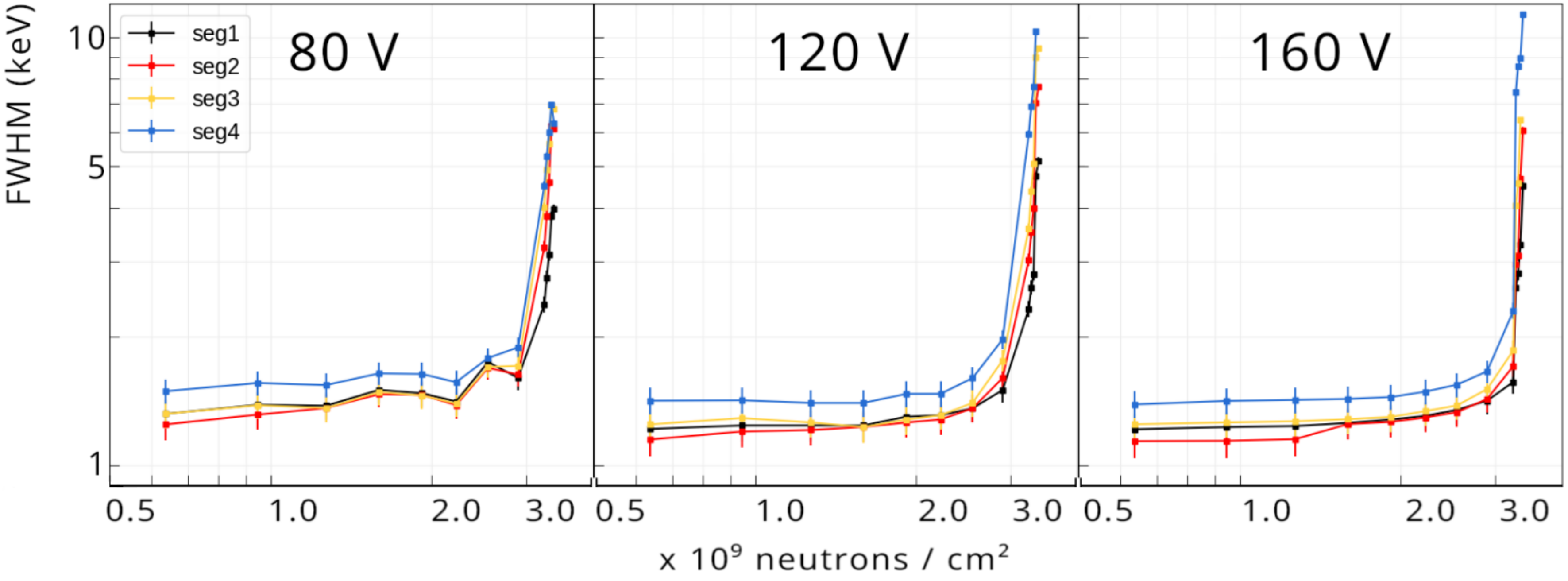


Neutrons damage on planar PLM segmented detector: After 2° run

Operational Voltage 80-120-160V
Neutron irradiation for 20 and 2 min to 5 min runs with ^{241}Am to better characterize resolution worsening

Drastic drop in resolution after
$\approx 3 \cdot 10^9$ neutrons/cm^2 irradiation fluence

^{241}Am
E = 59,5 keV
FWHM = < 2 keV until threshold



S. Bertoldo PhD thesis: **Developments on new detector technologies for high resolution gamma spectroscopy**

SUMMARY

- PLM technology can be apply to HPGe crystal (**hyperpurity preserve**)
- PLM junction is thin, segmentable and termally stable (**anneling**)
- PLM and segmentation technology can be applied to both planar and coxial detectors (2D to 3D PLM shape LNL-INFN has a collaboration agreement with MIRION)
- PLM segmented detector recovers after Neutron damage with a very good energy resolution (**anneling recovery**)

R&D Gamma ray detector Team

Davide De Salvador
Stefano Bertoldo
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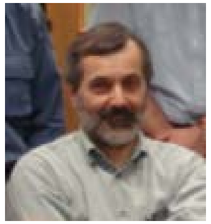
Gianluigi Maggioni
Francesco Recchia
Dino Bazzacco

Walter Raniero
Daniel Napoli
Chiara Carraro

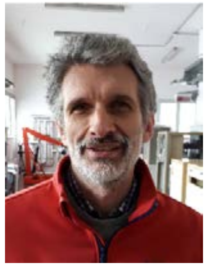
Stefano Capra
Giacomo Secci
Alberto Pullia
Bénédicte Million
Luciano Manara

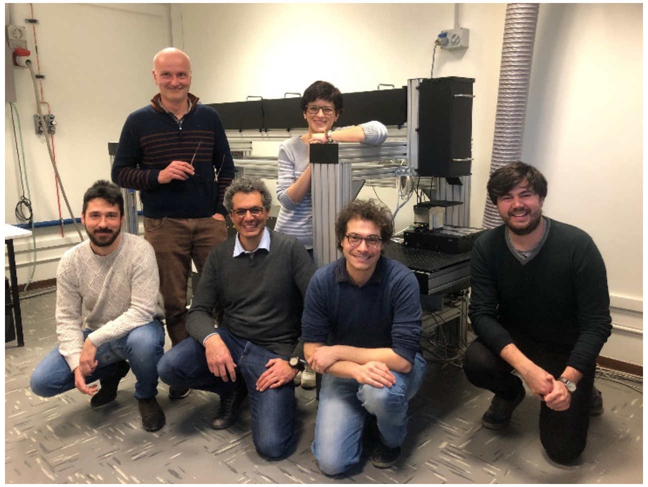
Andrea Mazzolari
Lorenzo Malagutti

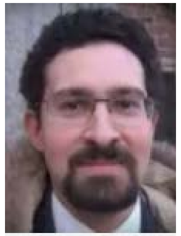
Andres Gadea

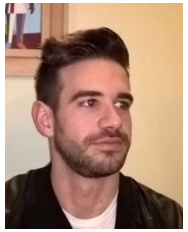













4th AGATA-GRETINA/GRETA
Tracking Arrays Collaboration Meeting

HPGe crystal research at LNL-INFN

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