Diamond Detector Development and Plans: RD42 Results and Status

Harris Kagan
Ohio State University
for the RD42 Collaboration

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Outline of Talk

- Introduction – Motivation, Diamond Detectors, RD42
- Radiation Tolerance
- Rate Studies
- Device Development – Test beam results of 3D diamond pixel devices
- Device Development – HL-LHC beam monitoring and abort (BCM')
- Summary
Introduction - Motivation

Present Situation:
  • Innermost layers $\rightarrow$ highest radiation damage ($\sim$100’s MHz/cm$^2$)
  • Current detectors designed to survive $\sim$12 months in HL-LHC
    $\rightarrow$ R&D for more radiation tolerant detector designs and/or materials

Diamond as a Detector Material:
  • Properties:
    radiation tolerance
    insulating material
    high charge carrier mobility
    Smaller signal than in same thickness of silicon

RD42 work:
  • Investigate signals and radiation tolerance in various detector designs:
    pad $\rightarrow$ full diamond as a single cell readout
    pixel $\rightarrow$ diamond sensor on pixel chips
    3D $\rightarrow$ strip/pixel detector with design to reduce drift distance
Introduction - The 2018 RD42 Collaboration

The 2018 RD42 Collaboration

A. Alexopoulos\textsuperscript{3}, M. Artuso\textsuperscript{20}, F. Bachmair\textsuperscript{24}, L. Bāni\textsuperscript{24}, M. Bartosik\textsuperscript{3}, J. Beacham\textsuperscript{13}, H. Beck\textsuperscript{23}, V. Bellini\textsuperscript{2}, V. Belyaev\textsuperscript{12}, B. Bentele\textsuperscript{19}, P. Bergonzo\textsuperscript{11}, A. Bes\textsuperscript{27}, J-M. Brom\textsuperscript{7}, M. Bruzzi\textsuperscript{4}, G. Chiodini\textsuperscript{26}, D. Chren\textsuperscript{18}, V. Cindro\textsuperscript{9}, G. Claus\textsuperscript{7}, J. Collot\textsuperscript{27}, J. Cumalat\textsuperscript{19}, A. Dabrowski\textsuperscript{3}, R. D’Alessandro\textsuperscript{4}, D. Dauvergne\textsuperscript{27}, W. de Boer\textsuperscript{10}, S. Dick\textsuperscript{13}, C. Dorfer\textsuperscript{24}, M. Dunser\textsuperscript{3}, G. Eigen\textsuperscript{30}, V. Eremin\textsuperscript{6}, J. Forneris\textsuperscript{15}, L. Gallin-Martel\textsuperscript{27}, M.L. Gallin-Martel\textsuperscript{27}, K.K. Gan\textsuperscript{13}, M. Gasta\textsuperscript{3}, C. Giroletti\textsuperscript{17}, M. Goffe\textsuperscript{7}, J. Goldstein\textsuperscript{17}, A. Golubev\textsuperscript{8}, A. Gorišek\textsuperscript{9}, E. Grigoriev\textsuperscript{8}, J. Grosse-Knetter\textsuperscript{23}, A. Grummer\textsuperscript{21}, M. Guthoff\textsuperscript{3}, B. Hiti\textsuperscript{9}, D. Hits\textsuperscript{24}, M. Hoeferkamp\textsuperscript{21}, T. Hofmann\textsuperscript{3}, J. Hosslet\textsuperscript{7}, J-Y. Hostachy\textsuperscript{27}, F. Hüggling\textsuperscript{1}, C. Hutton\textsuperscript{17}, J. Janssen\textsuperscript{1}, H. Kagan\textsuperscript{13}, K. Kanxheri\textsuperscript{28}, G. Kasieczka\textsuperscript{24}, R. Kass\textsuperscript{13}, M. Kis\textsuperscript{5}, G. Kramberger\textsuperscript{9}, S. Kuleshov\textsuperscript{2}, A. Lacoste\textsuperscript{27}, S. Lagomarsino\textsuperscript{4}, A. Lo Giudice\textsuperscript{15}, E. Lukos\textsuperscript{25}, C. Maazouzi\textsuperscript{7}, I. Mandic\textsuperscript{9}, A. Marino\textsuperscript{19}, C. Mathieu\textsuperscript{7}, M. Menichelli\textsuperscript{28}, M. Mikuz\textsuperscript{9}, A. Morozzi\textsuperscript{28}, J. Moss\textsuperscript{29}, R. Mountain\textsuperscript{20}, S. Murphy\textsuperscript{22}, M. Muškinja\textsuperscript{9}, A. Oh\textsuperscript{22}, P. Olivero\textsuperscript{15}, D. Passeri\textsuperscript{28}, H. Pernegger\textsuperscript{3}, R. Perrino\textsuperscript{26}, F. Picollo\textsuperscript{15}, M. Pomorski\textsuperscript{11}, R. Potenza\textsuperscript{2}, A. Quad\textsuperscript{23}, F. Rarbi\textsuperscript{27}, A. Re\textsuperscript{15}, M. Reichmann\textsuperscript{24}, G. Riley\textsuperscript{25}, S. Roe\textsuperscript{3}, D. Sanz\textsuperscript{24}, M. Scarringella\textsuperscript{4}, D. Schaefer\textsuperscript{3}, C. Schmidt\textsuperscript{5}, E. Schioppa\textsuperscript{3}, S. Schnetzer\textsuperscript{14}, S. Sciortino\textsuperscript{4}, A. Scorzoni\textsuperscript{28}, S. Seidel\textsuperscript{21}, L. Servoli\textsuperscript{28}, D.S. Smith\textsuperscript{13}, B. Sopko\textsuperscript{18}, V. Sopko\textsuperscript{18}, S. Spagnolo\textsuperscript{26}, S. Spanier\textsuperscript{29}, K. Stenson\textsuperscript{19}, R. Stone\textsuperscript{14}, B. Stugu\textsuperscript{30}, C. Sutera\textsuperscript{2}, M. Traeger\textsuperscript{5}, D. Tromson\textsuperscript{11}, W. Trischuk\textsuperscript{16}, C. Tuve\textsuperscript{2}, J. Velthuis\textsuperscript{17}, N. Venturi\textsuperscript{3}, E. Vittone\textsuperscript{15}, S. Wagner\textsuperscript{13}, R. Wallny\textsuperscript{24}, J.C. Wang\textsuperscript{20}, J. Weingarten\textsuperscript{23}, C. Weiss\textsuperscript{3}, N. Wermes\textsuperscript{1}, M. Yamouni\textsuperscript{27}, J. Zalieckas\textsuperscript{30}, M. Zavrtanik\textsuperscript{9}

\textsuperscript{1} Universitàt Bonn, Bonn, Germany
\textsuperscript{2} INFN/University of Catania, Catania, Italy
\textsuperscript{3} CERN, Geneva, Switzerland
\textsuperscript{4} INFN/University of Florence, Florence, Italy
\textsuperscript{5} GSI, Darmstadt, Germany
\textsuperscript{6} Ioffe Institute, St. Petersburg, Russia
\textsuperscript{7} IPHC, Strasbourg, France
\textsuperscript{8} ITEP, Moscow, Russia
\textsuperscript{9} Jožef Stefan Institute, Ljubljana, Slovenia
\textsuperscript{10} Universität Karlsruhe, Karlsruhe, Germany
\textsuperscript{11} CEA-LIST Technologies Avancées, Saclay, France
\textsuperscript{12} MEPHI Institute, Moscow, Russia
\textsuperscript{13} The Ohio State University, Columbus, OH, USA
\textsuperscript{14} Rutgers University, Piscataway, NJ, USA
\textsuperscript{15} University of Torino, Torino, Italy
\textsuperscript{16} University of Toronto, Toronto, ON, Canada
\textsuperscript{17} University of Bristol, Bristol, UK
\textsuperscript{18} Czech Technical University, Prague, Czech Republic
\textsuperscript{19} University of Colorado, Boulder, CO, USA
\textsuperscript{20} Syracuse University, Syracuse, NY, USA
\textsuperscript{21} University of New Mexico, Albuquerque, NM, USA
\textsuperscript{22} University of Manchester, Manchester, UK
\textsuperscript{23} Universität Gottingen, Gottingen, Germany
\textsuperscript{24} ETH Zürich, Zürich, Switzerland
\textsuperscript{25} University of Tennessee, Knoxville, TN, USA
\textsuperscript{26} INFN-Lecce, Lecce, Italy
\textsuperscript{27} LPSC-Grenoble, Grenoble, Switzerland
\textsuperscript{28} INFN-Pergugia, Pergugia, Italy
\textsuperscript{29} California State University - Sacramento, CA, USA
\textsuperscript{30} University of Bergen, Bergen, Norway

123 participants
30 institutes
Introduction – Diamond as a Particle Detector

- Diamond detectors are operated as ionisation chambers
- Metalisation on both sides
  - Plate
  - Strip (used for presented beam test results)
  - Pixel
- Readout with low noise electronics

sCVD diamond with strip metalisation and amplifier
Radiation Tolerance
Test Beam Setup

- characterization of irradiated devices in test beams
- transparent or unbiased hit prediction from telescope
- tracking precision at detector under test: \( \sim 2-3 \mu m \)
Radiation Tolerance - Analysis Strategy

- Measure signal response as a function of predicted position
  - Direct measurement of charge collection distance (CCD)
    - CCD = average distance e-h pairs drift apart under E-field
- Convert CCD to mean free path (MFP) - assume ~same MFP for e,h

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

- Damage equation: \( n = n_0 + k\phi \)
  \[ \downarrow \quad \downarrow \]
  \[ \frac{1}{mfp} = \frac{1}{mfp_0} + k\phi \]
  
  n number of traps
  n₀ initial traps in material
  k damage constant
  \( \phi \) fluence
  \( \lambda \) MFP
  \( \lambda_0 \) initial MFP

- Fit in \( 1/\lambda \) (=1/mfp) vs \( \phi \) space
Radiation Tolerance - Analysis Strategy

**Example - 800 MeV protons**

- Plot single-crystalline and polycrystalline on same graph
- Fit in $1/\lambda$ vs $\phi$ space
- Damage constant (=slope) for single-crystal and poly the same
- Do the same for all energies, species
Summary of Radiation Tolerance Study
Combined Damage Curve

- Obtained radiation damage constants are compared to 24 GeV protons
- Combined damage curve
  - Shift pCVD sample by
    \[ \varphi_0 = \frac{1}{\lambda_0 k} \]
  - Scale fluence by relative \( k \)
    \[ \phi_{eq.} = \frac{k_i}{k_{24 \text{ GeV protons}}} \times \phi_i \]

<table>
<thead>
<tr>
<th>Particle Species</th>
<th>Relative Damage Constant, ( \kappa )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 GeV p</td>
<td>1</td>
</tr>
<tr>
<td>800 MeV p</td>
<td>1.54 ± 0.13</td>
</tr>
<tr>
<td>70 MeV p</td>
<td>2.5 ± 0.4</td>
</tr>
<tr>
<td>25 MeV p</td>
<td>4.5 ± 0.6</td>
</tr>
<tr>
<td>fast neutrons</td>
<td>4.5 ± 0.5</td>
</tr>
</tbody>
</table>
**Radiation Tolerance - Shape Analysis**

**Signal Shape Analysis**

- Study the shape of the pulse height distribution after irradiation (5/10 algorithm)
- Use the ratio FWHM/MP which is a measure of the uniformity of the material
- 800 MeV proton irradiated
  - pCVD samples
  - linear decrease of FWHM/MP
  - scCVD samples
  - Smaller initial relative width
  - linear increase towards same value
- See similar results for other irradiation energies, species
Rate Studies
Rate Studies in pCVD diamond

- Done at PSI - 3 yrs ago published rates up to 300kHz/cm²
- 2 years ago w/new electronics, rates up to 10-20MHz/cm²
- Last year measured rate up to fluence of $4 \times 10^{15}$n/cm²
- Pad detector tested in ETH-Z telescope (uses CMS Pixels)
- Electronics is prototype for HL-LHC BCM/BLM

19.8ns bunch spacing clearly visible
Rate Studies in pCVD diamond

Last year rates up to $10\text{MHz/cm}^2$ + doses to $4\times10^{15}\text{n/cm}^2$

No rate dependence observed in pCVD up to $10$-$20\text{MHz/cm}^2$
No rate dependence observed in pCVD up to $4\times10^{15}\text{n/cm}^2$
No absolute pulse height and noise calibration yet
Now extending dose to $10^{16} \text{n/cm}^2$ then $10^{17} \text{n/cm}^2$
Device Development: 3D diamond pixel detectors
3D Device in pCVD Diamond

After large radiation fluence all detectors are trap limited
  • Mean free paths $\lambda < 50\mu m$
  • Need to keep drift distances ($L$) smaller than mfp ($\lambda$)

Comparison of planar and 3D 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 150$\mu m \times 150\mu m$; columns 6$\mu m$ diameter
3D Device in pCVD Diamond

Femtosecond laser converts insulating diamond into resistive mixture of various carbon phases: amorphous carbon, DLC, nano-diamond, graphite.

- Initial methods had 90% column yield → now >99% yield with Spatial Light Modulation (SLM)
- Initial column diameters 6-10μm → now 2.6μm (with SLM)
Simultaneously readout all 3 devices

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

Two years ago the first 3D device in pCVD diamond
- Compare pCVD strip detector (500V) with 3D (60V)

Last year the first 3D pixel detectors in pCVD diamond
This year 50µm x 50µm 3D cells read out w/ ATLAS, CMS electronics
3D Device in pCVD Diamond

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

3D cell size: 150μm x 150μm
3D Device in pCVD Diamond

- Measurements consistent with TCAD simulations:
  - Large cells, large diameter columns → lower field regions in saddle points

- Cell size: 150μm x 150μm
- Voltage: 25V

Device worked well enough to construct first pCVD 3D diamond pixel device

from: G. Forcolin, Ph.D. Thesis
Manchester University 2017
First 3D pixel device in pCVD (2017) - [150μm x 100μm cells]

- Produced cells with 150μm x 100μm size for CMS pixel readout chip
- Cleaning, photolithography, metal contact to pixel and bias - RD42
- Bump and wire bonding - Princeton
Results of CMS, ATLAS 3D pCVD Pixel Devices

3D Diamond Pixel
98.5% efficiency

- applied voltage: -55V
- pixel threshold: 1500e
- efficiencies flat in time

Planar Silicon Pixel (ref)
99.3% efficiency

- lower efficiency in diamond
  most likely due to low field regions

RD42 Preliminary
threshold 1500e
hit efficiency 98.5%

RD42 Preliminary
threshold 1500e
hit efficiency 99.3%

(a) efficiency maps  (b) hit efficiencies
Produced 7200 cell pixel prototype w/50μm x 50μm pitch

- Three fabricated:
  - Oxford 2 complete
  - Manchester 1 complete
- 50μm x 50μm cells ganged for CMS (3x2) and ATLAS (1x5)
- Metallization
  - CMS complete
  - ATLAS complete
- Bump bonding
  - CMS @Princeton complete
  - ATLAS @IFAE complete
- First one (CMS) tested in Aug 2017 Test Beam @PSI
Preliminary Results (50μm x 50μm cells)

- Readout with CMS pixel readout
  6 cells (3x2) ganged together
- Preliminary efficiency >99.2%
- Collect >90% of charge!

Applied voltage ~55V
Threshold 1500e
Hit efficiency >99.2%
Results of CMS, ATLAS 3D pCVD Pixel Devices

50µm x 50µm 3D ATLAS pixels

- Readout w/FE-I4 pixel readout
- 5 cells (1x5) ganged
- Tested @ CERN Oct 2018
- Worked well, awaiting results
Device Development: HL-LHC BCM’
Device Development: HL-LHC BCM’

Present ATLAS 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

Requires new sensor geometry and appropriate electronics
Initial Sensor Design Idea

- Build some dynamic range into sensor ✓
  - pad sizes from 1mm²-32mm² work well
- Compare 300µm vs 500µm thick sensors - in progress
  - 500µm thick sensors work well
- Test wire bonding sensor to chip ✗
  - lose sensitivity of small pads - bump bond instead
- Test with existing RD42 fast electronics ✓

Prototype test with 9.2 MHz/cm² @PSI

19.8ns bunch spacing clearly visible
New Sensor Design Idea

- Build some dynamic range into sensor
  - pad sizes from 1mm\(^2\)-32mm\(^2\) work well
- Bump bond diamond to electronics to reduce capacitance
- Use TSMC 65nm technology for increased gain-bandwidth
Device Development: HL-LHC BCM'

Electronics Design Path
• First version of preamp layout and simulations
Device Development: HL-LHC BCM’

Electronics Design Path
- First version of preamp layout and simulations
- Test in H6a@CERN last week

Lumi Preamp

Abort Preamp

100μm

285μm
Electronics Design Path

- Start with RD42 fast amp used in rate studies
  - designed in 130nm technology
  - risetime 3-6ns; baseline recovery time 12-18ns
  - noise for 2pf input: 550e
- Design 2 preamps to achieve large dynamic range
  - lumi sensitivity to MIPs at 7ke
  - abort threshold for safety at 25k-7.5M MIPS/cm²
  - electronics dynamic range 100:1
  - risetime 1-2ns; return to baseline (<2%) 12ns
- Optimize gain and speed vs SNR for lumi, abort separately
  - tune parameters based on beam tests
- End with 8 channel amp (4 lumi, 4 abort) in 65nm

Chip Submitted May 21, 2018, back Aug 24, 2018, TB Oct 2018
Summary of RD42 Work

Lots of progress in diamond with HL-LHC in view

- Quantified understanding of radiation and rate effects
  - pCVD shows no rate effect up to 20MHz/cm², 4x10¹⁵n/cm² @1000V
  - Irradiate devices to 10¹⁷ this year, continue rate studies to 10¹⁶

- 3D detector prototypes made great progress
  - 3D works in pCVD diamond
  - Scale up (x70) worked; continue scale up (x10) this year
  - Smaller cells (50µm x 50µm) worked; test smaller cells (25µm)
  - Thinner columns (2.6µm) worked; try 2.0µm for 25µm x 25µm cells

- 3D diamond pixel devices being produced
  - All work as expected; just tested 50µm cells irrad@3.5x10¹⁵p/cm²
  - Visible improvements with each step
  - Efficiencies look good, still a bit to be understood

- BCM' design underway
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