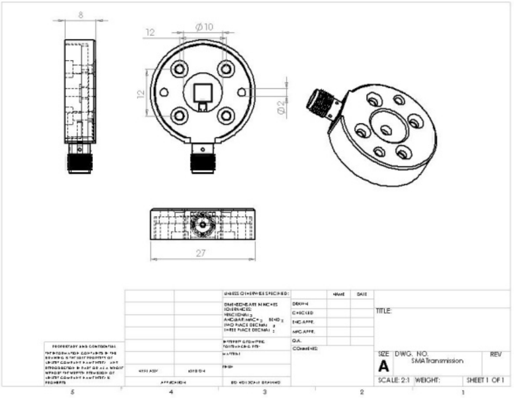
Practical Applications of

CVD Diamond Detectors



DDL : Kevin Oliver

Acknowledgements

- Element Six (Helen Murphy, Neil Perkins, Andrew Whitehead)
- RD42 (Harris Kagan, William Trischuk, Peter Weilhammer, Steve Schnetzer, Bob Stone)
- GSI/Nordhia (Eleni Berdermann)
- ESRF (John Morse)
- CEA (Phillipe Bergonzo)
- Scanditronix (Camilla Ronnqvist)

- Los Alamos National Laboratory
- CERN
- Fermilab
- Diamond Light Source/ Daresbury
- and many others...

Outline

- What makes diamond a good detector?
  - What can be detected by diamond?

- Diamond detector timeline

- Different types of diamond and its uses in different applications
  - Application of polycrystalline diamond: the Atlas Experiment
  - Application of single crystal CVD diamond: X-ray dosimetry
  - Fluorescence Detectors & Diamond Light Source

- Making diamond detectors available – Diamond Detectors Ltd

What makes diamond a good detector?

Intrinsic Properties

- Low Z (tissue equivalent)
- Low absorption
- High thermal conductivity
- Radiation Hardness
- Wide band gap (no thermally generated noise)
- High $\mu\tau$ product grades available (of same order as for GaAs)

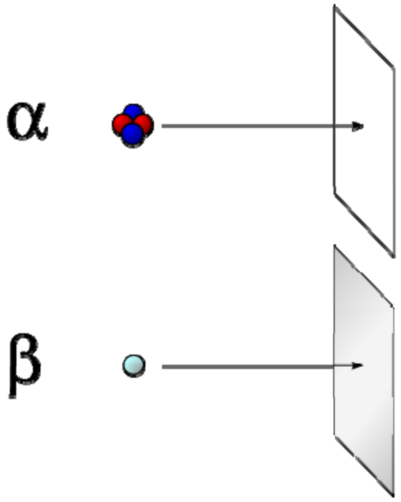
Detector Properties

- High sensitivity (application dependent)
- Good spatial and temporal resolution achievable
- Low (and stable) noise
- Low capacitance

Device Advantages

- Intrinsically simple device
  - can fabricate robust, compact devices
- High temperature operation (no need for cooling)

What can be detected by diamond?

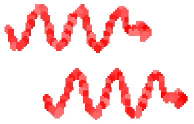


a) Charged particles e.g. Alpha, Beta, high energy ions

b)

Neutral particles for which diamond has a sufficiently high reaction cross-section e.g. neutrons with energies above 5.8MeV

c) Particles which can be converted into charged particles that can be detected by diamond e.g. thermal neutrons



d) Photons with energy > 5.5eV i.e. UV, X-ray and gamma rays

Diamond Detector Timeline

Natural Diamond

1920's	Naturals demonstrate UV response.
1940's	Naturals used to detect ionising nuclear radiation
1950's 1960's	Interactions of Alpha and high energy fast electrons with diamond studied
1962	Photoconductivity of naturals investigated
1970's	Advances made in forming electrical contacts to diamond
1980's	Commercial xray dosimeters for medical applications.

Polycrystalline CVD Diamond

early 1990's	Advances made in quality of polycrystalline CVD diamond Suggested use of pCVD in Super Conducting Super Collider. Commercial solar blind UV detector.
late 1990's	Beam position monitors for synchrotrons Charge Collection distance > 200 microns achieved suitable for high energy physics detector applications.

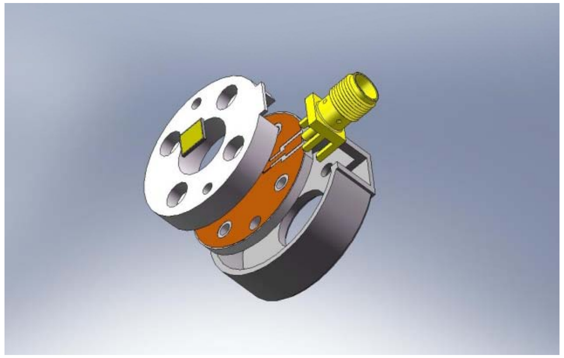
Single Crystal CVD Diamond

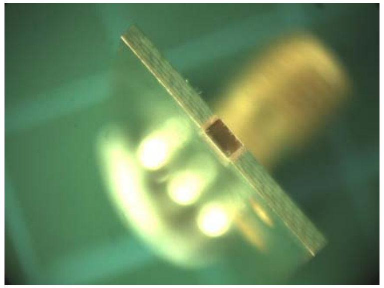
2000's	High purity single crystal CVD diamond with superior electronic characteristics.

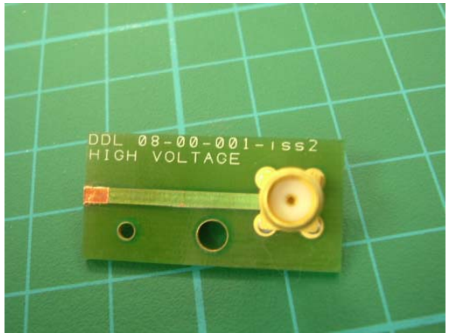
Diamond Detector Applications

A wide range of detector applications and detector types make diverse demands on the material

- Particle physics: beam condition monitors, trackers, beam abort systems
- Dosimetry: radiation therapy, equipment calibration, active exposure monitoring
- Nuclear applications: homeland security, nuclear reactors and fusion experiments
- Synchrotrons: white beam monitoring
- UV detectors: photolithography ,flame detection and solar physics
- Alpha/Beta: air-Flow and survey meters, waste incineration







Diamond Particle Detectors

High Energy Particle Physics: at CERN, BaBar, CDF etc
- solid state ionisation chambers- pixel, strip and dot detectors
- fluorescence detectors

(e.g. RD42)

Heavy Ions: start detectors and spectroscopy

(e.g. GSI and the Nordhia collaboration)

Neutron detection: nuclear industry, research and dosimetry
- Thermal neutrons: fluence and profile monitoring for nuclear reactors (e.g. Bergonzo *et al,* CEA)
- Fission neutrons : nuclear reactors (e.g. Schmid *et al,* Los Alamos)
- Fusion: Tokamaks (e.g. ITER)

Alpha and Beta detection:
- Energy resolution approaching that of silicon reported for high purity single diamond irradiated with Am-241.

Diamond Photon Detectors

Active Dosimetry : solid state ionisation chambers detecting x-rays or hadrons

(e.g. MAESTRO – “Methods and Advanced Equipment for Simulation and Treatment in Radiation Oncology” – EU funded project with a workpackage on diamond dosimetry

Synchotrons: solid state ionisation chambers and fluorescence detectors

continuous monitoring of white beams

Fluorescence detectors: work in progress for DLS (new UK synchrotron)
NSCL at MSU utilising hetero-epitaxial diamond
ESRF

UV detection: deep UV detectors.
Variety of applications for robust UV sensors that can survive harsh environment
e.g. Photolithography, Solar Physics (European Space Agency)
(e.g. Pace *et al*, Jackman *et al)*

Natural Diamond (ND) Detectors

ND detectors are made from highly selected natural stones

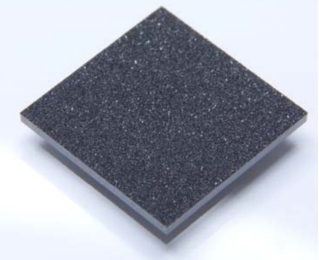
Applications include:

- dosimetry for use in medical physics and for calibration
- detecting proton spectra close to deuterium plasmas
- detecting high energy heavy ion spectra
- solar blind UV detectors

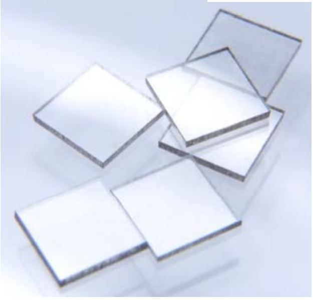
Cost and availability:

- only ~1% of all diamonds are type IIa
- a very small fraction of the 1% will ever make a useful detector.
  - You need to sort through many, many stones ...
- Even with extreme selection, the performance of ND detectors varies from one diamond to another
- Typical cost >> €2K

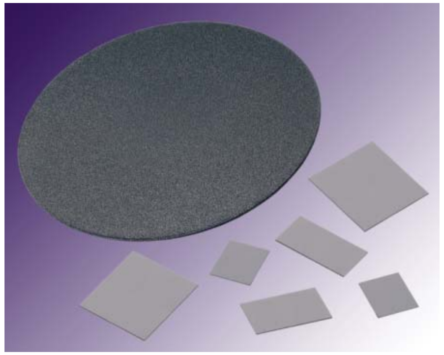
Choice of CVD Diamond Grade/Type

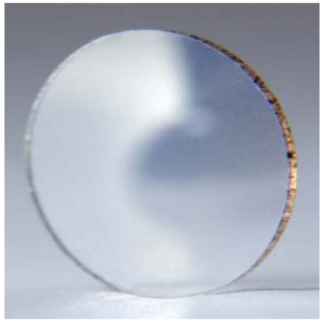


Differing types/grades of CVD diamond
- very different properties

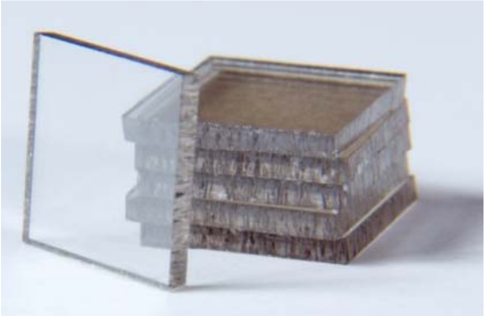


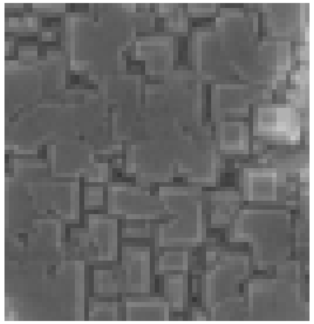
Selection based on desired detector performance, considering:





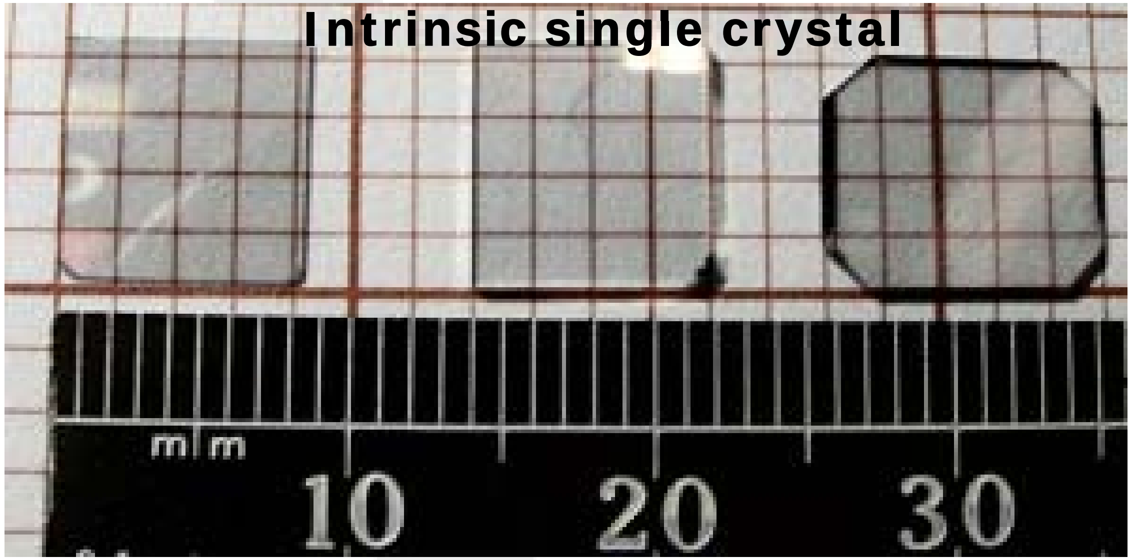
Key Considerations
Detector type
Charge Collection Distance (CCD)
Detector Area
Fast decay time
Operating voltage
Low leakage through bulk
Minimum beam perturbation
Flourescence
Opacity





Electronic grades of CVD diamond


Intrinsic Polycrystalline


Intrinsic single crystal

μ_e = 1800 cm^2/Vs
μ_h = 1000 cm^2/Vs
V_{BD} ~ 0.5 MV/cm

CCD ~250 µm at 1 V/µm field

μ_e = 4500 cm^2/Vs
μ_h = 3800 cm^2/Vs
V_{BD} ~ 4 MV/cm

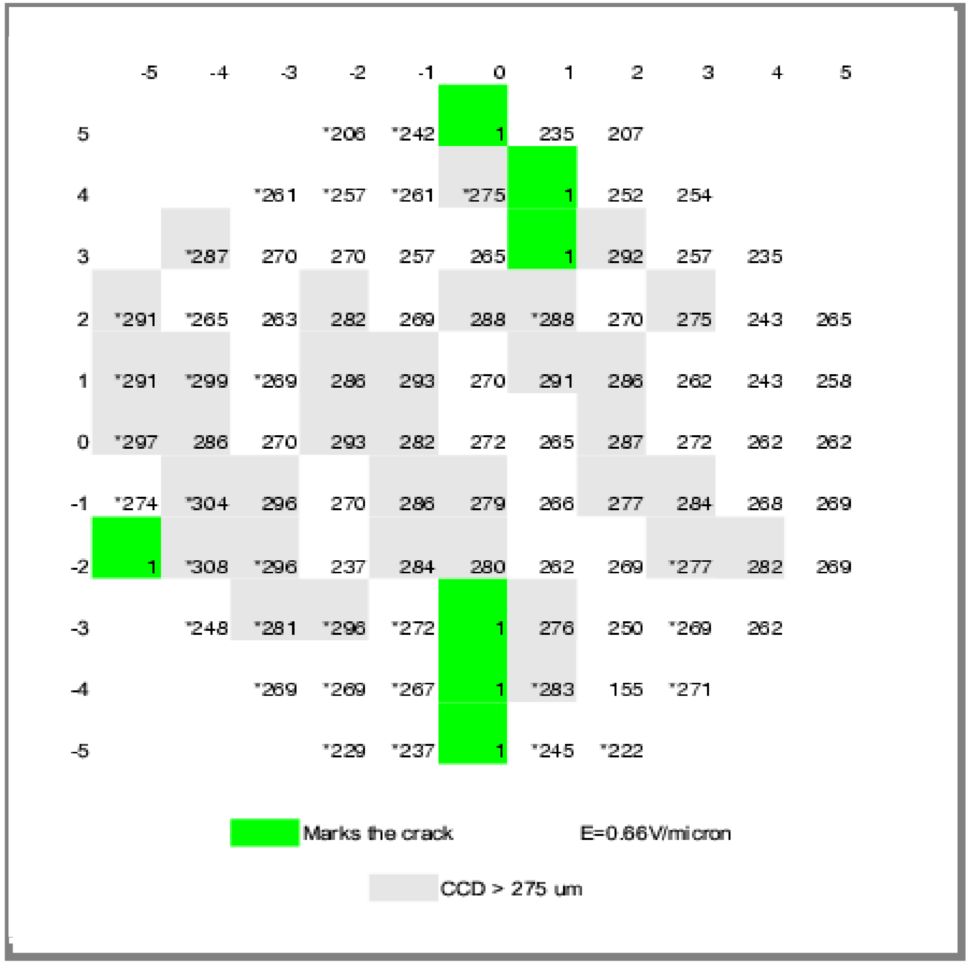
CCD is thickness limited

EL Polycrystalline CVD Diamond (E6)

Developed for use in HEP experiments

Charge collection efficiency at 1V/µm: >40%
Charge Collection Distance at 1V/µm: >200 µm
- Low nitrogen content
- Large grains

High breakdown voltage
- Low sp^2 incorporation

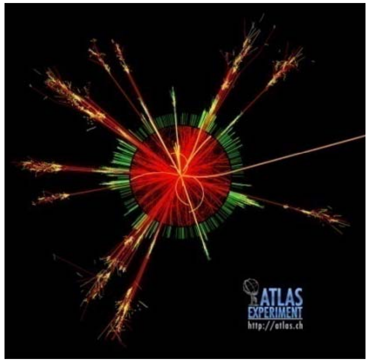


	-5	-4	-3	-2	-1	0	1	2	3	4	5
5				*206	*242	1	235	207			
4			*261	*257	*261	*275	1	252	254		
3		*287	270	270	257	265	1	292	257	235	
2	*291	*265	263	282	269	288	*288	270	275	243	265
1	*291	*299	*269	286	293	270	291	286	262	243	258
0	*297	286	270	293	282	272	265	287	272	262	262
-1	*274	*304	296	270	286	279	266	277	284	268	269
-2	1	*308	*296	237	284	280	262	269	*277	282	269
-3		*248	*281	*296	*272	1	276	250	*269	262	
-4			*269	*269	*267	1	*283	155	*271		
-5				*229	*237	1	*245	*222			

🟩 Marks the crack E=0.66V/micron

▨ CCD > 275 um

Polycrystalline Diamond Detectors



Diverse requirements for Beam Condition Monitoring in high energy particle physics

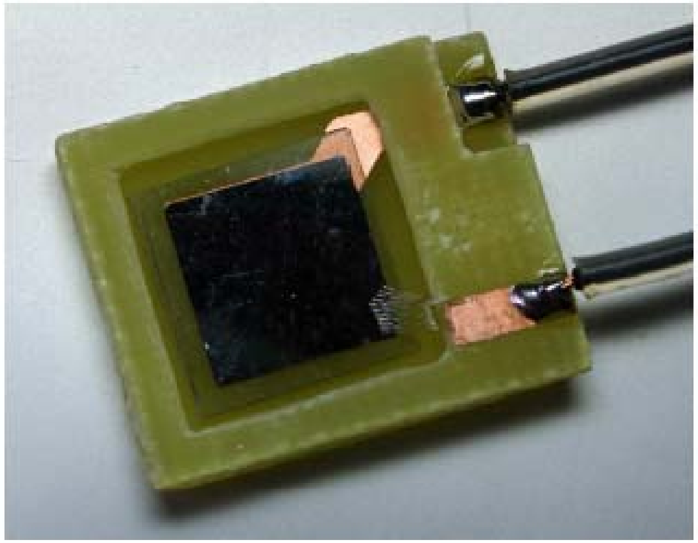
Single particle counting

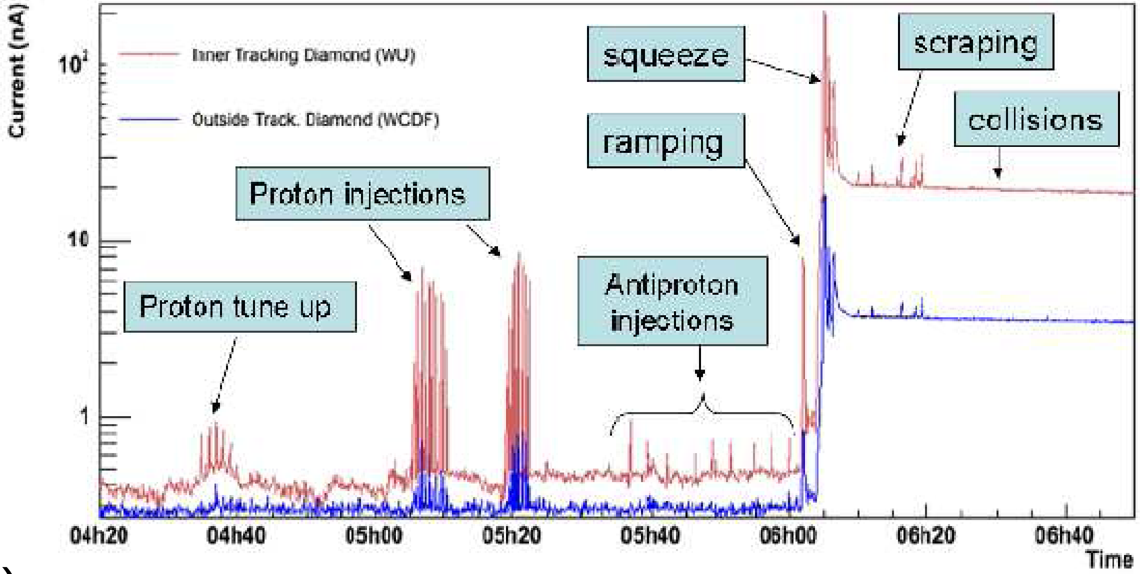
Example:
ATLAS @ CERN, Switzerland

Particle flux measurement

Examples:
Babar @ Stanford, USA
Belle @ KEK, JAPAN
CDF @ Fermilab, USA

Flux Measurement at CDF





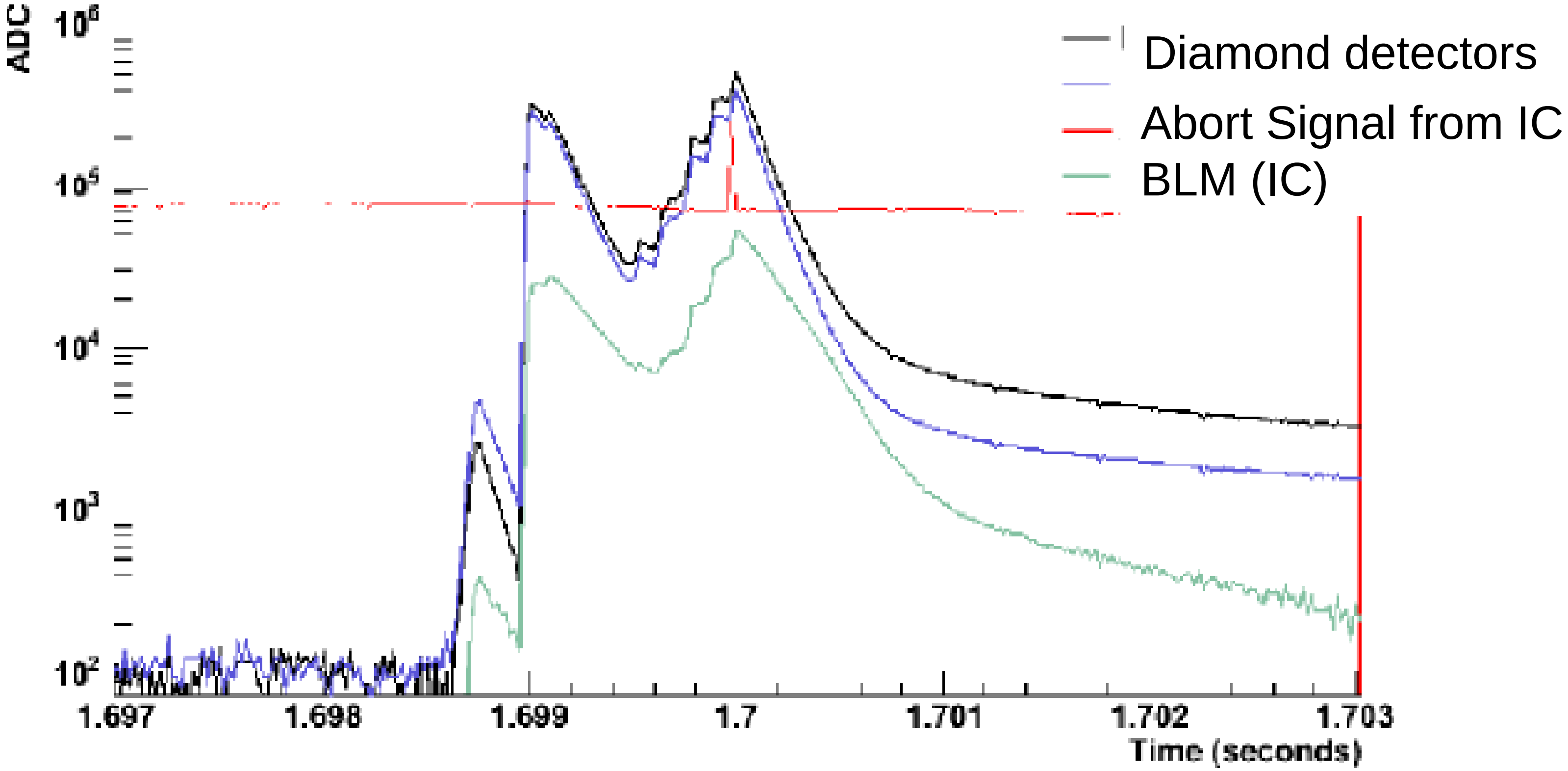
The Collider at Fermilab (CDF)

- 2 pCVD diamond detectors since 2004
- Their performance paved the way for the ATLAS BCM.

Now has 13 pCVD diamonds : 8 inside and 5 more outside near the existing beam loss monitor (BLM).

A BLM monitors the beam and will shut it down if it detects a problem.

Beam Incident at CDF



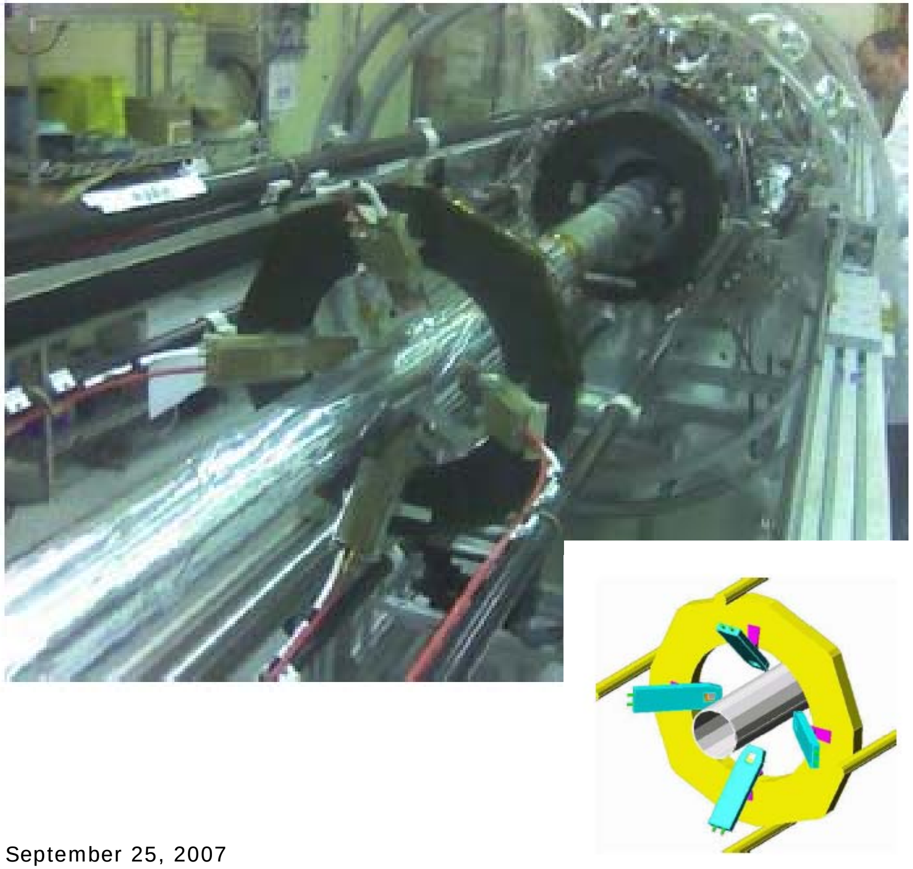
During a beam Incident (November 2006):

- Diamond detectors and ionisation chambers were monitoring the beam
- Diamond responded quicker
- Diamond detectors now being commissioned.

Single Event Detection at ATLAS :

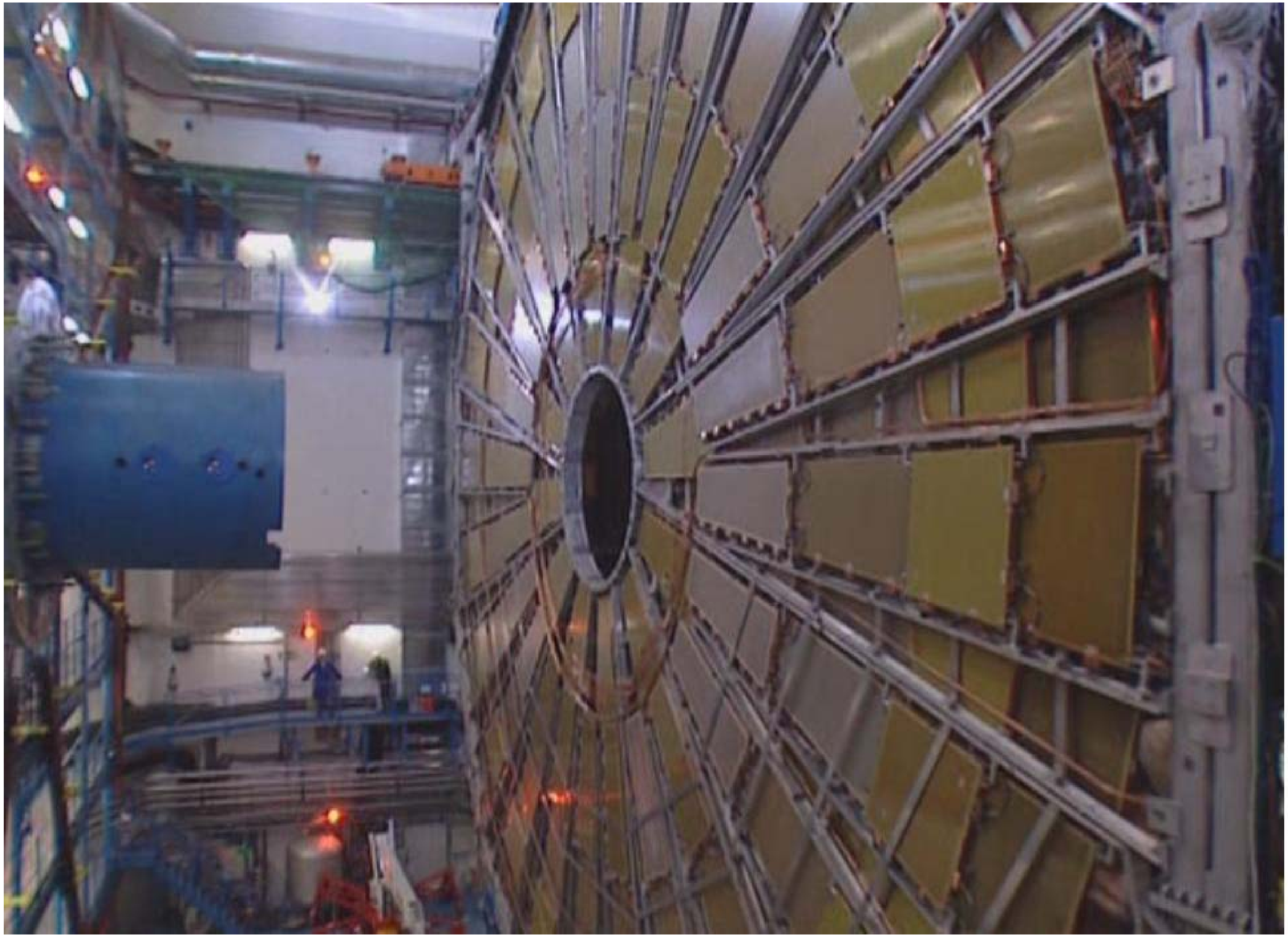
The ATLAS Beam Conditions Monitor (BCM)

Time of flight measurement to distinguish collisions from background

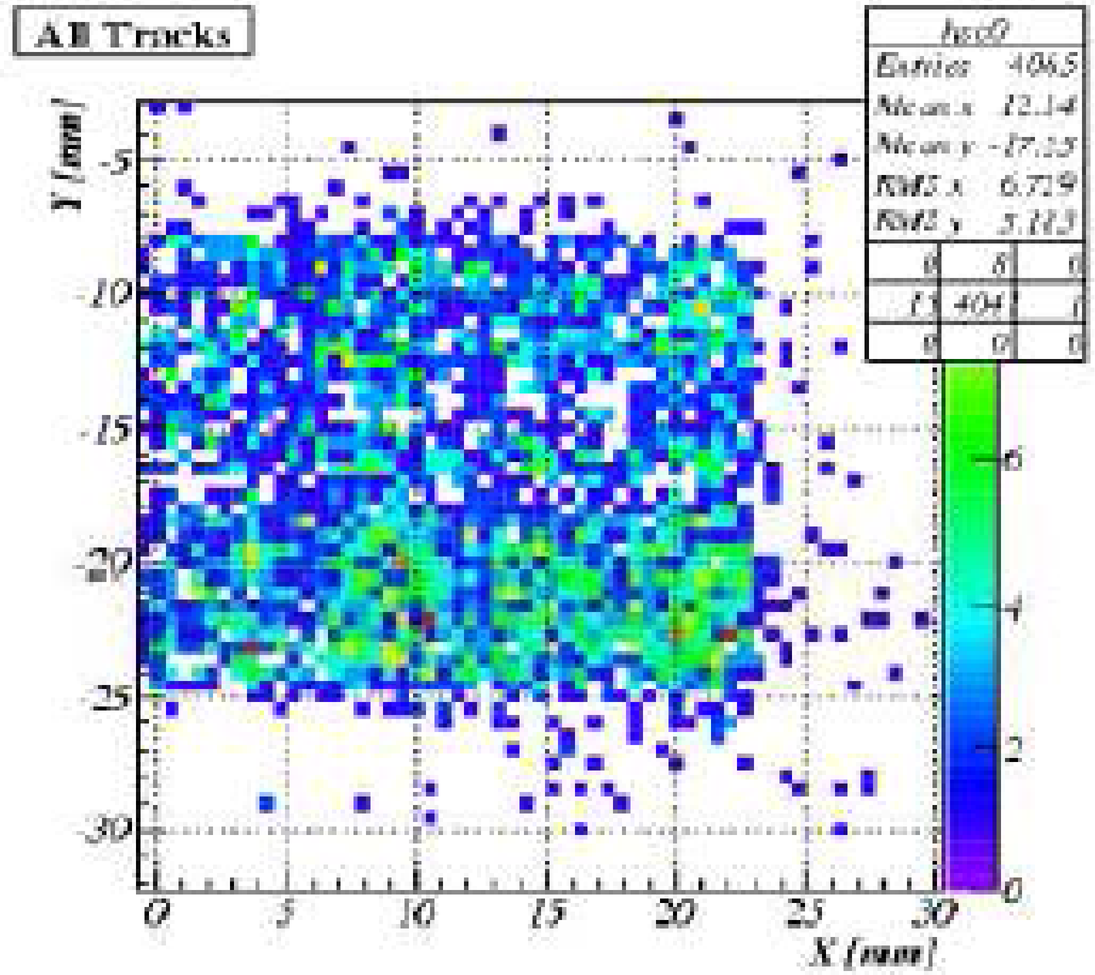


- Tracking devices close to interaction region
- Single particle counting
- Requires low noise and fast readout
- High precision tracking
- Allows timing correlations
- Must survive harsh environment for 10 years

ATLAS Detector, CERN



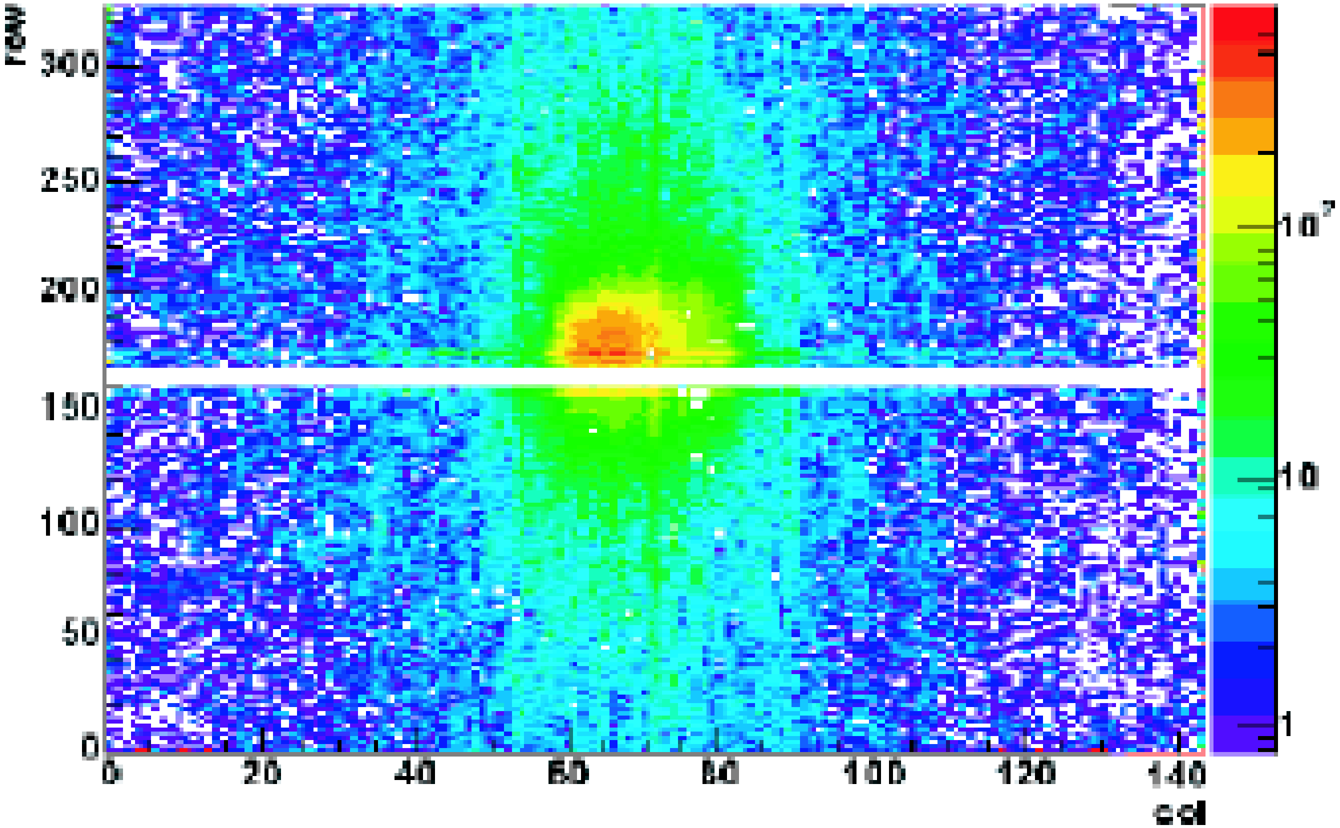
Data from ATLAS BCM (Installed January 2007)



Meets all of the design specifications

Module Signal to noise ~13:1
(specification 10:1)

Large EL Polycrystalline Pixel Detector 64x19mm

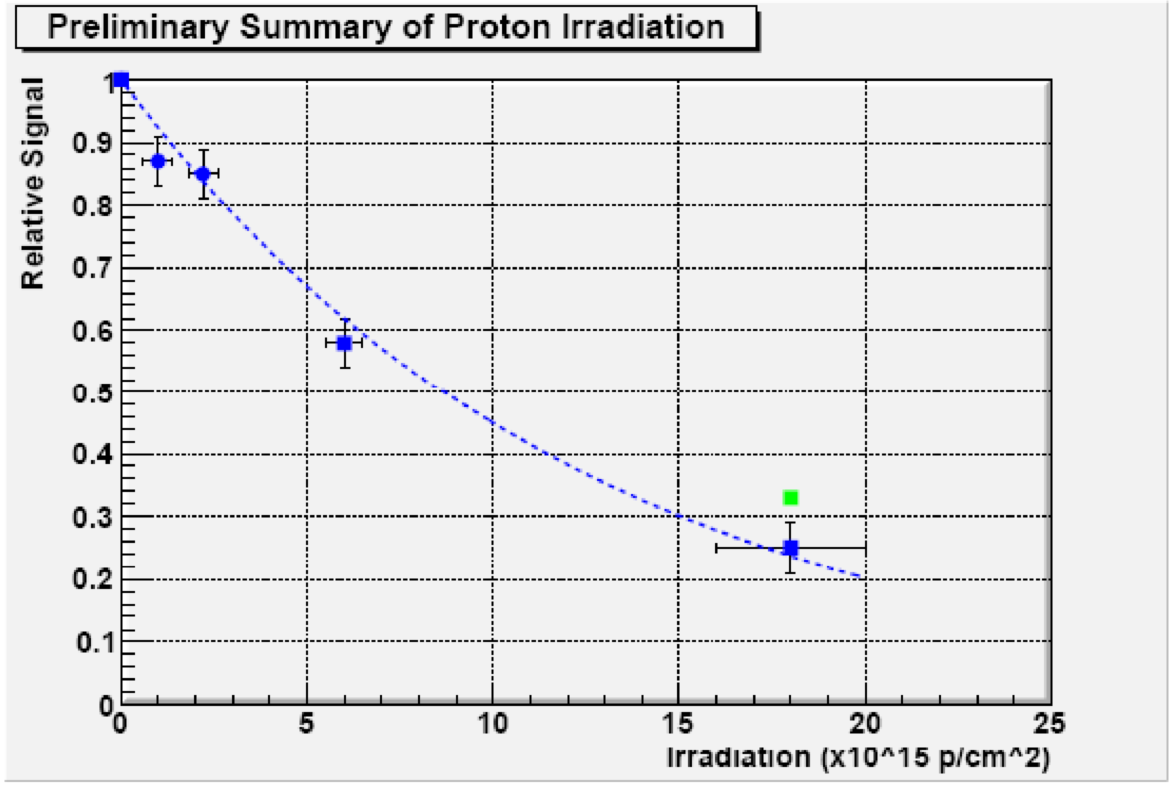


- Pixel detector ~45000 pixels
- Pitch 50 x 400 microns
- Resolution ~ pitch/ $\sqrt{12}$

Particle beam intensity map taken at Large Hadron Collider, CERN

Radiation Hardness : Polycrystalline Diamond

Proton Irradiation of EL Poly Tracker



ATLAS detectors must withstand 50 Mrad over 10 years

Accelerated test
1.8×10^{16} p/cm^2
~500Mrad
24 GeV protons

Blue E=1V/µm
Green E= 2 V/µm

Fluorescence Detector for Diamond Light Source

Diamond Light Source (DLS) is a new synchrotron at Harwell, UK

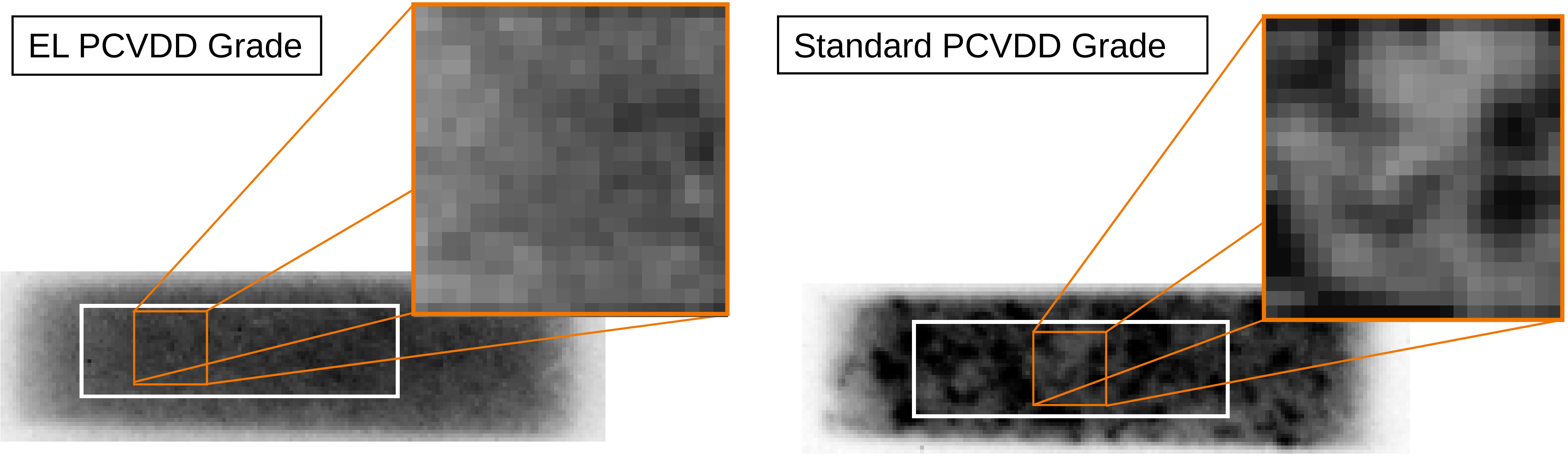
A range of different poly CVD diamond grades are being evaluated for use as a large area fluorescence detector at DLS

Why a diamond detector for the synchrotron?

- **Excellent Thermal Conductivity-** can withstand heat-load of white beam Therefore can provide continuous white beam monitoring - unique!
- **Excellent Mechanical Stability-** can provide a vacuum barrier. Therefore can act as window <u>and</u> beam position monitor
- **Low absorption of X-ray and visible light**
- **Can be brazed or diffusion bonded**
- **Thin samples allow attainment of higher spatial resolution due to the focal plane of the imaging camera**

Fluorescence Detector for Diamond Light Source

Preliminary results from Drakopoulos *et al* at Daresbury, UK:



EL PCVDD Grade

Standard PCVDD Grade

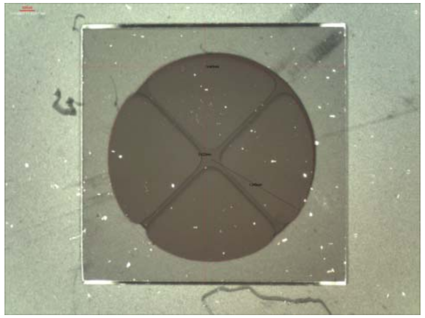
Images of visible light fluorescence excited by 10 keV x-ray radiation

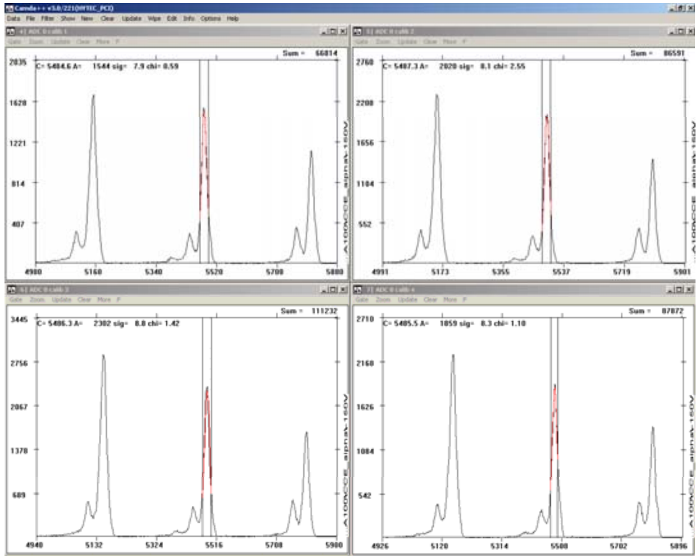
	Relative Luminescence Yield per deposited power	**Comments**
EL PCVD D	**1423**	**Most uniform luminescence**
Optical grade	**1177**	
Standard grade	**397**	**Less uniform luminescence** **Speckle - unsuitable**

Single Crystal CVD Diamond Detectors

High purity electronic grade SC CVDD:

- High charge collection efficiency (approaching 100%)
- High mobilities
- High spatial resolution
- High energy resolution
- High sensitivity in some applications
- Lower saturation field (0.2 V/μm).
- Low energy and angular dependence (Xray)
- Radiation hard





Diamond Dosimetry in Radiation Therapy

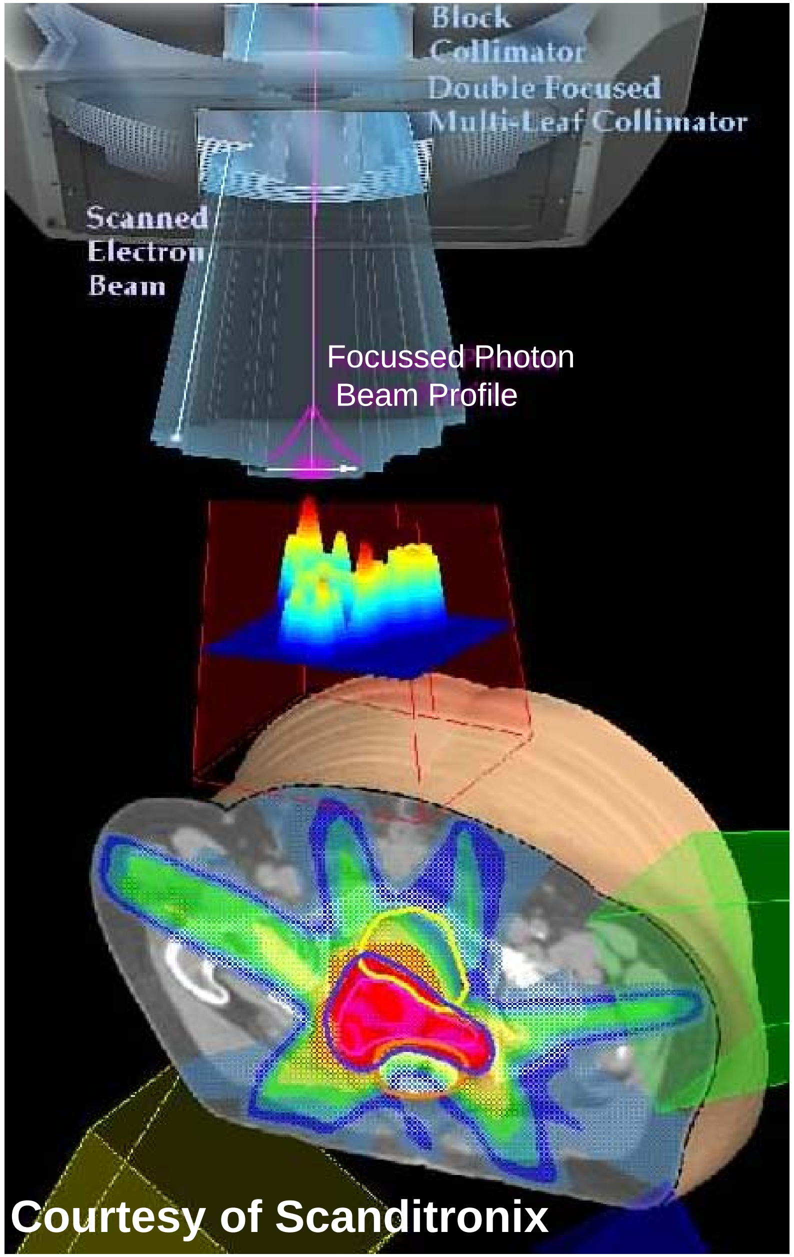
Intensity Modulated Radiation Therapy (IMRT): a new technique for cancer treatment driving improvements in dosimetry

Scanditronix Wellhöfer (SW) provide high-end dosimetry equipment for use in hospitals and industry across the world.

IMRT demands high spatial resolution.

Arrays are desirable to speed up the mapping process.

Commercial production of SC detector material is allowing SW to switch from silicon detectors and ionisation-chambers to synthetic diamond.



Courtesy of Scanditronix

Example Application of EL SC CVD Diamond:

Intensity Modulated Radiation Therapy

Before treatment of patient:

- Dummy run with detector
- Detector placed in tissue equivalent material to assess beam profile
- Detector must be moved several times to collect enough information
  - an array of detectors would be ideal

Treatment:

- Patient typically receives 3 treatments, each from a different angle of entry

X-ray Sensitivity for Different Diamond Typ

Sample Type	Dose Rate (Gy/min)	Signal (nC/Gy/mm^3)	Priming (Gy)
E6 High Purity SC CVDD	0.5	308	0
E6 Standard purity SC CVDD	2	26	3
Commercially available natural diamond dosimeter	2	48	8

Data for samples irradiated with 5MV X-ray beam courtesy of Scanditronix

High Purity SC CVD diamond gave ~6x signal of commercially available natural diamond dosimeter

X-ray Sensitivity Comparison for Different Dosimeter Types

Higher sensitivity of High Purity SC CVDD

⇨ **Smaller devices**

⇨ **Improved spatial resolution**

	E6 HP SC CVD diamond	Commercial Silicon dosimeter	Air-filled Ionisation chamber
Sensitivity (nC/Gy)	240	74	7.5
Active Detector Volume (mm^3)	0.3	0.2	120

Data for samples irradiated in a 6MV photon beam with a 10cm x 10cm field at a source-to-detector distance of 100cm, courtesy of Scanditronix

Tailoring Diamond for Applications

Overview

A diamond detector is an intrinsically simple device

BUT

Its performance is critically dependent on:

- Surface preparation
- Edge preparation
- Metallisation
- Packaging

These activities need to be bespoke to each application and potentially to each customer.

Diamond Detectors Ltd (DDL)

Why DDL was created?

- The focus of Element Six Ltd is on material development and bulk material synthesis.
- The detector market requires a diverse range of engineered products and skills. Including development, manufacture and sales.
- DDL has been formed to provide market focus and develop a range of packaged devices. To provide research and industry with a partner capable of providing the added processes needed to take diamond from material to characterised detector.

DDL was formed in February 2007, and now consists of a small experienced team.

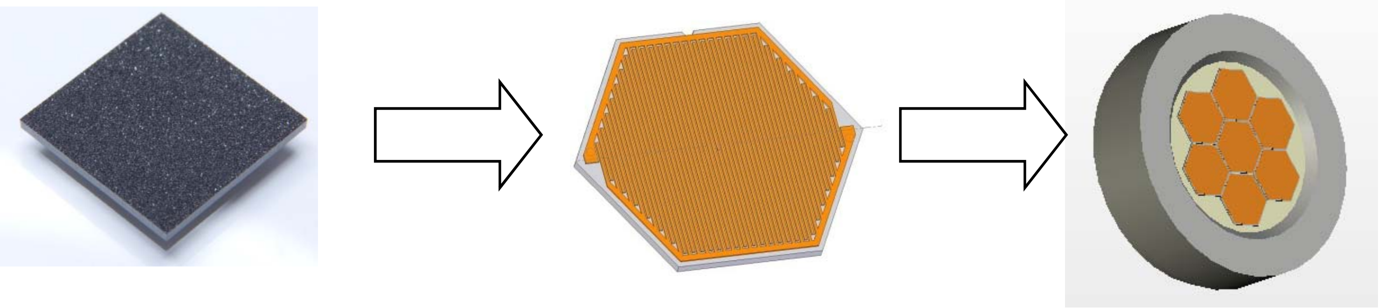
DDL – Providing Detectors

Diamond
Synthesis
Element Six

DDL
- Material Processing
- Die Fabrication and Test
- Die/Wire Bonding.
- Packaging
- Characterisation.

Market Driven
Requirements or
Specification

Packaged Solutions to
Customers in R&D and Industry

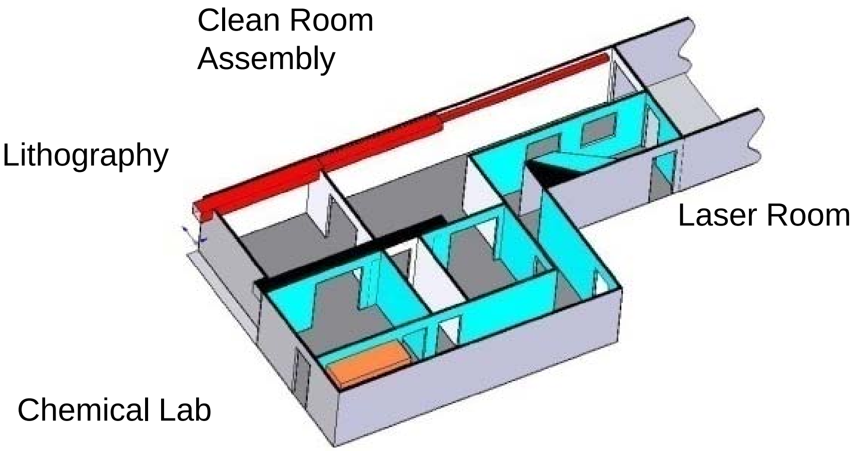


DDL – Roadmap – 2007/08

- Phase-I (2007 - Q3)
  - Technology Transfer from E6 to DDL (Completed)
  - Build Start (access to premises from 2nd June 2007)

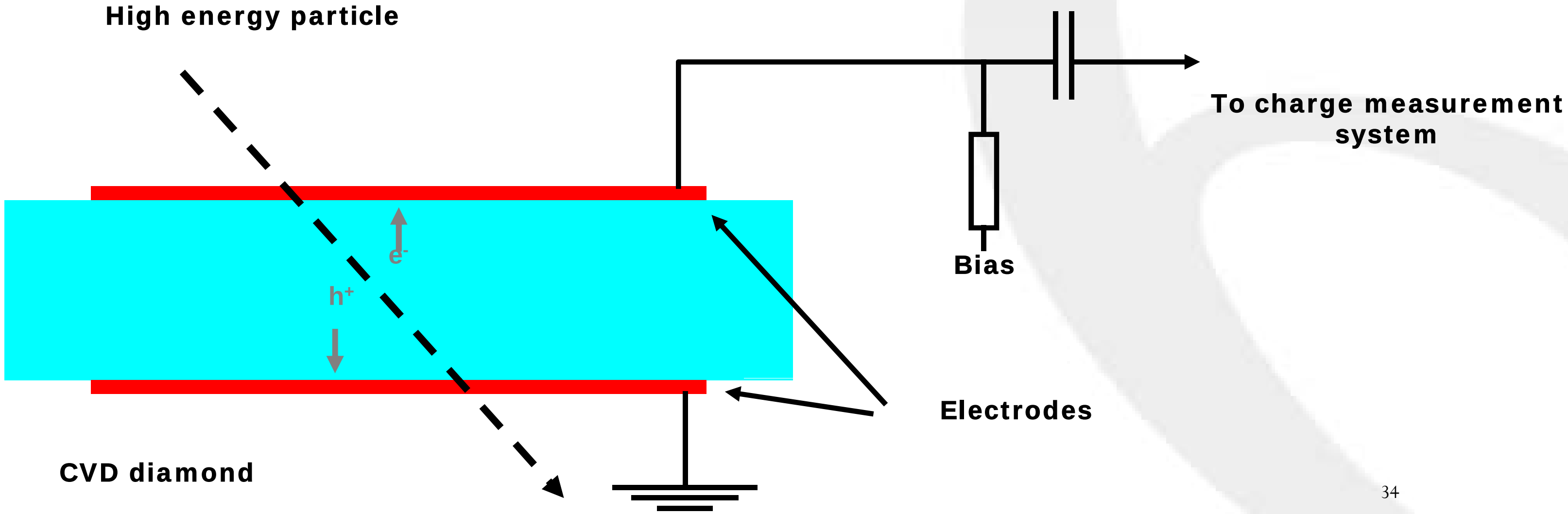
- Phase-II (2007 - Q4)
  -Fabrication and packaging of simple devices
  - Build Completion.

- Phase-III (2008)
  -Fabrication and packaging of more complex devices



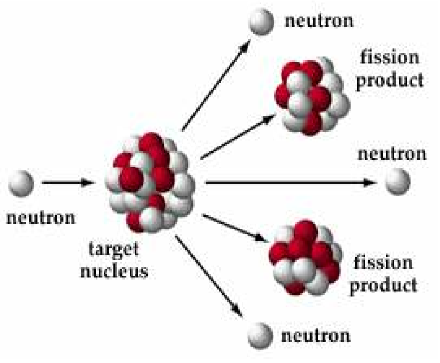
DDL- Markets

• **HEP**	**:- High Energy Physics Community.**
• **X-rays**	**:- Medical/Health Physics (High Flux Applications)**
• **UV (<220nm)**	**:- Photolithography, Flame, Military Application**
• **Neutrons**	**:- Reactor Monitoring, Military Dosimeters, Well logging**
• **Alpha /Beta**	**:- Air Flow, Nuclear Waste Incineration, Military.**



DDL – Target Market Example

Neutron Detection



Neutrons "Well Logging & Reactor Monitoring"

Logging companies have confirmed interest/merit in replacing ^{3}He tubes.

Logging while drilling is more important in deeper wells and in modern technologies like horizontal drilling.

Current solutions last 1 - 6 hours in this harsh high temperature/pressure environment.

In 2001 there were 2018 rotary rigs operations world wide.

Material Summary

- From early experiments using naturals, diamond detectors have now grown into diverse applications with substantial commercial opportunities.
- CVD diamond provides consistent performance, and is much more available than natural diamond
- The grade of CVD diamond, including whether it is SC or poly, needs selecting according to application.
-

Market Summary

- New markets are being opened up by improved material quality, larger available sizes, and an increased understanding of diamond performance
- New diamond detector applications are being driven by technological advances in other fields e.g. radiation therapy
- In exploitation of diamond detectors careful device fabrication is essential
- A new detector company, Diamond Devices Ltd, has been set up to service these markets

DIAMOND DETECTORS LIMITED

The End
Thank you

CVD-SC Diamond Characteristics

	Impact	Si	GaAs	4H SiC	GaN	Diamond	Units
Max. Electric Field	**P_{out} (V_{max})**	0.31	0,48	3	5	**20**	MV/cm
Electron Mobility	**R, f_t, P_{out}(I_{max})**	1450	8600	900	2000	**4500**	cm^2/Vs
Hole Mobility	**R, f_t, P_{out}(I_{max})**	480	130	120	200	**3800**	cm^2/Vs
Saturation Velocity	**f_t**	0.86	0.72	2	2.5	**2.7**	10^7 cm/s
Thermal Conductivity	**P_{out}(T), f_t (T)**	1.5	0.46	5	1.3	**24**	W/cmK

Comparison of material properties [R : series resistance, f_t = current gain cut-off frequency, I_{max} = maximum current density, V_{max} : maximum bias voltage, P_{out} = maximum output power]

Single particle detection with a risetime less than 300ps and the (1/e-) falltime is 1ns

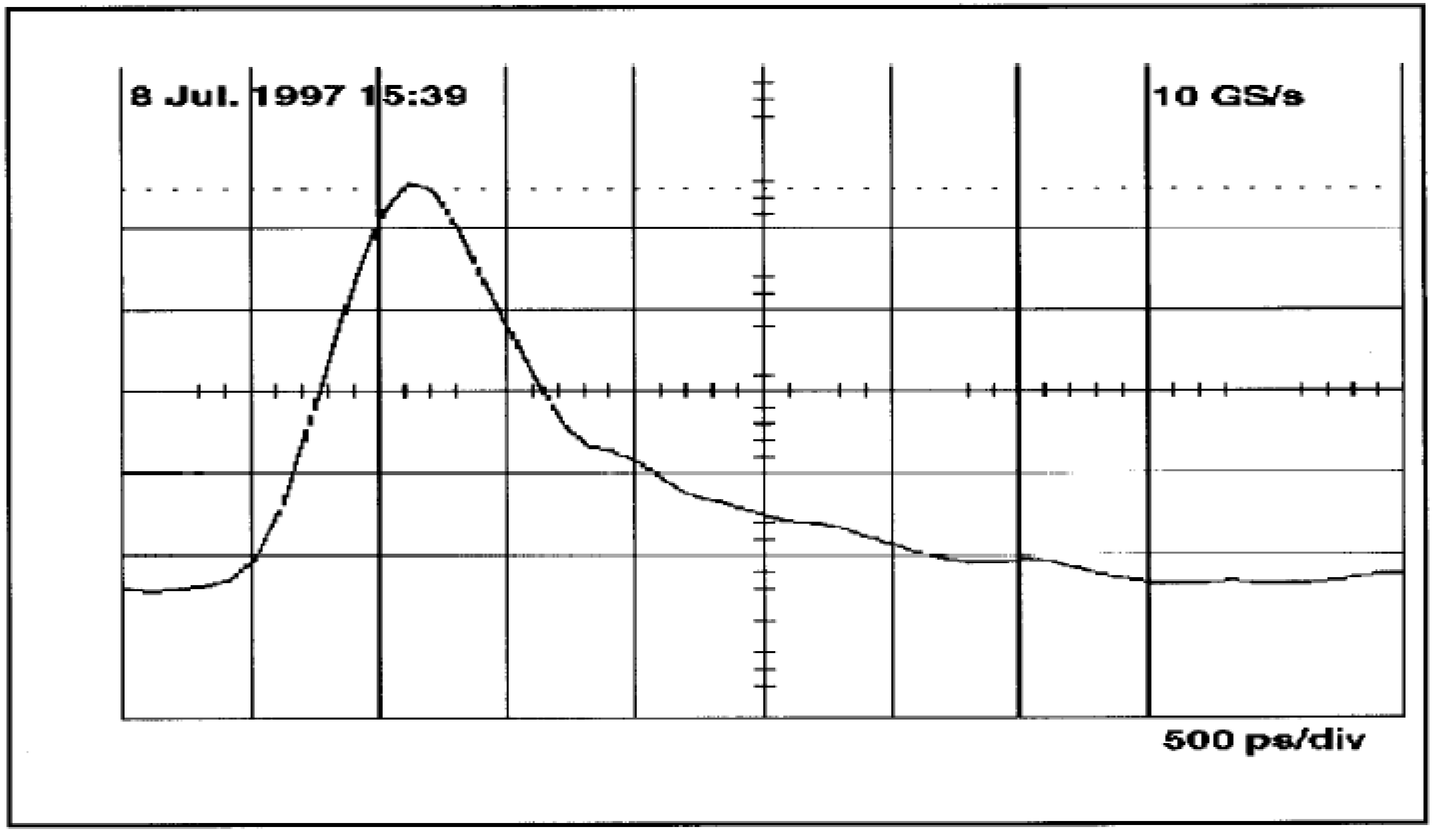
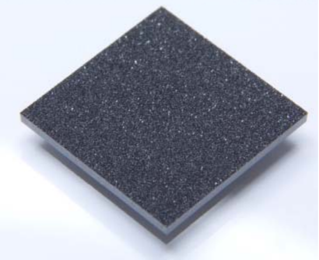


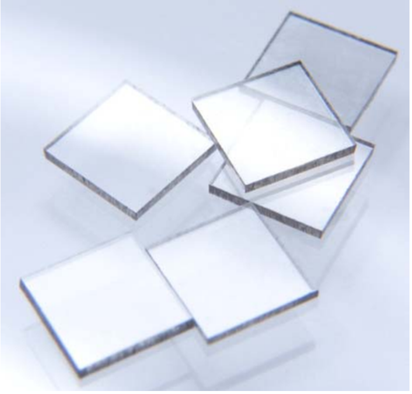
FIGURE 2. Diamond detector signal from a single ^{12}C ion at 200 MeV/u.

From paper Diamond for Subnanosecond time resolution GSI

Choice of CVD Diamond Grade/Type



⇦ **Differing types/grades of CVD diamond**
- very different properties ⇨



Selection based on desired detector performance, considering:

Key Considerations	**Material Selection**
Detector type	Ionisation Chamber style, Thermoluminescence, …
Charge Collection Distance (CCD)	> 200 μm for high quality thick poly ~100% efficiency for high purity single crystal. (CCD determined by sample thickness)
Detector Area	Polycrystalline material: up to 140 mm diameter Single crystal: up to 5 x 5 mm pieces available in volume – can be tiled
Fast decay time	Select material containing sufficient traps, **or** If high CCD also required: Thin high quality single crystal
Operating voltage	Polycrystalline material: high quality poly enables device operation at up to 2 V/μm. (In poly, ccd varies linearly with applied field). High purity single crystal: enables lower operating voltages (ccd saturates at ~0.2 V/μm)
Low leakage through bulk	High quality poly High purity single crystal
Minimum beam perturbation	Thin high purity single crystal of high crystalline quality,
Flourescence	Select grade to give desired level of fluorescence and absence of speckle
Opacity	Do you want visible light to pass through, such as laser light?