Nuclear Inst. and Methods in Physics Research, A 924 (2019) 297–300

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Diamond detector technology, status and perspectives

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

[1] *Universität Bonn, Bonn, Germany*
[2] *INFN/University of Catania, Catania, Italy*
[3] *CERN, Geneva, Switzerland*
[4] *INFN/University of Florence, Florence, Italy*
[5] *GSI, Darmstadt, Germany*
[6] *Ioffe Institute, St. Petersburg, Russia*
[7] *IPHC, Strasbourg, France*
[8] *ITEP, Moscow, Russia*
[9] *Jožef Stefan Institute, Ljubljana, Slovenia*
[10] *Universität Karlsruhe, Karlsruhe, Germany*
[11] *CEA-LIST Technologies Avancees, Saclay, France*
[12] *MEPHI Institute, Moscow, Russia*
[13] *The Ohio State University, Columbus, OH, USA*
[14] *Rutgers University, Piscataway, NJ, USA*
[15] *University of Torino, Torino, Italy*
[16] *University of Toronto, Toronto, ON, Canada*
[17] *University of Bristol, Bristol, UK*
[18] *Czech Technical University, Prague, Czech Republic*
[19] *University of Colorado, Boulder, CO, USA*
[20] *Syracuse University, Syracuse, NY, USA*
[21] *University of New Mexico, Albuquerque, NM, USA*
[22] *University of Manchester, Manchester, UK*
[23] *Universität Goettingen, Goettingen, Germany*

* Corresponding author.
E-mail address: harris.kagan@cern.ch (H. Kagan).

https://doi.org/10.1016/j.nima.2018.06.009
Received 6 March 2018; Received in revised form 6 May 2018; Accepted 4 June 2018
Available online 7 June 2018

[24] ETH Zürich, Zürich, Switzerland
[25] University of Tennessee, Knoxville, TN, USA
[26] INFN-Lecce, Lecce, Italy
[27] LPSC-Grenoble, Grenoble, France
[28] INFN-Perugia, Perugia, Italy
[29] California State University, Sacramento, CA, USA

A R T I C L E I N F O

Keywords:
Chemical vapor deposition
pCVD diamond
Diamond detectors
3D diamond detectors
Radiation tolerant detectors

A B S T R A C T

Detectors based on Chemical Vapor Deposition (CVD) diamond have been used extensively and successfully in beam conditions/beam loss monitors as the innermost detectors in the highest radiation areas of Large Hadron Collider (LHC) experiments. The startup of the LHC in 2015 brought a new milestone where the first polycrystalline CVD (pCVD) diamond pixel modules were installed in an LHC experiment and successfully began operation. The RD42 collaboration at CERN is leading the effort to develop polycrystalline CVD diamond as a material for tracking detectors operating in extreme radiation environments. The status of the RD42 project with emphasis on recent beam test results is presented.

1. Introduction

The RD42 collaboration [1,2] at CERN is leading the effort to develop radiation tolerant devices based on pCVD diamond as a material for tracking detectors operating in harsh radiation environments. Diamond has properties which make it suitable for such detector applications. During the last few years the RD42 group has succeeded in producing and measuring a number of devices to address specific issues related to use at the HL-LHC [3,4]. This paper presents the status of the RD42 project with emphasis on recent beam test results. In particular, results are presented on the status of the first diamond pixel detector based on pCVD material, on the independence of signal size on incident particle rate in pCVD diamond detectors over a range of particle fluxes up to 20 MHz/cm^2 and on the 3D diamond detectors fabricated in pCVD diamond.

2. Status of the ATLAS diamond beam monitor

The startup of the LHC in 2015 brought a new milestone for diamond detector development where the first planar diamond pixel modules based on pCVD diamond were installed in an LHC experiment, the ATLAS experiment [5], and successfully began operation. The ATLAS Diamond Beam Monitor (DBM) [6,7] was designed to measure the instantaneous luminosity, the background rates and the beam spot position. A single DBM module consists of an 18 mm × 21 mm pCVD diamond 500 μm thick instrumented with a FE-I4 pixel chip [8]. The 26,880 pixels are arranged in 80 columns on 250 μm pitch and 336 rows on 50 μm pitch resulting in an active area of 16.8 mm × 20.0 mm. This fine granularity provides high precision particle tracking. The deposited charge from a particle is measured in the FE-I4 by Time-over-Threshold.

The ATLAS DBM uses diamonds with a charge collection distance (the average distance an electron–hole pair move apart under the influence of the applied electric field) of 200–220 μm at an applied bias voltage of 500 V. Three telescopes each with 3 diamond DBM modules (plus 1 telescope with silicon sensors) mounted as a three layer tracking device were installed inside the pixel detector services on each side of the ATLAS interaction point at 90 cm $< |z| <$ 111 cm, 3.2 $< |\eta| <$ 3.5 and at a radial distance from 5 cm to 7 cm from the center of the beam pipe. The modules have an inclination of 10°with respect to the ATLAS solenoid magnetic field direction to suppress erratic dark currents [9] in the diamonds. The ATLAS DBM data-acquisition system is shared with the ATLAS IBL [10]. After initial installment, data were collected in the July 2015 run. These data have been analyzed and the first results of the ATLAS DBM tracking capabilities are shown in Fig. 1. A clear separation between background particles from unpaired bunches (open circles) and collision particles from colliding bunches (filled circles) is observed. After two electrical incidents in 2015 with consequent loss of several silicon and diamond modules, the DBM has now been re-commissioned and is again in the operation phase.

3. Rate studies in pCVD diamond

In order to study the dependence of signal size on incident particle rate, RD42 performed a series of beam tests in the πM1 beam line of the High Intensity Proton Accelerator (HIPA) at Paul Scherrer Institute (PSI) [11]. This beam line is able to deliver 260 MeV/c π^+ fluxes from a rate of ∼5 kHz/cm^2 to a rate ∼20 MHz/cm^2 in bunches spaced 19.8 ns apart.

Sensors using pCVD material [12] were tested in a tracking telescope [13] based on 100 μm × 150 μm silicon pixel sensors read out by the PSI46v2 pixel chip [14]. The diamond signals were amplified with custom-built front-end electronics with a peaking time of ∼6 ns, return-to-baseline in ∼16 ns and 550e noise with 2 pf input capacitance. The amplified signals were recorded with a DRS4 evaluation board [15] operating at 2 GS/s. The entire system was triggered with a scintillator which determined the timing of the beam particles with a precision of ∼0.7 ns.

A series of cuts were applied to the data including: removing 60 s of triggers at the beginning of each run, removing triggers from heavily ionizing particles with saturated waveforms (mostly protons), removing calibration triggers, removing triggers in the wrong beam bucket, removing triggers with no tracks in the telescope and removing triggers with large angle tracks in the telescope. After applying this procedure all telescope tracks which project into the diamond fiducial region have a pulse height well separated from the pedestal distribution in the diamond i.e. the diamond is 100% efficient at all rates. The same procedure was applied to all particle flux points and the resulting mean pulse height (in arbitrary units) versus rate is shown in Fig. 2 for both positive and negative bias voltage. The uncertainty on the data points in the plot include both statistical and systematic sources. The systematic uncertainty was determined by assuming any deviations in pulse height for rates below 80 kHz/cm^2 were due to systematic effects. Thus the spread in the data points at a given rate indicates the reproducibility of the data. Fig. 2 indicates the mean pulse height in pCVD diamond detectors irradiated up to 5×10^{14} n/cm^2 does not depend strongly on rate up to rates of 20 MHz/cm^2.

4. 3D diamond pixel detectors

3D sensors with electrodes in the bulk of the sensor material were first proposed in 1997 [16] in order to reduce the drift distance of the