23.4.2021

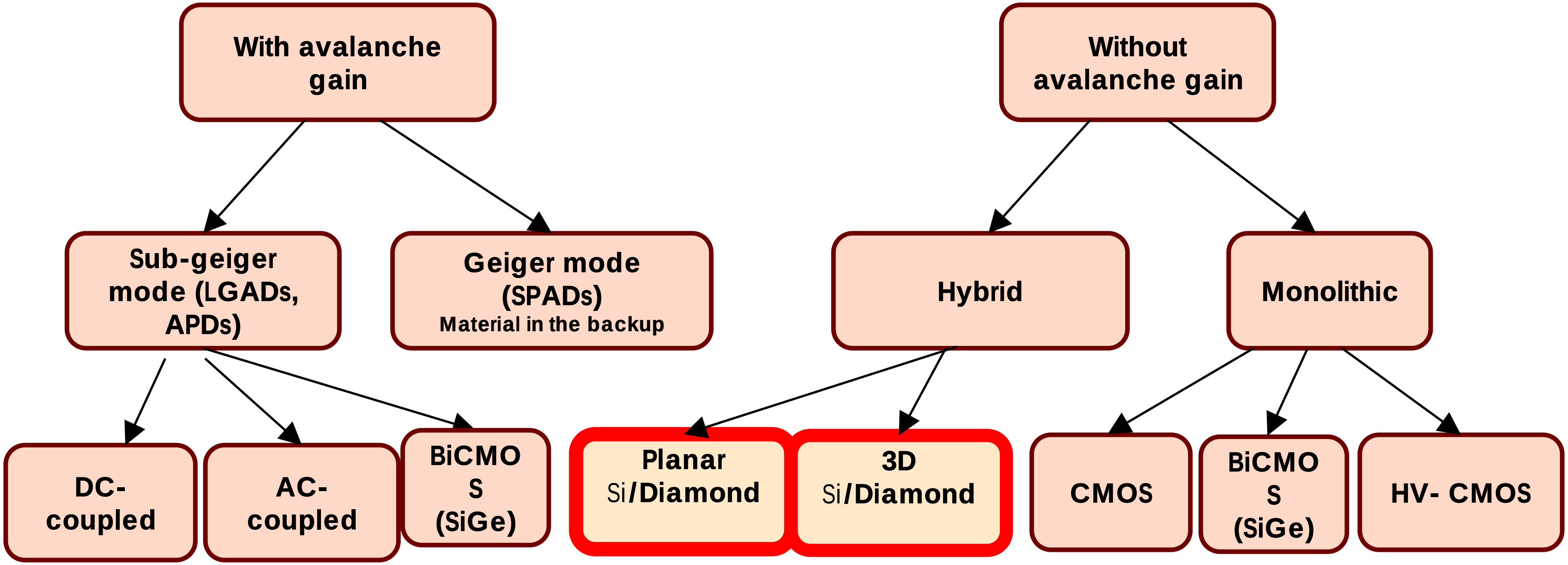
Use of diamond detectors in 20 years

What R&D needs to be done to use it in the first layer of FCC?

Alexander Oh
University of Manchester

Results and material from the **RD42** collaboration.

Solid state detectors for future (4D) trackers



With avalanche gain

Without avalanche gain

Sub-geiger mode (LGADs, APDs)

Geiger mode (SPADs)
Material in the backup

Hybrid

Monolithic

DC-coupled

AC-coupled

BiCMOS (SiGe)

Planar Si/Diamond

3D Si/Diamond

CMOS

BiCMOS (SiGe)

HV- CMOS

FCC first layer requirements

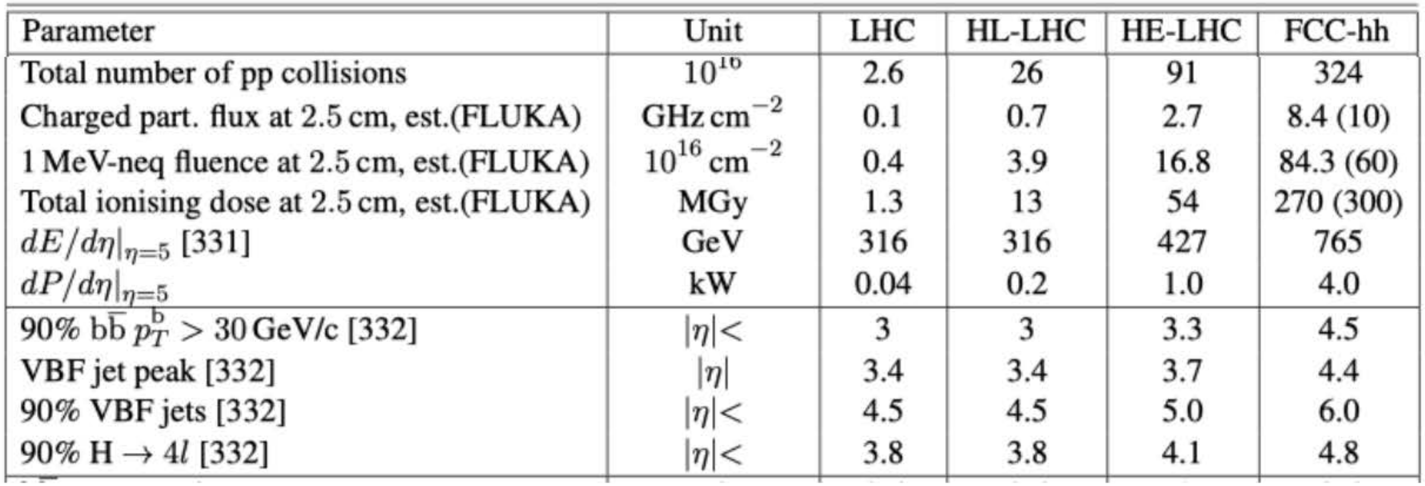
Unprecedented particle flux and radiation levels

- 10 GHz/cm^2 charged particles
- 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1}

Rate & Radiation challenge

@ r=2.5cm

Table 7.1: Key numbers relating the detector challenges at the different accelerators.



Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% H $\rightarrow$ 4l [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

First tracking layer:

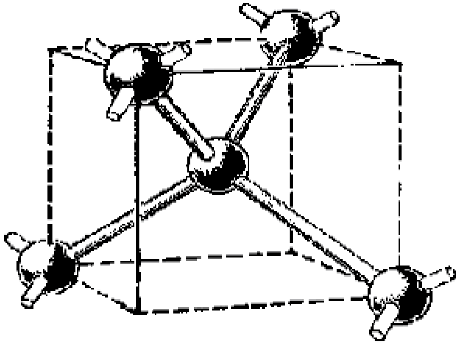
10GHz/cm^2 charged particles

10^{18} hadrons/cm^2 for 30ab^{-1}

Increased Boost at 100TeV 'spreads out' light SM physics by 1-1.5 units of rapidity.

Diamond properties

Property	Diamond	Silicon
band gap	5.47	1.12
mass density [g/cm^3]	3.5	2.33
dielectric constant	5.7	11.9
resistivity [Ωcm]	>10^{11}	2.3e5
breakdown [kV/cm]	1e3...20e3	300
e mobility [cm^2/Vs]	1700	1400
h mobility [cm^2/Vs]	2100	440
therm. conductivity [W / cm K]	10..20	1.5
radiation length [cm]	12	9.4
Energy to create an eh-pair [eV]	13	3.6
ionisation density MIP [eh/mm]	36	89
ion. dens. of a MIP [eh/ 0.1 ‰ X_0]	450	840



– Low dielectric constant ➔ low capacitance

– Low leakage current ➔ low noise

– Room temperature operation

– Fast signal collection time

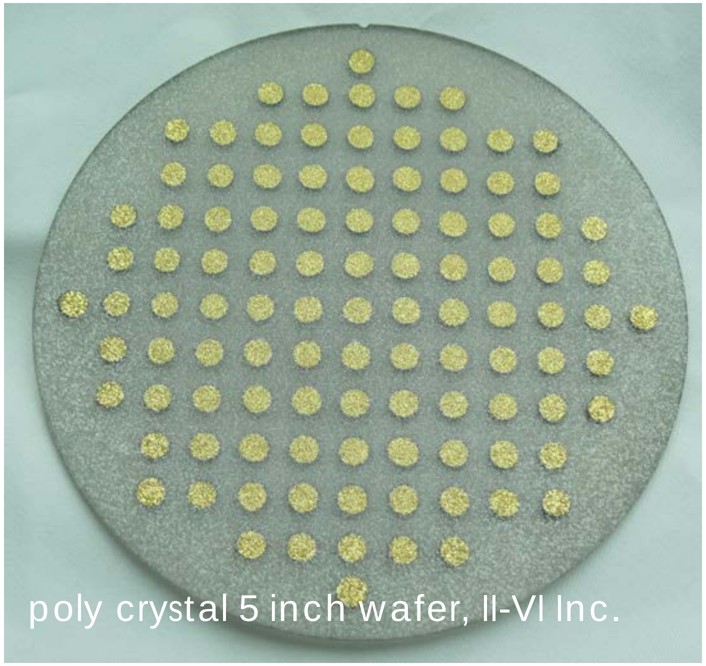
–MIP signal ~2 smaller at same X_0

–Efficiency < 100% (pCVD)

Development of CVD Diamond for detector applications

- Today two main manufacturers of detector grade diamond
  - **ElementSix Ltd UK**
    - **polycrystalline** wafers
    - **small single crystal** diamonds
  - **II-VI Inc. USA**
    - **large polycrystalline** wafers
    - development effort underway

- Alternative sources
  - Diamond on Iridium (DoI) (Audiatec, Germany)
  - Hetero-epitaxially grown -> **medium area**
  - **Highly oriented crystallites.**



poly crystal 5 inch wafer, II-VI Inc.

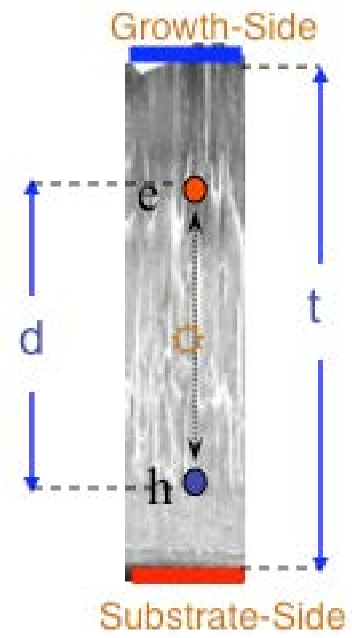
single crystal

DoI, 155ct

Development of CVD Diamond for detector applications

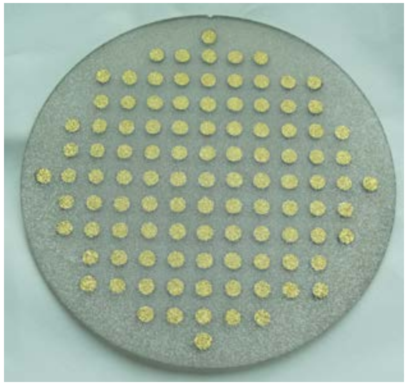
- Impressive progress over the last 25 years.
- Current state of the art for **polycrystalline** CVD diamond δ ~ **320 μm in 500um thickness**
  - **(~11500 e/MIP)**
  - **commercially available.**

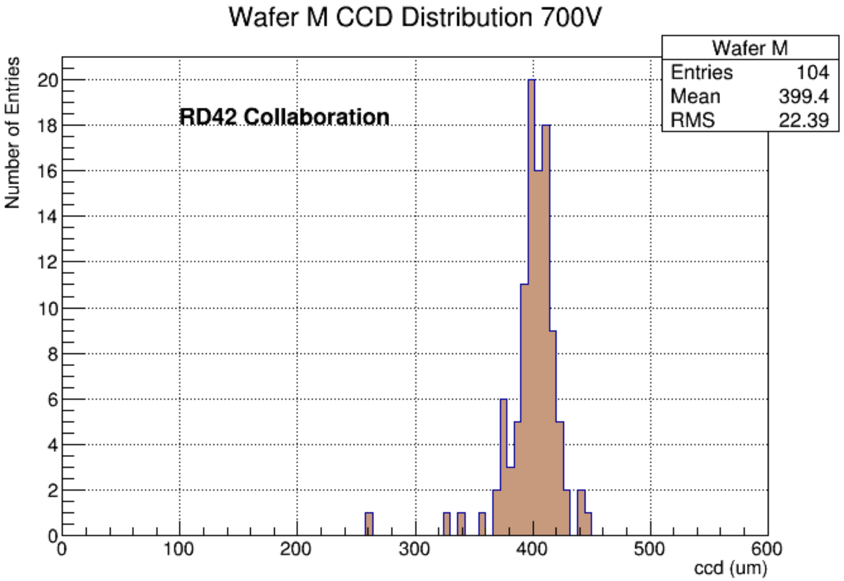
- 1995: δ ~ 50 μm
- 2000: δ ~ 180 μm
- 2020: δ ~ 320 μm



CVD Diamond development goals

- removal of surface defects
  - few per cm² → **< 1 per cm²**
- wafer CCD in pCVD
  - 400 um → **500 um**
- size of wafers = 15cm (6 inch) diameter state of art
  - fixed by microwave frequency (not expected to change)
- wafer uniformity
  - 5% → **2% across whole wafer.**
- price per cm²
  - ~1500USD / cm² → **800USD / cm²**



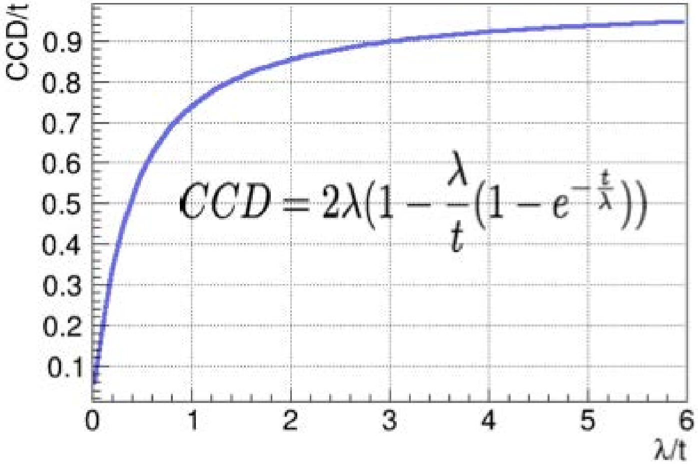


Radiation Hardness

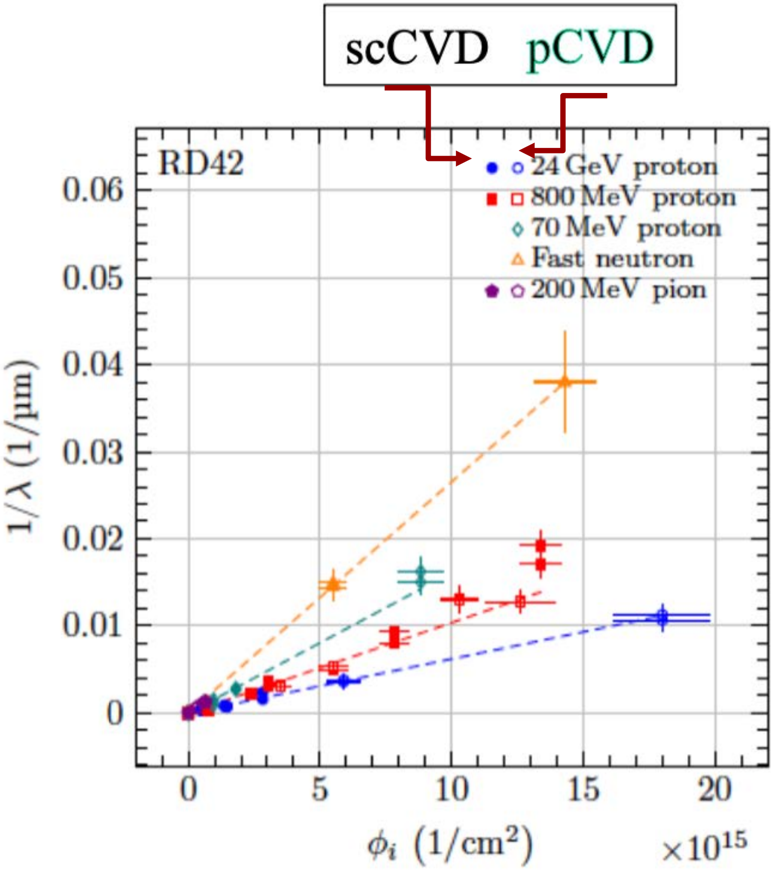
- **Irradiated polycrystalline and single crystal CVD diamond.**
  - Protons 25MeV, 70MeV, 300MeV, 800MeV, 24GeV
  - Pions 300MeV
  - Neutrons ~1MeV (TRIGA reactor)
- **Signal response tested in test-beam.**
  - 120 GeV proton
  - pad, strip and pixel-detector pattern, $E = \pm 2V/\mu m$
  - Samples pre-exposed to Sr^{90} to fill traps (aka *pumping*)
  - Require track on active area, no threshold on strip signals.
  - Build signal of five highest contiguous signals within 10 strips around the track.

Radiation Hardness

- "Charge Collection Distance" (*CCD*) is measured.
- Traps reduce the life-time of charge carriers, or "Schubweg" (λ).
  - Relation between *CCD* and λ:



$$CCD = 2\lambda\left(1 - \frac{\lambda}{t}\left(1 - e^{-\frac{t}{\lambda}}\right)\right)$$



Radiation damage is fitted with simple damage model:

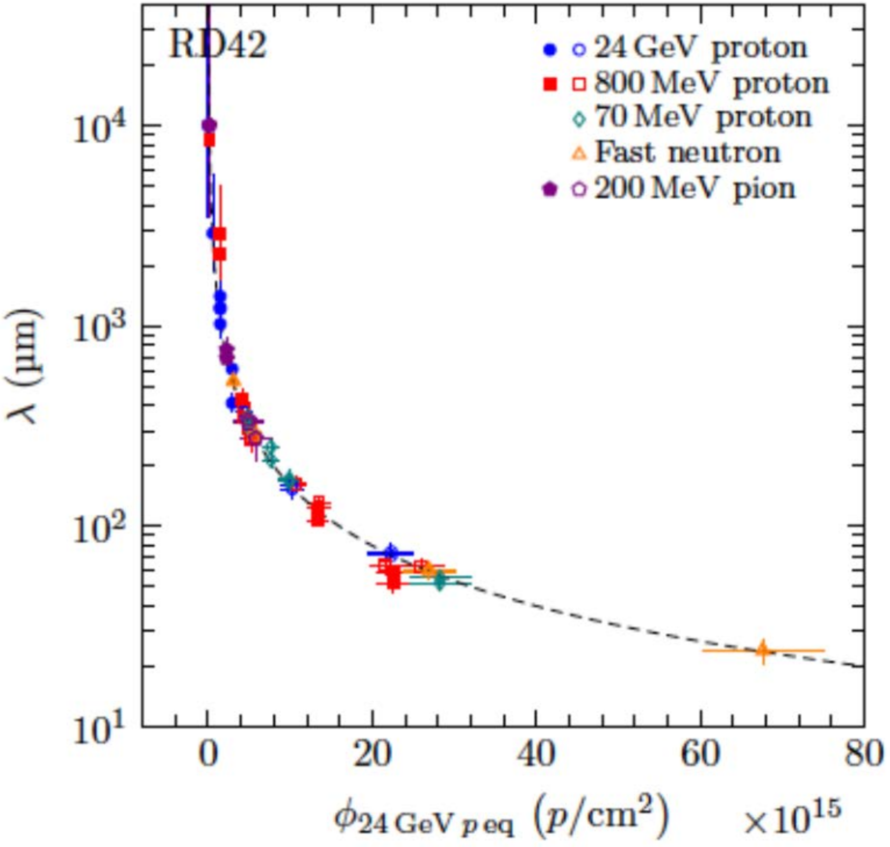
damage constant

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \Phi$$

particle fluence

Radiation Hardness (planar)

- **Scaling to 24 GeV protons**
  - Universal scaling for all particle types with fluence.
  - Poly and single crystal diamond show consistent damage constants.
  - Predictions are possible for any particle type and fluence.



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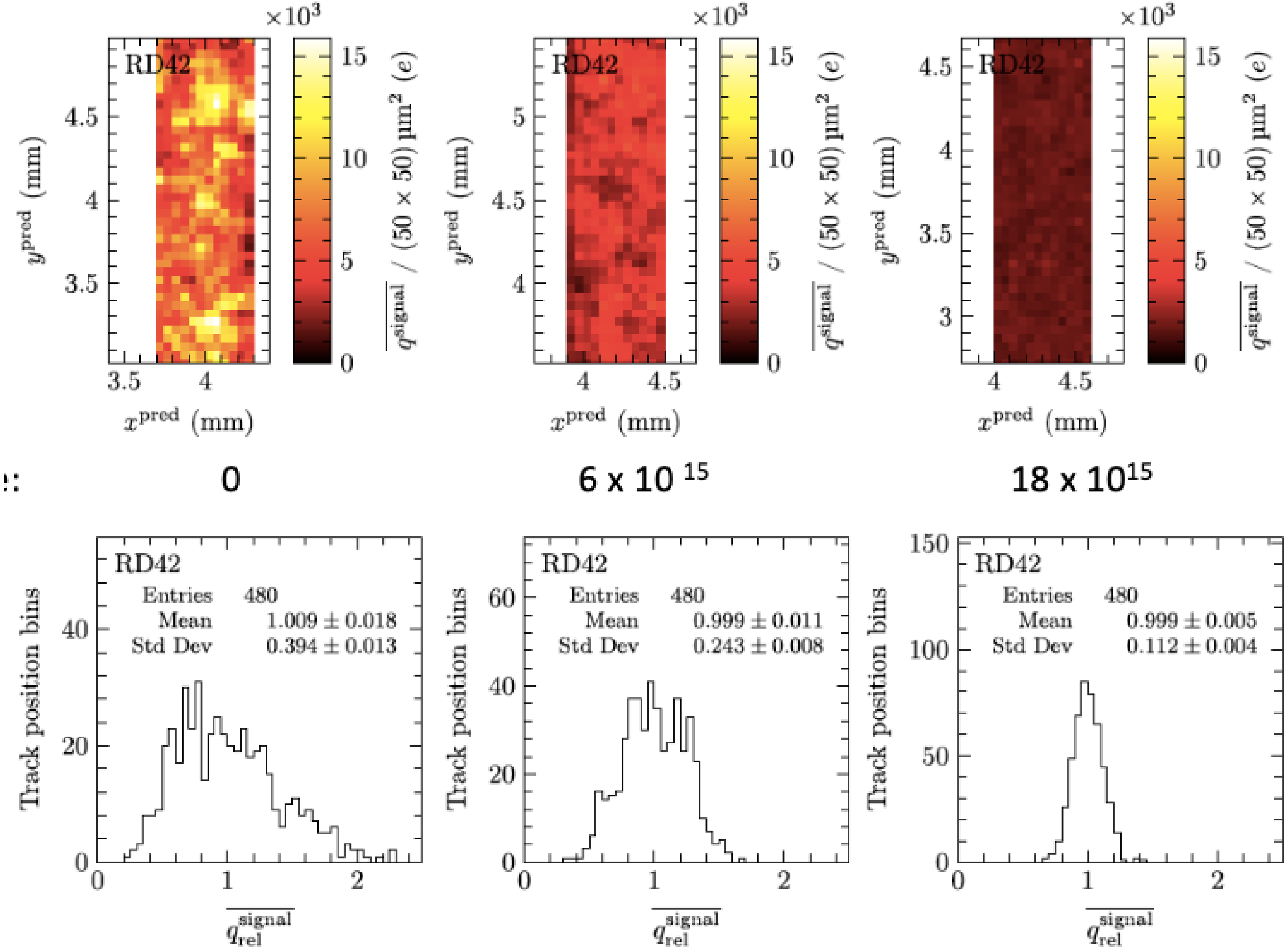
Radiation Hardness: Signal Uniformity



0

6 x 10 15

18 x 10^{15}

- Re-writing λ, ϕ relation:

$$\lambda = \frac{\lambda_0}{1 + \lambda_0 k \phi}$$

- Differentiating:

$$\frac{d\lambda}{d\phi} = -k\lambda^2.$$

- Highest signal regions
- Suffer largest degradation
- FWHM narrows

Radiation Hardness

- Summary of RD42 irradiation results:*

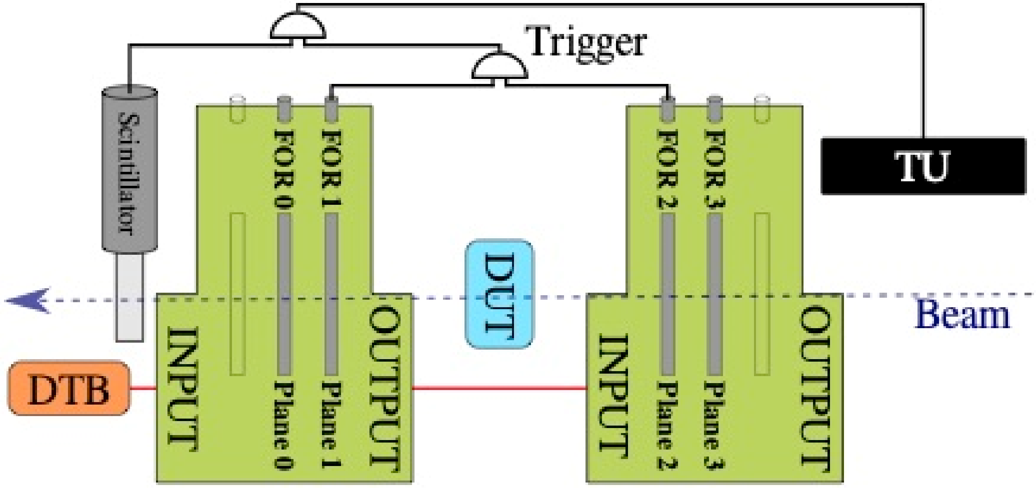
Irradiation Species	k_i
200 MeV pions	3.2 ± 0.8
Fast neutrons	4.27 ± 0.33
70 MeV protons	2.60 ± 0.27
800 MeV protons	1.67 ± 0.09
24 GeV protons	1

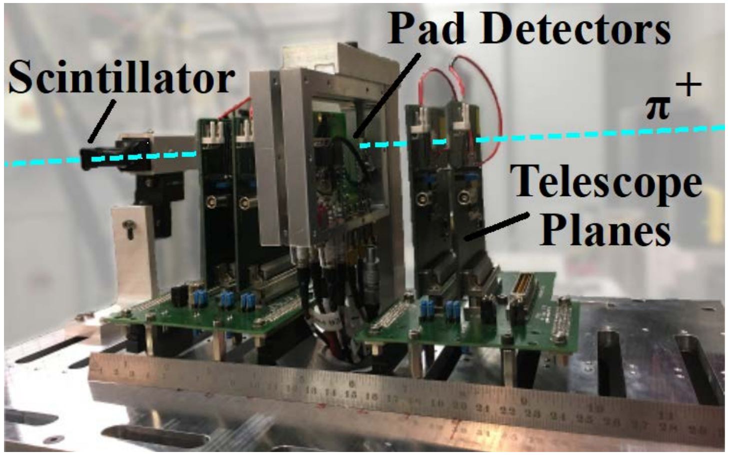
”Back-of-an-envelope calculation, expect Schubweg of:
$\lambda \sim 16\mu$m at 10^{17} cm^{-2} protons_24 GeV_eq

*normalized to 24GeV protons

High Rate tests

- Tests the pulse height as function of particle rate.
- Test single and poly crystalline diamond.
- Irradiated and un-irradiated.



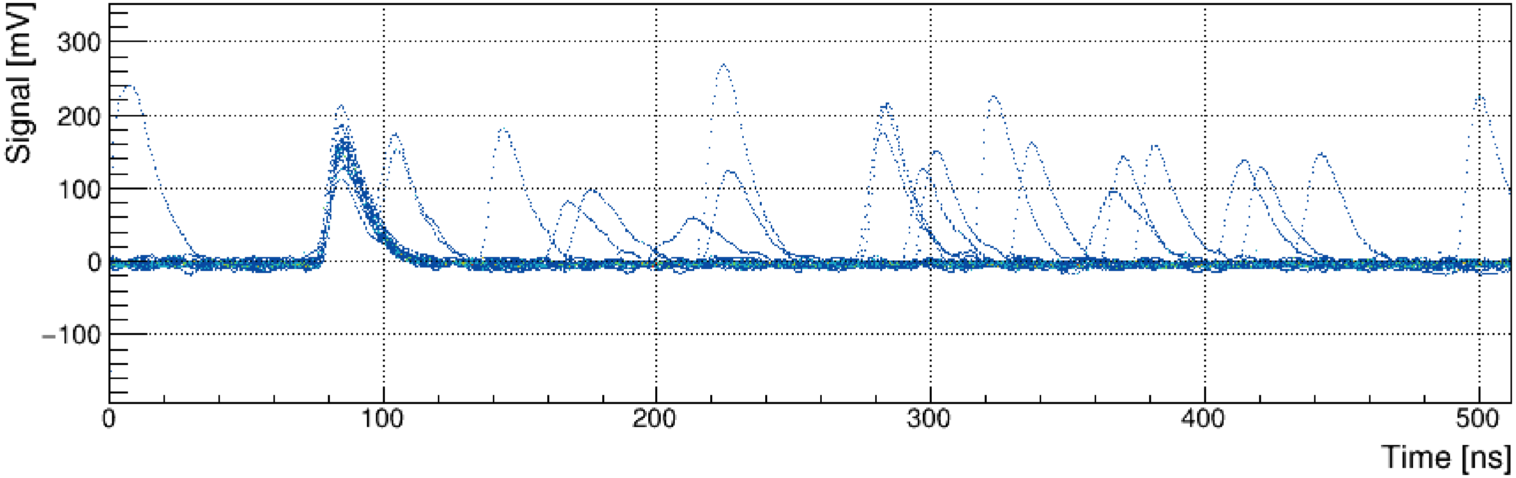


Reference planes use CMS Pixel detectors: track position 100um

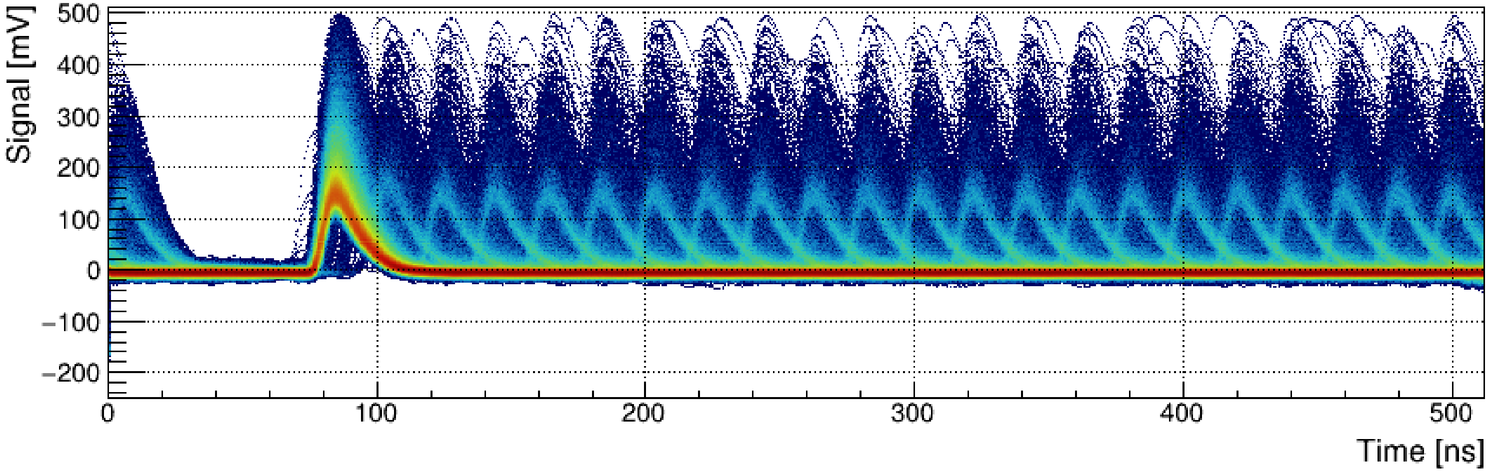
Diamond pads (8x8mm^2) readout with DRS4 flash ADC (5GS/s)

High Rate tests

- Raw Data from 10 MHz/cm^2 Flux



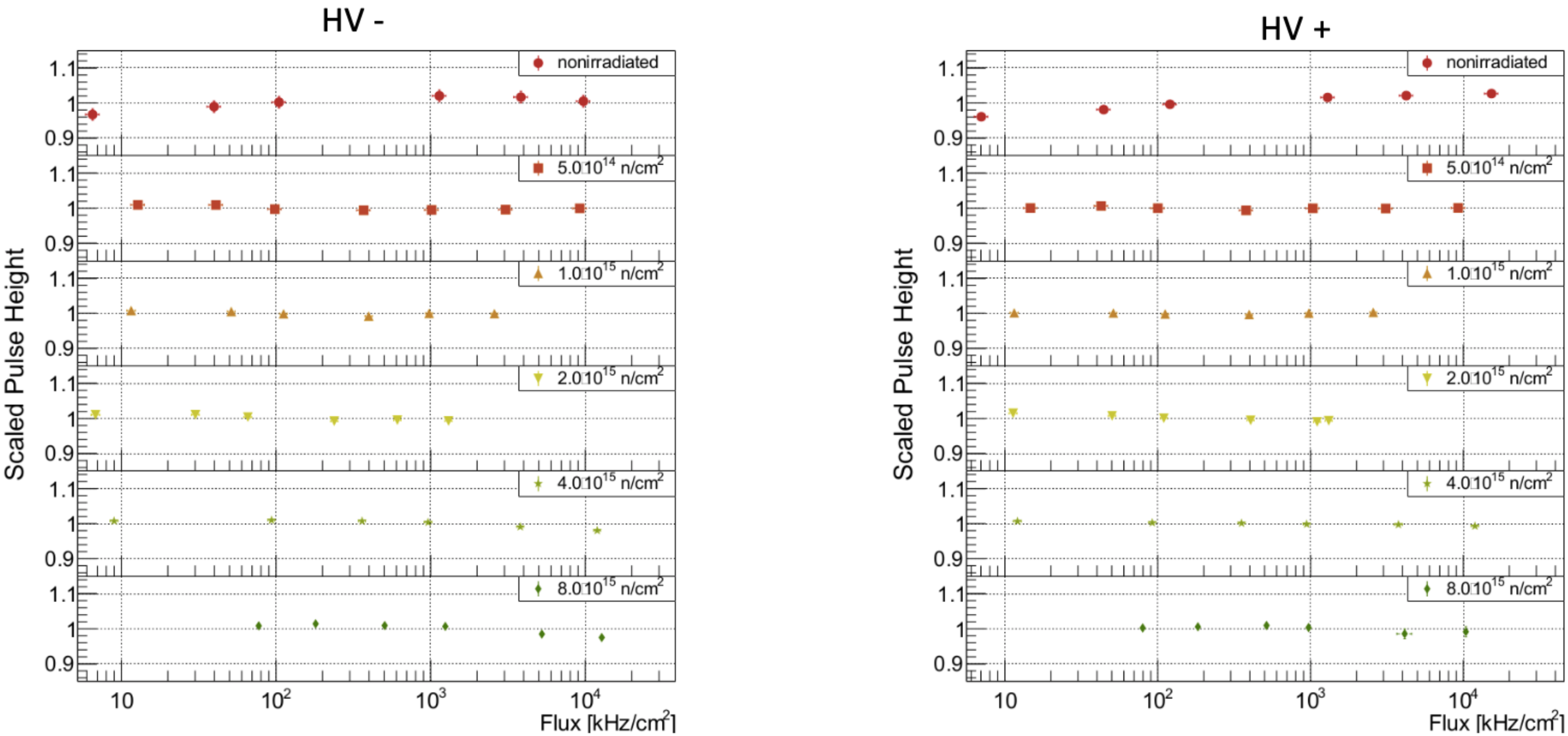
20 triggers



Full run
(5000 triggers)

High Rate tests

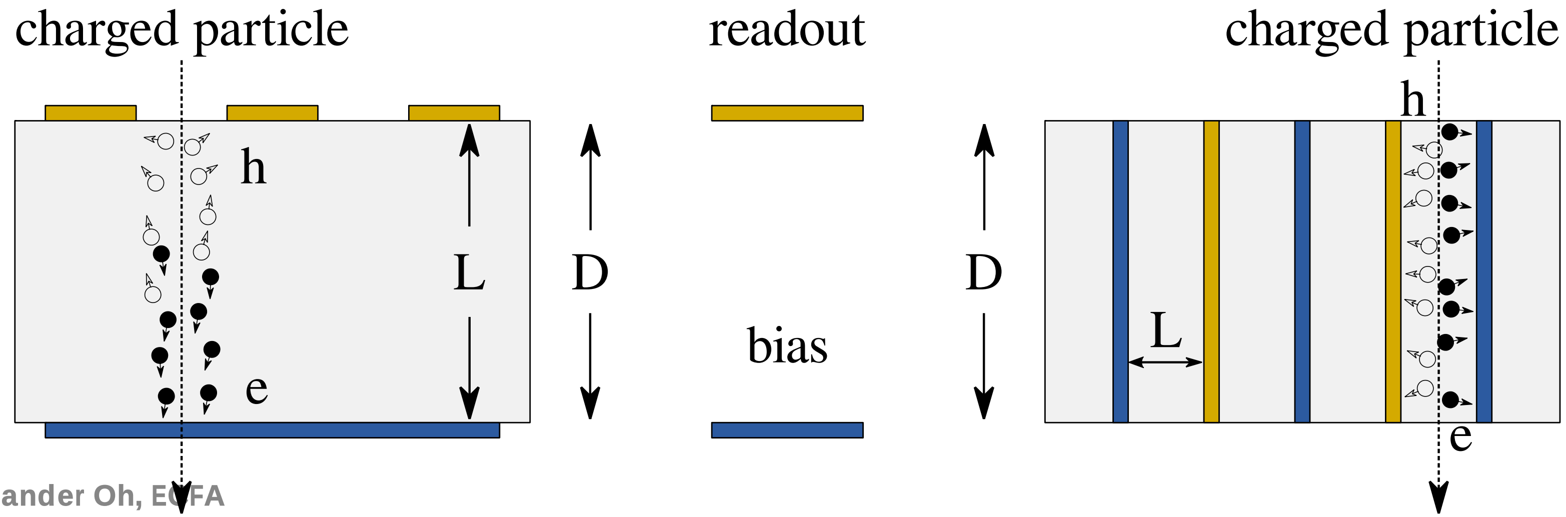
- neutron irradiated pCVD



Flat to better than 2% up to 10-20 MHz/cm^2. Exploring systematics of O(1%)

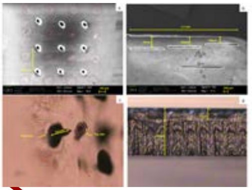
Carrier lifetime challenge – 3D diamond detectors

- After large radiation fluence all detectors are trap limited
- Mean free paths (schubweg) λ< 50µm
- Need to keep drift length (L) smaller than mfp(λ)
- Build 3D detectors to reduce transit time.
- Huge progress made in fabrication of 3D diamond detectors in the last 10 years.

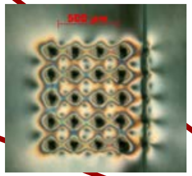


3D diamond? (2008)

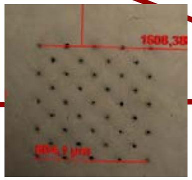
Lasered graphitic structures in pCVD ('10)



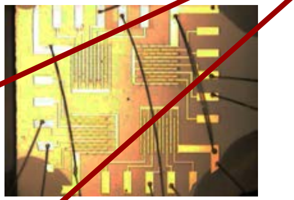
Single crystal with column structure ('11)



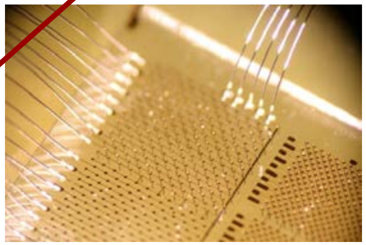
Pico second laser for improved graphitic electrodes ('12)



Femto second laser processing and **TCAD simulation ('13,'14)**



Phase modulated laser processing ('15,'16)



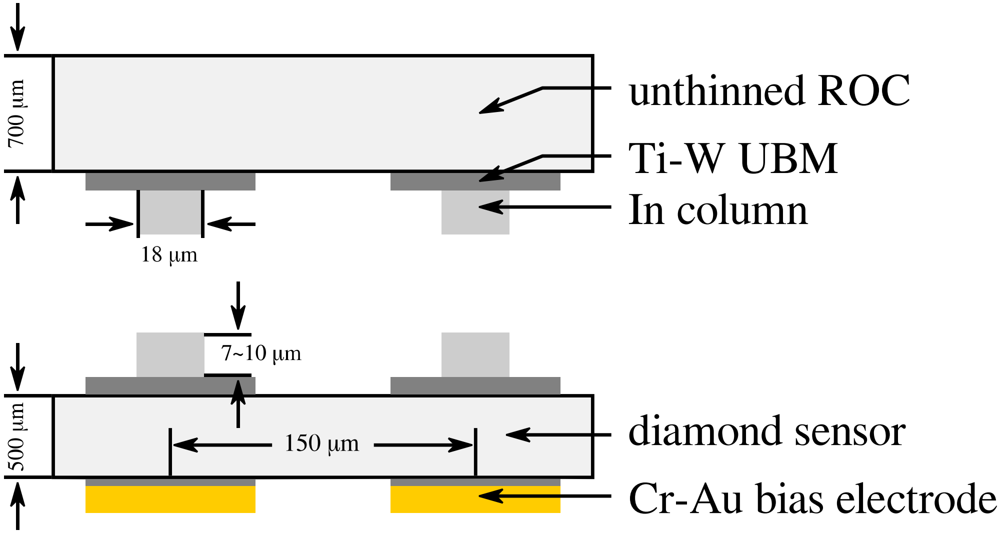
Polarised & Phase modulated laser processing ('17,'18)

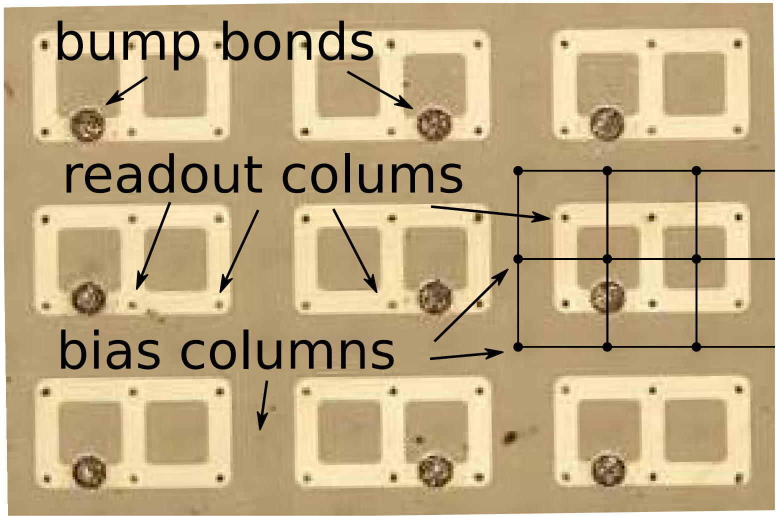
Prototypes with poly and single crystal diamond (2019 ++.

Several Prototypes tested at
Diamond Light Source
CERN test beam
RBI proton beam
Clinical Photon beam

3D diamond prototypes

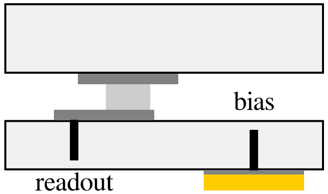
- CMS and ATLAS pixel prototypes tested:

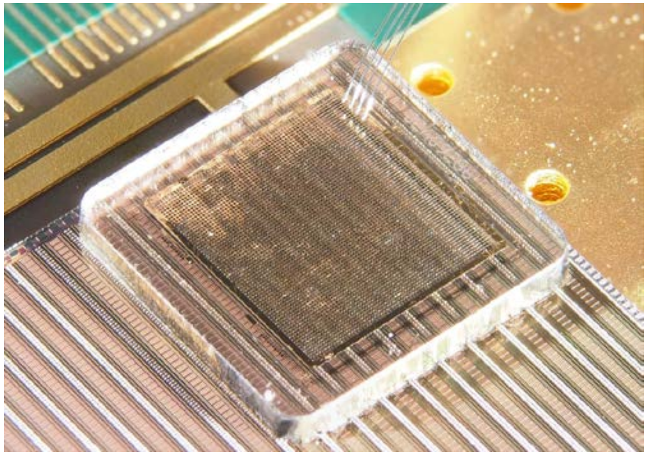


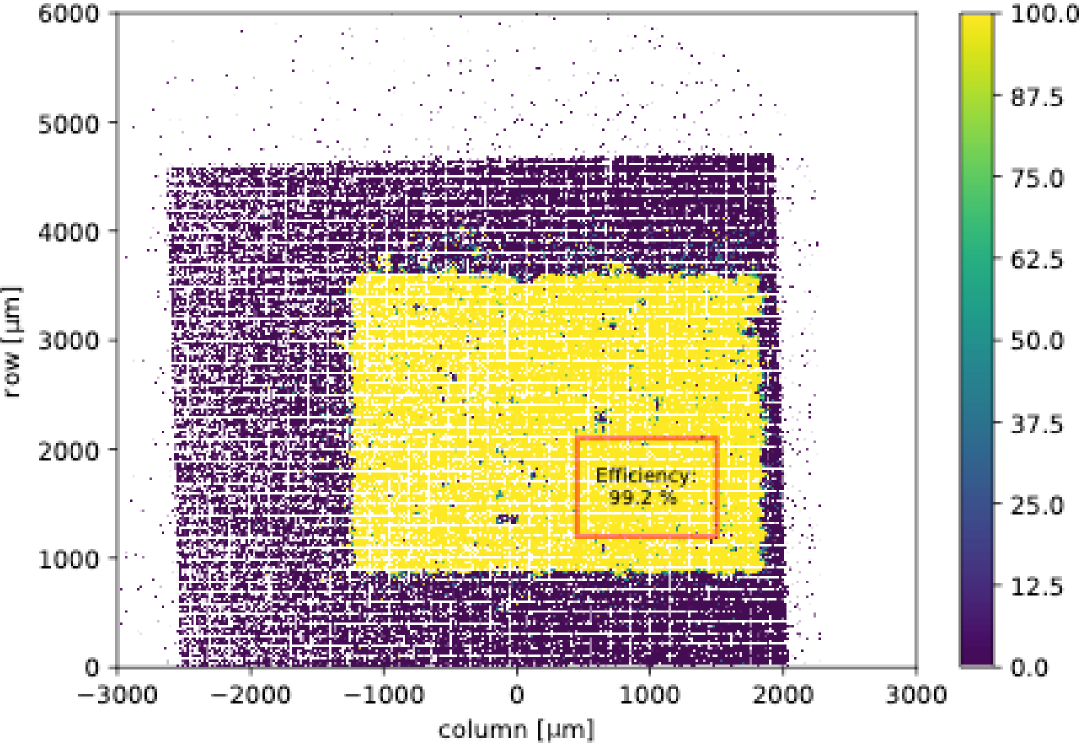


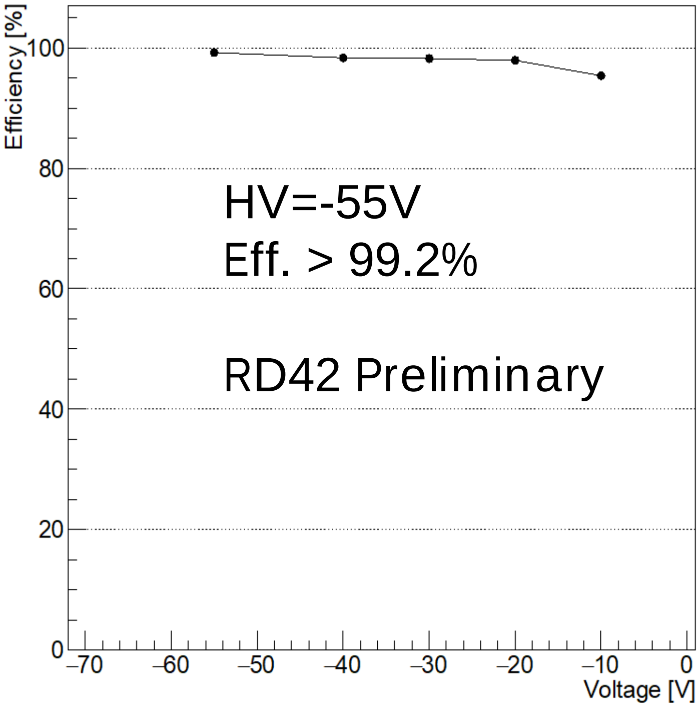
3D diamond prototypes

- CMS and ATLAS pixel prototypes tested:









HV=-55V
Eff. > 99.2%

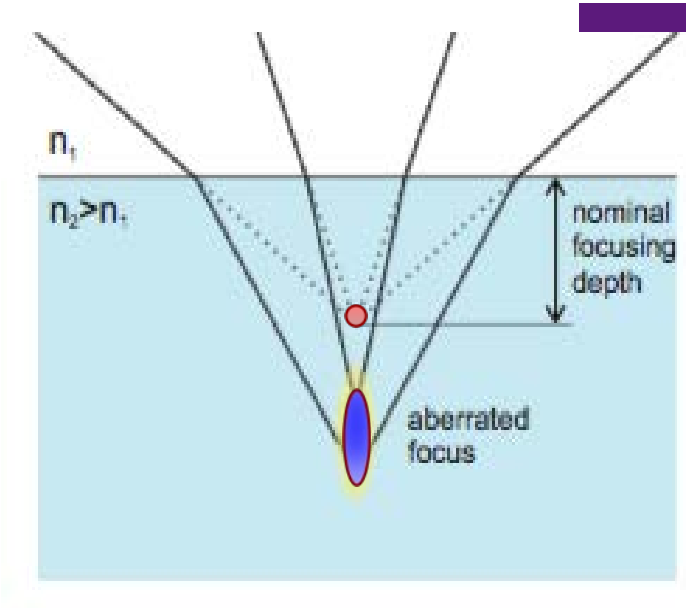
RD42 Preliminary

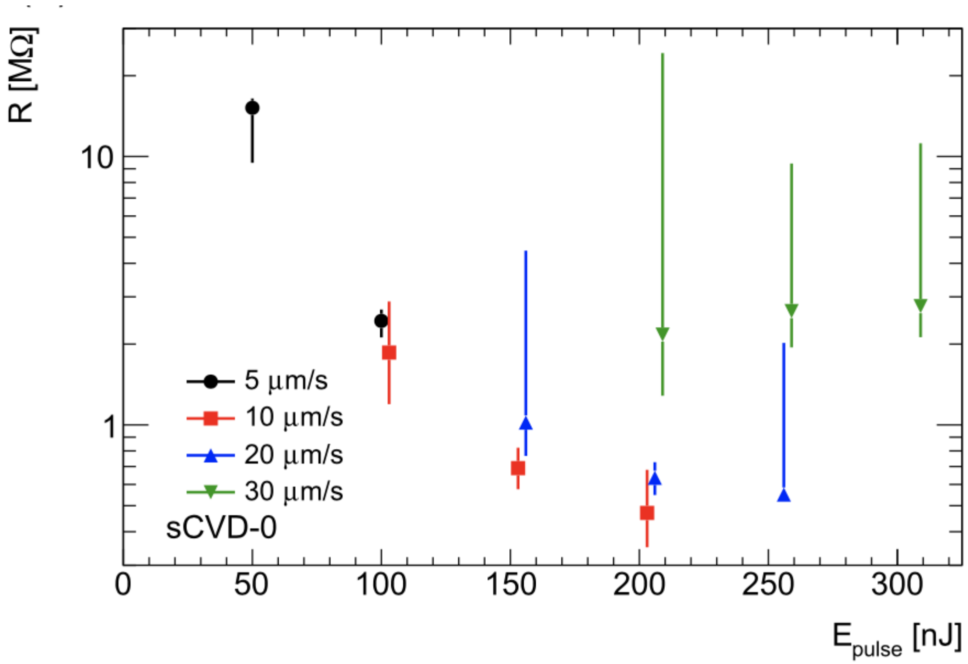
3D diamond detectors challenges for the future

- **Optimise graphitisation process for 3D diamond production in terms of:**
  - **Resistivity**: currently at (1 - 0.1Ωcm) aim for <0.1Ωcm.
  - **Processing speed**: currently O(10um/s), aim to speed up and/or parallel processing of wires.
  - **Wire thickness / uniformity**: Little data available, needs more research effort.
- **Optimization of internal electric field**
  - **Geometry**: Recently internal cage structure optimise E field.
  - Will explore the full potential (see later slides).
- **Radiation hardness**:
  - Need to check predictions with latest devices.
  - 25um cells in 3D.

Resistivity challenge

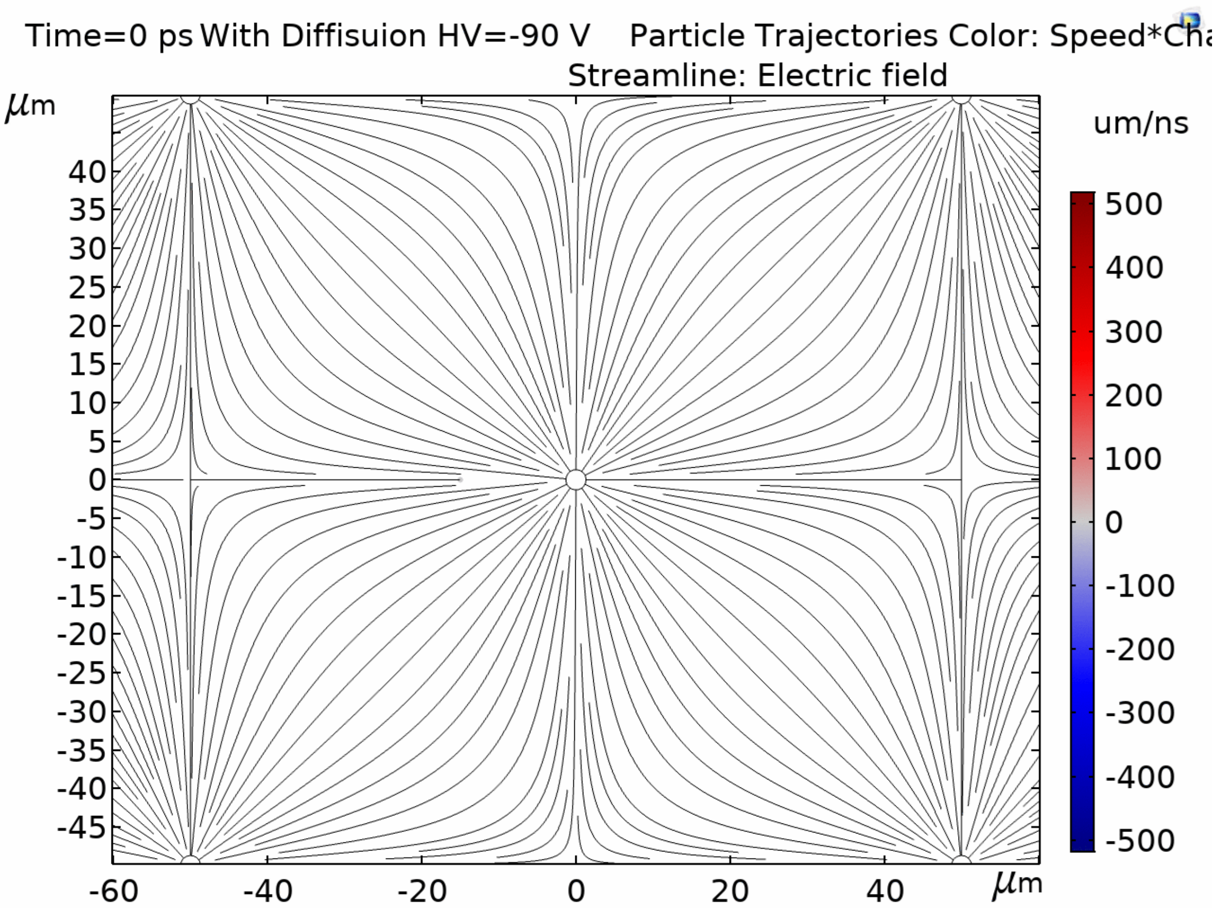
- Laser wave front shaping helps to decrease resistivity.
- Dependence on processing parameters being studied.
- **More research needed to lower resistivity.**





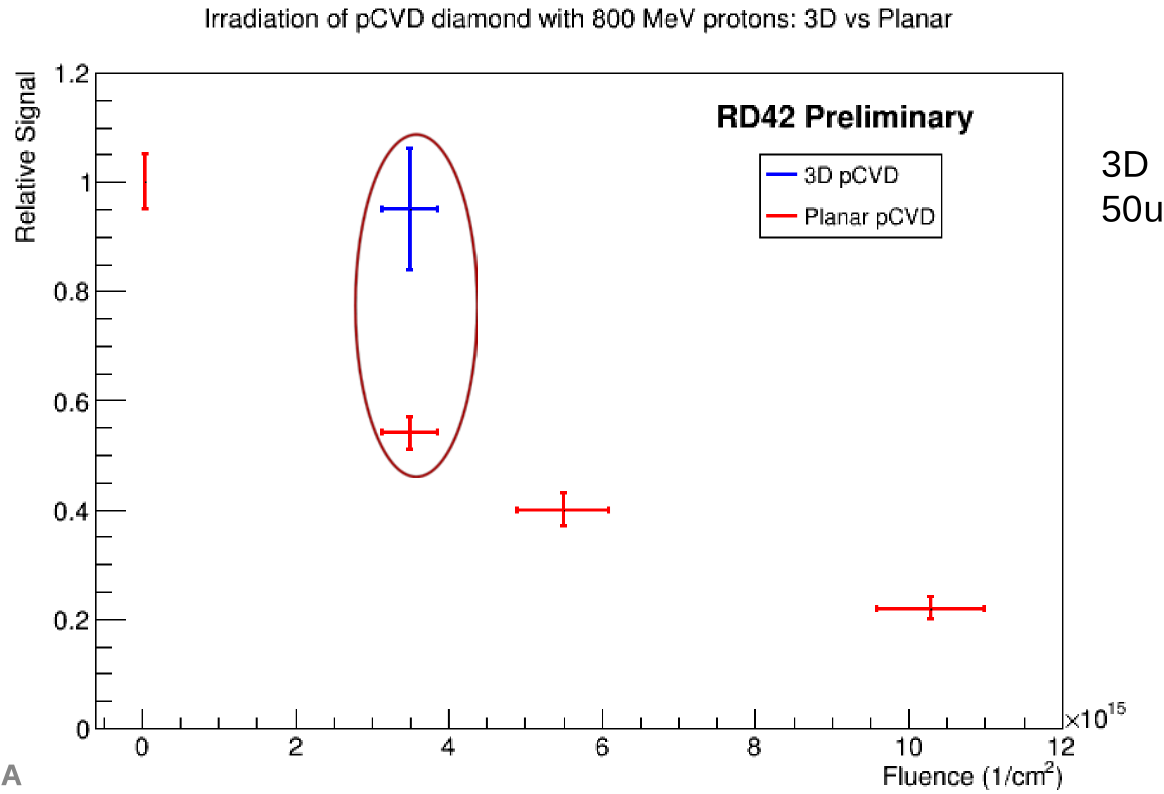
Carrier lifetime challenge – 3D diamond detectors

- Low field regions might effect transit time.
- Preliminary simulations show not a concern due to diffusion.
- More work needed to quantify impact of radiation damage.

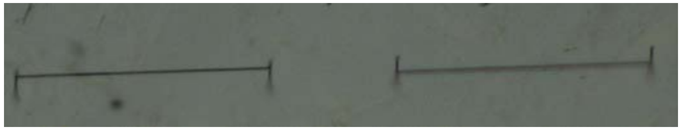


3D diamond detectors: Radiation challenge

- Few radiation hardness data available, but promising:
  - Compare signal loss in 3D pixels to published results from planar
  - **3D sensors collect twice as much charge when unirradiated**
  - **3D sensors see 5±10 % reduction** in signal at 3.5 $x10^{15}$
  - **Planar sensors see 45±5 % reduction** for 3.5 $x10^{15}$

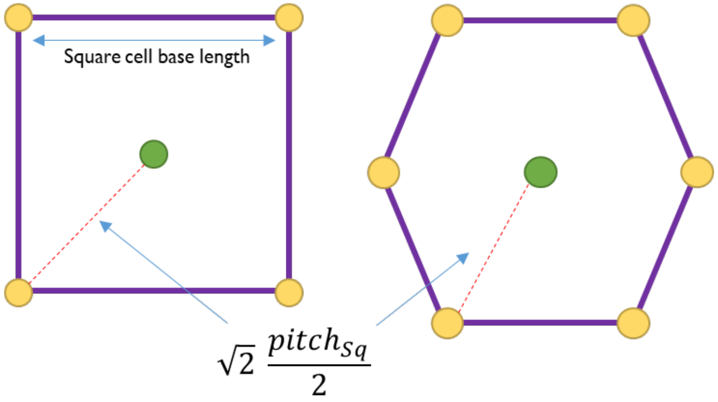


3D cell size:
50um x 50um

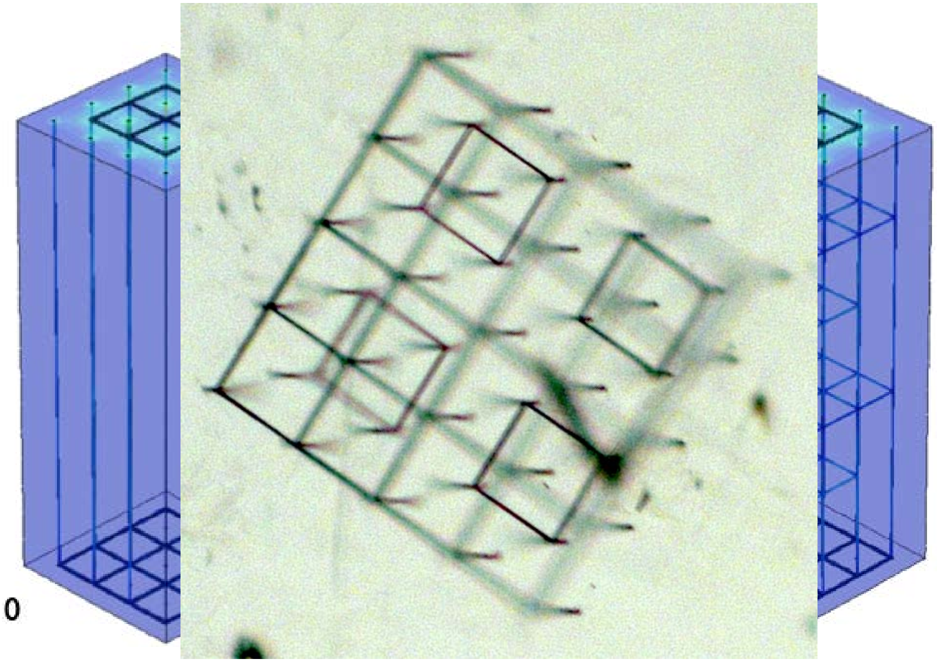


3D diamond detectors Geometry challenge

- Laser processing allows any geometry, including horizontal wires.
  - Exiting possibility to optimise the electric and weighting field.
  - Small cell sizes realizable, wire diameter at abut 1μm.
  - Simulation studies currently ongoing.
- Future research in this area:
  - Optimise geometry
  - Wire processing
  - cell sizes $<(25\mu m)^2$
  - Simulation – Prototyping – Characterization.

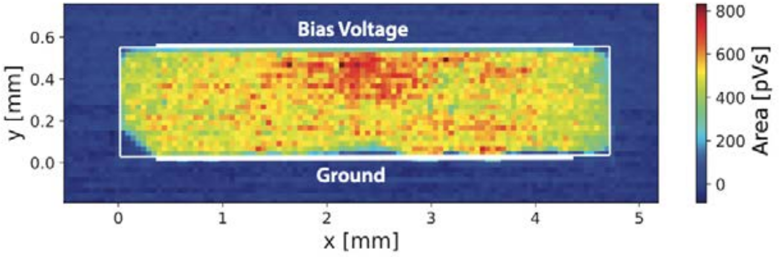


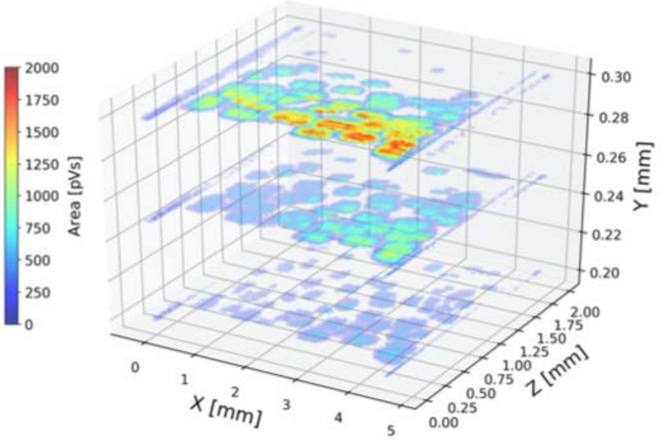
$$\sqrt{2}\,\frac{pitch_{sq}}{2}$$



3D diamond detectors: Characterization challenge

- TPA demonstrated.
- More accurate ionization profiles possible using same beam shaping techniques as in production of wires.
- Research needed to fully exploit technique for characterizations.





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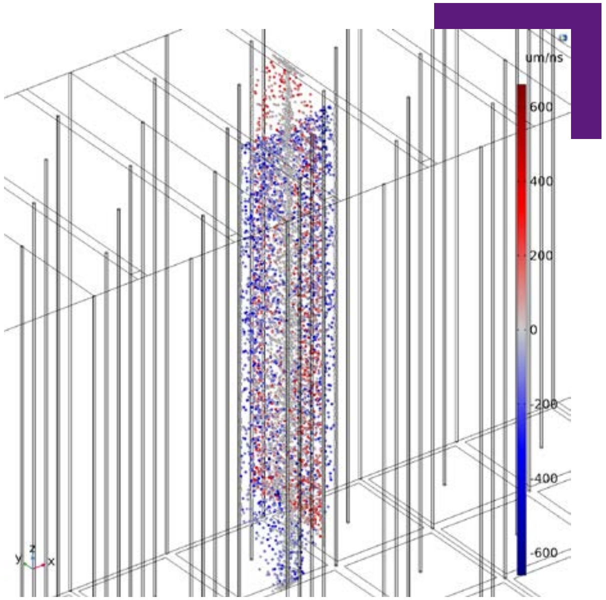
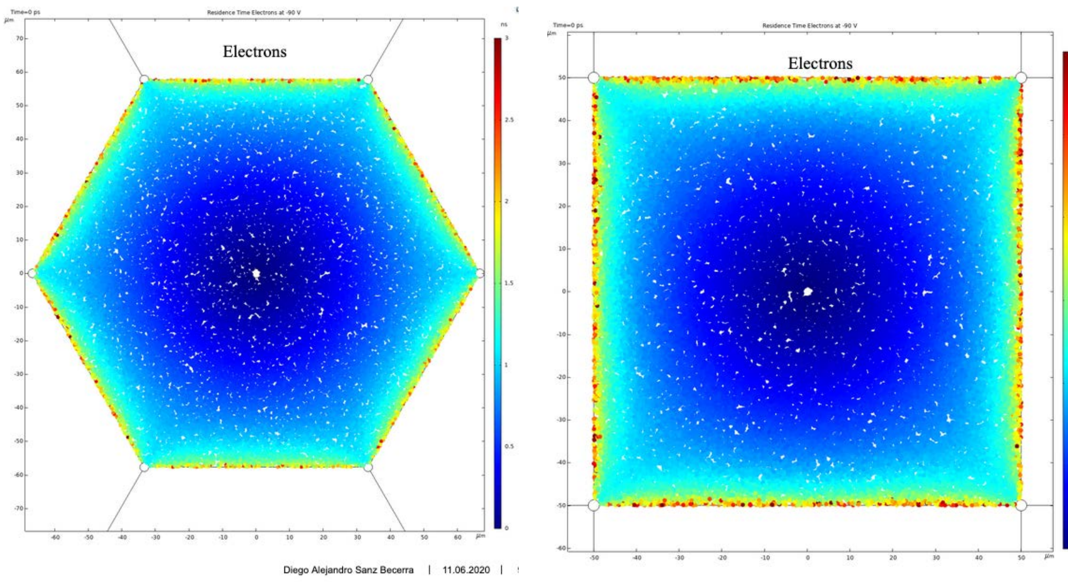
3D diamond detectors Simulation challenge



- Lack of build-in models, especially pCVD and traps / polarisation in current TCAD tools being addressed.

- Need effort to improve simulations:
  - polycrystalline CVD diamond, grain boundaries.
  - graphitic wire simulation
  - radiation damage
  - new geometries

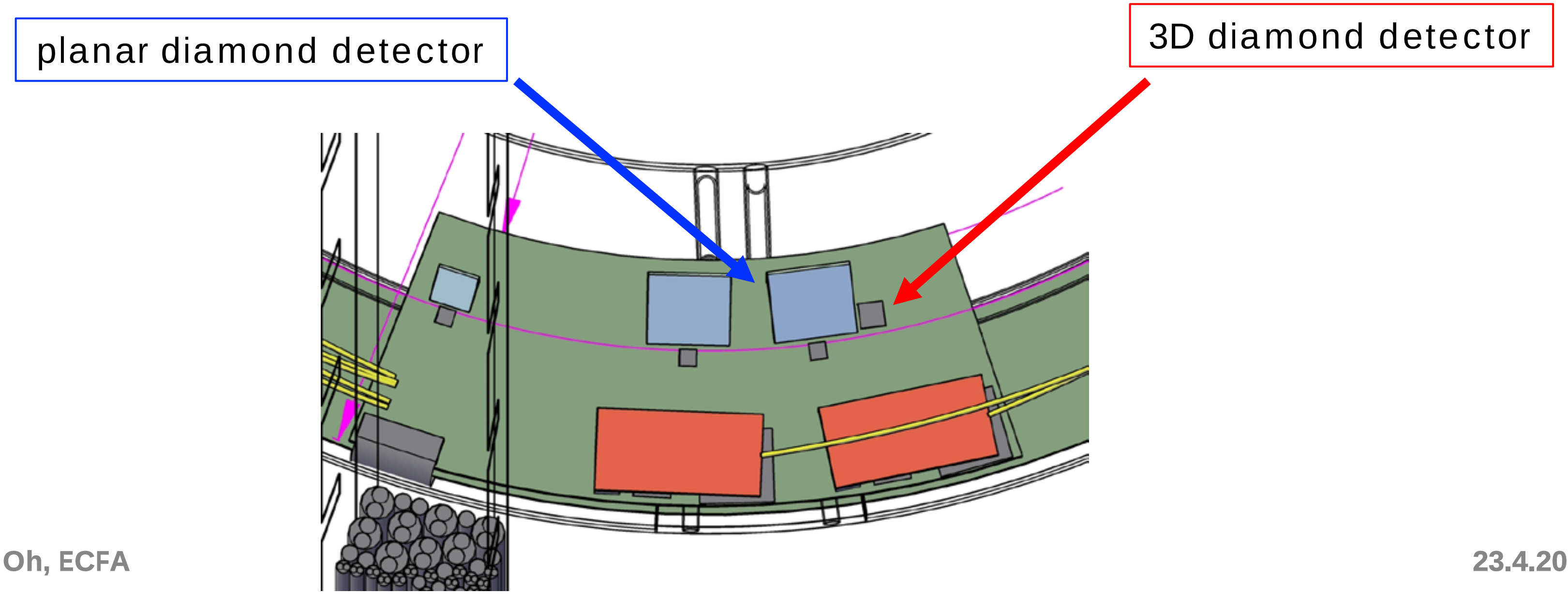


Diego Alejandro Sanz Becerra | 11.06.2020 |

3D diamond simulation examples from RD42

3D diamond detectors
Devices in future experiments

- The BCM’ phase-2 project of ATLAS will feature a small area **3D diamond detectors**.
  - Prove technology readiness for small cells.
  - Stepping stone for larger area application.



planar diamond detector

3D diamond detector

3D diamond detectors Possible FCC devices

- 3D seems to be a viable option to enhance radiation tolerance.
- Radiation hardness requirement and resulting λ dictate cell size.
- Cell size determined by wire-diameter (1μm) and cell capacitance.
- $(25\mu m)^2$ or even below seems feasible.
  - Loss of efficiency small at 10^{17} peq
    $25 \div 2 \times \sqrt{2} = 18$ μm drift path vs λ=18 μm
  - **Leakage current not an issue.**
- Main technological challenge for large scale application is the scaling of wire production.

Research Challenges for the next 20y Summary

- **Polycrystalline CVD diamond.**
  - Collection distance 25% increase.
  - Decrease price by 50% (happens with larger use as in Si).
- **Radiation tolerance.**
  - Go to smaller cell size.
  - True 3D field electrodes (internal cages) offer huge potential to optimize electric field distribution to minimize drift time.
  - Also offer possibility of gain in diamond.
- **Processing of 3D graphitic wires in diamond.**
  - Reduce resistivity.
  - Scale production capability.

Discussion