The path to Germanium Drift Detectors

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Outline

☐ Motivation

☐ State of the art of present low-capacitance detector developments in Ge and compound materials

☐ The INFN R&D project DESIGN

☐ Technical challenges for the development of a fully planar Ge-drift Detector

☐ First production & measurement plan

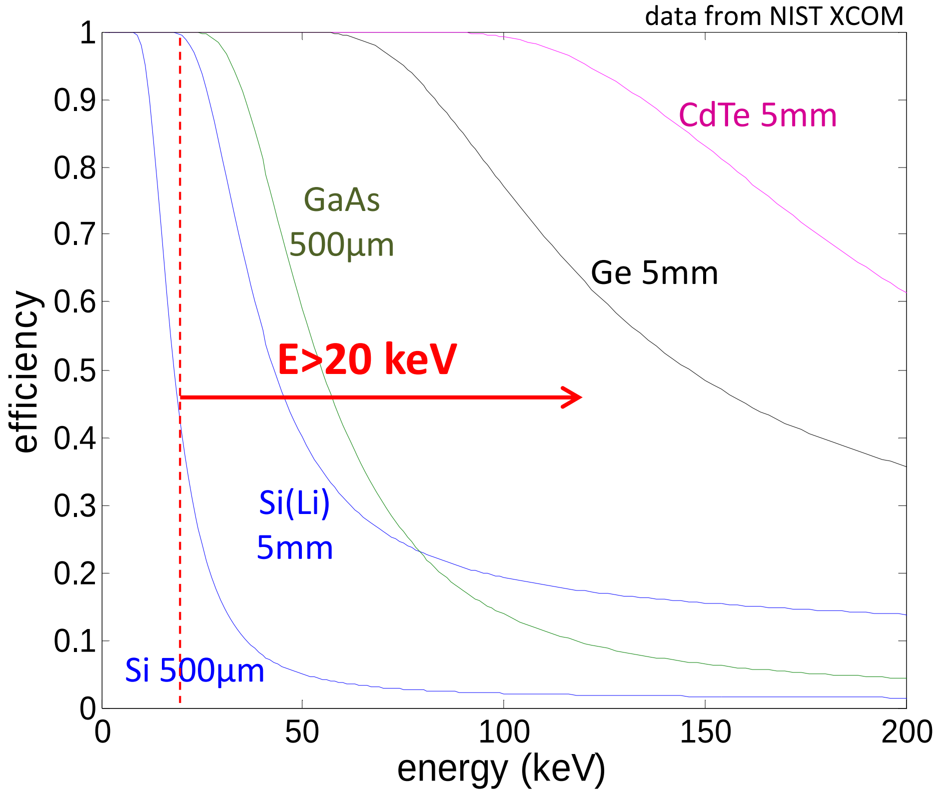
☐ Conclusions and outlook

Motivations

- In «thin» silicon technology (<1mm), **Si-drift detectors** brought a performance jump in X-ray spectroscopy by **breaking the tie between sensitive area and anode size**

- **Drift topologies** to a point-like contact in **high-Z and/or high-thickness materials** have been recently investigated to gain a number of advantages:
  - low capacitance, low electronic noise
  - shorter processing time / higher rate
  - screening of the signal charges during drift

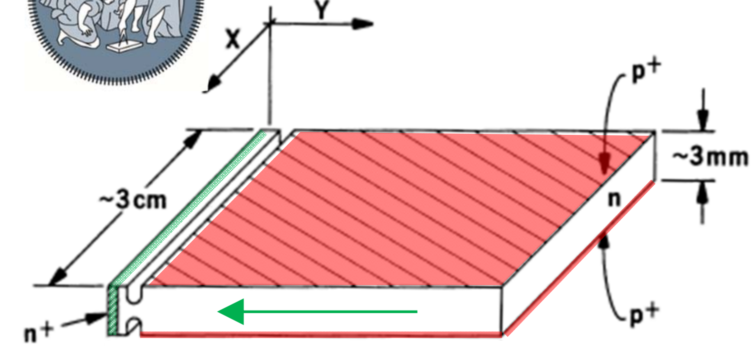
- **Ge is a natural candidate for drift topologies** given the superior properties of carrier transport and high-quality fabrication capability of planar Ge detectors (strips, pixels)



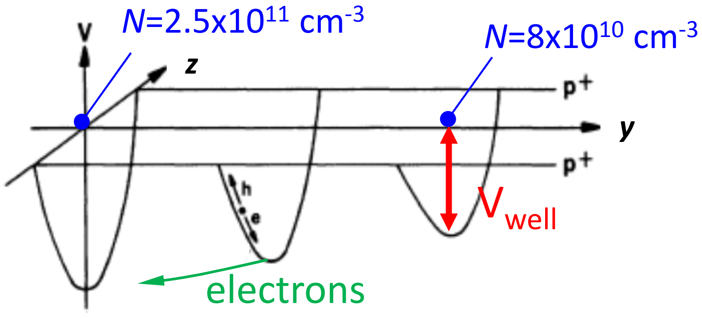
→ **Planar Ge-drift detectors** will open to high performance **above the ~20 keV limit** and – in perspective - to **monolithic arrays**

One of the first (& successful) GeDD (1985)

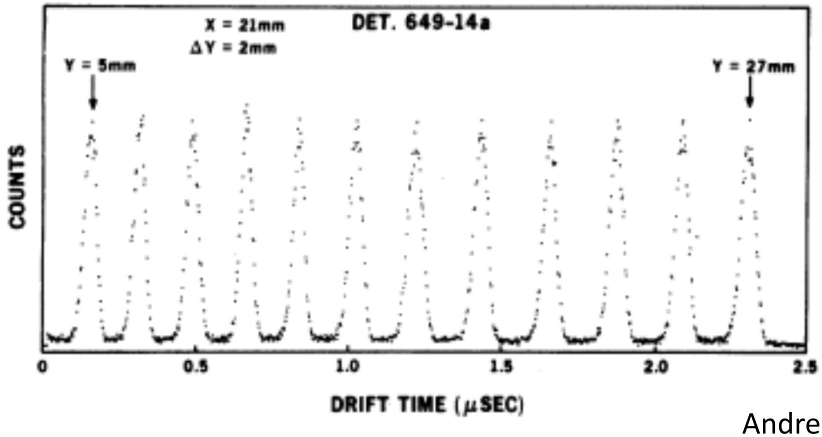
P.N.Luke, N.W.Madden, F.S.Goulding, IEEE TNS (1985)



d*N*/dy impurity gradient



Time spectra of y-scans (60 keV)



- **impurity concentration gradient along the drift** coordinate used to obtain the transverse field without contact segmentation.
- if the impurity concentration N(x) grows towards the anode, depletion occurs at increasing bias giving rise to a **'built-in' transverse field**:

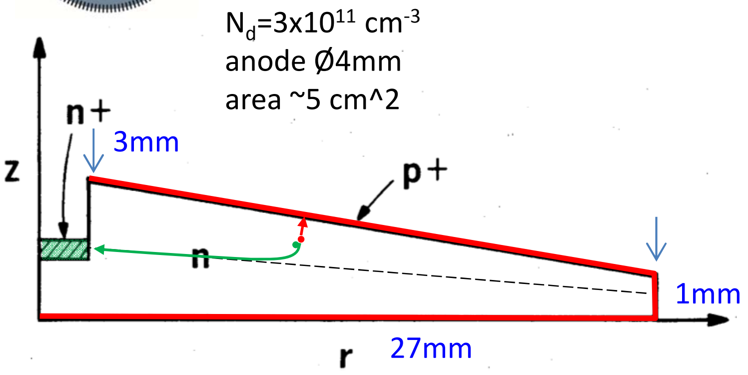
$$E_{drift} = \frac{dV_{well}}{dy} = \frac{qd}{8\varepsilon}\frac{dN(y)}{dy}$$

- makes use of the increasing n-type concentration towards the tail of Ge crystal during growth

  → slice cut parallel to the growth axis (!)

- The obtained drift fields ~50 V/cm allow position-sensing (el. speed ~10µm/ns)
- moderate spectral resolution/transport quality due to trapping & uncontrolled impurity gradient in the material

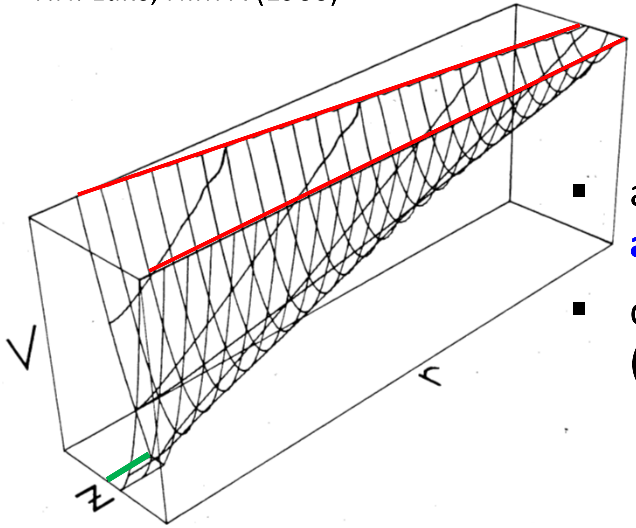
Tapered structures (1988)



- cylindrical geometry for spectroscopic applications
- radial impurity concentration unpracticle:

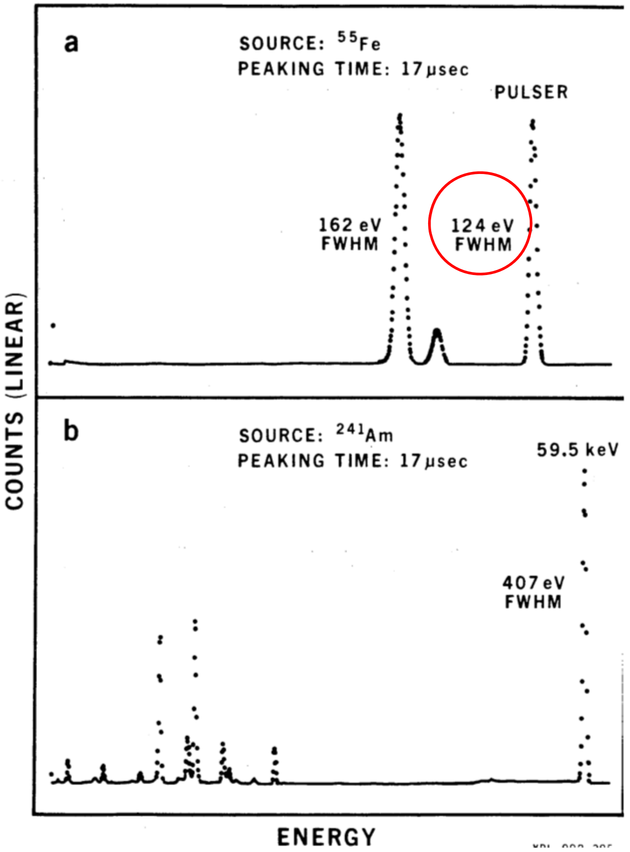
  → **tapered structure**
- depletion will occur first at the rim of the device and then propagates towards the anode

P.N. Luke, NIM A (1988)



- at full depletion **1.4 pF anode capacitance**
- drift field from 180 V/cm (rim) to 450 V/cm (anode)

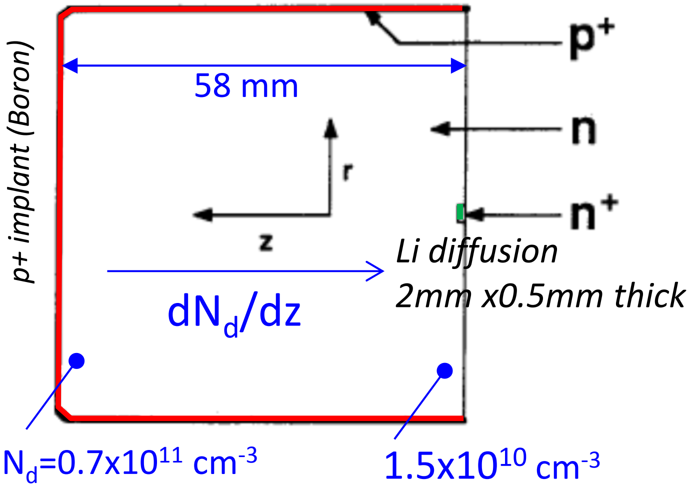
  → collection time ~300ns



- no significant trapping effects
- **obtained 124 eV FWHM/53 eV rms (JFET 2N4416 !)**

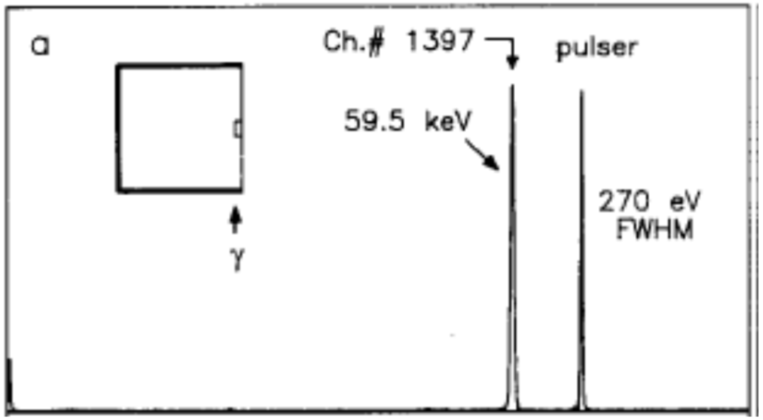
Point-contact (field-shaping) in Ge detectors

N-type «shaped-field» HPGe det.



P.N.Luke, et al. IEEE TNS 1989

- several designs proposed with field-shaping in the Ge detector towards a **small point-contact (anode)**
- main drive is the upgrade of large-mass Ge detectors for ultra-low background experiments /dark matter
- an **axial field is obtained** with an **axial impurity gradient**, already available as a result of segregation (e.g. P) during crystal growth



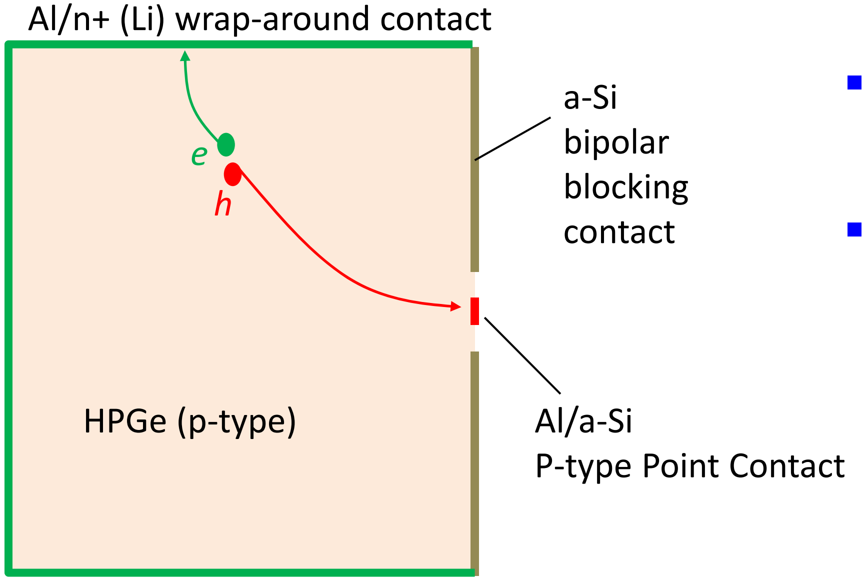
- achieved **0.9 pF** capacitance and **270 eV FWHM** noise
- electron trapping effects greatly enhanced in this geometry: peak shift of the order of 3%

P-type Point-Contact (PPC) HPGe detectors

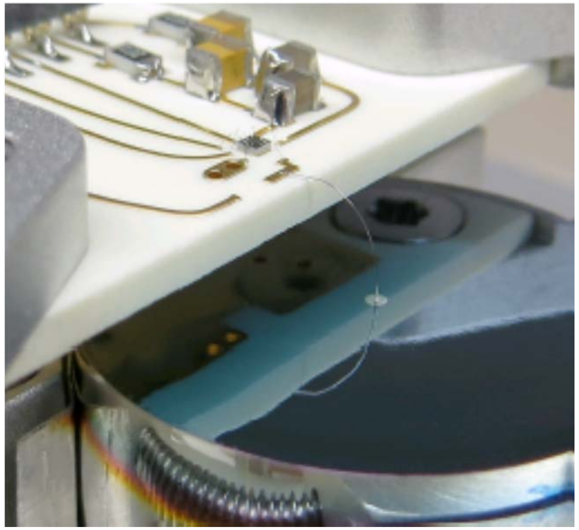
- P-type HPGe version

P.S.Barbeau, J.I.Collar, O.Tench, J. Cos. Astr. Phys (2007)

P.Barton et al., NIM A 812 (2016)

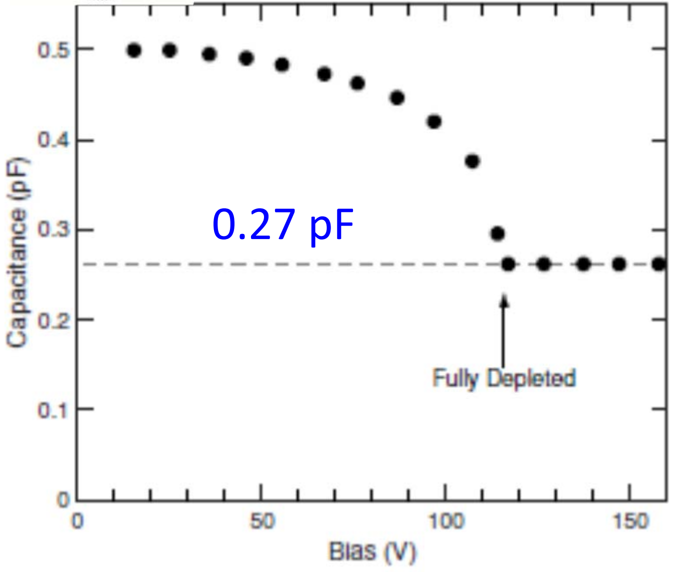


- same as before but **P-type starting material**:
  - improve trapping effects (electrons more sensitive to dislocations)
  - increase dead layer of closed-end with thick (~0.5mm) Li diffusion to reduce background (beta’s, x-rays, etc)
- a-Si used as passivation for back contact due to bipolar-blocking properties
- a-Si more effective as electron-blocking contact (w.r.t to a-Ge) for the point-contact

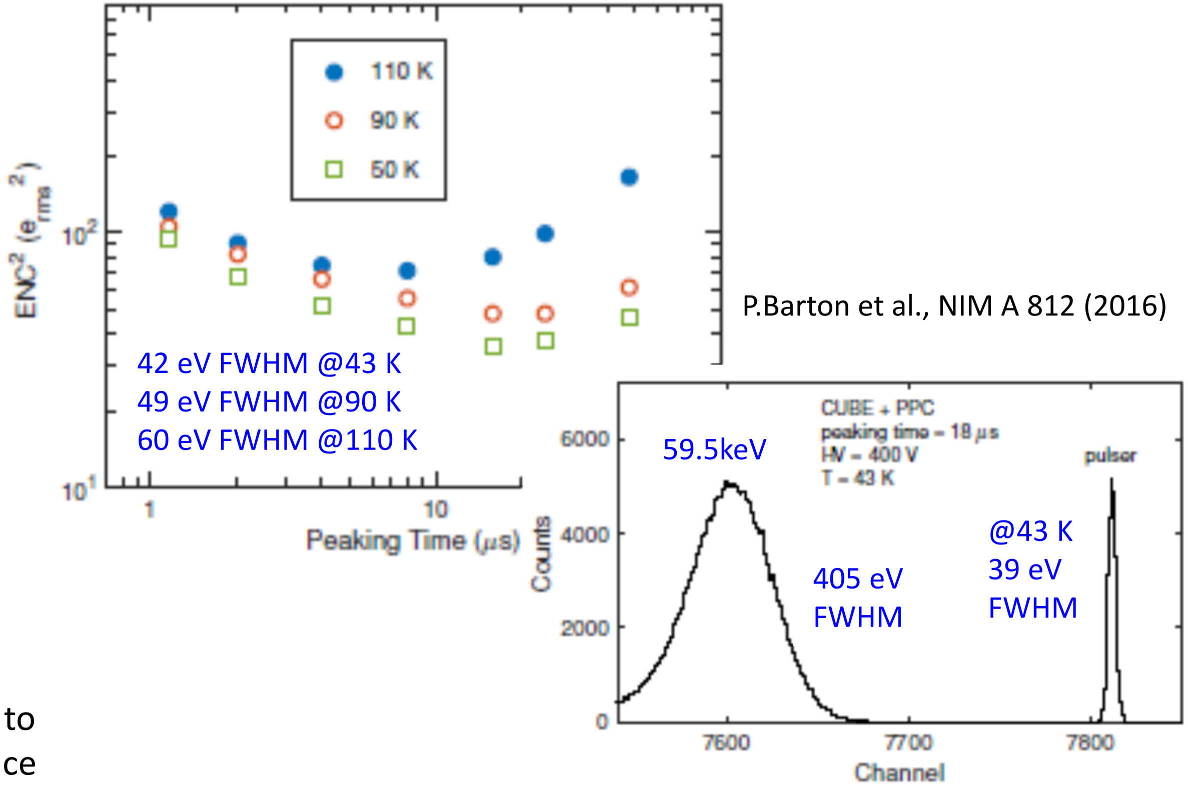


reduced size of point-contact (0.75mm)
wedge bonding (instead of a tensioned pin)

P-type Point-Contact Ge detectors: best results & open challenges



0.27 pF



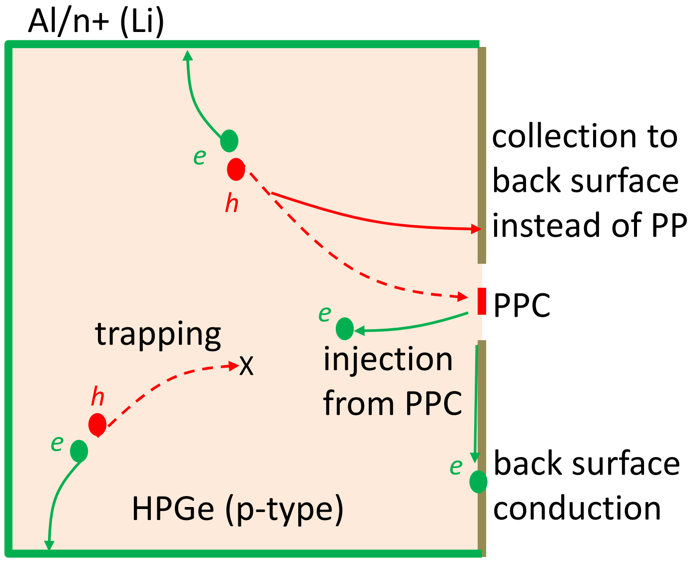
42 eV FWHM @43 K
49 eV FWHM @90 K
60 eV FWHM @110 K

P.Barton et al., NIM A 812 (2016)

59.5keV

405 eV FWHM

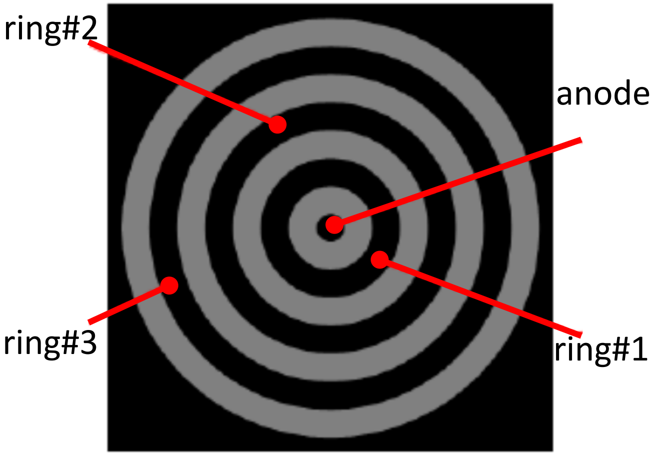
@43 K 39 eV FWHM



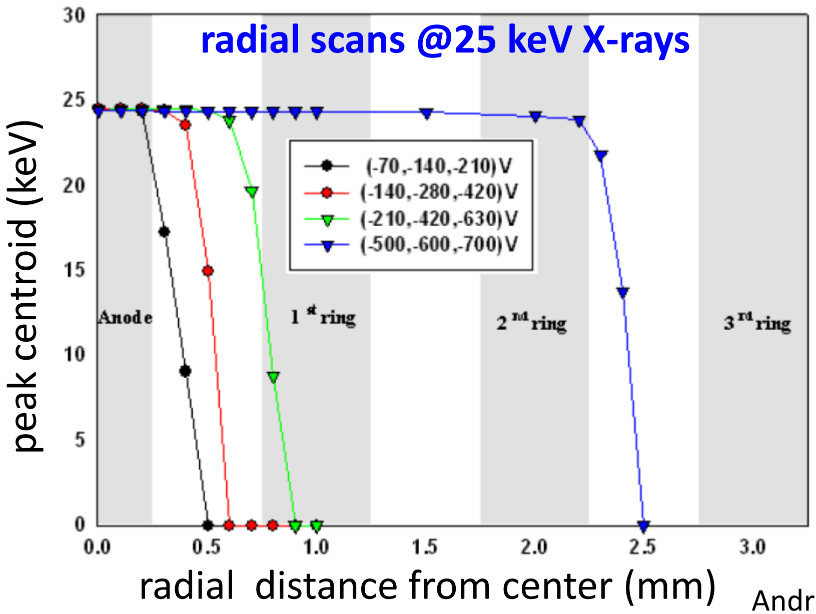
- field-shaping towards a **small point contact** and **low noise readout**: noise levels among the lowest with HPGe.
- open challenges:
  - trapping
  - back surface effects
  - injection from point-contact

CZT drift ring detector

CZT 2.3mm thick (Redlen)
0.5mm anode
0.5mm rings + 0.5mm gaps

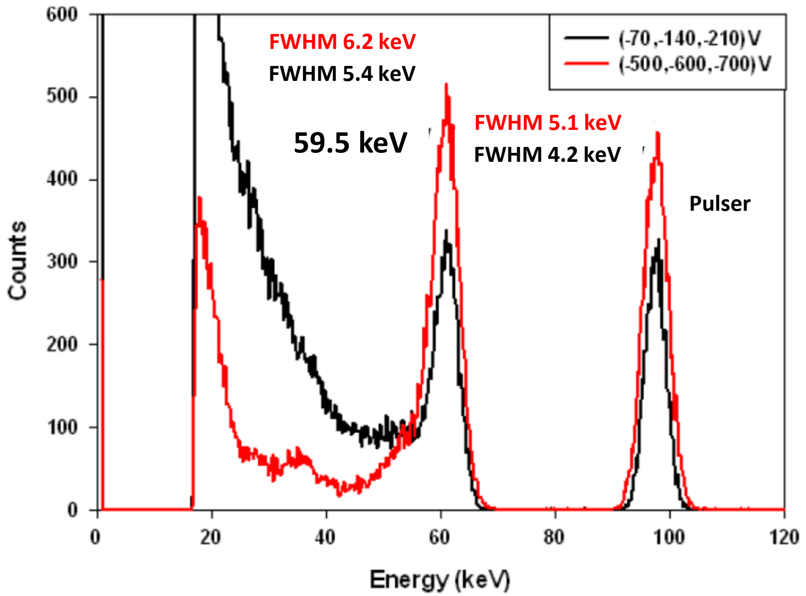


A. Alruhaili, et al. JINST (2015)



- good quantum efficiency / room temperature operation for spectroscopy at high energies
- poor hole transport requires PSD techniques or novel electrode geometry to avoid severe degradation of energy spectra

  → cylindrical drift topology



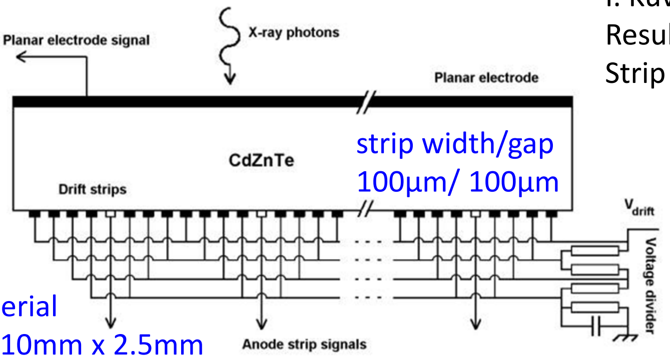
- increasing lateral & bulk fields improves CCE
- leakage current <0.2nA
- 5-6 keV energy resolution @59.5keV (center of CZT)

CZT drift-strip detector

I. Kuvvetli, et al., NIM A624 (2010)

- developed for X- and gamma ray detectors for future HE Astrophysics (high detection efficiency, good energy resolution as well as position sensitivity).

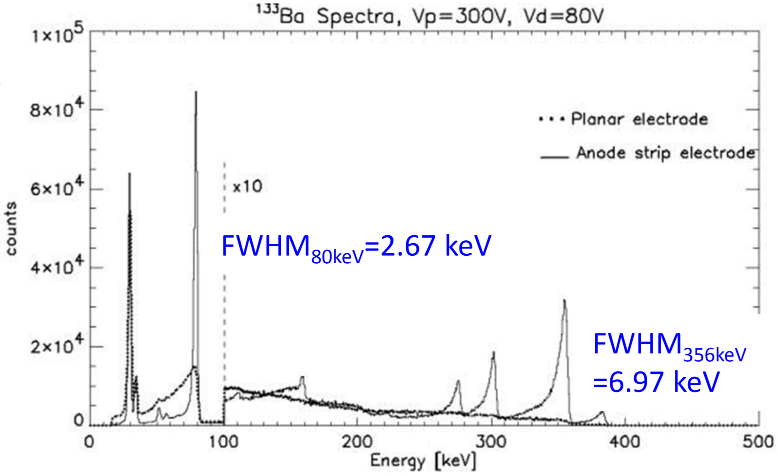
- drift-strip topology reduces sensitivity to holes' trapping and allows correction for residual contribution of holes (cathode/anode signal ratio)



strip width/gap
100µm/ 100µm

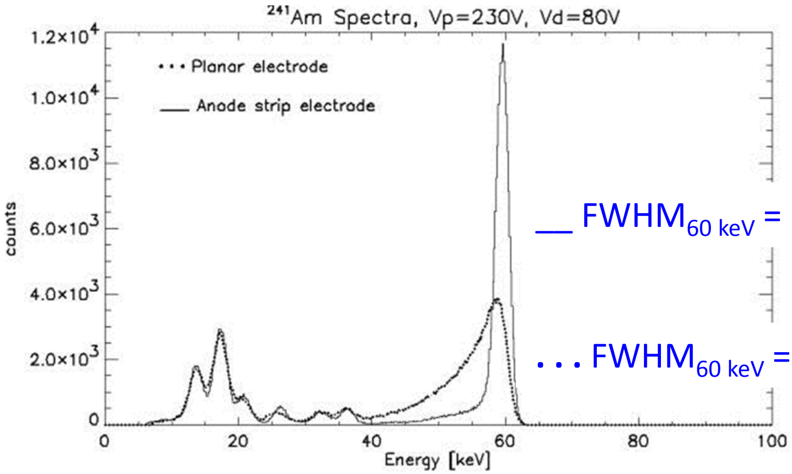
CZT material
10mm x10mm x 2.5mm
(eV product)

I. Kuvvetli, et al., New Results for the CZT Drift-Strip Detector (2018)



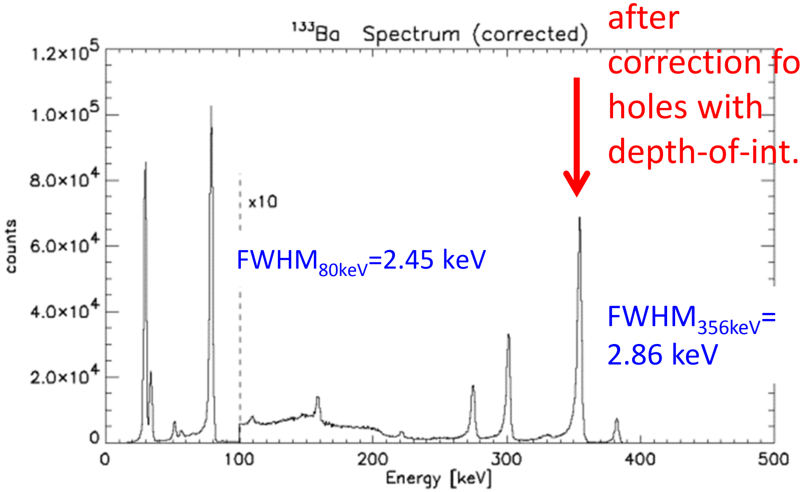
FWHM_{80keV}=2.67 keV

FWHM_{356keV} =6.97 keV



—— $\text{FWHM}_{60\ keV}$ = 2.18 keV

. . . $\text{FWHM}_{60\ keV}$ = 6.31 keV



after correction for holes with depth-of-int.

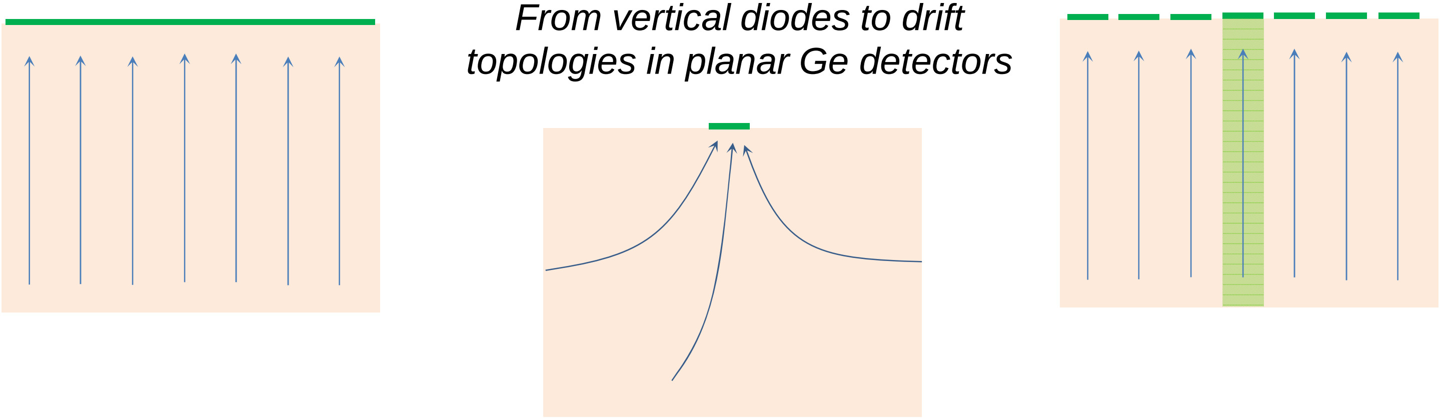
FWHM_{80keV}=2.45 keV

FWHM_{356keV}= 2.86 keV

R&D project DESIGN

Innovative **D**rift topologi**E**s in thick **SI**licon or **G**erma**N**ium detectors for hard X- and gamma-ray spectroscopy

- A pilot R&D project approved by Istituto Nazionale Fisica Nucleare (INFN) to investigate feasibility of **novel Ge-drift prototypes** in **full planar technology** and qualify technological/detector properties.



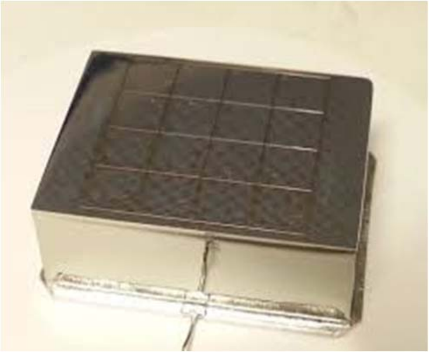
From vertical diodes to drift topologies in planar Ge detectors

The good opportunity to go “planar”…

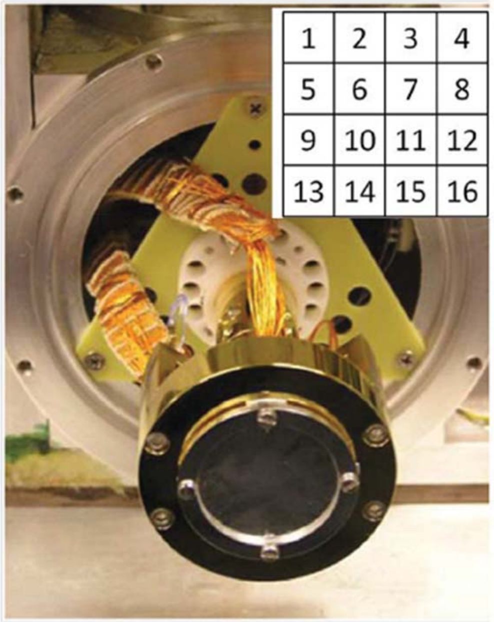
❑ Planar process for HPGe detectors at Semic. Lab, FZ Julich (D)

- semiconductor lab founded by D. Protić and continued by T. Krings, well known producer of detectors for NP experiments and synchrotron experiments in EU and US.
- well known expertise in the field for Ge/Si(Li) segmented detectors of high quality (microstrips, pads, pixels)
- intention to upgrade the fabrication process of HPGe detectors to make it adequate for the implementation of drift topologies.

Si(Li) detector for the EXL experiment at GSI



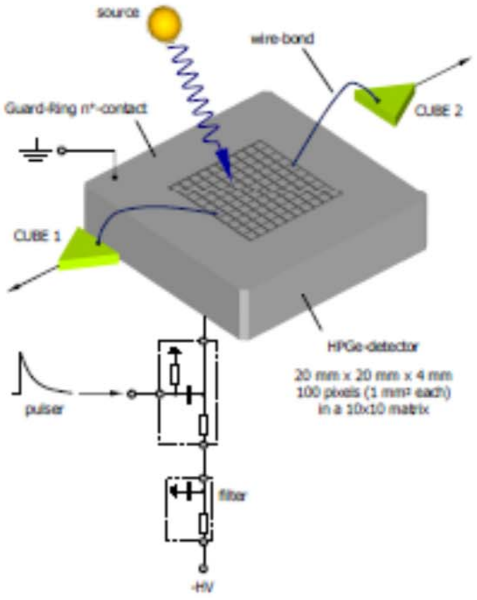
T. Krings, 15th Intl. Workshop on Radiation imaging Detectors, IWORID 2013



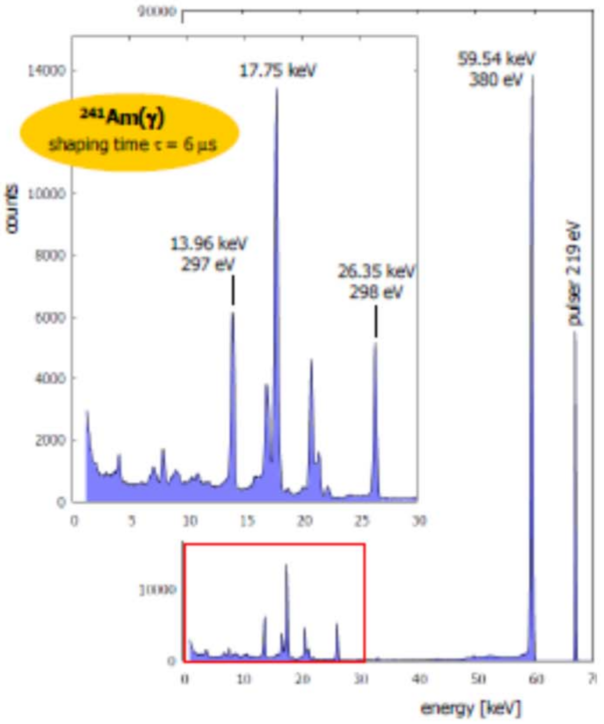
1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

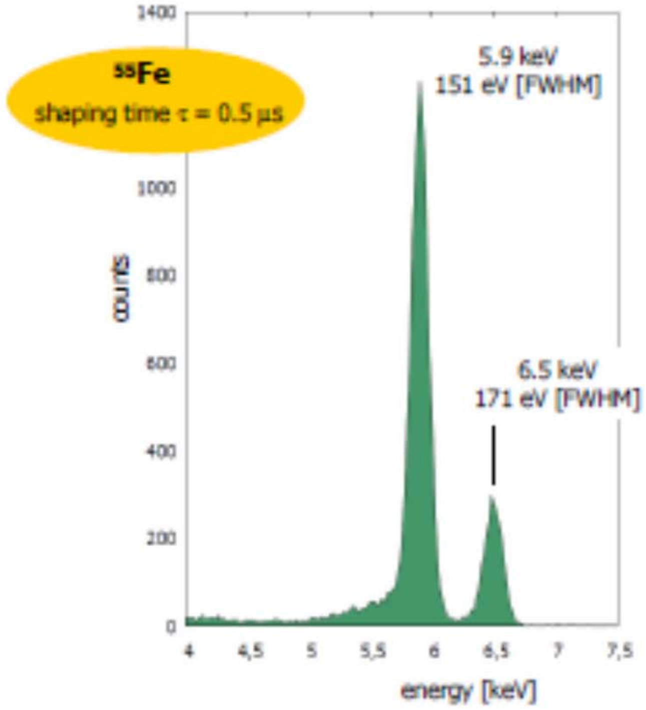
Fig. 2. The crystal holder mounted in the cryostat with an aluminum foil 10 μm thick acting as infrared radiation shield. The orange flat cables are the kapton insulated cables connecting the CPCB to the feedthroughs on the rear flange. The diagram shows the correspondence between channels and pads as the crystal is seen from the entrance window.

Production technology of HPGe at FZ Julich and compatibility with low-noise goal



T Krings, et al., JINST, May 2014





- quality of FZJ production technology of HPGe detectors (e.g. leakage, contacts, minimum line-width) proved suitable for low-noise/high-energy resolution measurements in multi-element HPGe detectors.

Open points/technical challenges

❑ Technological issues

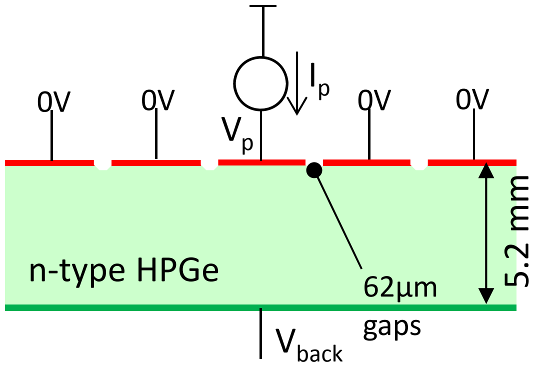
- double-side/multi-mask process (p- and n-contacts on same side)
- contact choice/reliability (Li diffusion, Boron implant, a-Ge, a-Si, …)
- fabrication of the inter-strip grooves between p+/ p+ and p+ /n+

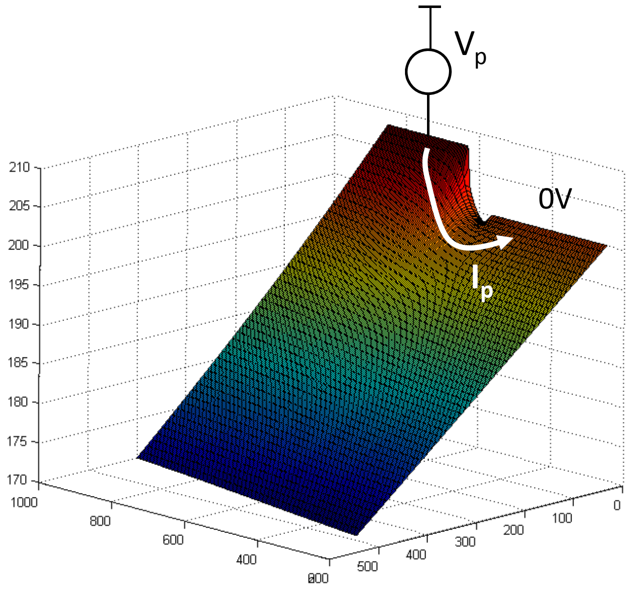
❑ Design issues

- Very High-Resistivity substrates (HPGe)
  - Loose spatial confinement of generated charge cloud in the bulk
  - Difficult to move the electron cloud towards the anode located at the surface
- Charge collection in the anode region
  - «groove» technology penetrates in the bulk, risk for charge loss close to the collection anode
- Punch-through between adjacent p+ strip/properties of the surface in the inter-strip region
- Optimization of electrode geometry, bias, doping, thickness

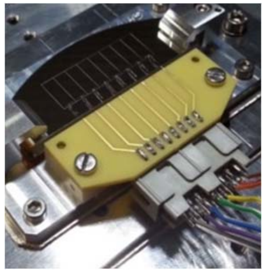
“Punch-through” tests on HPGe @77K

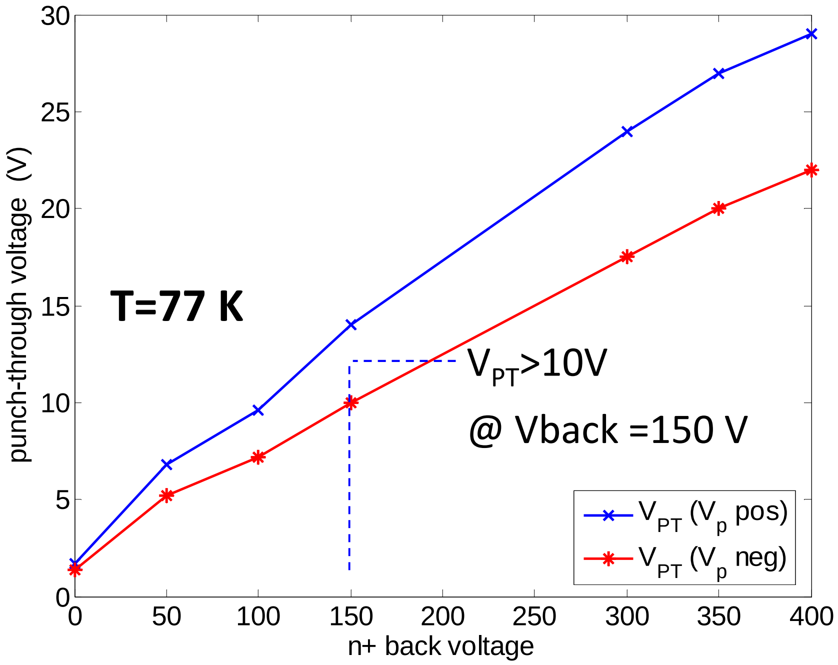
- prerequisite for achieving sufficient drift fields
- onset of hole conduction (punch-through) between adjacent p+ strips, as a function of depletion voltage of back contact
- (average) punch-through voltage >10 V @Vback=150V



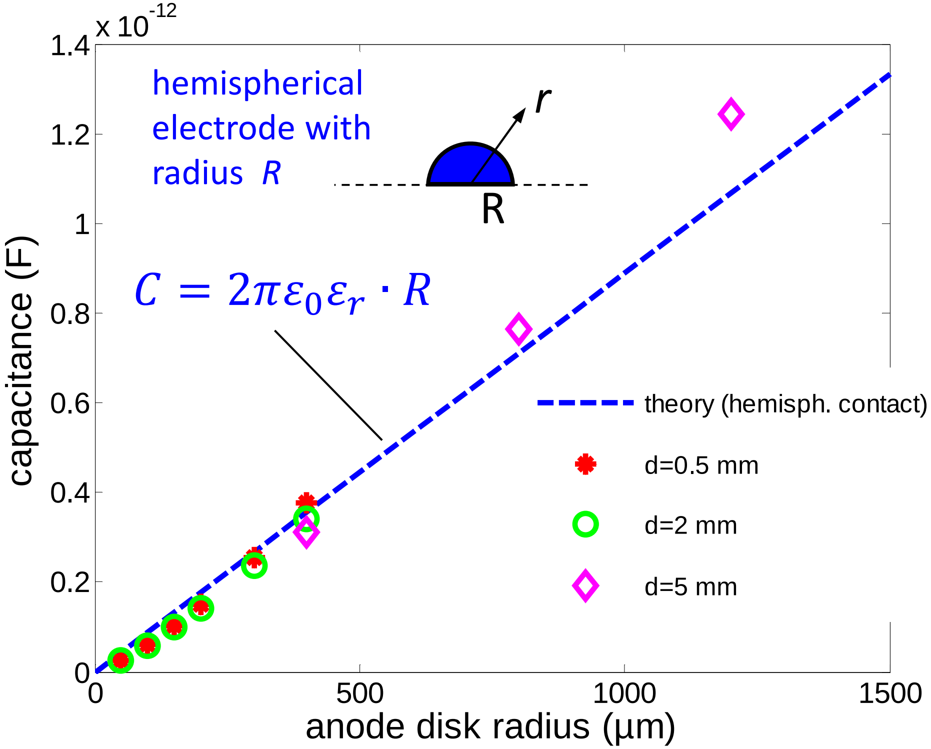


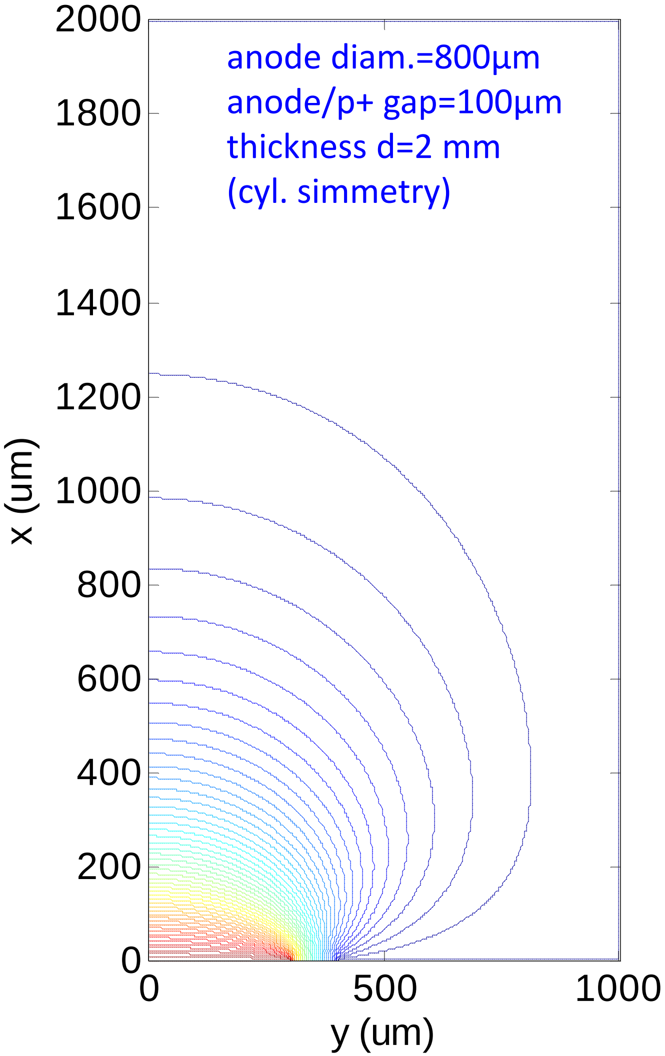
HPGe material
7.5-8 10^9 cm^-3
5.2 mm thickness





Anode capacitance in planar technology



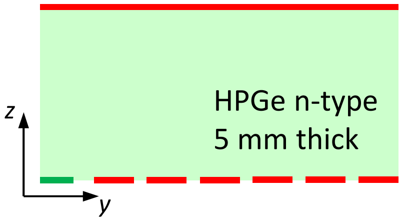


- anode capacitance (simulated) in planar technology as a function of anode radius for different parameters (thickness, electrode gap, etc.)
- anode cap dependent only on anode size:

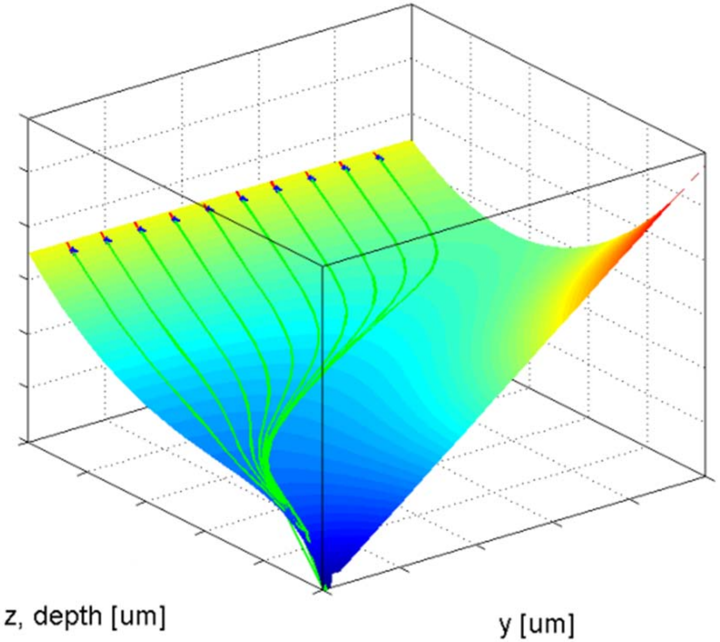
anode diameter 1 mm → C_{anode} < 0.5 pF

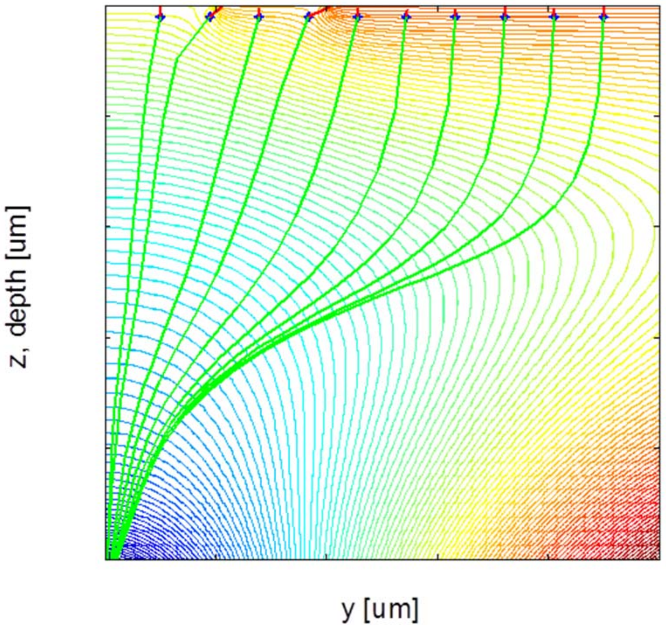
Simulation of carrier transport cylindrical GeDD in planar technology (1)

- uniform back-side



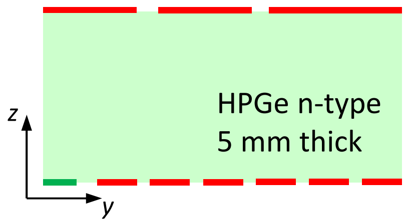
- Ge thickness 5mm
- T= 77K
- central region:
    - o 20 µm/ns
- max e+h collection time: 310 ns/5mm



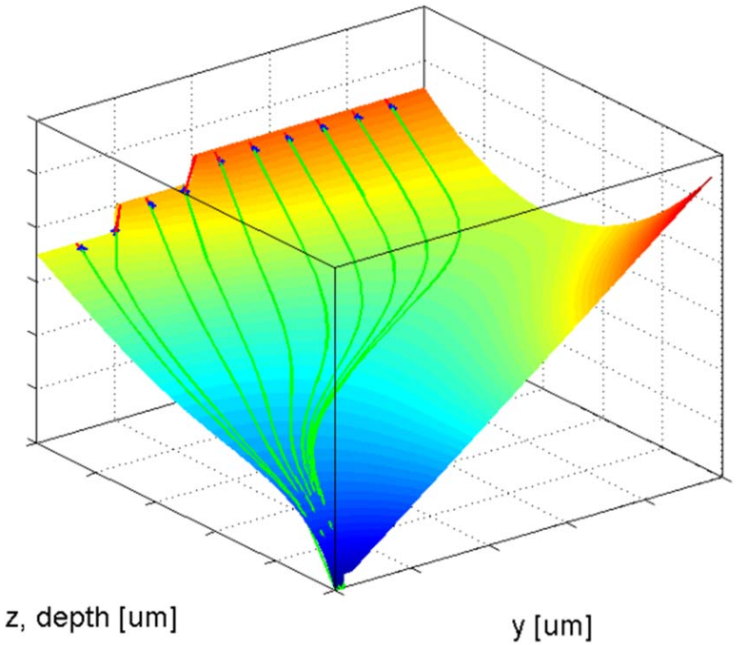


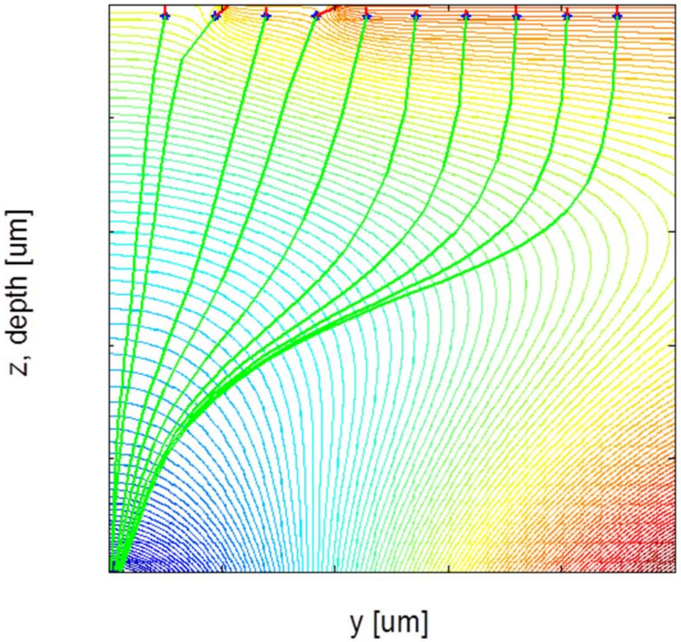
Simulation of carrier transport cylindrical GeDD in planar technology (2)

- segmented back-side



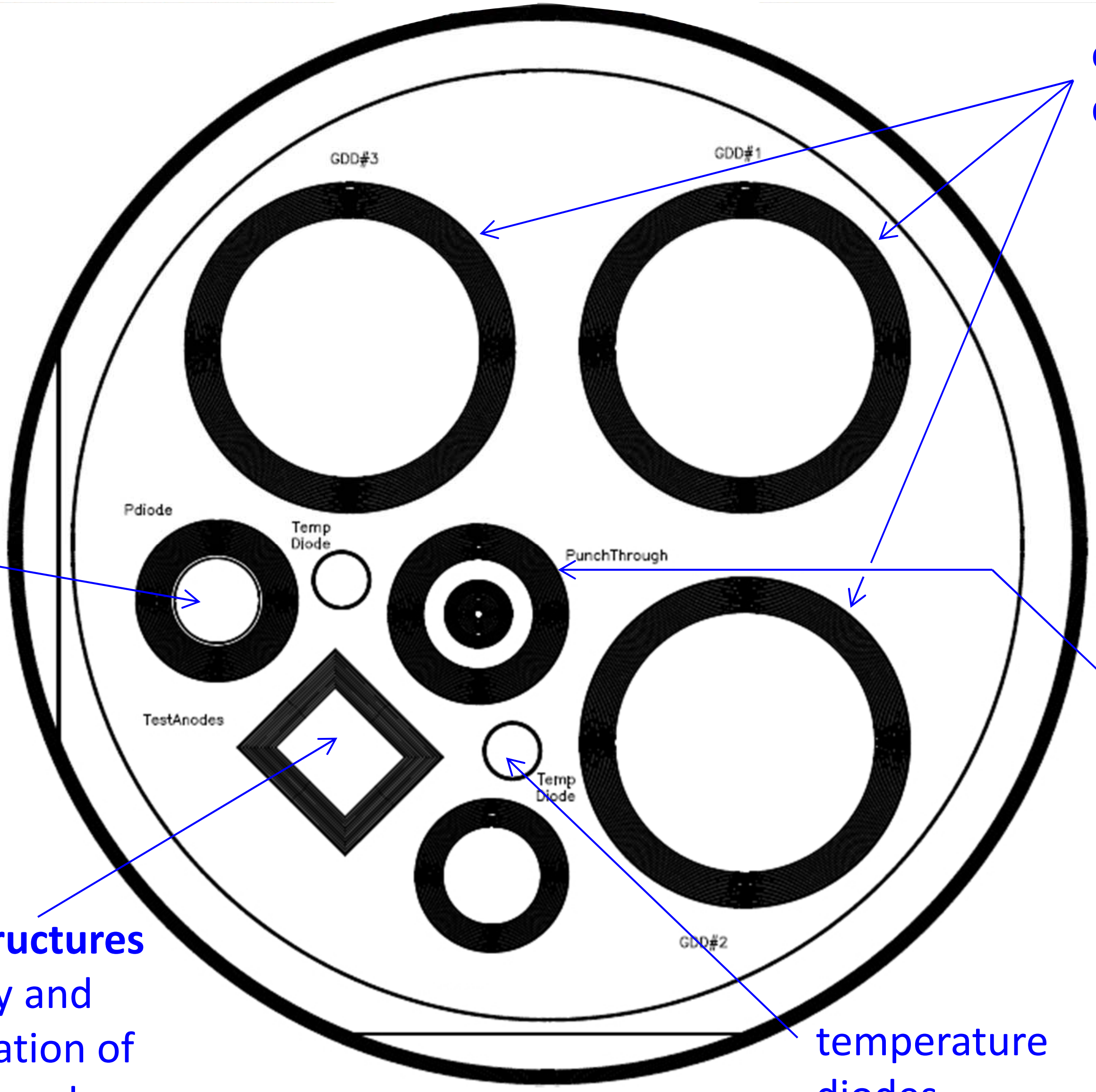
- Ge thickness 5mm
- T= 77K
- central region:
    - o 25 µm/ns
- max e+h collection time: 210 ns/5mm





segmentation of back side can be used to effectively increase electron velocity/reduce collection times

1st production batch of test structures and drift prototypes on 3-inch HPGe wafer @FZJ



cylindrical drift prototypes

[strip geometry (drift and HV region)
drift field/max el. velocity
radial charge collection]

pn diodes for material qualification (leakage, capacitance, doping, etc.)

study of **punch-through** effects between strips of different geometry

anode test structures for technology and noise optimization of readout front-end

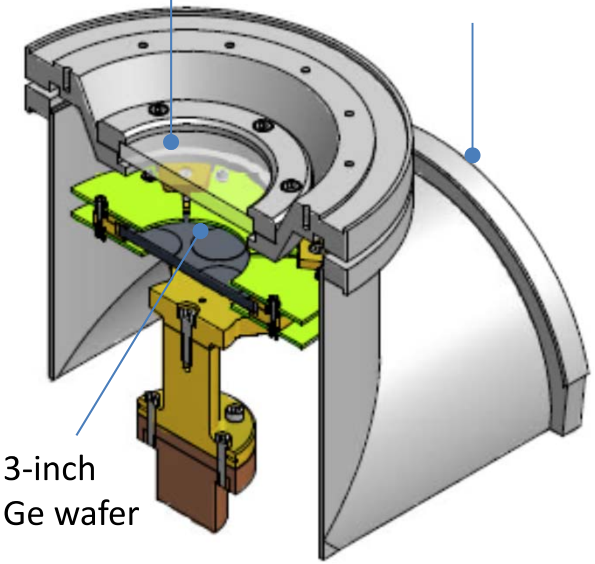
temperature diodes

feb 2018
masks finalized

Measurement plan

quartz window for
optical injection
(IR laser)

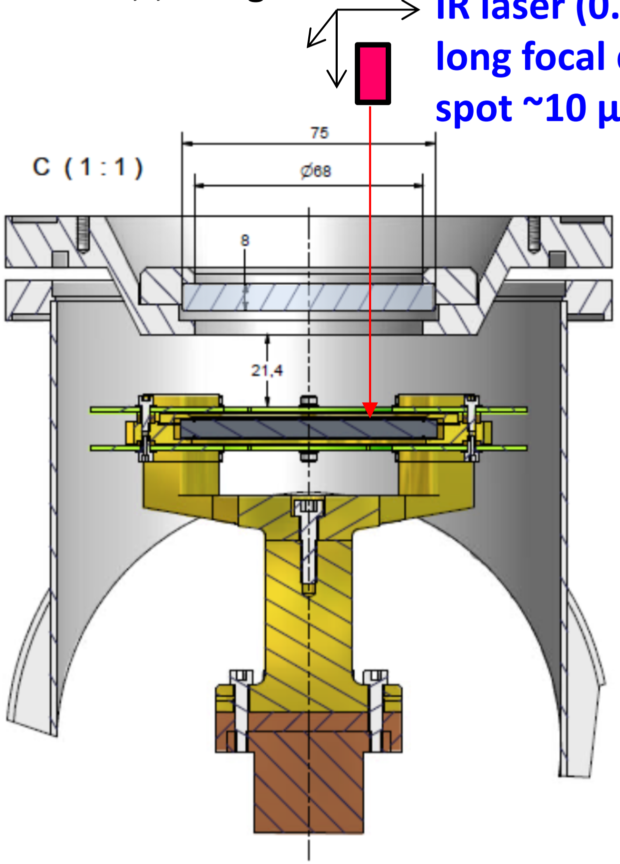
side flange for
mechanical feed-thru
to move collimated
radioactive source



3-inch
Ge wafer

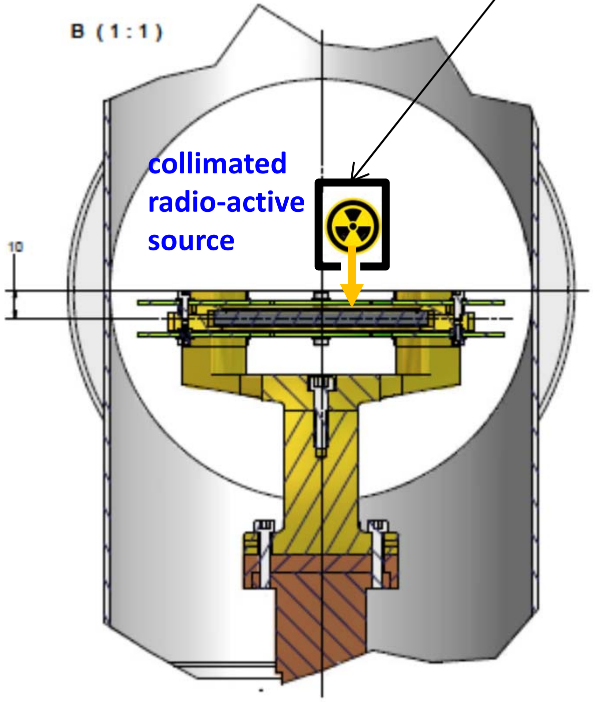
cryostat

X,Y,Z stages



IR laser (0.1ns, 705-905nm)
long focal distance
spot ~10 µm

1-D mechanical
feed-thru

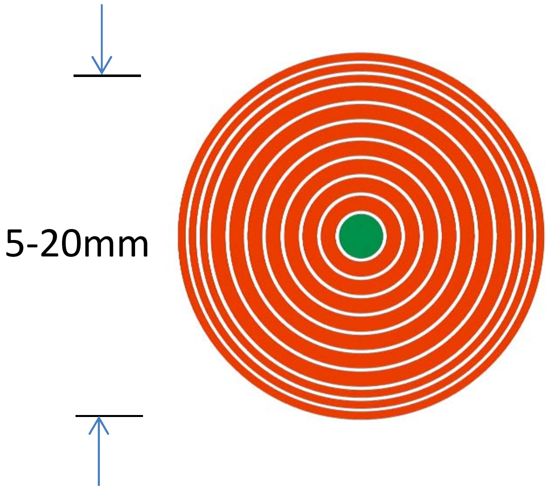


collimated
radio-active
source

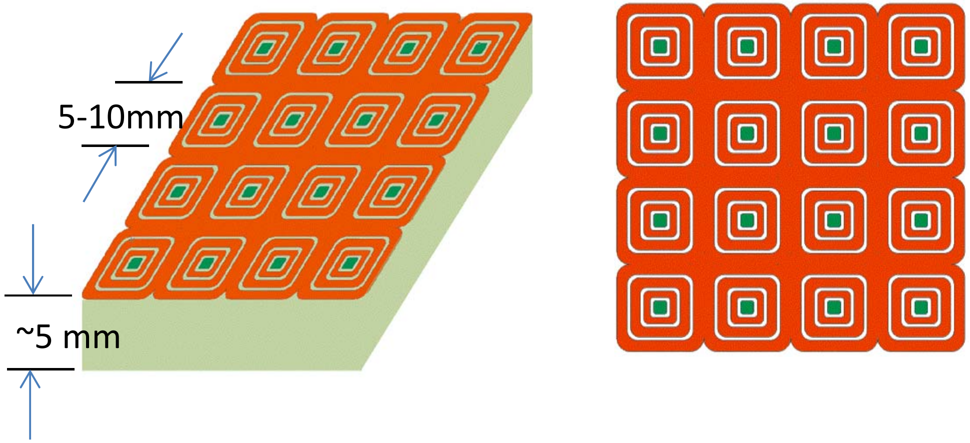
- 2-D scans with IR pulsed laser (~10 µm) and collimated radioactive sources (~0.5mm) to perform carrier transport studies at wafer level without unmounting the wafer from its holder

Planar technology: the key element towards multi-detector arrays

- «large» area single drift-detector unit



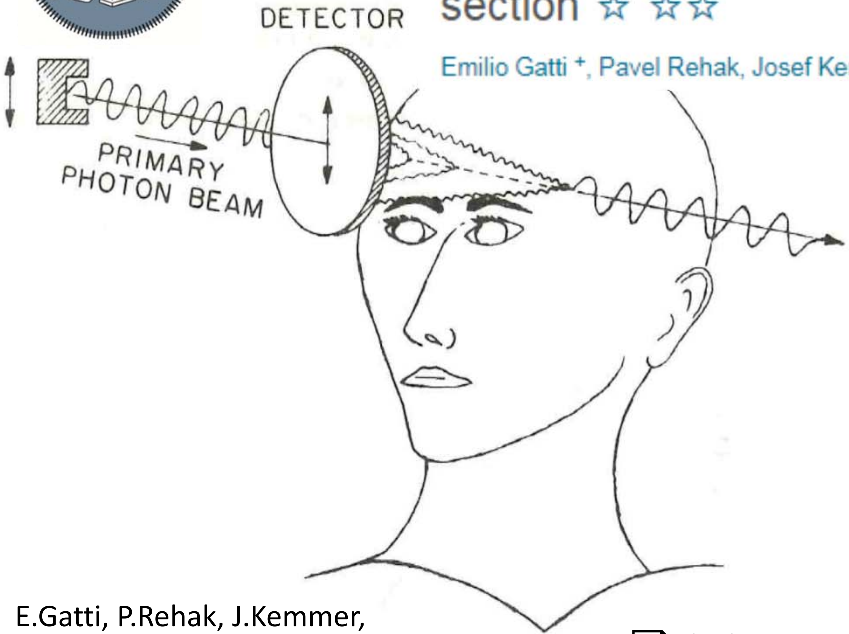
- drift-detector macro-cells suitable for monolithic arrays



- implemention of a GeDD in a full planar process opens the way to integration of «drift» topologies into «macro-pixels» to build energy-resolving high-resolution monolithic arrays that can be optimized to the specific application/experiment.

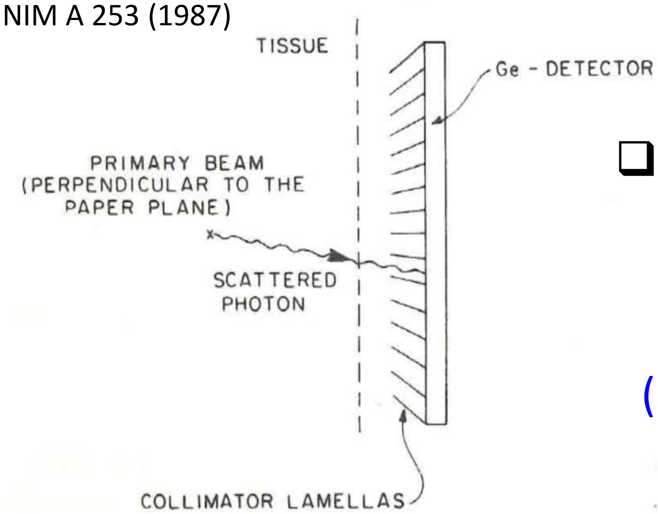
Germanium drift detector: A new tomographic device providing information on the chemical properties of a body section ☆ ☆☆

Emilio Gatti +, Pavel Rehak, Josef Kemmer NIM A 253 (1987)

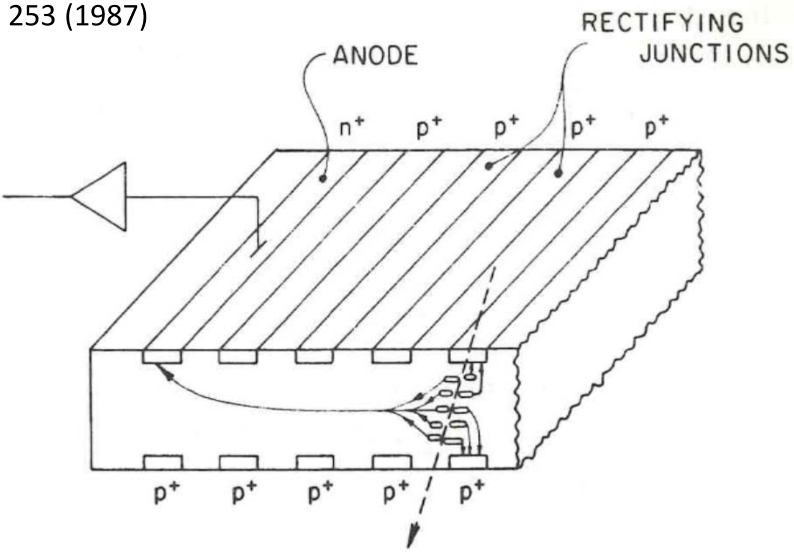


(a)

E.Gatti, P.Rehak, J.Kemmer,
IEEE TMI (1986)
NIM A 253 (1987)



(b)



- ☐ it is a work of 1986/87, already assuming the availability of position-sensing GeDD’s, just after the group in LBL developed the first working GeDD
- ☐ they even proposed a <u>fully-depleted CCD in thick Ge</u> with these words: «A fully depleted CCD has not yet been built. However (…) we are confident that our analysis is correct»

(and they were actually right, at least for the concept of the fully depleted CCD…)

Conclusions and outlook

- Given the nowadays established technology in high-quality Ge planar detectors, times are mature to start a challenging R&D program towards the implementation of **Ge-drift topologies in a fully planar process**.

- Progress in technology and tools has been very significant in these years and should aid the upgrade of the traditional Ge detector fabrication process to a **double-side/multi-mask** approach.

- Main goal of the INFN project DESIGN is to demonstrate the feasibility of the planar approach for Ge-drift detectors, it aims at **opening the way to a more substantial development and engineering of future high-performance Ge detection systems**.

- In future perspective:
  - **monolithic arrays** of detection cells
  - tailoring of back-side implant profile to **optimize low-energy response** and achieve a single detector with wide energy response.