Large Area pcCVD diamond detectors and 3D Diamond Detectors

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Diamond Sensors Laboratory CEA-LIST

Journee d'etude sur les detecteurs diamant
09 June 2015, LPSC Grenoble

Talk outline

Introduction: Diamond Detectors

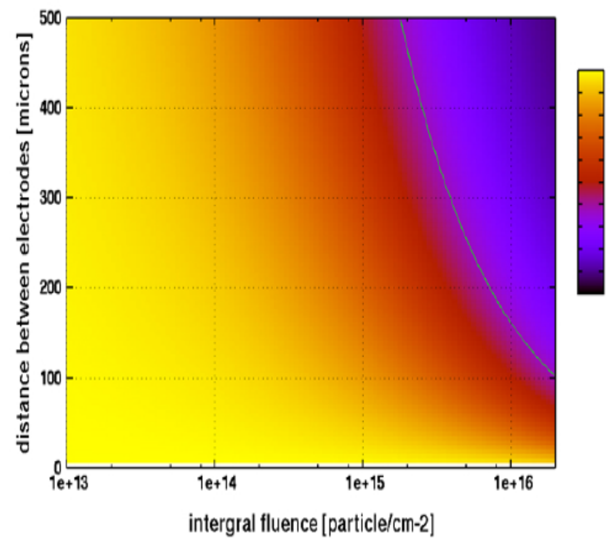
'Large Area' (LA) pcCVD: Experimental results (GamHadron)

3D Diamond Detectors: Status after 5 years of 'no-funds' project

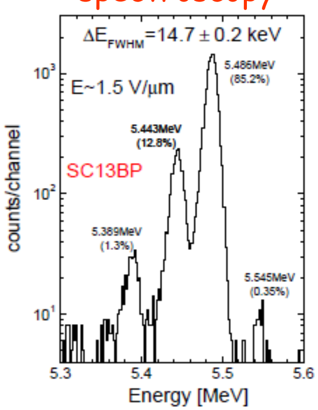
Introduction: Why Diamond

property	diamond	silicon	4H-SiC	detector operation
band gap $[eV]$	5.48	1.12	3.26	+ high T operation
dielectric strength $[V/cm]$	10^7*	3×10^5	5×10^6	+ high field operation
intrinsic resistivity $[\Omega/cm]$	$>> 10^{11}$	2.3×10^5	$> 10^5$	+ low leakage current
electron mobility $[cm^2/Vs]$	$1900 - 4500$*	1350	1000	+ fast signal
hole mobility $[cm^2/Vs]$	$1800 - 3500$*	480	115	+ fast signal
electron lifetime [s]	$10^{-10} - 10^{-6}$*	$> 10^{-3}$	5×10^{-7}	+ full charge collection
hole lifetime [s]	$10^{-10} - 10^{-6}$*	10^{-3}	7×10^{-7}	+ full charge collection
saturation velocity $[cm/s]$	$1.2 - 2.7 \times 10^7$*	1×10^7	3.3×10^6	+ fast signal
density $[g/cm^3]$	3.52	2.33	3.21	
average atomic number	6	14	10	+ therapy - tissue equiv.
dielectric constant	5.72	11.9	9.7	+ low capacitance
displacement energy $[eV]$	43	$13 - 20$	$20 - 35$	+ radiation hardness
thermal conductivity $[Wm^{-1}K^{-1}]$	2000	150	120	+ heat dissipation
energy to create e-h $[eV]$	$11.6 - 16$*	3.62	7.8	- lower signal
radiation length, X_0 $[cm]$	12.2	9.36	8.7	+ low background
Energy loss for MIPs $[MeV/cm]$	4.69	3.21	4.32	
Aver. Signal Created / 100 μm	3602	8892	5100	+ lower signal
e-h pairs/X_0 $(10^6 cm^{-1})$	5.7	10	4.5	

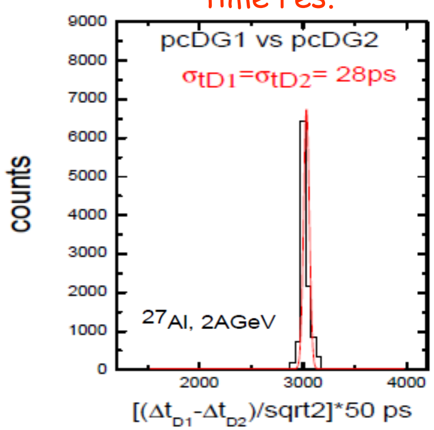
radiation hardness (26 MeV p)



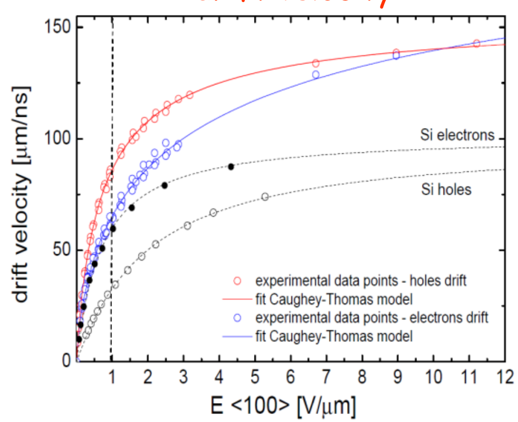
spectroscopy



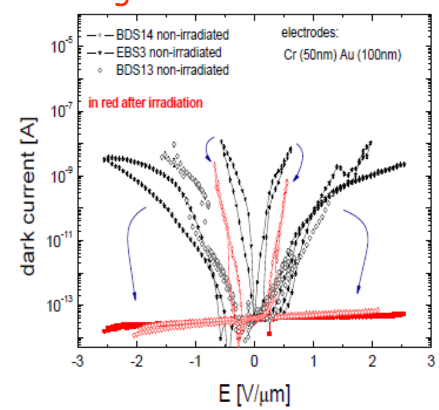
time res.



drift velocity



leakage current after irrad.



Introduction: Diamond Material

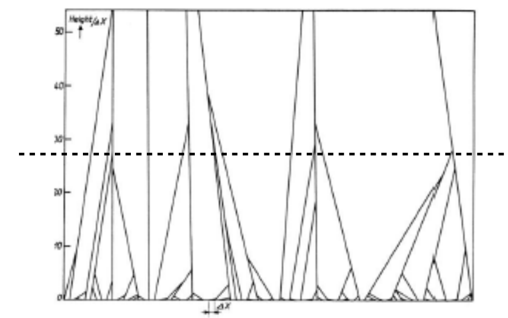
polycrystalline CVD diamond (pcCVD):

- atomic imurities [N0] → trapping
- grain bundaries 2D → 'erratic' currents, trapping
- inclusions (?)

best CCD/CCE: CCD ~300 microns (10k e/mip) (counting)

commercially available from Diamond Mat., E6, others(?)

up to 8 cm diam., price: ~ 1.5kGBP (10x10x0.5 mm) EL



single crystal CVD diamond (scCVD):

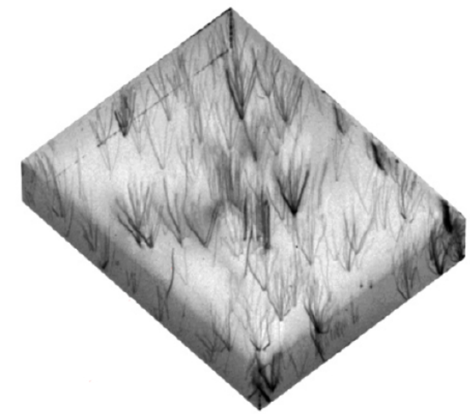
- atomic impurities [N0] → trapping
- dislocations → limited trapping, erratic currents, breakdown
- inclusions → erratic currents, breakdown

commercially available from e6, IIa techn.

up to 8x8 mm, price: ~ 1.5kGBP (4.5x4.5x0.3 mm) EL

R&D: 2 inch mosaic wafers (S. Shikata, Japan)

best CCD/CCE: 100% CCE for EG (500 microns) (spectroscopic)

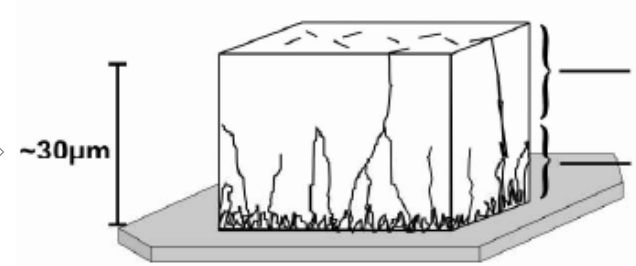


diamond on iridium DoI (CVD):

- atomic impurities [N0]
- dislocations 1D (high density) - trapping
- inclusions(?)

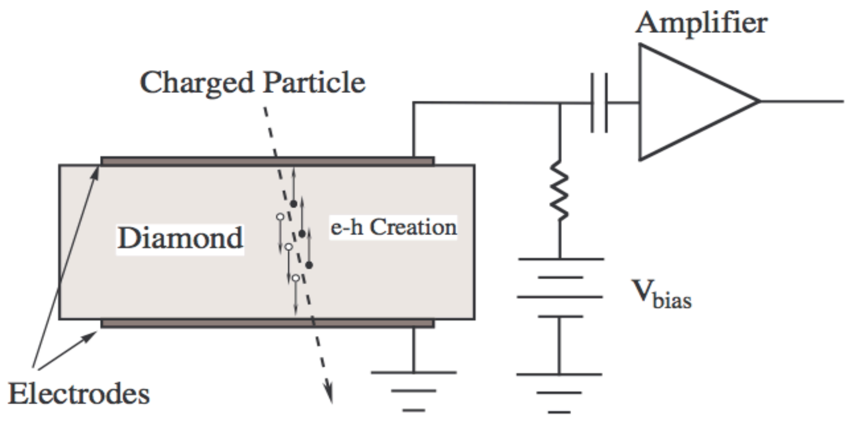
R&D: 2x2 cm samples produced (Augsburg Univ.)

best CCD/CCE: approaching 100% (h) (almost spectroscopic)
low ~20% (e)



Introduction: Parallel Plates Diamond Detector

Schematic:

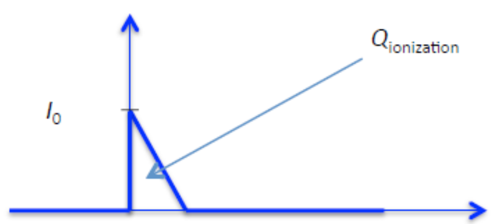


Ramo Current (traversing particle const. dE eg. a mip)

$$I_0 = \frac{Q_{ionization}}{d} \cdot V_d = \frac{dE}{dx} \cdot V_d$$

Bethe-Bloch

Independent of thickness



36 e-h/micron per mip

courtesy E. Griesmayer

ATLAS: 1 MIP 1 uA in 50 Ω: 50 uV -> 40 dB gain

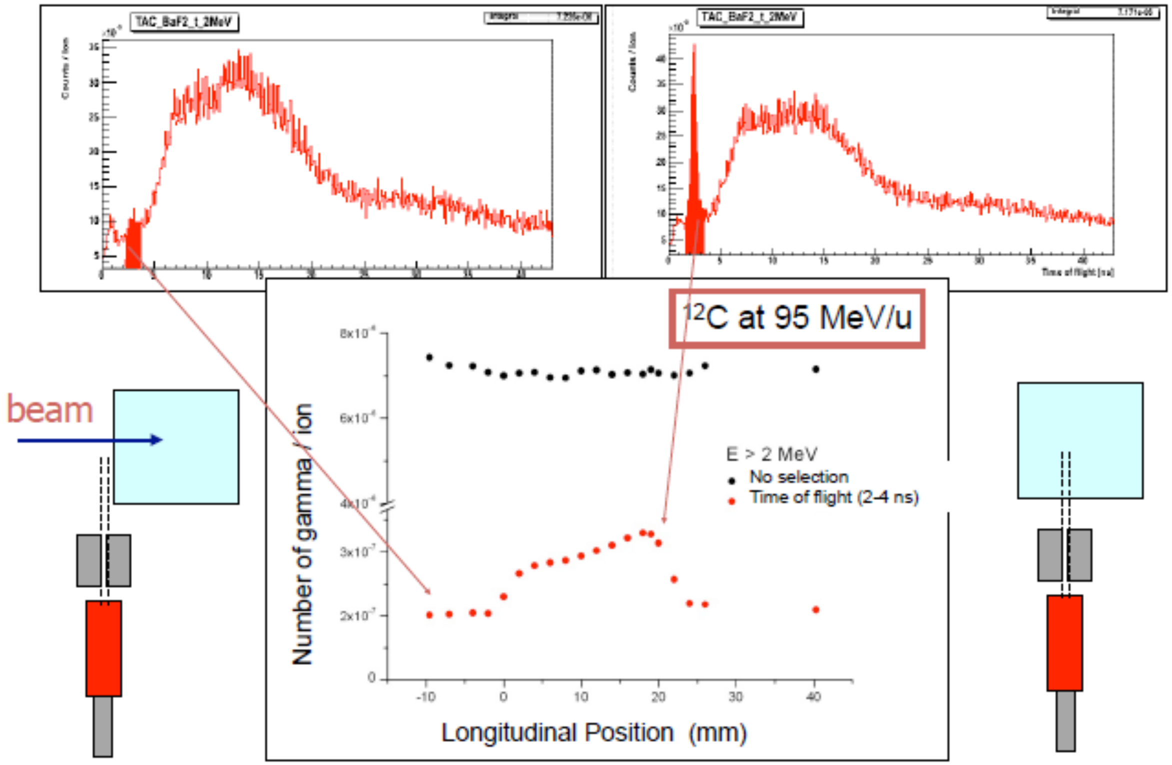
Large Area pcCVD: GamHadron

GamHadron - Compton Camera for in vivo real time dose imaging in hadron therapy

- IPN Lyon
- CREATIS Lyon
- LPC Clermont-Ferrand

Large Area pcCVD: GamHadron

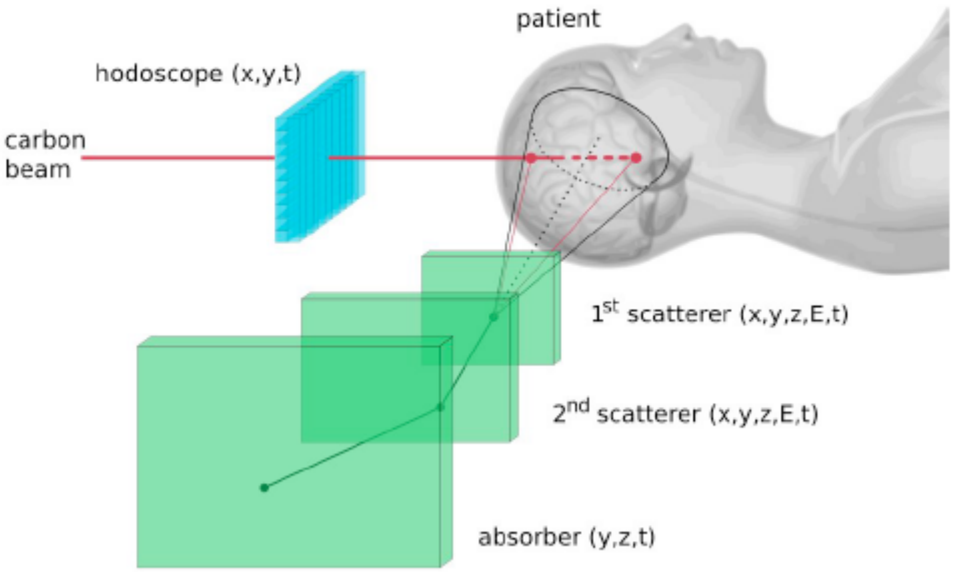
Prompt γ imaging: principle and feasibility studies



E. Testa *et al.*, *Appl. Phys. Lett.* **93,** 093506 (2008)

All content here Denis Dauvergne, IPN Lyon

A Beam-triggered Compton



- Initial design study: 3 interaction-system
- Hodoscope: x,y,T
- Reconstruction = line-cone intersection

Large Area pcCVD: GamHadron

Requirements for GamHadron Hodoscope:

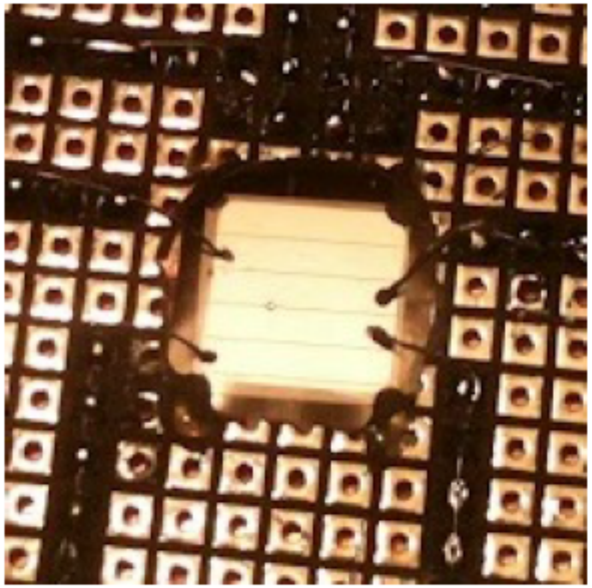
- area 10 x 10 cm^2
- position resolution <1 mm
- time resolution < 1 ns
- rate capability > 1 GHz/total area
- radiation hard

two candidates: scintilating fibers and diamond hodoscope

diamond part co-authors@CEA-LIST: ***Benoit Caylar, Dominique Tromson, Philippe Bergonzo***

Large Area pcCVD: Diamond Hodoscope

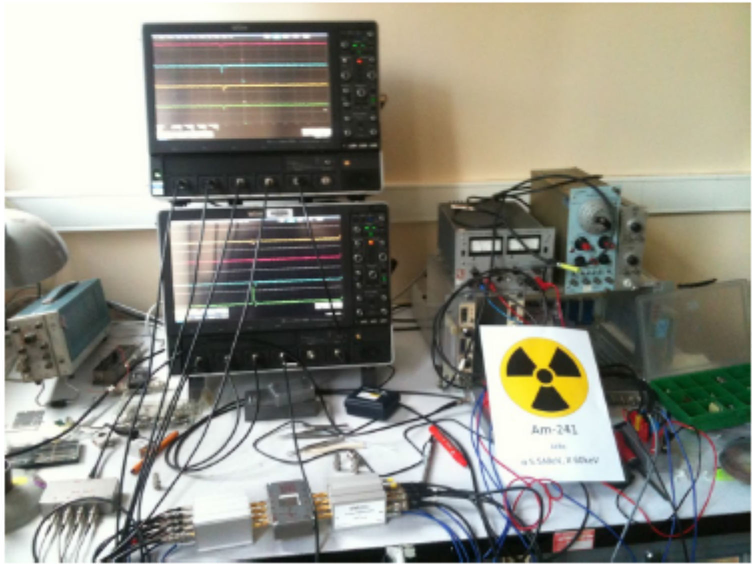
3 x 3 cm^2 pcCVD diamond forseen for the test crushed just three days before beamtime.....



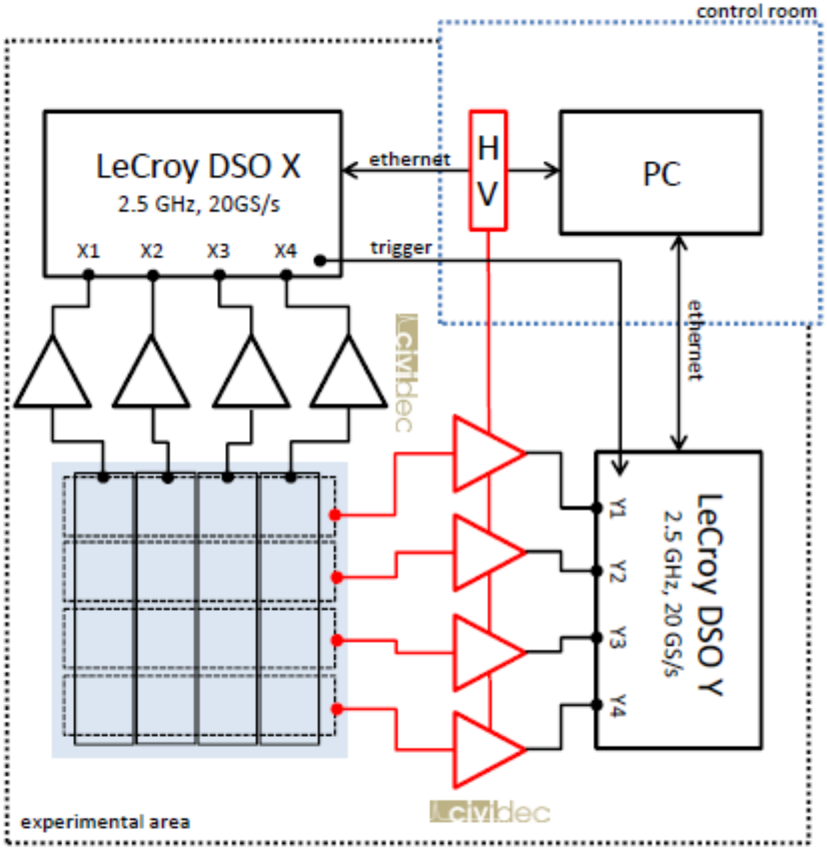
Final configuration:

1x1 cm^2 EG pcCVD diamond (500 μm thick), Al 1.8 mm 4(X)x4(Y) strips with 100 μm pitch

Large Area pcCVD: Electronics and DAQ



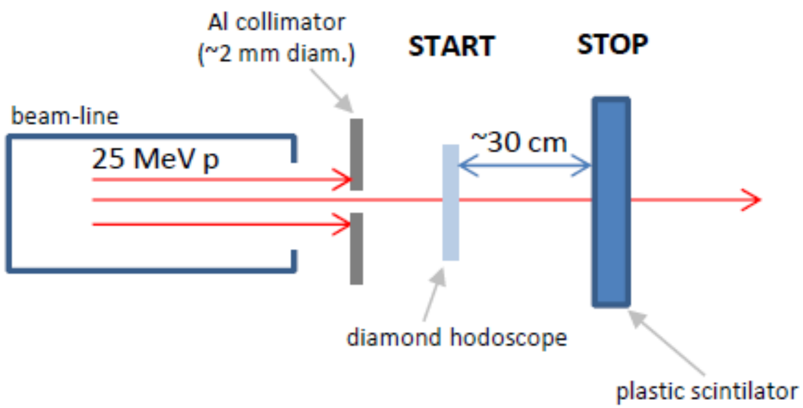
Laboratory testing with 5.48 MeV α source

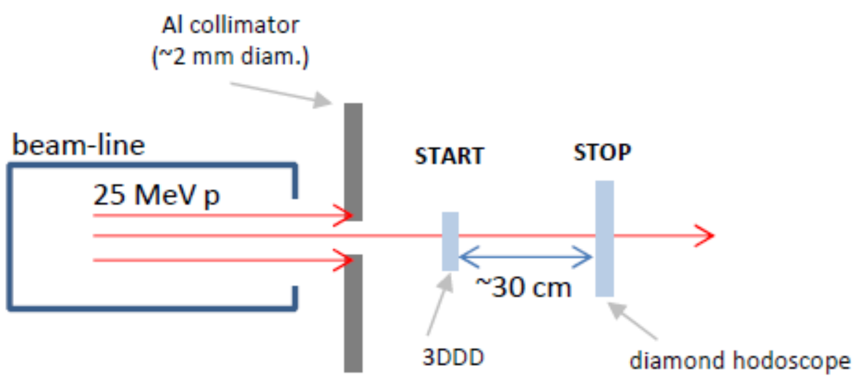


Electronics (8x Cividec voltage amplifiers) and DAQ (2 x LeCroy 2GHz DSO)

Large Area pcCVD: Beamtime setup

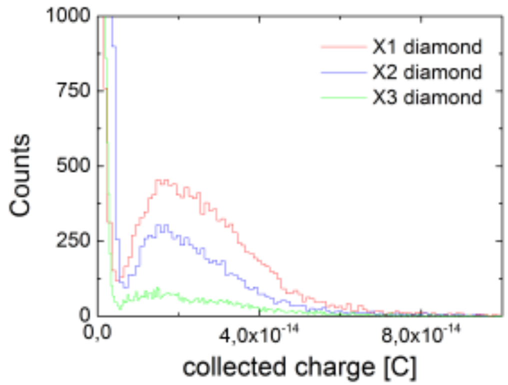
IPN Orsay tandem accelerator ALTO, 25 MeV p, 3.75MeV deposited in 500 μm diamond

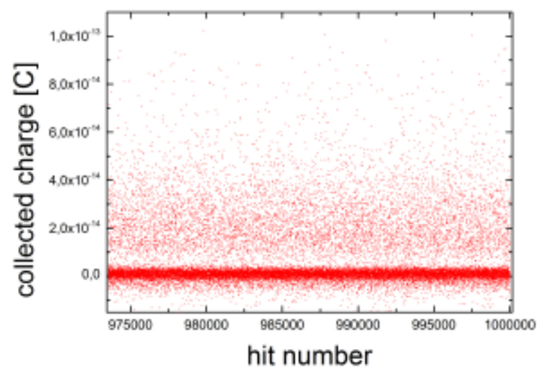


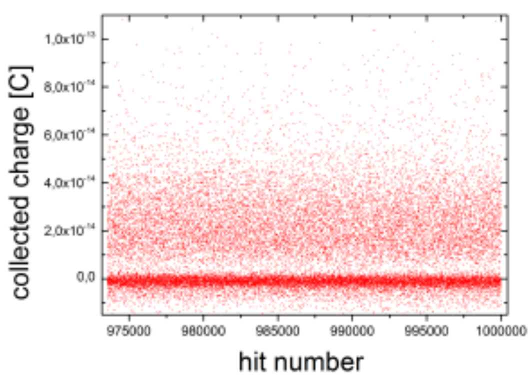


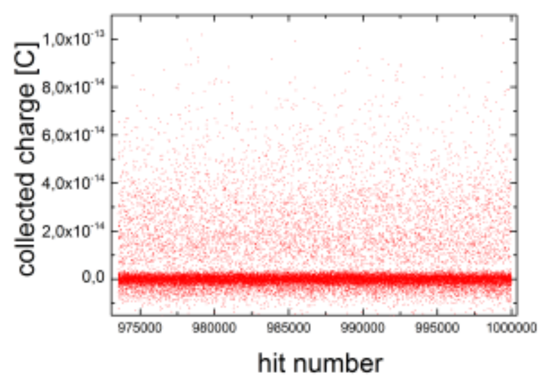
Large Area pcCVD: Charge Collection Spectra

Integral of current pulses for X1, X2, X3 strips from X plane, plastic trigger, HV = 700 V





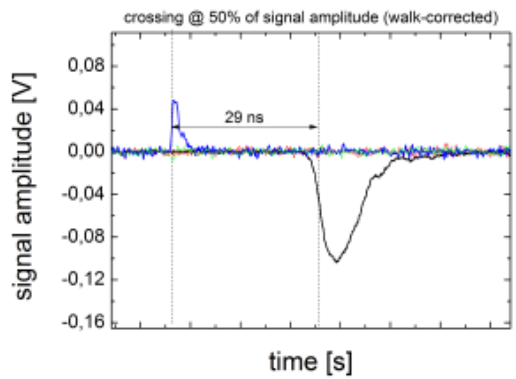


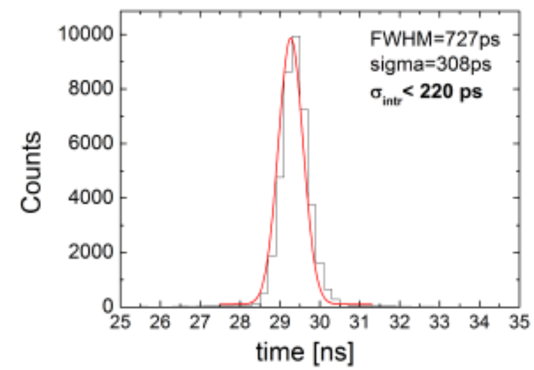


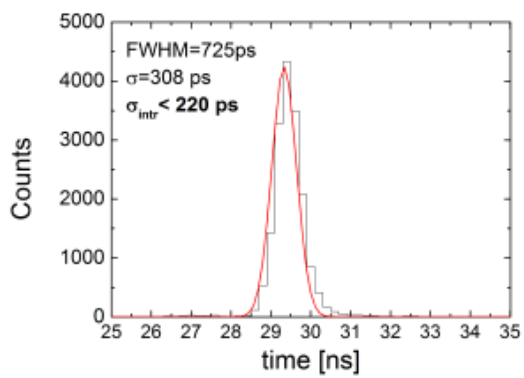
Large Area pcCVD: Time Measurements

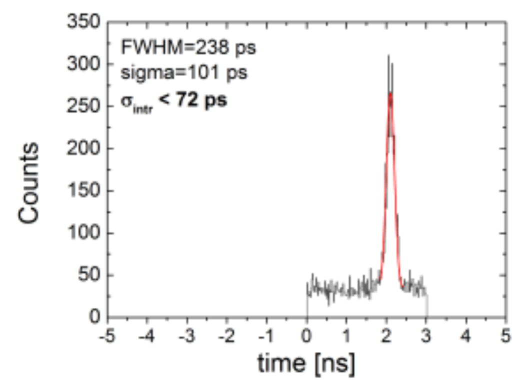
Δt pcCVD diamond hodoscope (@700V) vs. plastic

and pcCVD hodoscope (@150V) vs. 3DDD (@150V)





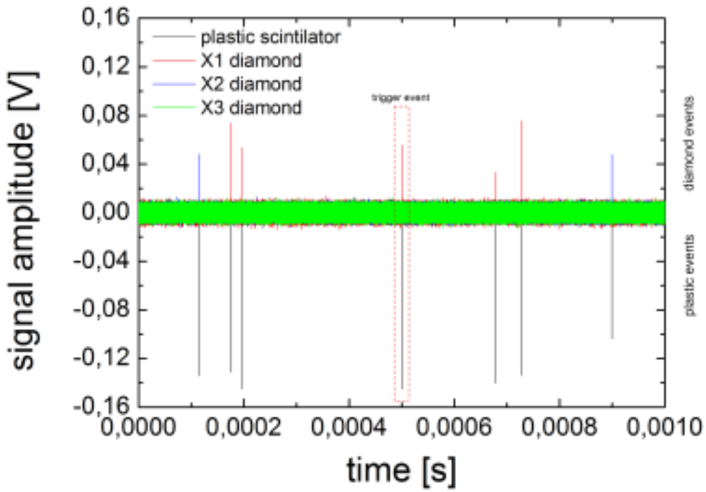




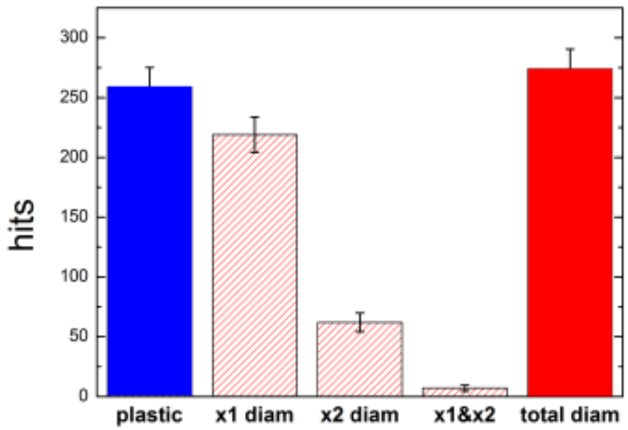
Large Area pcCVD: Detection Efficiency

About 100 random single-shots with aquistion time of 1 ms

trigger event = plastic and diamond X(i) coincidence



An example of single-shot

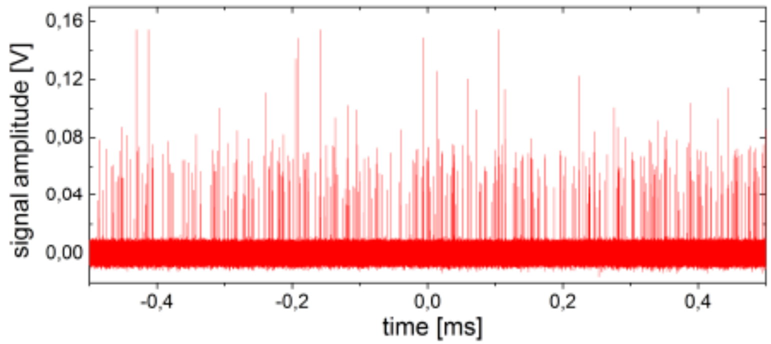


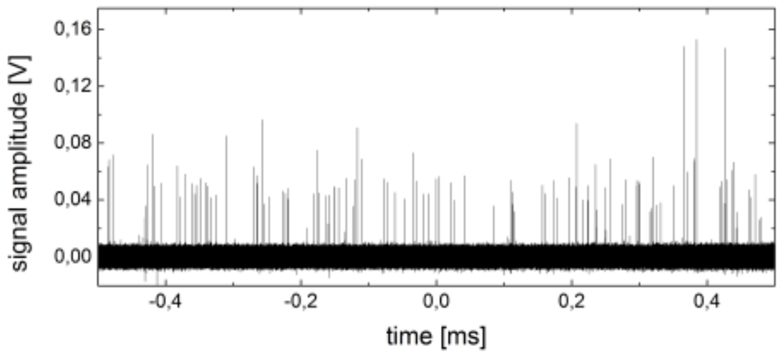
hit efficiency (inter-strip events corrected)

100% detection efficiency vs. plastic

Large Area pcCVD: High Rate

Plastic out of the beam, no collimator, asked operators for highest intensity possible ...





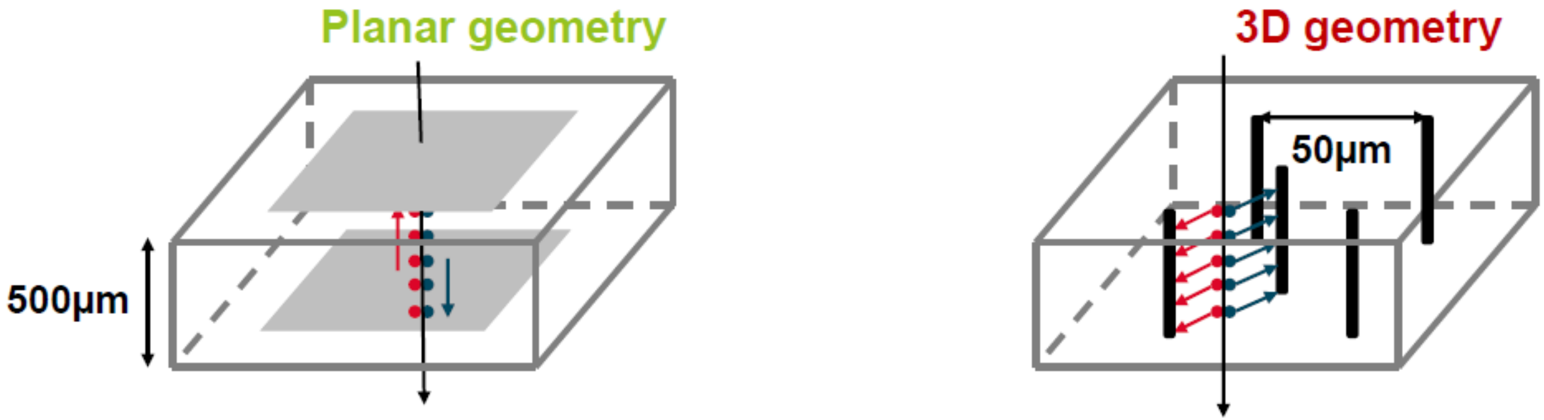
stable, no cross-talk

Large Area pcCVD: Summary

1 x 1 cm^2 pcCVD diamond double sided strip detector tested in 25 MeV proton beam. All requirements (apart of size.....) of GamHadron hodoscope fulfiled:

- position resolution - strip size limited (more precise for inter-strip events)
- time resolution σ =308 ps (vs. plastic (plastic limited)) and σ =101 ps (vs. 3DDD (low E field))
- rate capability (drift velocity limited) 0.1 GHz per strip for 500 μm thick
- stable operation, no evidence of cross-talk
- radiation hard (?)

3D Diamond Detectors – 3DDD

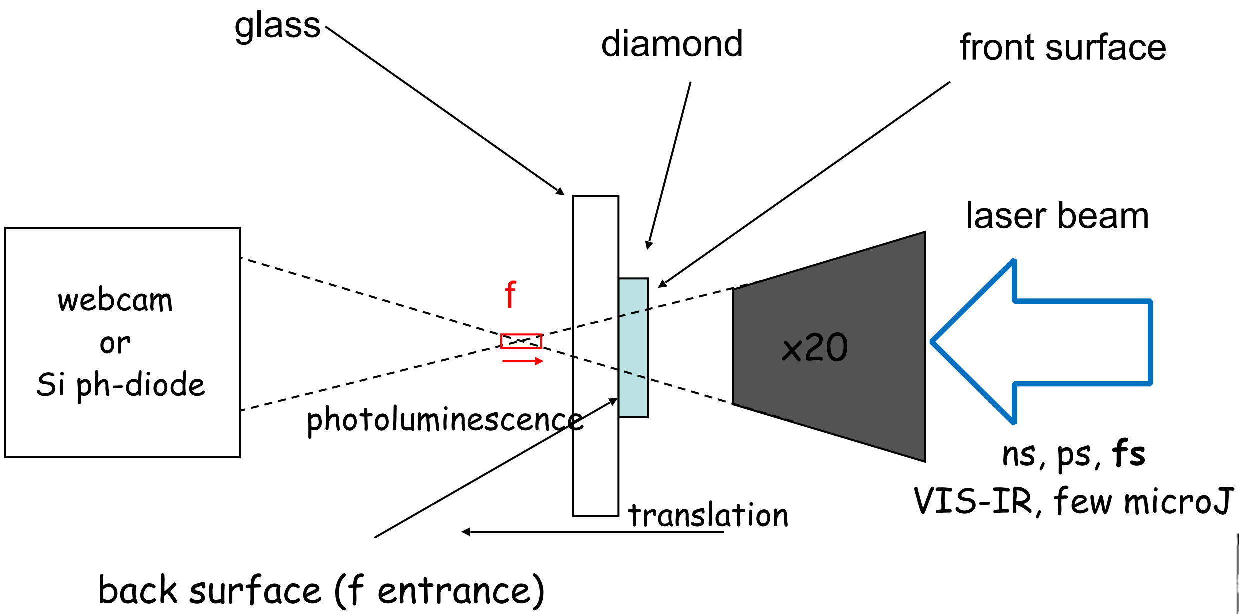


- Q_{MIP} = 18000 e-h pairs
- Q_{MIP} = 18000 e-h pairs

- Analytically calculated currents generated by a MIP

3DDD contributors@CEA-LIST: ***Benoit Caylar, Dominique Tromson, Philippe Bergonzo***

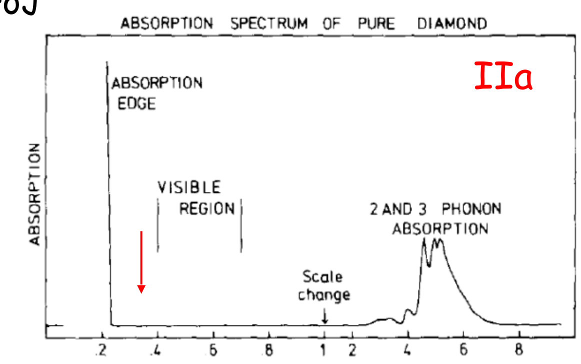
3DDD - How to create conductive buried electrodes

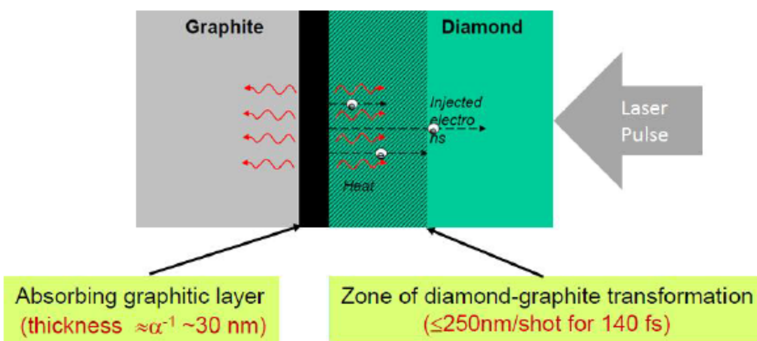


1. holder-diamond interface
   - graphitisation threshold

2. focal within the bulk

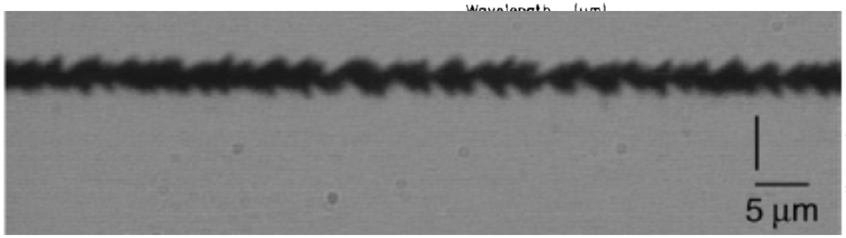
3. diamond-air interface
   - surface damage





T.V. Kononenko et Al – Rus'nanotech (2010)

No heat accumulation



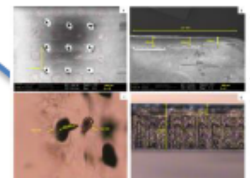
3DDD Some History

3D Diamond Research

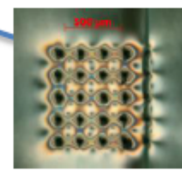
3DD

University of Manchester,
CEA Saclay,
CERN,
ETH Zurich,
Ohio State University

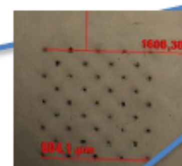
Lasered graphitic structures in pCVD ('10)



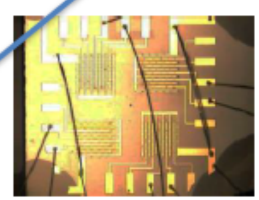
Single crystal with column structure ('11)



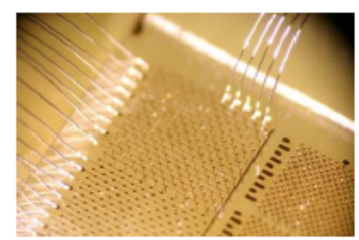
Femto second laser for improved graphitic electrodes ('12)



Improved laser processing and **TCAD simulation ('13)**

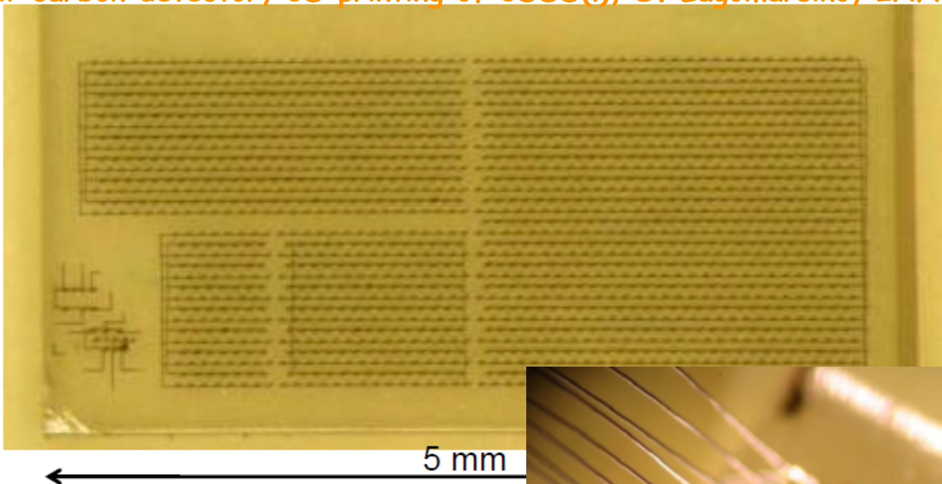


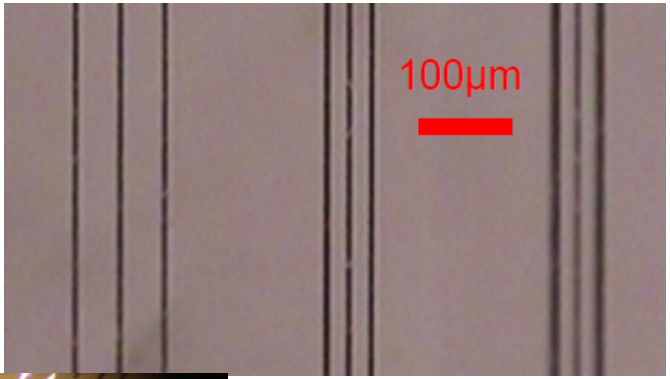
Several Prototypes tested at
Diamond Light Source ('09,'10,'11, '13)
CERN test beam ('12)
RBI proton beam ('13).

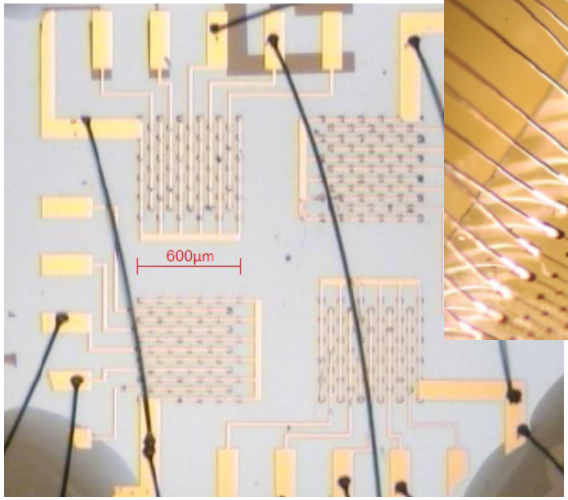


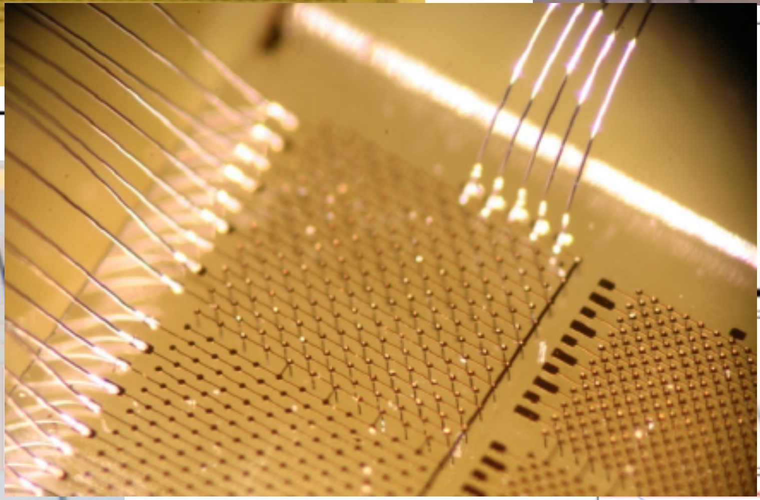
3DDD – Femtosecond laser processing examples

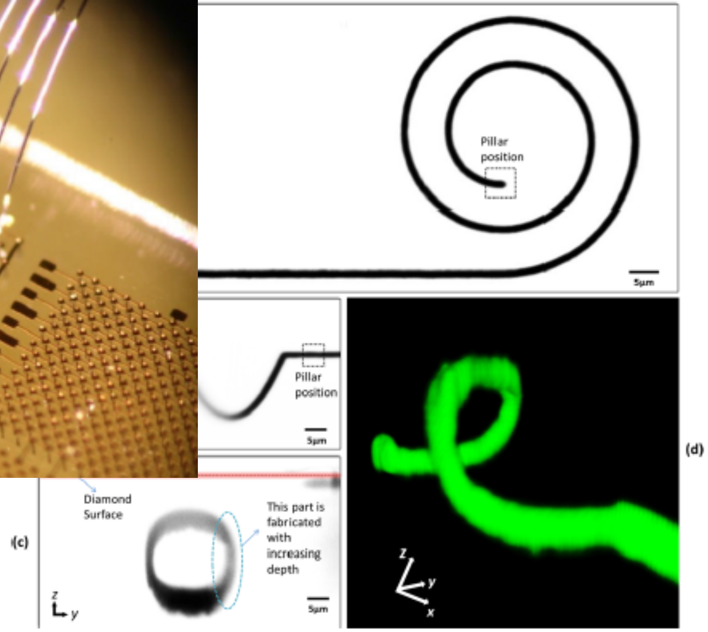
all-carbon detector, 3D printing of 3DDD(!), S. Lagomarsino, INFN







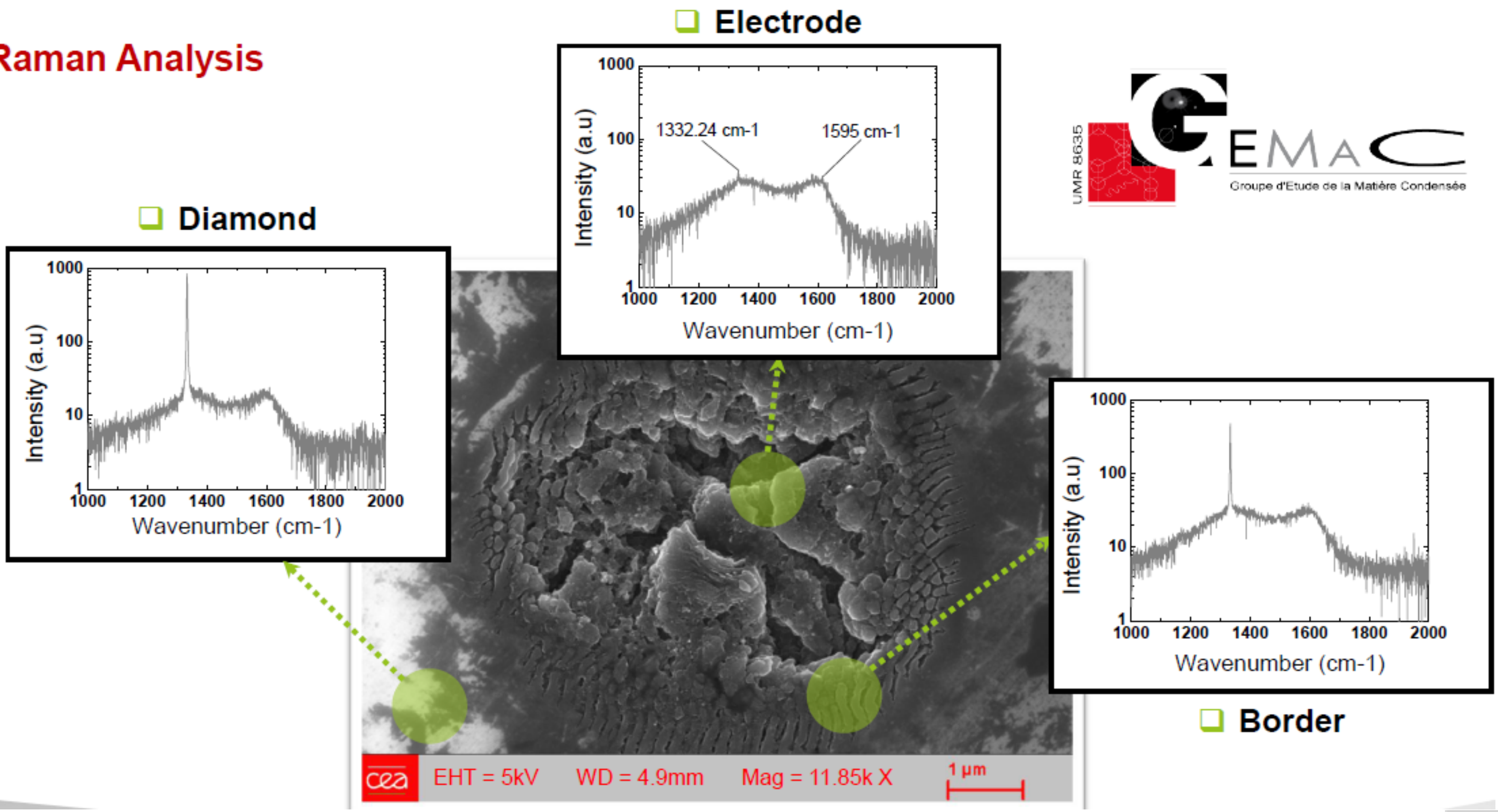




Appl. Phys. Lett. 105, 231105 (2014)

3DDD - Graphitic columns - Structure

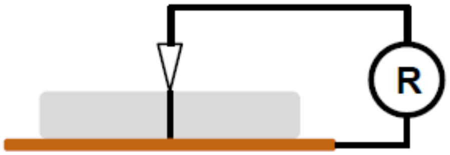
Raman Analysis

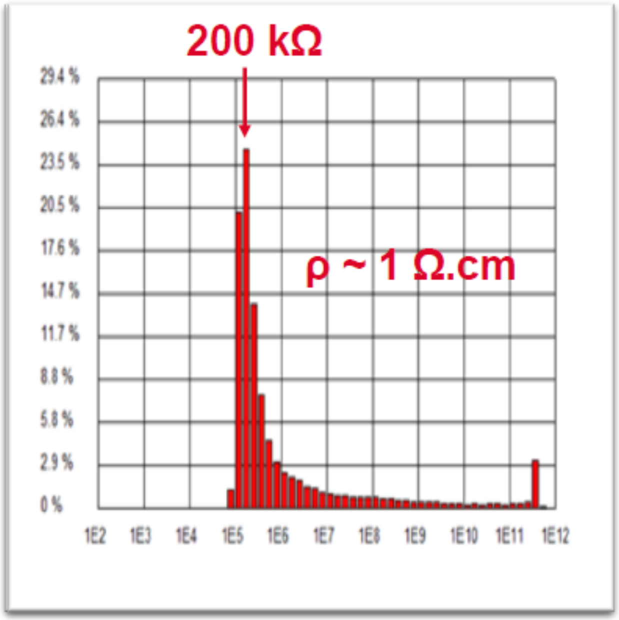


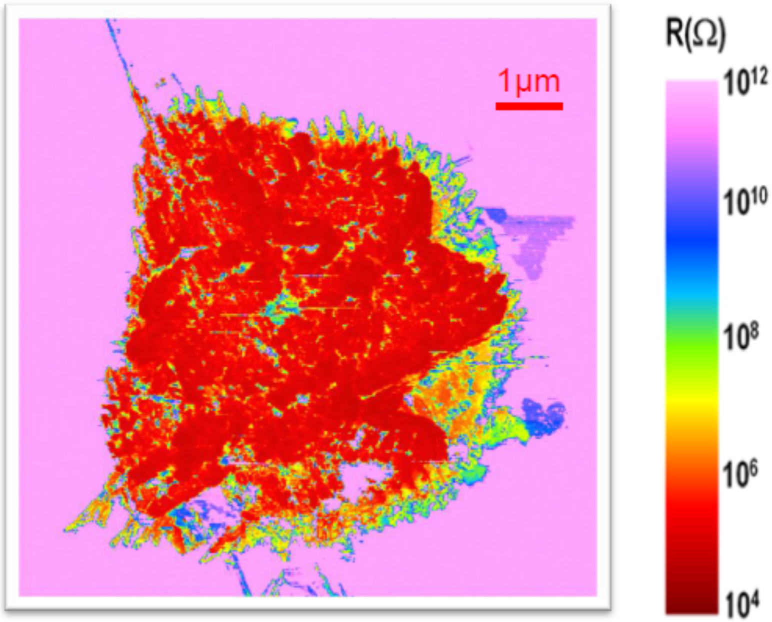
3DDD - Graphitic columns - Resitivity

AFM measurements courtesy **J. Alvarez** (Laboratoire de Génie Electrique de Paris)

Electrode mapping using Conductive probe AFM







- Resistance distribution in the mapping area
- Resistance mapping

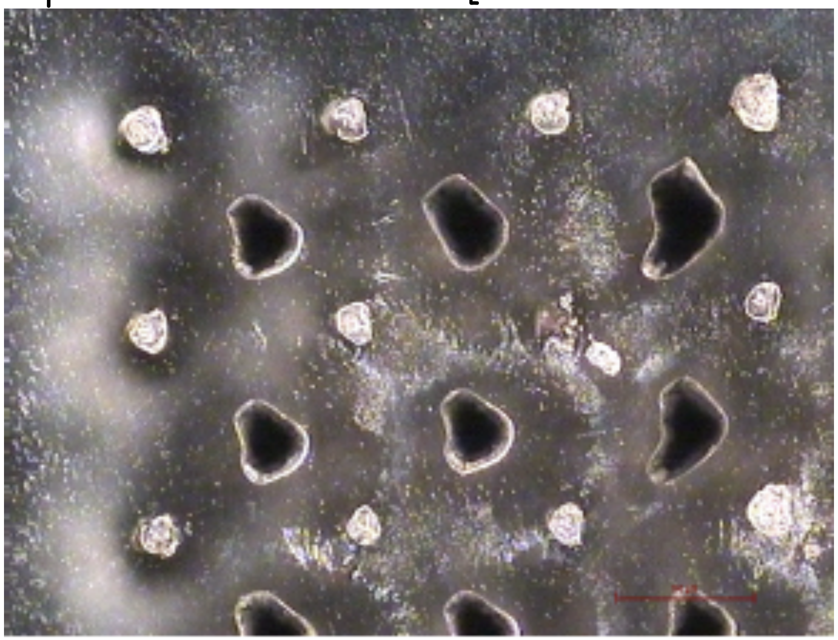
0.022 Ωcm reported in Appl. Phys. Lett. 105, 231105 (2014)

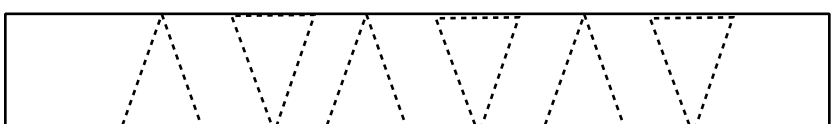
3DDD – Charge Collection Characteristics - pcCVD

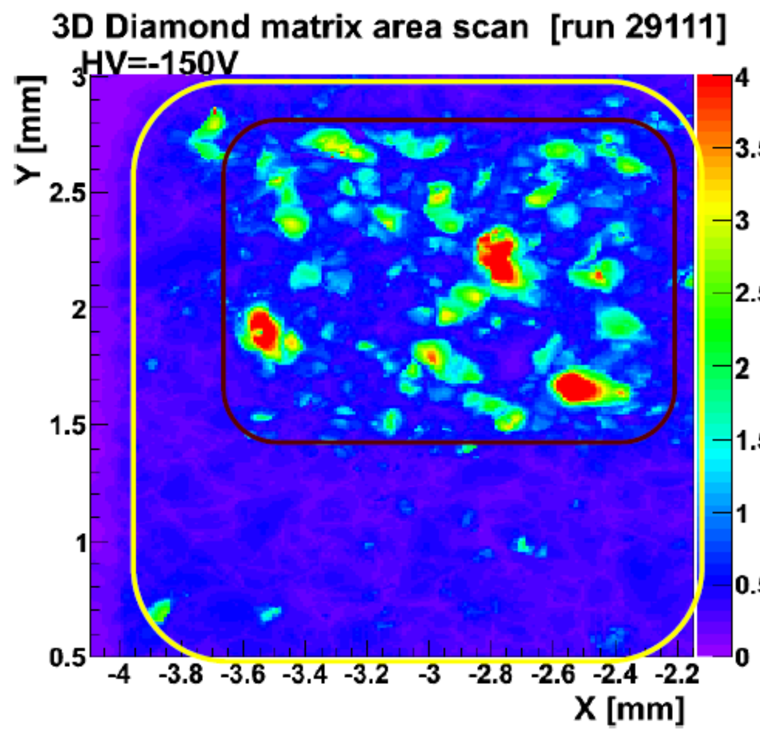
First hint for higher CCE: 2011 beamtime @ Diamond Light Source, UK

Raster scan with X-ray microbeam 15 keV, 4 microns spot FWHM, 10^9 photons/s

'crude' 3D structure, matrix of cones, covered with planar metal electrodes [1064nm **ns** YAG laser]





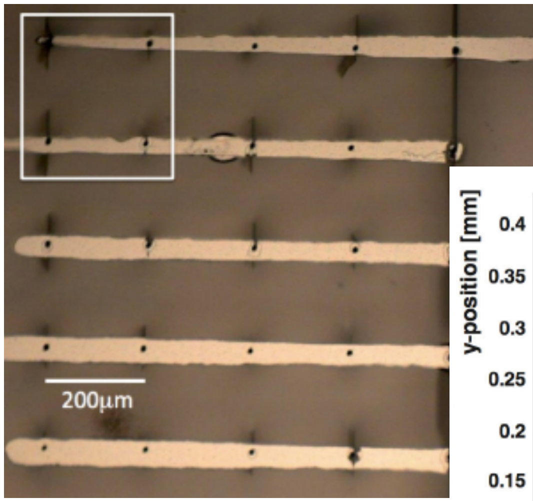


XBIC of the pcCVD sample

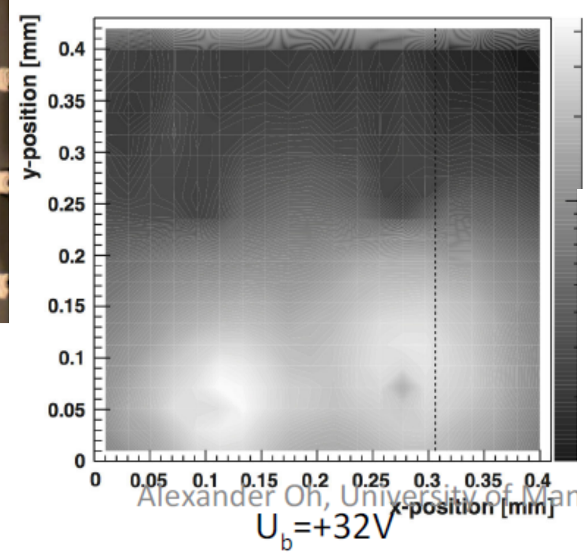
3DDD – Charge Collection Characteristics - scCVD

First scCVD [3ns 337nm N laser, ~3microJ]:

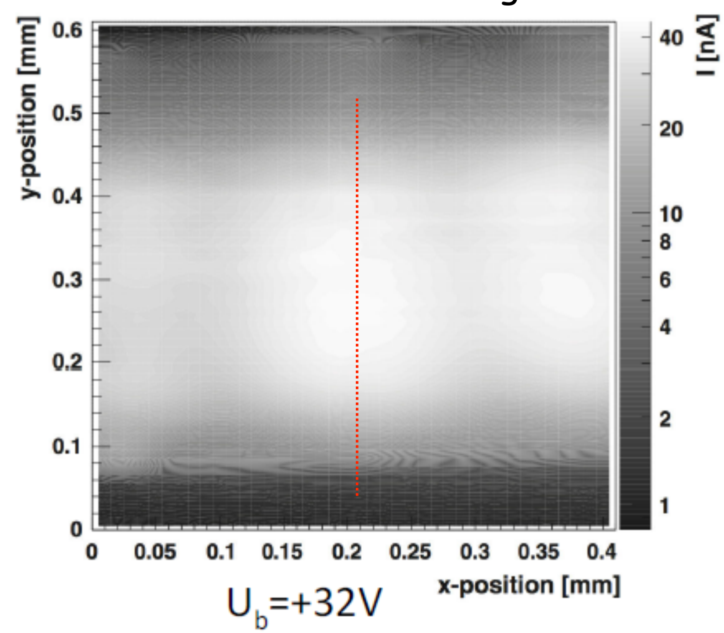
2012 beamtime @ Diamond Light Source, UK



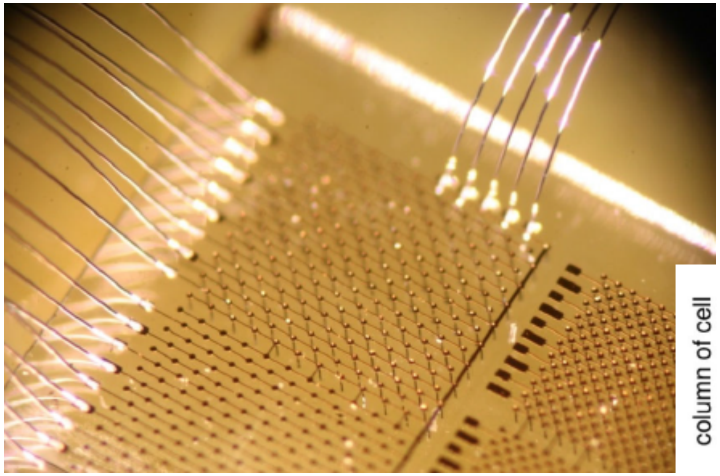
XBIC front shooting



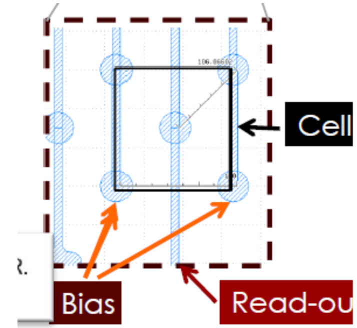
XBIC side shooting

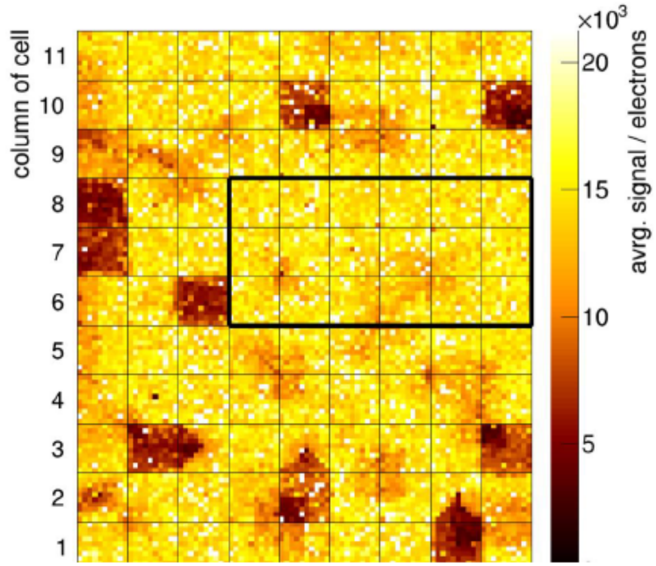


3DDD – Charge Collection Characteristics - scCVD

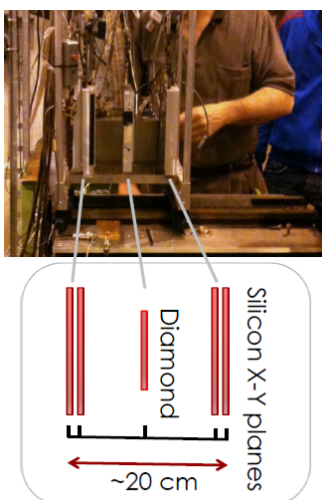


EG scCVD [100**fs** 800 nm laser, ~1microJ]
500 microns scCVD (3D structure+strips+3D only metal pattern)
cubic cell base size 150 microns (99 cells)

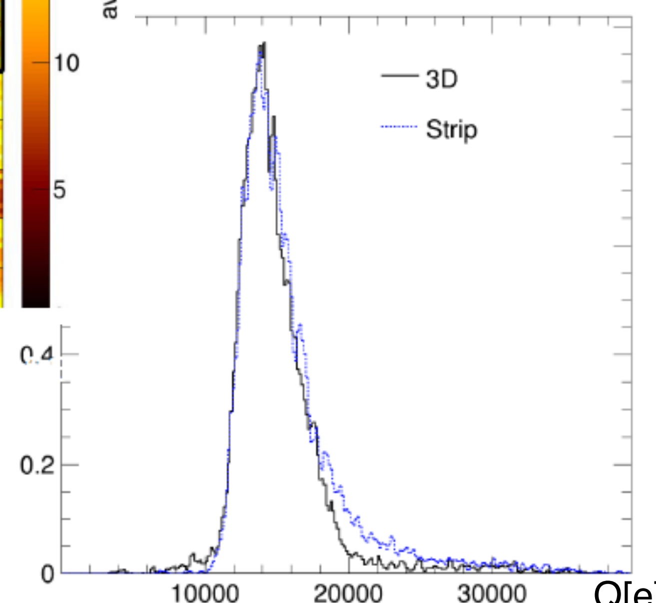




CERN Test-beam set-up 2013

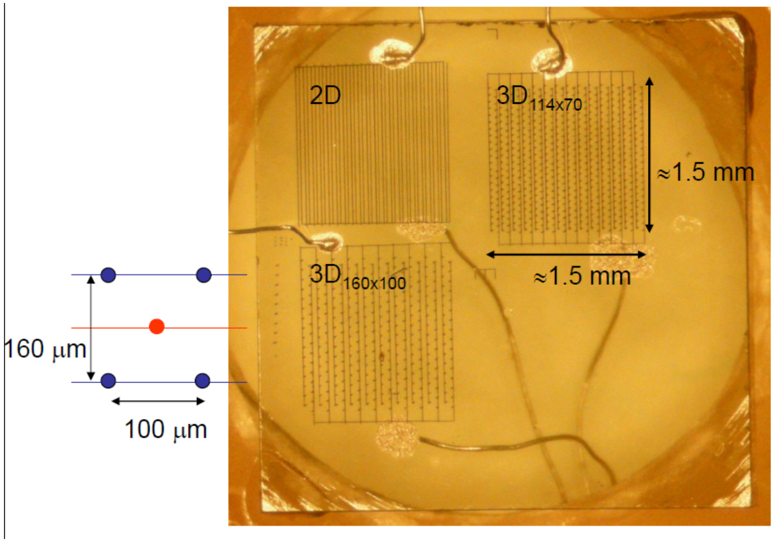


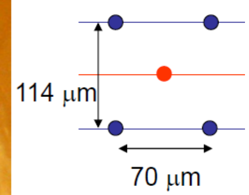
- **protons with p=120 GeV/c**
- spill every 40 sec
- ~4k events / spill
- readout VA2 low-noise CMOS
- silicon telescope for track rec.

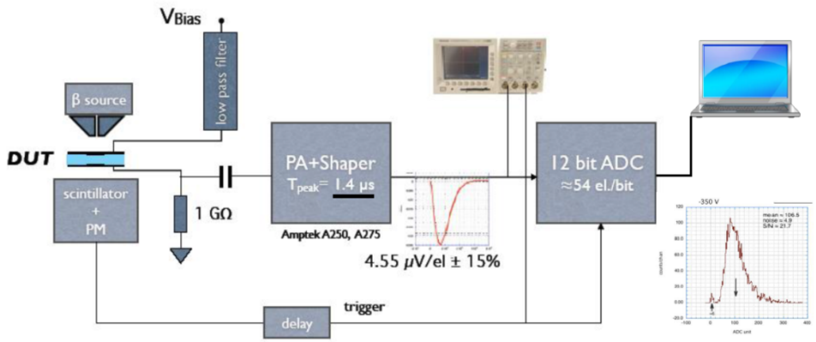


3DDD – Charge Collection Characteristics - pcCVD

all content here from: http://www-adamas.gsi.de/ADAMAS03/talks/Lagomarsino_INFN.pdf





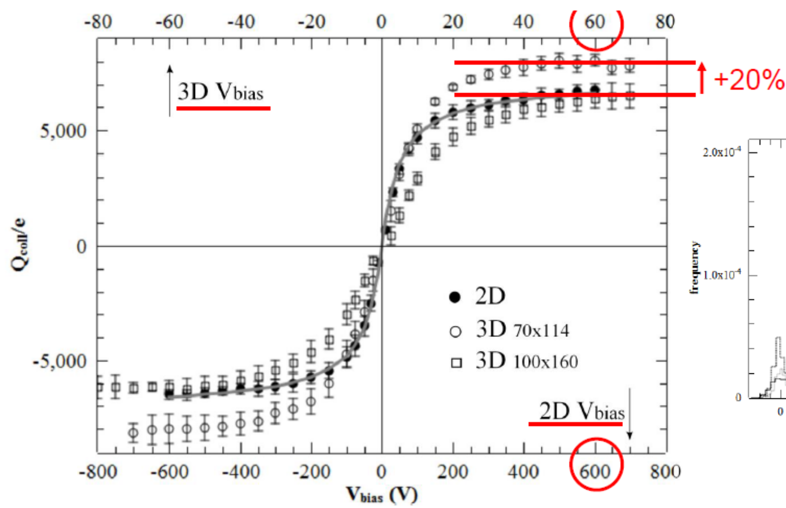


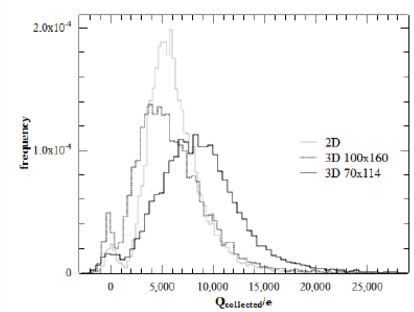
EG pcCVD [30fs, 800nm laser]

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).

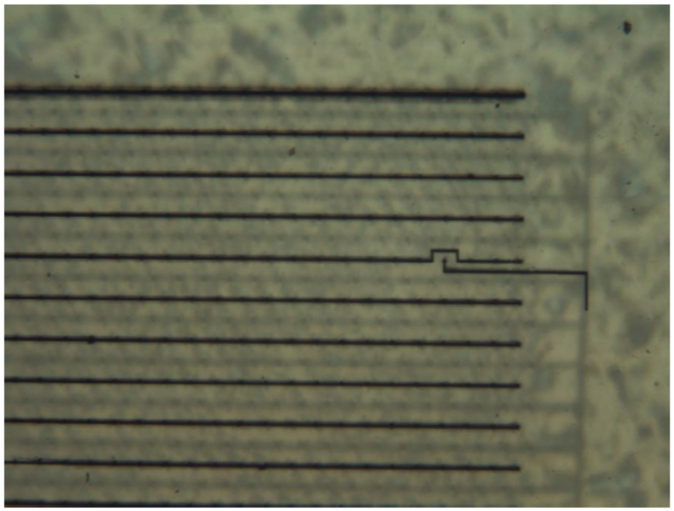
The separations of the 10% percentile of the distribution from the pedestal are comparable for 2D and 3D detectors.



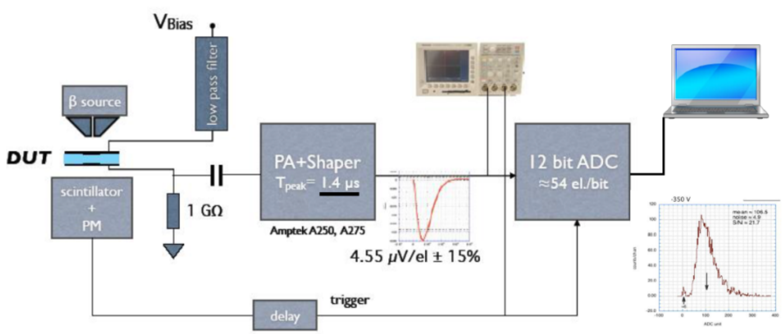


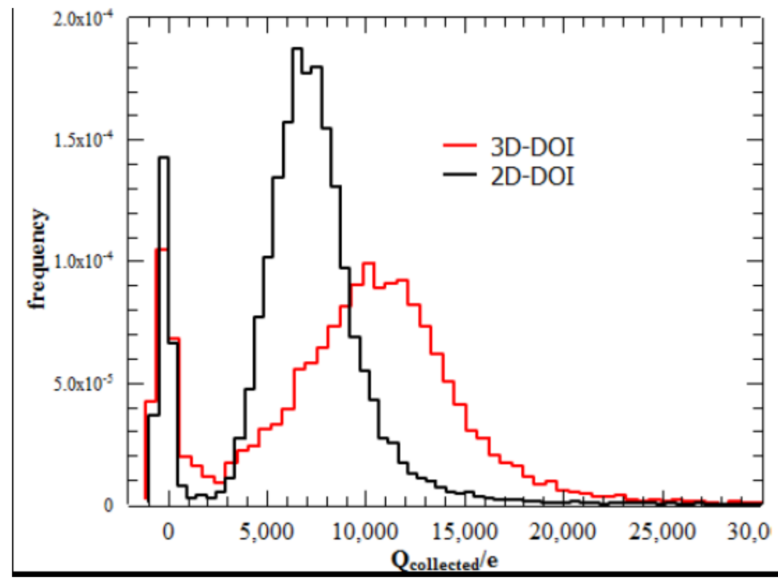
3DDD – Charge Collection Characteristics - DoI

all content here from: http://www-adamas.gsi.de/ADAMAS03/talks/Lagomarsino_INFN.pdf



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





→ 2D (at 600 V) = 7600 e (39% CCE)

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

Summary

LA pcCVD: electronic grade pcCVD (e6) fulfil all requirements for hadrontherapy (C) diamond hodoscope (but need real LA)

3D Diamond Detectors: **it works!**

all-carbon detector with laser 3D printing of ready to use 3DDD

scCVD same CCE as planar at much lower bias

pcCVD + DoI increase in CCE for 3D geometry

to optimise:

production yield (~ 90% now) of the graphitic columns

lower resistivity of columns (few kOhms for 500 microns now)

higher radiation hardness of 3DDD to be confirmed

Thank you for your attention!