Testing a New Technology for Producing High-Purity Germanium Segmented Detectors

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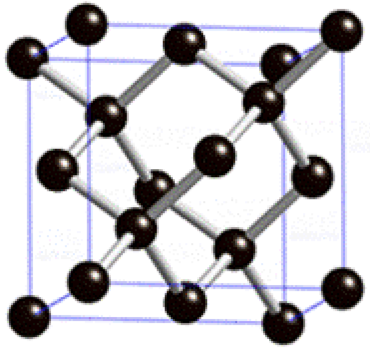
NN 2024

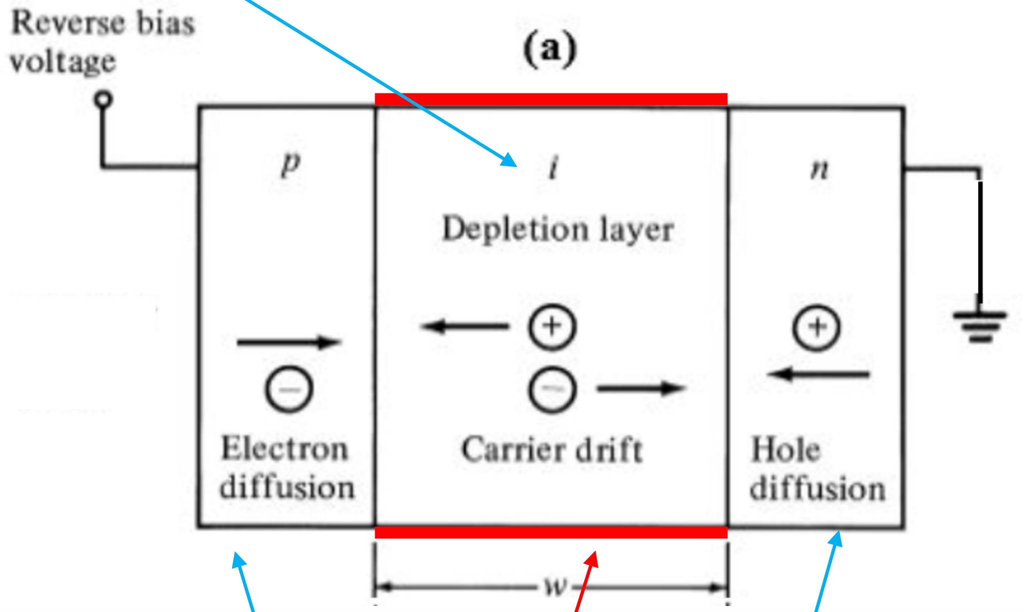
Outline

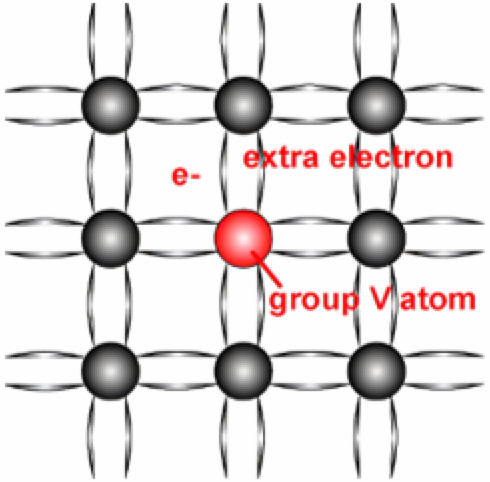
- Hyperpure Germanium (HPGe) gamma-ray detectors
- *Pulse Laser Melting* (PLM)*:* New contacts for HPGe detectors
- PLM applications to planar and coaxial HPGe detectors
- Test on neutron damage in PLM planar segmented detectors

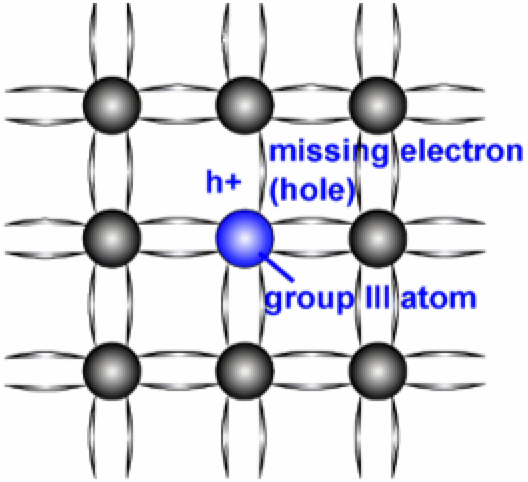
Hyperpure Germanium (HPGe) gamma-ray detectors



Intrinsic HPGe Charge carrier density 10^{10} cm^{-3}





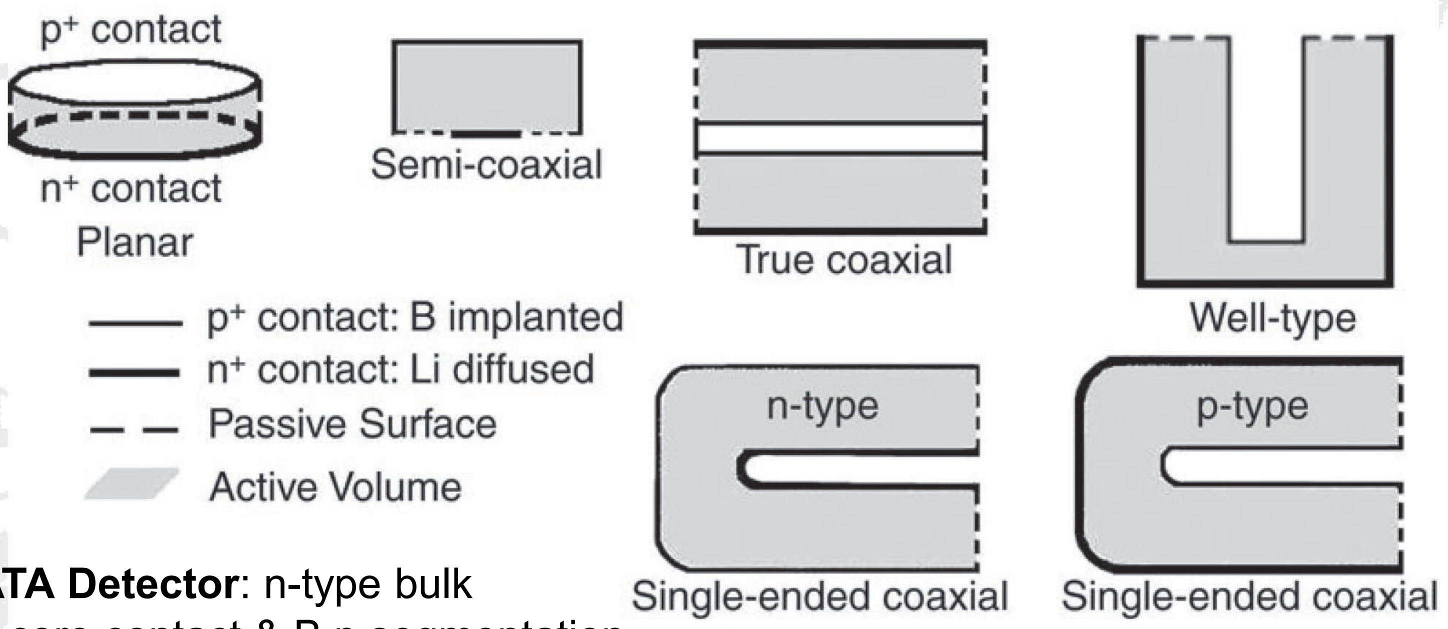


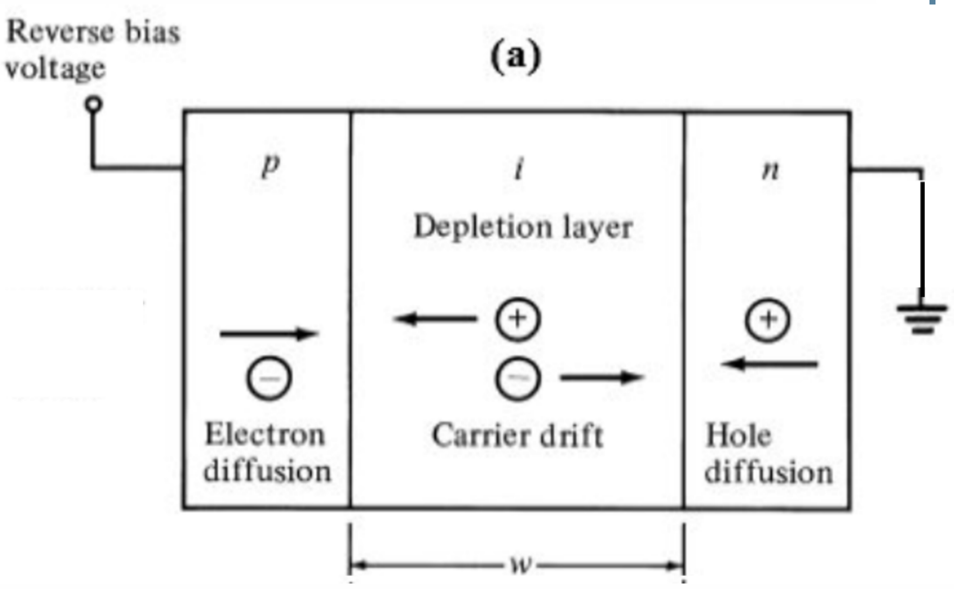
0.3 µm B implanted contact

0.9 mm Li diffused contact

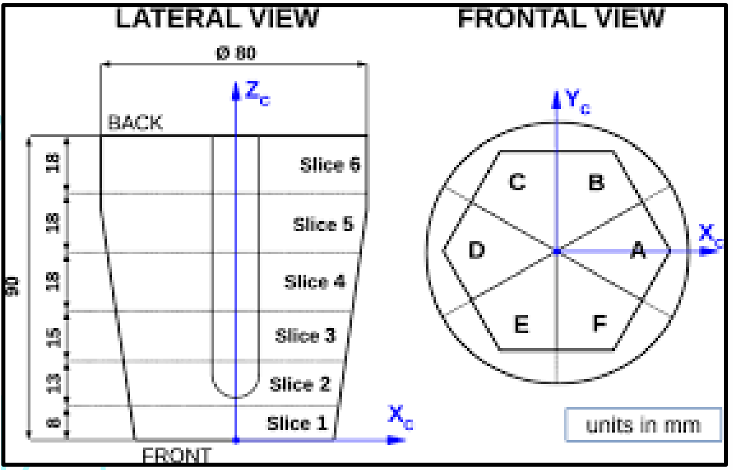
It is necessary a surface passivation in between both contacts to avoid leakage currents

Hyperpure Germanium (HPGe) gamma-ray detectors





AGATA Detector: n-type bulk
Li n^+ core contact & B p segmentation



Typical commercial HPGe contacts for in-beam Spectroscopy (**n-type**)

p+: 0.3 µm thin B ext. implanted contact

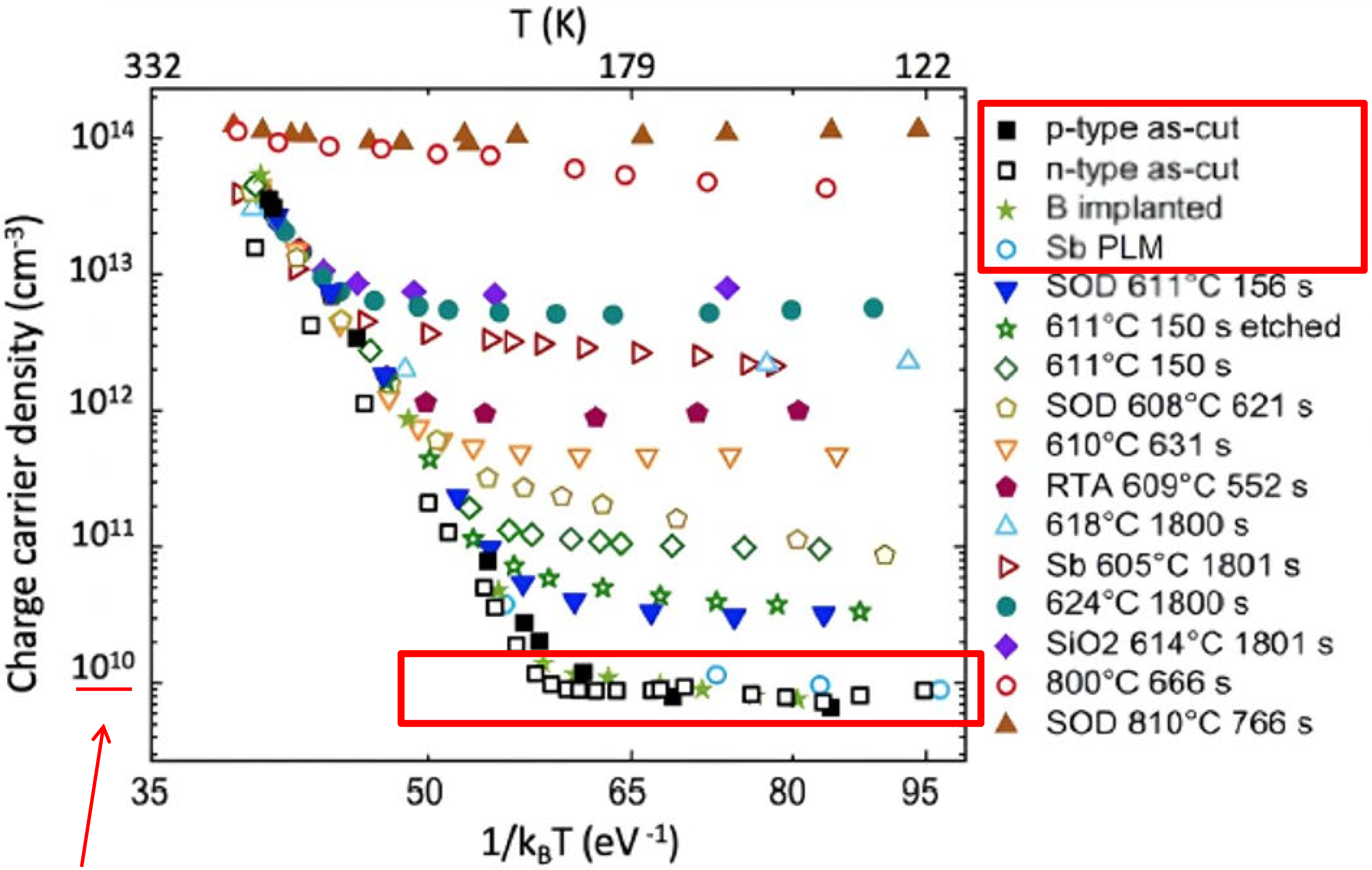
n+: 0.9 mm thick Li internal contact

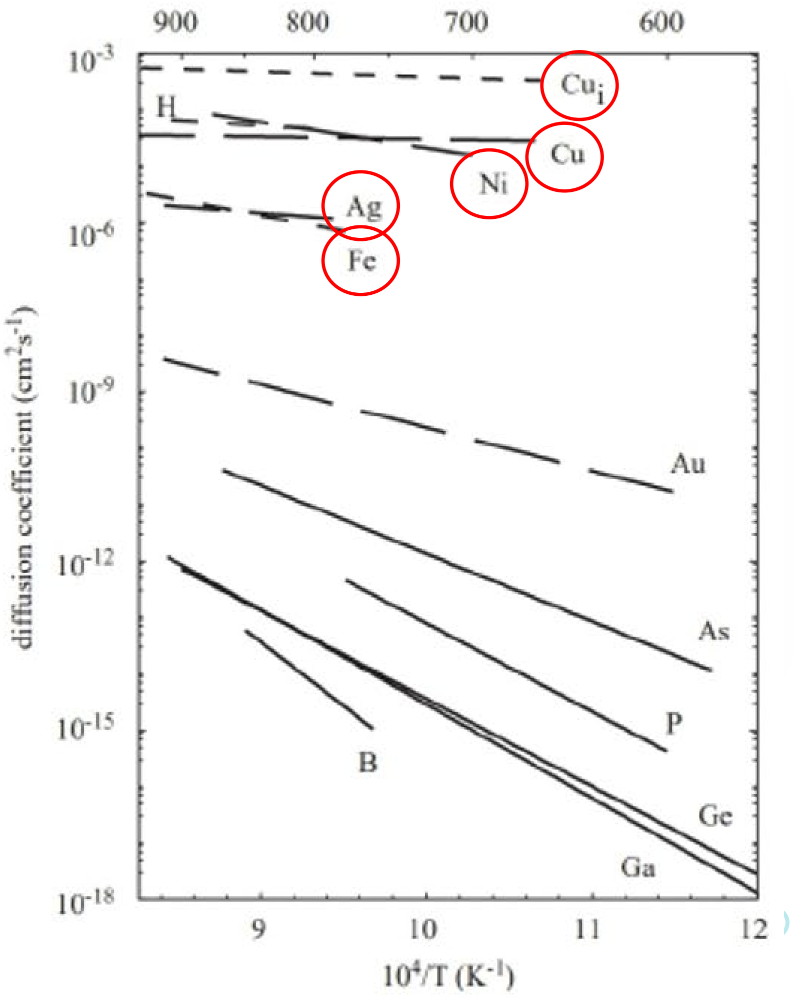
Typical commercial HPGe detectors that do not need to affoard thermal cycles

p-type HPGe with B and Li contacts
or
p+ & **n+** Germanium amorphous contacts

Need of a thin and Temperature- stable n+ contact for HPGe dets.

Why PLM?: Impurities concentration in bulk Ge





Intrinsic HPGe **Charge** carrier density 10^{10} cm^{-3}

V.Boldrini et al. J. Phys. D: Appl. Phys. 52(3), 035104 (2018)

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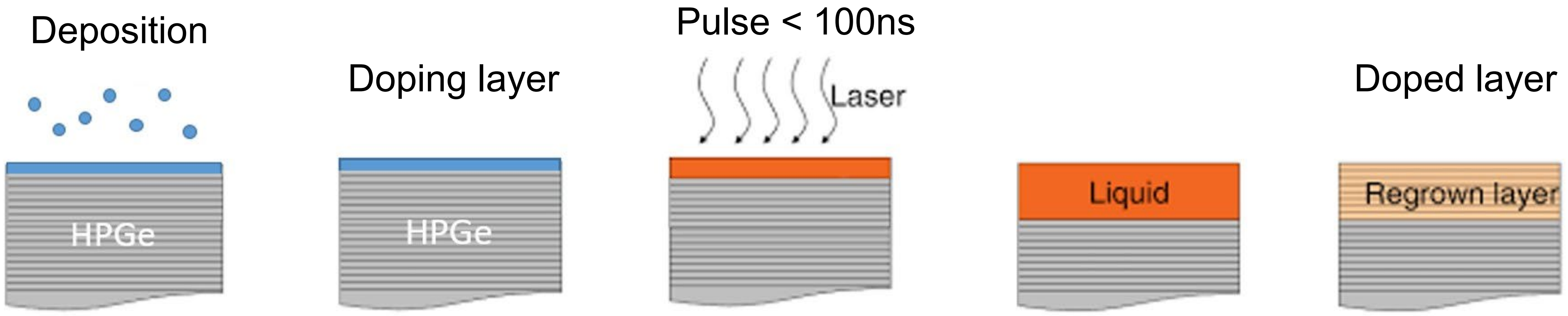
New contact/junction on HPGe: PLM (Pulse Laser Melting)



Pulse Laser Melting is a Strong Out of Equilibrium Difussion Process

PLM is a very clean process suitable for preserving the HPGe hyperpurity
It is well known in microelectronics and we have been adapted it for HPGe detectors showing a new way for producing these high resolution gamma detectors.

- Ultrafast: Melting temperature is reached - short time (~100 ns)
- Limited to the Surface: (< 1 μm) is melted and the HPGe intrinsic bulk remains at room temperature
- Hyperdopant: with high dopant concentrations (>10^{20} at/cm^3) with very sharp dopant profile
- Dopant flexibility because can be use with heavy elements without crystal damage
- Suitable for complex contact geometries and segmentation

PLM

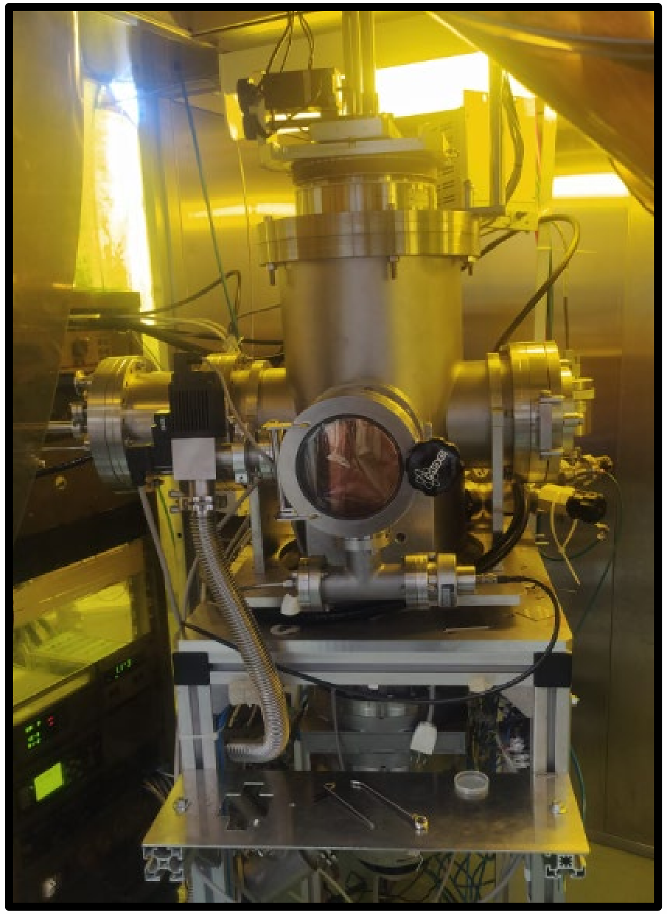
- PLM is well known in micro-electronics and we have been adapted it for HPGe detectors showing a new way for the production of HPGe gamma detectors. This technology preserves hyper-purity in the intrinsic bulk of the HPGe crystals and can be applied for producing thin, segmentable and thermally stable (annealing recovery) contacts in different 2D or 3D geometries.

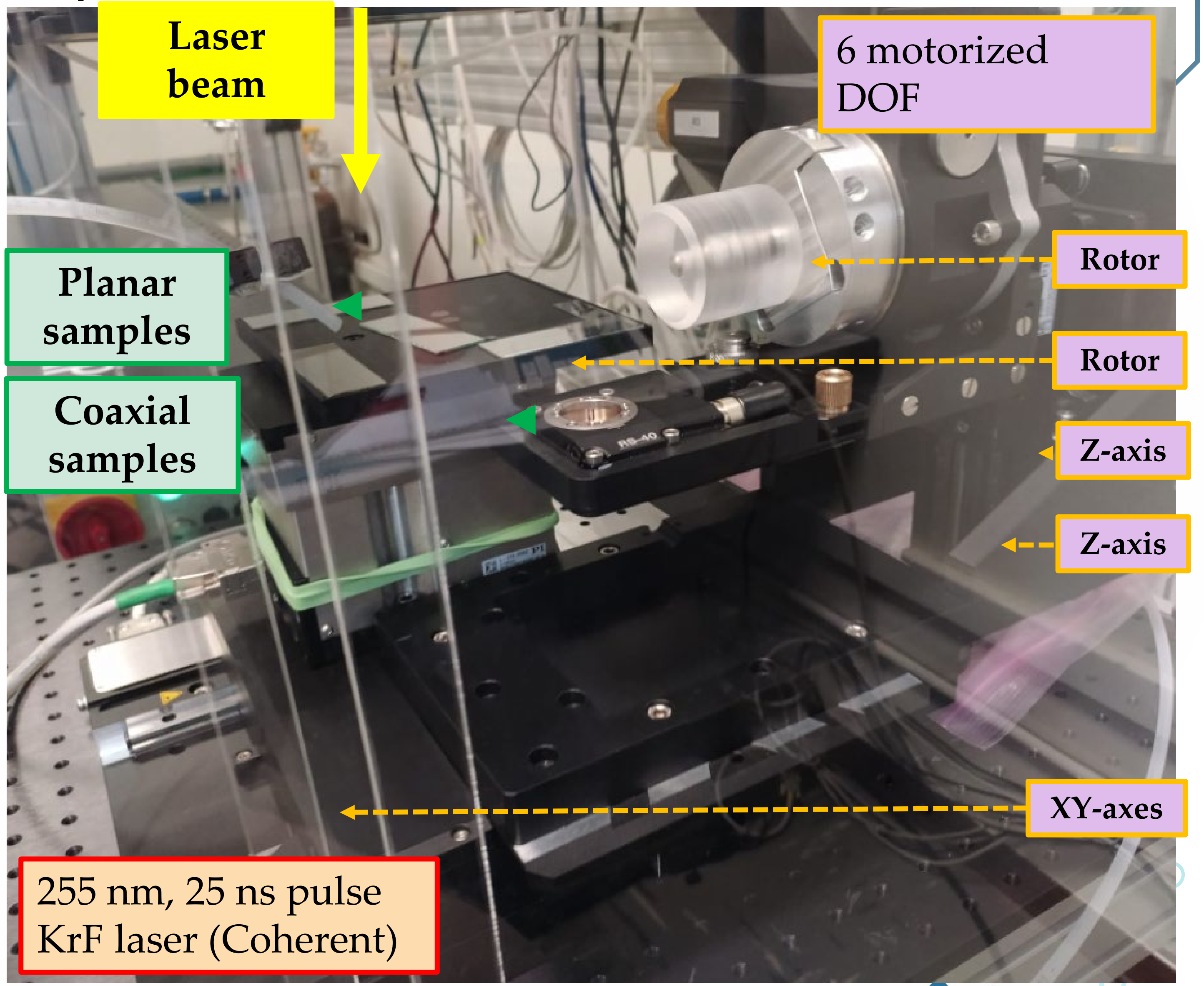
- We have established the steps needed to obtain a working detector from a raw HPGe crystal and improved it through the characterization and validation of these steps through RBS or SEM-EDS (surfaces) Van Der Pauw (sheet resistance), Hall (charge carriers), Secondary Ions Mass Spectrometry (SIMS for deep characterization of dopants), I – V (and occasionally I – T or C – V) diode measurements and of course gamma ray spectroscopy tests.

Reality is not always so simple

Surface Preparation

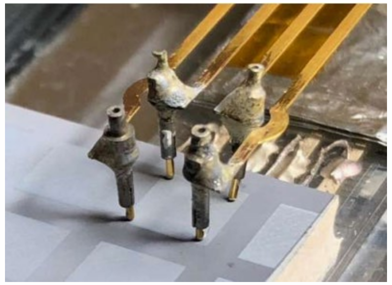
Magnetron Sputtering deposition





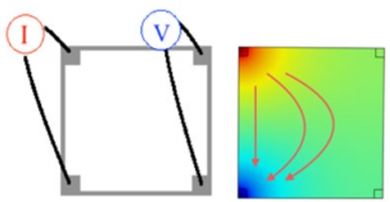
255 nm, 25 ns pulse
KrF laser (Coherent)

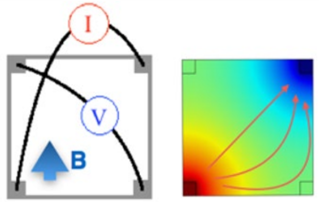
Control the PLM process on HPGe crystals



Van Der Pauw

Hall





Sheet resistance

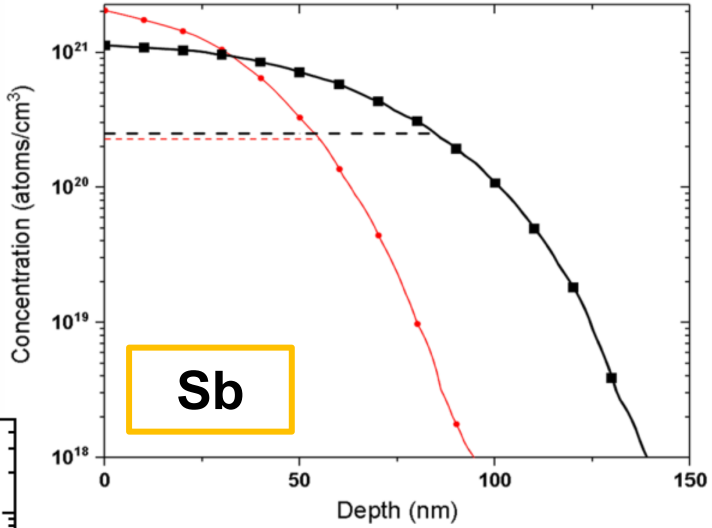
Charge carriers

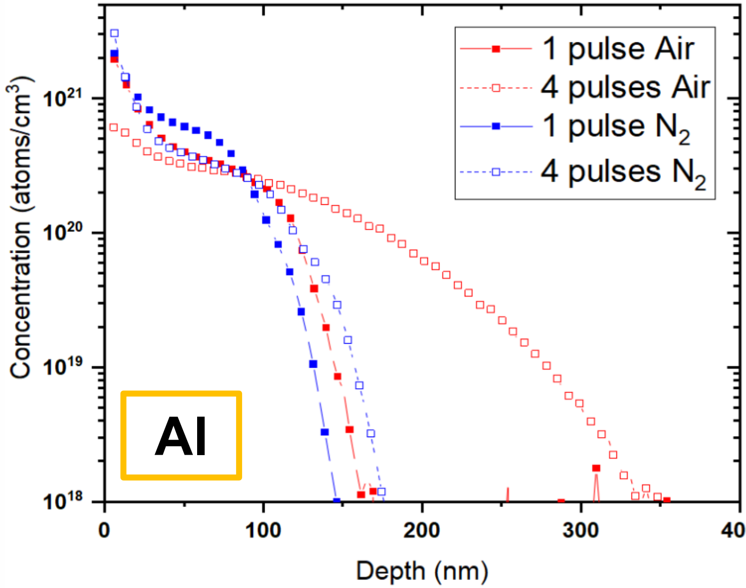
To determine Charge Carriers Density

SIMS (Secondary Ions Mass Spectrometry)

To determine specific concentration profiles inside the crystals

1 pulse
1 pls activation
4 pulses
4 pls activation





Concentration plots (atoms/cm^3) as a function of depth (nm)

V. Boldrini et al., J. of Physics D 52 (2018) 3

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Control of the process

We have established the steps needed to obtain a working detector from a raw HPGe crystal and improved it through the characterization and validation of these steps through

RBS or SEM-EDS (surfaces)

Van Der Pauw (sheet resistance),

Hall (charge carriers),

Secondary Ions Mass Spectrometry (SIMS for deep characterization of dopants),

I – V (and occasionally I – T or C – V) diode measurements

Gamma ray spectroscopy tests

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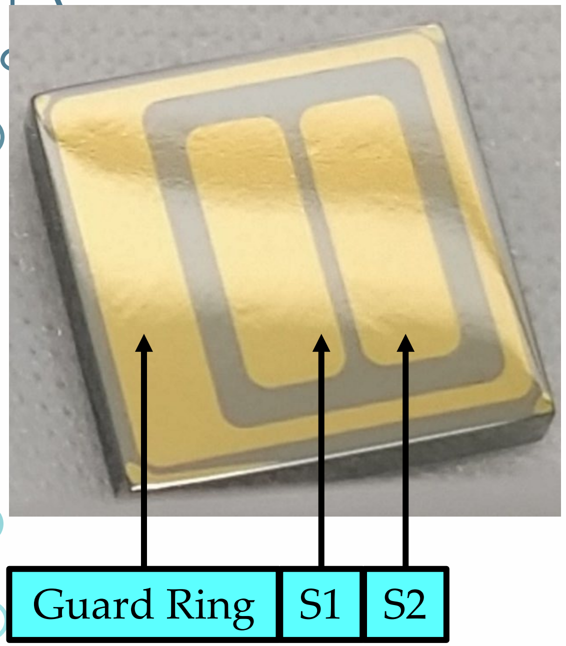
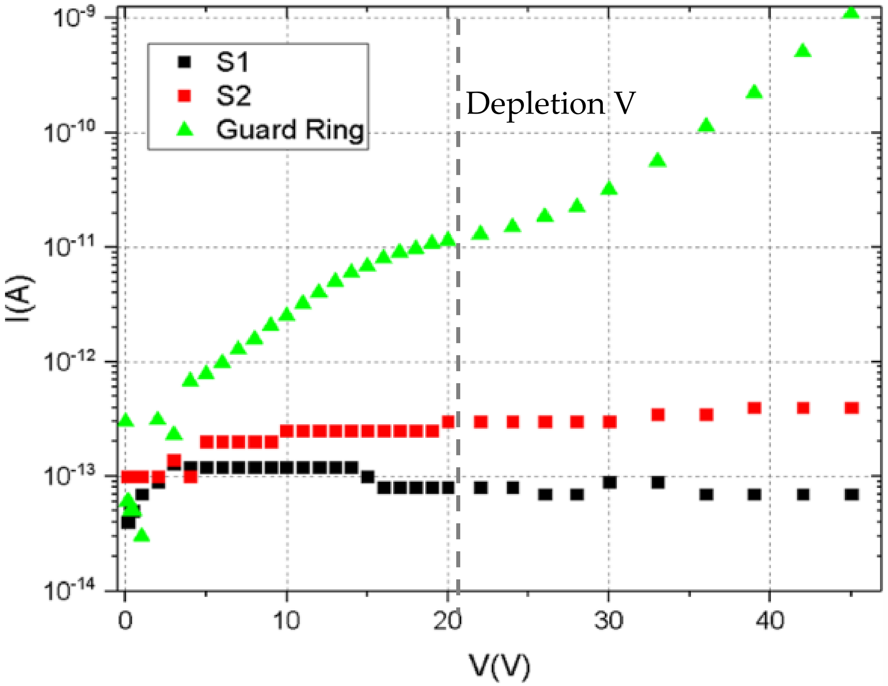
Thin planar HPGe detectors

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



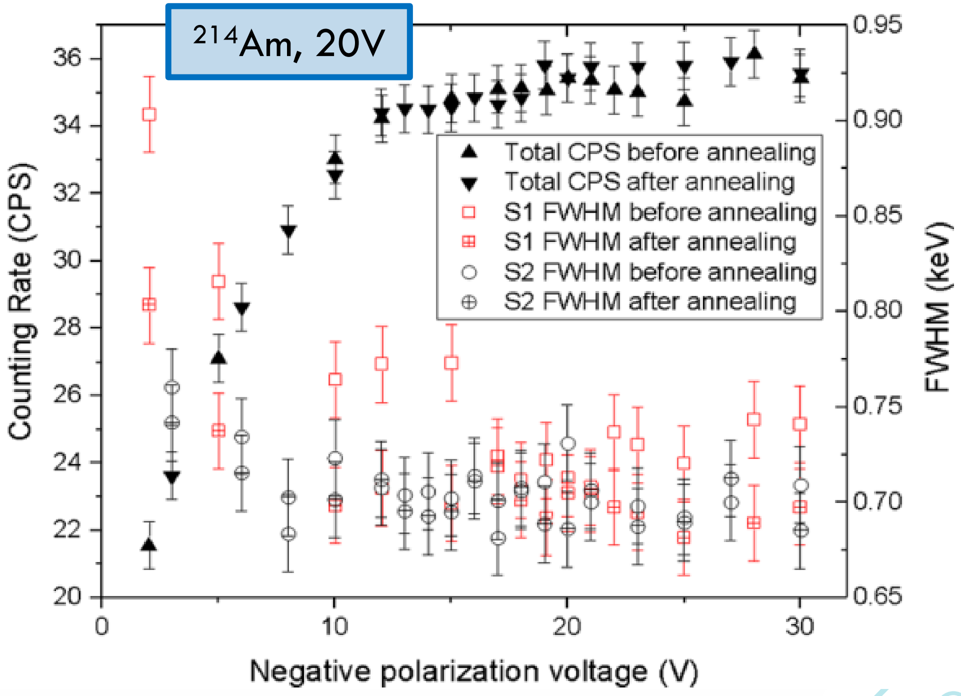
Measured before and after recovery annealing and re-passivation to test junction stability

Electrical test:
reverse I-V characteristics



Gamma ray test:
241Am spectra acquisition

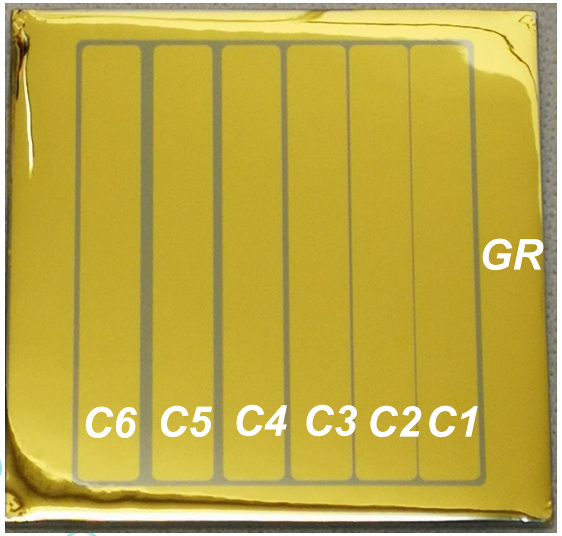
Annealing at 105°C



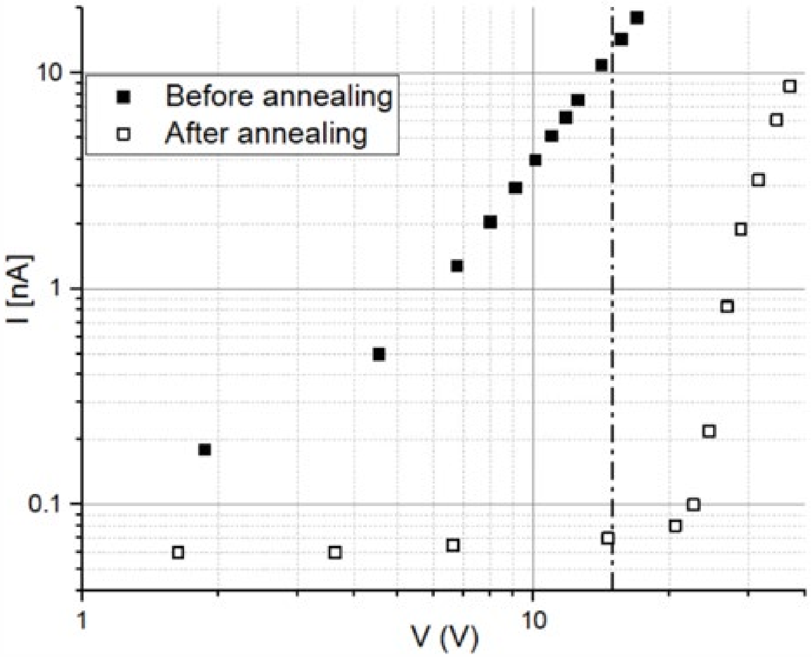
S. Bertoldo et al., **Eur. Phys. J. A** (2021) 57:177

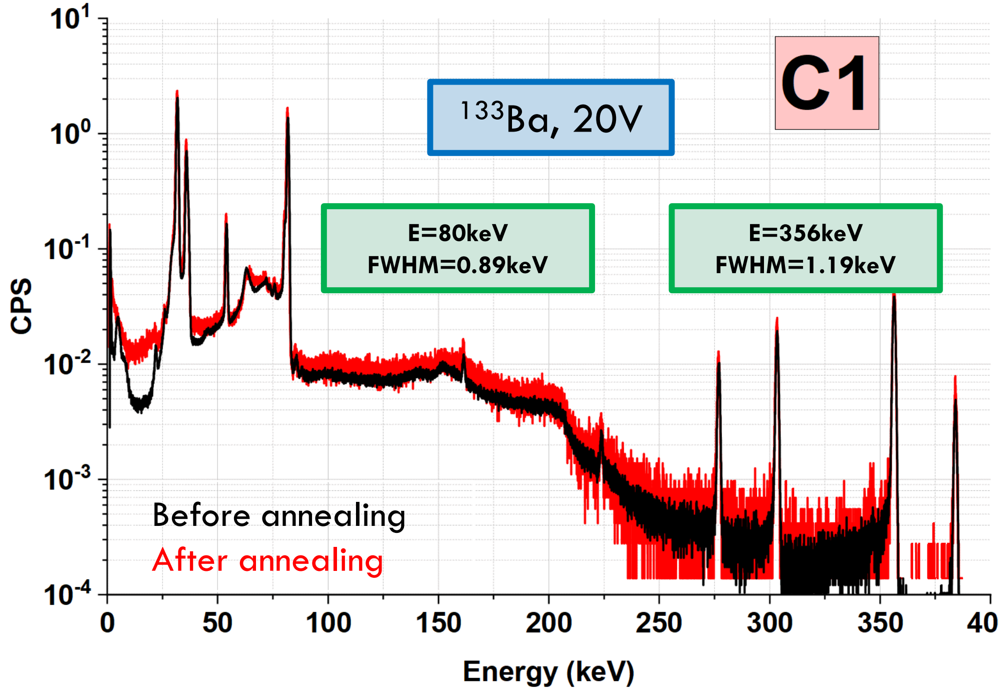
Thin planar HPGe detectors

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



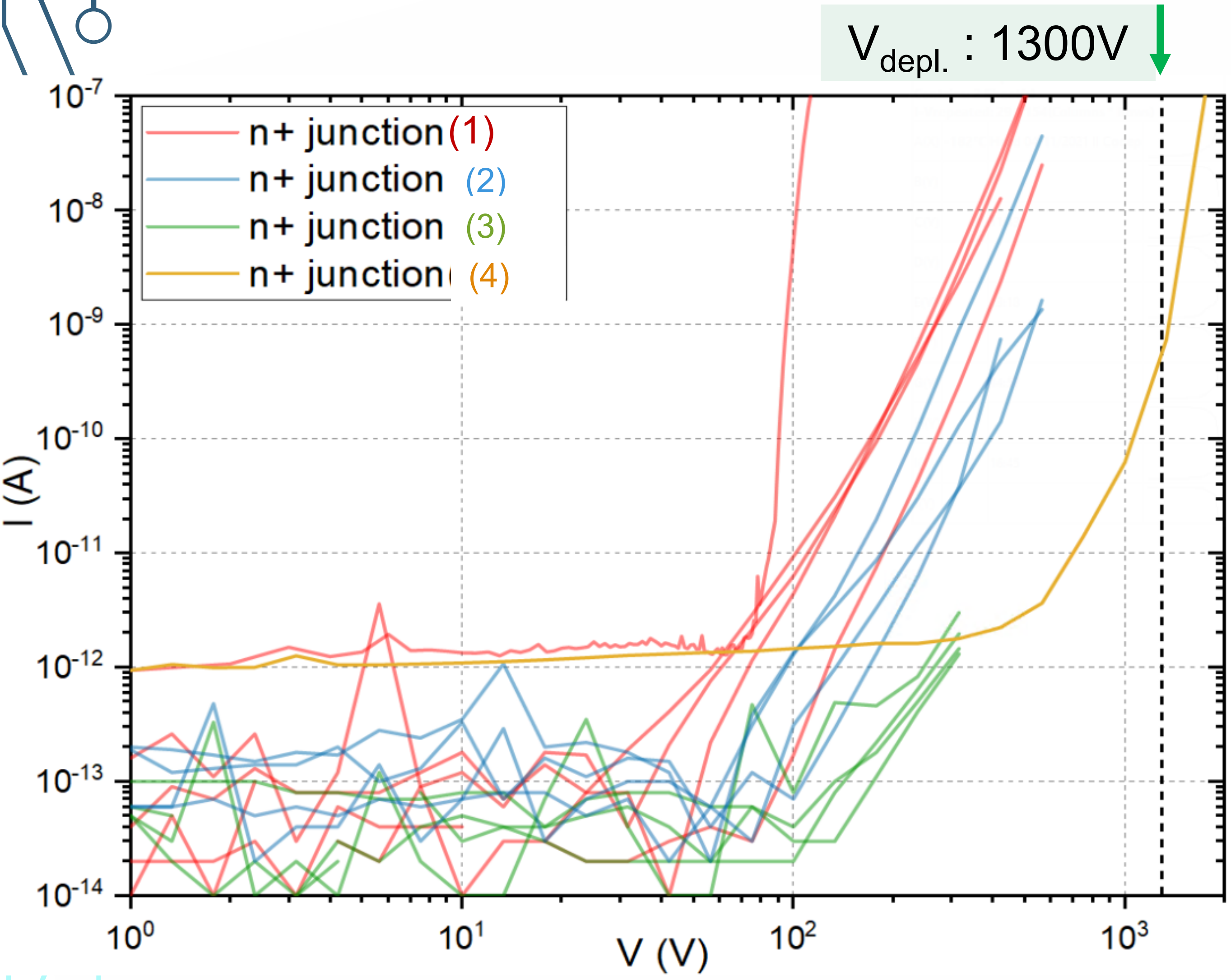
Minimum gap tested 0.1 mm

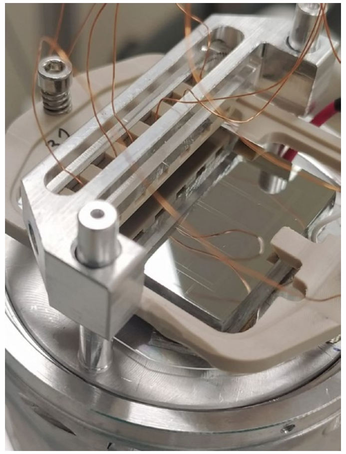




W. Raniero et al., **Il NUOVO CIMENTO 44 C** (2021) 154

Thick planar HPGe detectors



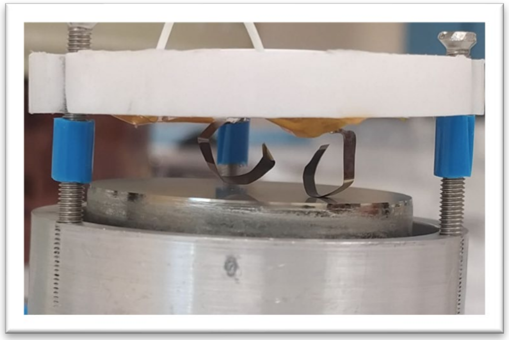


Sb/p-HPGE/Al,
L= 30 mm,
thick= 10 mm

n+ junction with comercial spring contacts (1)

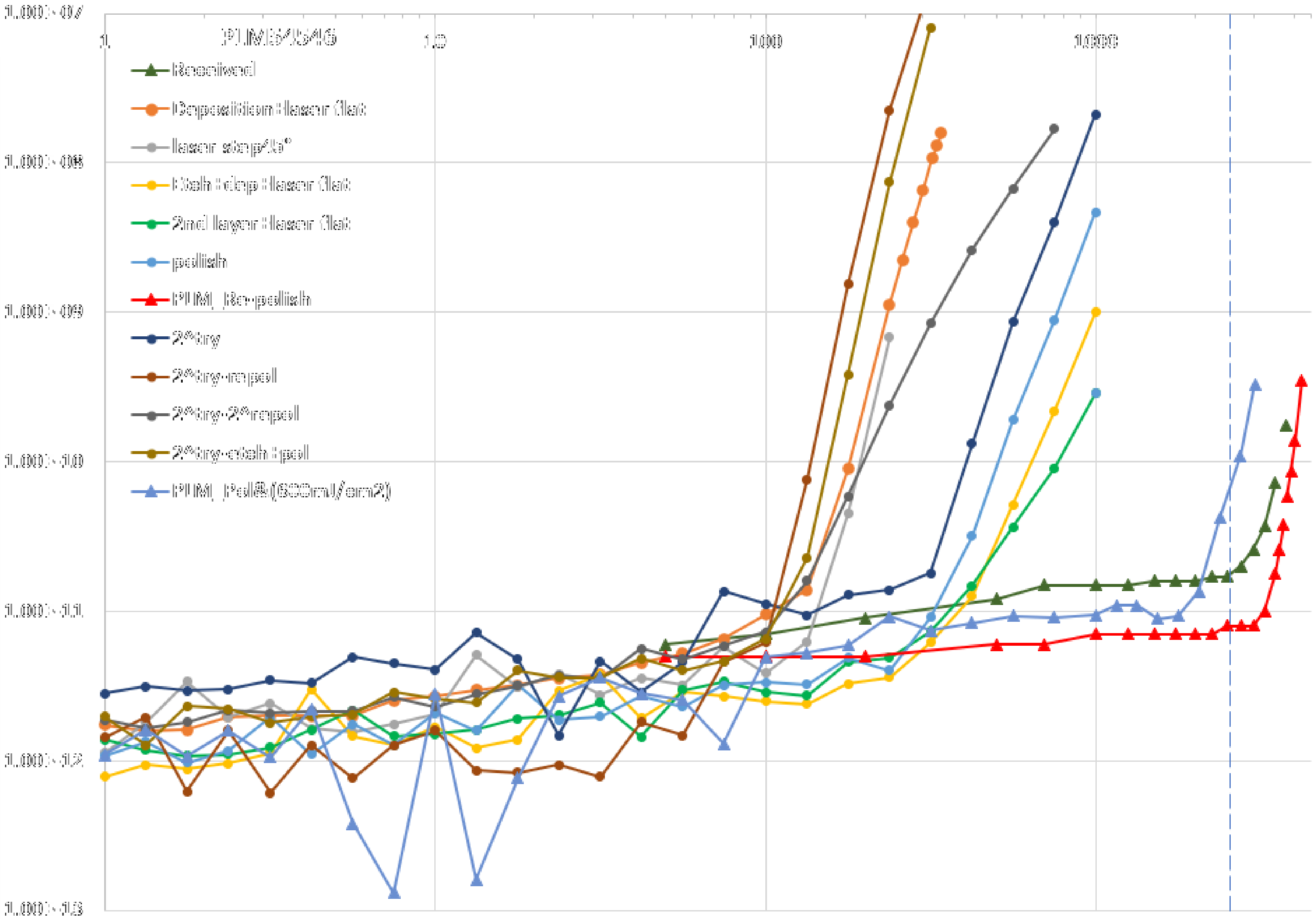
Sb/p-HPGE/Al,
D=40mm, t=20mm

n+ junction (2) / (3) indium pad



n+ junction with elastic tabs (4)

Thick HPGe detectors help us to upgrade our methods!



Improvements

Surface preparation before dopant deposition. The new preparation is chemical and mechanical.

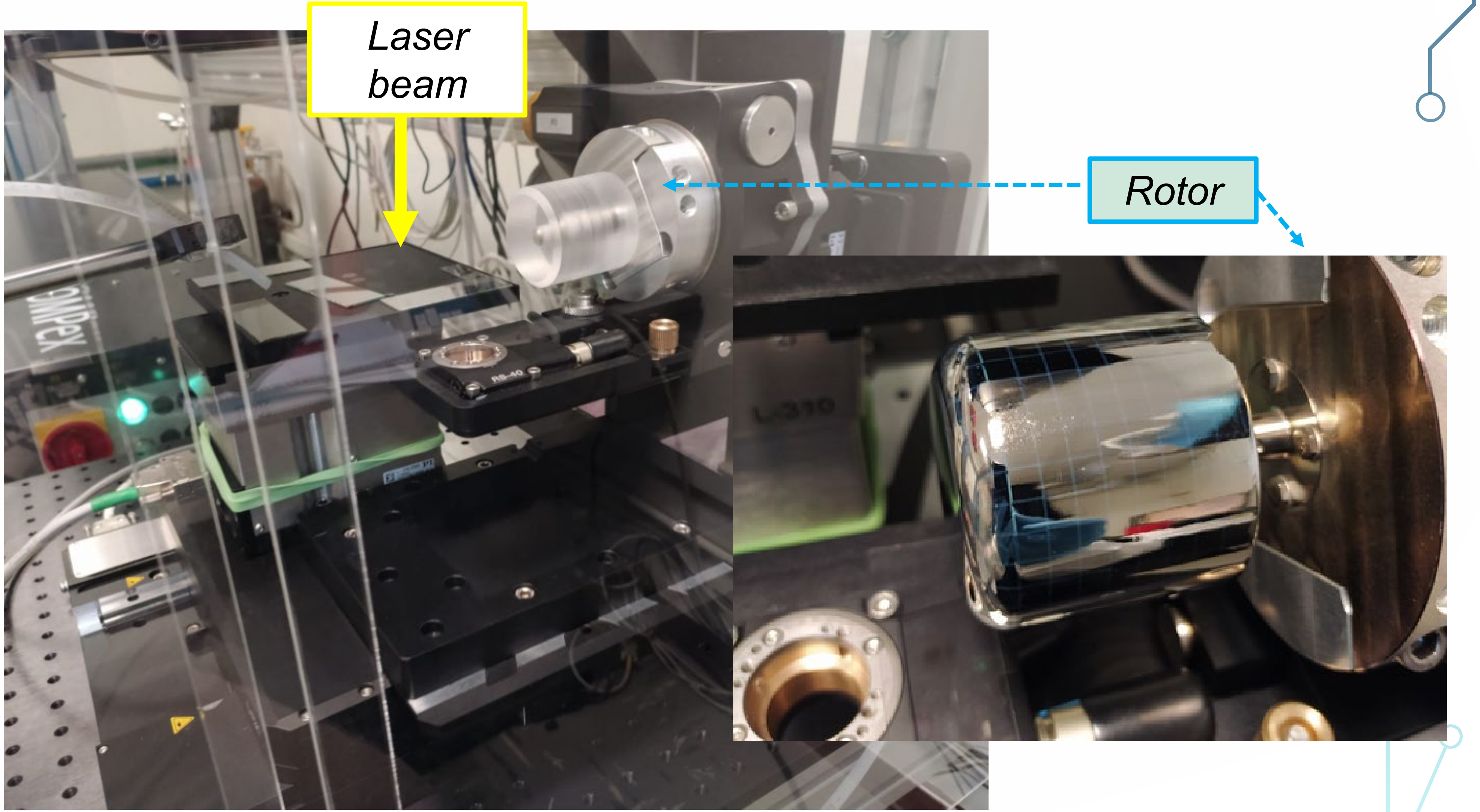
Slightly reduction of the Laser energy.

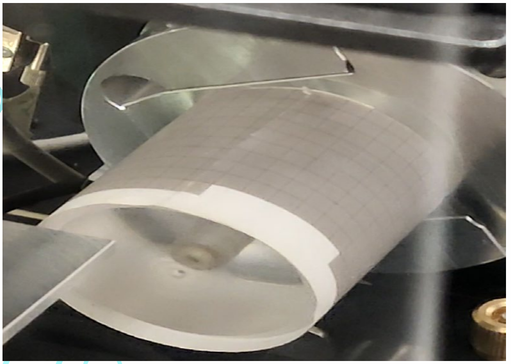
Covering the contacts with Al when possible.

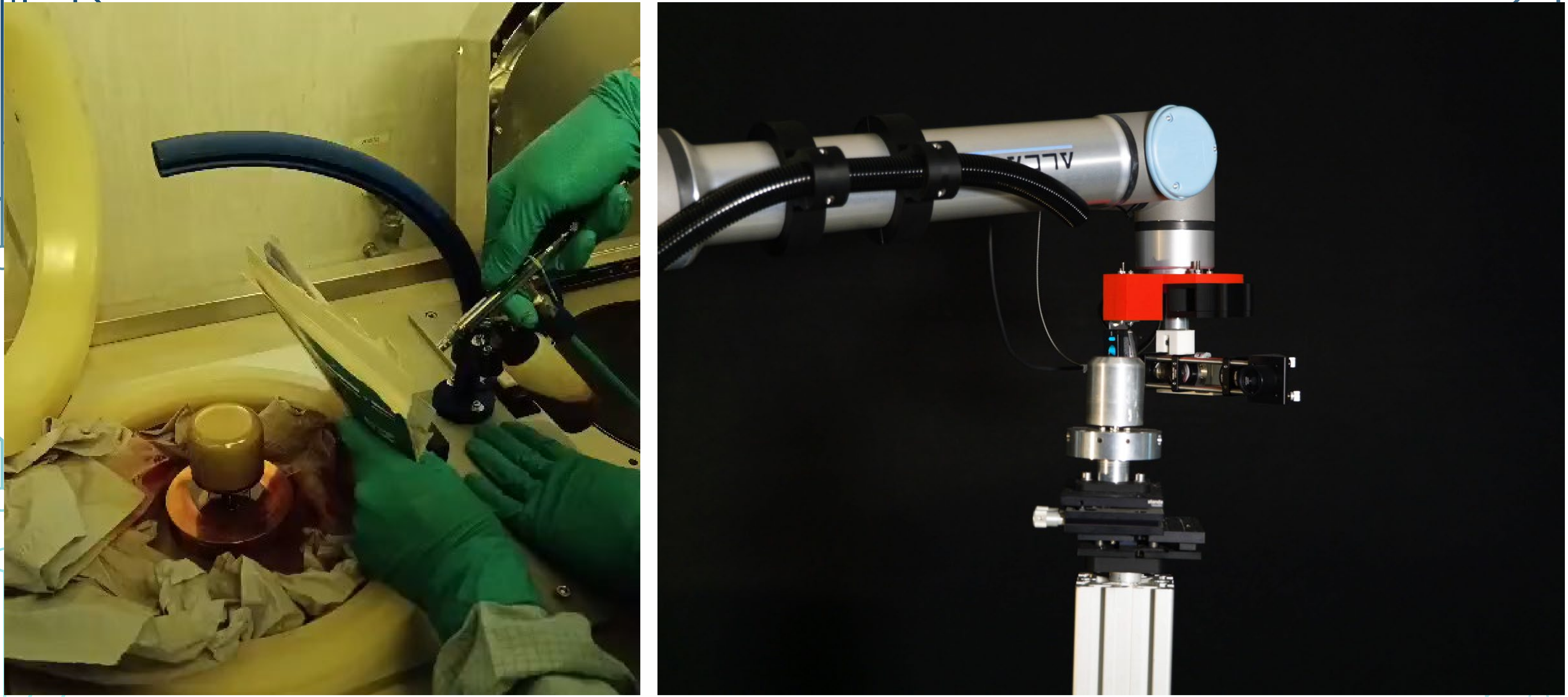
Improving the electrical contacts of the cryostat.

Founded *markers* candidates

PLM on massive cilindrical HPGe







We have adapted Photolitography (PLP) for preserving HPGe hyperpurity as well for working with big samples. After PLP on gold plated surfaces, a gold-free lithography was developed exploiting the spatial control of the PLM Laser beam.

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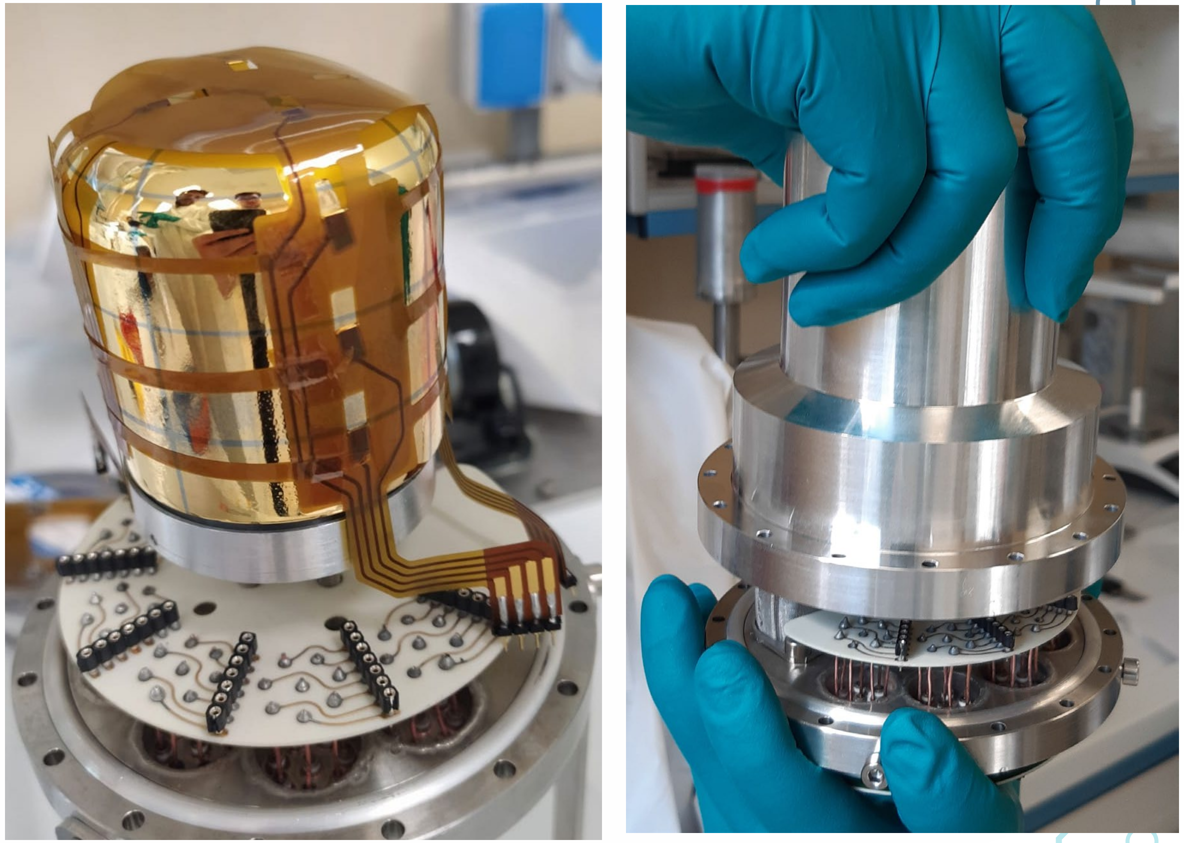
Encapsulation of the Coaxial detector

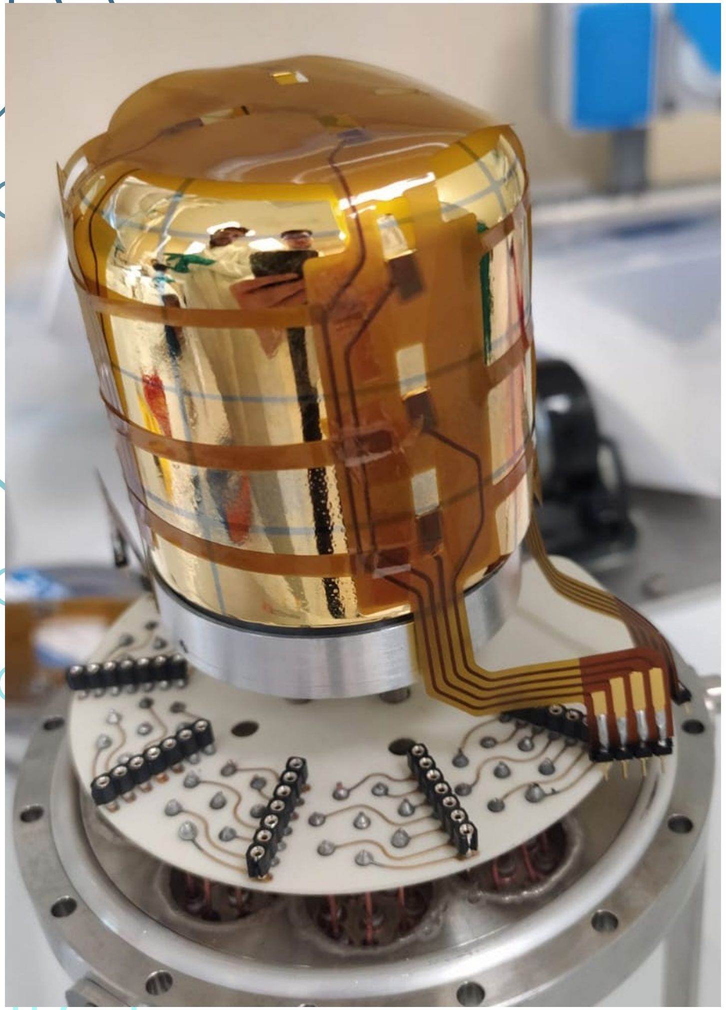
Flexible Kapton PCB

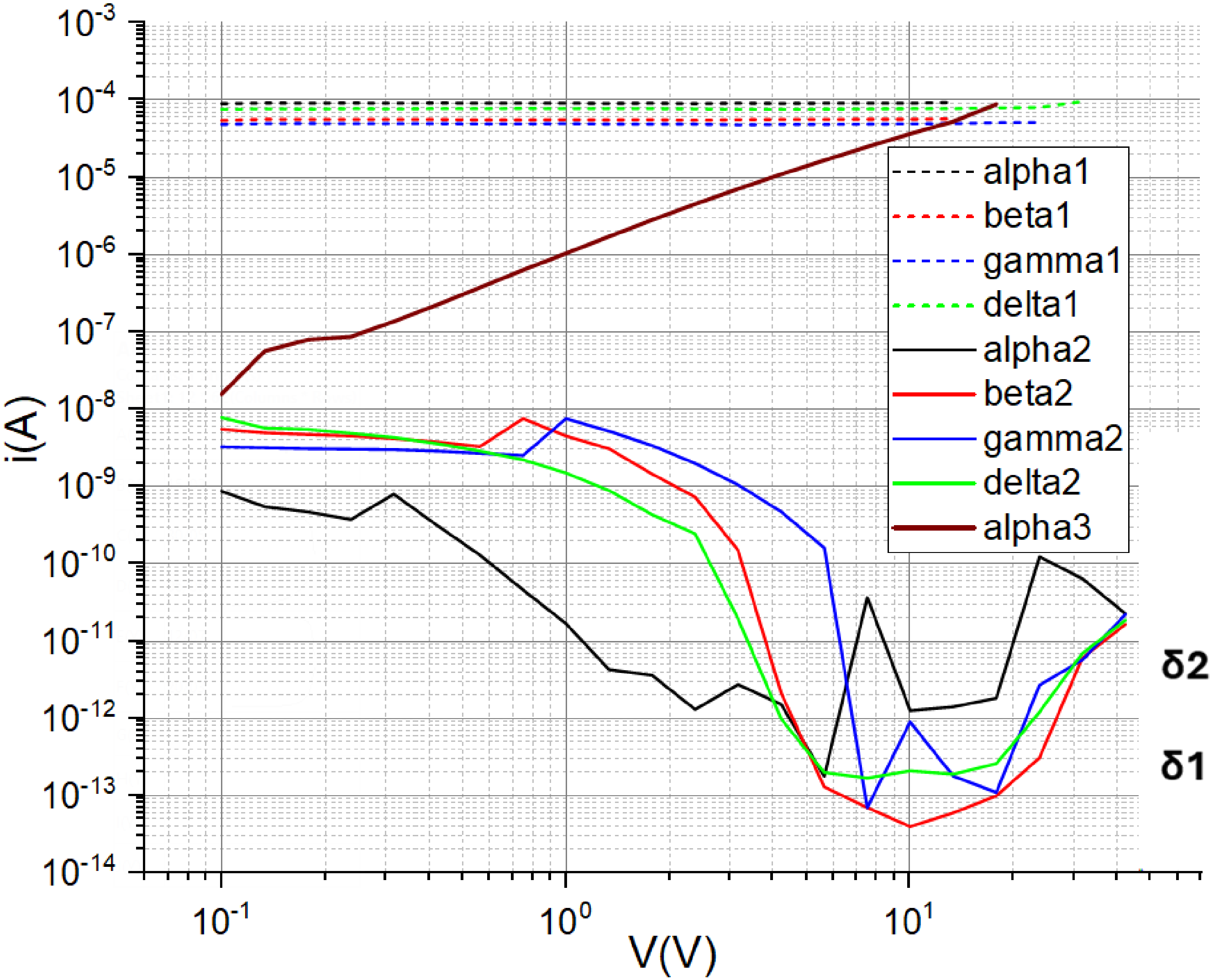
Vacuum - tight canister



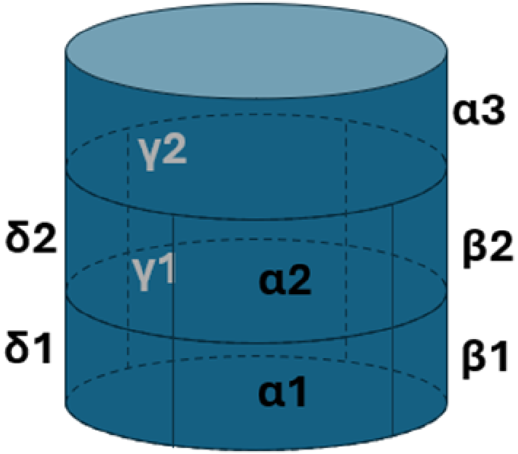
S. Capra et al, JINST 19 C01011 (2024)

1° Coaxial Prototype: 50 mm x 50mm, n-type crystal, AlGe PLM junction, Li core



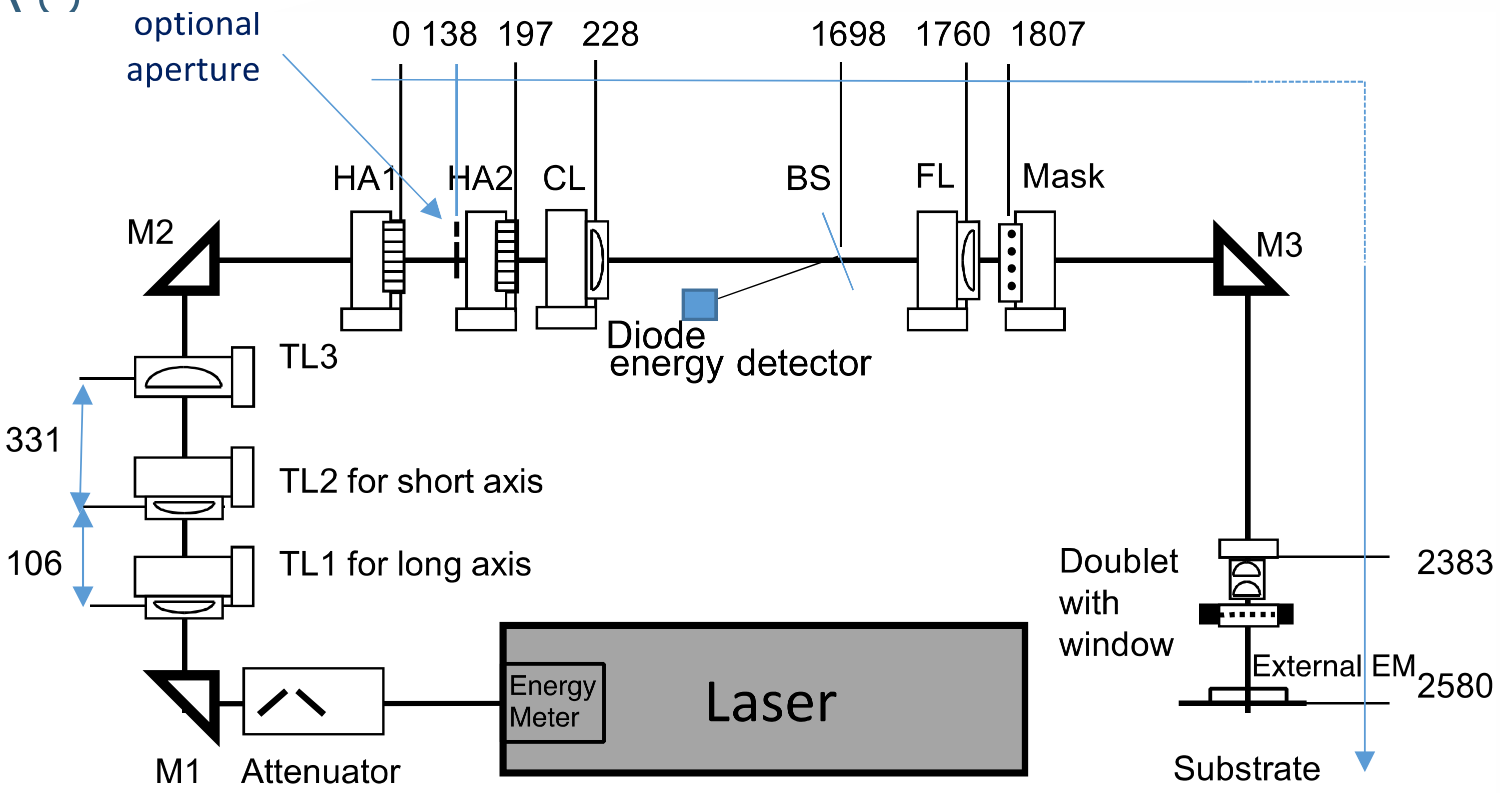


R(row2)
$\alpha\beta = 14\ T\Omega$
$\beta\gamma = 3\ T\Omega$
$\gamma\delta = 8\ T\Omega$
$\delta\alpha = 3\ T\Omega$



This system is under development

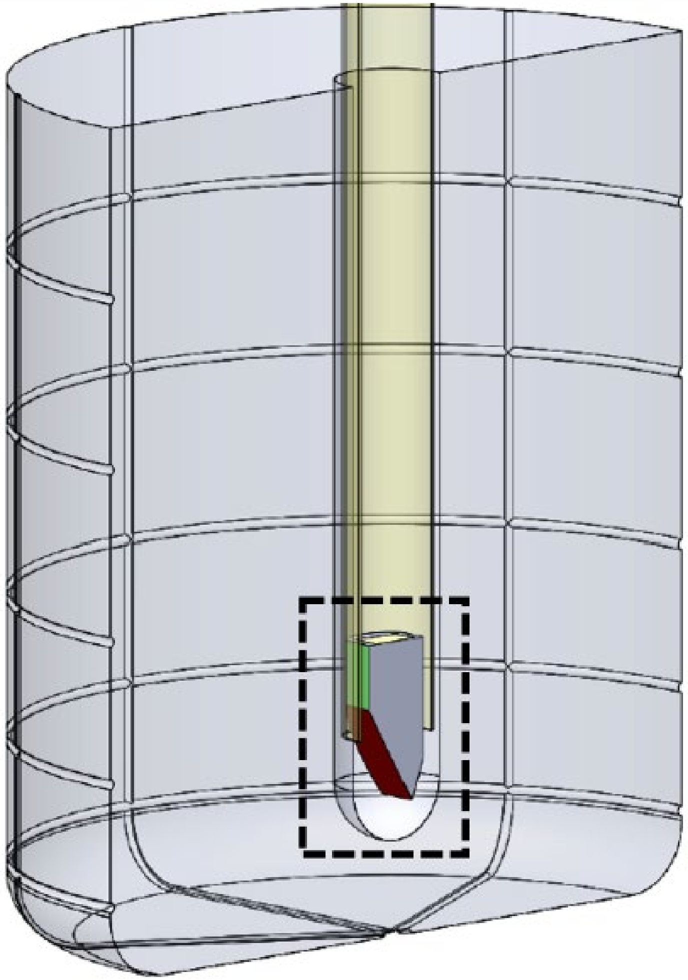
PLM on coaxial detectors: future tests



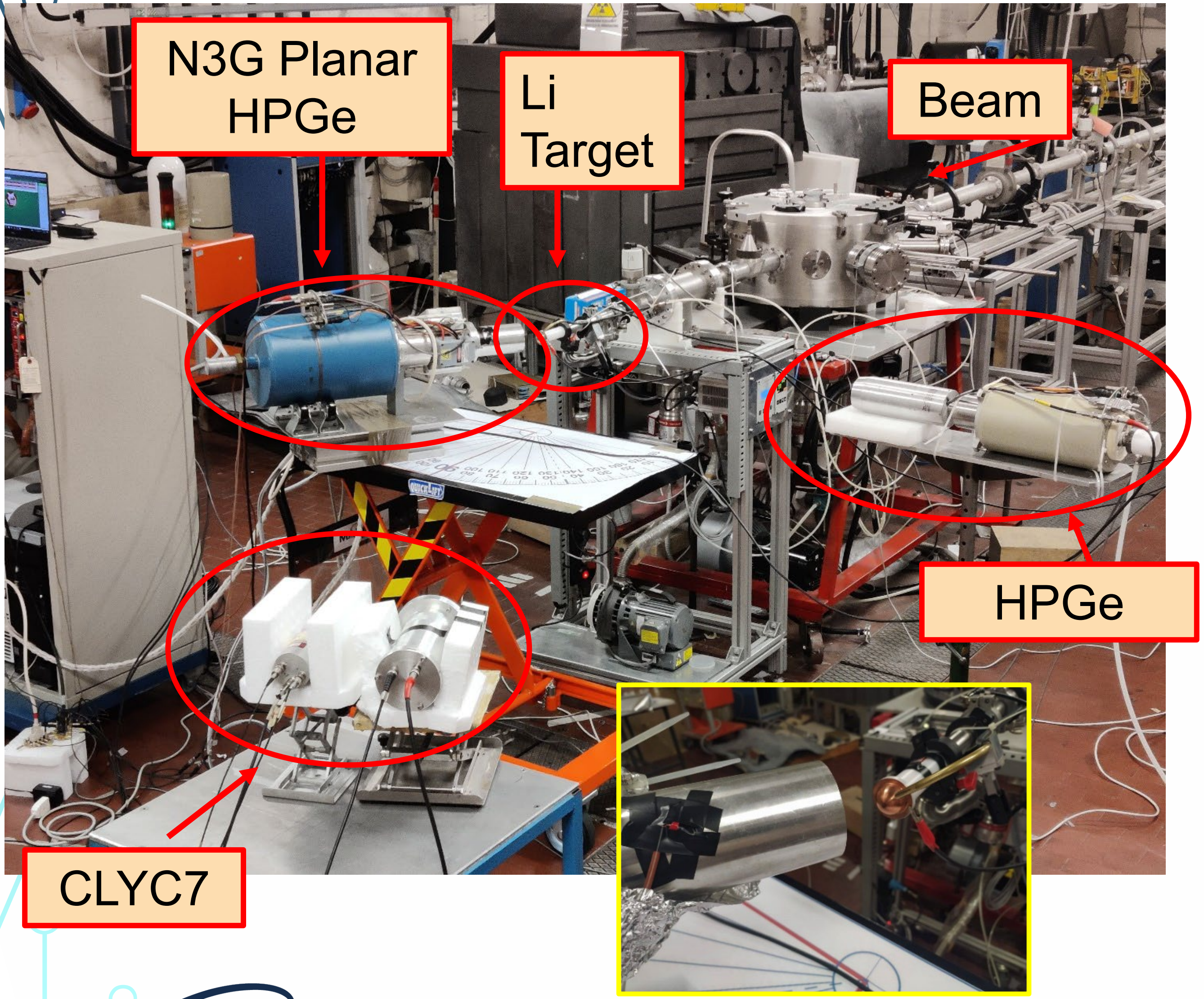
Excimer Coerent
KrF laser

- 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 stages & rot.

In preparation:
Prismatic guide for lasering
the inner coaxial detector hole



Neutrons damage on planar PLM segmented detector



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

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

Prototype detector is located at 30°, 9.5 cm

Neutrons are directly measured with

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

(^{7}Be + e- → ^{7}Li $\rightsquigarrow$ 477.6 keV)

R. Escudeiro, "Neutron radiation damage on a planar segmented Ge detector", XXXVII Mazurian Lakes Conference on Physics, Poland 2023

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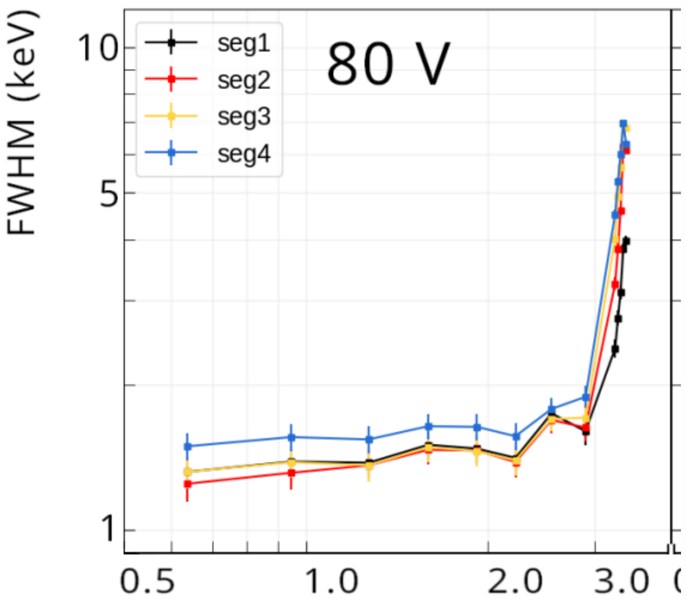
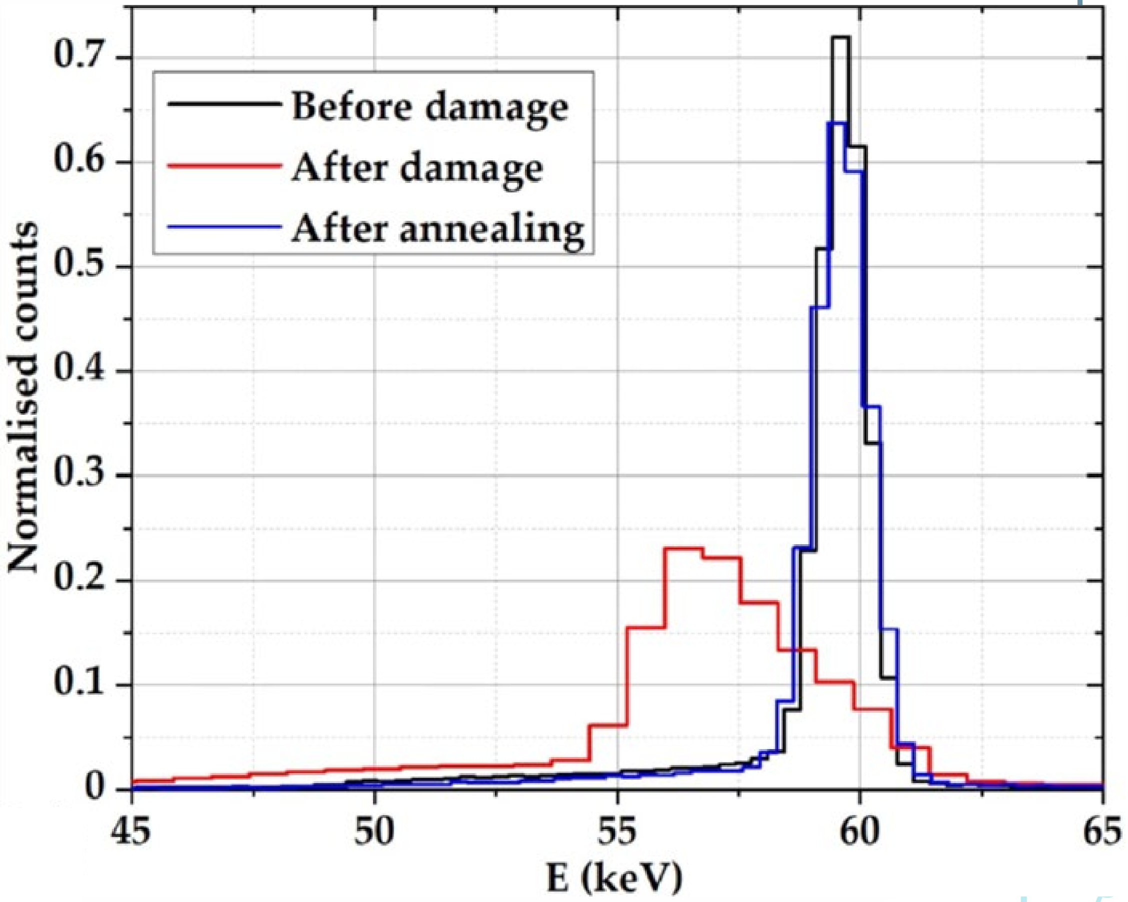
Neutrons damage on planar PLM segmented detector: After 2° run

Operational Voltage 80 V
Neutron irradiation for few minutes followed by 5 min gamma acquisition with ^{241}Am source to better characterize resolution worsening



Drastic drop in resolution after ≈ 3·10^{9} neutrons/cm^{2} irradiation fluence



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

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

Summary 1 – PLM detectors

- PLM is well known in microelectronics and we have been adapted it for HPGe detectors showing a new way for the production of HPGe gamma detectors. This technology preserves hyperpurity in the intrinsic bulk of the HPGe crystals and can be applied for producing thin, segmentable and thermally stable (annealing recovery) contacts in different 2D or 3D geometries.

- We have adapted Photolitography (PLP) for preserving HPGe hyperpurity as well for working with big samples. After PLP on gold plated surfaces, a gold-free lithography was developed exploiting the spatial control of the PLM Laser beam.

Summary 2 – shape and size of the PLM detectors

- Most of the variations have been tested in thin samples (2 mm thick) with two segments and the guard-ring on one side and a single contact in the other. The rate of success (breakdown voltage higher than depletion voltage and FWHM of 241Am < 0.7 keV) has been around 50%. In most of these cases we have collected transient signals that have been compared with simulations made within the COMSOL Multiphysics framework.

- For thicker crystals we have to upgrade our procedures in order to arrive to a breakdown voltage higher that the depletion voltage. For that, we have improved all the steps of the crystal surface preparation. We succeeded in obtaining a 2 cm thick planar detector with 1 nA at the depletion voltage. A critical point for this limit are the electrical contacts inside the cryostat which extract the signals from the crystal. We are developing new PCB coated elastic contacts.

Summary 3

- PLM segmented detectors recovers its resolution and efficiency after neutron damage for both p-type and n-type bulks.

- The PLM process has been implemented for producing a first segmented coaxial detector (50x50) that has been partially tested (only for the central row of the lateral segments) in a homemade encapsulation developed ad hoc. This work is in progress

- The PLM technology is the subject of a Research Collaboration Agreement between INFN (Italy) and Mirion Tecnologies (France) aimed to understand if this technique could be used for the fabrication of HPGe devices in an industrial framework.

R&D Gamma ray detectors Team

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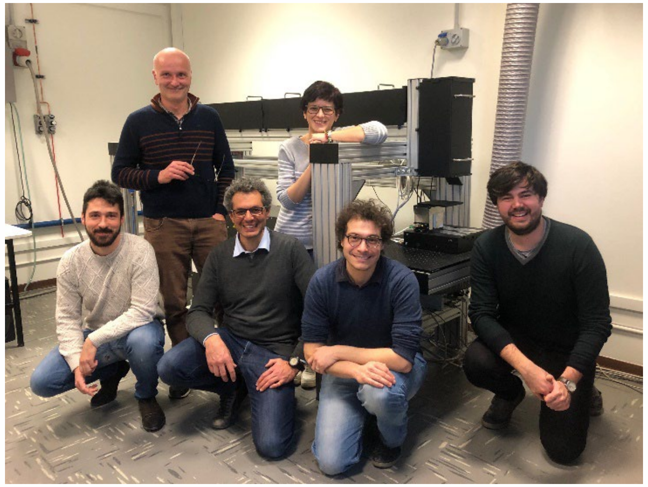
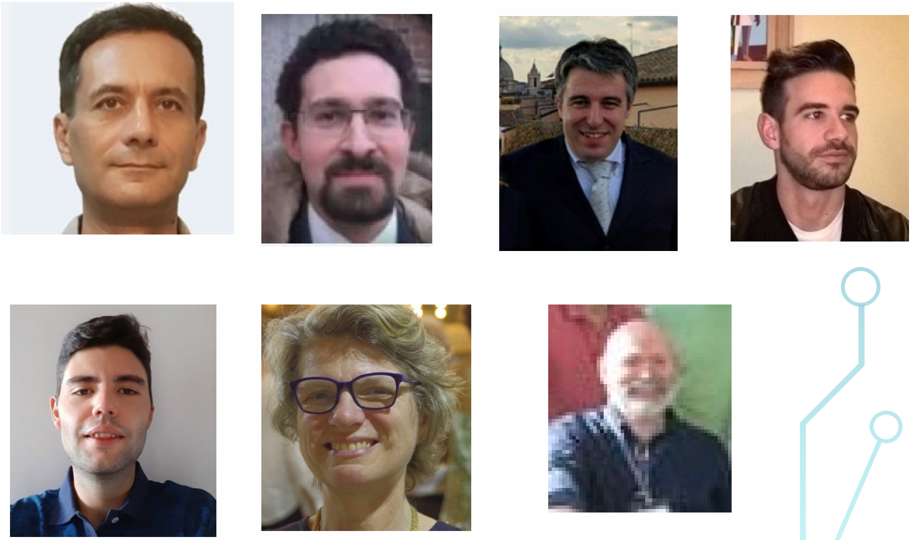
IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas





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