TCT simulations of synthetic diamonds using Allpix squared

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Why Diamond Particle Detector?

Diamond's advantages as sensor material in HEP

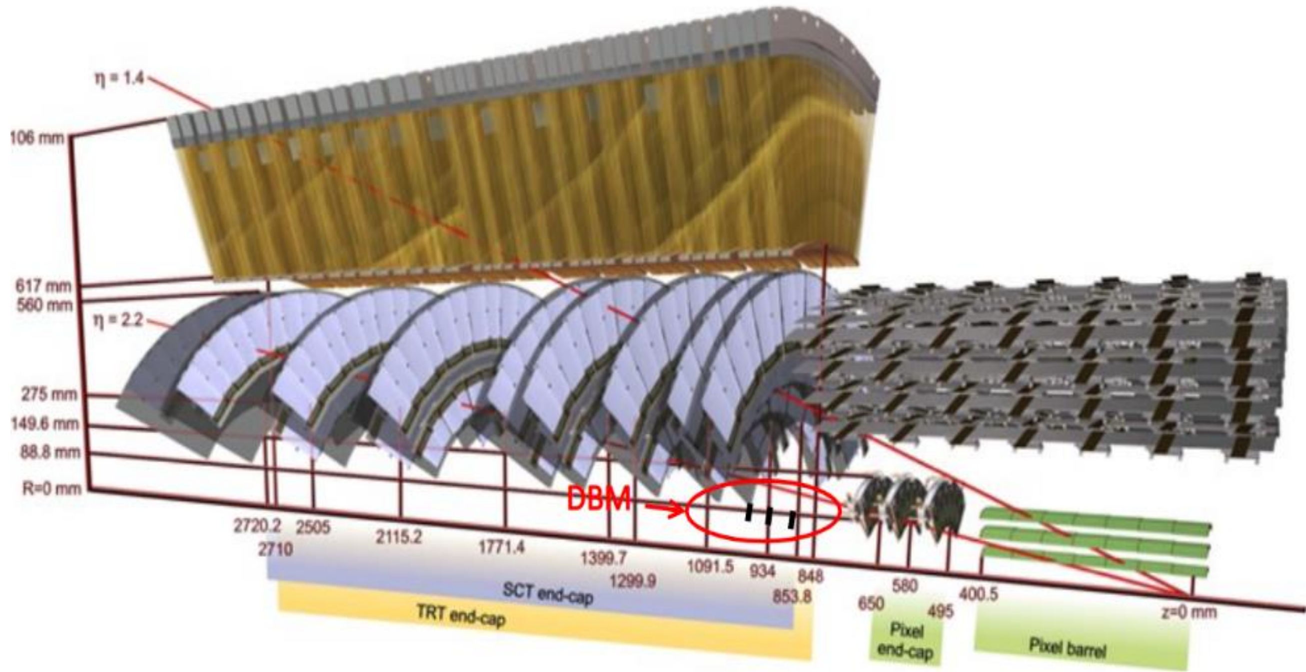
- Low Atomic Number – ideal for tracking detectors but low signal
- 43 eV Displacement energy – Radiation hard
- High drift velocities – Fast Signal Readout

Property	Diamond	Silicon	
Band Gap (ev)	**5.5**	1.12	**Low Noise**
Atomic Number (z)	$\mathbf{6}$	14	**Low Signal**
Displacement Energy ($ev/atom$)	$\mathbf{43}$	$13-20$	**Radiation Hard**
Mobility (cm^2/Vs)*	$\mathbf{1900}(e),\mathbf{2300}(h)$	$1350(e)480(h)$	**Fast Signal**
Saturation Velocity ($10^7\ cm/s$)	$\mathbf{1.3}(e),\mathbf{1.7}(h)$	$1.1(e), 0.8(h)$	**Fast Signal**
Aver. Signal Created/100 um (e)	**3602**	8892	**Low Signal**

*4551(e),2750(h) https://doi.org/10.1002/pssa.201532230
4500(e),3800(h) DOI: 10.1126/science.1074374

Applications in HEP

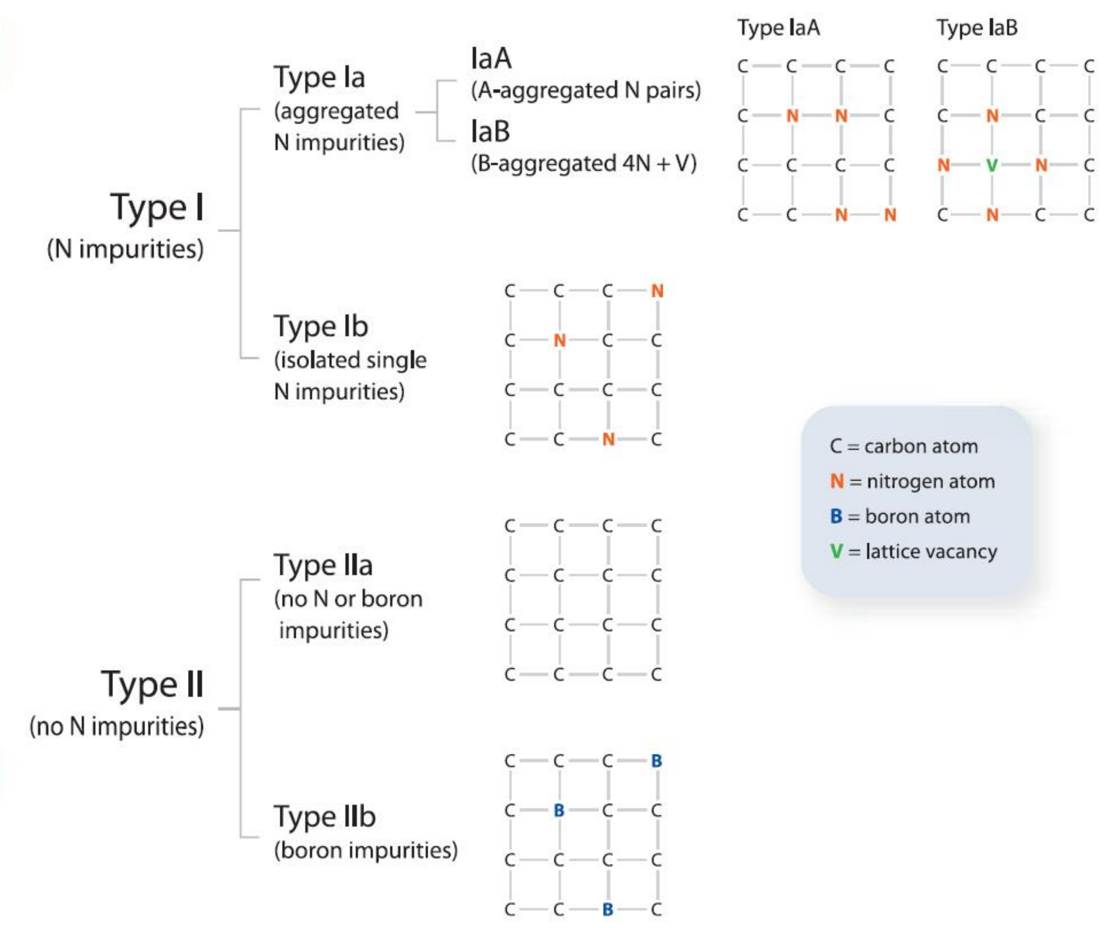
- LHC (CERN) [1] and CDF (Collider Detector at Fermilab) [2] use diamond sensors for beam monitoring and accident Protection. ATLAS BCM/BLM, CMS BCM/BCM-F
- LHCb BCM
- ATLAS Diamond Beam Monitor (DBM)
- Inner layer ? Big disadvantage is cost (financial aspect, not physics)



[1] F. Hugging: Diamond Detectors
[2] FERMILAB-CONF-07-112-E

Classification of Diamond

- Type IIa is desired with single crystal structure



https://www.whiteflash.com/diamond-education/diamond-types/

TCT-TOF

- A simple single-crystal CVD sensor sandwiched between two metallic electrodes
- metal-insulator-metal (MIM) detector

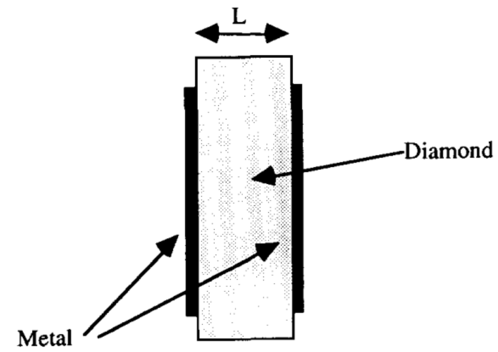
$$V_{drift} = \frac{d}{t} = \frac{L}{\tau}$$

$$V_{drift} = \mu(E)E$$

$$L = \mu E \tau$$

- the important parameters

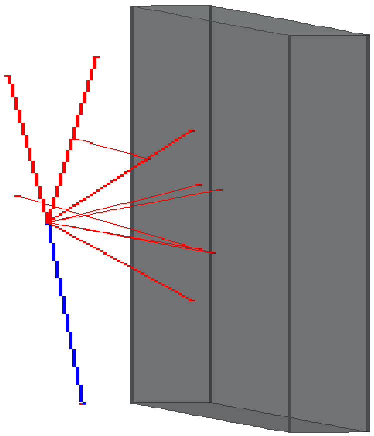
$$\mu, \tau \text{ and } \mu\tau$$



Schematic diagram of a MIM

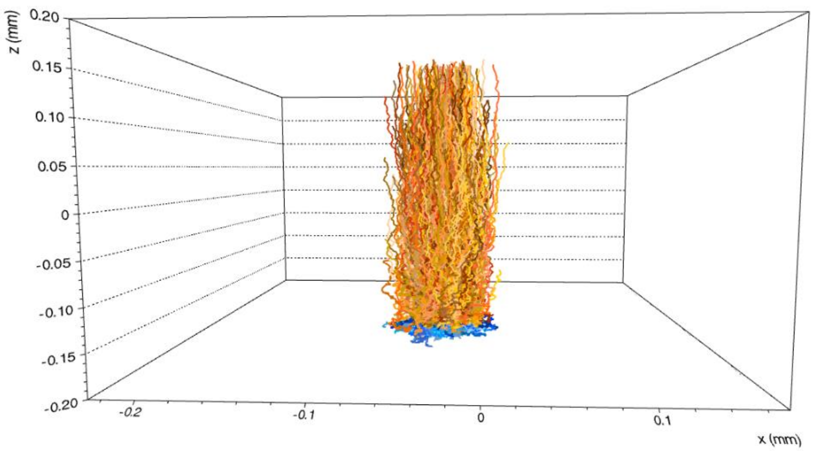
doi.org/10.1016/0925-9635(93)90266-5

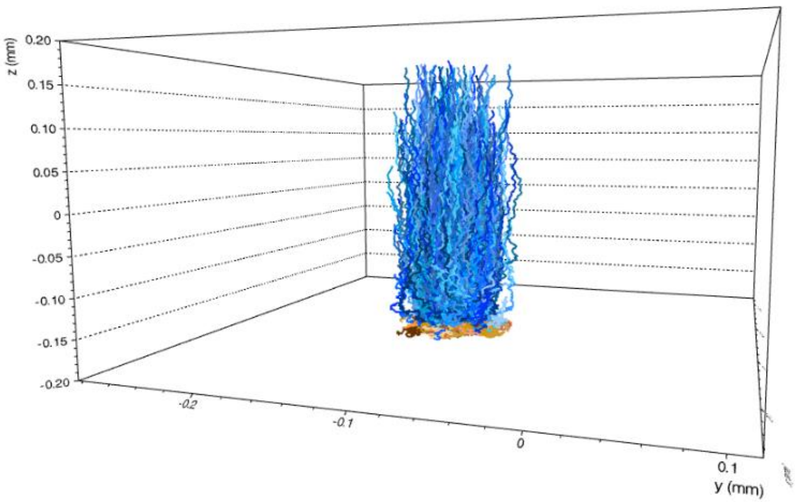
- Detector Type: pixel scCVD
- Detector Size: (3mm × 3mm) × 500um
- Mobility Model: Caughy model (custom)
- Energy Source: Am-241 Alpha source
- Energy Deposited: 5.486 MeV
- Applied Bias Voltage = -1000V



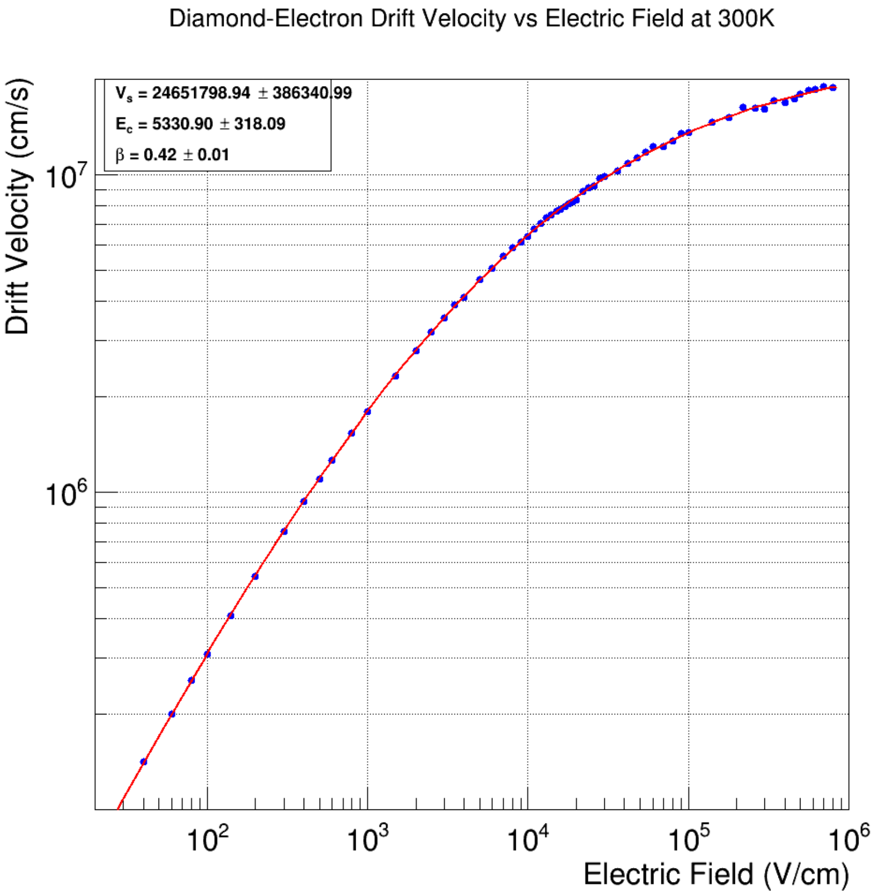
TCT with Am-241 alpha source

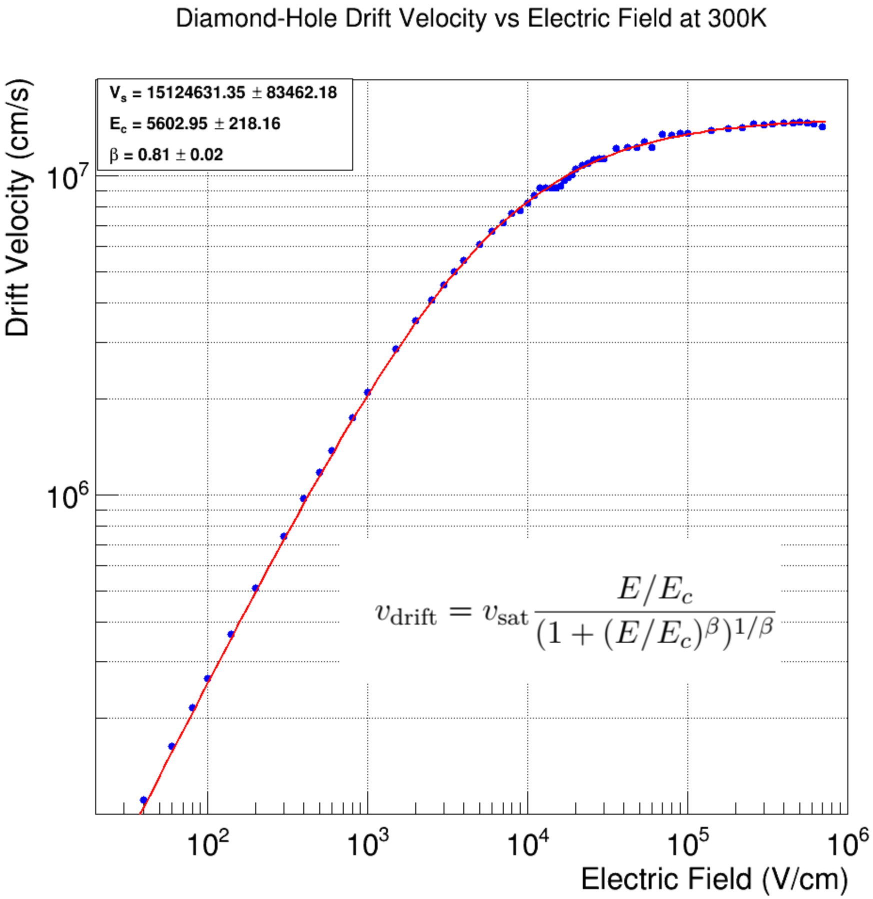
- TCT with an alpha source, an efficient technique to investigate the dynamics of charge carriers individually.





Diamond Drift Velocity





Values in Literature

- $V_s = 2.63\times 107 \pm 0.2\times 10^7\, cm/s$
- $E_c = 5779 \pm 772$
- $\beta = 0.42 \pm 0.01$

https://doi.org/10.1002/pssa.201532230

Values in Literature

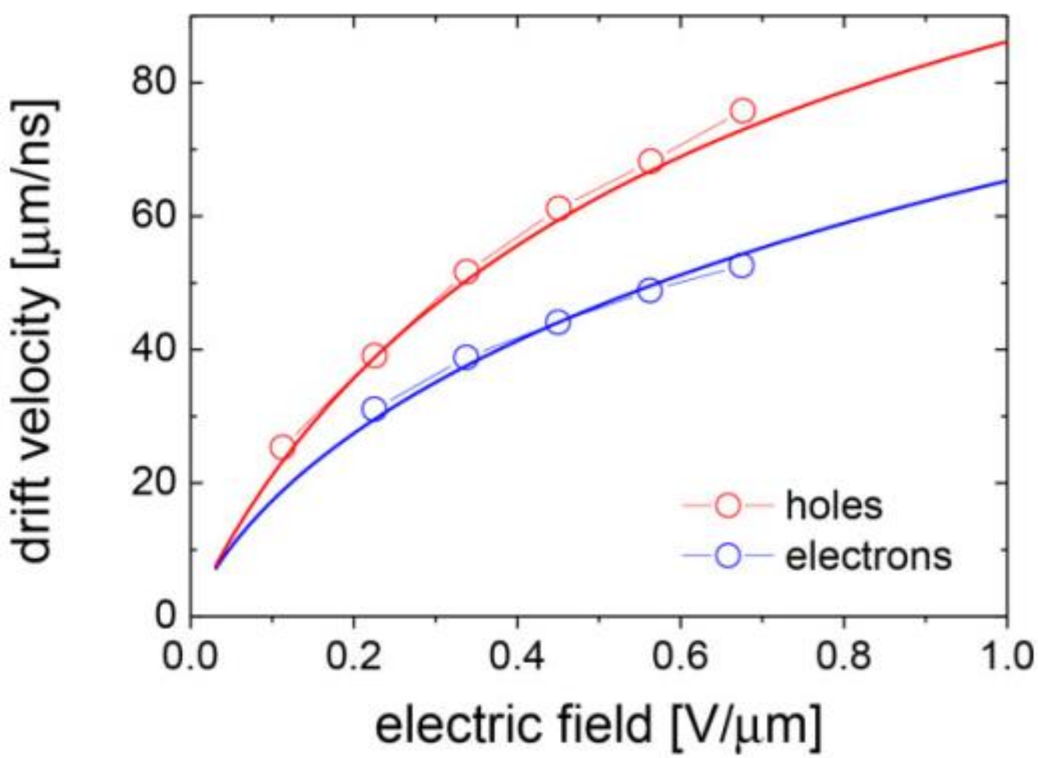
- $V_s = 1.57\times 107 \pm 0.14\times 10^7\, cm/s$
- $E_c = 5697 \pm 529$
- $\beta = 0.81 \pm 0.01$

https://doi.org/10.1002/pssa.201532230

Diamond e-h Drift Velocity

- e-h derift velocities for scCVD diamond Left: Experimental (Literature), Right: Simulation with Allpix-Squared

Literature



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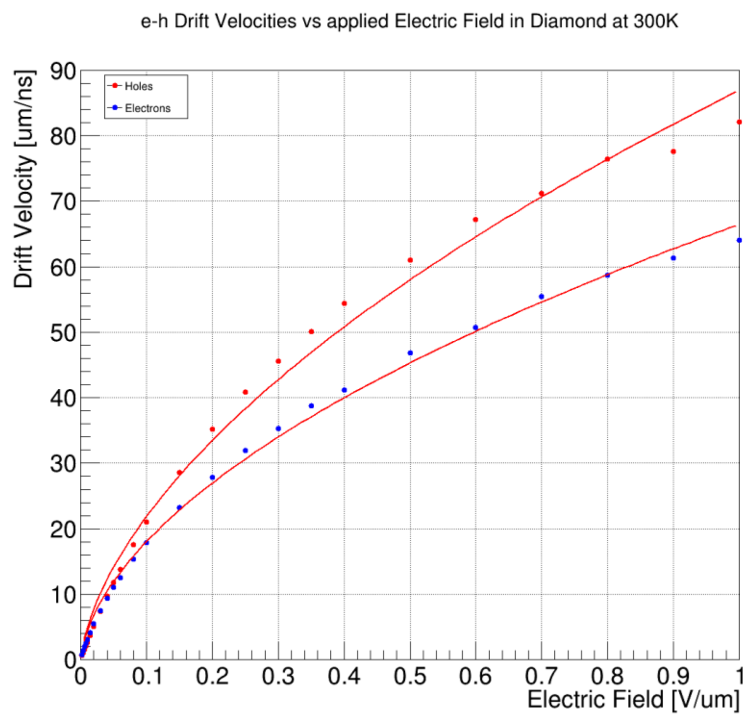
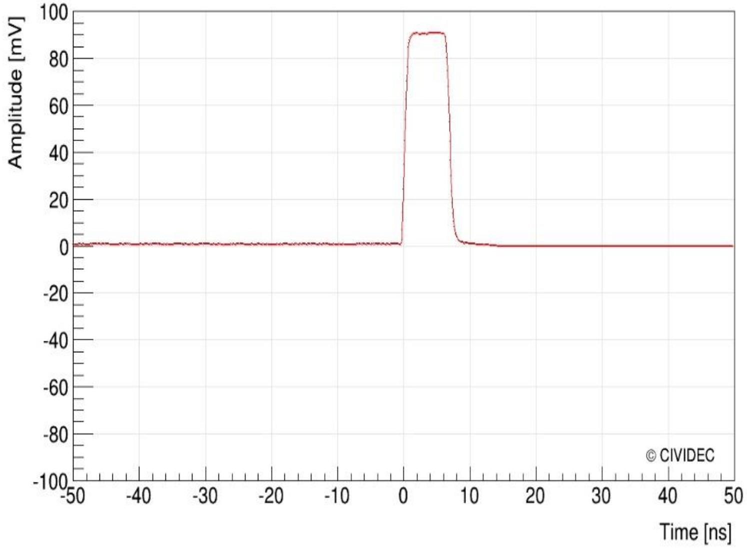


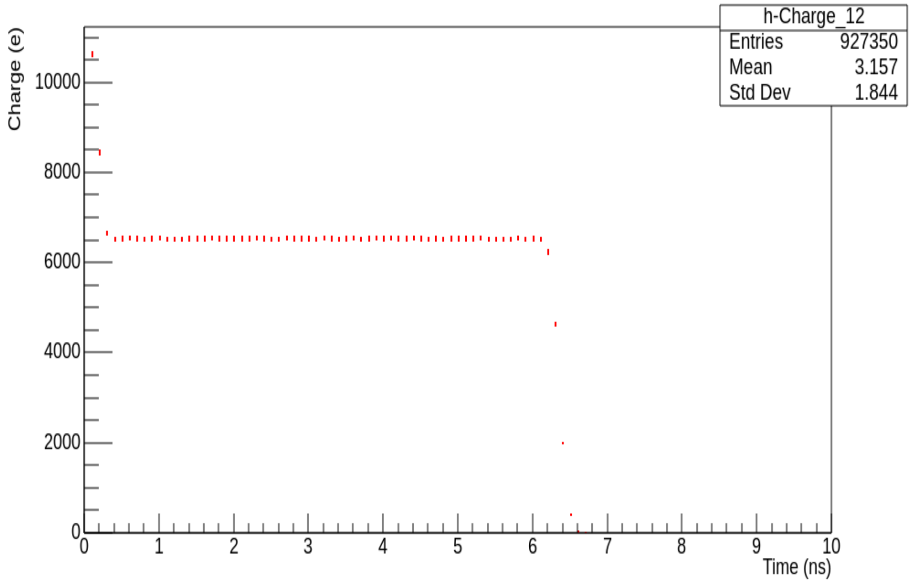
Single Crystal Diamond

- sc CVD diamond TCT signal with alpha source
- Constant amplitude -> impurities below detection limit
- Very fast signal read out (orders of nano seconds)

- BUT scCVD Diamond is very expensive, pcCVD is a cost efficient alternative

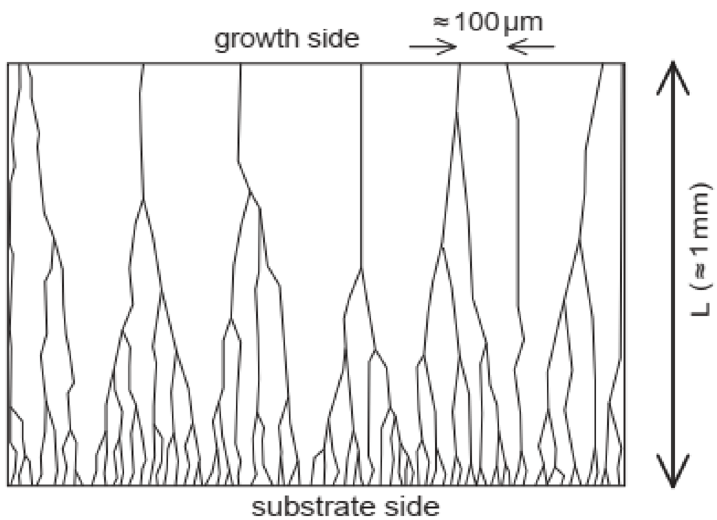


https://cividec.at/electronics-C2-TCT.html

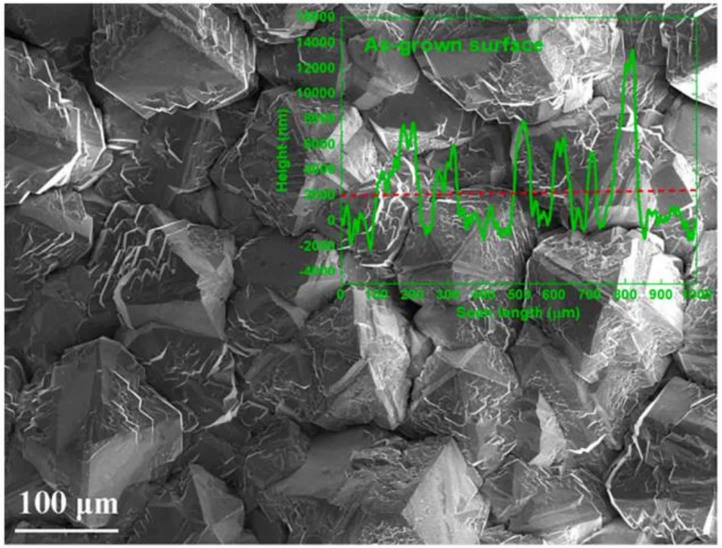


pcCVD Diamond

- Grain boundaries and deep level traps of pcCVD diamond needs implementation of diamond specific trapping models
- RD42 model: pcCVD Diamond = irradiated scCVD Diamond
- Mean free path (*λ*) = charge collection distance (CCD): detector performance parameter



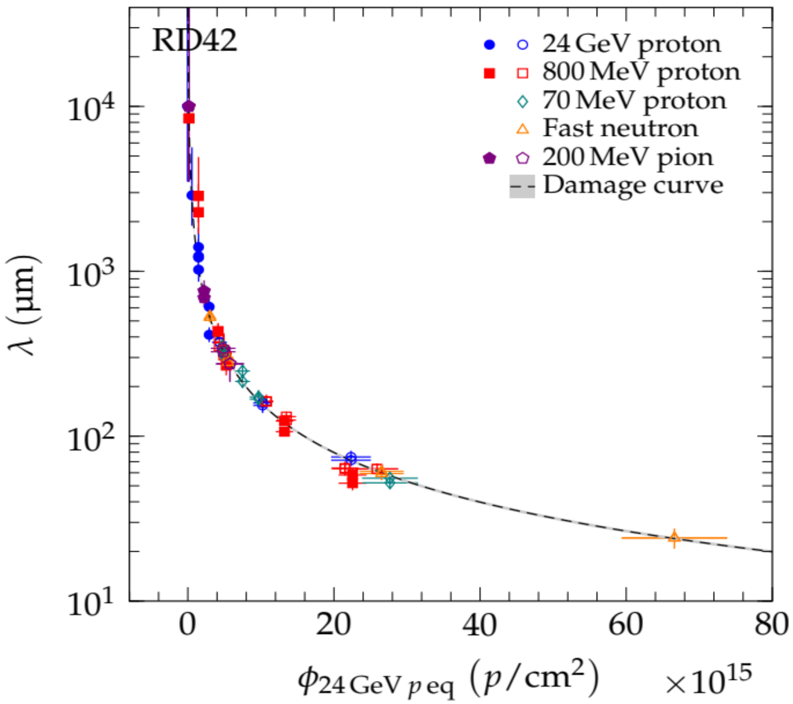
Grain boundaries in pcCVD Diamond
From Particle Detectors: Fundamentals and Applications by Kolanoski & Wermes



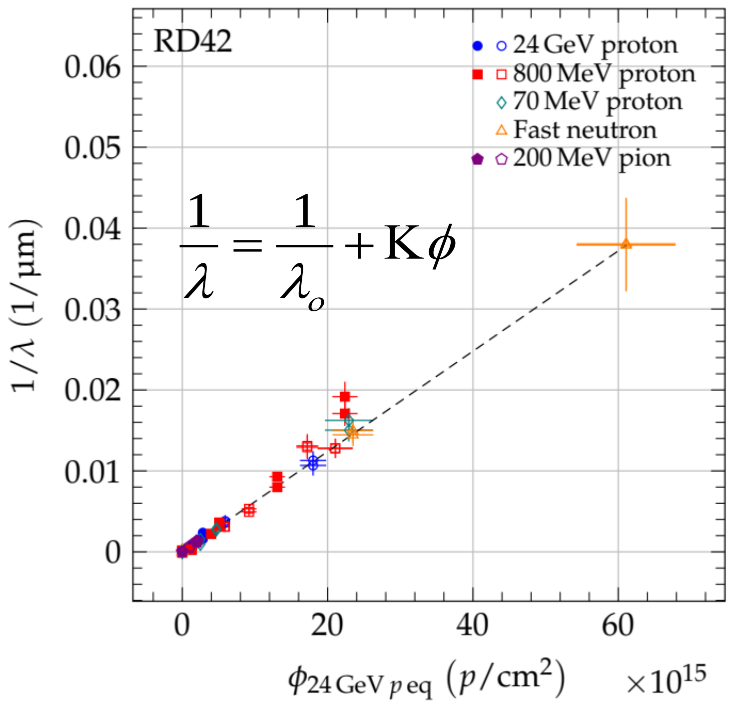
Scanning electron microscope (SEM) image the growth surface of pcCVD film
https://doi.org/10.1016/j.diamond.2021.108461

RD42 Radiation Damage Model

- Same radiation damage constant for pcCVD and scCVD
- scCVD shifted to left by $\emptyset = 3.8 \times 10^{15} p/cm^2$ (left plot)



pcCVD and scCVD lies on the same fit line 2018
https://doi.org/10.1016/j.nima.2019.162675



Universal Radiation Damage constant for pcCVD and scCVD diamonds
https://doi.org/10.1016/j.nima.2019.162675

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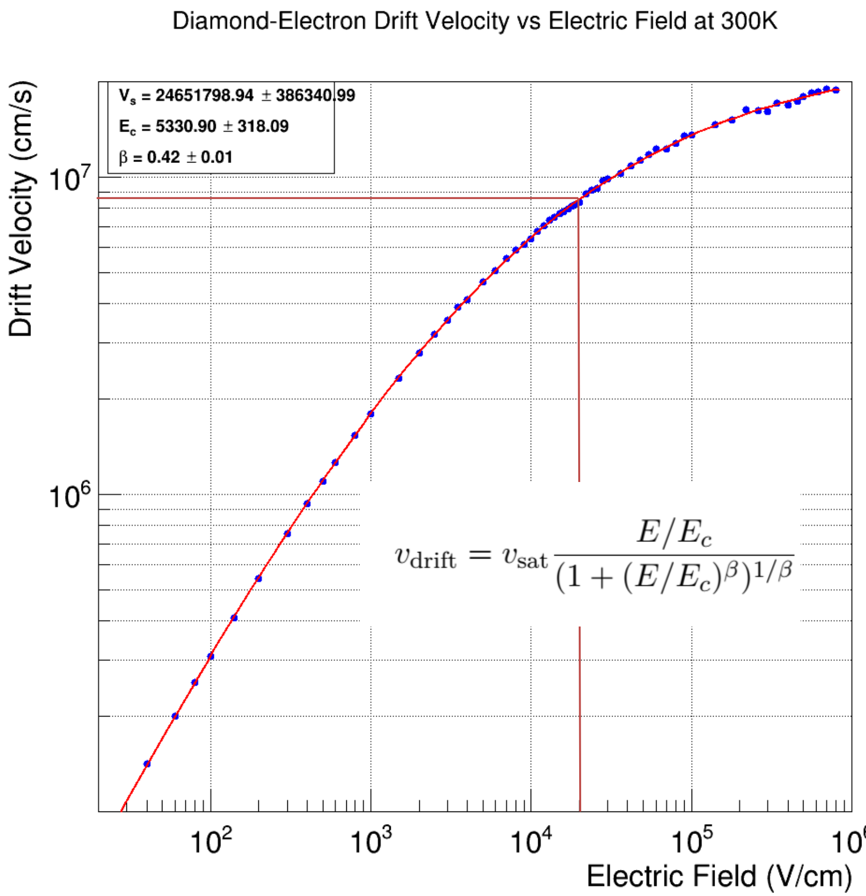
Charge carrier life times

- Trapping times from Mean free path for the electric field of 2V/um (20000/cm)

$$\frac{1}{\lambda} = \frac{1}{\lambda_o} + K\phi$$

$$\frac{1}{\tau} = \frac{1}{\tau_o} + (K\upsilon_{drift})\phi$$

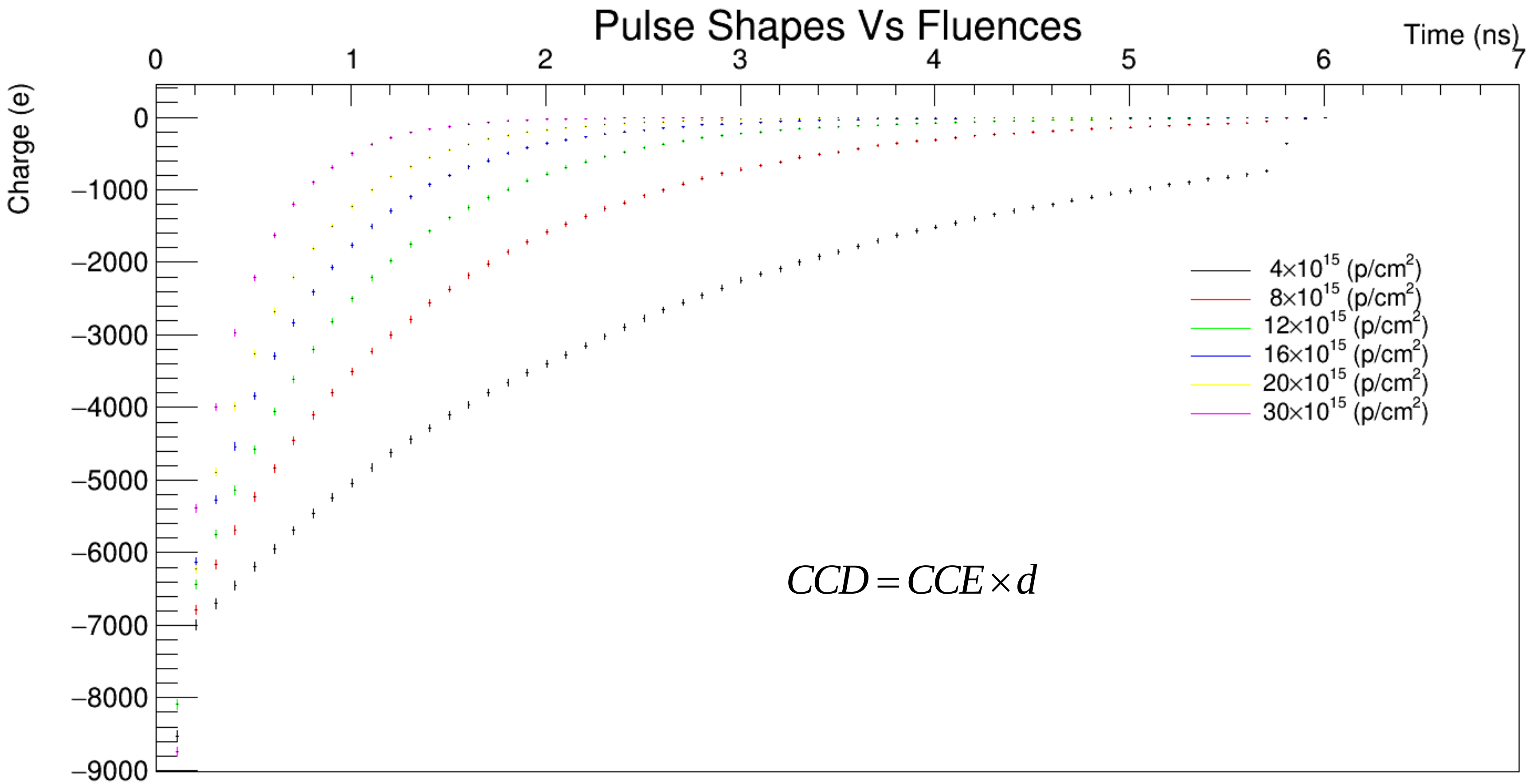
$$\frac{1}{\tau} = \frac{1}{\tau_o} + \beta\phi$$



- Different β parameter values reported from 0.42 to 1.
- Affects the value of drift velocity at specific electric field value

Pulse shapes

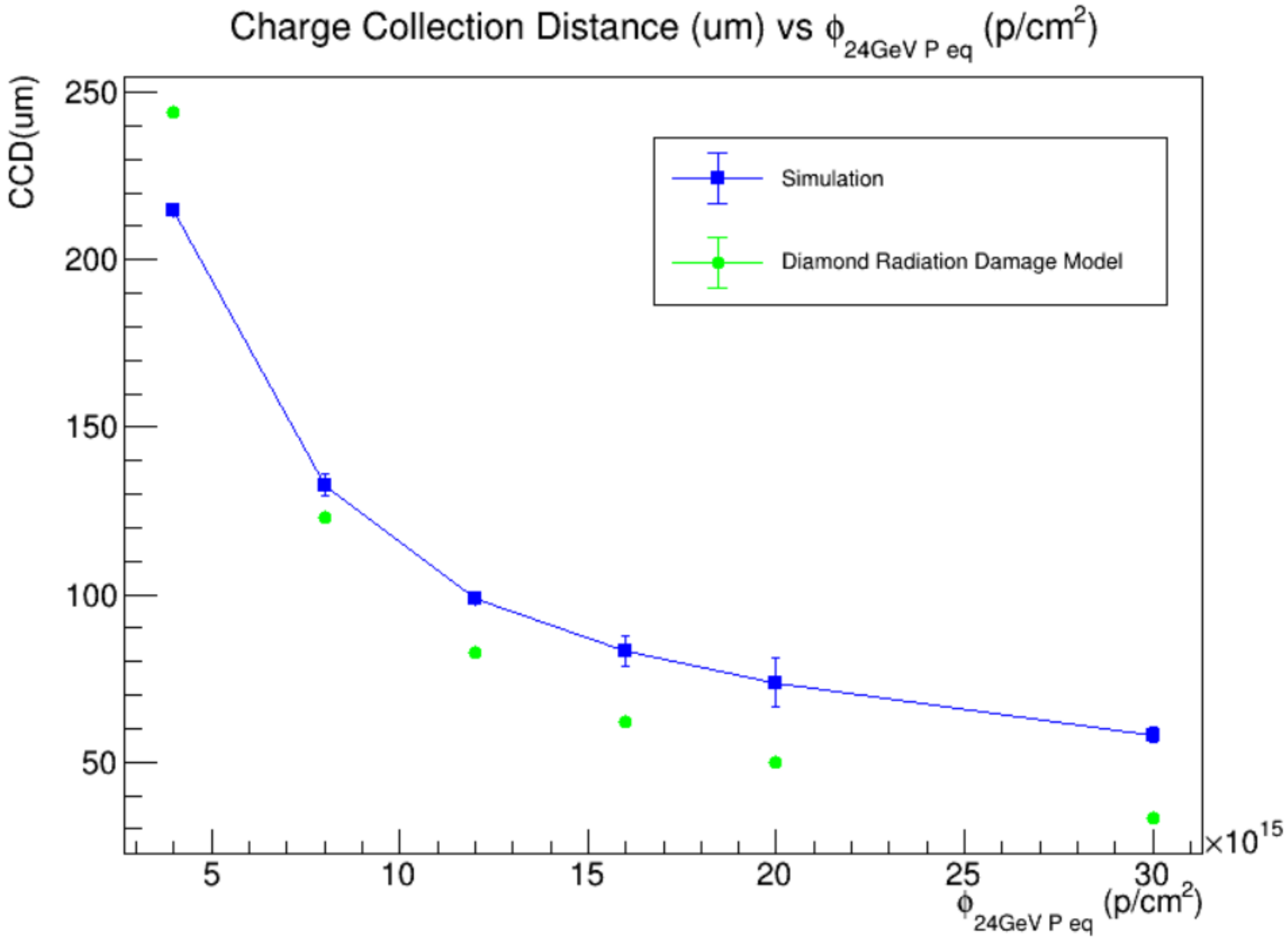
- TCT pulse shapes -> smooth curves – no real information about defects distribution
- Needs TCAD simulations of electric fields



CCD simulation

- Higher CCD predicted values by simulation at higher fluence

$$CCD = CCE \times d$$



Summary

- Low field Mobility parameters implemented, -> predict drift velocities
- Implemented RD42 model -> pcCVD diamond = scDiamond + radiation damage in terms of CCE and CCD.
- Trapping times from RD42 Test beam data, predict CCD and TCT pulse shapes by simulation
- **Next steps:** TCT experiments in the lab with alpha and beta sources, TCAD simulations

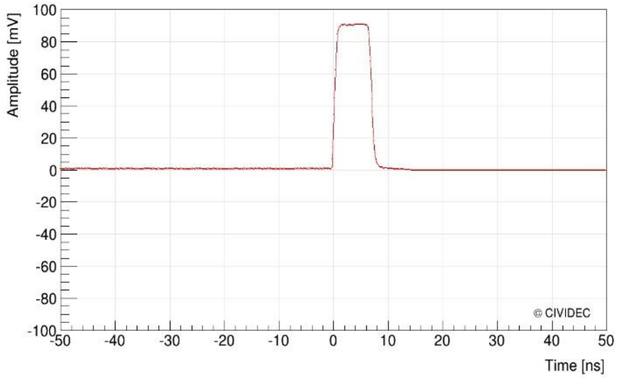
Thank You

Backup

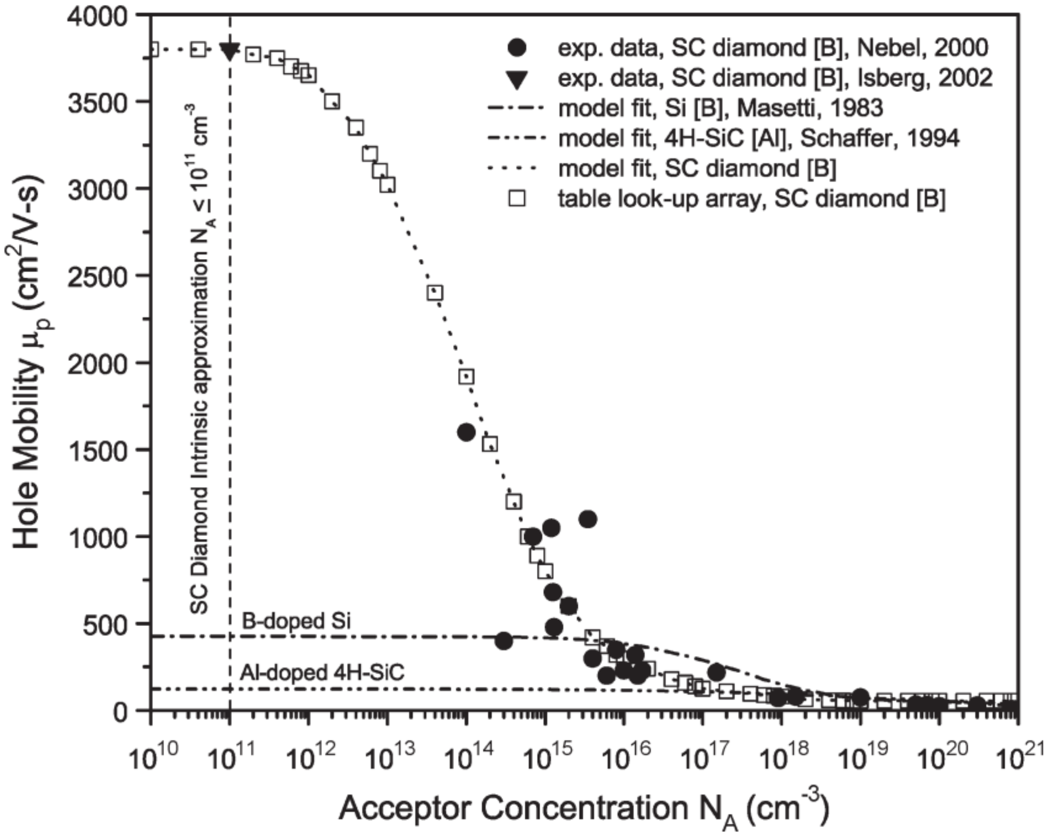
- Low Atomic Number – ideal for tracking detectors as radiation length $X_o \alpha \frac{1}{Z^2}$
- Radiation Hardness – 43 eV Kick off energy, Strong lattice bonds – Damage constant is lower
- Fast signal readout – High drift velocities
- High thermal conductivity – Large band gap
- High spatial resolution
- Optical Transparent

Impurity Concentration

- Diamond mobility is affected by very low concentrations of impurities
- Needs to be implemented in Allpix squared



https://cividec.at/electronics-C2-TCT.html

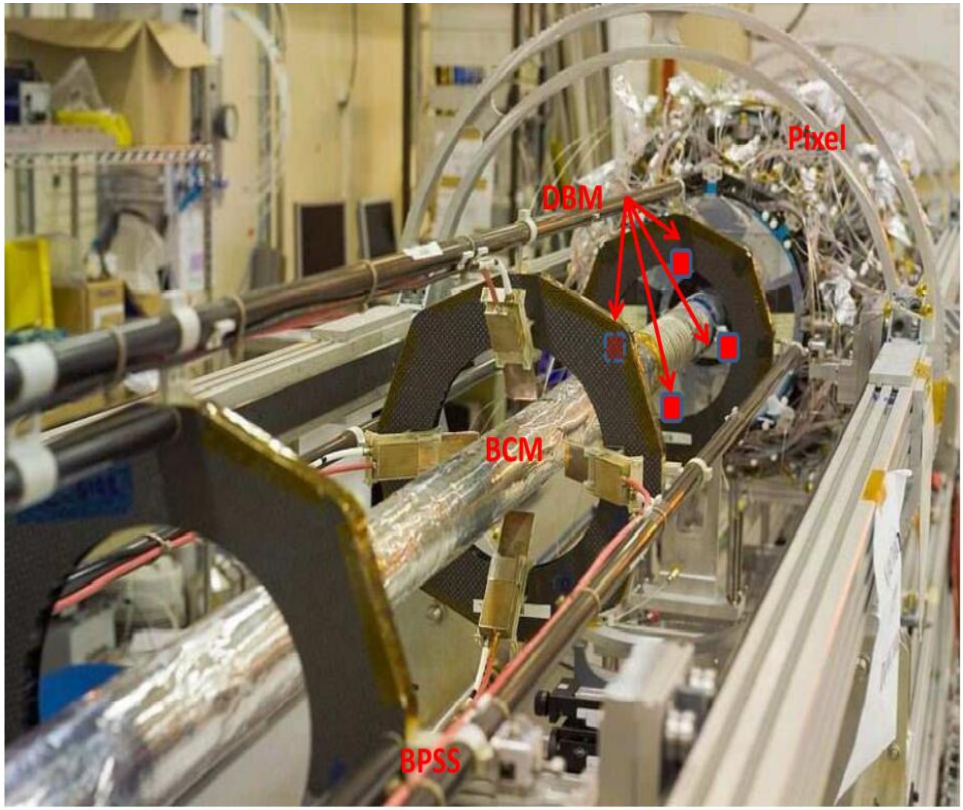


10.1109/TED.2008.2003225

The ATLAS Diamond Beam Monitor

Designed to measure the instantaneous luminosity, the background rates, and the beam spot position.

- **Single DBM module: 18 mm × 21 mm** pCVD diamond **500 µm thick** instrumented with an **FE-I4 pixel chip**.
- **26,880 pixels:** in 80 columns on 250 µm pitch and 336 rows on 50 µm pitch. This fine granularity provides high-precision particle tracking.
- **charge collection distance of 200-220 µm** at an applied bias voltage **of 500 V**.



CERN-LHCC-2018-015 / LHCC-SR-005 27/05/2018

Marko Mikuz: Diamond Sensors