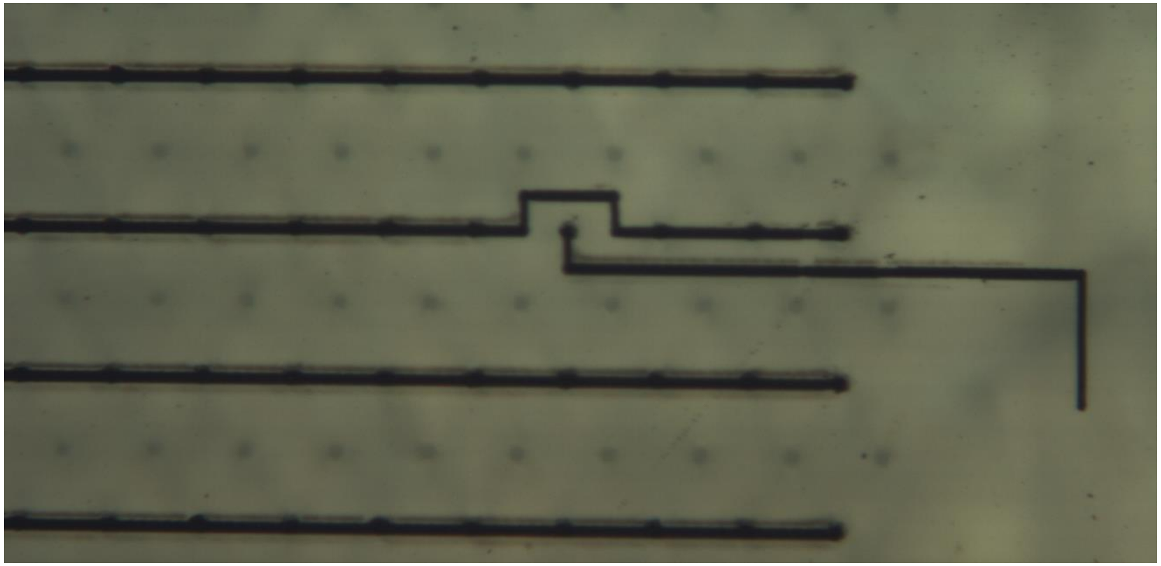
Radiation hardness of 3D poly-crystal diamond detectors



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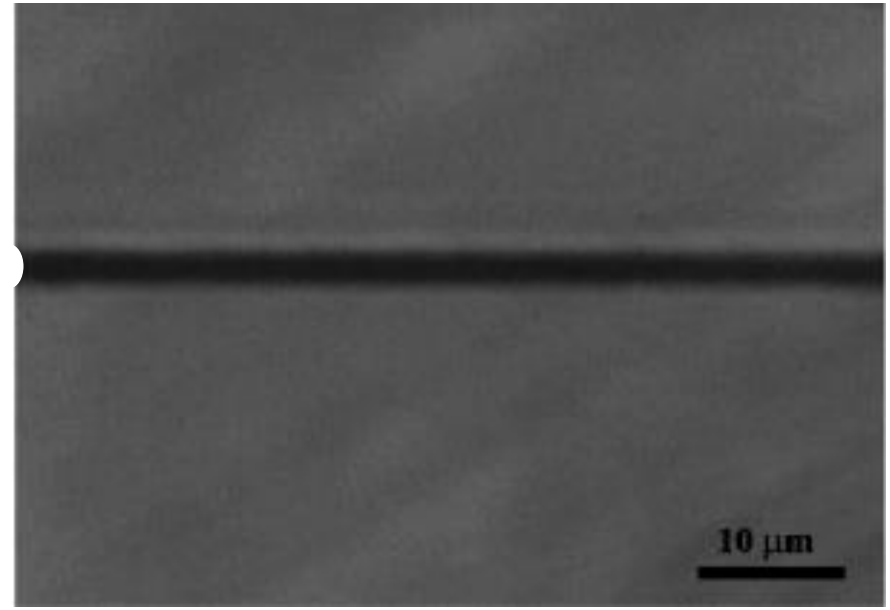
Fabrication of 3D Diamond detectors

The present approach to 3D-diamond detectors fabrication is based on a simple pulsed laser technique which creates graphitic structures in the bulk diamond.



T.V. Kononenko et al., Femtosecond laser microstructuring in the bulk of diamond, Diamond and Relat. Mater. 18 (2009) 196–199

T.V. Kononenko et al., Three-dimensional laser writing in diamond bulk, Diamond and Related Materials 20 (2011) 264–268

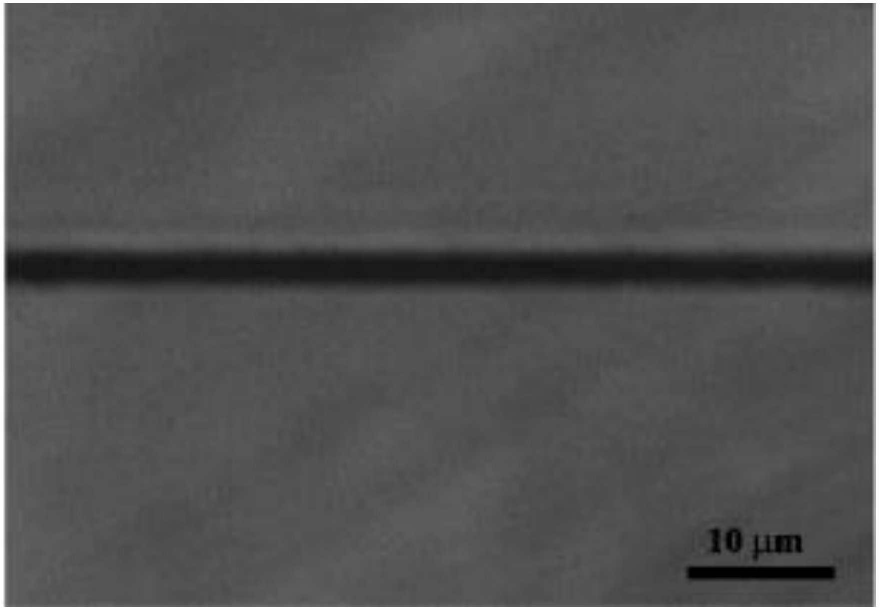
A. Oh et al. A novel detector with graphitic electrodes in CVD diamond. Diamond and Related Materials 38 (2013) 9-13

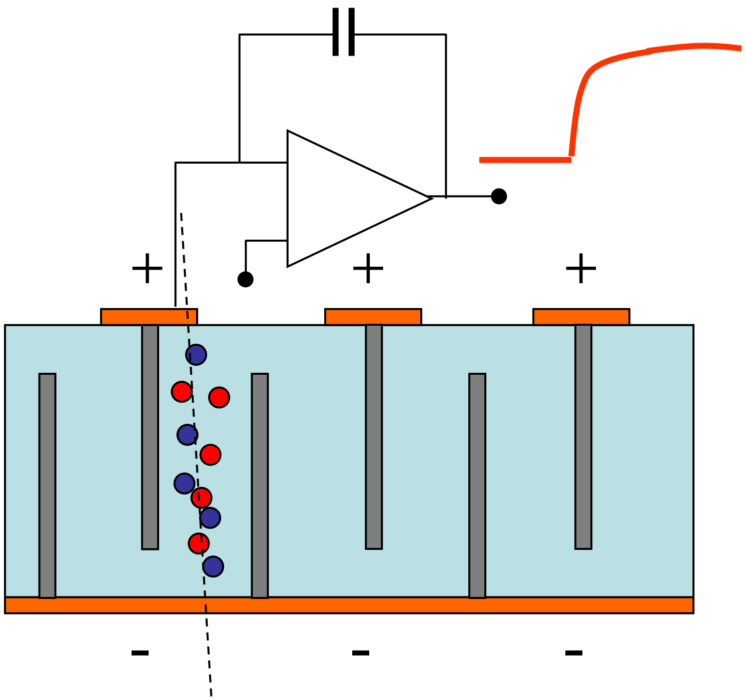
B.Caylar, M.Pomorsky, P.Bergonzo. Laser processed three dimensional graphitic electrodes for diamond radiation detectors. Appl. Phys. Lett. 103 (2013) 043504

S. Lagomarsino et al. Three-dimensional diamond detectors: charge collection efficiency of graphitic electrodes, Applied Physics Letters 103, 233507 (2013)

Fabrication of 3D Diamond detectors

This technique allows the easy implementation of the 3D concept in diamond detectors:





- Shorter path and collection times: lower levels of charge trapping in the bulk
- Lower bias voltages
- Faster response

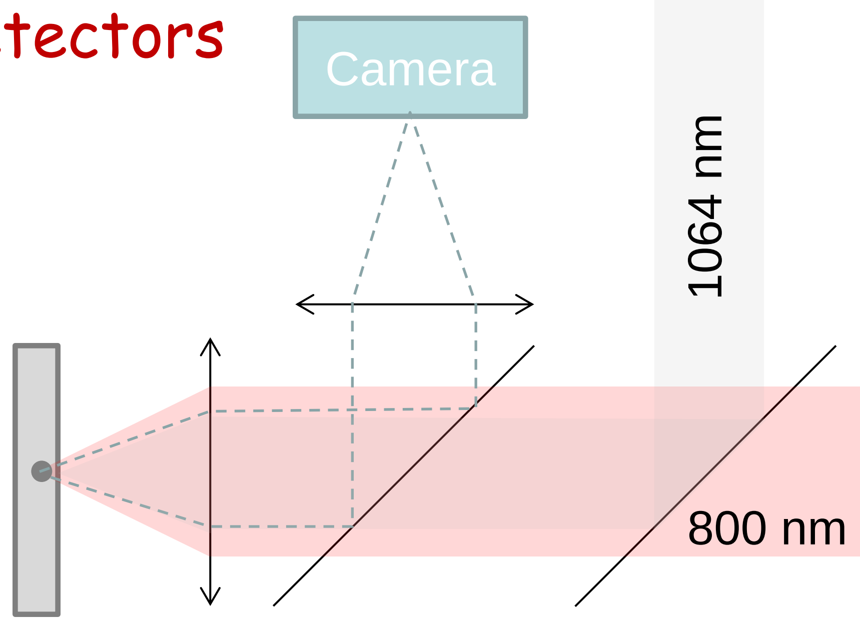
These make 3D-detectors interesting for radiation tolerance characteristics

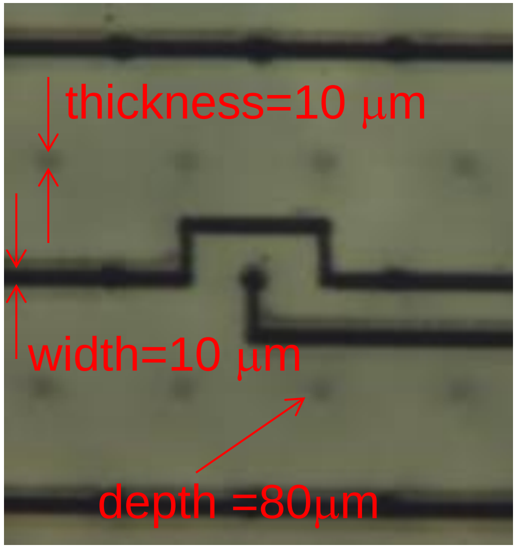
Fabrication of 3D Diamond detectors

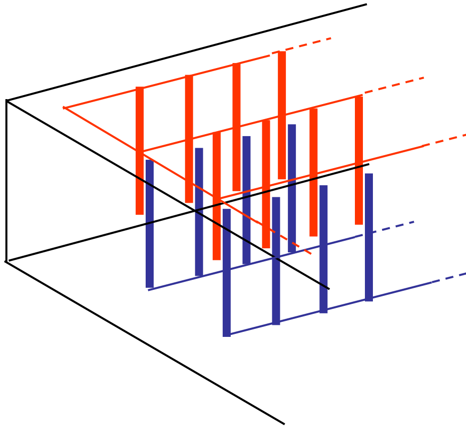
We have integrated this approach with

1) A confocal visualization system which permits to align the system at a micrometric level and to control the lenght of the columns with a 10-20 μm resolution

2) An alternative line for the micro-writing of superficial graphitic wires (Nd:YAG, 8ns-pulse duration).







Fabrication of 3D Diamond detectors

This approach allows the realization of all-carbon 3D diamond detectors

1) One session fabrication
2) No superficial treatments (plasma treatments)
3) No mask-aligning

For the purposes of the present research, also:

4) No metal activation under neutron irradiation
5) No re-metallization after radiation damage

→ Easy and fast tests after each irradiation session

- Resume of the results with 3D scCVD detectors
- Perspectives and problems with pcCVD
- Fabrication and test of 3D-pcCVD detectors
- Expected behavior under neutron irradiation
- Radiation tolerance of 3D-pcCVD detectors
- First data by 3D-DOI detectors
- Conclusions and acknowledgments

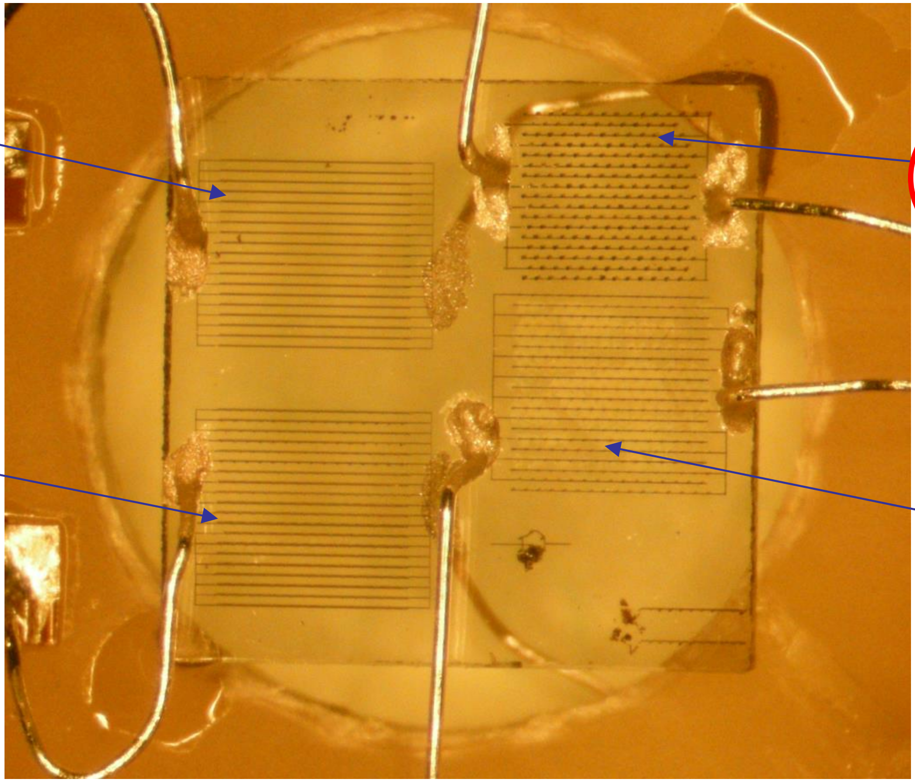
Resume of the results with 3D scCVD detectors

Several devices has been fabricated on 5x5x0.5 mm^3 diamond samples, and then connected to the read-out electronics with silver paste.

Single Crystal Diamond

2D detector

3D Detector
(30 fs laser pulses,
800 nm)

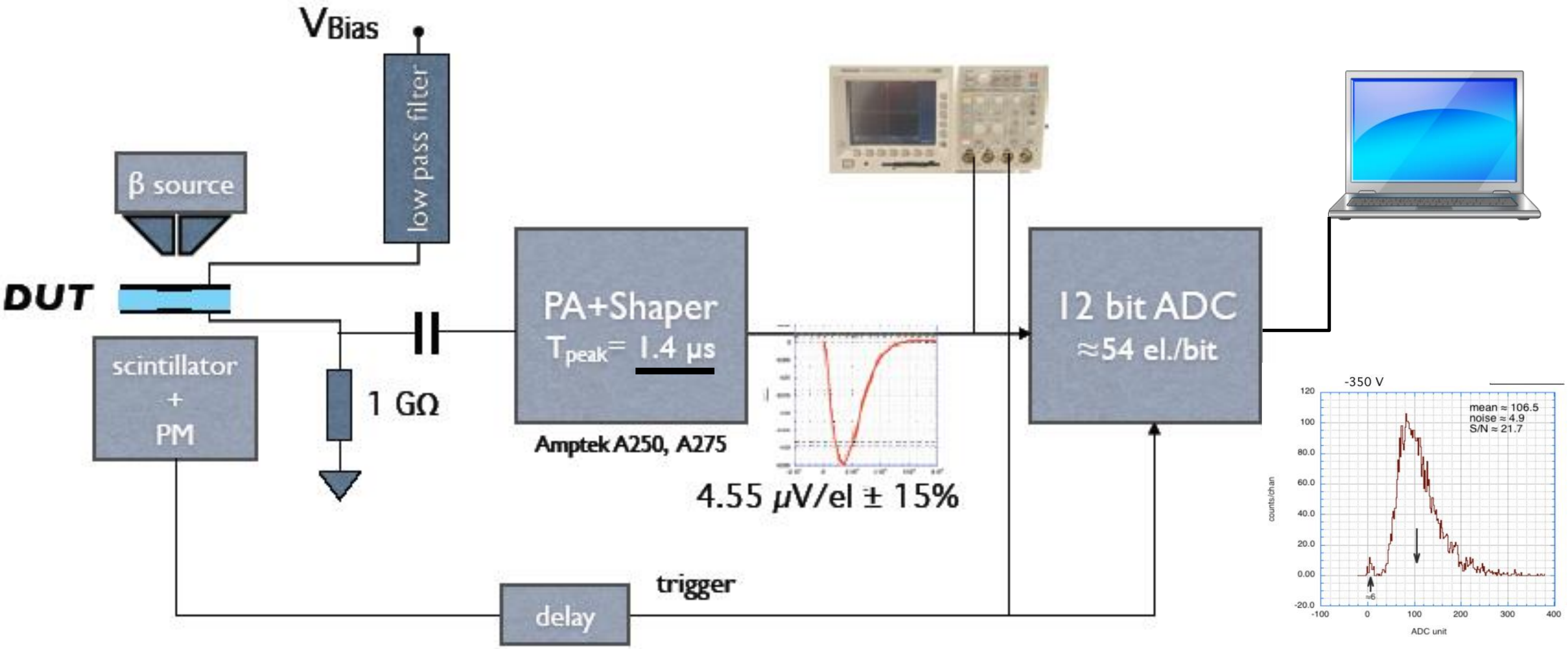


3D Detector
(8ns laser pulses,
1064 nm)

3D Detector
(8ns laser pulses,
1064 nm)

~ 260 to 600 columns for each device

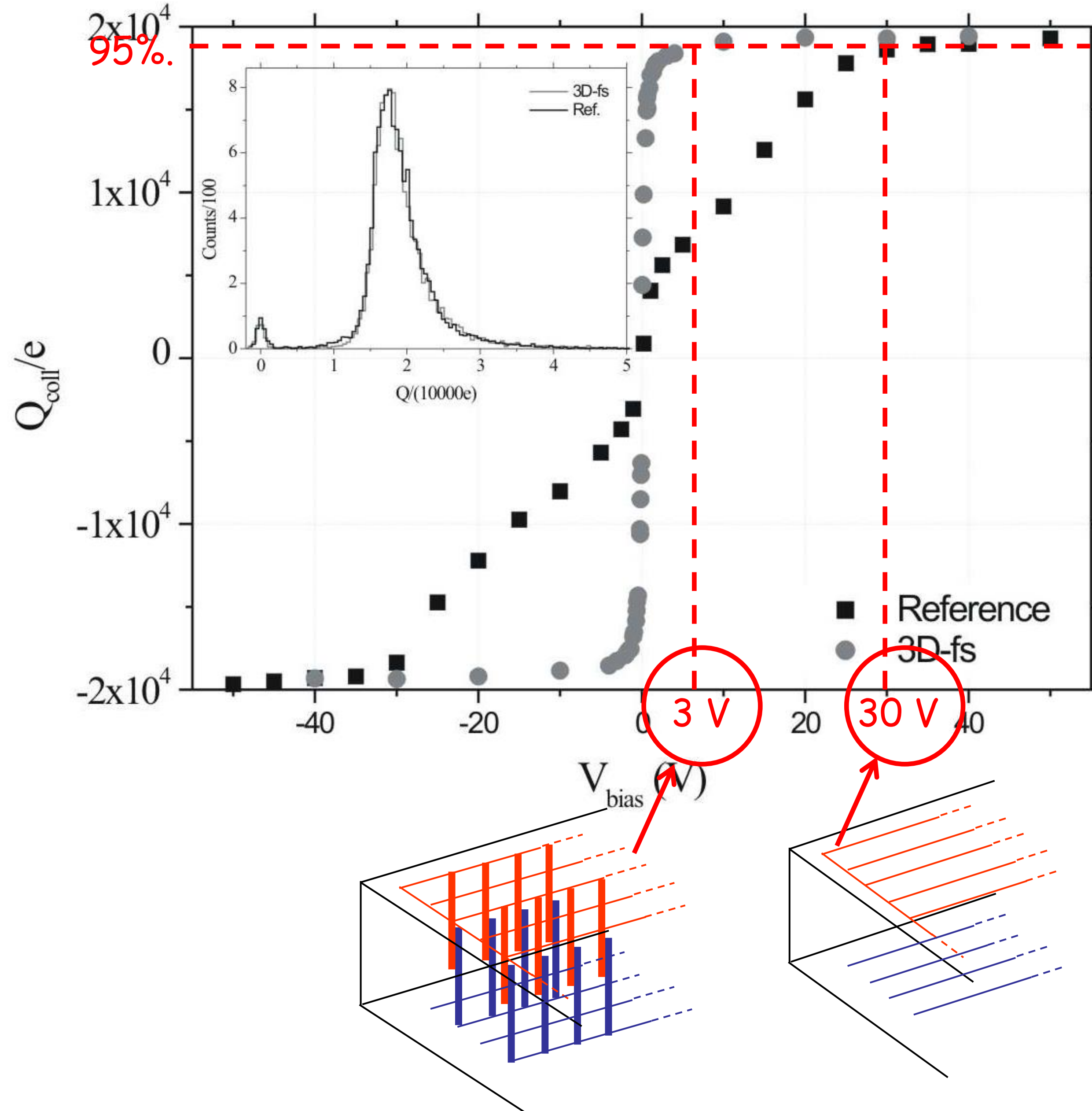
Resume of the results with 3D scCVD detectors



Charge collection efficiency of β-induced signals in diamond was tested for all the devices fabricated in SCr and PCr diamond.

Resume of the results with 3D scCVD detectors

The 3D columns created with the 30 fs 800 nm pulses exhibit full collection, as well as the reference planar contacts, but saturation takes place at 3V instead of 30 V.



Resume of the results with 3D scCVD detectors

Since we have a detector

- Exhibiting a S/N ratio of about 50 (at $\approx$ 1 μs formation time)

- Transit time of the carriers <1ns

- Dark currents $\approx$50 fA/column

- Vbias = 3 V

Why to move to poly-crystalline diamond?

Perspectives and problems with pcCVD

Perspectives with pcCVD diamond :

- Price and size (ratio sc/pc CVD $\approx$ 3, diameters of pcCVD wafers of order of inches)

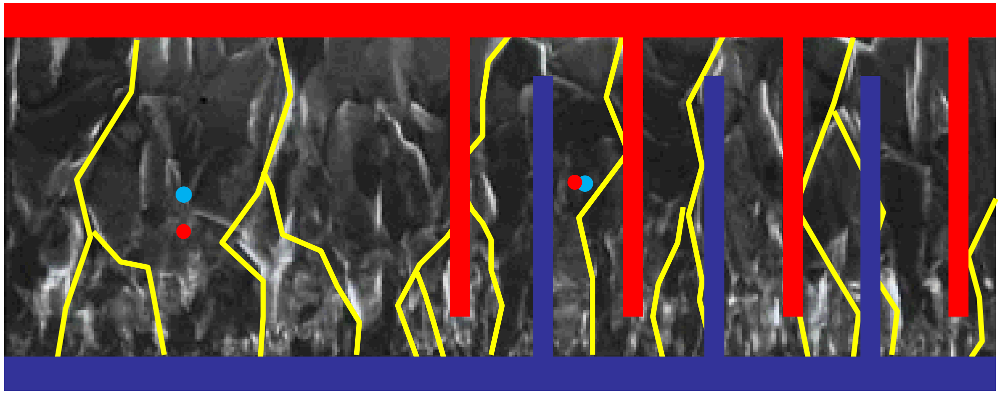
- Shortening the carrier path from 500 μm to 70-100 μm (without detriment of the overall generated charge) could increase significantly the collected charge.

- pcCVD diamond presents a relatively higher resistance to radiation damage if compared with scCVD (both exhibit comparable efficiencies at 10^{16} cm^{-2} 28 GeV protons fluence)

Perspectives and problems with pcCVD

Problems with pcCVD diamond:

Grain boundaries are surfaces which high concentration of trapping centers, but the columnar structure of the grains in pcCVD diamond reduces their relevance in conventional planar sensors (the most of the charges are not trapped at the grain boundaries)



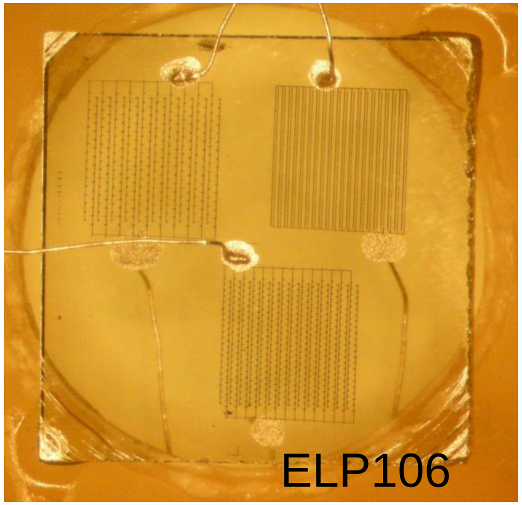
On the contrary, in the 3D configuration, the reduction of the mean free path can be very relevant.

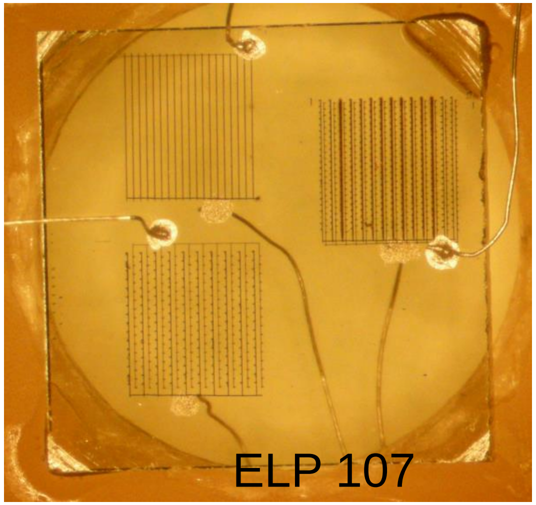
There has to be a maximum inter-electrode distance to obtain acceptable charge collection.

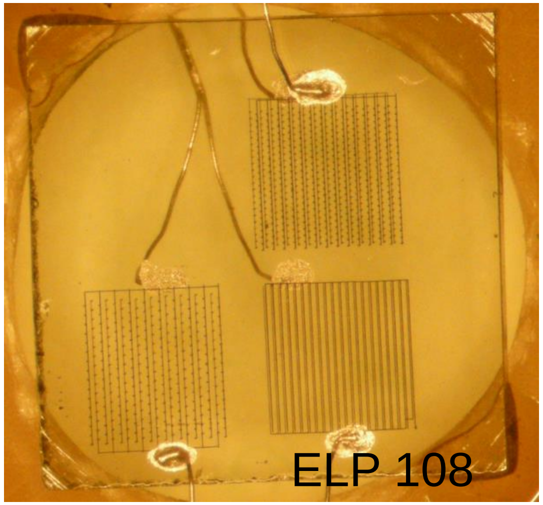
Question: how close the columns have to be?

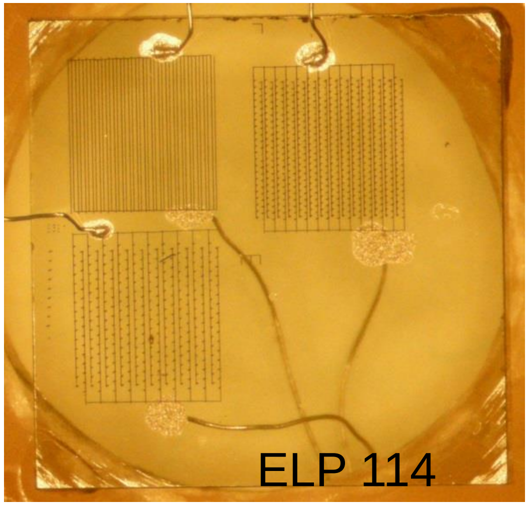
Fabrication and test of 3D-pcCVD and 3D-DOI detectors

In order to study the thematics connected with 3D-pcCVD diamond sensors, we fabricated 3 different kind of detectors on 4 separated pcCVD sample of a same batch from E6:









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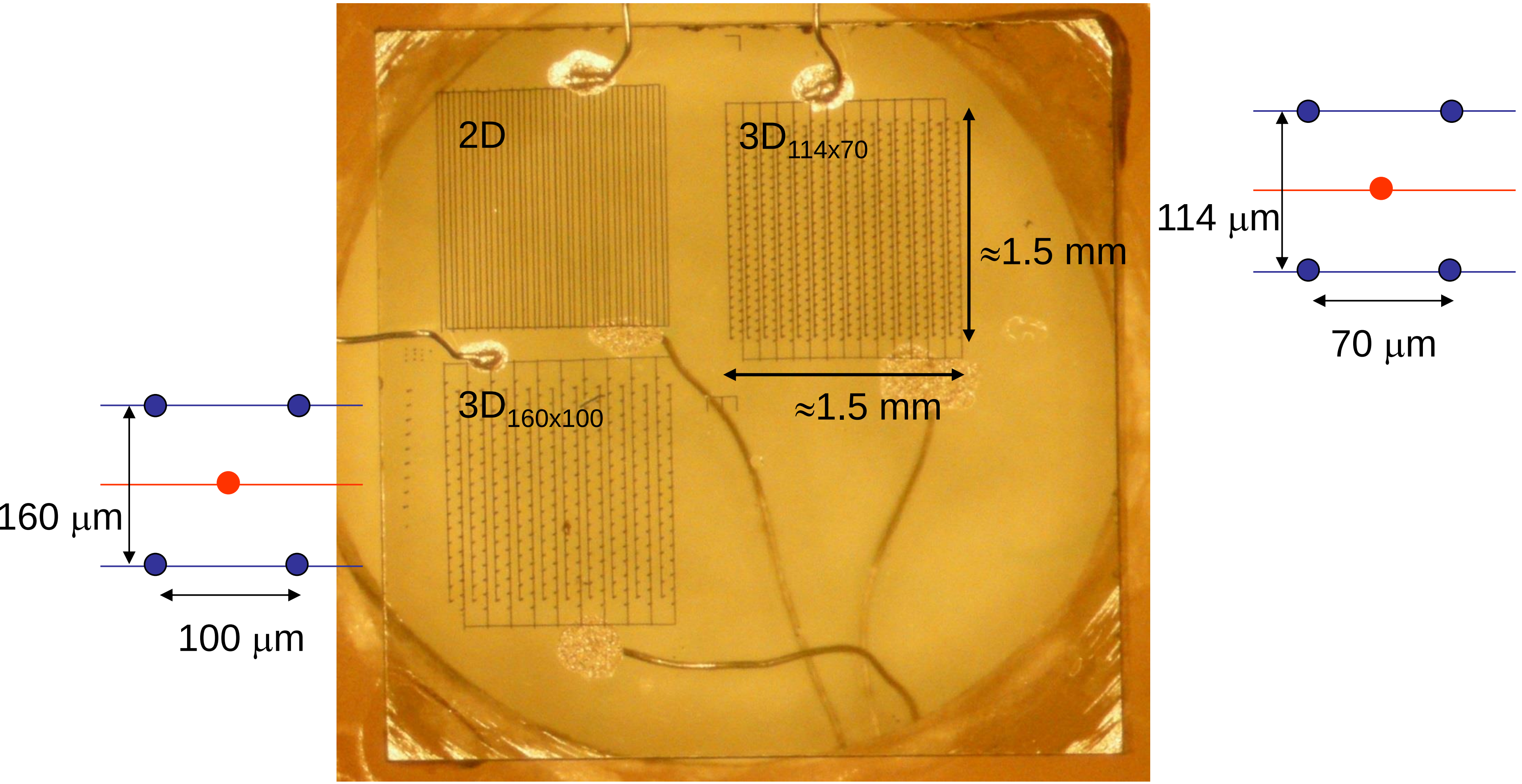
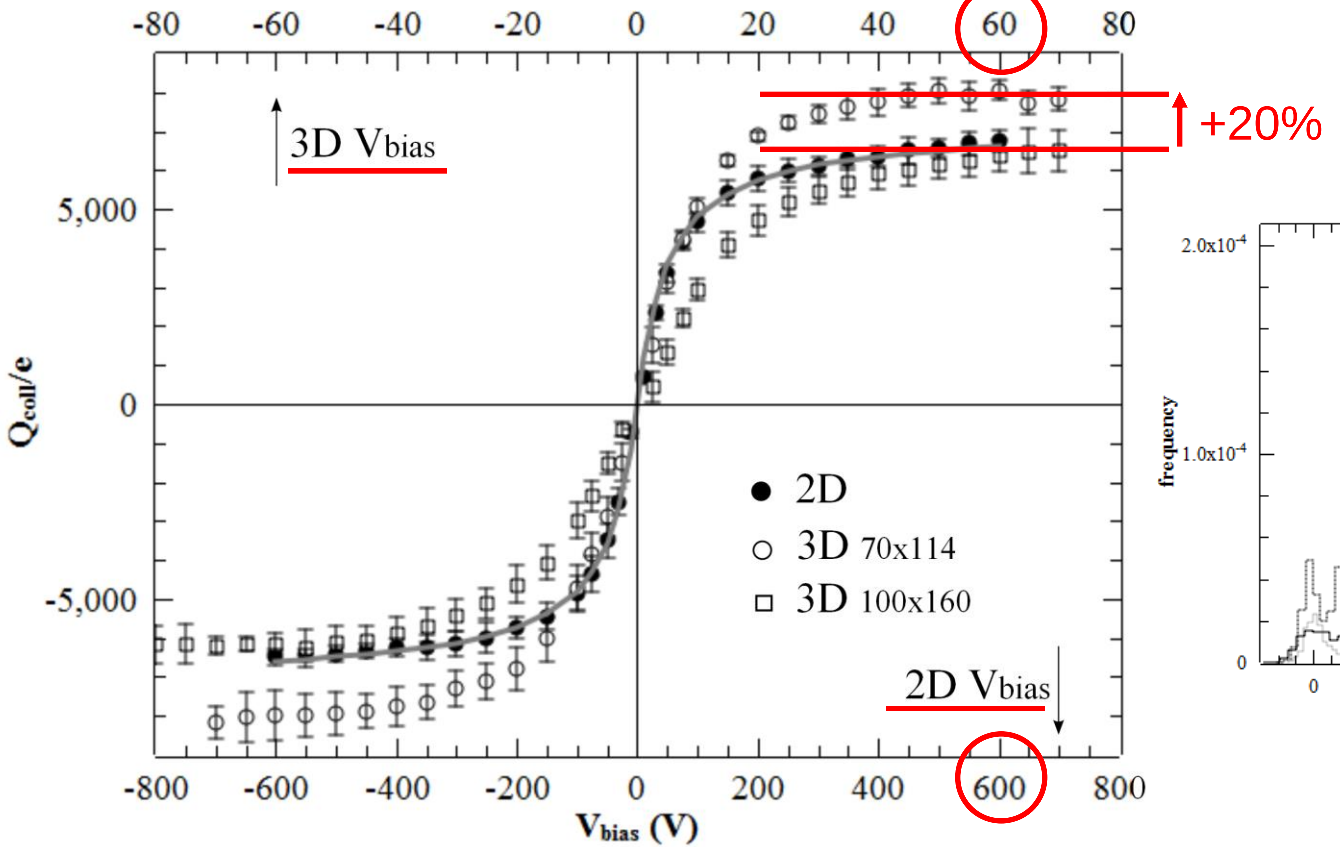
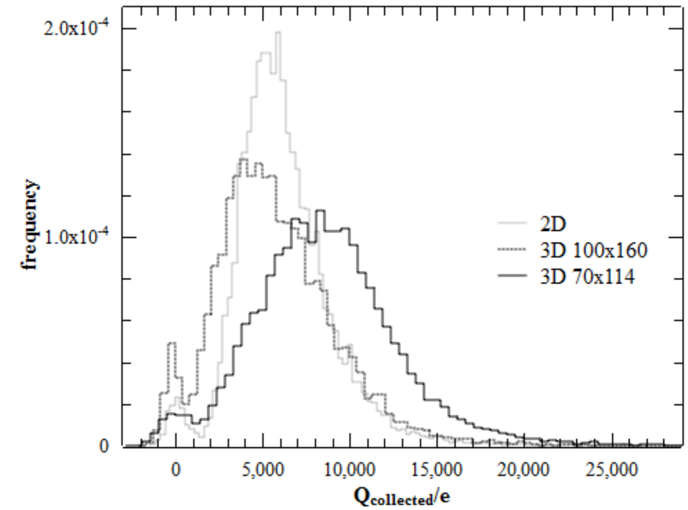


Fabrication and test of 3D-pcCVD and 3D-DOI detectors





Saturation occurres at voltages ten times lower for the 3D compared with 2D sensors.

3D have a higher efficiency compared with 2D sensors (≈20%), if the electrodes inter-distance is small enought (<100μm).

The separations of the 10% percentile of the distribution from the pedestal are comparable for 2D and 3D detectors.

Expected behavior after radiation damage

Moreover: the same 3D detectors, if compared with 2D-ones, are expected to behave even better once undergone to radiation damage.

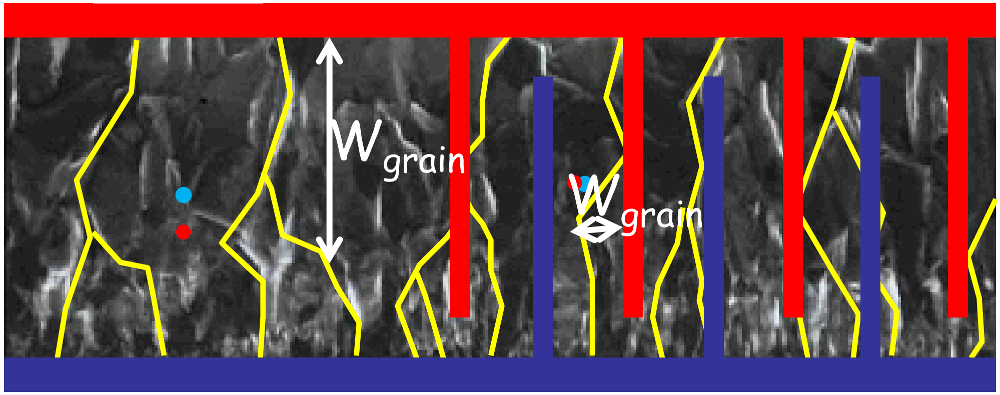
$$\frac{1}{\lambda} = \frac{1}{v_d(E) * \tau_{trap}} + \frac{1}{w_{grain}}$$

Mean free path ← λ

$v_d(E)$ → Drift velocity (field dependent)

τ_{trap} → Bulk trapping time

w_{grain} → Mean trapping lenght at the grain boundaries (configuration dependent)



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$$\frac{1}{\lambda} = \frac{1}{v_d(E) * \tau_{trap}} + \frac{1}{w_{grain}}$$

The radiation damage is supposed to shorten τ_{trap} according to a term proportional to the fluence ϕ

$$\frac{1}{\lambda} = \frac{1}{v_d(E)}\left(\frac{1}{\tau_{trap}} + K\phi\right) + \frac{1}{w_{grain}}$$

In a 3D detector, were inter-electrode distance is chosen in a way to compensate the shorter W_{grain}, the therm $K\phi$ has a much lower weight.

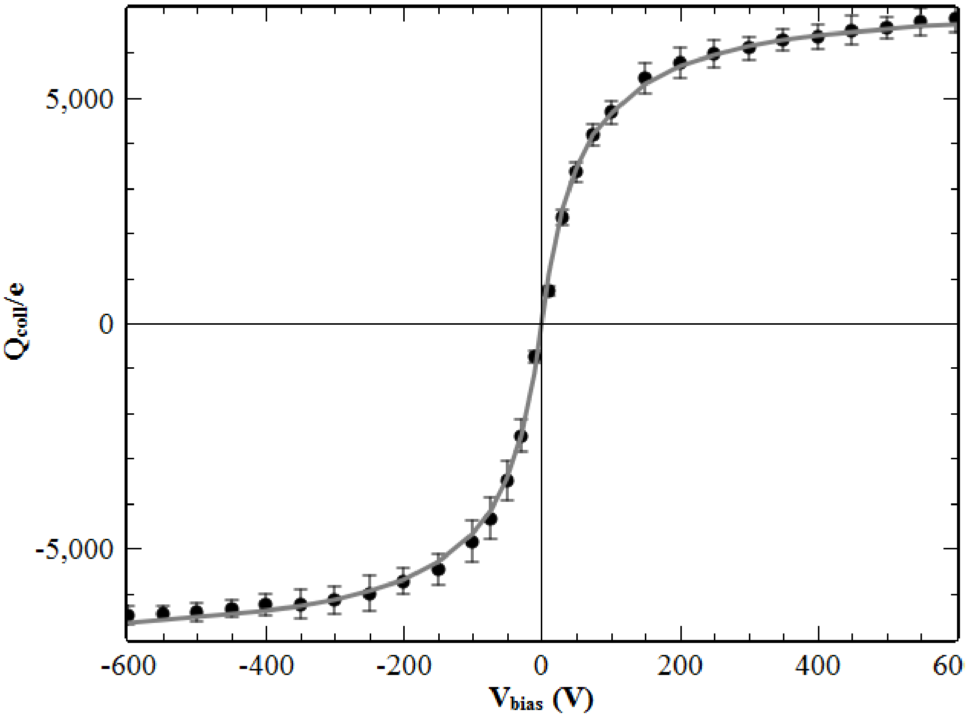
Expected behavior after radiation damage

We have fitted the 2D-sensor S-curve by means of the Hecht formula, in order to calculate τ_{trap} and W_{grain}

$$Q_{coll} = Q_{gen}\left(\frac{\lambda}{D} - \frac{\lambda^2}{D^2}\left(1 - \exp\left(-\frac{D}{\lambda}\right)\right)\right)$$

D= detector thickness

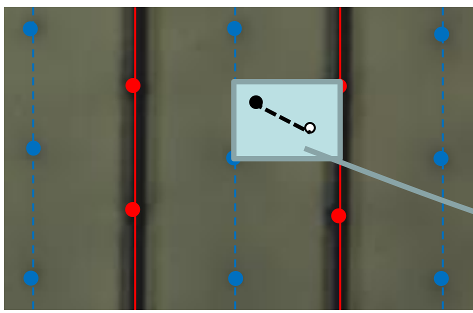
$$\frac{1}{\lambda} = \frac{1}{v_s(E) * \tau_{trap}} + \frac{1}{W_{grain}}$$

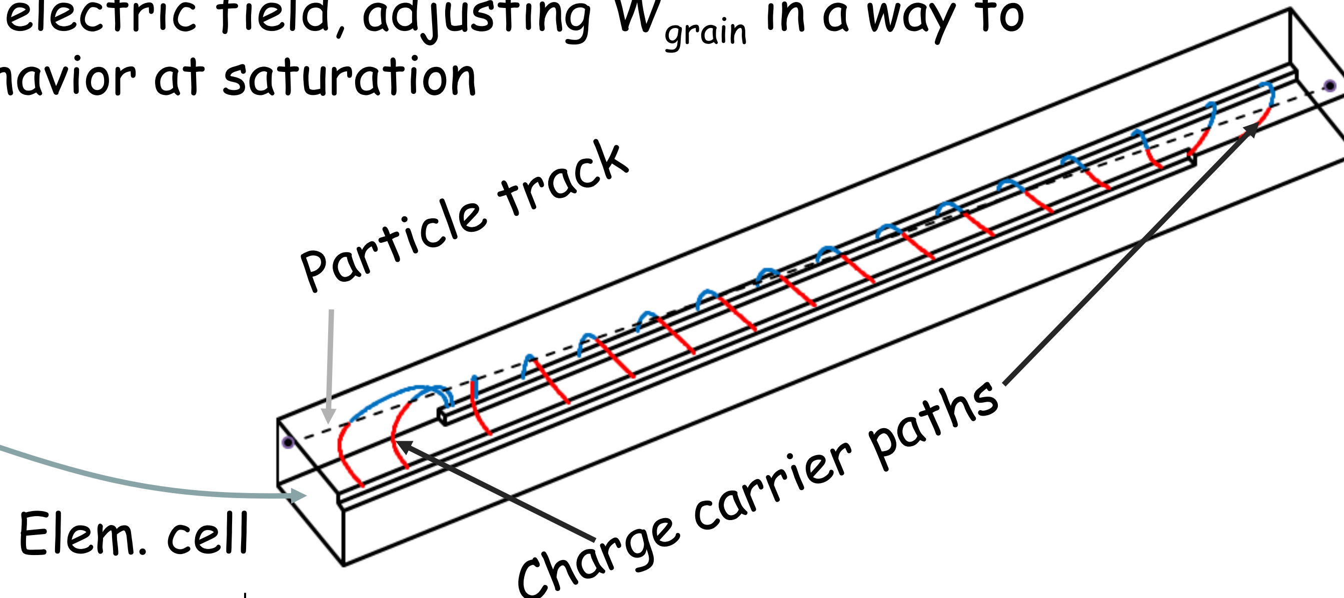


	2D	$3D_{160x100}$	$3D_{114x35}$
τ_{trap}	4.3 ns fitted		
W_{grain}	fitted 160 μm		

Expected behavior after radiation damage

Thus we simulated the charge-collection of 3D-sensors by means of a Monte Carlo algorithm using a three-dimensional finite-element calculation of the electric field, adjusting W_{grain} in a way to reproduce the behavior at saturation





	2D	$3D_{160x100}$	$3D_{114x35}$
τ_{trap}	4.3 ns fitted	4.3 ns fixed	4.3 ns fixed
W_{grain}	fitted 160 μm	> fitted 25 μm	= fitted 25 μm

bulk trapping time (configuration-independent) →fixed

Effective grain size (different in 3D and 2D) →fitted

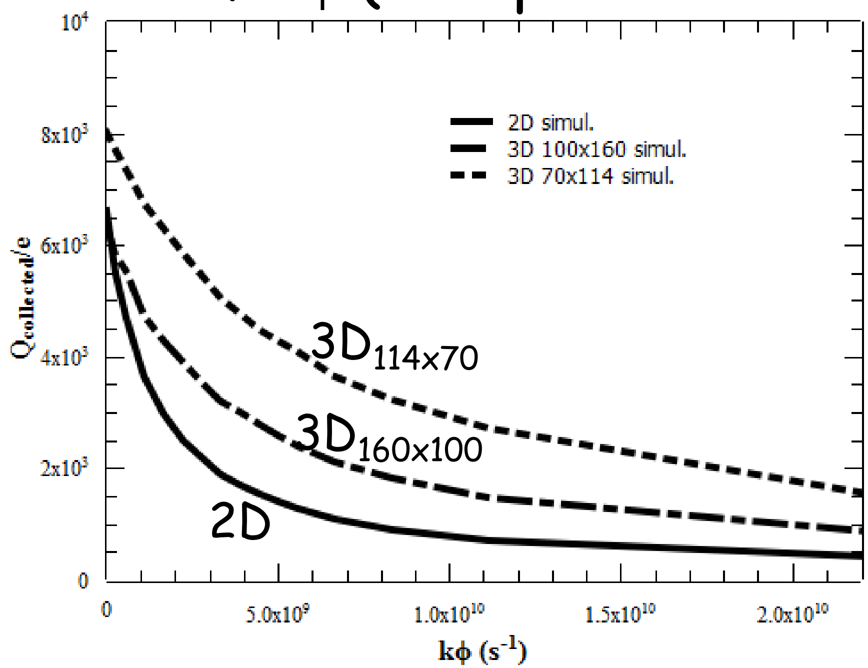
Compatible with the columnar size and shape

Expected behavior after radiation damage

	2D	$3D_{160x100}$	$3D_{114x35}$
τ_{trap}	4.3 ns fitted	4.3 ns fixed	4.3 ns fixed
W_{grain}	fitted 160 μm	fitted 25 μm	fitted 25 μm

$$\frac{1}{\lambda} = \frac{1}{v_d(E)}\left(\frac{1}{\tau_{trap}} + K\phi\right) + \frac{1}{w_{grain}}$$

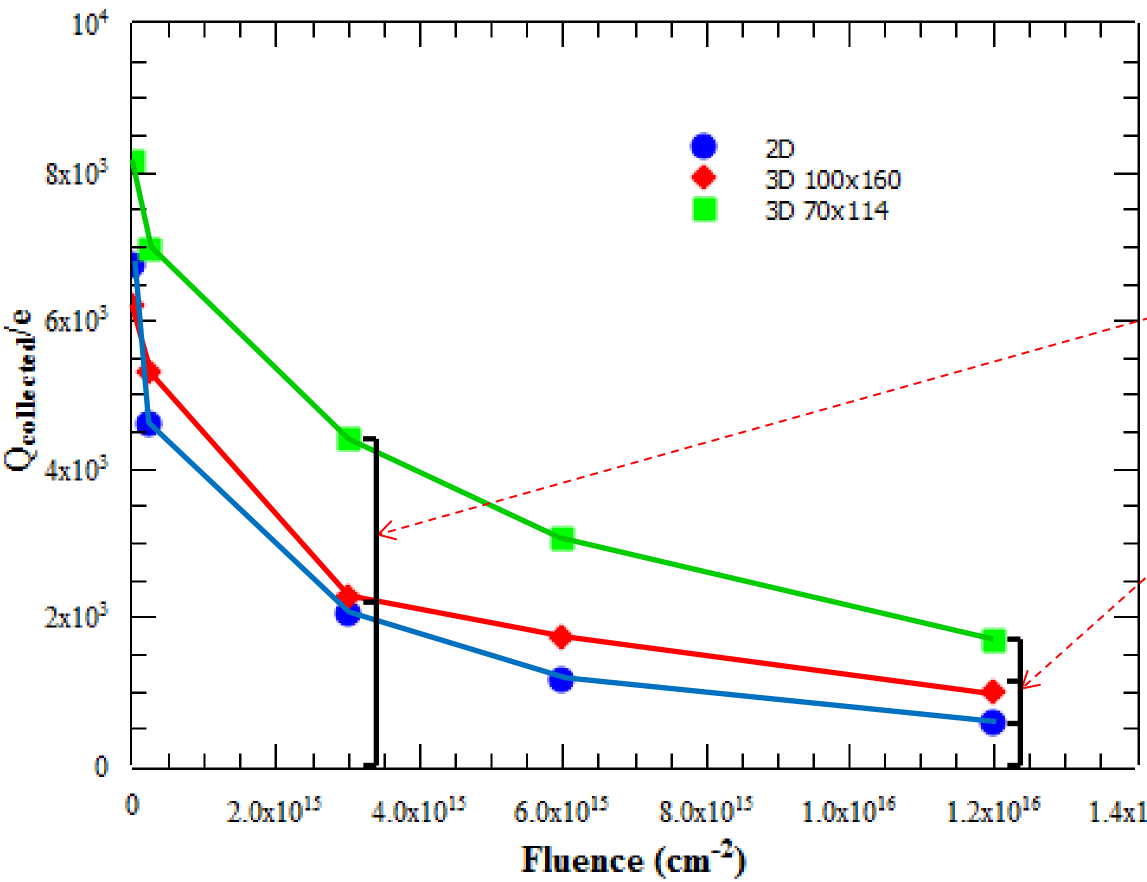
Then we simulated the expected charge collected as a function of kφ (K depends on the radiation (energy, specie))



We expect, for high fluences, a signal up to 3 times higher for the 3D-sensors, compared to the conventional planar ones.

Radiation tolerance of 3D-pcCVD detectors, preliminary results

We have irradiated our samples at the Jozef Stefan Institute facility of Lubljiana (SLO), at 1MeV-equivalent neutron fluences up to 1.2 $\times 10^{16}$cm^{-2}.



It results a signal from 2 to 3 times higher for the 3D-compared to the 2D-sensors, depending on the fluence experimented.

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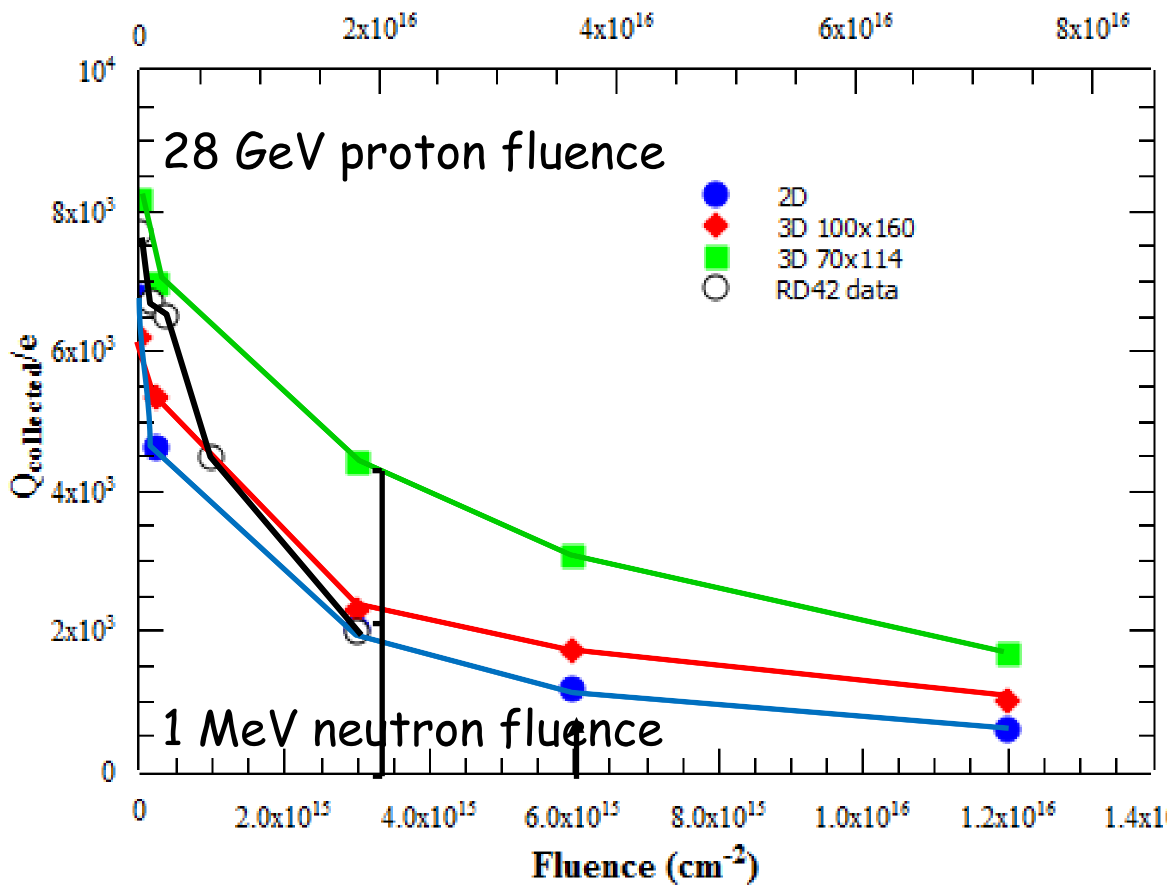

Comparison with the RD42 data, referred to 28-GeV protons, requires to take into account a hardness factor of about 6 of the 1-MeV neutrons in comparison to protons.

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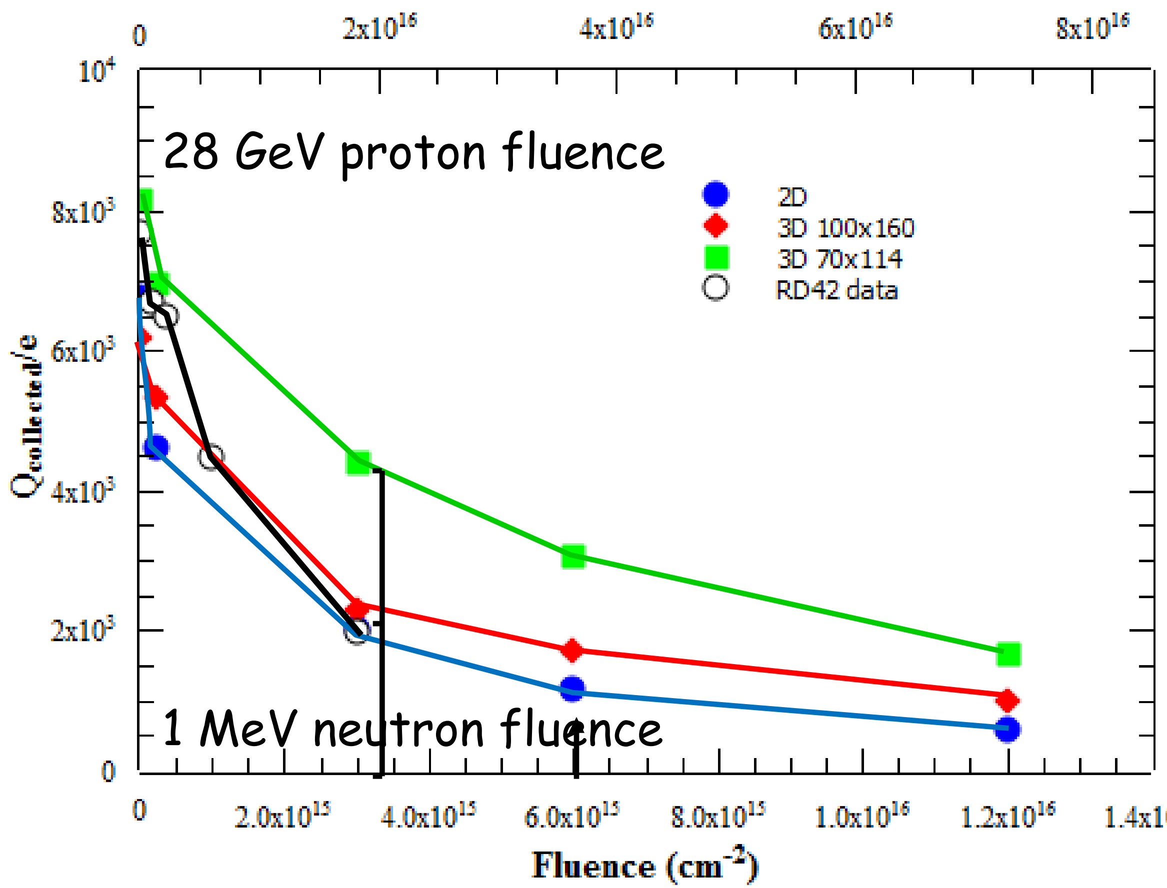

It results that 3D diamond promises to collect at least a double charge than planar one also after proton fluences exceeding 2×10^{16} cm^{-2}

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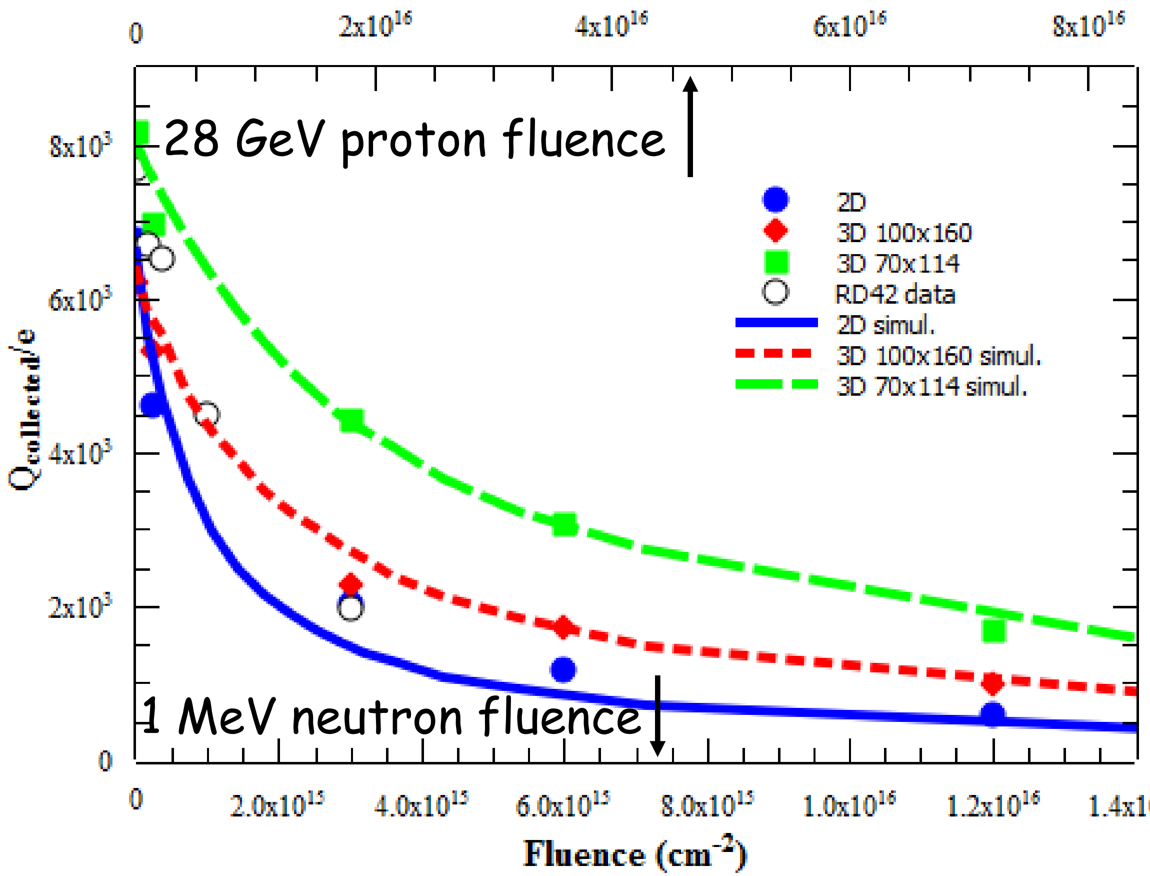
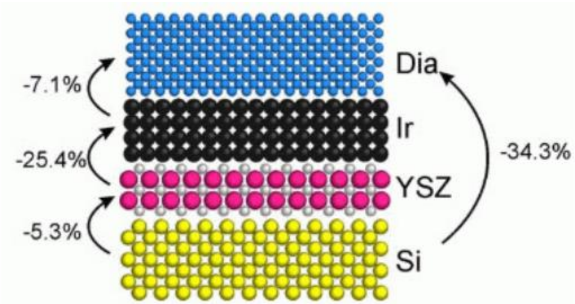
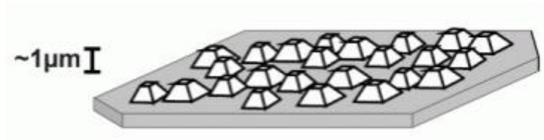
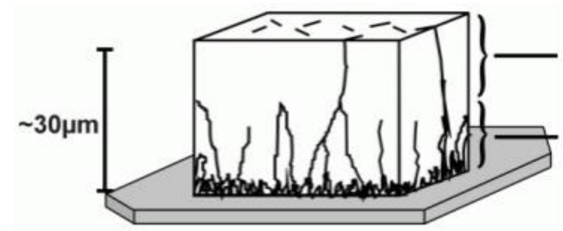


Comparison with the simulations gives a quite satisfactory accordance, at least at high fluences, confirming that the better behavior of 3D diamond is due to the lesser weight of the $k\phi$ factor.

First data by 3D-DOI detectors





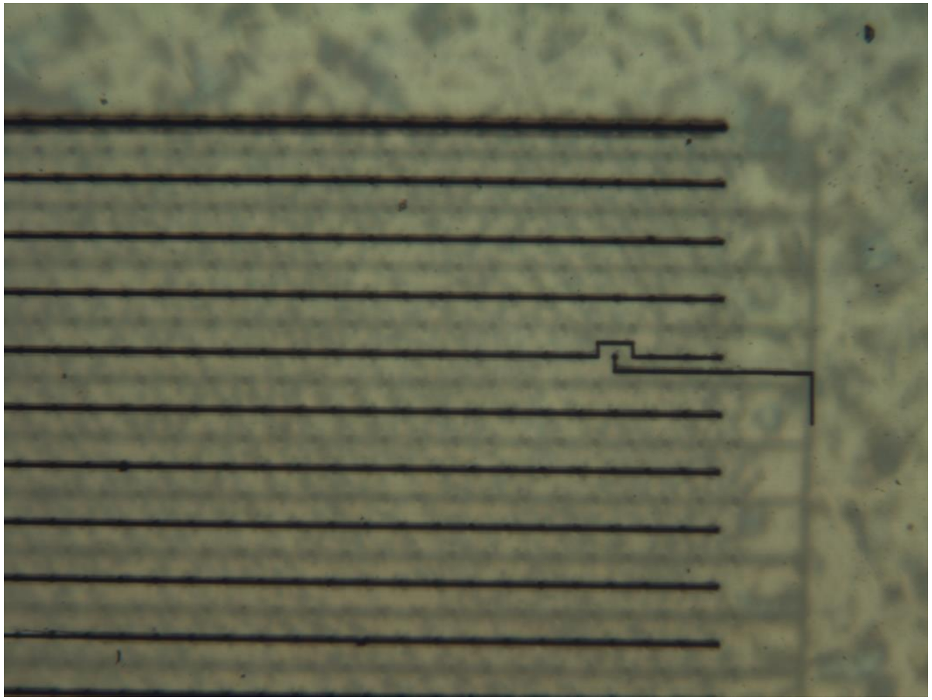


The properties of Diamond-On-Iridium, in which grain boundary formation is hampered by an appropriate texture-growth step, are placed somewhere in the middle between scCVD and pCVD diamond:

- CCE at the level of the best pCVD E6 samples
- Better homogeneity compared to pCVD
- Possibility to produce larger samples than scCVD

First data by 3D-DOI detectors

We fabricated a 3D 70x114 sensor and a planar sensor also in a DOI sample grown at Augsburg University



In this sample we have inserted an insulated column to also test the behavior of a 1-pixel sensor.

We began the measurements very recently, the preliminary results are quite interesting.

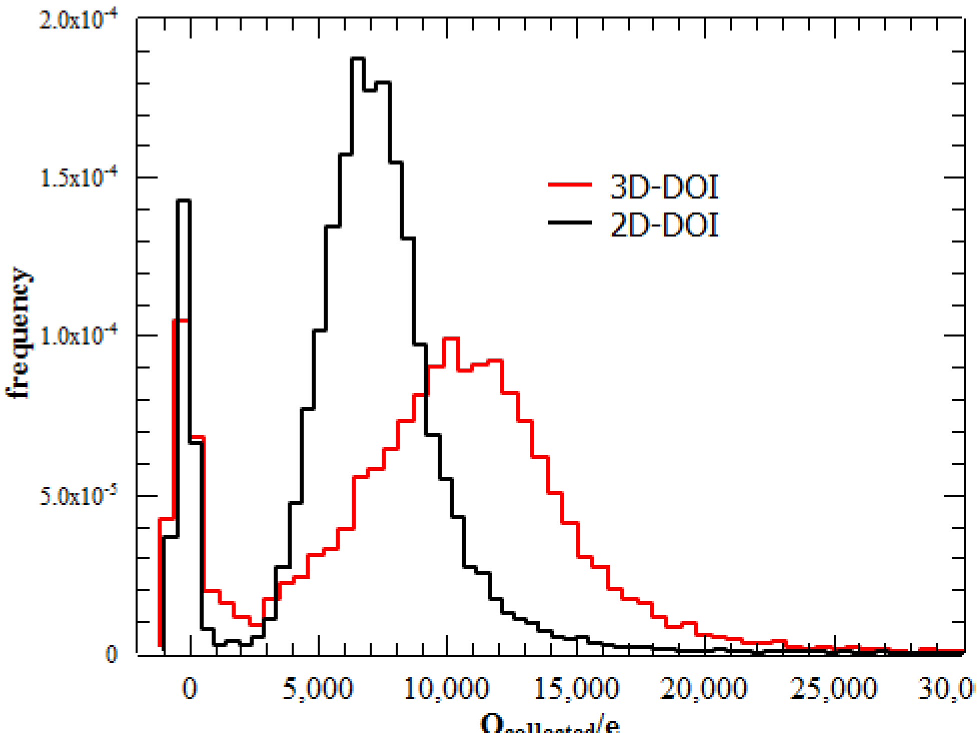
First data by 3D-DOI detectors

The sample is about 500 μm thick: averall ^{90}Sr-β generated charge = 19400 e

Collected charge

→ 2D (at 600 V) = 7600 e (39% CCE)

→ 3D (at 140 V) = 11000 e (58% CCE), relative gain +50%



Results after pumping (>100 Gy β-irradiation)

2D signal before pumping ≅ 4000 e (21 % CCE)

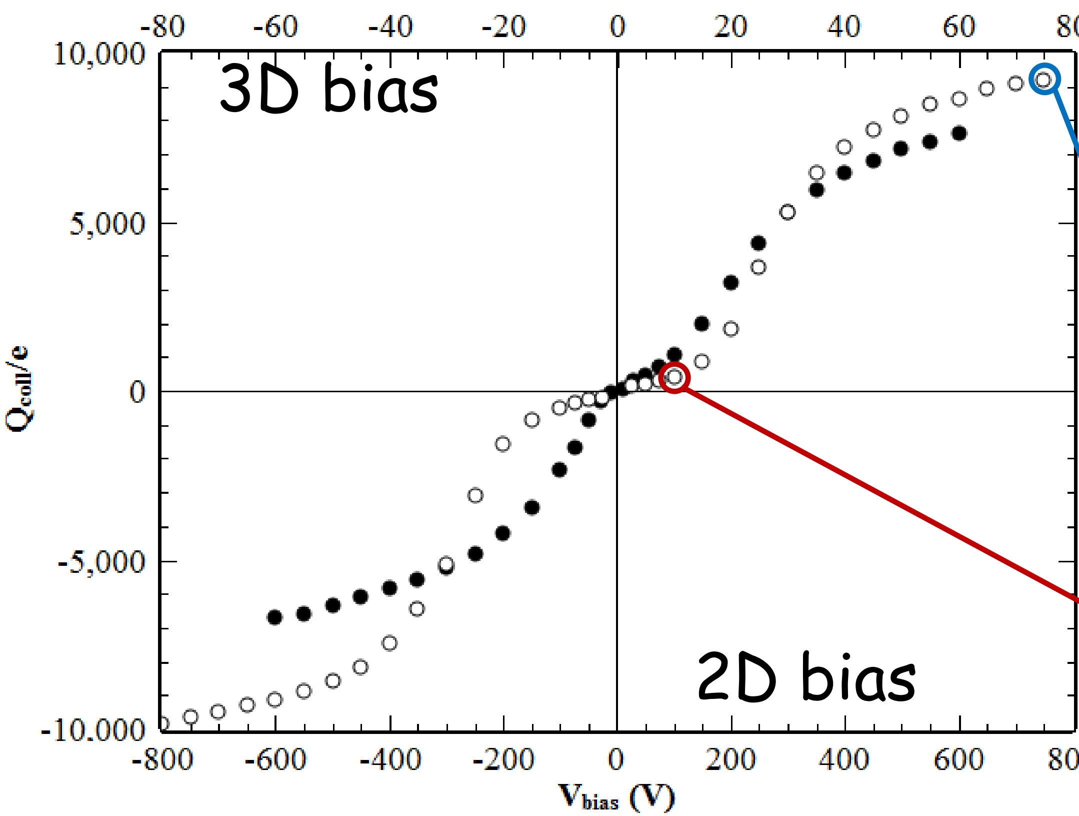
First data by 3D-DOI detectors

Signal vs. bias voltage characteristics:

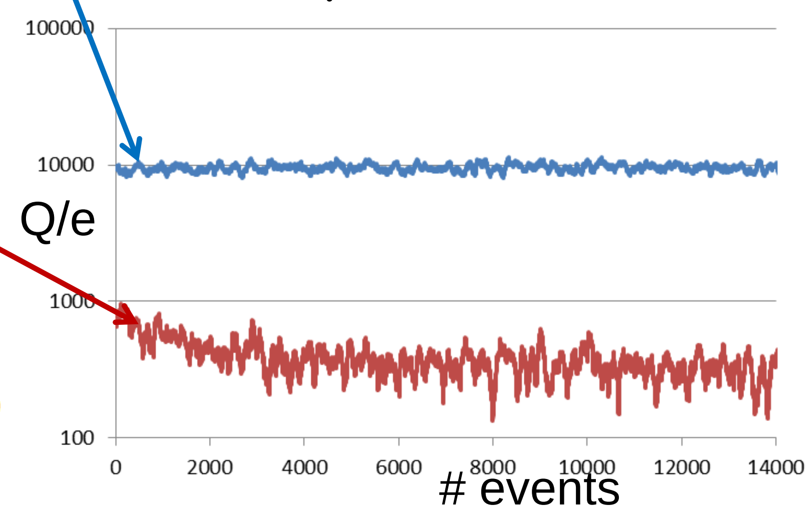
Onset bias voltage at

± 25 V for the 3D sensor

asymmetric (-50 V; +150 V) for the 2D sensor



Suppression of the signal under the threshold partially due to polarization



Conclusions

3D pcCVD diamond sensors exhibit

- Better performance compared to the 2D, in term of saturation bias voltave (1 order of magnitude lower), saturation signal (20% higher), same S/N ratio and dark currents.
- Much higher radiation tolerance. (up to three times higher signals at $1.2x10^{16}$ 1MeV-neutrons/cm^2)

3D-DOI diamond sensors exhibit

- Even better performances compared to the 2D (signal≈ + 60%)

In the next future:

- Fabrication of 3D pixel detectors
- Radiation hardness of 3D-DOI detectors?

Acknowledgments

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