Diamond detector technology, status and perspectives

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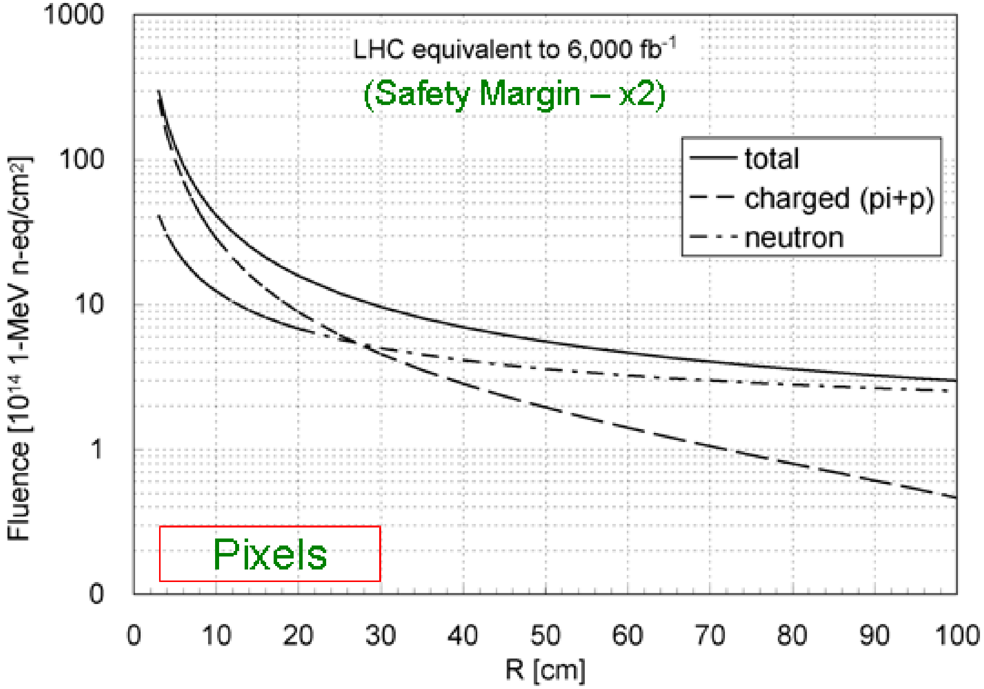
Outline of Talk

- Introduction – Motivation, RD42, Properties and Charge Collection
- Radiation Tolerance
- Diamond Devices in the LHC and Experiments
- Rate Studies
- Diamond Device Development – 3D Diamond
- Diamond Device Development – BCM'
- Summary

Introduction - Motivation

Physics Experiments at the Energy Frontier

HEP experiments are physically large devices composed of high precision inner detectors (r=3-25cm) which must withstand large radiation doses!



Radiation Tolerance Scale of inner layers is 10^{16}-10^{17}cm^{-2} (>500Mrad)

Introduction - Motivation

Diamond has the following properties:

Electronic Properties:

- Radiation tolerance - no frequent replacements
- Low dielectric constant - low capacitance
- Low leakage current - low readout noise
- Good insulating properties - large active area
- Room temperature operation - no cooling necessary
- Fast signal collection time – no ballistic deficit
- Smaller signal than Silicon – larger energy to create eh-pair

This talk is about:

- Polycrystalline Chemical Vapor Deposition (pCVD) Diamond
- Single Crystal Chemical Vapor Deposition (scCVD) Diamond

Introduction - The 2017 RD42 Collaboration

The 2017 RD42 Collaboration

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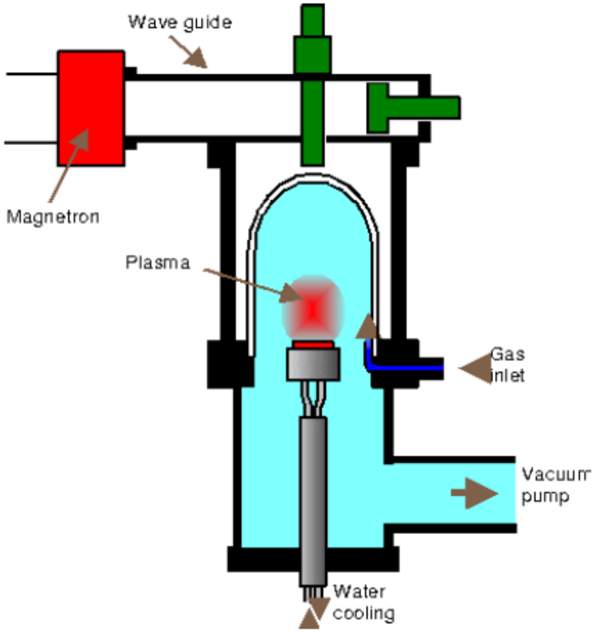
130 participants

32 institutes

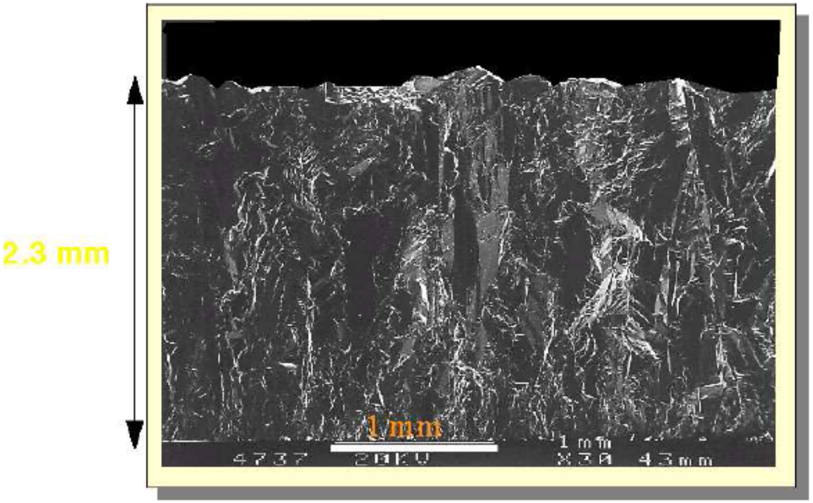
Introduction: Properties and Charge Collection

Chemical Vapor Deposition (CVD) Diamond Growth

Micro-Wave Reactor Schematic



Side View of pCVD Diamond



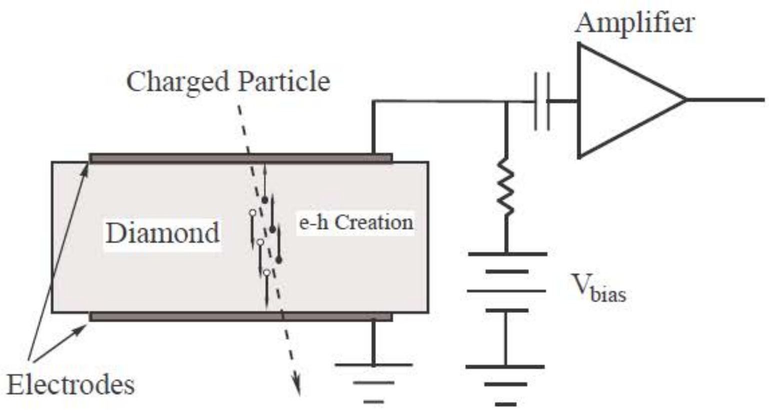
(Courtesy of Element Six)

- Diamonds are "synthesized" from a plasma
- The diamond "copies" the substrate

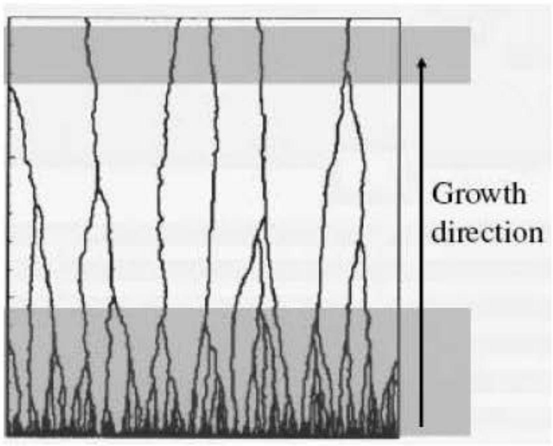
Introduction: Properties and Charge Collection

Detectors Constructed with Diamond:

Signal formation



pCVD Schematic Side View



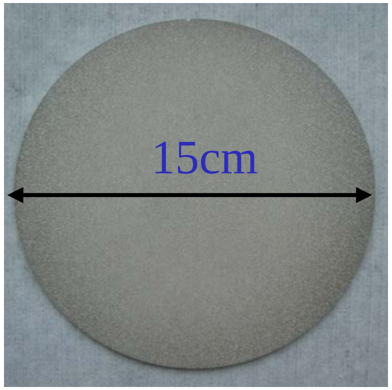
- d=$(\mu_e\tau_e + \mu_h\tau_h)$E where d = collection distance = ave. dist. e-h pair move apart
- d=μEτ = vτ

  with $\mu = \mu_e + \mu_h$ $\rightarrow$ $v = \mu$ E

  and $\tau = \frac{\mu_e\tau_e + \mu_h\tau_h}{\mu_e + \mu_h}$
- Q=$\frac{d}{t}Q_0$ $\rightarrow$ for large charge need good collection distance - must maximize μ and τ
- I=$Q_0\frac{v}{d}$

Introduction: Properties and Charge Collection

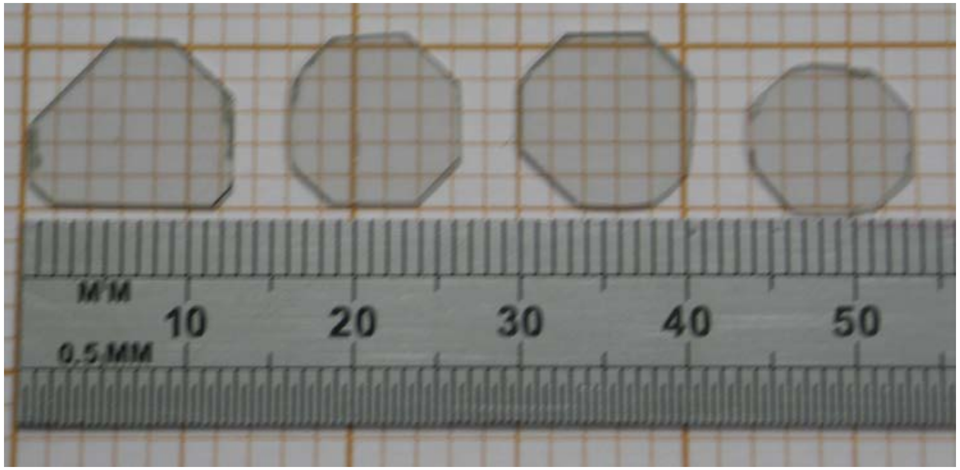
Polycrystalline CVD (pCVD) Wafer Growth



Wafers 15cm diameter; wafer collection distance 400μm-500μm

Uniformity across wafer ~5%

Single-crystal CVD (scCVD) Wafer Growth

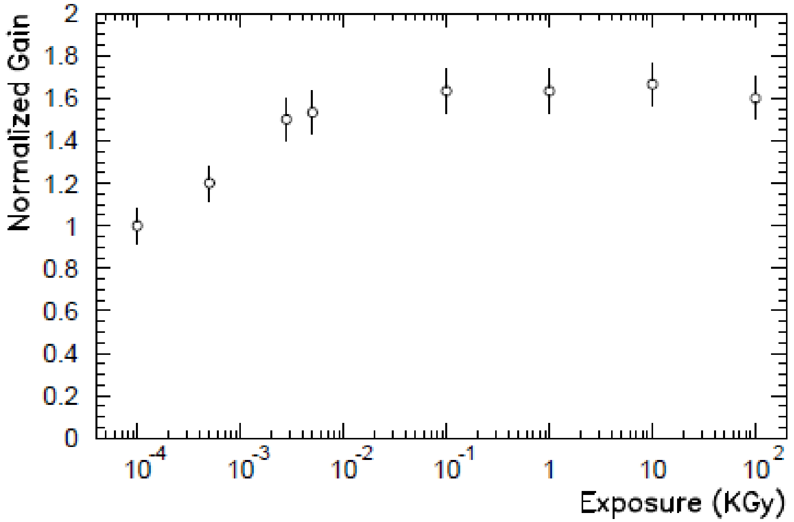


Wafers 5-10mm x 5-10mm; scCVD diamond collects full charge

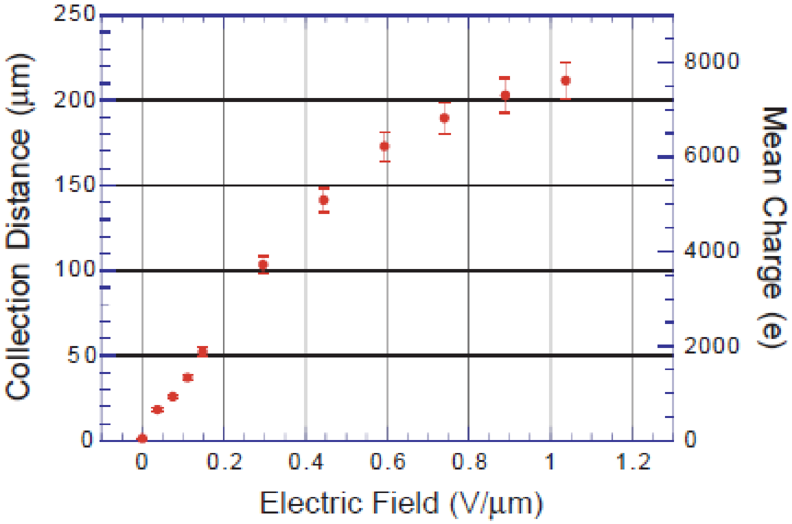
Introduction: Properties and Charge Collection

Characterization of Diamond:

Signal formation



Signal versus applied electric field



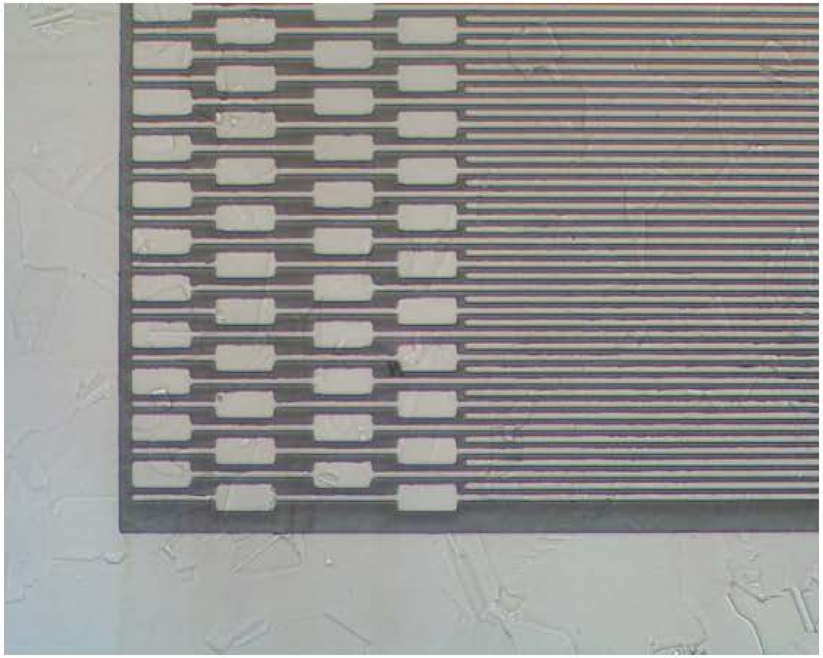
- High quality pCVD diamond typically "pumps" by a factor of 1.5-1.8
- Traps/defects in material → ionization creates carriers which may fill traps
- Usually operate at E=1-2V/µm → drift velocity saturated
- Charge collection distance of 100µm → Average charge of 3600e

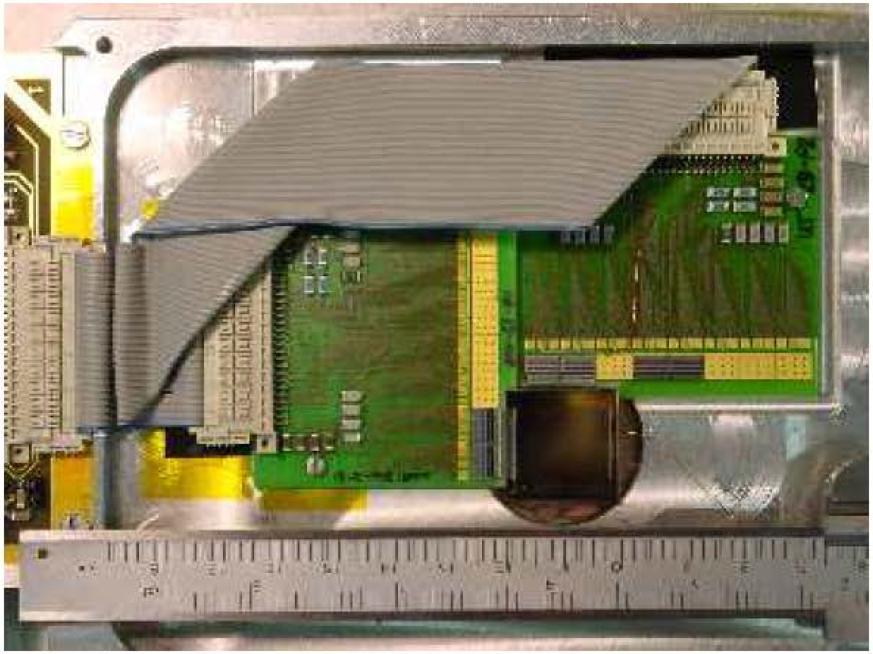
Radiation Tolerance

- *binding energy, displacement energy*
- *charge collection distance*
- *mean free path, drift distance*
- *elastic, inelastic, total cross section*

Radiation Tolerance

pCVD Diamond Trackers:

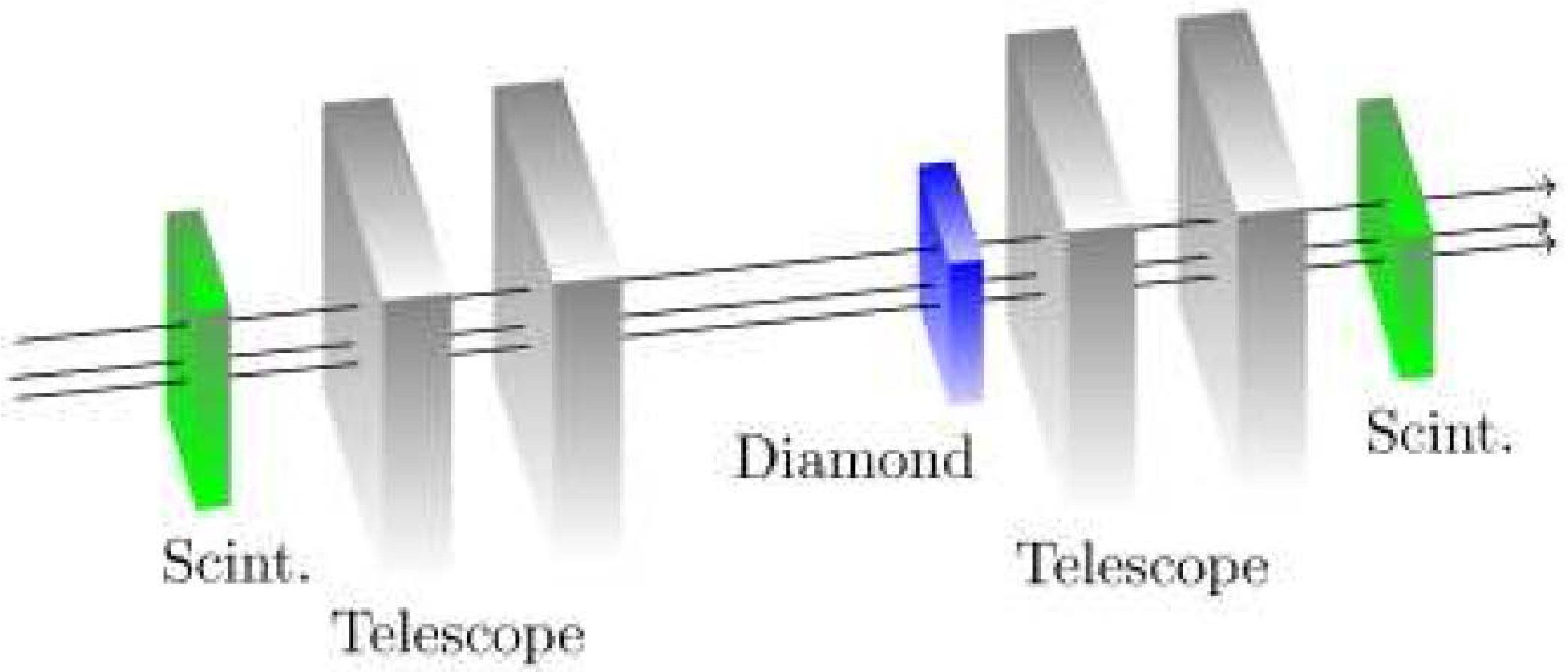




- Patterning the diamond → pads, strips, pixels!
- Successfully made double-sided devices; ∼edgeless.
- Segmented devices critical in radiation studies - charge and position.

Radiation Tolerance

Test Beam Setup



Irradiated devices characterized in test beams - transparent or unbiased prediction from telescope.

Radiation Tolerance

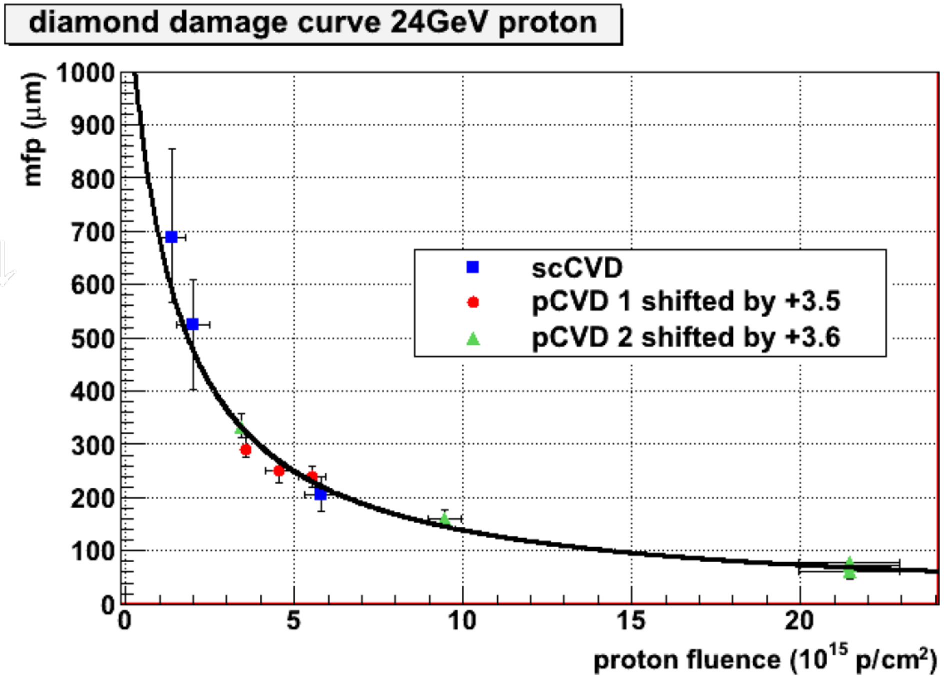
Proton Irradiation Summary - CERN PS 24 GeV protons

Damage Equation:

$$n = n_0 + k\phi$$

$$\downarrow \qquad \downarrow$$

$$\frac{1}{\text{mfp}} = \frac{1}{\text{mfp}_0} + k\phi$$



- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\text{mfp}_e = \text{mfp}_h$

Irradiation results up to 2.2 x 10^{16} p/cm^2 (~500Mrad)
Same damage curve, same damage constant (k) for pCVD and scCVD diamond
Larger mfp_0 performs better at any fluence
24 GeV proton damage characterized

Radiation Tolerance

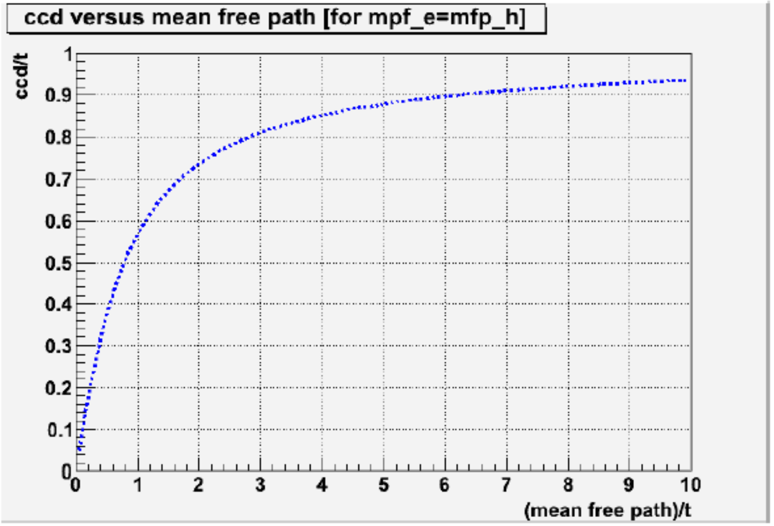
Charge Collection Distance versus Mean Free Path

- For pCVD ccd $<$ thickness; however for scCVD ccd $\sim$ thickness. To compare must use correct form of damage equation ccd $\rightarrow$ mfp

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k\phi$$

- Collection Distance coincides with Mean Free Path when ccd $<<$ t
- Collection Distance is raw data $\rightarrow$ no correction.
- Mean Free Path is correct theory but must correct data $\rightarrow$ assumptions

$$\frac{ccd}{t} = \sum_i \frac{mfp_i}{t}\left[1 - \frac{mfp_i}{t}\left(1 - e^{-\frac{t}{mfp_i}}\right)\right]$$



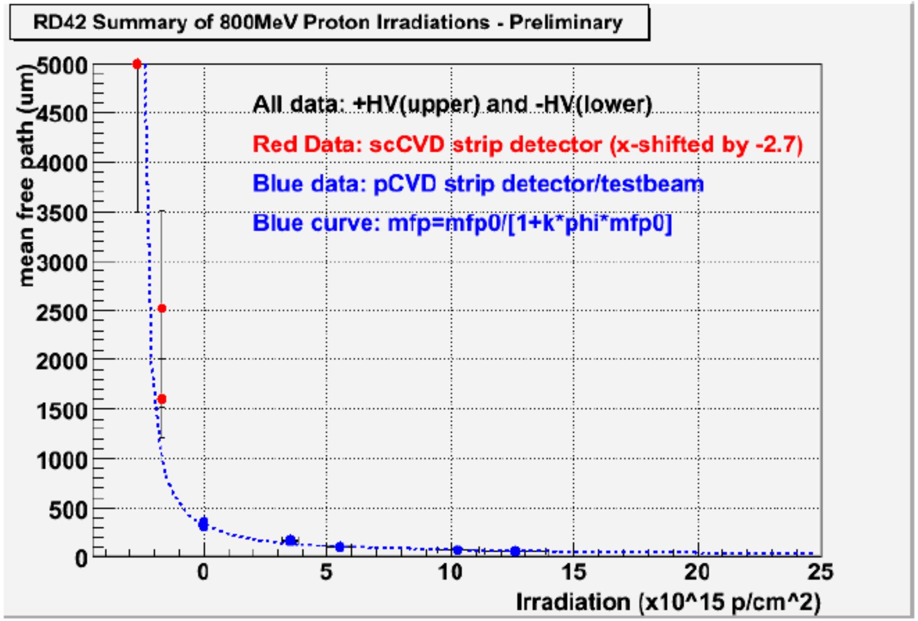
Radiation Tolerance

Proton Irradiation at Lower Energy - LANL 800 MeV protons:

Damage equation:

$$\frac{1}{\mathrm{mfp}} = \frac{1}{\mathrm{mfp}_0} + k\phi$$

- mfp_0 initial traps in material
- k damage constant
- ϕ fluence
- Assume $\mathrm{mfp}_e = \mathrm{mfp}_h$



New results from low energy irradiation

Irradiation results up to 1.3×10^{16} *p/cm*^{2}

Same damage curve: 1/mfp=1/mfp$_0$ *+k* $\phi \rightarrow k = 1.2 \times 10^{-18} \mu m^{-1} cm^2$

800 MeV protons 1.6-1.8$\times$ *more damaging than 24 GeV proton*

Radiation Tolerance

Summary of proton, neutron and pion irradiations

Particle	Energy	Relative k
p	24 GeV	1.0
	800 MeV	1.79±0.13
	70 MeV	2.4±0.4
	25 MeV	4.5±0.6
n	1 MeV	4.5±0.5
π	200 MeV	2.5 - 3.0

Damage curves are beginning to be mapped out

Applications in the LHC and Experiments

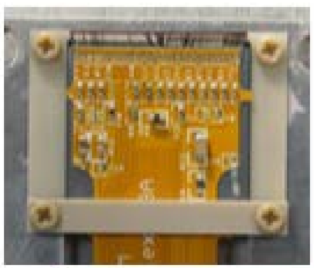
- beam condition/beam loss monitors
- pixel detectors
- 3D devices

Diamond devices in experiments

- Beam Conditions Monitors/Beam Loss Monitors
  - Essentially all modern collider experiments
- Current generation Pixel Detectors
  - ATLAS Diamond Beam Monitor (DBM)
- Future HL-LHC Trackers
  - 3D diamond
- Future BCM'
  - Multipad design

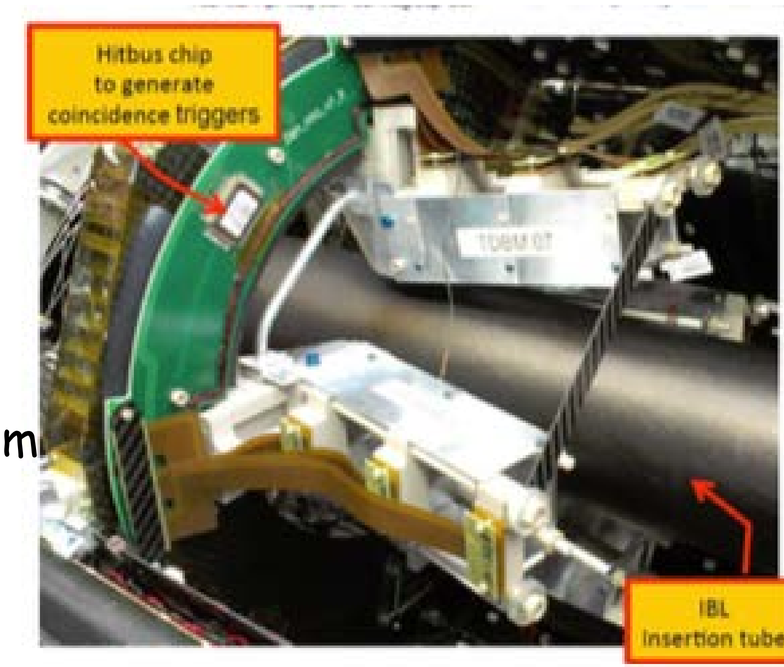
Diamond devices in experiments

- ATLAS DBM: diamond pixel detectors in ATLAS (tracking)
- Total production: 45 diamonds (500μm thick) w/FE-I4b
- Modules Assembled at CERN
- Installed during LS1



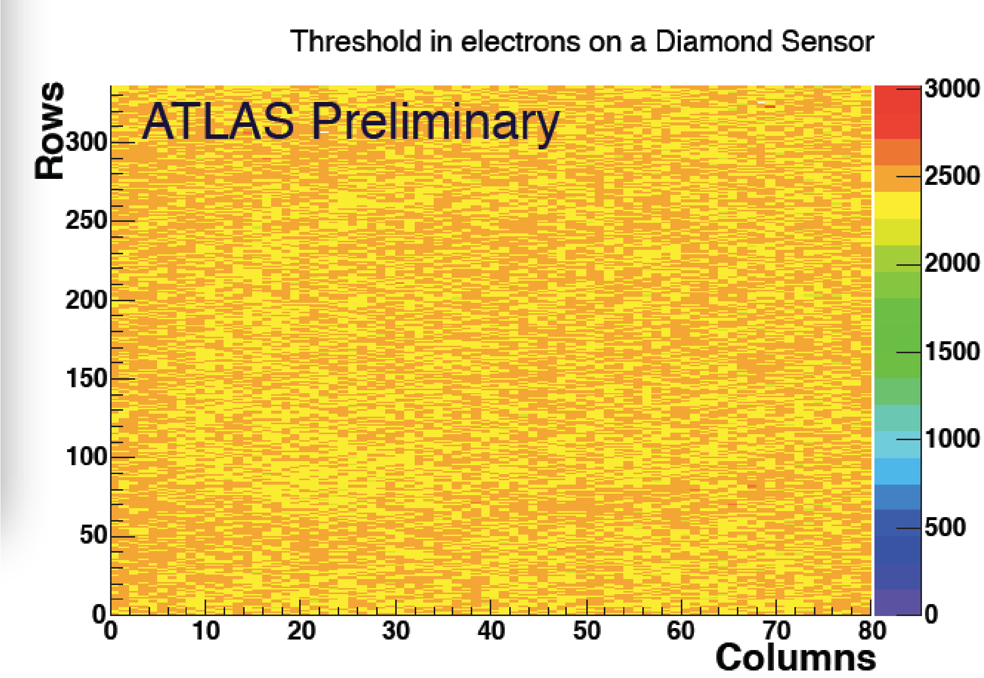
8 telescopes
(2 Si\6 Diamond)
symmetric
around ATLAS IP

854mm < |z| < 1092mm
3.2 < |η| < 3.5



Diamond devices in experiments

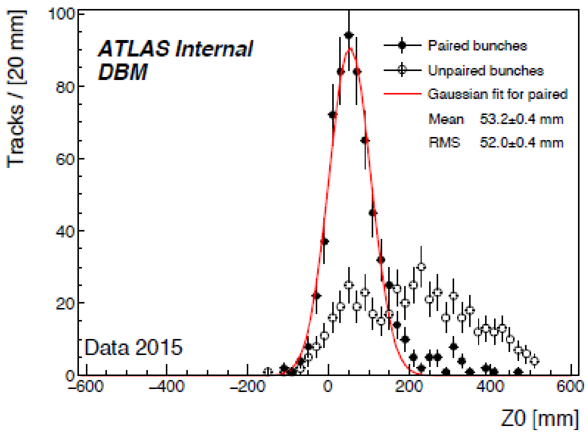
- ATLAS DBM integrated in ATLAS readout in 2015
- Thresholds tuned to 2500e



  - Would like to lower this (1100e possible on bench)
- Took data – found operation issues

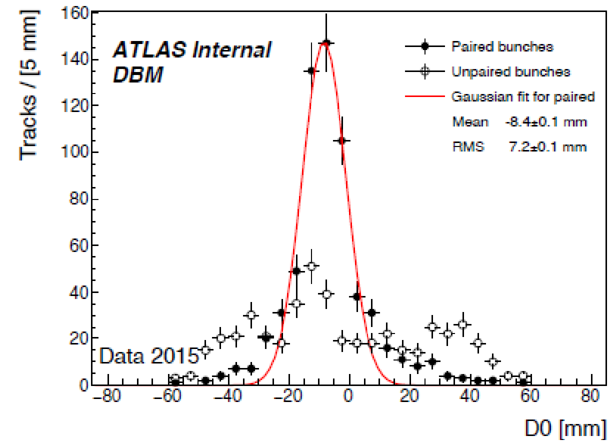
Diamond devices in experiments

- Use hits from the 3 modules for reconstructing tracks



Run of July 2015
clear separation:

Collisions:
vs
Background:



Longitudinal distance of the projected particle tracks to the interaction point

Radial distance of the projected tracks of the closest approach to the interaction point

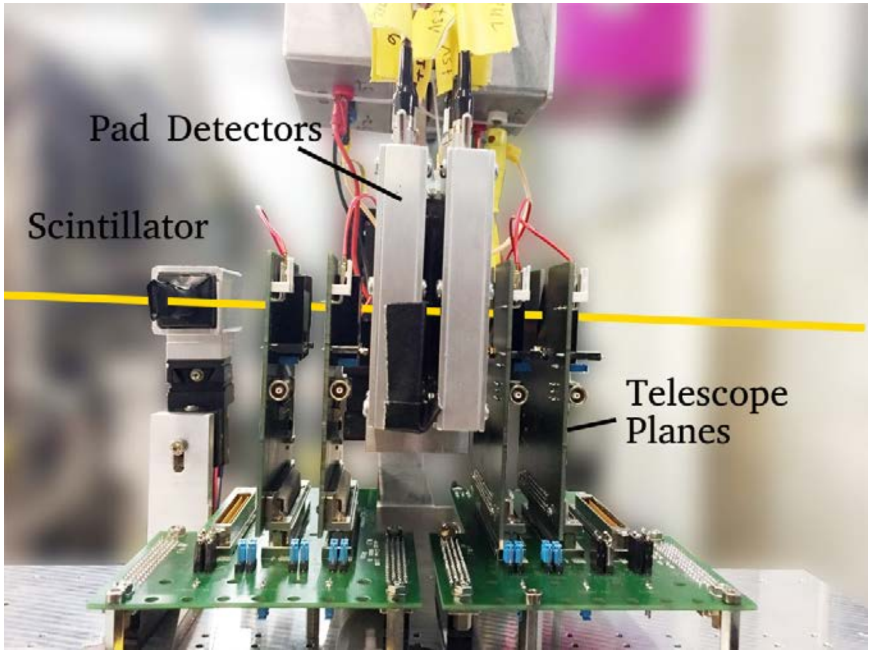
- Can discriminate between IP and background particles
  - Plots above use initial alignment
- 2 electrical incidents in 2015 caused loss of modules(Si/D)
  - now in re-commissioning phase

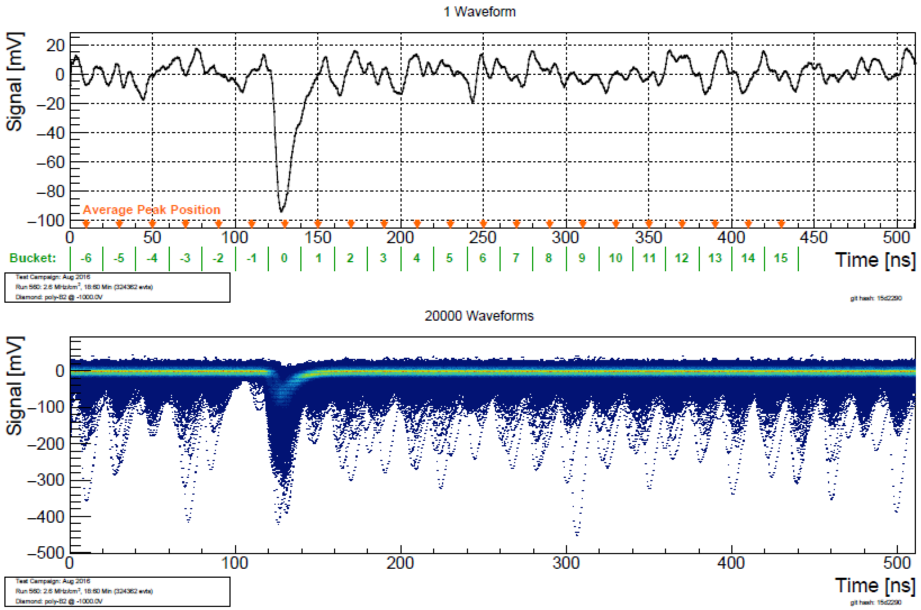
Rate Studies

- bunch spacing
- fast electronics
- rate effects

Rate studies in pCVD diamond

- Done at PSI - 2 yrs ago published rates up to 300kHz/cm^2
- Last year w/new electronics, rates up to 10-20MHz/cm^2
- Pad detector tested in ETH-Z telescope (CMS Pixels)
- Electronics is prototype for HL-LHC BCM/BLM

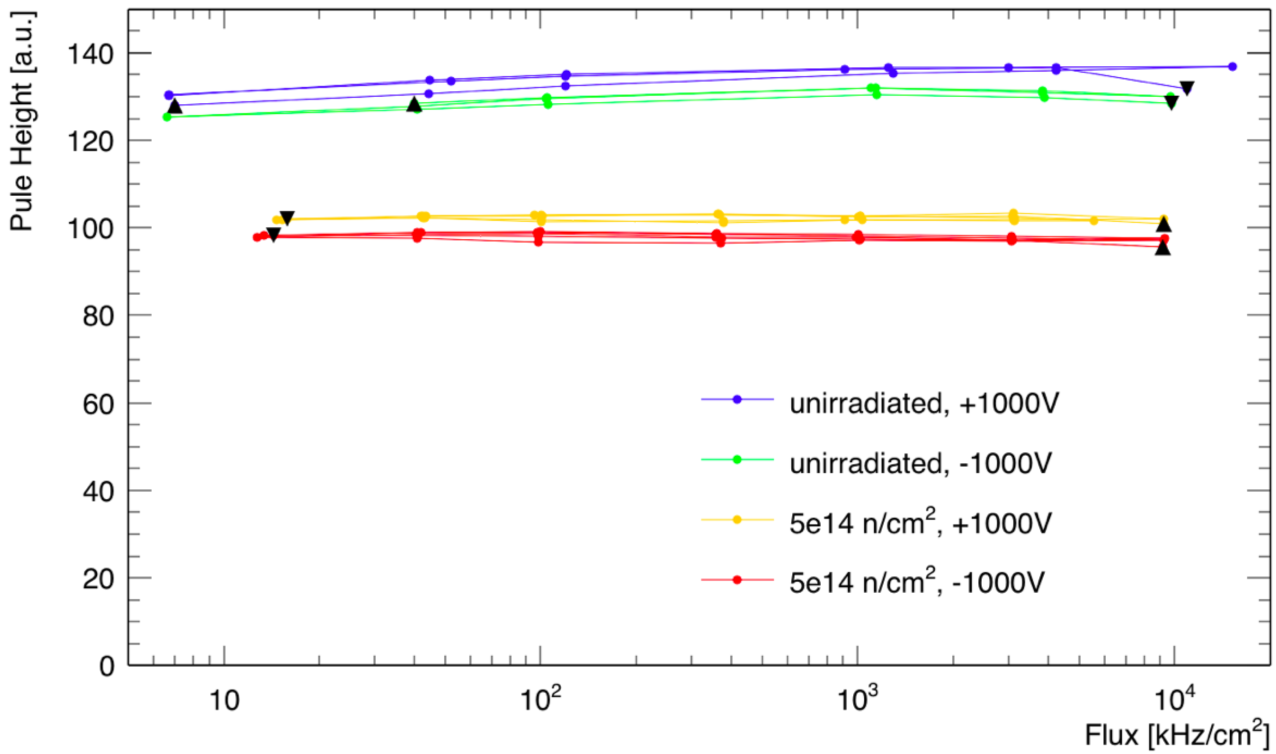




19.8ns bunch spacing clearly visible

Rate studies in pCVD diamond

- Done at PSI - two years ago rates up to 300kHz/cm^2
- Last year w/new electronics, rates up to 10MHz/cm^2



No rate dependence observed in pCVD up to 10-20MHz/cm^2
Now extending dose to 10^{16} n/cm^2

Device Development – 3D Diamond

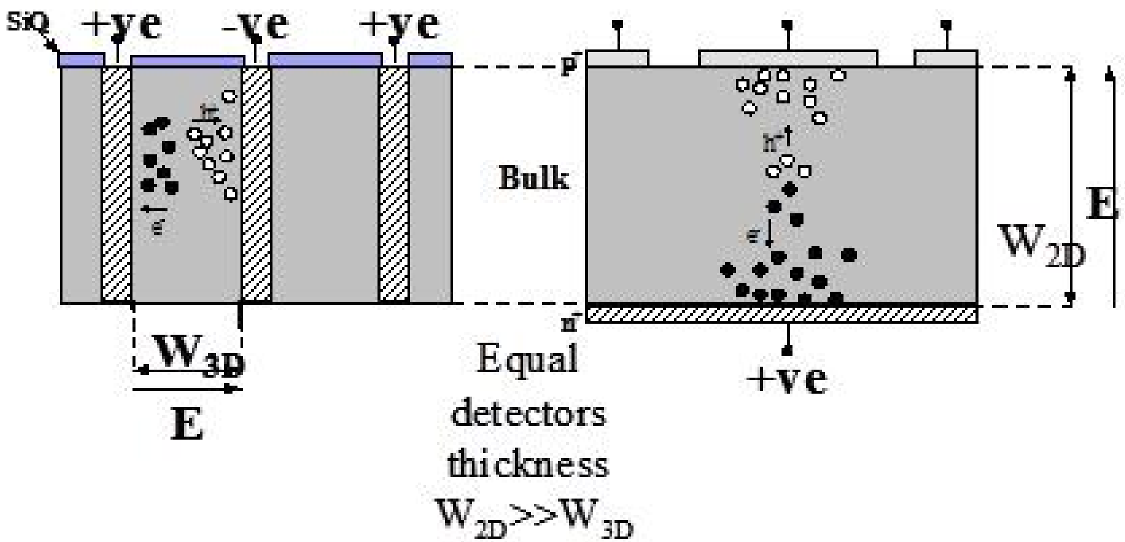
- mean free path, drift distance
- planar strip, phantom, 3D
- pixel detectors

3D device in pCVD diamond

After large radiation fluence all detectors are trap limited
- Mean free paths < 75μm
- Would like to keep drift distances smaller than mfp

Comparison of 3D and planar devices

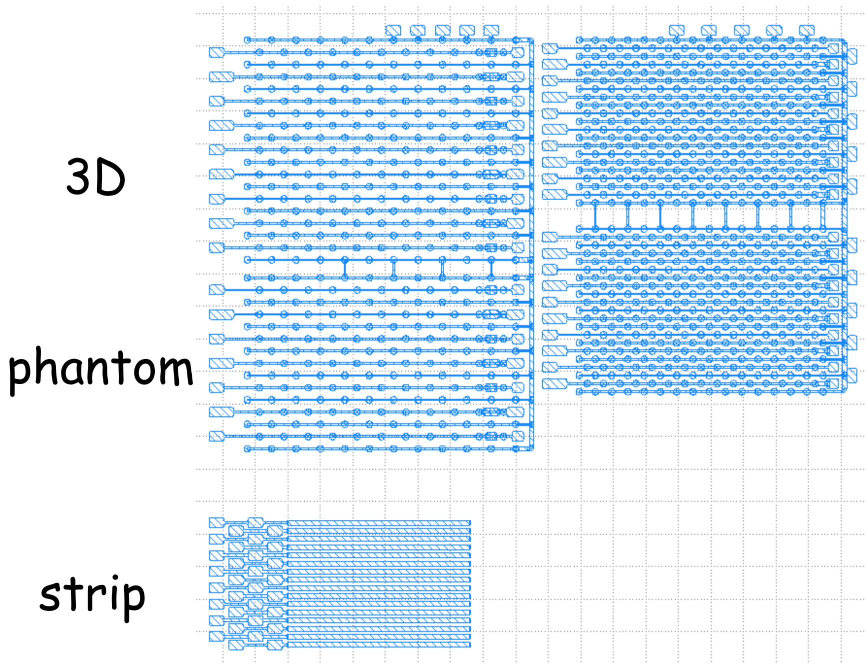
Can one do this in pCVD diamond?

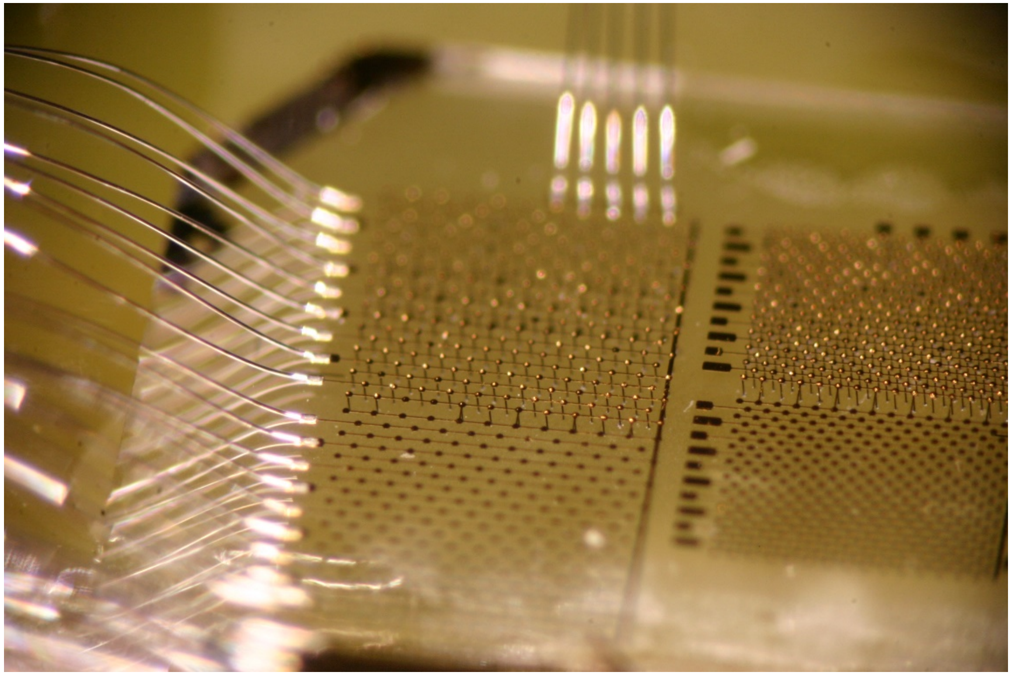


Have to make resistive columns in diamond for this to work
- -columns made with 800nm femtosecond laser
- -initial cells 150μm x 150μm; columns 6μm diameter

3D device in pCVD diamond

Simultaneously readout all 3 devices





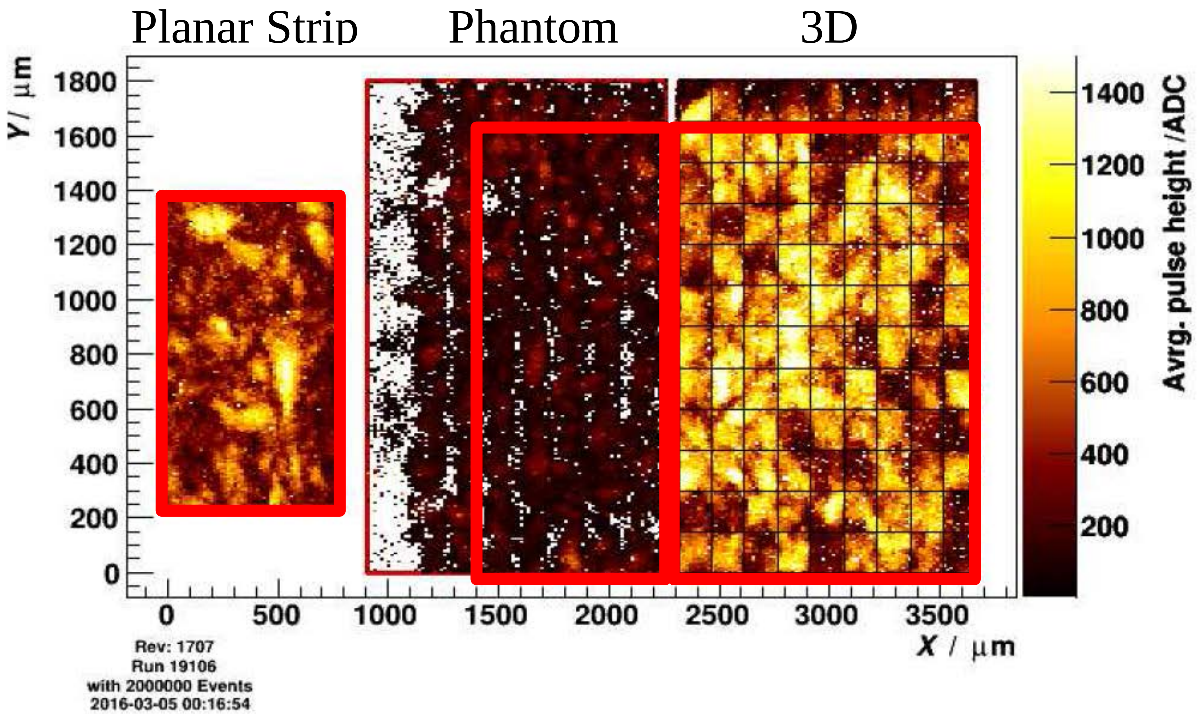
Two years ago we showed the results in scCVD diamond
- -Compared scCVD strip detector (500V) with 3D (25V)

Last year the first 3D device in pCVD diamond
- -Compare pCVD strip detector (500V) with 3D (60V)

This year the first 3D pixel detector in pCVD diamond

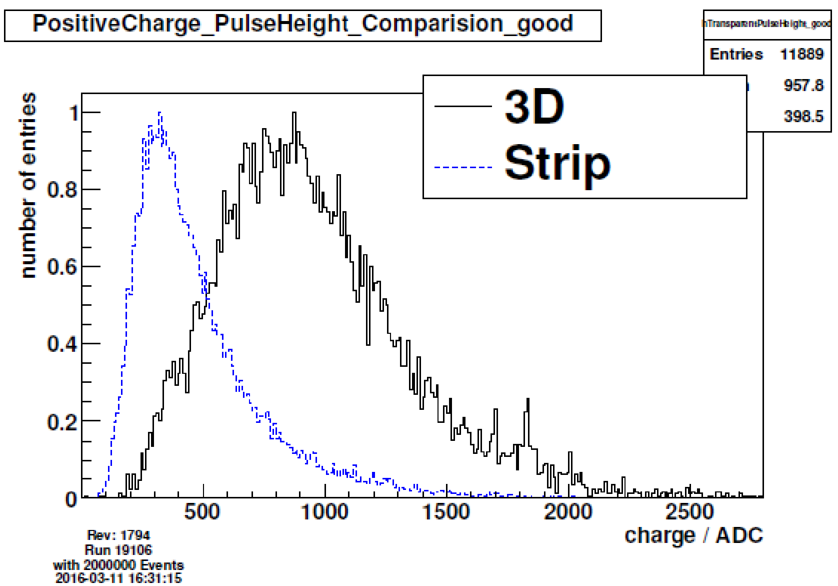
3D device in pCVD diamond

- Measured column efficiency: 92%
- 3D cells are 150μm x 150μm
- Measured noise ~proportional to capacitance
- Measured Signal read out as ganged cells
  - Visually 3D gives more charge than planar strip!



3D device in pCVD diamond

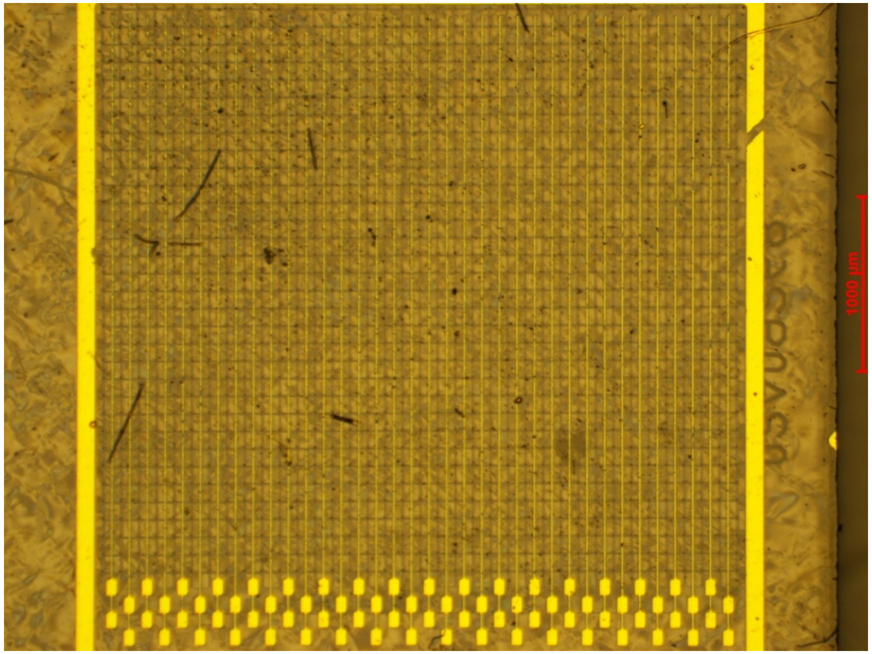
- Measured signal (diamond thickness 500um):
  - Planar Strip ave charge
    6,900e or ccd=192um
  - 3D ave charge
    13,500e or ccd_{eq}=350-375um
- For the first time collect >75% of charge in pCVD



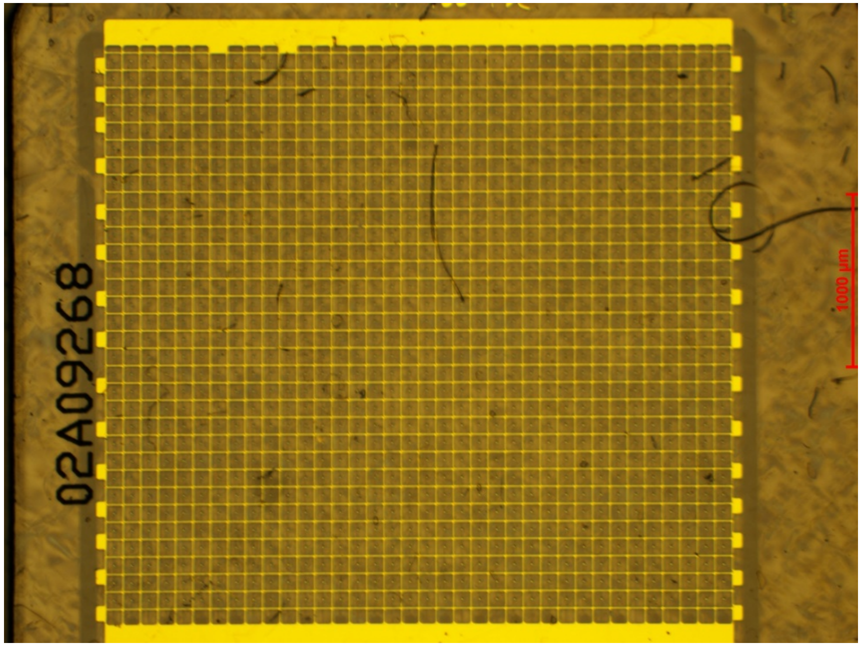
3D device in pCVD diamond

- In May/Sept 2016 tested first full 3D in pCVD with three dramatic improvements
  - An order of magnitude more cells (1188 vs 99)
  - Smaller cell size (100μm vs 150μm)
  - Higher column production efficiency (99% vs 92%)

Readout side



HV bias side



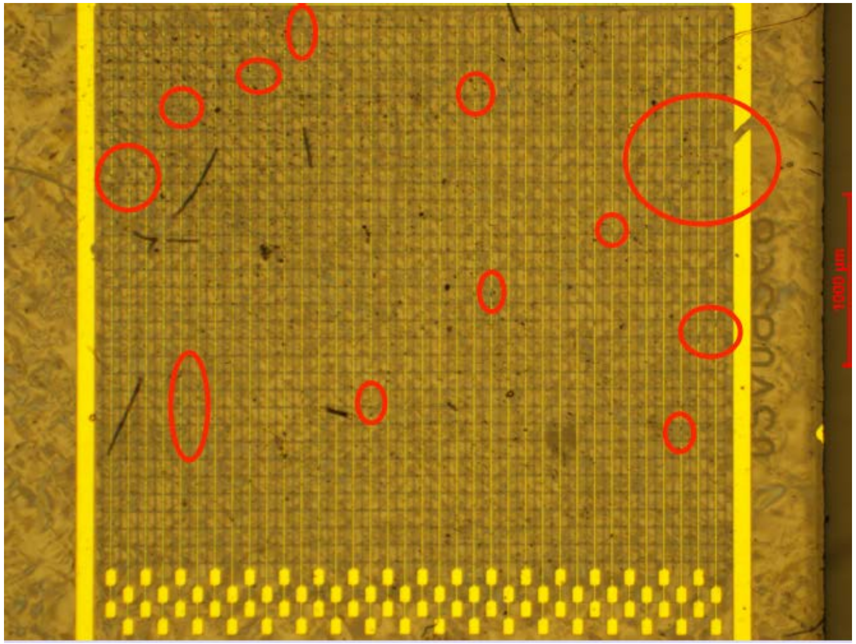
3D device in pCVD diamond

Proved viability (>99%) of new column fabrication procedure

Issues mainly due to communications about handling procedures – led to:

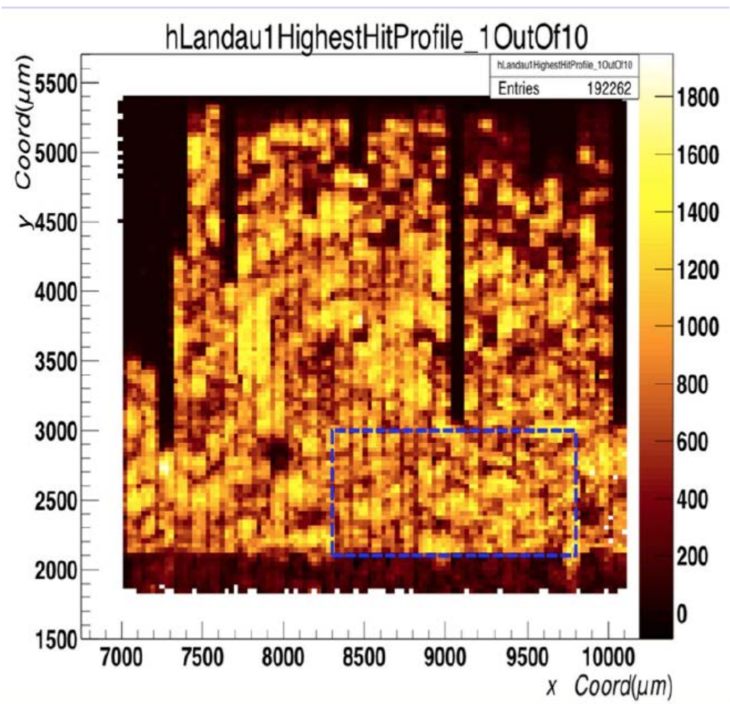
- Surface contamination
- Breaks in surface metallization

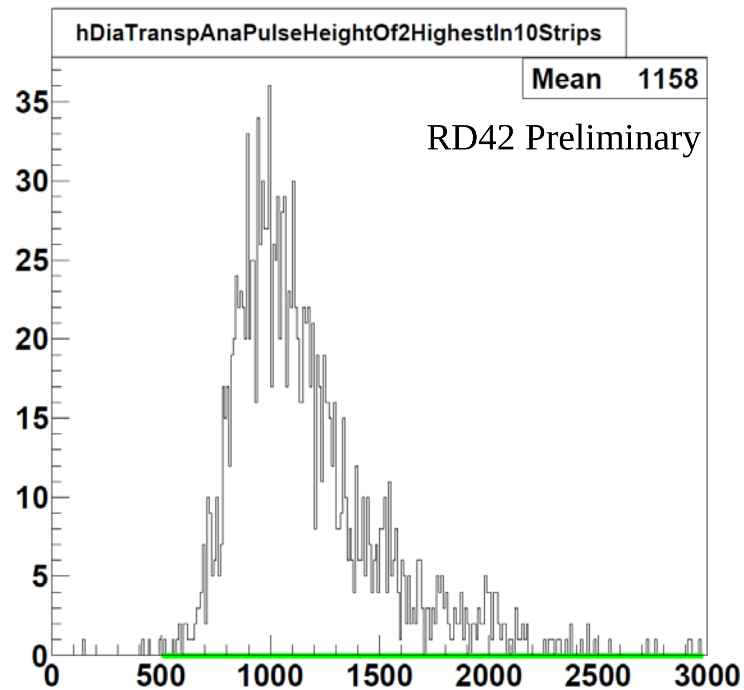
All fixable!



Production Plans: ATLAS, CMS 3D pCVD Pixels

- Preliminary results of full 3D - device works well
  - First plots of 3D ave charge in entire detector
  - Largest charge collection in pCVD diamond
    - >85% of charge collected in contiguous region
- Analysis in progress of full detector





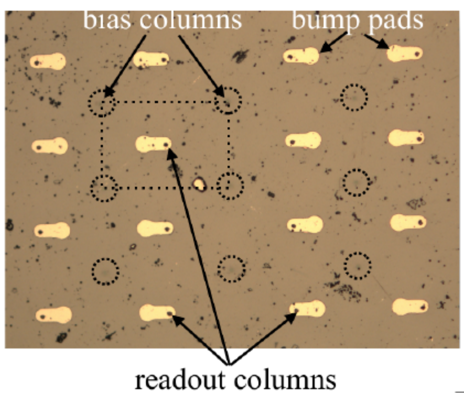
Production Plans: ATLAS, CMS 3D pCVD Pixels

Production of first 3D pixel device in pCVD - CMS pixel chip

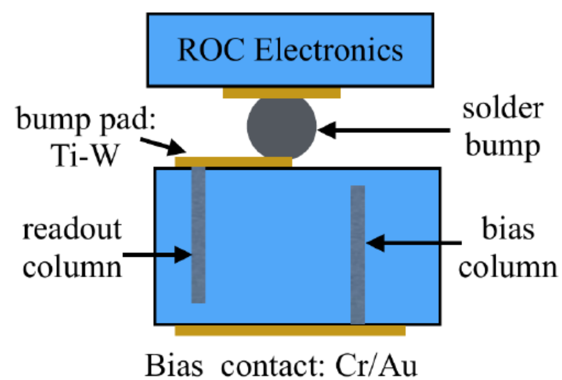
Fabrication

Metallisation & Bump Bonding

- connect to bias and readout with surface metallisation
- cleaned and prepared for photo-lithography at OSU
- photo-lithography and metalisation of HV back plane at OSU
- photo-lithography and metalisation of pixel readout at Princeton by Bert Harrop
- bump and wire bonding at Princeton



(a) pixel readout metalisation

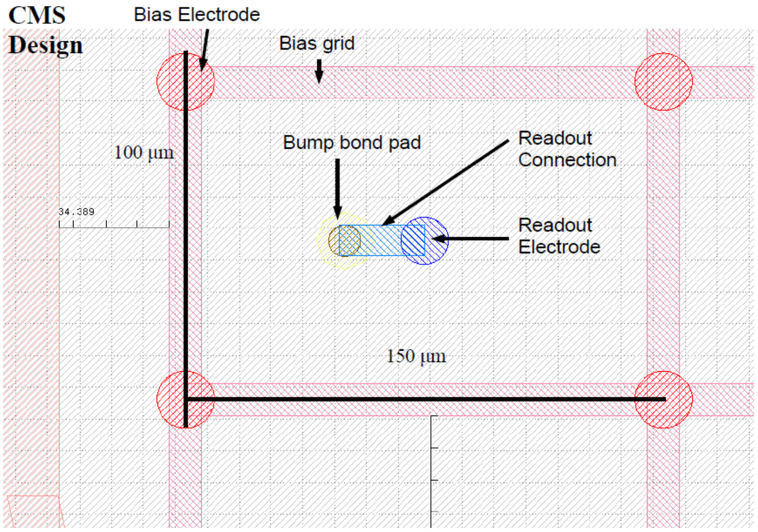


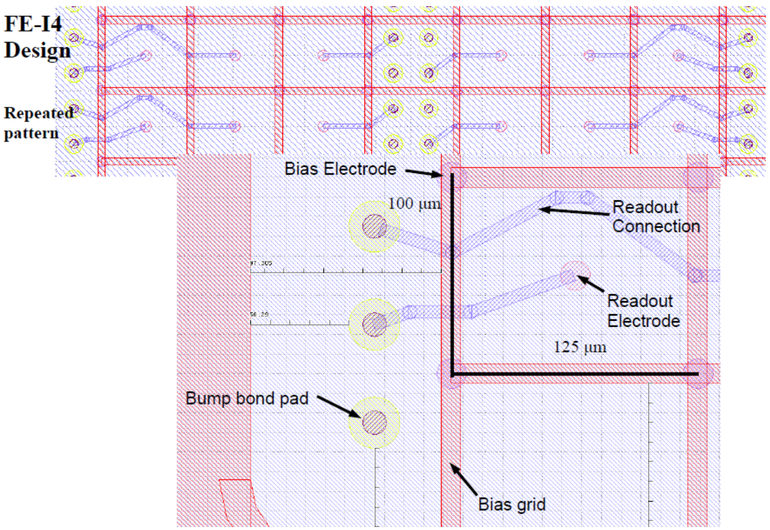
(b) final scheme

M. Reichmann (ETHzürich) | CMS 3D Pixel Detector | 11th April 2017 | 6 / 24

Production Plans: ATLAS, CMS 3D pCVD Pixels

- Laser fabrication of resistive columns: Oxford
- Mask set: Manchester
- Cleaning/Backplane metallization: Ohio State
- Bump Bonding/Pixel metallization: Princeton
- Module Building/Testing:ETH-Zürich, Rutgers
- Irradiation: JSI/Ljubljana (still to be done)
- Beam Tests:ETH-Zürich, Ohio State

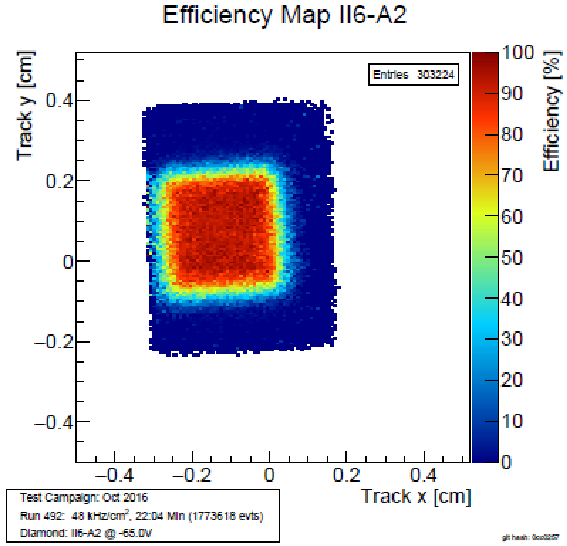


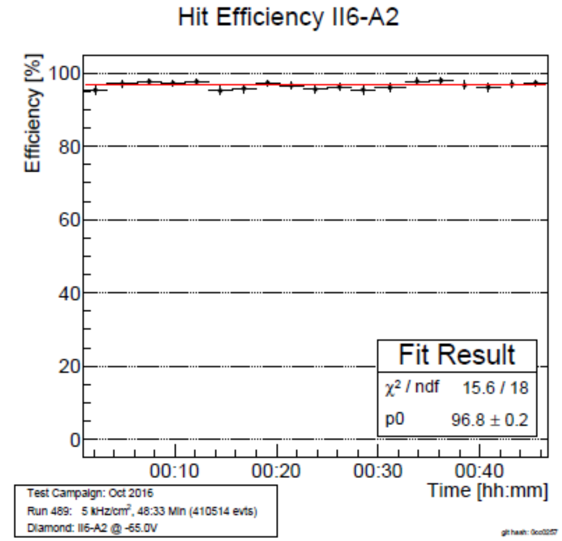


Production Plans: ATLAS, CMS 3D pCVD Pixels

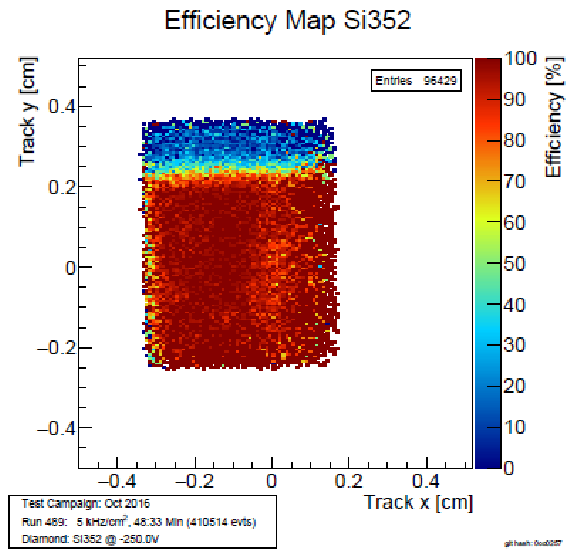
3D Diamond Pixel Efficiency (97%)

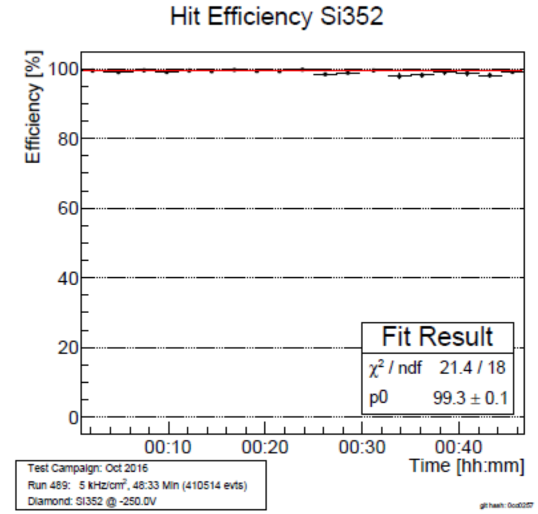
Some configuration issues with pixel chip





Planar Silicon Pixel Efficiency (99%)

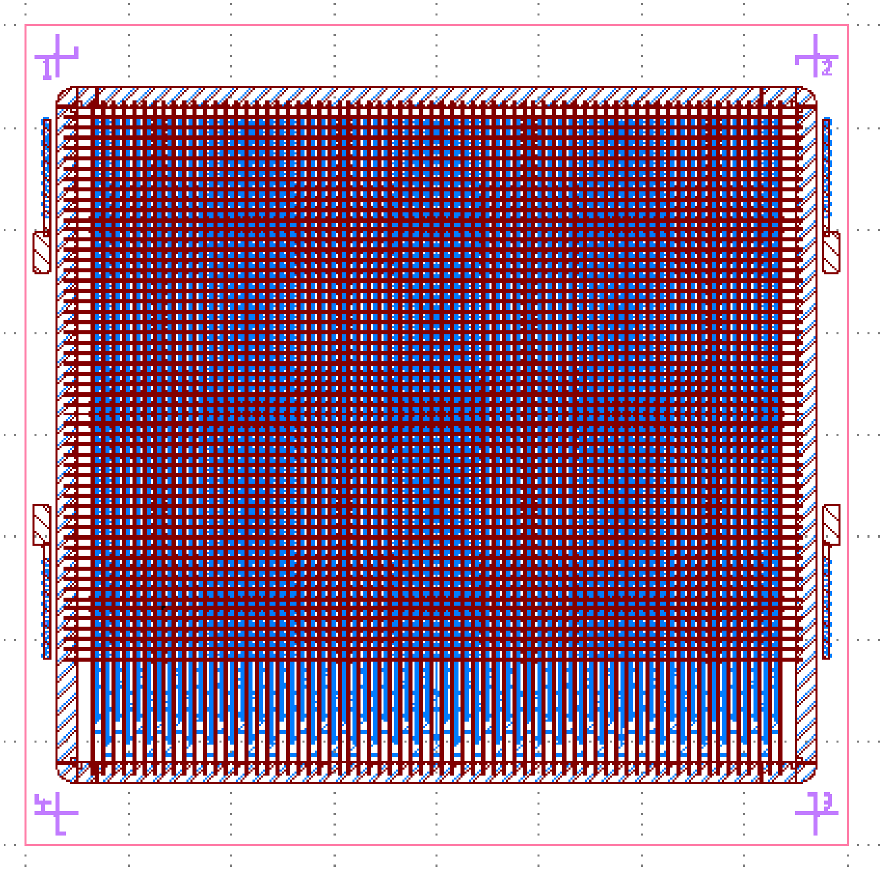




Production Plans: ATLAS, CMS 3D pCVD Pixels

Presently producing 3500 cell pixel prototype

- Two being drilled now:
  - Oxford (complete)
  - Manchester (mid-June)
- Metallization in progress
- Bump bonding
  - ATLAS @IFAE
  - CMS @Princeton
- Hope to be ready for June test beams



Summary

- Worked closely with manufacturers to increase quality
- Diamonds in the LHC machine making impact moving forward
- ATLAS/CMS -BCM, BLM, DBM will see collisions again soon
  - Abort, luminosity and background functionality in all LHC expts
- First pixel project is about to start taking data again
  - ATLAS DBM being re-commissioned for 13 TeV collisions
- 3D detector prototypes made great progress
  - 3D works in pCVD diamond; scale up worked; smaller cells worked
- Quantified understanding of rate effects in diamond
  - pCVD shows no rate effect up to 10-20MHz/cm^2
- 3D diamond pixel devices being produced (10^{17}/cm^2)
  - Efficiency looks good; PH in progress

Backup Slides

Device Development – BCM'

- abort threshold
- danger level, safety margin
- luminosity

Diamond development – BCM'

Abort and Luminosity Functions

Abort

- Require out-of-time and in-time signals above threshold signifying beam background at the danger Level
- Danger levels can be very high

  ATLAS SCT 25k/cm^2/BC i.e. ~4000x lumi signal
- Need to keep flexibility for threshold settings

Luminosity

- Main algorithm: (absence of) in-time hits

  Max sensitivity ~1.6 hits/cell
- Need robust device, signal stability paramount

Diamond development – BCM'

Present BCM suffers from abort-lumi incompatibility

- Abort thresholds can not be set higher without abandoning lumi
- Fast timing needed for abort lowers S/N thus limiting lumi stability

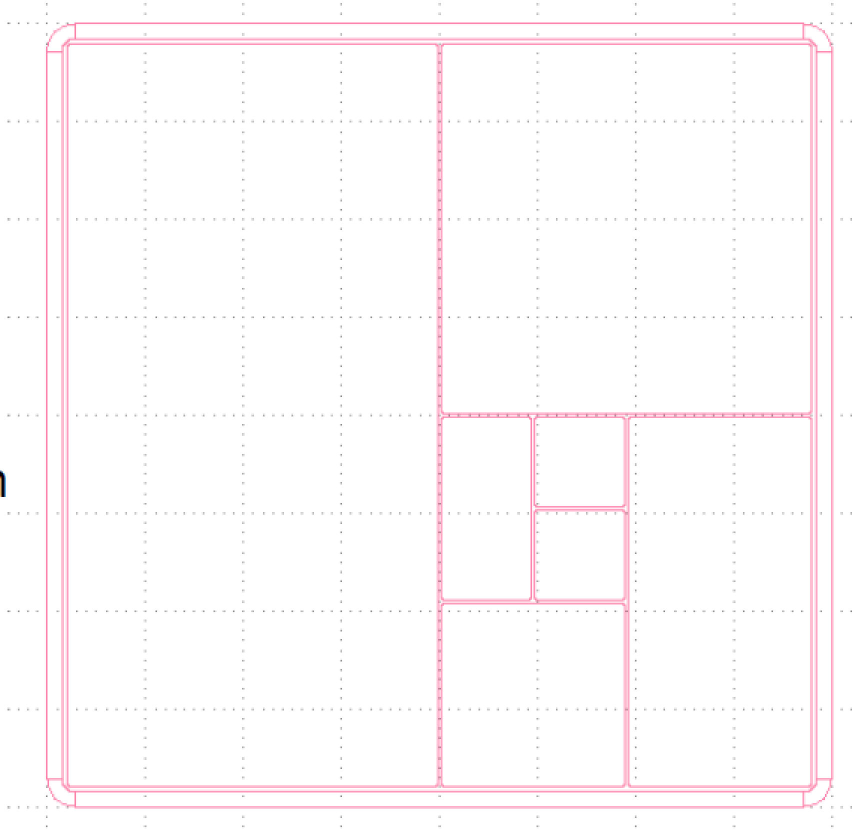
Separate functions at the HL-LHC

- Two fast devices from sensor to off-detector
- Keep as much commonality as possible
- 4 stations/side with abort, lumi-BCM', BLM

Diamond development – BCM'

Sensor Design

- Build in dynamic range into sensor design
- 6 different pads from 1 to 32 mm^2
  - occupancy from 0.06 to 2 at μ=200
    - covers sweet spot for lumi
  - 250 to 80000 MIP's at the declared SCT danger level (25k/cm^2/BC)
  - need to update the ballpark danger level for ITK asap !
- pCVD diamond substrate 300-500 μm thick
- Pads bonded to chip
- Prototype produced, to be tested in PSI TB at 5-10 MHz/cm^2 end of May



Tested @PSI last week with RD42 fast amp used for Rate Studies!

Diamond development – BCM'

Start with RD42 fast amp used in rate studies

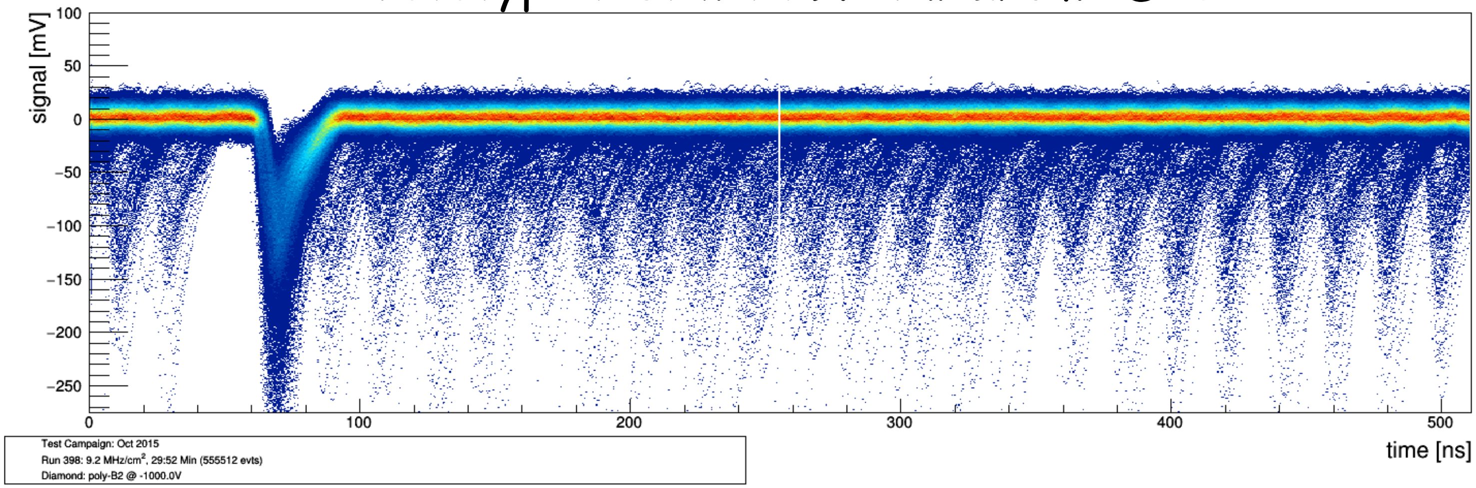
- Designed in 130nm; will be updated to 65nm
- Rise time 3-6ns; Baseline recovery time 12-18ns
- Noise for 2pf input ~550e

ATLAS electronics ideas

- Two preamp designs since otherwise large dynamic range (10^4) needed to cover lumi and abort in same channel
- High gain for lumi; low gain for abort. Optimize gain and speed vs SNR for lumi and abort separately
- Rise time ~few ns; return to baseline 10ns
- Tune parameters based on beam tests
- 16 channels (8/8 lumi/abort)

Diamond development – BCM'

Prototype test with 9.2 MHz/cm² @PSI



- Bunches 19.8ns apart clearly separated
- Trigger is at 69ns
- Hits in bunch before trigger not allowed