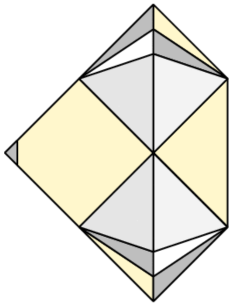
Diamonds for Present/Future HEP Applications

- Diamond growth
- Radiation hardness
- Detector system experience
  - CDF and ATLAS beam conditions monitors
  - The ATLAS pixel detector upgrade

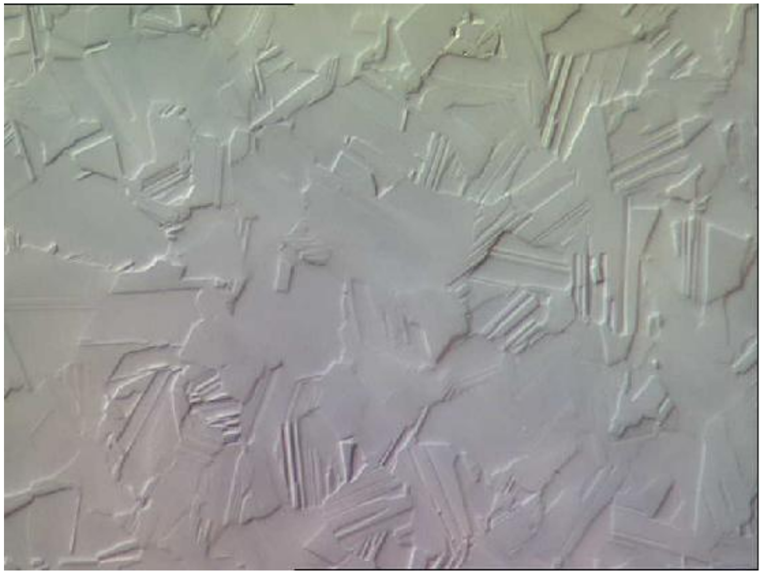


William Trischuk
University of Toronto
April 2013

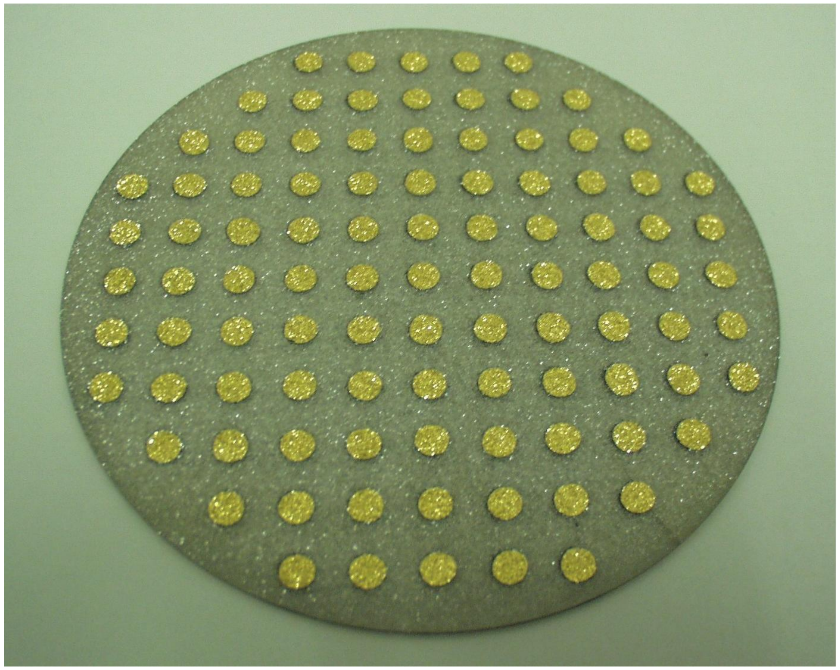
Properties of Diamond and Silicon

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	
Breakdown field [V/cm]	10^7	$3x10^5$	
Intrinsic resistivity @ R.T. [Ω cm]	> 10^{11}	$2.3x10^5$	Low leakage
Intrinsic carrier density [cm^{-3}]	< 10^3	$1.5x10^{10}$	
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	

Examples of CVD Material



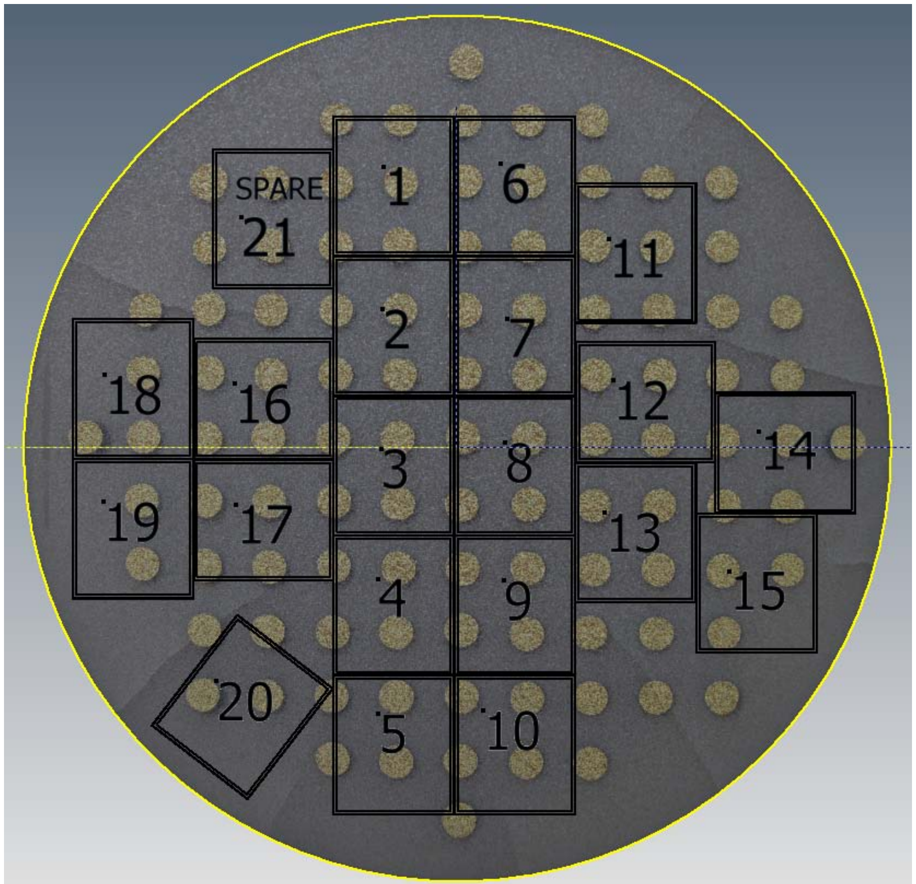
Surface image of pCVD sample
(Courtesy Element6)



- pCVD diamond wafer
- Dots are on 1 cm grid

- High quality wafers grown 12 cm in diameter
- Best material from wafers grown up to 2 mm thick

New US Manufacturer

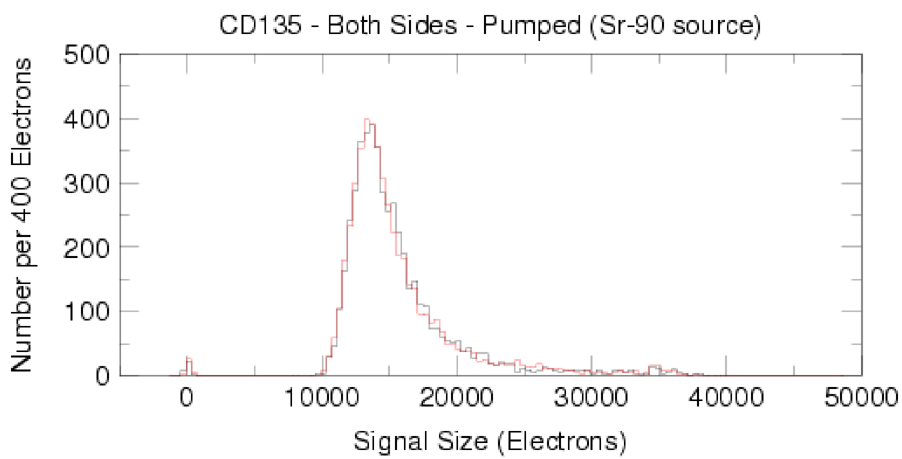


- II-VI Semiconductor
- Producing diamond sensors over past year
- Have seen 300 μm quality material
- Now three wafers to provide 20 sensors for ATLAS
- CMS (ETH) also has an order in place

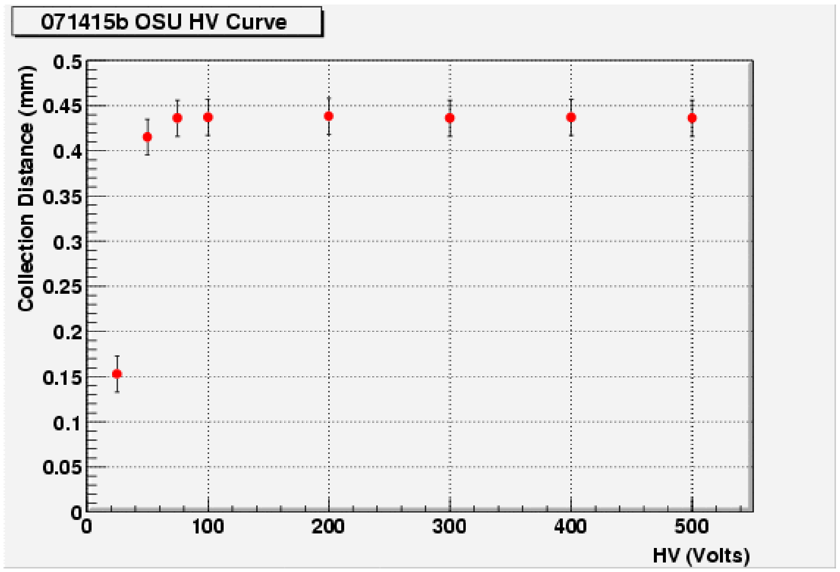
Single Crystal (scCVD) Diamond

- Improve material eliminating grain boundaries, defects/charge traps
- Almost a decade trying to scale up area from 0.5×0.5 cm^2

Isberg *et al*, Science 297 (2002), p1670



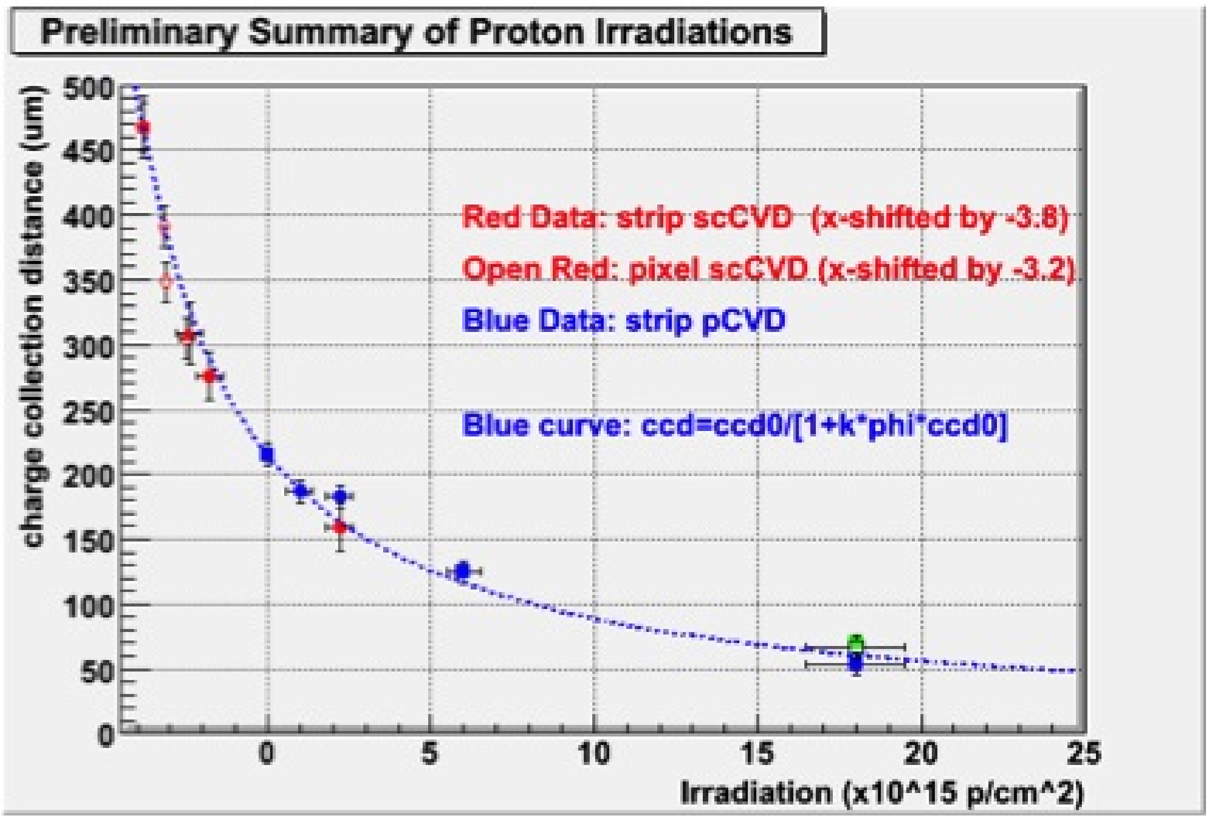
- Features of this material include
  - Full collection at 0.2 V/μm



  - Collection distance $\equiv$ thickness
  - Charge collection very uniform
- Grain boundaries limit pCVD

24 GeV Proton Irradiations

- Have irradiated:
  - pCVD samples to 1.8×10^{16} p/cm^2
  - scCVD samples to 5×10^{15} p/cm^2
- Characterise signal at intermediate fluences



- Default $E = 1$ V/μm
- Green at $E = 2$ V/μm
- Align by shifting -3.8×10^{15} p/cm^2

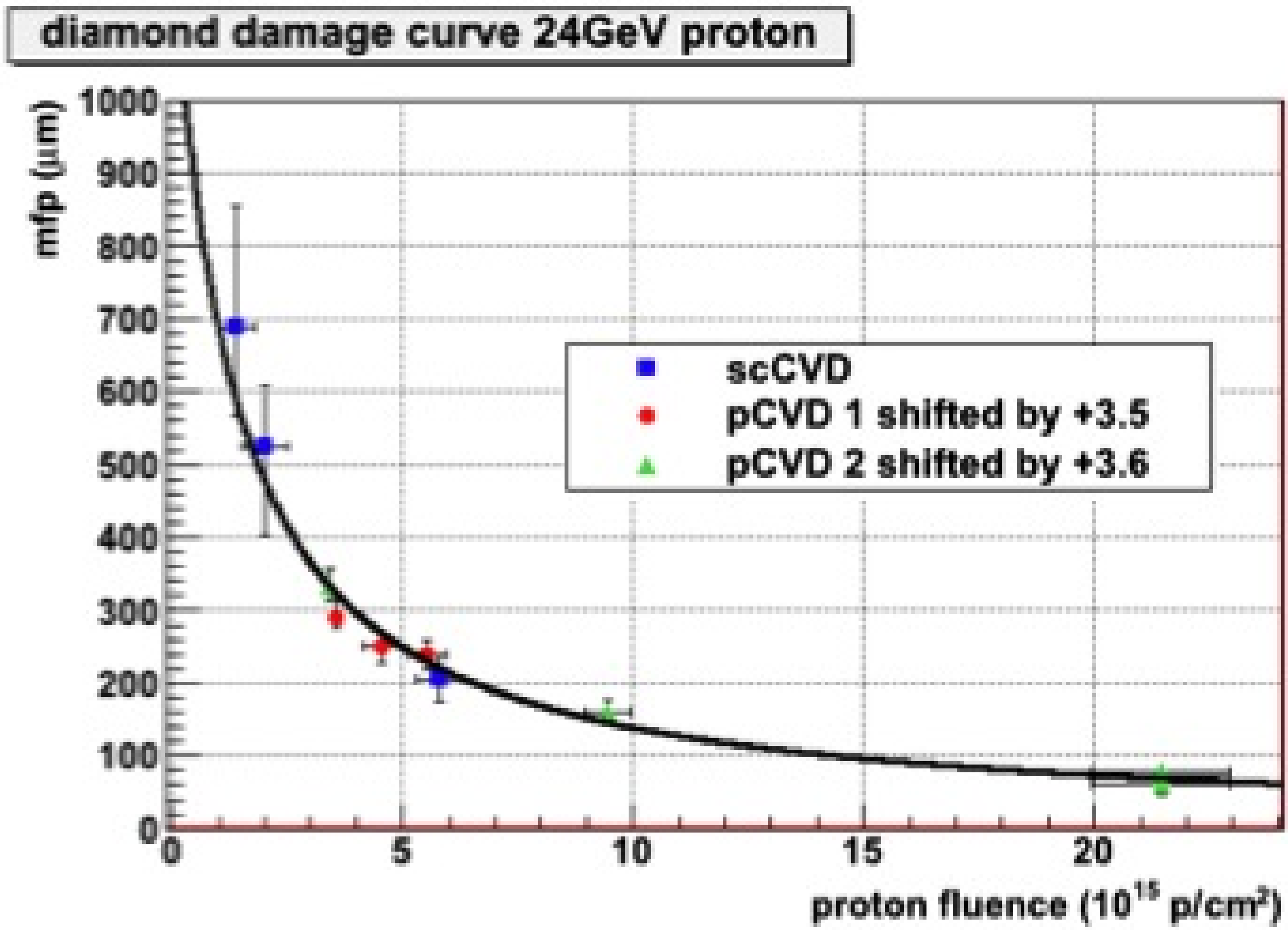
This pCVD material $\equiv$ scCVD material **after** $\approx 3.8 \times 10^{15}$ p/cm^2

- pCVD and scCVD follow same damage curve:

$$1/\mathrm{d} = 1/\mathrm{d}_0 + k\phi$$

$$k \approx 0.7 \times 10^{-18}\ \mu\mathrm{m}^{-1}\ \mathrm{cm}^2$$

Mean Free Path degradation with dose



Applications of Diamond Sensors

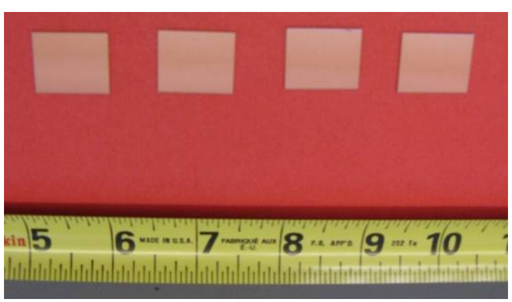
- Several exciting applications for pCVD diamond sensors
  - High Energy Physics
  - Heavy Ion beam diagnostics
  - Synchrotron light source beam monitoring
  - Neutron and α detection
- Beam monitoring at
  - FNAL/Tevatron (CDF)
  - LHC (ATLAS, CMS, LHCb)
- Pixel beam monitors for ATLAS and CMS

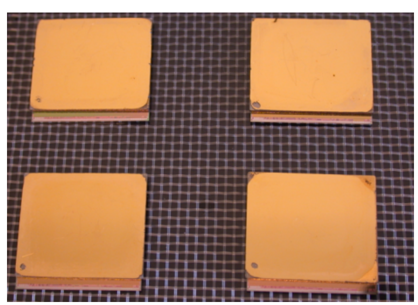
Diamond Sensor Requirements for Tracking

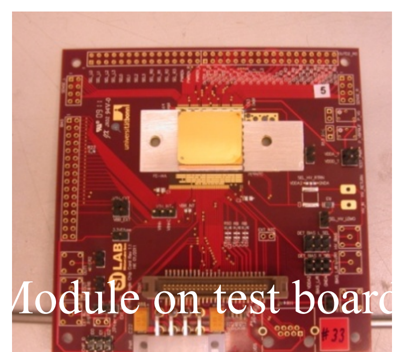
Requirement	Specification
Sensor size	5 x 5 cm^2
Sensor Thickness	400 microns
Minimum charge mean free path	250 microns
Minimum average charge before irradiation	9000 electrons
Minimum mean free path/ charge after 10^{16} cm^{-2}	150 microns/ 5400 electrons
Minimum signal/threshold after 10^{16} cm^{-2}	3
Single hit efficiency	>99.9%
Spatial resolution	<14 μm
Maximum operating voltage	1000 V
Maximum total leakage current (@1000 V)	100 nA

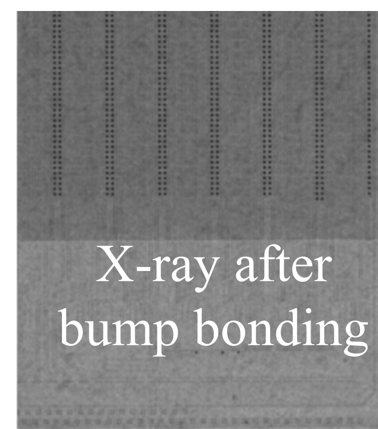
Lessons Learned: Module Production

- Sensors
  - 35 old sensors recycled from E6 (UK) from IBL work
  - 10 new sensors ~~in hand~~ (at IZM) from E6 (UK)
  - 17 sensors ~~ordered~~ (in hand) from II-VI (US) - ~~about to arrive~~
- Quality Control
  - 9/35 old sensors/ 9/10 new sensors passed QC (ccd, I)
- Bump bonding
  - ~~4 prototype~~ (6 production) modules bump-bonded by IZM
  - ~~17~~ (21) sensors at IZM for bump-bonding









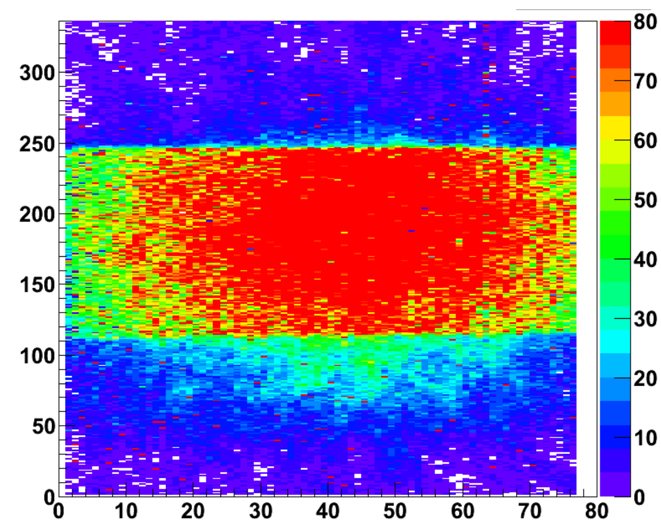
Lessons Learned: Testbeam

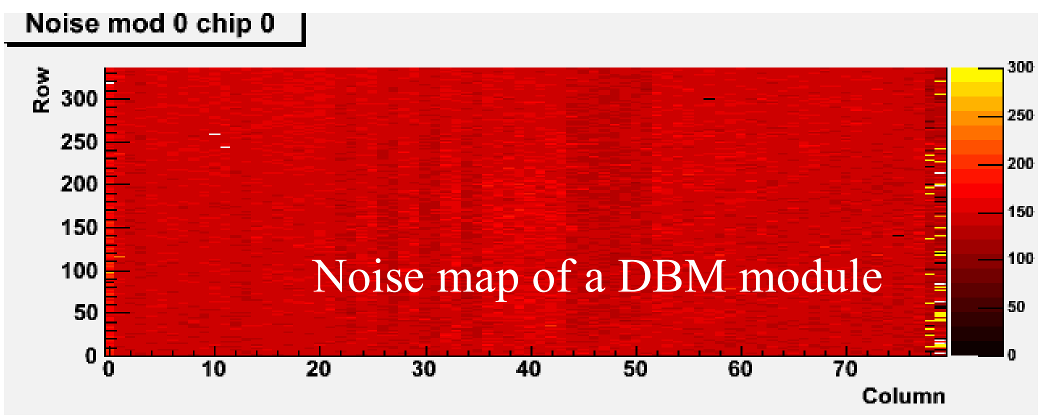
Prototype Modules Tested:

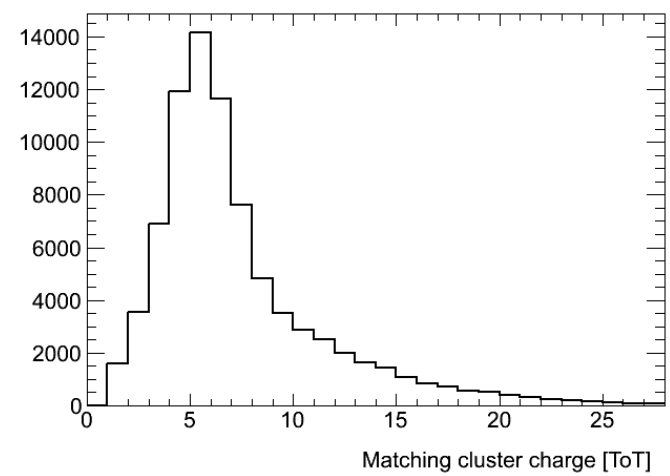
- 21mmx 18mm pCVD diamond w/FE-I4
- 336 x 80 = 26880 channels
- 50 x 250 μm^2 pixel cell

Results

- Noise map uniform
- Efficiency >95%







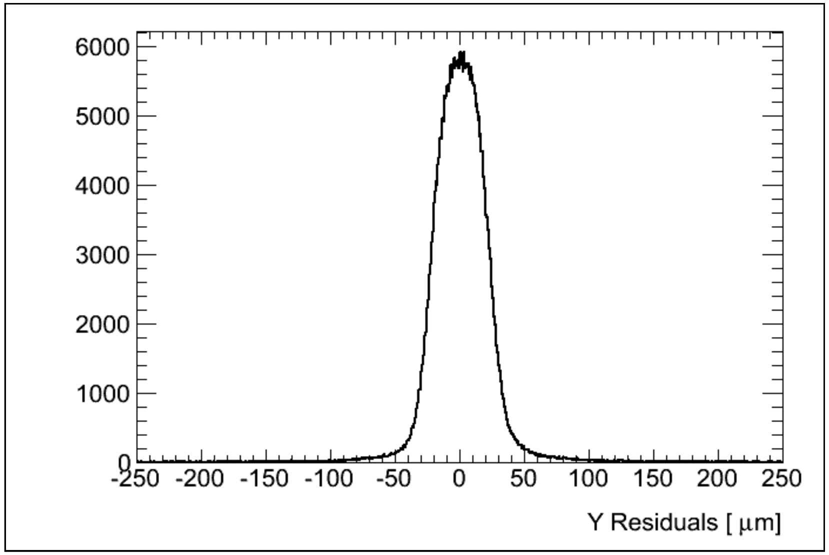
Lessons Learned: Testbeam

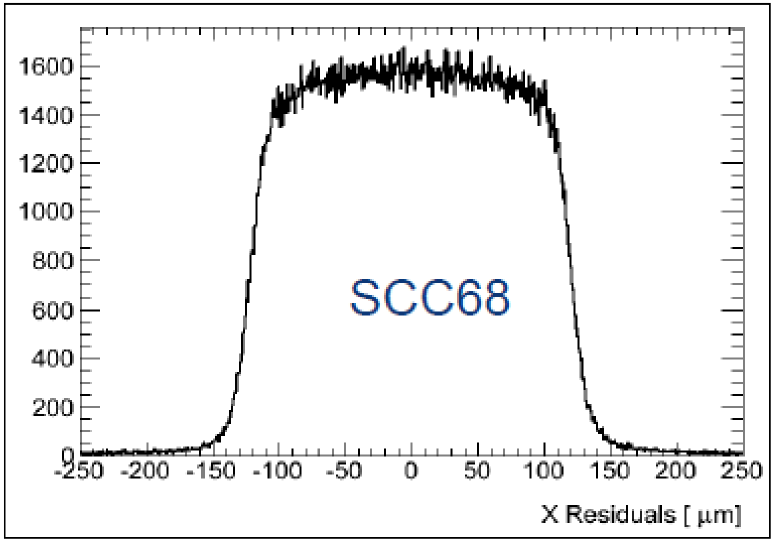
Prototype Modules Tested:

- 21mmx 18mm pCVD diamond w/FE-I4A
- 336 x 80 = 26880 channels
- 50 x 250 μm^2 pixel cell

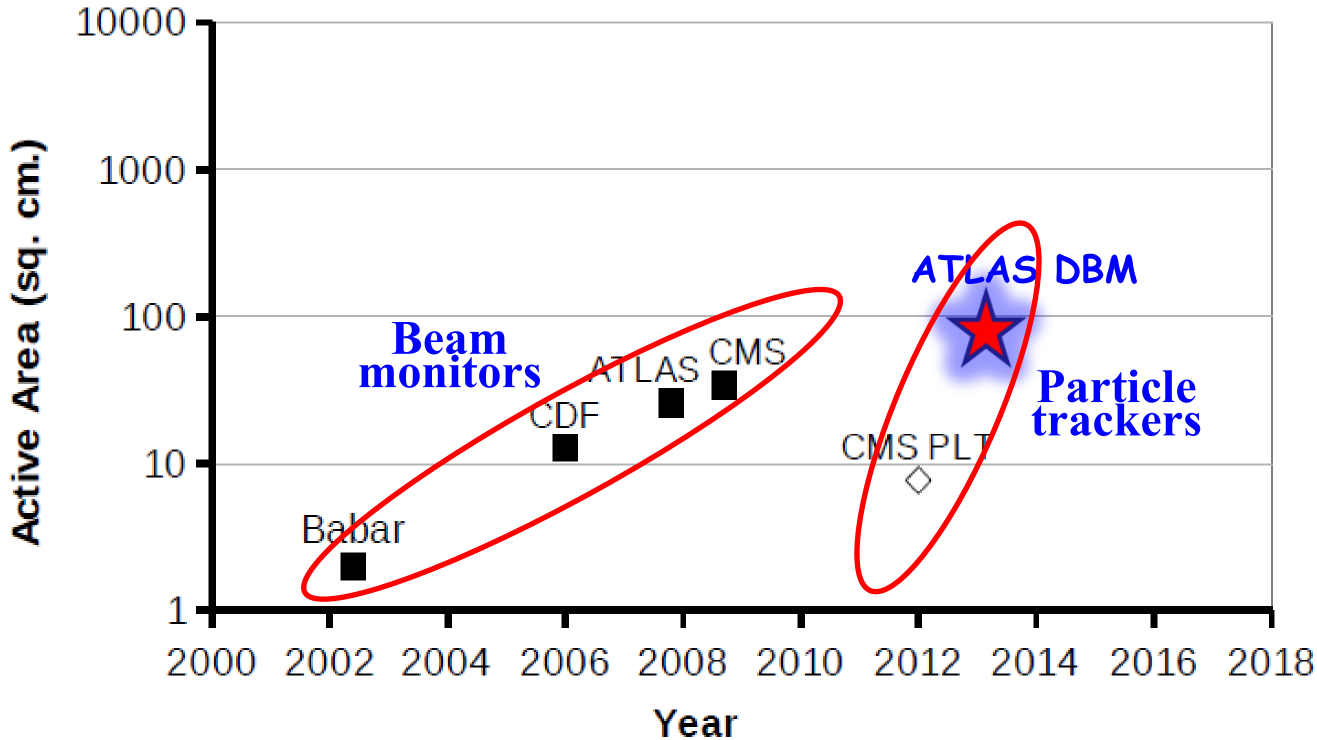
Results

- Spatial resolution looks digital





Diamond Production



Future detectors will require 10x – 100x more devices

Summary

- pCVD sensors with signals of $9,000$ electrons over large areas
- Proven radiation tolerant up to 2×10^{15} particles per cm^2
- Established universal charge-trap density for protons beyond 10^{16}/cm^2
- Diamond sensors are finding applications in a number areas
  - Beam abort systems at Tevatron and LHC
  - Pixel beam monitors for CMS and ATLAS
- Currently working to:
  - Commercialise module production for the ATLAS upgrade
  - For phase 0 LHC running: build and commission:
    - The ATLAS Diamond Beam Monitor
    - The CMS Pixel Luminosity Telescope

The RD42 Collaboration

M. Artuso[25], D. Asner[22], L. Bäni[29], 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], G. Chiodini[32], D. Chren[23], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[24], A. Dabrowski[3], R. D'Alessandro[6], W. de Boer[13], M. Dinardo[24], D. Dobos[3], W. Dulinski[10], J. Duris[20], V. Eremin[9], R. Eusebi[30], H. Frais-Kolbl[4], A. Furgeri[13], C. Gallrapp[3], K.K. Gan[16], J. Garofoli[25], M. Goffe[10], J. Goldstein[21], A. Golubev[11], A. Gorisek[12], E. Grigoriev[11], J. Grosse-Knetter[28], M. Guthoff[13], 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], H. Merritt[16], M. Mikuz[12], M. Mishina[7], M. Moench[29], J. Moss[16], R. Mountain[25], S. Mueller[13], G. Oakham[22], A. Oh[27], P. Olivero[18], G. Parrini[6], H. Pernegger[3], R. Perrino[32], M. Pomorski[14], R. Potenza[2], A. Quadt[28], 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], S. Spagnolo[32], S. Spanier[31], 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], R. Wallny[29], J.C. Wang[25], R. Wang[26], P. Weilhammer[3,♦], J. Weingarten[28], N. Wermes[1]

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31 University of Tennessee, Knoxville TN USA
32 INFN-Lecce, Lecce, Italy

Over 100 Collaborators from 32 institutions

Signal from diamond: CCD and MFP

- Charge Collection Distance (ave distance e-h move apart) defined by

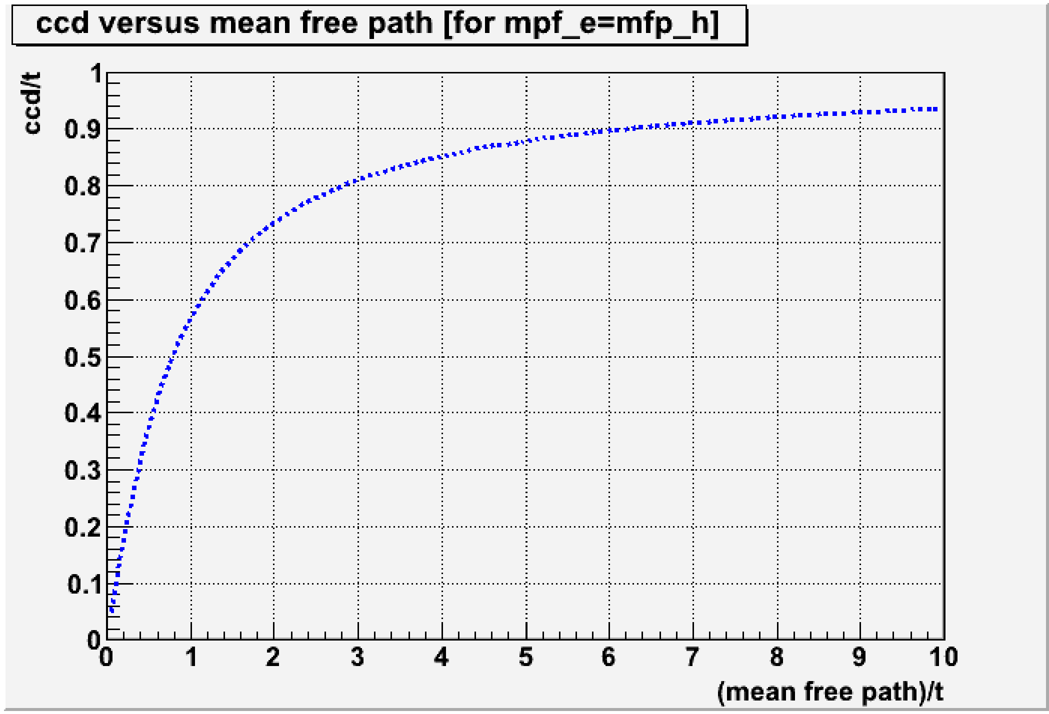
$d = d_e + d_h = (v_e t_e + v_h t_h) = (\mu_e \tau_e + \mu_h \tau_h)E$

$Q_{col} = Q_{created}\ d/t$ d=ave distance eh move apart

t = detector thickness

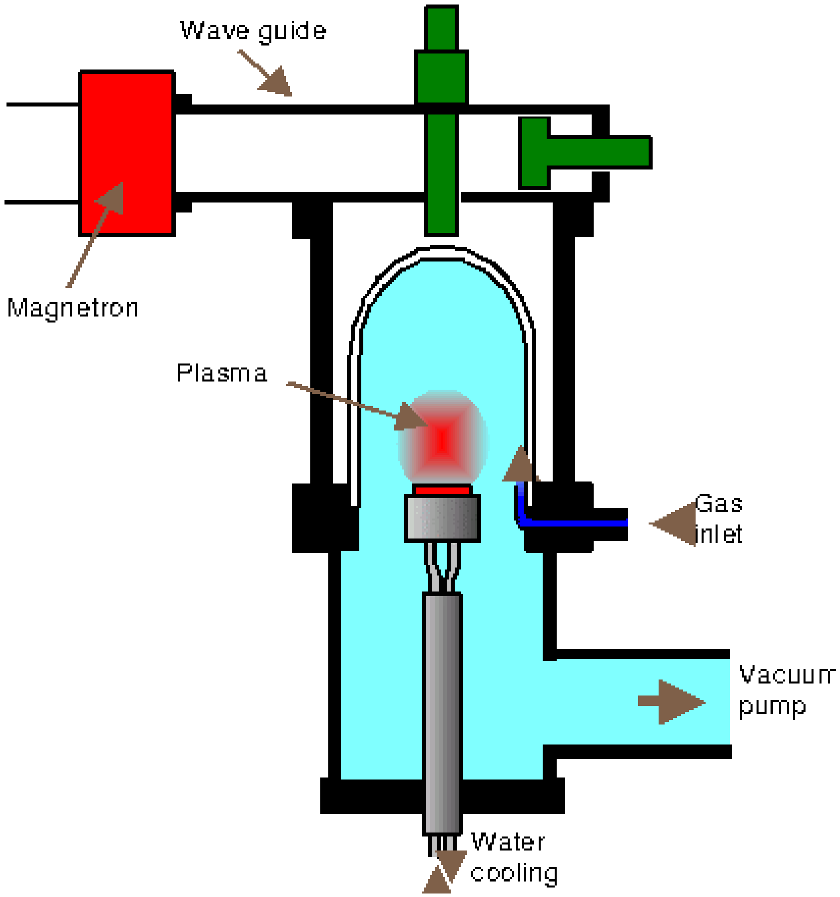
- Charge Collection Distance coincides with Mean Free Path when CCD $\ll t$

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

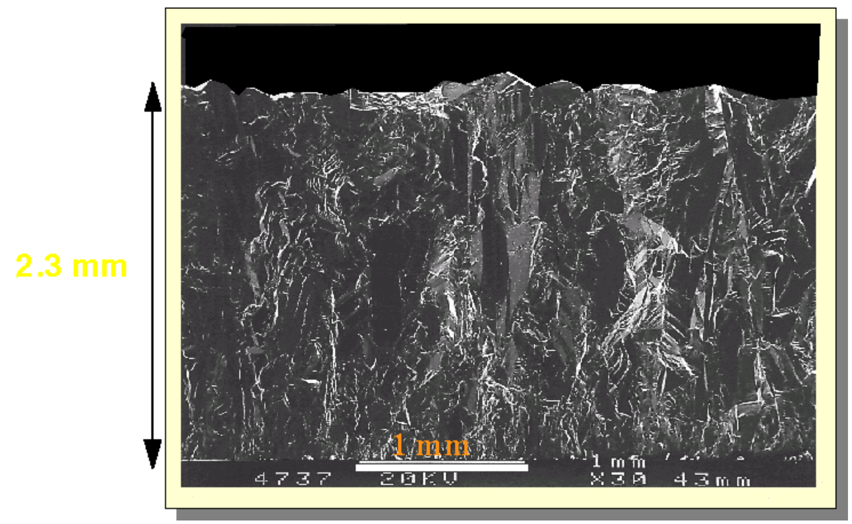


CVD Diamond as a Particle Detector

- Microwave growth reactor



- Material copies substrate
- Dominant crystallites appear

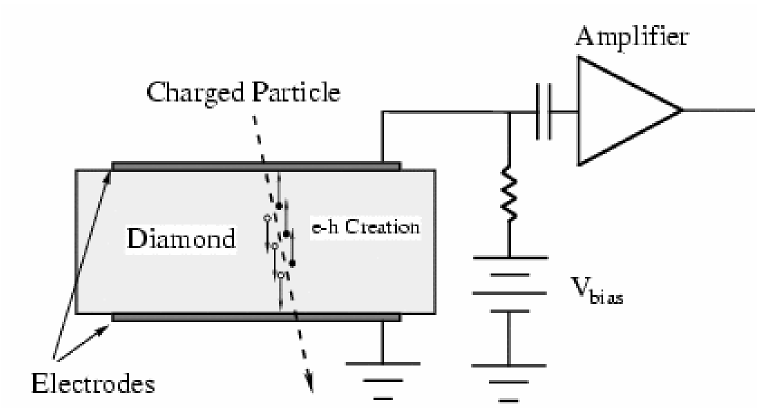


- Edge view of pCVD sample
  (Courtesy of Element6)

- Diamond synthesized from plasma

Signals from Diamond Sensors

- Image charge signal
  - induced on surface electrodes

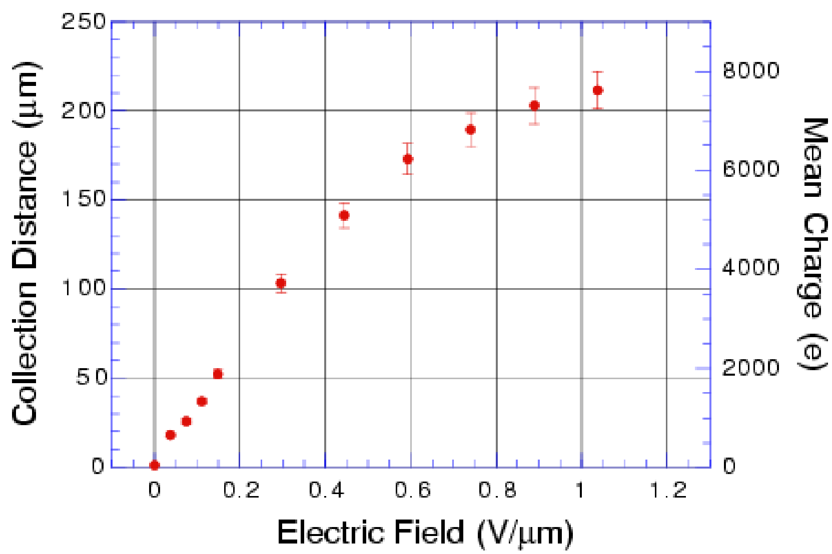


- Charge collected, Q

$$Q = \frac{d}{t}\ Q_0$$

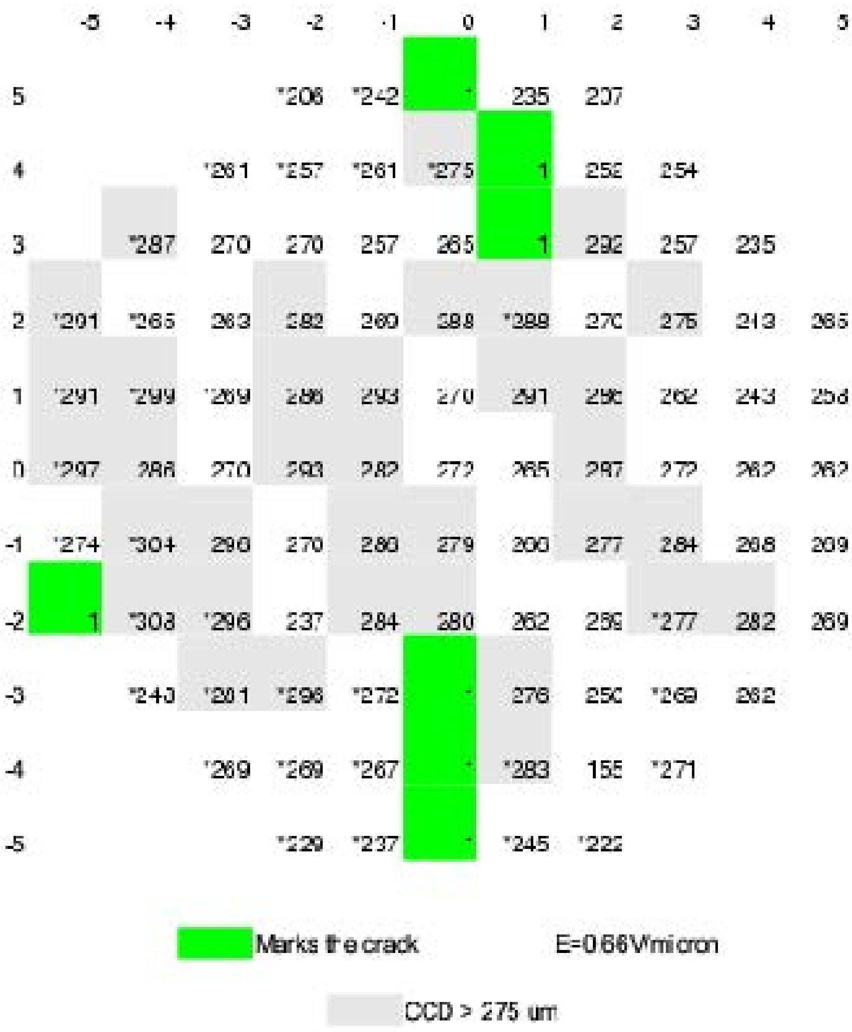
$$d \equiv (\mu_e \tau_e + \mu_h \tau_h)|\vec{E}|$$

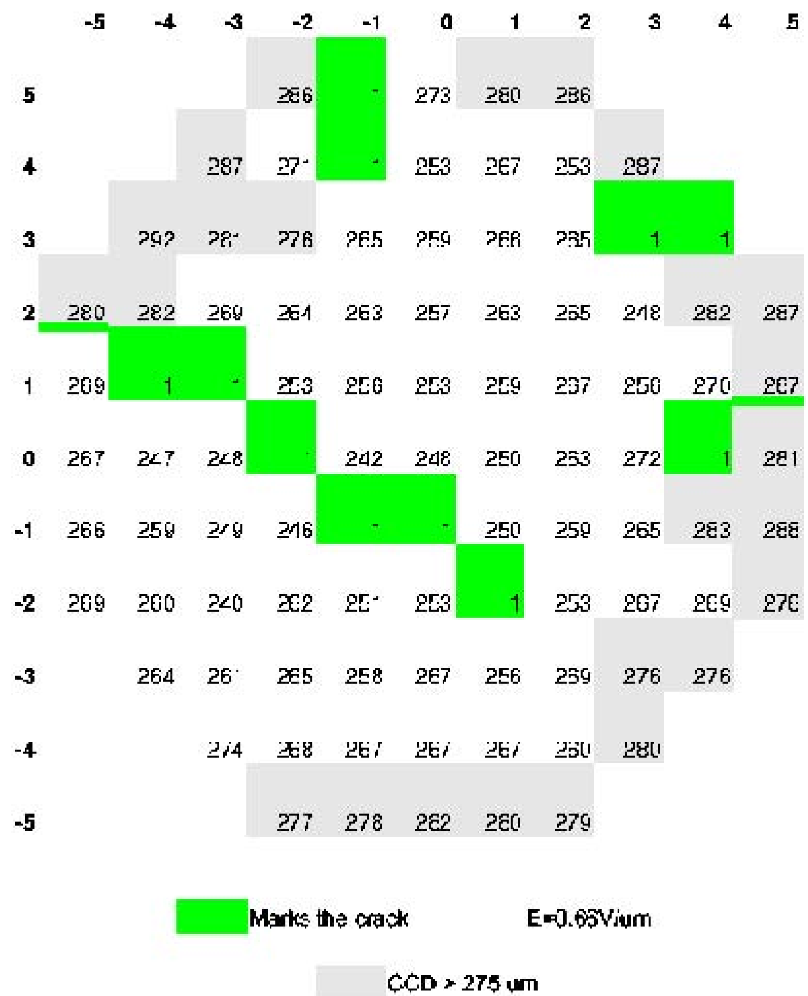
- d is the Charge Collection Distance



- Mobility saturates at $|\vec{E}| \approx 1V/\mu$m
- Operate typical sensor at 300-400 V

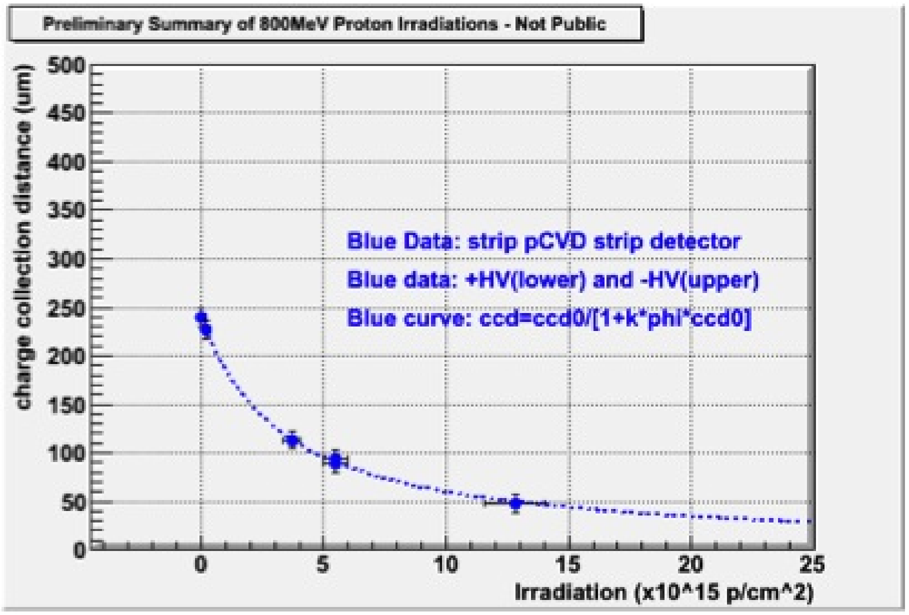
Characterisation of Wafers

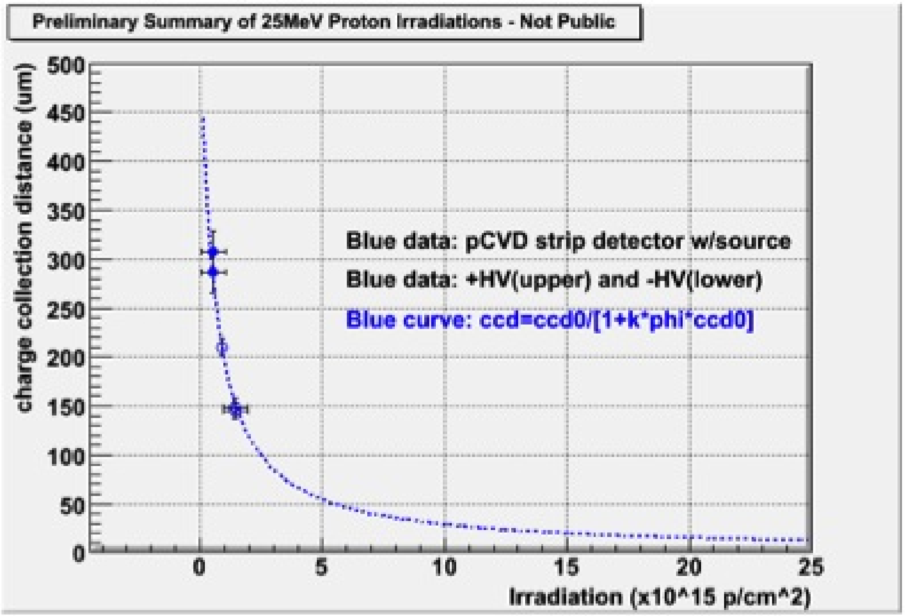


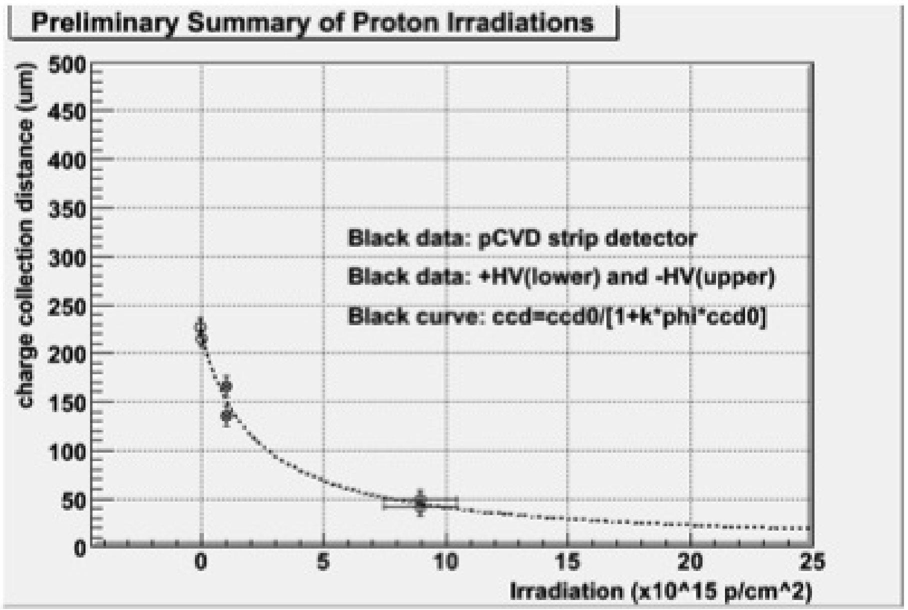


Wafers now have typically 250-200 μm collection distance

Irradiations with Lower Energy Protons





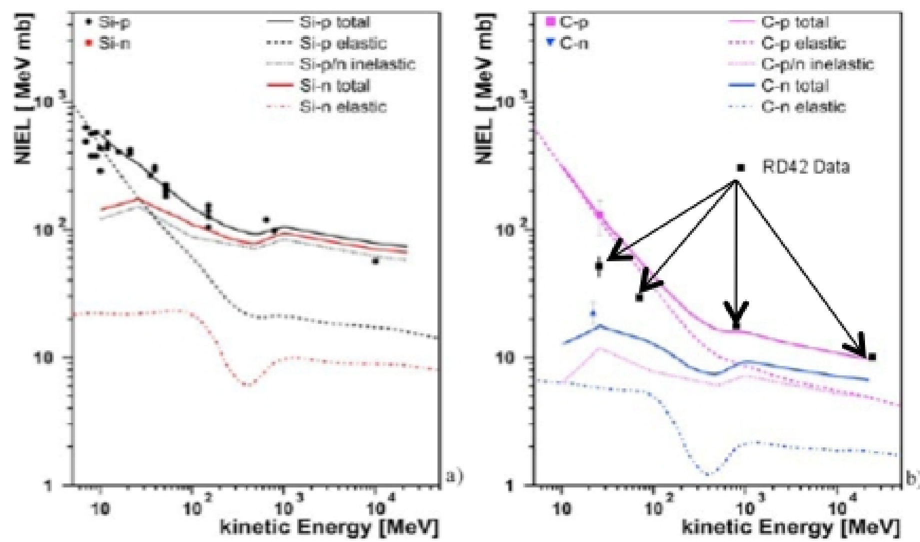


- 800 MeV protons (Los Alamos):
  1.9 times 24 GeV protons
- 70 MeV protons (Sendai):
  2.9 times 24 GeV protons
- 25 MeV protons (Karlsruhe):
  4.7 times 24 GeV protons

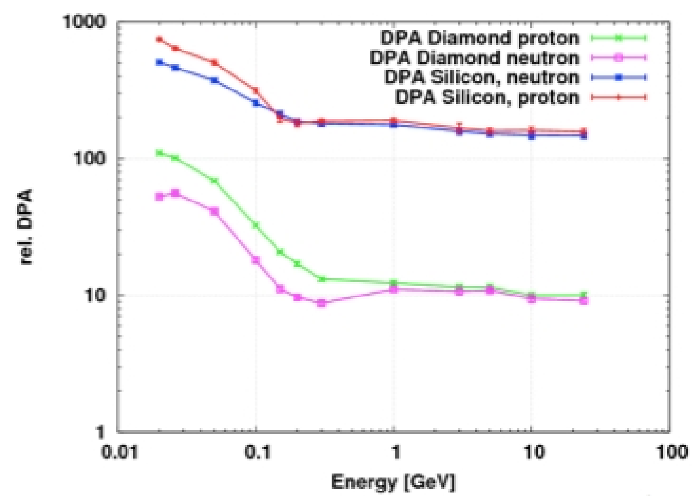
Damage from Lower Energy Protons

- Non-ionising energy calculations predict:
  - 0.8/24 GeV p: 2 – confirmed
  - 0.07/24 GeV p: 6 – see factor of 3
  - 0.025/24 GeV p: 15 – see factor of 5
  - 10 MeV $n \equiv$ 24 GeV p – in progress

- FLUKA calculations give
  - Protons: 1.2, 5, 10 for 800, 70, 25 MeV
  - Neutrons: 6

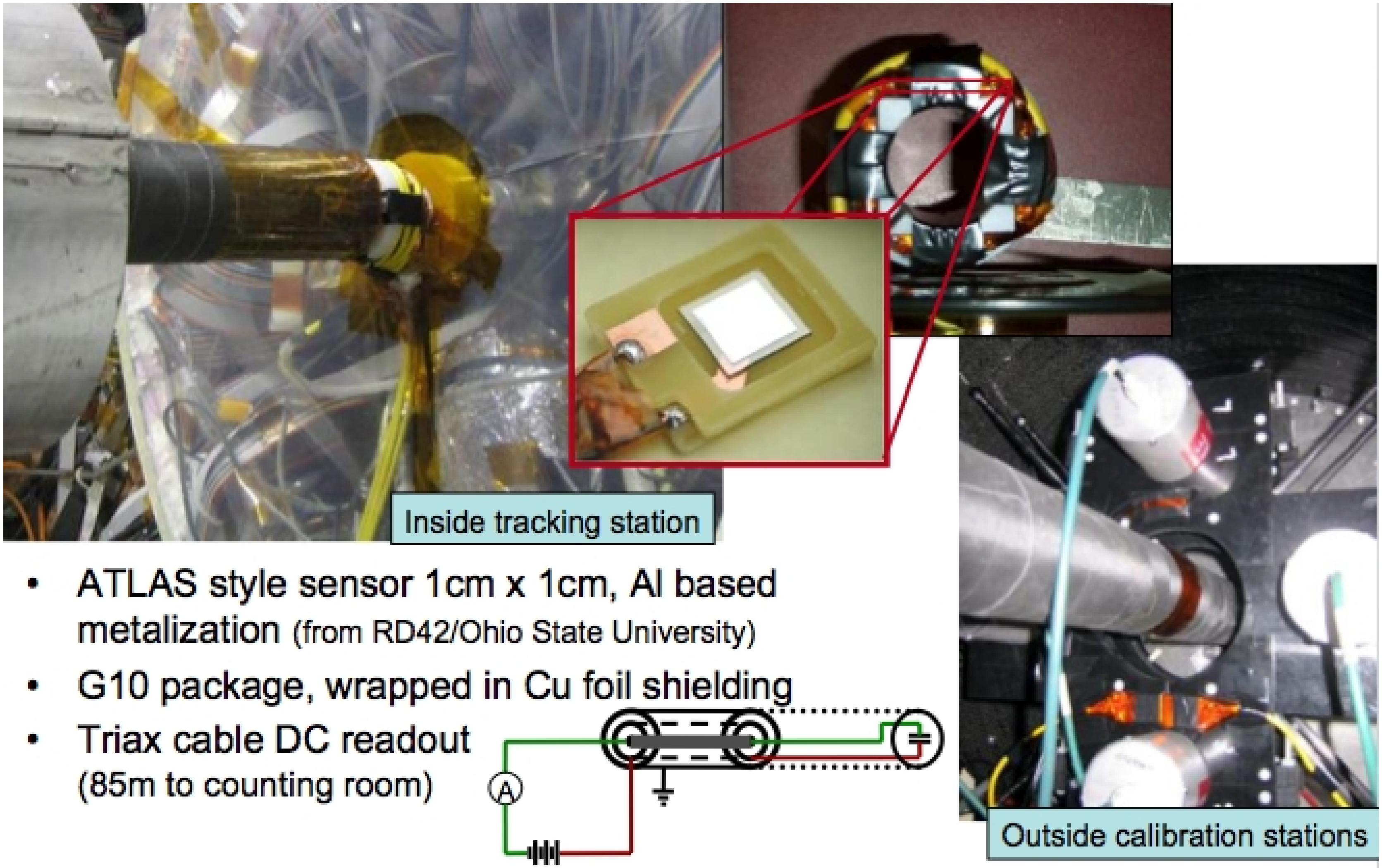


W. de Boer et al.
phys. stat. sol. (a) 204, No. 9 (2007)3009



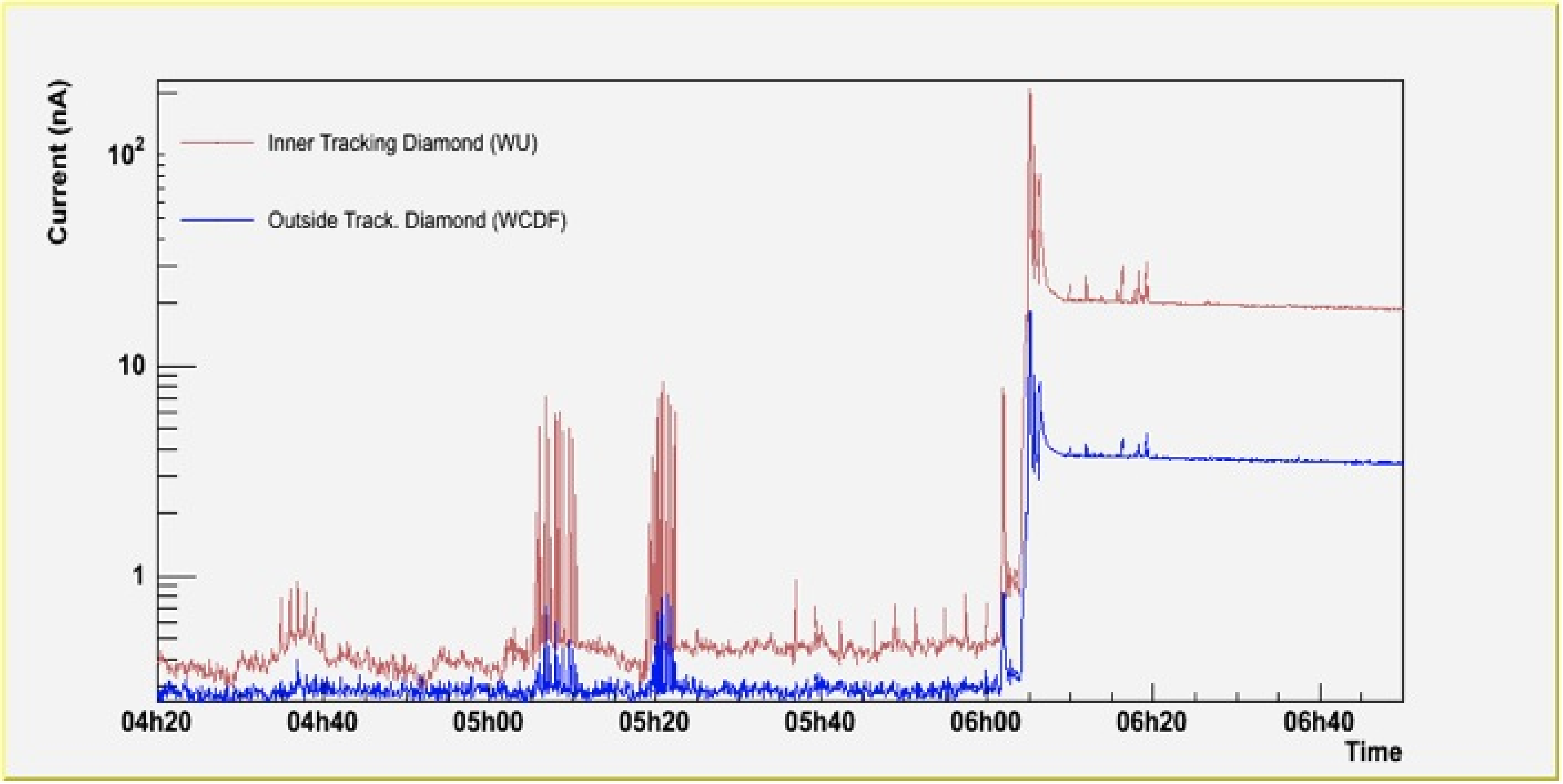
Steffen Mueller - preliminary
RD-42 meeting, April 2010

pCVD Diamond Sensors in CDF



- Monitors beam(loss) induced currents in diamond sensors
- Installed 2005, Monitoring 2006, Operational 2007-2011

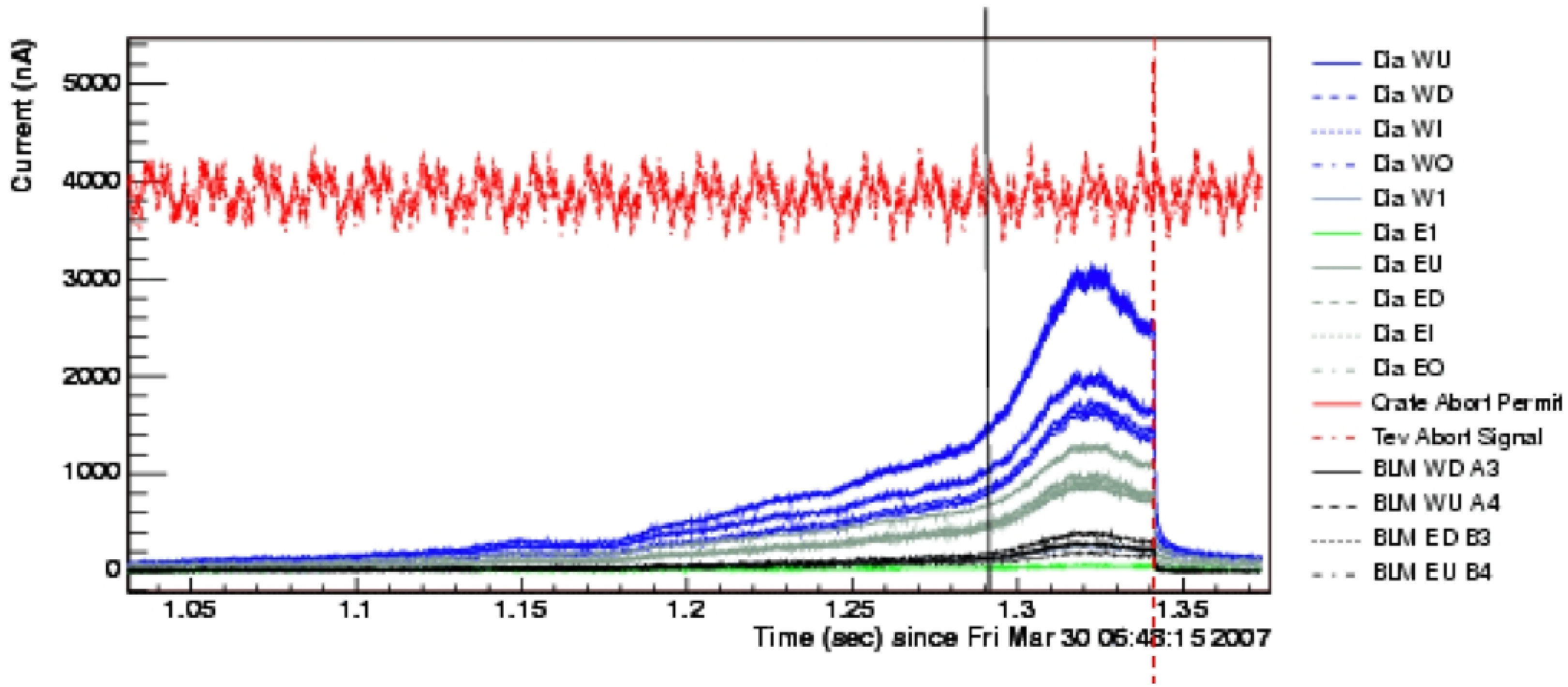
Sensitivity to Tevatron 'events'



- Sensors near IP (red) much more sensitive to losses
- Tevatron has *learned* a lot about what goes on at IP during injection

A Typical Tevatron Abort

- During 11-month monitoring phase (2006)
  - Tuned diamond abort algorithm
  - Observed four aborts that diamond could have triggered sooner



- Was the primary CDF abort system for the last 4 years of Run II
- Post-operation assessment shows no degradation of sensors

ATLAS Diamond Pixel Sensor EOI

- Submitted 2007
- Institutions:
  - Bonn, Carleton, CERN, Ljubljana, Ohio State, Toronto
- Approved 2008
- Goals:
  - Make 10 modules
  - Industrialise fabrication
  - Test radiation hardness
- IBL sensor decision 2011
- B-layer replacement? 2013
- Tracker upgrade 2018?

ATLAS project	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	*Institute Document No.*	*Created:* **11/05/2007** *Modified:*	*Page:* **1 of 12** *Rev. No.:* **1.0**

Abstract

The goal of this proposal is the development of 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 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 1.8x10^{16} p/cm^2. In this proposal we outline the results in these three areas and propose a plan to build and characterize a number of diamond ATLAS pixel modules, 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 .

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)**		

Pixel Diamond Prototypes

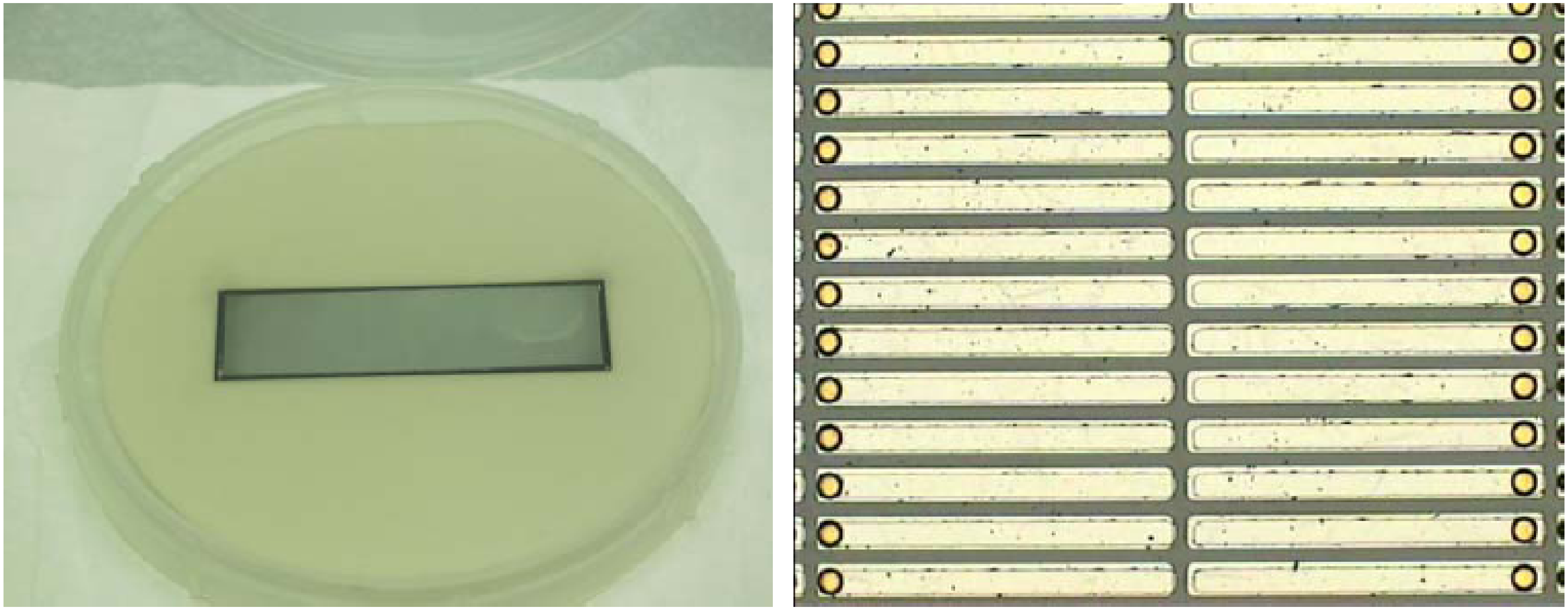


Figure 5: (a) Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b) Zoom view of the pixel pattern after the under-bump metal is deposited.

- Sensor metalised at Ohio State, bumps deposited at IZM-Berlin
- Transferring complete process to IZM

Diamond Pixel Prototypes

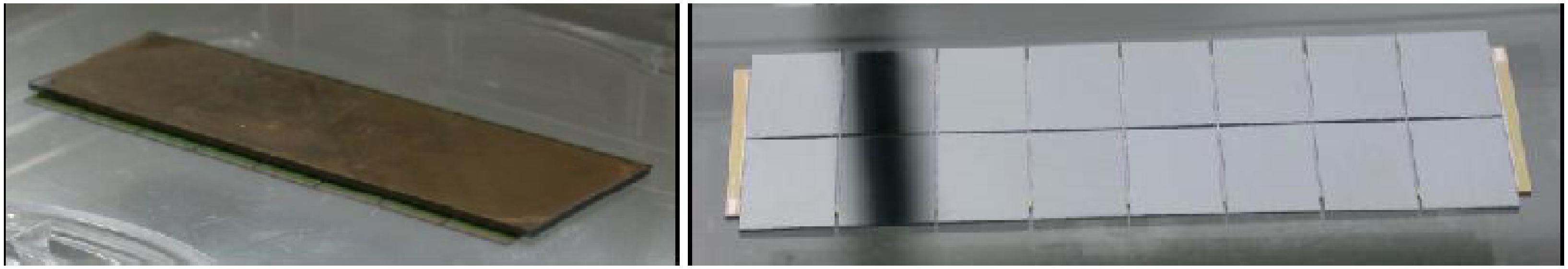


Figure 6: Photograph of the detector side (a) and electronics side (b) of the final ATLAS pixel module.

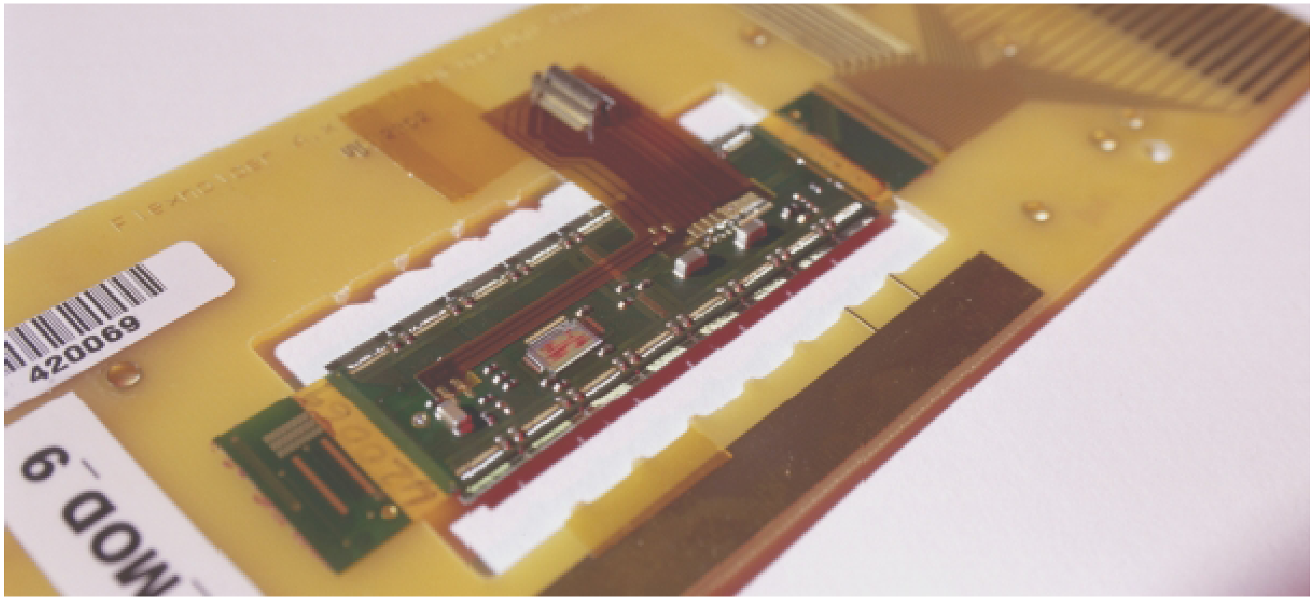
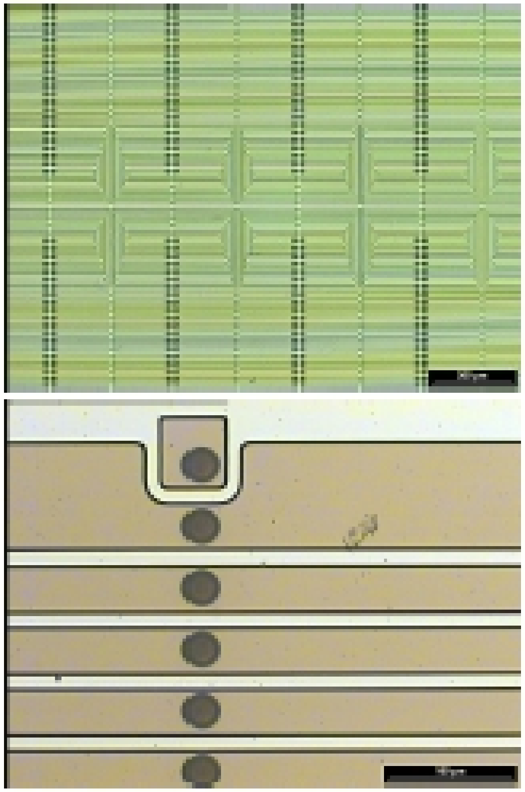


Figure 7: Photograph of the fully dressed diamond ATLAS Pixel Module ready for test.

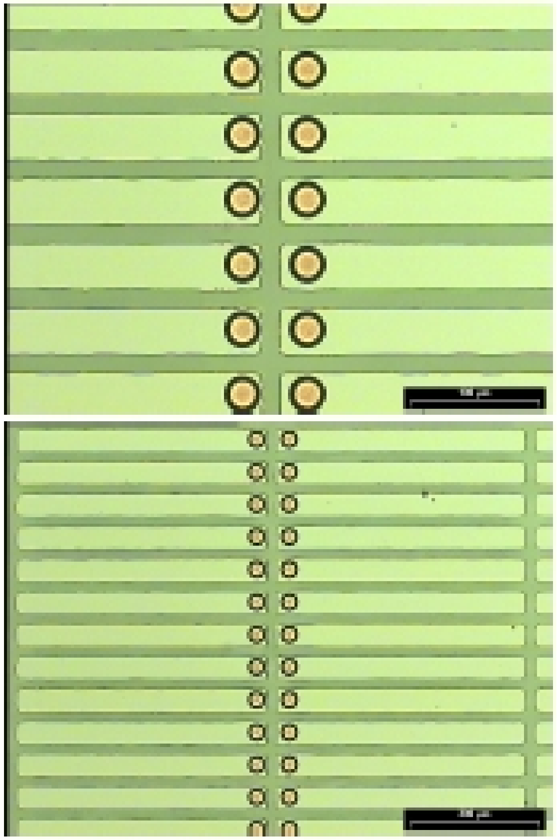
- Modules bump-bonded at IZM, tested at Bonn
- Noise: 140e^-, Efficient threshold: 1500e^-, In-time threshold: 2300e^-

Pixel Patterning in Industry (IZM-Berlin)

Diamond sensor pixel metallisation



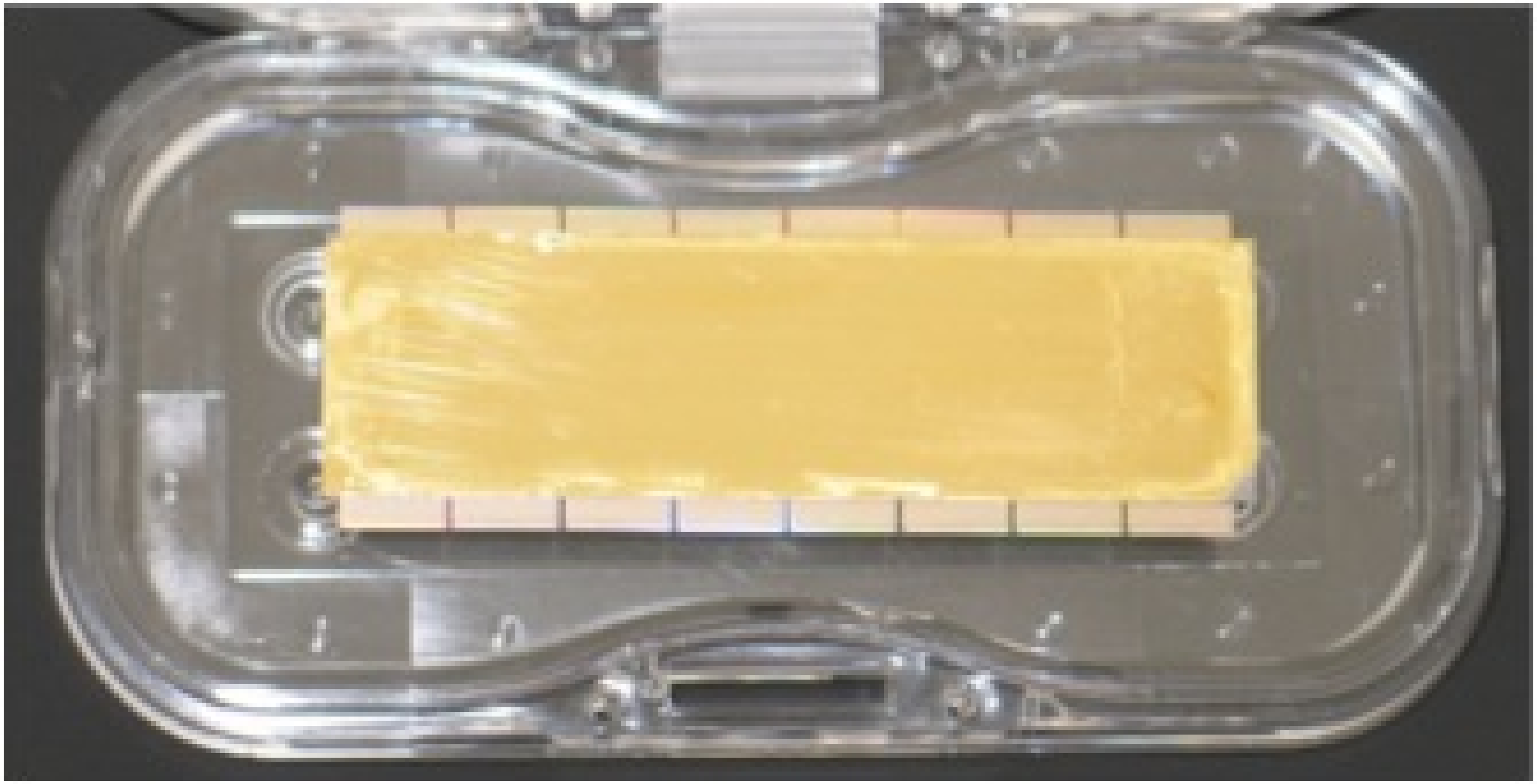
Status after elelctroplating of pad metallisation and lithography for pixel metallisation patterning



result after pixel metallisation patterning

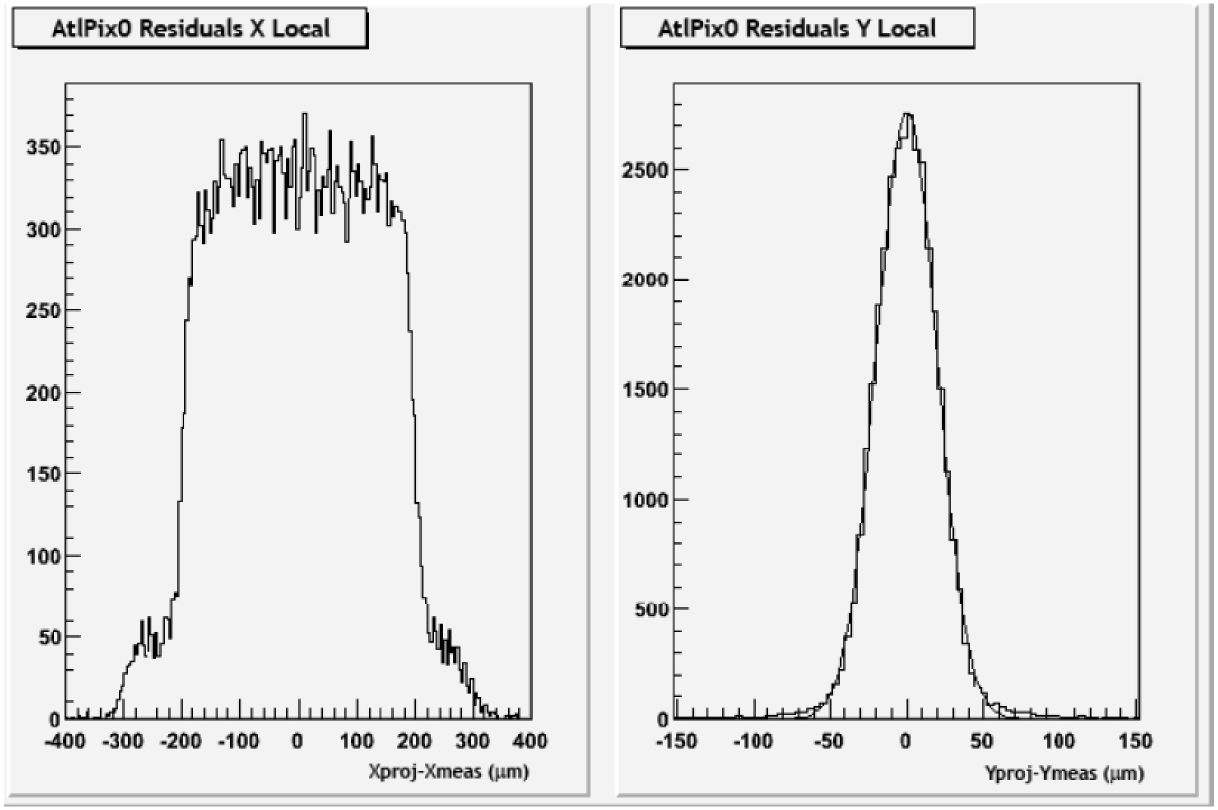
Fraunhofer Institut Zuverlässigkeit und Mikrointegration

First IZM Module



- Bump-bonded in early 2012
- In testbeam at CERN during last summer

Results from Pixel Prototypes



- Position resolution of 14μm (17μm residual includes telescope)
- Few % missing bonds – dominant inefficiency