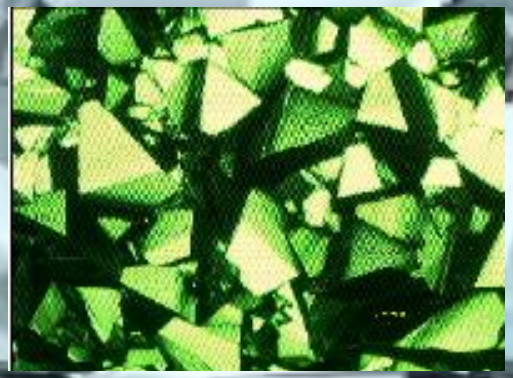
Diamond Sensors



Marko Mikuž
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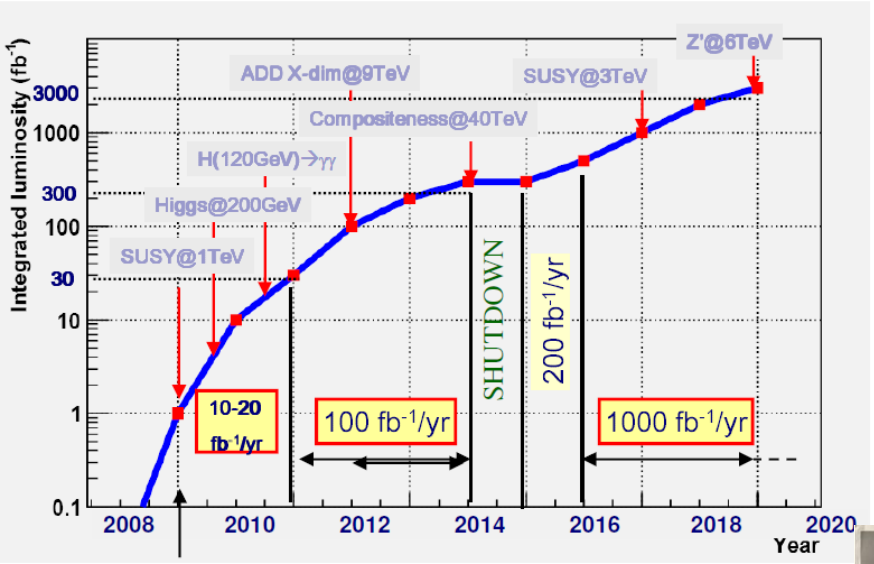
Vertex2010
Loch Lomond, Scotland, UK
June 6-11, 2010

Outline

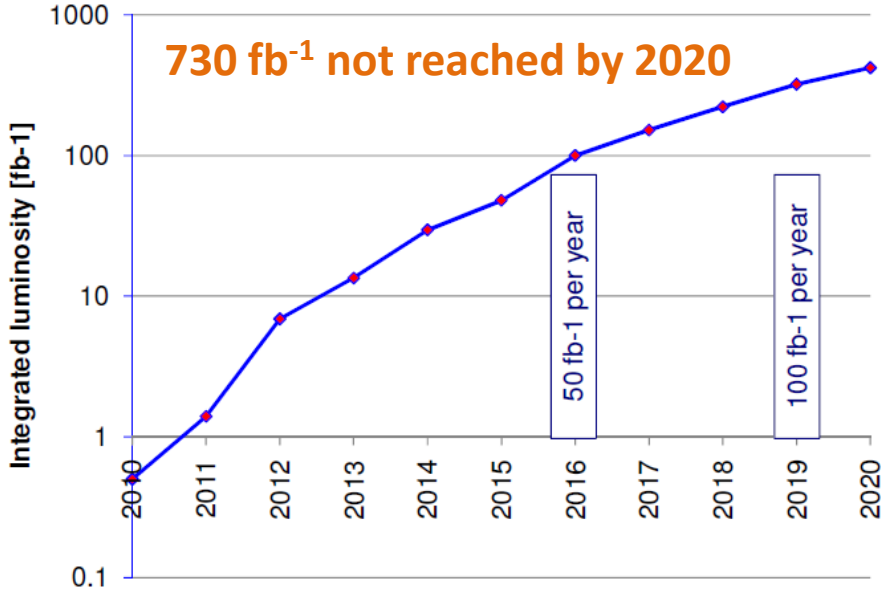
- From LHC to SLHC – the 10^{16} ballpark
- Diamond as sensor material
- Radiation hardness: RD-42
- Diamond sensor applications (focus on ATLAS)
  - ATLAS BCM/BLM
  - Pixel modules
  - ATLAS dPIX project
- Diamond sensor vendors

From LHC to SLHC

- Chamonix 2010 brought (cruel) reality into LHC luminosity forecast



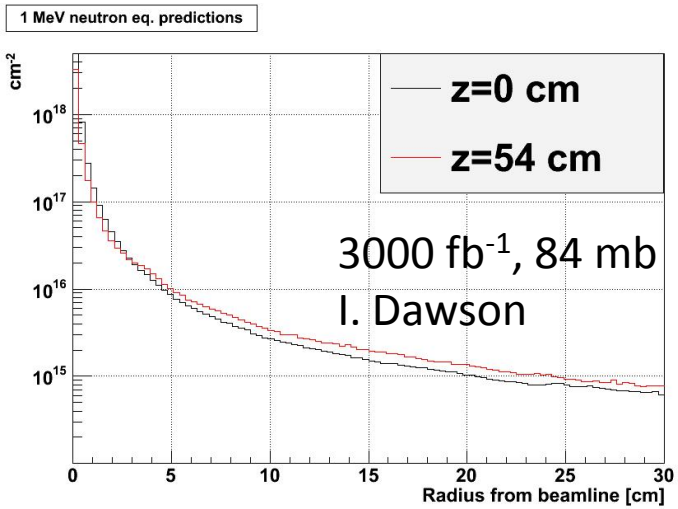
"Standard" LHC/sLHC scenario (not-so-far-pre-Chamonix)

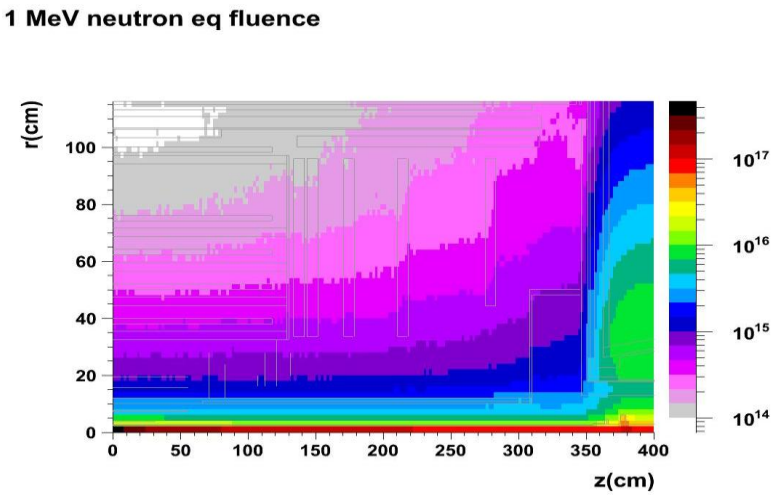


M. Lamont: Chamonix 2010

SLHC sensor requirements

- Small radii: 3-5 cm
- Main constraint: radiation damage after 6000 fb^{-1} (by 2030)
  - Ballpark fluence 10^{16} n_{eq}/cm^2
  - Could be a factor 2-3 more, depending on exact radius (~$1/r^2$), flat along z
  - Predominantly pions (>90 %)
  - Broad energy spectrum peaked at O(100 MeV)





10^{16} n_{eq}/cm^2 fluence ballpark

- Order of magnitude higher than LHC sensors designed for 730 fb^{-1} with ballpark fluence 10^{15}
  - Remember, sensors believed to be fit for LHC only following a decade-long R&D campaign
  - Pixel B-layer planned to be replaced at ½ fluence

- Despite slow LHC ramp up, time is in short supply
  - ATLAS plans for IBL sensor choice early next year
  - 5x 10^{15} n_{eq}/cm^2 benchmark !

Sensors contending 10^{16}

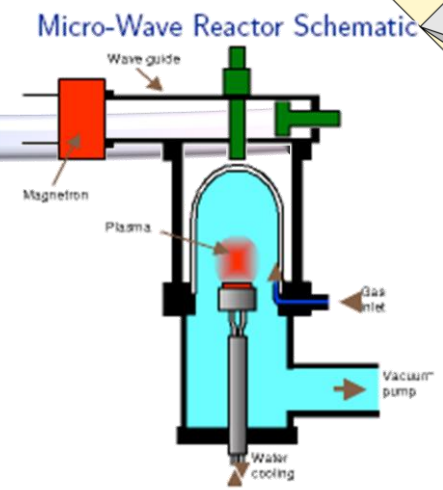
- Planar silicon
  - Exploiting charge multiplication
- 3-D silicon
  - Novel silicon processing
- Diamond
  - New material

- All three options rely on technology / mode of operation not utilized in HEP so far
  - Obviously, there is no free lunch

Diamond as sensor material

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	
Breakdown field [V/cm]	10^7	3×10^5	
Intrinsic resistivity @ R.T. [Ω cm]	> 10^{11}	2.3×10^5	☺ Low leakage
Intrinsic carrier density [cm^{-3}]	< 10^3	1.5×10^{10}	
Electron mobility [cm^2/Vs]	1900	1350	☺ Fast signal
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	1.3(e)-1.7(h)x 107	1.1(e)-0.8(h)x 10^7	
Density [g/cm^3]	3.52	2.33	
Atomic number - Z	6	14	
Dielectric constant - ε	5.7	11.9	☺ Low capacitance
Displacement energy [eV/atom]	43	13-20	☺ Radiation hard
Thermal conductivity [W/m.K]	~2000	150	☺ Heat spreader
Energy to create e-h pair [eV]	13	3.61	
Radiation length [cm]	12.2	9.36	
Spec. Ionization Loss [MeV/cm]	6.07	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	☹ Low signal
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323	

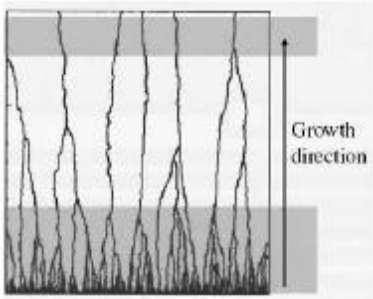
Sensor types - pCVD

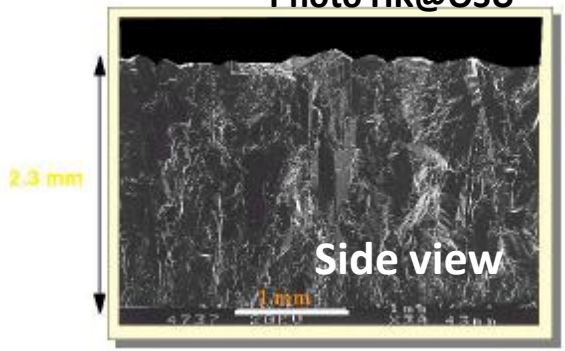


- Polycrystalline Chemical Vapour Deposition (pCVD)
  - Grown in µ-wave reactors on non-diamond substrate
  - Exist in Φ = 12 cm wafers, >2 mm thick
  - Small grains merging with growth
  - Grind off substrate side to improve quality
    → ~500-700 µm thick detectors
  - Base-line diamond material for pixel sensor

Photo HK@OSU

Test dots on 1 cm grid

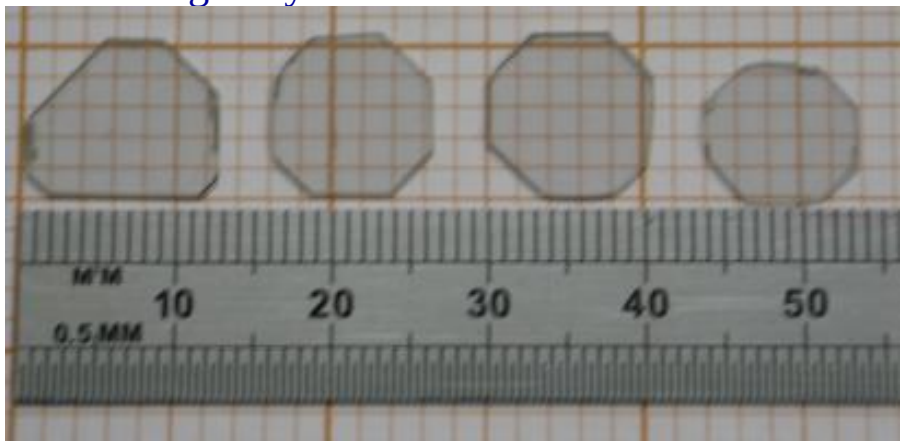




Photograph courtesy of E6

Sensor types - scCVD

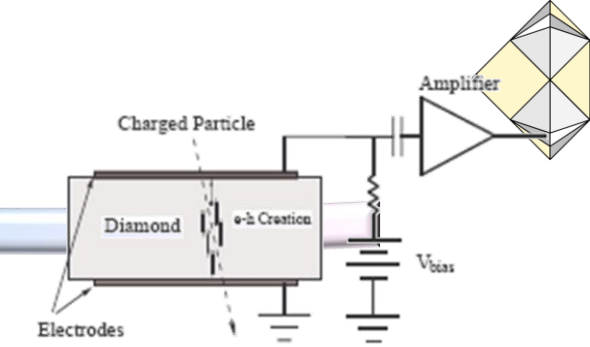
- Single Crystal Chemical Vapour Deposition (scCVD)
  - Grown on HTHP diamond substrate
  - Exist in ~ 1 cm^2 pieces, max 1.4 cm x 1.4 cm, thickness > 1 mm
  - A true single crystal



☺ Fall-forward for sLHC pixel upgrade (single chips, wafers ?)
- Needs significant improvement in size & price
- After heavy irradiations properties similar to pCVD, headroom ~$3x10^{15}$ p/cm^2

☹ Recent developments in adverse direction
- Concentrate on max. ~5x5 mm^2 pieces & packaging, main target market: dosimetry

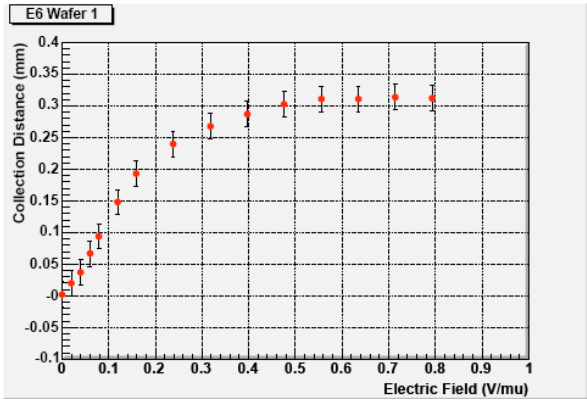
Signal from CVD diamonds



- No processing: put electrodes on, apply electric field
- Trapping on grain boundaries and in bulk
  - much like in heavily irradiated silicon
- Parameterized with Charge Collection Distance, defined by

$$CCD = \frac{< Q_{col} >}{36 \frac{e_0}{\mu m}}$$

☝ **mean** not **most probable**



CCD measured on 1.4 mm thick pCVD wafer from E6

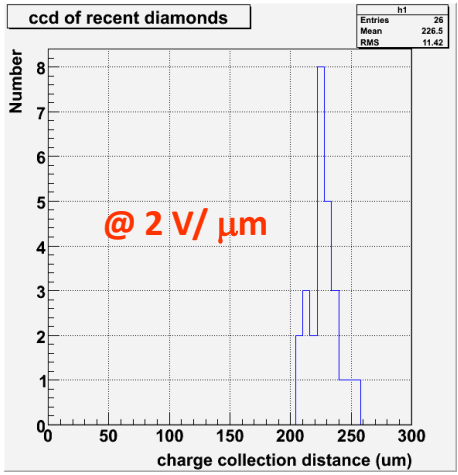
- CCD = average distance e-h pairs move apart
- Coincides with mean free path in infinite ($t \gg CCD$) detector

$$Q_{col} = Q_{created} \frac{d}{t}$$

$$d = d_e + d_h - \text{distance e-h move apart}$$

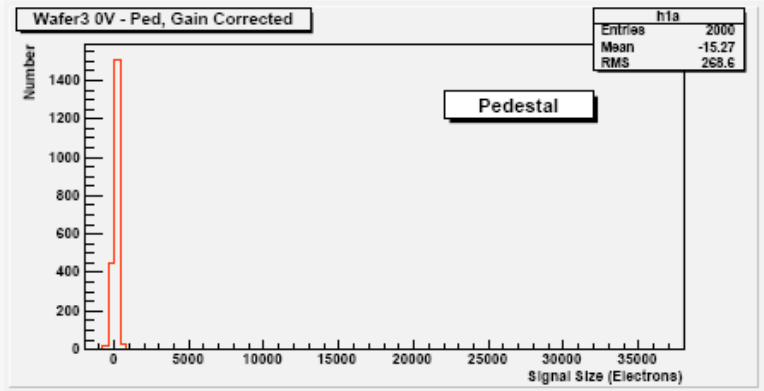
$$t - \text{detector thickness}$$

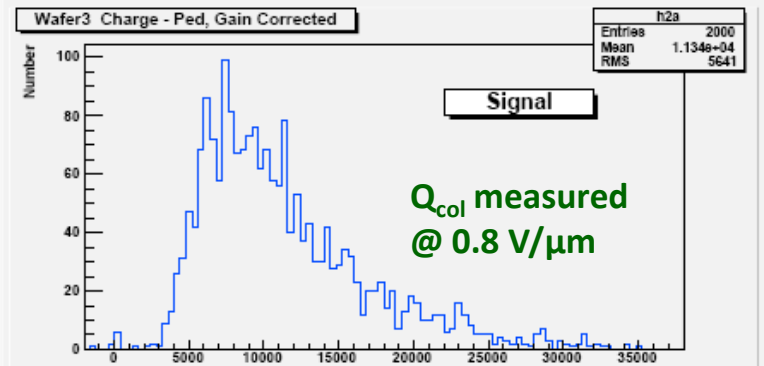
CCD of BCM 0.5 mm thick pCVD detectors

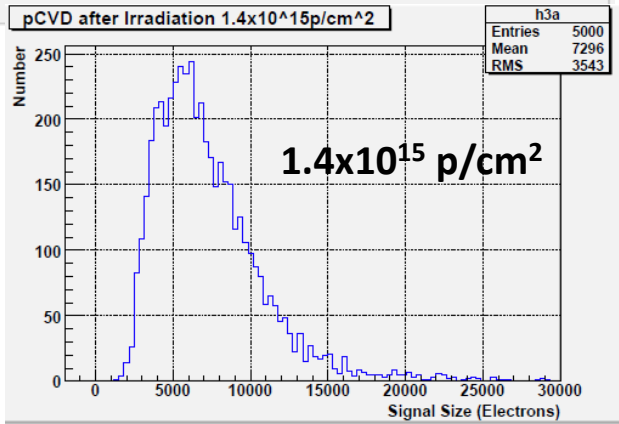


Charge collected in pCVD diamonds

- Electrodes stripped off and reapplied at will
  - Test dot → strip → pixel on same diamond
  - Charge collection usually done with strip detectors and VA chips in SPS high-energy pion test beam
- Non-irradiated detectors
  - ✓ MIP spectrum well separated from pedestal
    - ➢ $\langle Q_{col} \rangle$ = 11300 e
    - ➢ $\langle Q_{MP} \rangle$ ~ 9000 e
    - ➢ 99% of events above 4000 e
  - ➢ FWHM/MP ~ 1 (~ 0.5 for Si)
    - Consequence of large non-homogeneity of pCVD material
- Irradiated detectors
  - ➢ FWHM/MP < 1
    - Trapping in bulk starts to dominate
    - Radiation homogenizes pCVD material

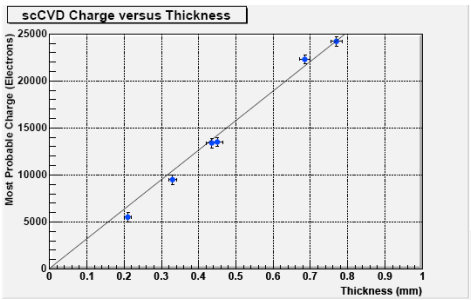


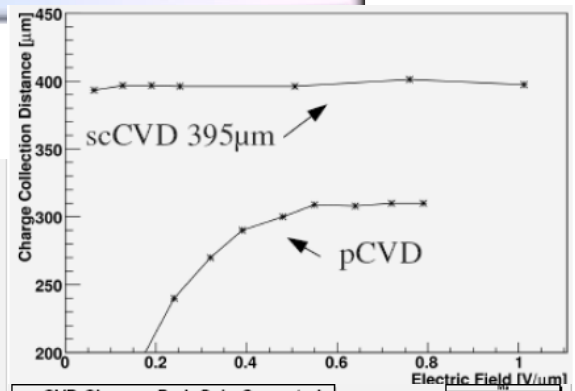


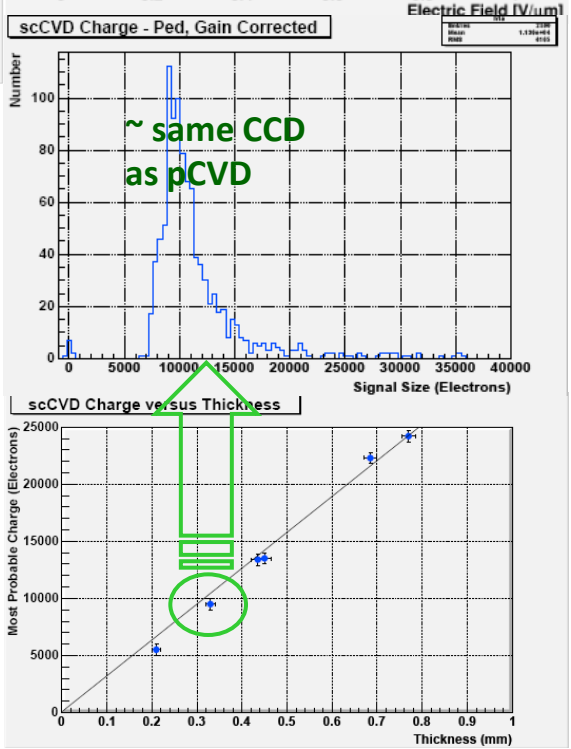


Charge collected in scCVD diamonds

- CCD = thickness at E > 0.1 V/µm
  - Collect all created charge
  - "CCD" hardly makes sense
- ➢ FWHM/MP ~ 1/3
  - scCVD material homogenous
  - Can measure diamond bulk properties with TCT

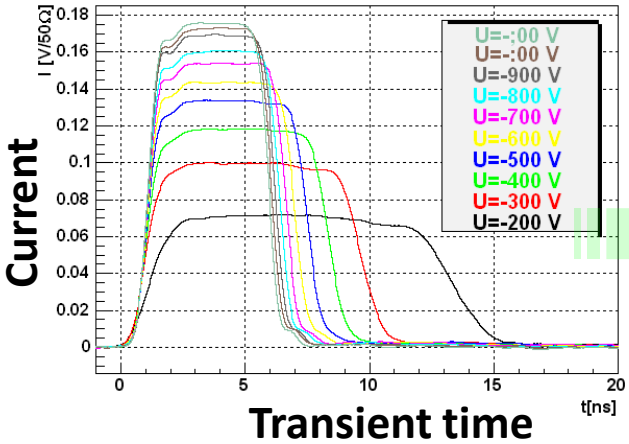


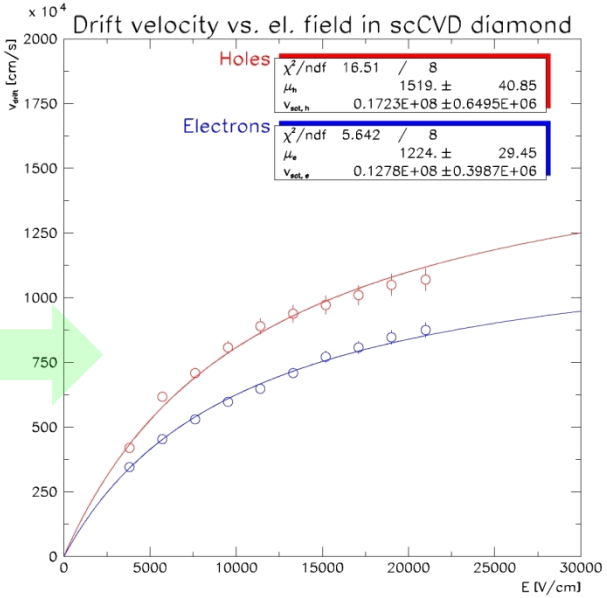




scCVD measured in Ljubljana

e-injection with α-particles





Radiation damage in diamond

Radiation induced effect	Diamond	Operational consequence	Silicon	Operational consequence
Leakage current	small & decreases	none	$I/V = \alpha\Phi$ $\alpha \sim 4\times10^{-17}$ A/cm	Heating Thermal runaway
Space charge	~ none	none	$\Delta N_{eff} \approx -\beta\Phi$ $\beta \sim 0.15$ cm^{-1}	Increase of full depletion voltage
Charge trapping	Yes	Charge loss Polarization	$1/\tau_{eff} = \beta\Phi$ $\beta \sim 4\text{-}7\times10^{-16}$ cm^2/ns	Charge loss Polarization

Charge multiplication

- At extreme fluences charge trapping the paramount radiation damage effect
- Difference O(10) in x-section between charged/neutral traps
  - Filled (neutral) traps trap less (of the opposite carrier)
  - Basics of "pumping"
- E_{gap} in diamond 5 times larger than in Si
  - Many processes freeze out
  - Typical emission times order of months
- Works also in Si at 300/5 = 60 K – "Lazarus effect"

$$\frac{1}{\tau_{eff}} = \sum_t N_t (1 - P_t) \sigma_t v_{th}$$

Radiation damage studies: RD-42

RD42 Collaboration 2010

M. Artuso[25], D. Asner[22], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], S. Blusk[25], A. Borgia[25], J-M. Brom[10], M. Bruzzi[5], D. Chren[23], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[24], R. D'Alessandro[6], W. de Boer[13], D. Dobos[3], I. Dolenc[12], W. Dulinski[10], J. Duris[20], V. Eremin[9], R. Eusebi[7], H. Frais-Kolbl[4], A. Furgeri[13], K.K. Gan[16], M. Goffe[10], J. Goldstein[21], A. Golubev[11], A. Gorisek[12], E. Griesmayer[4], E. Grigoriev[11], D. Hits[17], M. Hoeferkamp[26], F. Huegging[1], H. Kagan[16,♦], R. Kass[16], G. Kramberger[12], S. Kuleshov[11], S. Kwan[7], S. Lagomarsino[6], A. La Rosa[3], A. Lo Giudice[18], I. Mandic[12], C. Manfredotti[18], C. Manfredotti[18], A. Martemyanov[11], D. Menichelli[5], M. Mikuz[12], M. Mishina[7], J. Moss[16], R. Mountain[25], S. Mueller[13], G. Oakham[22], A. Oh[27], P. Olivero[18], G. Parrini[6], H. Pernegger[3], M. Pomorski[14], R. Potenza[2], K. Randrianarivony[22], A. Robichaud[22], S. Roe[3], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], S. Seidel[26], S. Smith[16], B. Sopko[23], K. Stenson[24], R. Stone[17], C. Sutera[2], M. Traeger[8], D. Tromson[14], W. Trischuk[19], J-W. Tsung[1], C. Tuve[2], P. Urquijo[25], J. Velthuis[21], E. Vittone[18], S. Wagner[24], J. Wang[25], R. Wallny[20], P. Weilhammer[3,♦], N. Wermes[1]

♦Spokespersons

87 Participants

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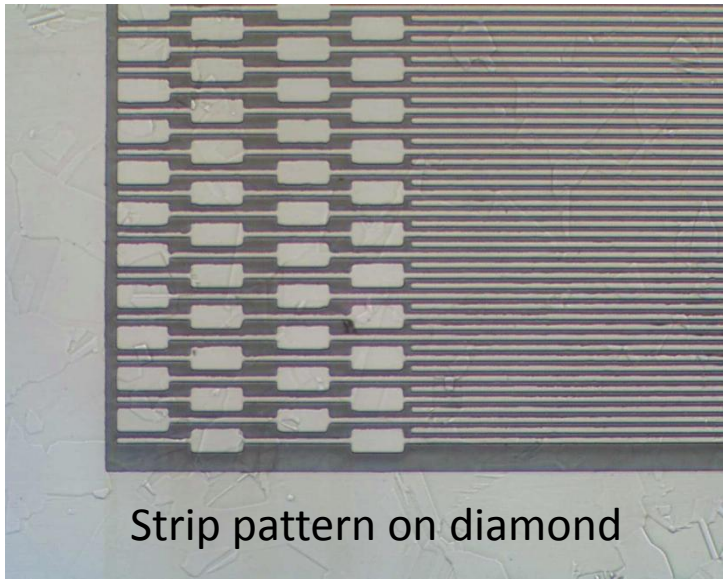
27 University of Manchester, Manchester, UK

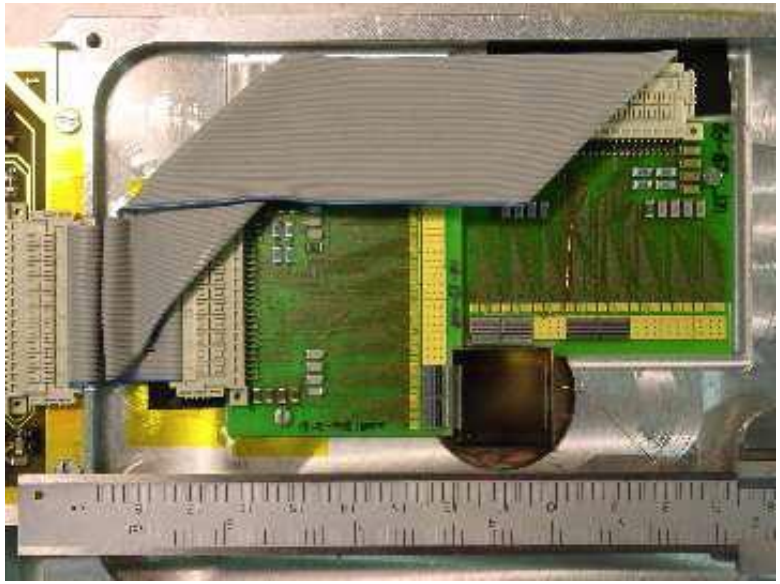
27 Institutes

Test beam studies

- Preferred way of radiation damage assessment
  - Test beam before and after irradiation
  - Using strip detectors of 50 μm pitch, read out by VA2 electronics in a tracking telescope
- Reliable & reproducible results on pulse spectrum, efficiency and position resolution



Strip pattern on diamond



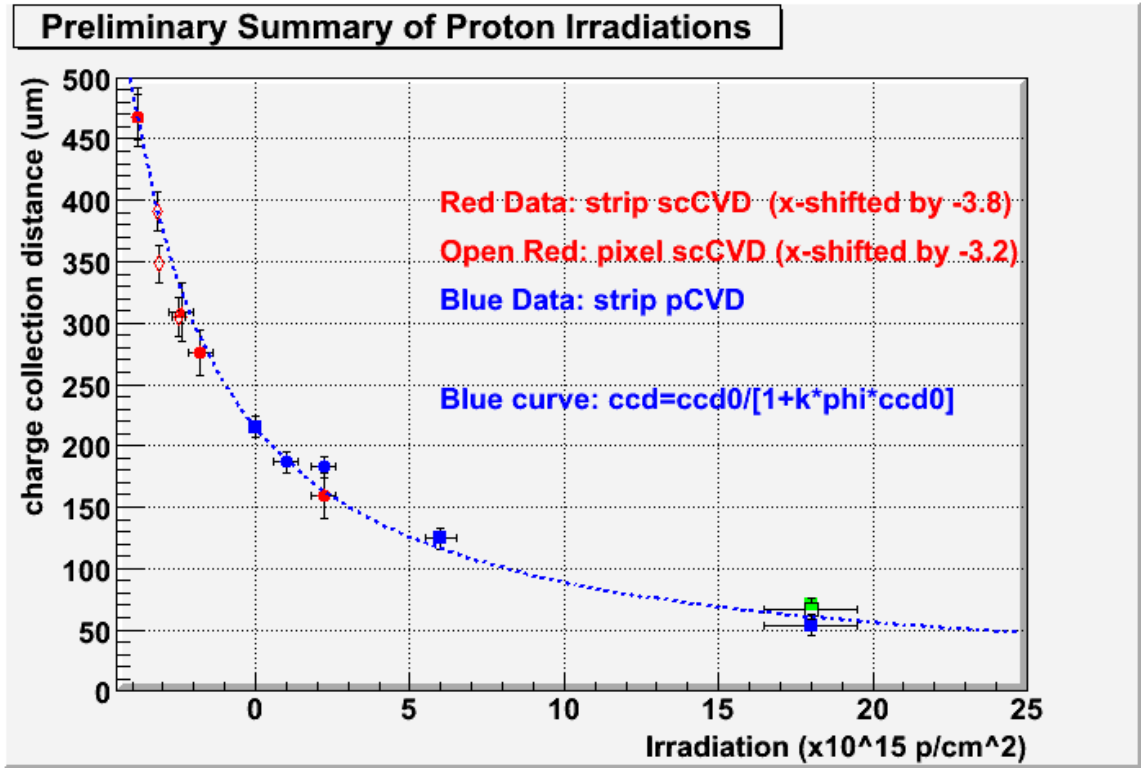
Test beam assembly

PS protons

- For mean free path in infinite detector expect

$$\frac{1}{CCD} = \frac{1}{CCD_0} + k \times \Phi$$

- With CCD_0 initial trapping on grain boundaries, k a damage constant
  - Larger CCD_0 **performs better (larger collected charge) at any fluence**
  - Can turn 1/ CCD_0 into effective "initial" fluence, expect $CCD_0 \sim \infty$ for SC
  - **pCVD and scCVD diamond follow the same damage curve**
  - $k \sim 0.7 \times 10^{-18}\ \mu m^{-1} cm^{-2}$

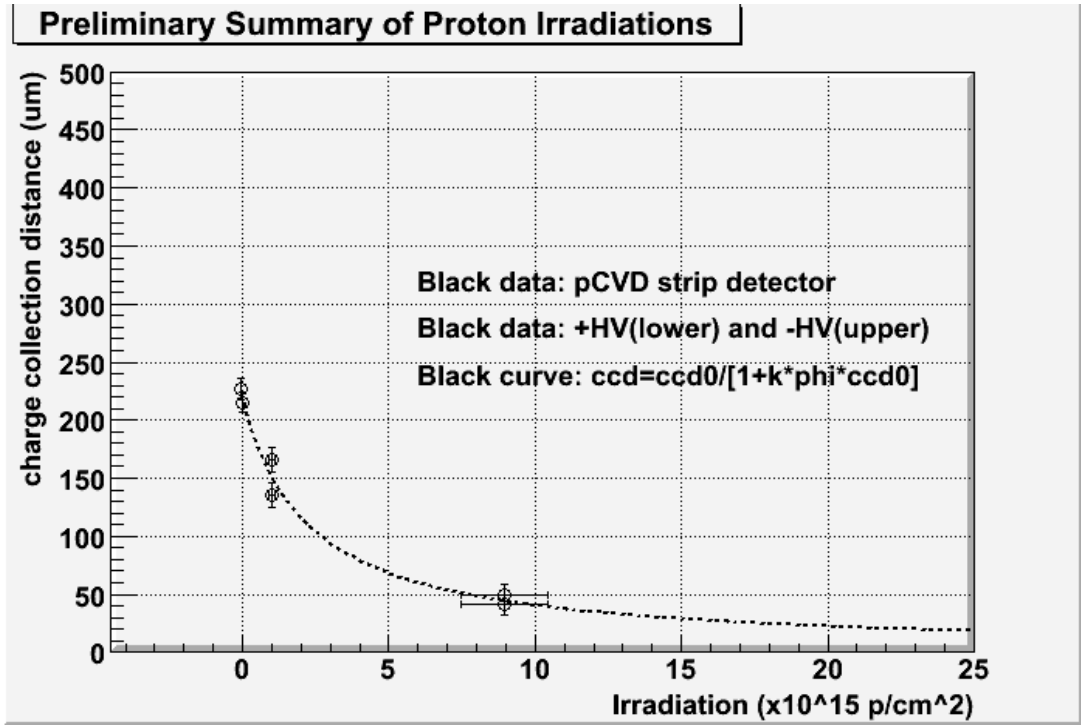


Test beam results

70 MeV protons (Sendai)

- Recent irradiations with 70 MeV protons at Cyric Facility in Sendai, Japan
- 3x more damaging than PS protons

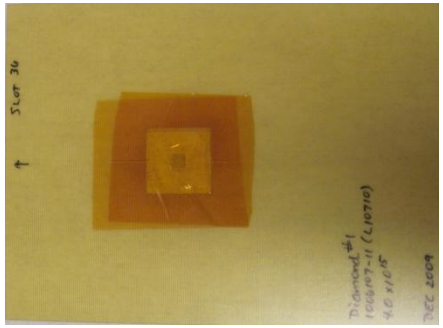
  $k \sim 2\times10^{-18}\ \mu m^{-1} cm^{-2}$
- NIEL prediction
  - factor of 6
  - NIEL violation ?!



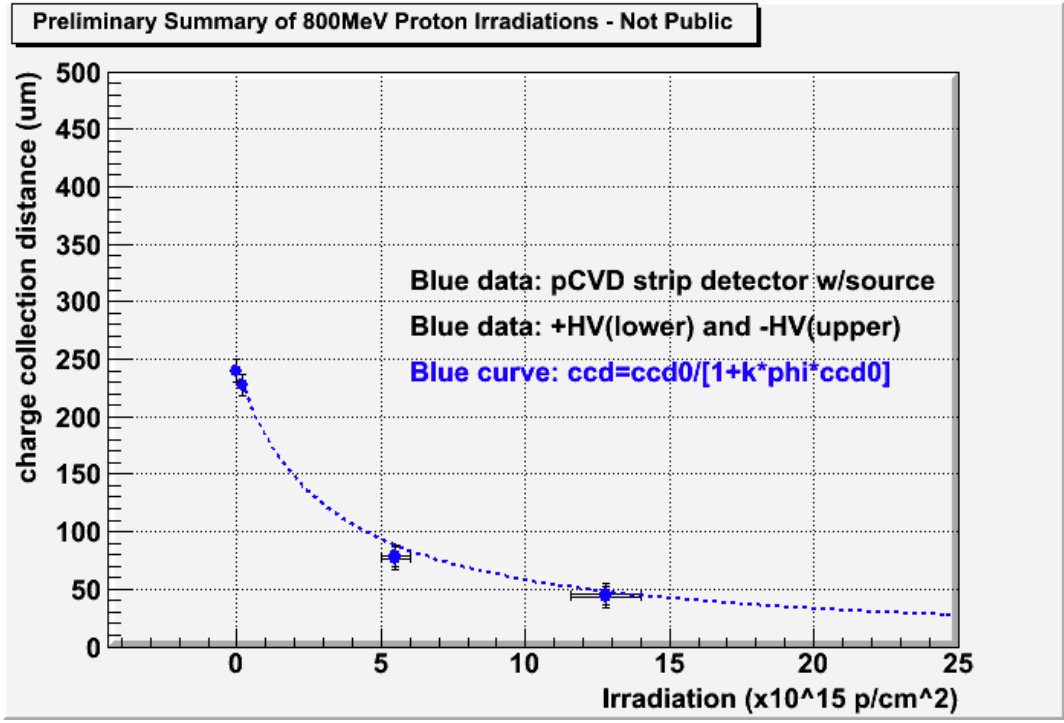
Test beam results

800 MeV protons (LANL)

- 800 MeV protons in LANL, December 09



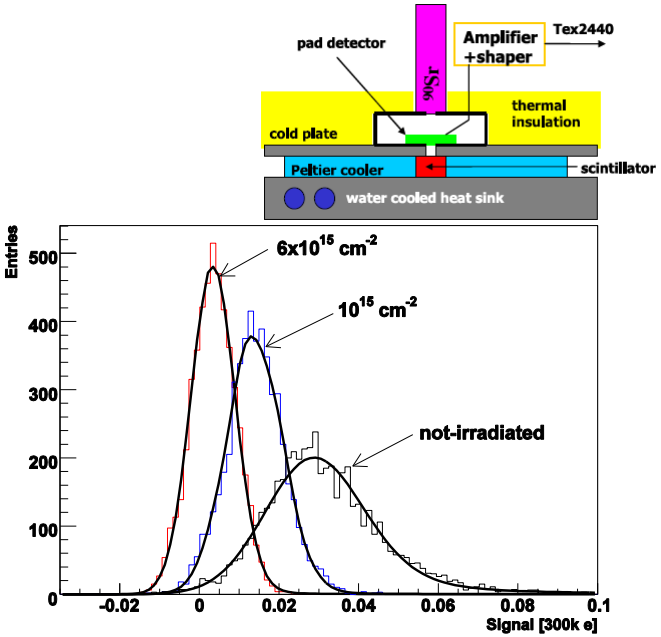
- Appear approximately 2x more damaging than PS protons
- Source results only, test beam ongoing now

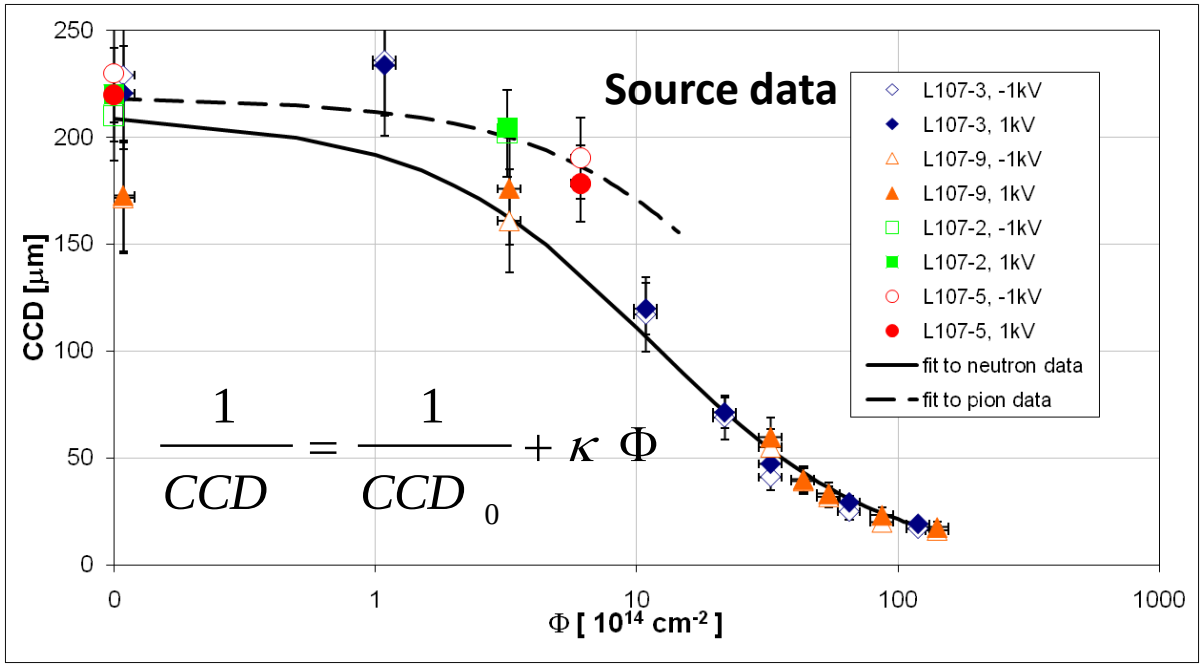


Source results – test beam in progress

More (recent) irradiations

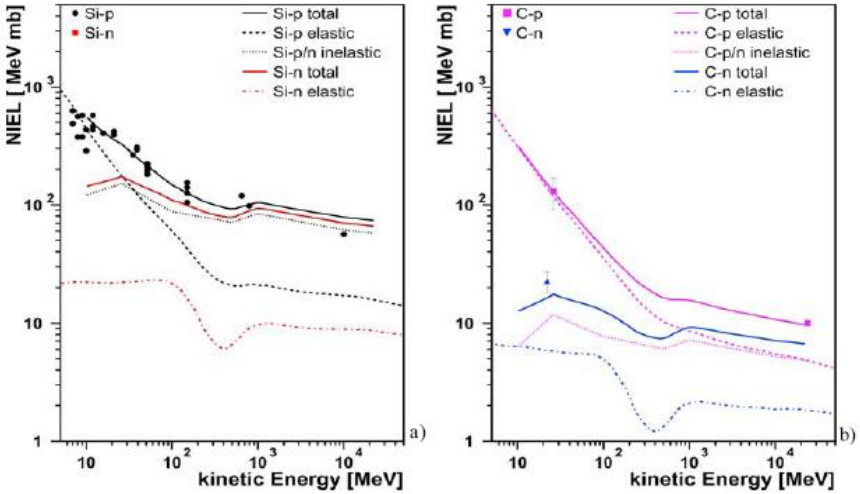
- pCVD (2) with reactor neutrons up to 1.3×10^{16} n_{eq}/cm^2 (in 6 steps)
  - k ~ $3\text{-}5\times10^{-18}$ $\mu m^{-1}cm^{-2}$
  - Discrepancy between source and test-beam data
  - Source overestimates damage
- pCVD with PSI 200 MeV pions up to 6×10^{14} π/cm^2
  - k consistent with ~$1\text{-}3\times10^{-18}$ $\mu m^{-1}cm^{-2}$





NIEL/DPA calculations

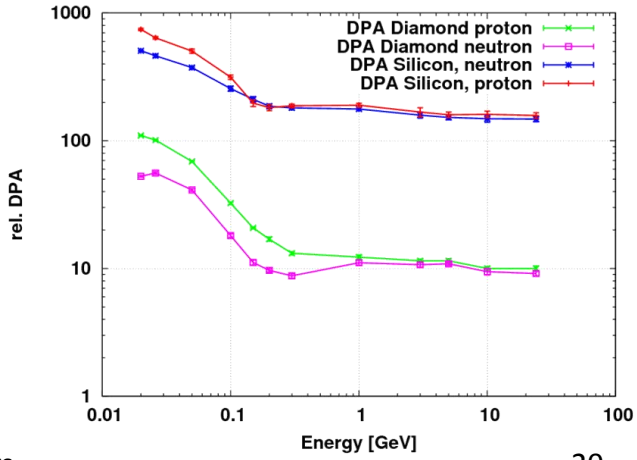
- NIEL calculations published by KIT group in Phys. Stat. Sol.
  - Protons
    - Ratio 800 MeV / 24 GeV: ~ 2 ✓
    - Ratio 70 MeV / 24 GeV: ~ 6 !!
  - Neutrons
    - 10 MeV n ~ 24 GeV p !!



W. de Boer et al.
phys. stat. sol. (a) 204, No. 9 (2007)3009

- Recent calculation by S. Mueller based on displacement per atom (DPA) value given by FLUKA (development version, preliminary)
  - Proton ratios: 1.2; 5 (800; 70 MeV)
  - p(24 GeV)/n(10 MeV) ratio: 6 ✓

Steffen Mueller - preliminary
RD-42 meeting, April 2010



NIEL/DPA vs. measurement

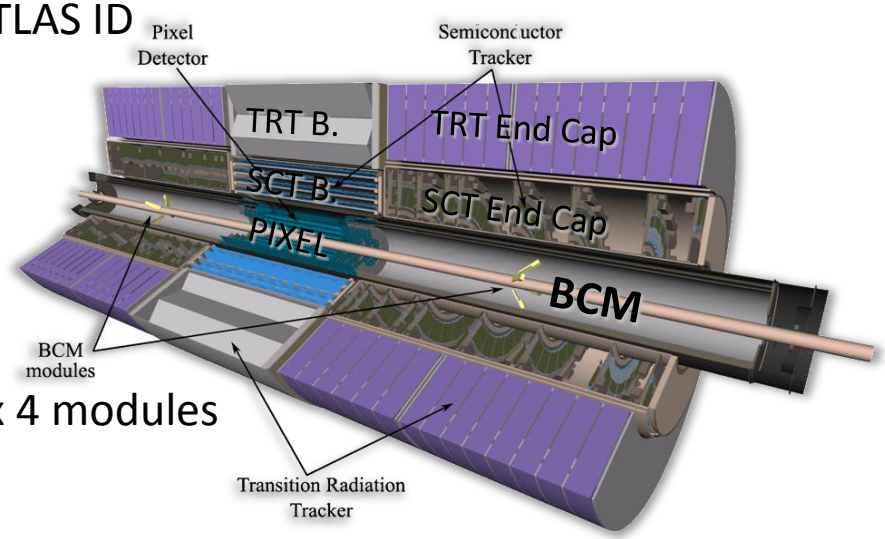
- Some resemblance of NIEL/DPA results to measurements
  - Don't expect miracles, NIEL scaling is broken in Si trapping, too !
- For sLHC, and especially IBL
  - No time left to disentangle discrepancies, no headroom
- ➢ Need pions in the *n x 100* MeV energy ballpark
  - Applied for beam at PSI (with RD-50)
    - Use scCVD to maximize damage effect
    - Campaign starts August 15
  - Negotiate very simple pion line at LANL
    - If approved, could reach sLHC fluences
    - Quick evaluation with strip detectors in 800 MeV proton beam

Diamond sensor applications

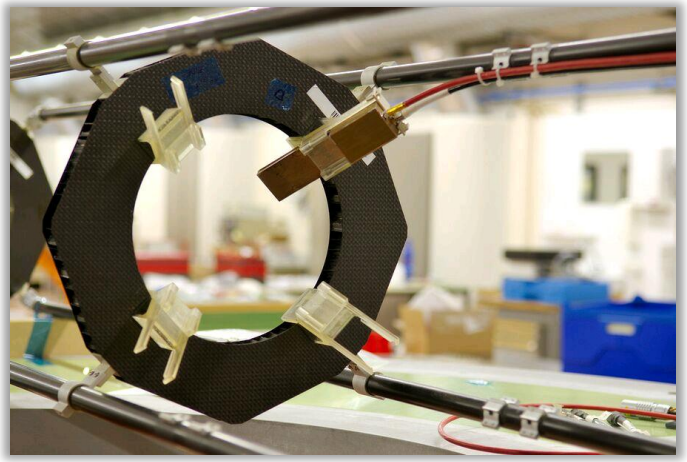
- All LHC exp's use diamonds for beam monitoring & accident protection
  - Current and counting mode operation, TOF capability
  - *O*(100) diamond sensors employed
- CMS is building Pixel Luminosity Telescope
  - 48 scCVD pixel modules (5 mm x 5 mm)
- Upgrade plans include diamond as candidate for innermost pixel tracker layer(s)
- Elaborate on two projects
  - ATLAS BCM
  - ATLAS DPix

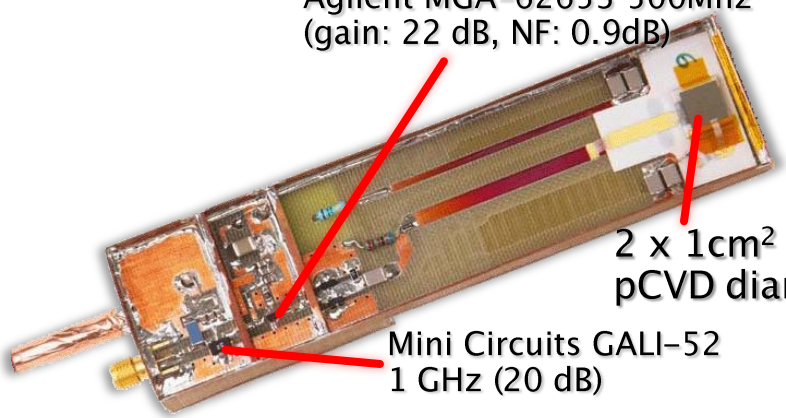
ATLAS BCM

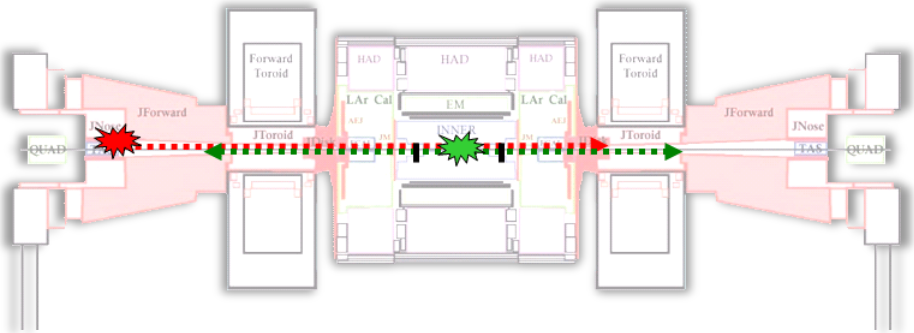
ATLAS ID



2 x 4 modules

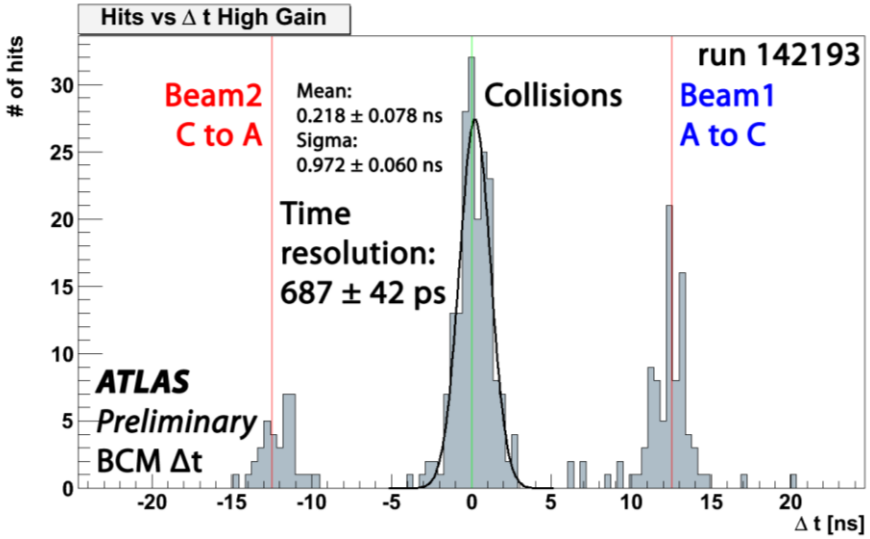




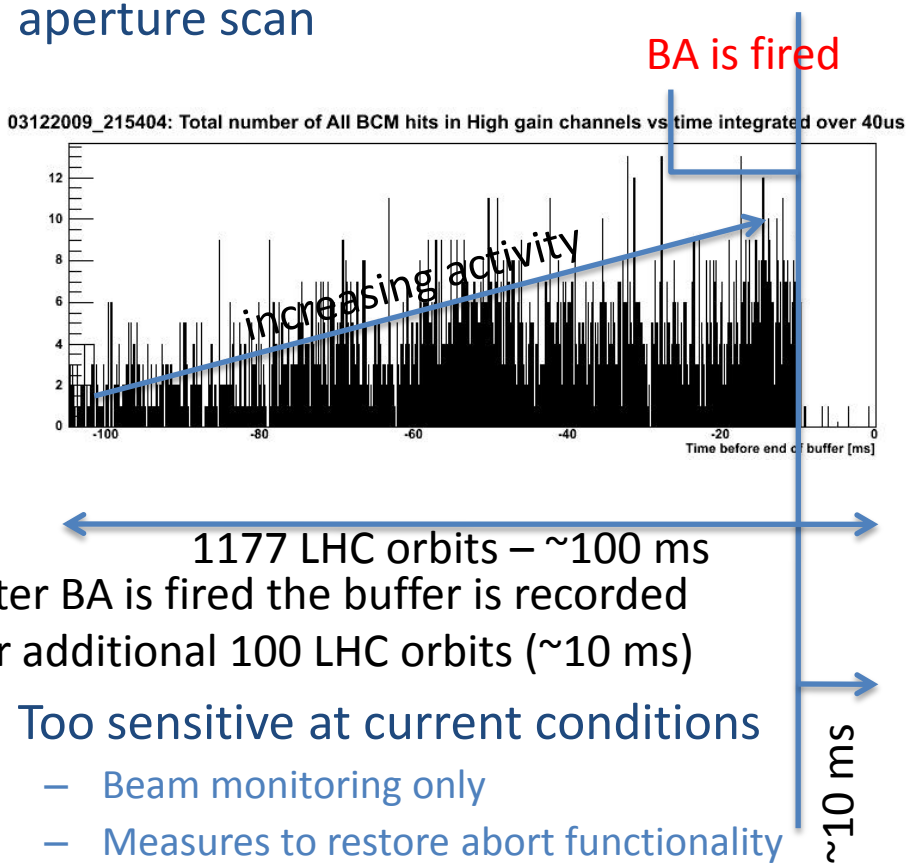


BCM performance

- Time difference hit on A side to hit on C side
- Most of data reconstructed offline
- Sub ns resolution of BCM clearly visible (0.69 ns) without offline timing corrections applied



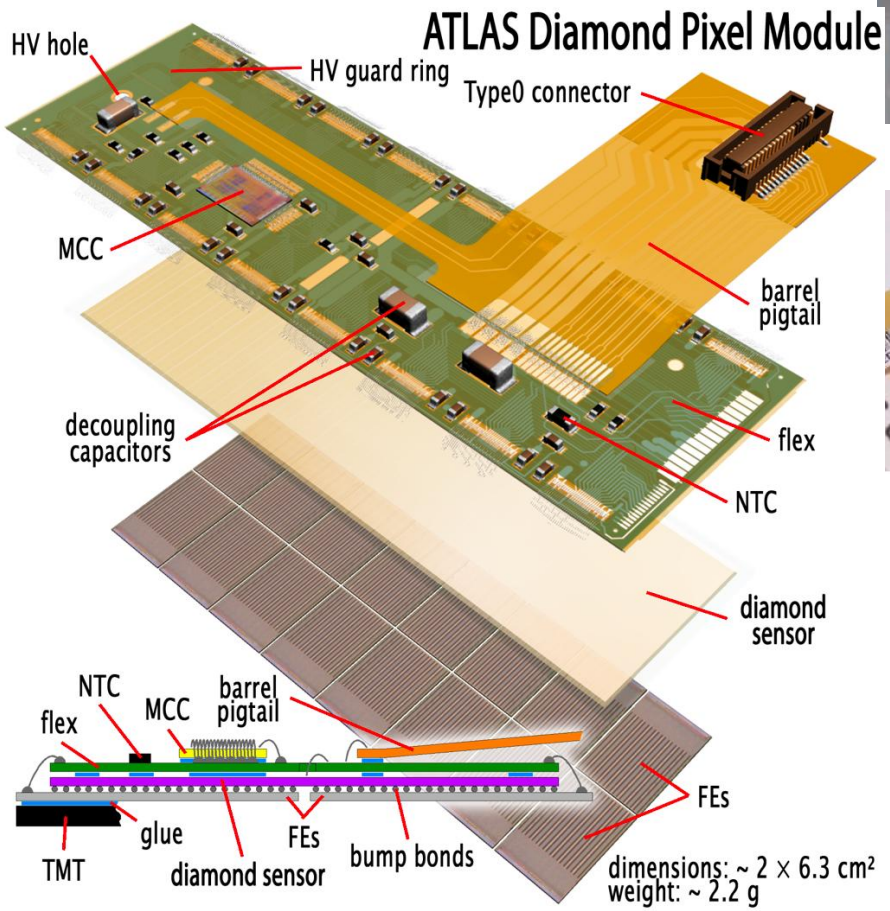
- Beam dump fired by BCM during LHC aperture scan

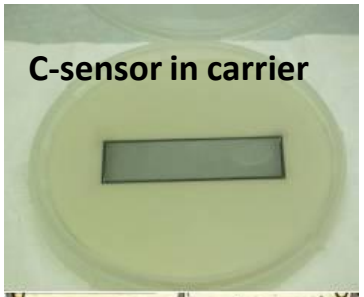


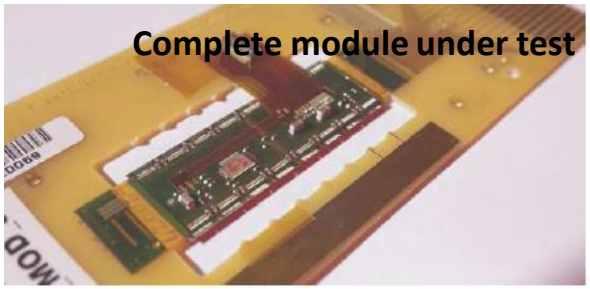
- Too sensitive at current conditions
  - Beam monitoring only
  - Measures to restore abort functionality

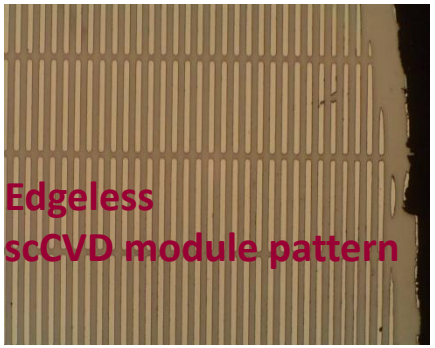
Diamond pixel modules

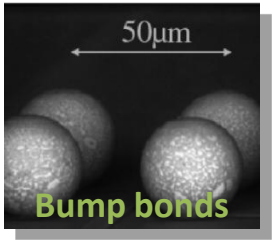
- Full modules built with I3 pixel chips @ OSU, IZM and Bonn









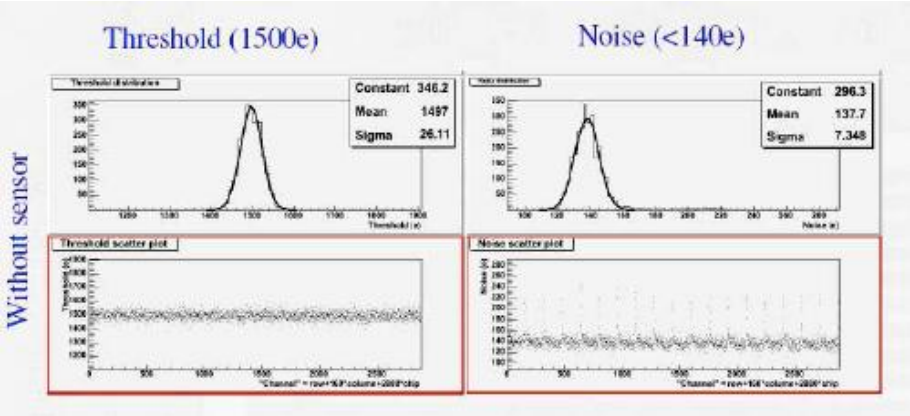


Diamond pCVD Pixel Module – Results

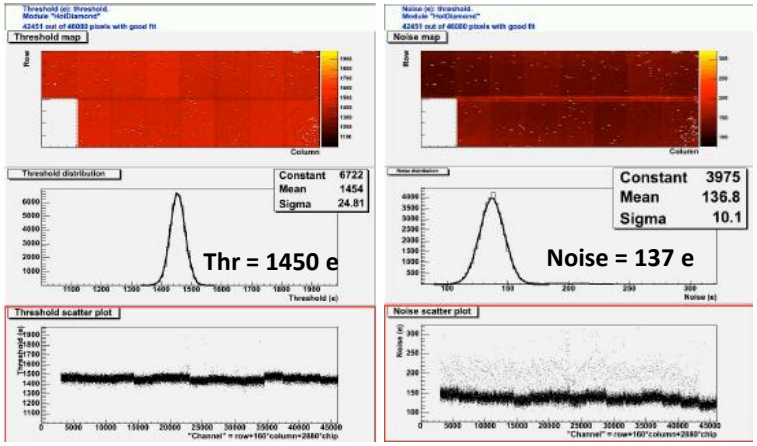
- pCVD full module
  - Tests show no change of threshold and noise from bare chip to module
    - **A consequence of low sensor *C & I***
    - **Noise 137 e**
    - **Threshold: mean 1450 e, spread 25 e**
    - **overdrive 800 e**
  - reproduced in test beams

Many properties (e.g. resolution, time-walk) scale with S/N and S/T !

Bare chip



Full module



Diamond tracker upgrade proposal

DPix Collaboration

- Bonn
- Carleton
- CERN
- Ljubljana
- Ohio State
- Toronto

- Approved by ATLAS EB Mar'08
  - EDMS: ATU-RD-MN-0012

ATLAS project

Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade

ATLAS Upgrade Document No:	Institute Document No.	Created: 15/05/2007	Page: 1 of 14
		Modified: 21/12/2007	Rev. No.: 1.8

Abstract

The goal of this proposal is to construct diamond pixel modules as an option for the ATLAS pixel detector upgrade. This proposal is made possible by progress in three areas: the recent reproducible production of high quality polycrystalline Chemical Vapour Deposition diamond material in wafers, the successful completion and test of the first diamond ATLAS pixel module, and the operation of a diamond after irradiation to 1.8×10^{16} p/cm^2. In this proposal we outline the results in these three areas and propose a plan to build 5 to 10 ATLAS diamond pixel modules, characterize their properties, test their radiation hardness, explore the cooling advantages made available by the high thermal conductivity of diamond and demonstrate industrial viability of bump-bonding of diamond pixel modules. Based on availability and size polycrystalline Chemical Vapour Deposition diamond has been chosen as the baseline solution. The use of single crystal Chemical Vapour Deposition diamond is reserved as a future option if the manufacturers can attain sizes in the range 16mm x 16mm.

Contact Person: Marko Mikuž (marko.mikuz@cern.ch)

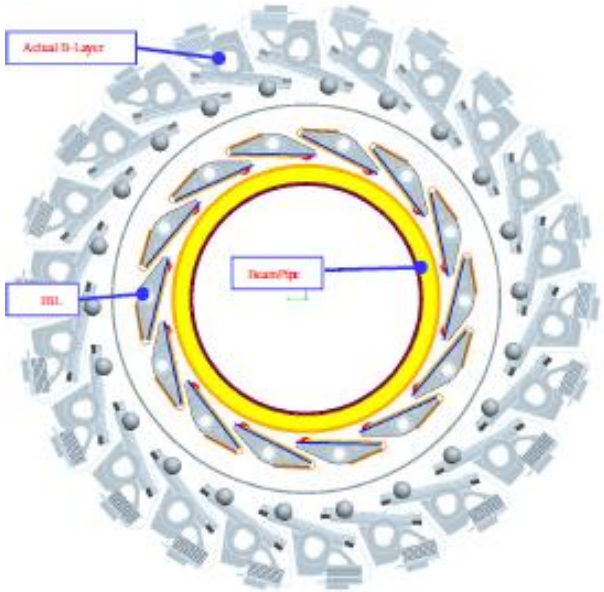
Prepared by:	Checked by:	Approved by:
H. Kagan (Ohio State University) M. Mikuž (Jožef Stefan Institute, Ljubljana) W. Trischuk (University of Toronto)		

Distribution List

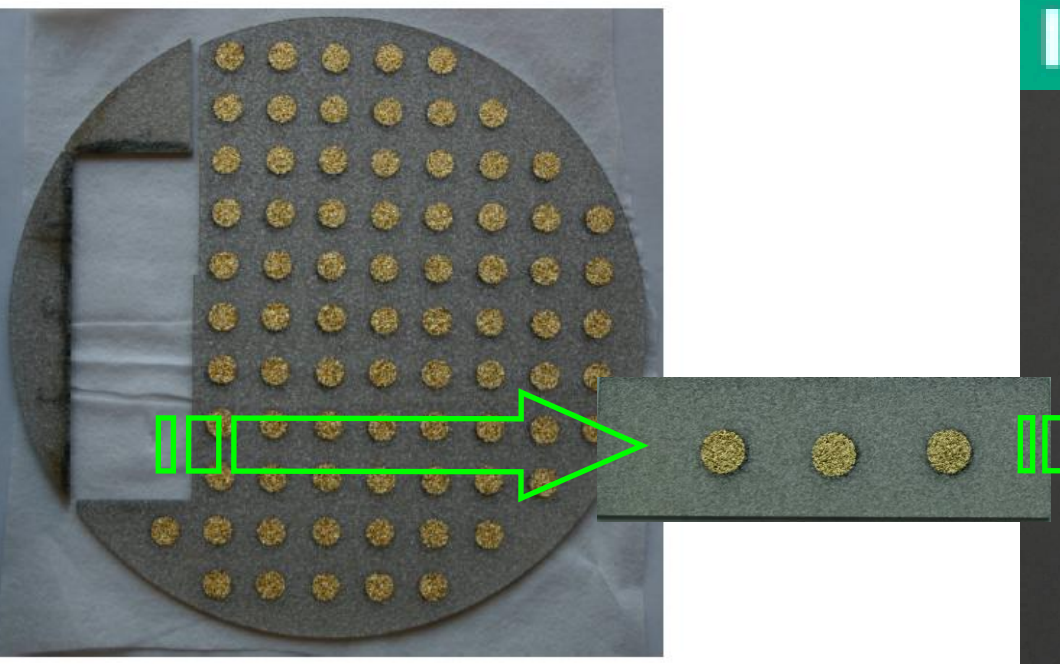
ATLAS High Luminosity Steering Group

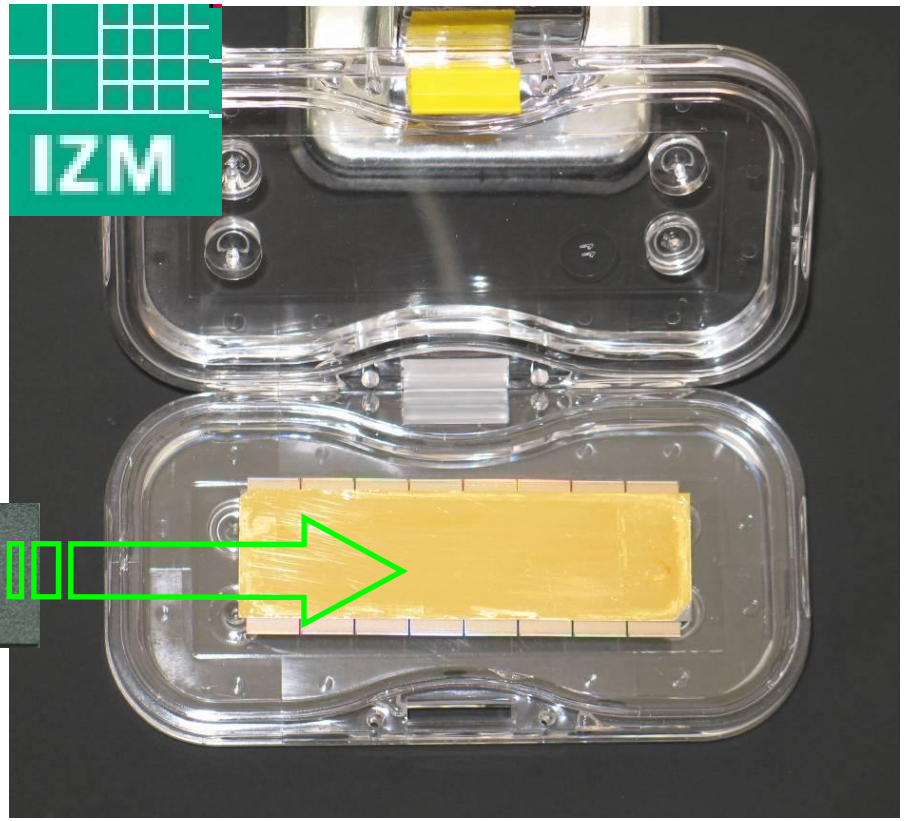
Original R&D proposal goals

- Industrialize bump bonding to diamond sensors (make 5-10 modules)
- Quantify radiation tolerance of full ATLAS pixel modules
- Optimisation of front-end electronics
- Lightweight mechanical support – exploit minimal cooling requirement
- Financial resources to make 10 parts:
  - ☑ Diamond sensors
  - ☑ Bump-bonding contracts
  - ☠ 200 FE-I3 + 25 MCC's
  - ☐ Module support prototypes
  - ☐ Three year beam-test program (2008-2010)
- Aimed at tracker upgrade, bidding for IBL



Industrialization: 2nd full pixel pCVD module





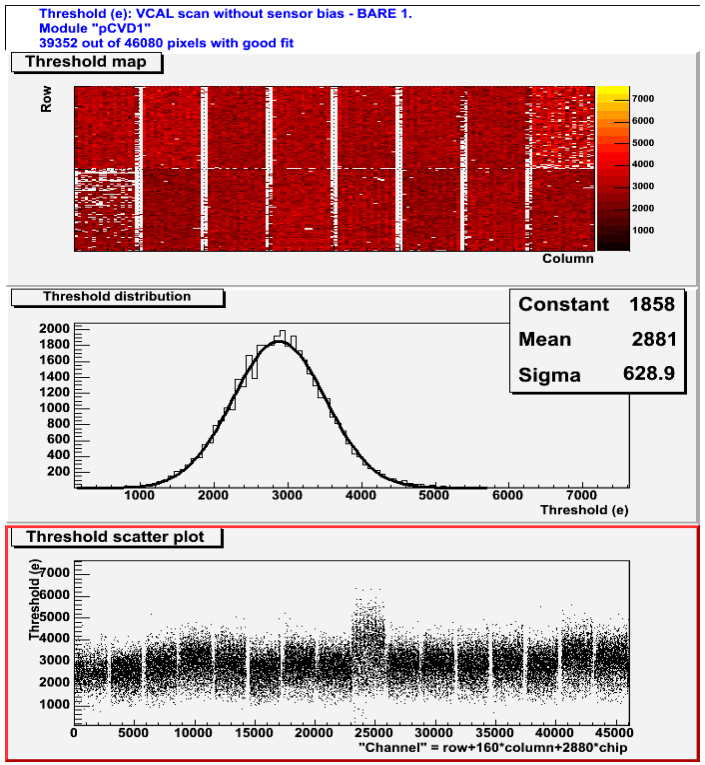
- 1st module to be built in industry
- All steps from polished sensor to bump-bonding performed at IZM Berlin

- Embedding in a ceramic wafer
- Wafer scale metallization & UBM process
- Removal from the ceramics
- Backside metallization & cleaning
- Flip chip

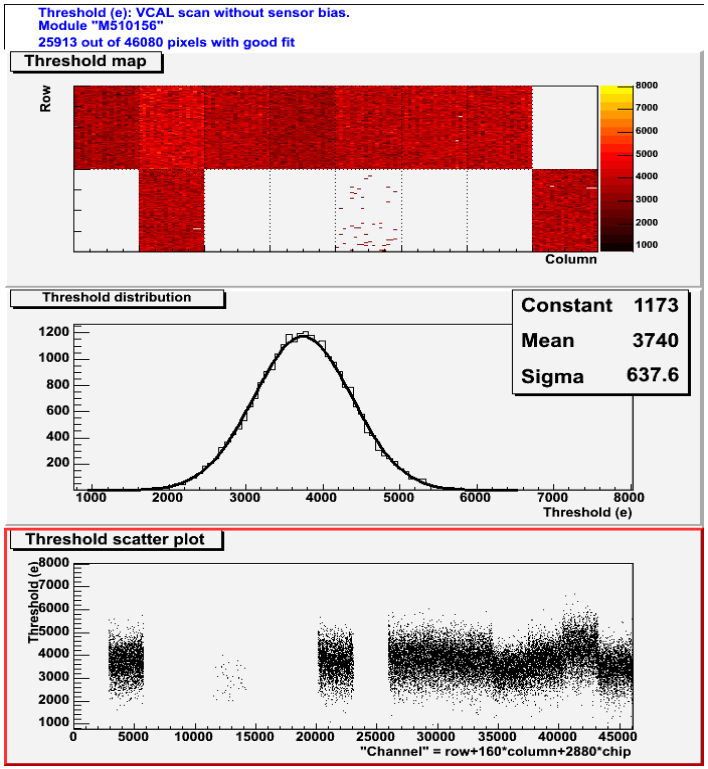
Industrialization hic-up

- Edge of diamond left metalized – module damaged
  - Voltage short across edge

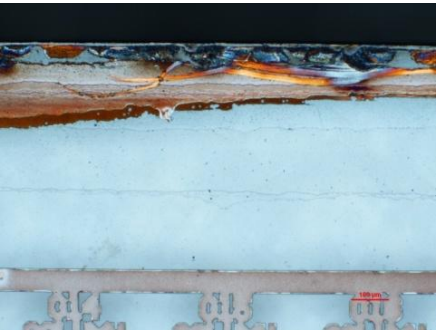
- Before applying 10 V

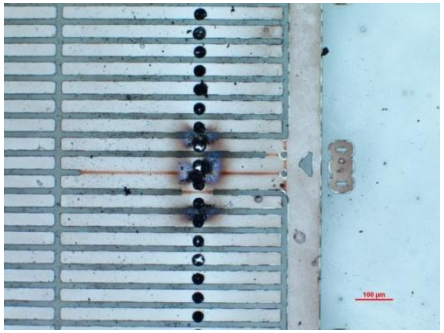


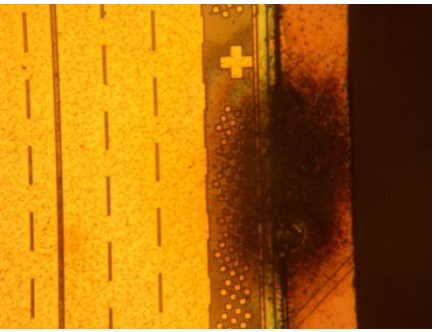
- After applying 10 V

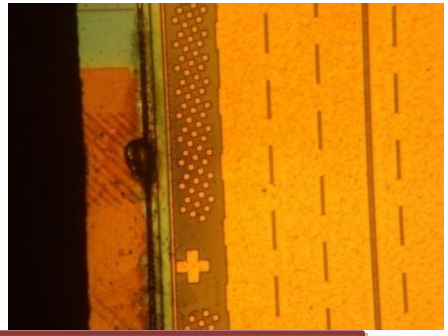


Industrialization: repair @ IZM







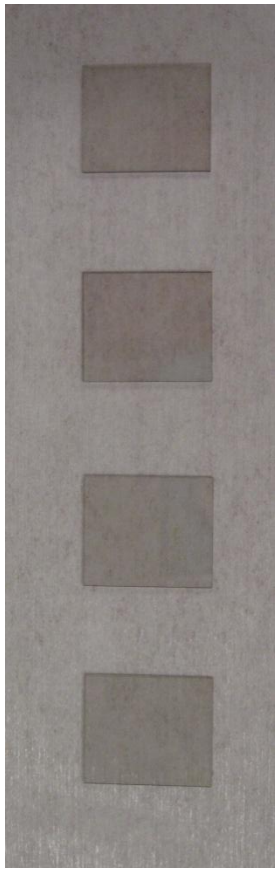


Reworked module

- 7/16 chips stopped functioning
- Back to IZM for re-build
  - Module taken apart – visual damage to sensor and chips
  - Backside metallization redone
  - Improved cleaning of the module rim by using plasma etching
  - All FE chips replaced
- Successful re-build proves concept of diamond sensor recycling in case of module QA failure !
  - Successfully done before on single-chip assemblies

Diamond vendors: DDL (E6)

- Our (and RD-42) long-term supplier – considered qualified
  - Reproducible material
  - Quote for 500 pcs (900 kGBP)
- Have 4 18 mm x 64 mm sensors for the original dPix programme based on I3
  - CCD was guaranteed above 275 µm
    - Achieved on one part only
    - Others 250-270 µm, rejected,
    - Refurbished, not a big change (235-250 µm)
    - DDL agreed to re-evaluate their polishing procedures
- Have 4 I4 shaped sensors at hand
  - Ordered as 17.4 mm x 20.6 mm
  - Measured at 17.5 mm x 20.7 mm
    - 10-20 um RMS spread = cutting precision
    - Can be thinned & trimmed to envelope
  - Measured CCD between 240 and 260 µm



Diamond vendors: II-VI

- New US producer
  - Large company (sold eV products to EI recently) based in Saxonburg, PA

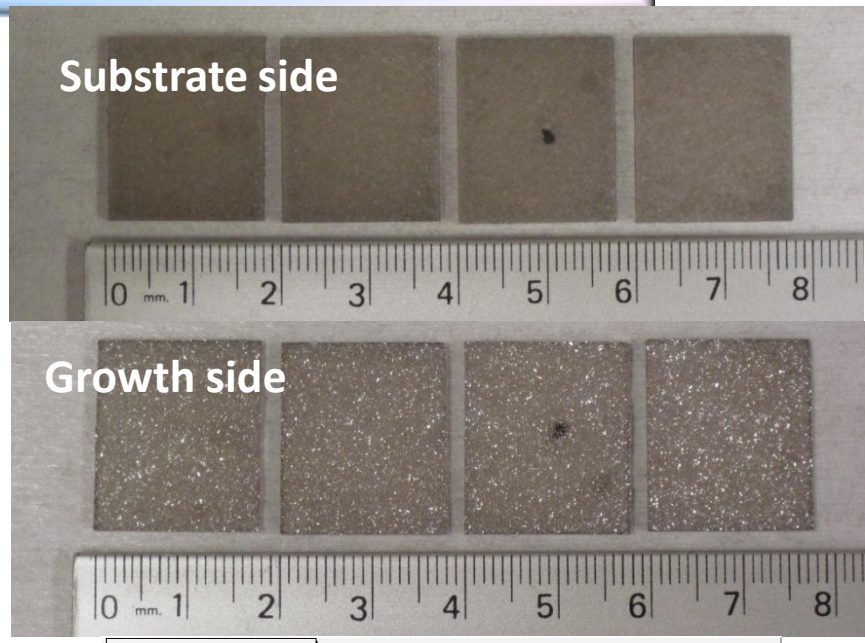
II-VI INCORPORATED THE WORLDWIDE LEADER IN CRYSTAL GROWTH TECHNOLOGY

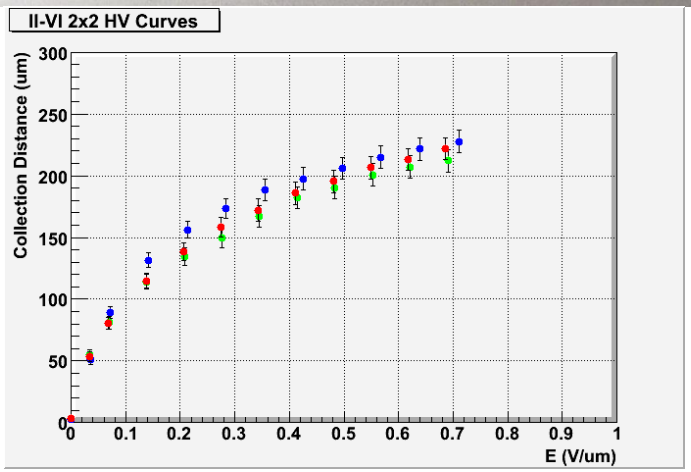
  - Interested in electronic grade diamonds to enrich their product line
  - Working closely with OSU on development for HEP
  - Produced a 1.5 mm thick 5” wafer in their “normal” process
    - Not tailored to HEP applications at all
  - 4 I4-shaped pieces delivered to OSU for testing
    - As grown – no processing at all

II-VI (cont.)

- Really as grown, 1.5 mm thick
- Surprisingly good results
  - CCD uniform across all samples
  - 220-230 µm @ 0.7 V/µm, not saturated
    - Error in metallization, CCD lower limit
- Suspect very good intrinsic CCD
- Start working on a programme to (im)prove it
  - Take off substrate side in steps
    - First 50 µm step done, CCD increase ~20 µm
  - Go to higher fields
- Work with II-VI to optimize further
  - Reduce growth rate
- Ultimate goal : 300^3

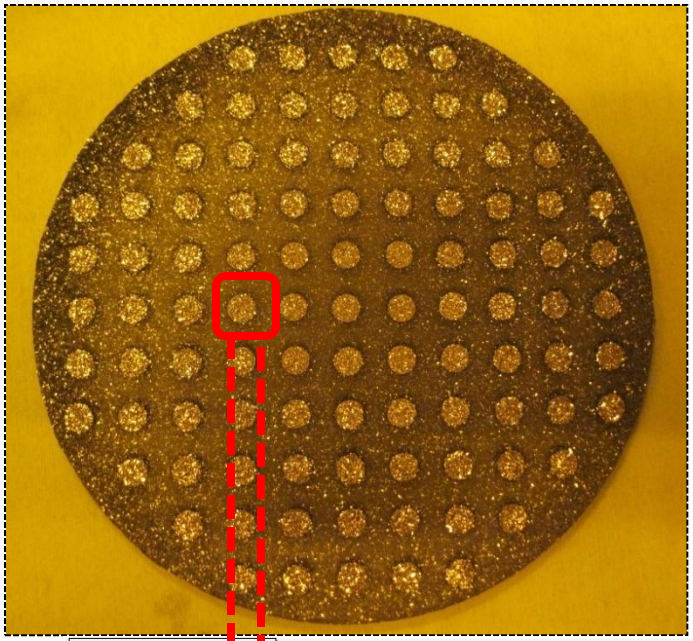
➢ 300 USD/cm^2, 300 µm CCD, 300 µm thick
  - 400 average will also do (e.g. 400, 300, 500)

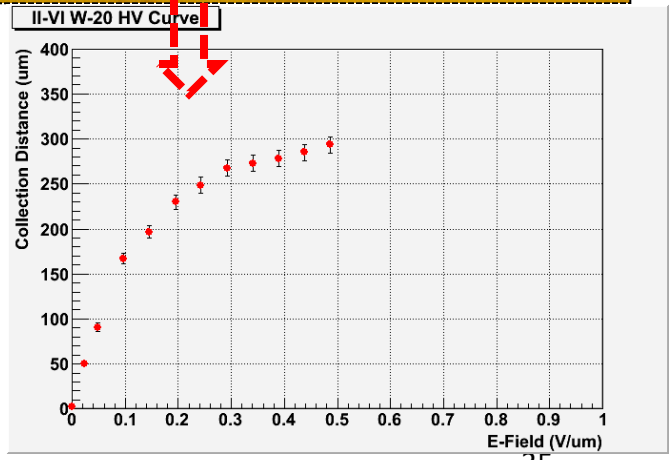




II-VI (latest)

- Last news
  - Got a 5” wafer for evaluation
    - Not for HEP applications
    - 2 mm thickness at centre
    - 2.5 mm at rim
  - Spectacular CCD results
    - 300 μm at 0.5 V/μm !
  - Starting to grow a wafer for us
  - Eagerly awaiting delivery
    - Suspect close to scCVD quality when thinned down to 500 μm
- Could change the whole perception of pCVD diamond





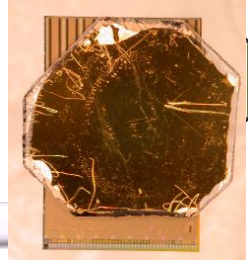
Summary

- Recent progress in the diamond world
  - Improved understanding of radiation damage
  - Application in all LHC experiments
  - Building of pixel modules in industry
  - New producer with VERY promising initial performance

Very interesting times with promises of spectacular performance ahead of us !

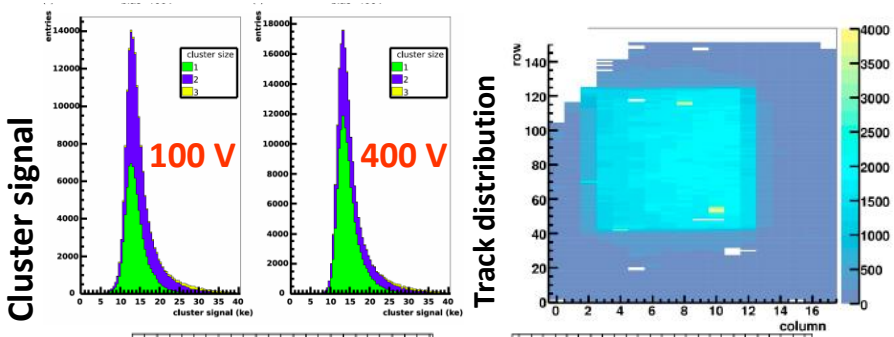
Backup

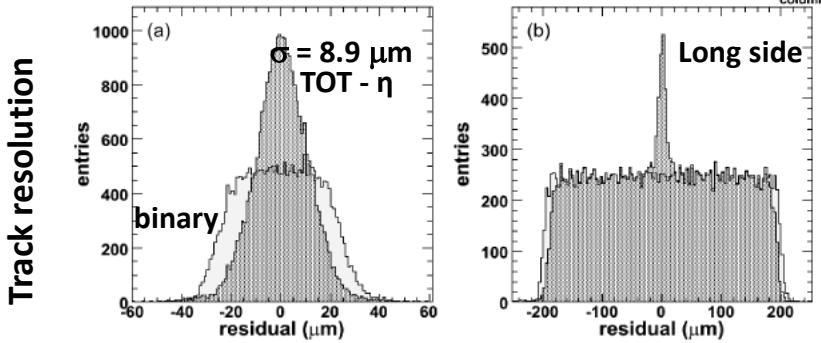
Diamond scCVD Pixel Module – Results

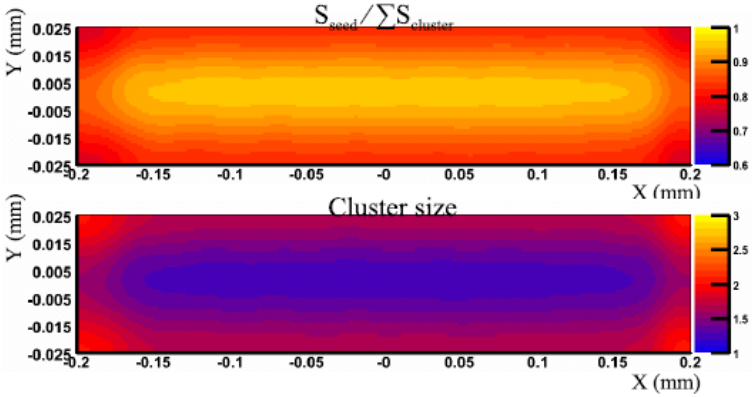


scCVD single chip module

- Analysis (M. Mathes PhD, Bonn) of SPS test beam data exhibits excellent module performance
  - Cluster signal nice Landau
  - Efficiency 99.98 %, excluding 6/800 problematic electronic channels
  - Unfolded track resolution using η-algorithm from TOT exhibits s ≈ 8.9 mm
  - Charge sharing shows most of charge collected at high voltage on single pixel – optimal for performance after (heavy) irradiation







IBL pCVD diamond sensor cost estimate

- IBL = 14 staves of 32 (= 448) single-chip sensors
- Active sensor: 16.8 mm x 20 mm
- Count on 20 % loss during production (recycling)

  => need ~0.2 m^2 of diamond
- Budgetary estimate – DDL quote for 500,1000 20x20 mm^2 pCVD diamond sensors
  - Cost 900 kGBP for 500 pcs
    - 1.5 MGBP for 1000 pcs

DIAMOND DETECTORS LTD

16 Fleetsbridge Business Centre
Upton Road
Poole,Dorset BH17 7AF
UK

Estimate

VAT REG NO	Tax Date	Quotation #
GB 904 1112 82	26/05/2009	174

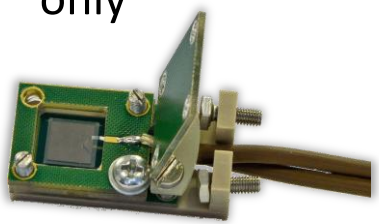
For further information please contact
sales@DiamondDetectors.com
Tel: +44 1202 441030
Fax:+44 1202 441039

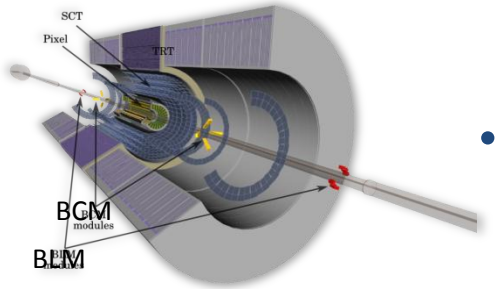
Name / Address
University of Toronto (Physics) McLennan Labs. rm 320 60 St George Street Toronto ON M5S 1A7 CANADA

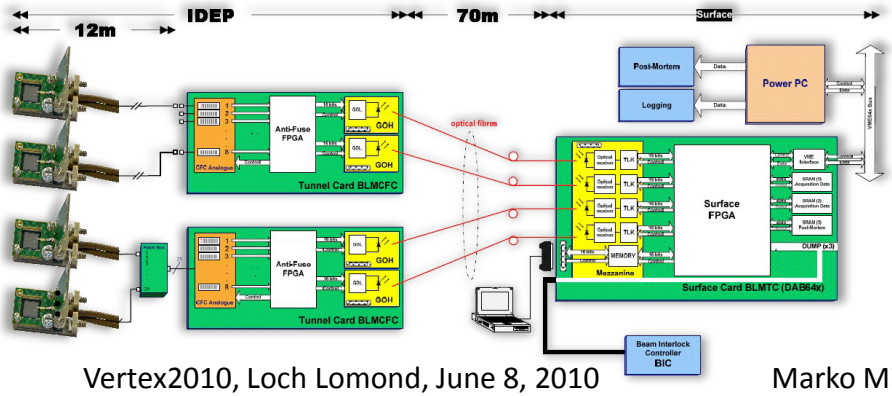
Item	Description	Qty	Rate	VAT AMT	Total
60-PROJECT ...	CERN - 20x20x0.75P2 Electronic Grade Polycrystalline Plates Size 20x20 +/- 0.2mm with rounded corners 1mm radius. Thickness 0.75mm, minimal removal from growth surface, thinned from the nucleation surface to final thickness. Polished both surfaces to a final average roughness Ra <12nm as measured using our optical profiler. The above prices are budgetary based upon high yields and donot include any additional capital costs to ramp up production to meet delivery expectation. Prior to accepting any order detailed discussions would be required.	500	1,815.00	0.00	907,500.00
60-PROJECT ...	CERN - 20x20x0.75P2 Electronic Grade Polycrystalline Plates Size 20x20 +/- 0.2mm with rounded corners 1mm radius.	1,000	1,490.00	0.00	1,490,000.00

ATLAS BLM

- 8x8 mm^2 0.5 mm thick diamond sensors used
- 6 sensors on each side (A and C) installed on ID End Plate
- Readout adopted from LHC BLM system with minor modifications
- Redundant system to BCM – safety only







- 7 TeV p on TAS collimator gives ~1 MIP/BLM module → ~1 fC of charge
  - 25 pA of current "spike" for single occurrence (possible with pilot bunch)
  - 40 nA of current for continuous loss (only when full LHC bunch structure)
- Diamond dark currents
  - In magnetic field, should be O(10 pA)
  - Erratic currents, several nA w/o magnetic field
- Require 2 ch. above threshold simultaneously

several hours
single channel
max. rates / sec