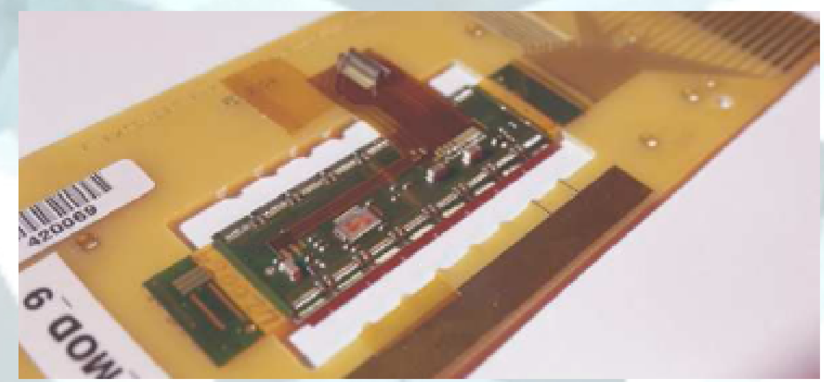
Radiation Hardness Studies of Diamond for Tracking Applications



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For the RD42 Collaboration

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RD-42 Collaboration

RD42 Collaboration 2010

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Diamond as sensor material

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	✪ Low leakage
Breakdown field [V/cm]	10^7	3×10^5	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	2.3×10^5	
Intrinsic carrier density [cm^{-3}]	$< 10^3$	1.5×10^{10}	
Electron mobility [cm^2/Vs]	1900	1350	
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	$0.9(e)-1.4(h) \times 10^7$	0.82×10^7	
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	
Interaction length [cm]	24.5	45.5	
Spec. Ionization Loss [MeV/cm]	6.07	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	★ Low signal, ✪ Low Noise
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323	

Signal from diamonds

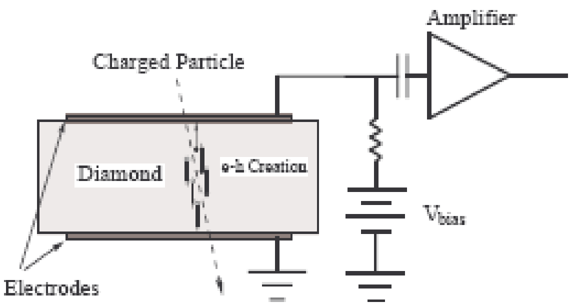
- No processing: put electrodes on, apply electric field
- Traps determine signal size
  - much like in heavily irradiated silicon
- Introduce Charge Collection Distance, defined by

$d = d_e + d_h = (\mu_e\tau_e + \mu_h\tau_h)E$

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

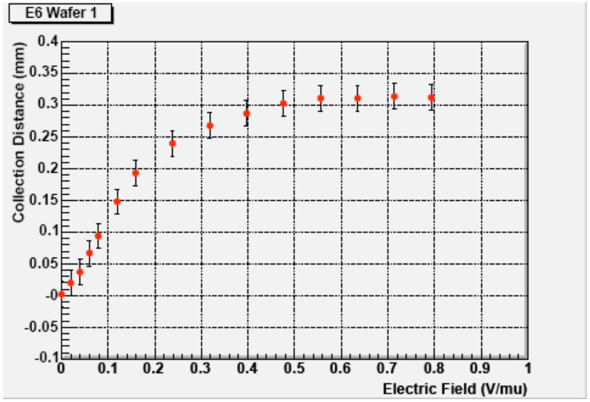
t = detector thickness

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



$\mathrm{CCD} = Q_{col}/(36e/\mu m)$

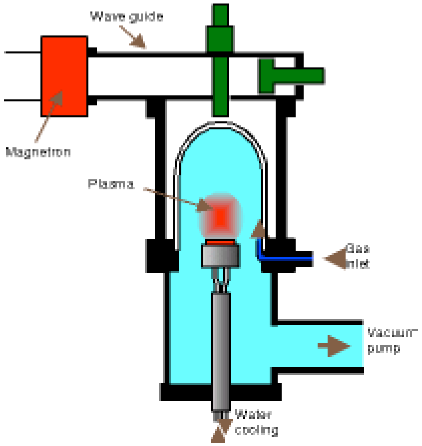
CCD related to **mean** not **most probable charge**



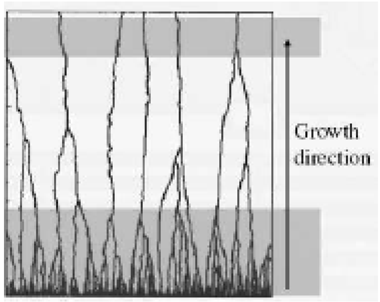
CCD measured on recent 1.4 mm thick pCVD wafer

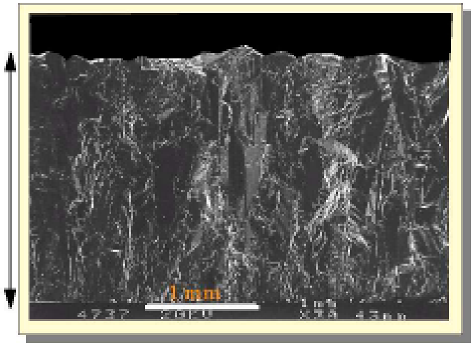
CDV Diamond Sensor Types

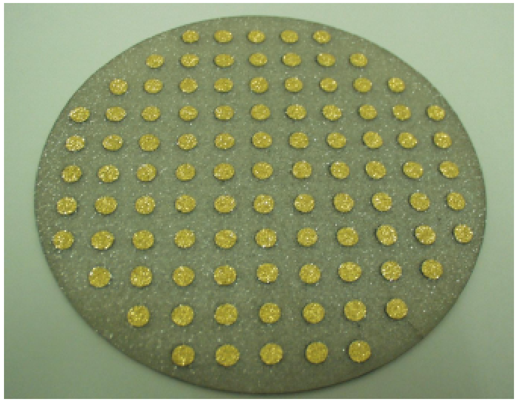
Micro-Wave Reactor Schematic



- 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

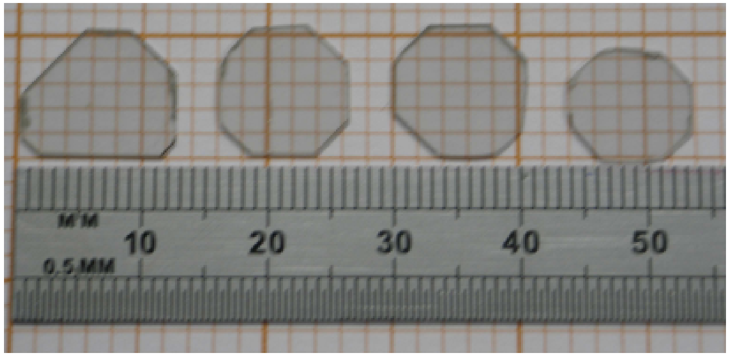




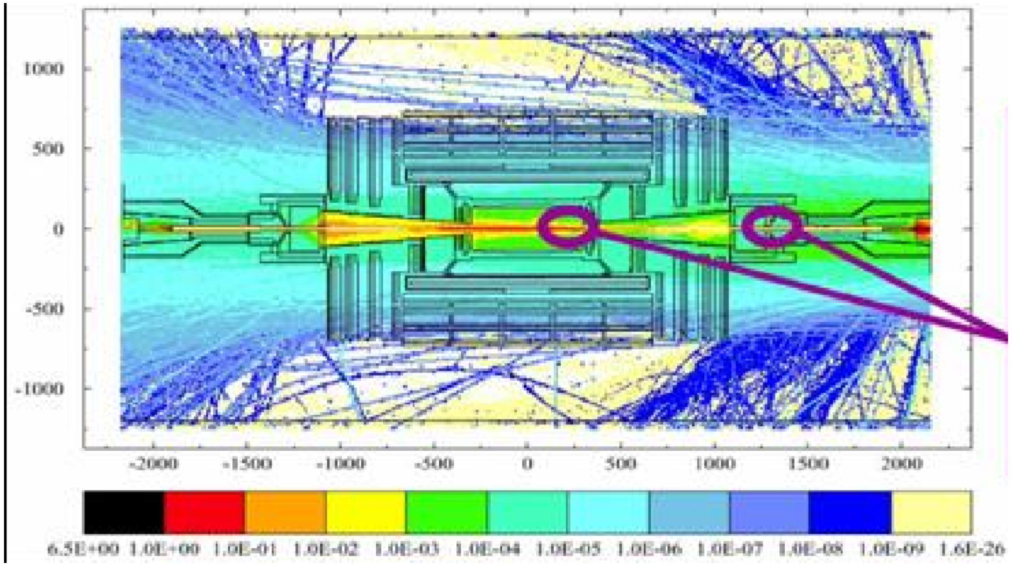


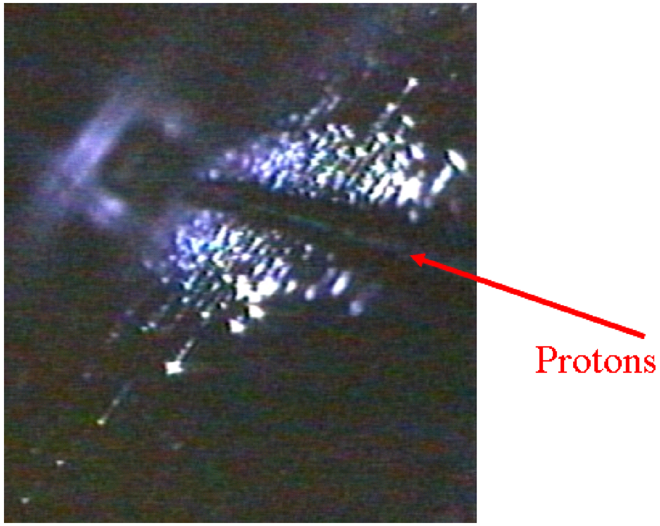
Test dots on 1 cm grid

- Single Crystal
  - Grown in μ-wave reactors on diamond substrate
  - Exist in ~ 1cm^2 pieces, thickness > 1 mm



The First Key: Radiation Tolerance

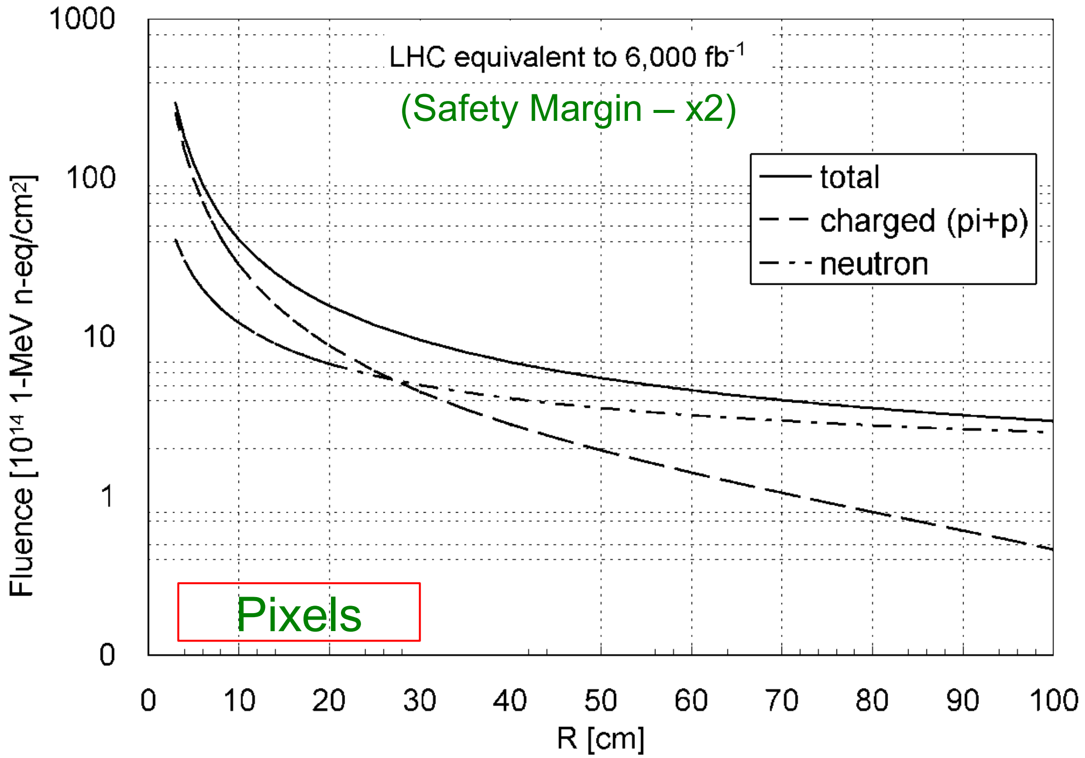




- Radiation Monitoring crucial for Si operation/abort
- Abort beams on large current spikes
- Measure calibrated daily and integrated dose
- Every LHC experiment now uses diamond

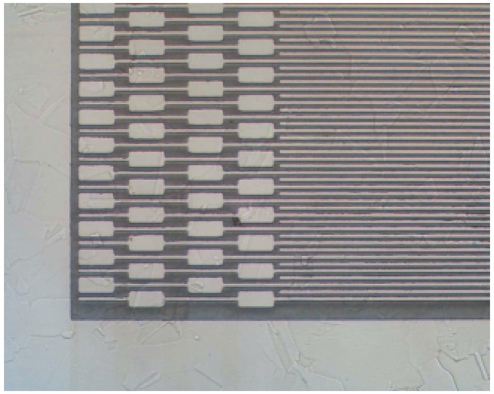
The Second Key: Radiation Tolerance

Expected SLHC Fluence (from Nobu)

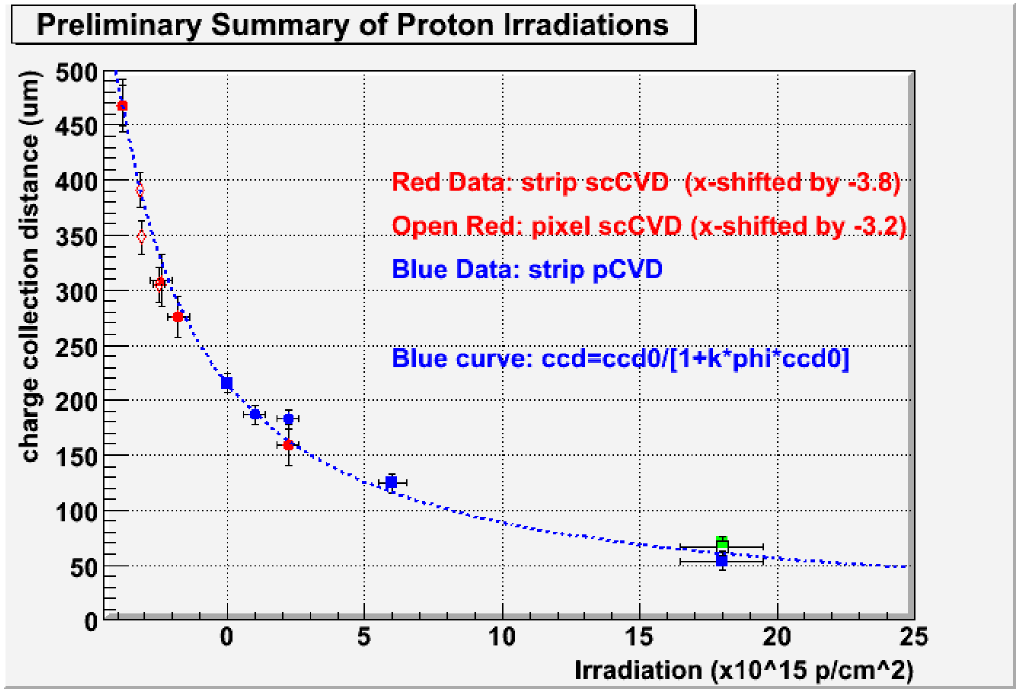


- Pixels r=3-30cm, strips r=30-100cm
- Below r=25cm charged particles dominate
- Inner pixels not necessarily the same technology as outer pixels

Diamond Radiation Tolerance: 24GeV protons



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



Test beam data

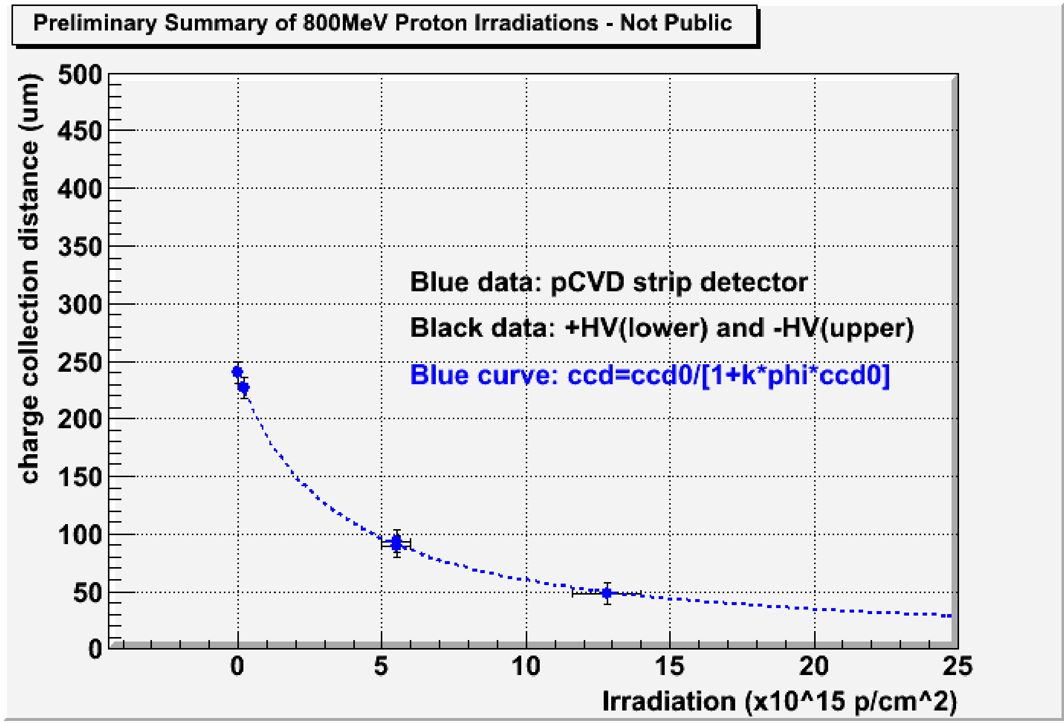
- CCD_0 initial traps in the material, k is the damage constant
- Test beam data shown – source data over-estimates damage!
- Single-crystal CVD and poly CVD fall along the same damage curve
- Larger CCD_0 performs better at any fluence
- Proton damage well understood, k~**0.7x10^{-18} μm^{-1}cm^{-2}**

Diamond Radiation Tolerance: 800MeV protons

Recent Irradiation with 800 MeV protons at LANSCE Facility in Los Alamos, US

- Result: 800 MeV protons 1.9x more damaging than 24GeV protons

  $k \sim \mathbf{1.3x10^{-18}}\ \mathbf{\mu m^{-1}cm^{-2}}$
- NIEL prediction 1.8x
  - NIEL ok !
- 2 more data points being analyzed



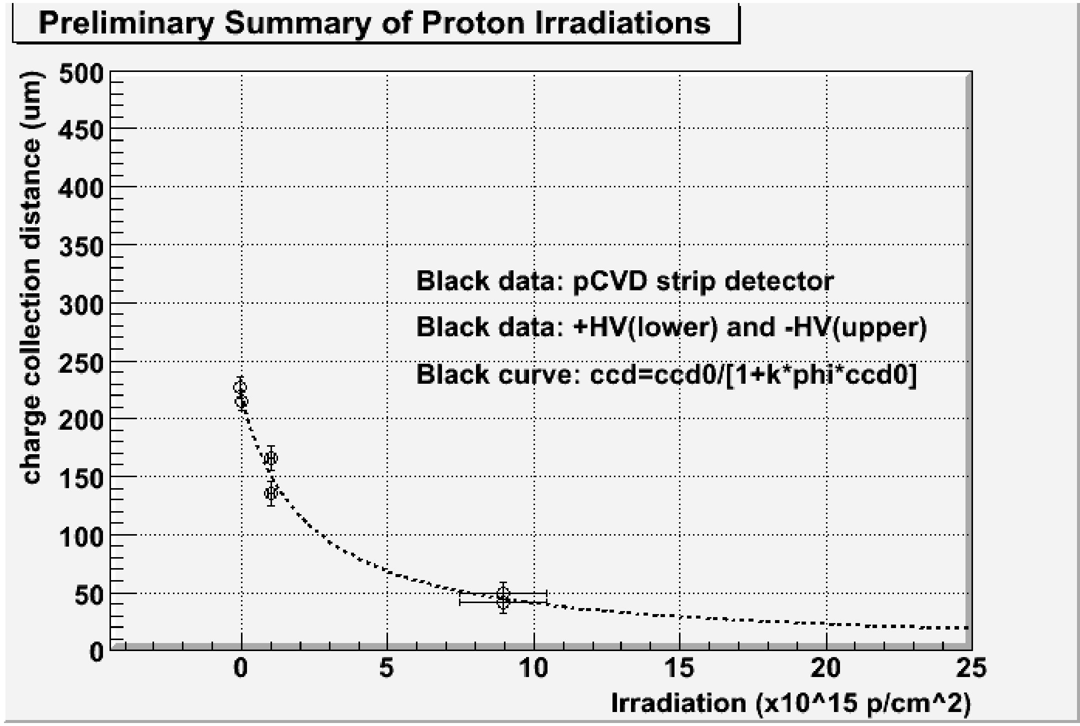
Preliminary Test beam Results

Diamond Radiation Tolerance: 70MeV protons

Recent Irradiation with 70 MeV protons at Cyric Facility in Sendai, Japan

- Result: 70 MeV protons 3x more damaging than 24GeV protons

  k ~ 2x10^{-18} μm^{-1}cm^{-2}
- NIEL prediction 6x
  - NIEL violation ?!
- Awaiting 1 sample from Japan



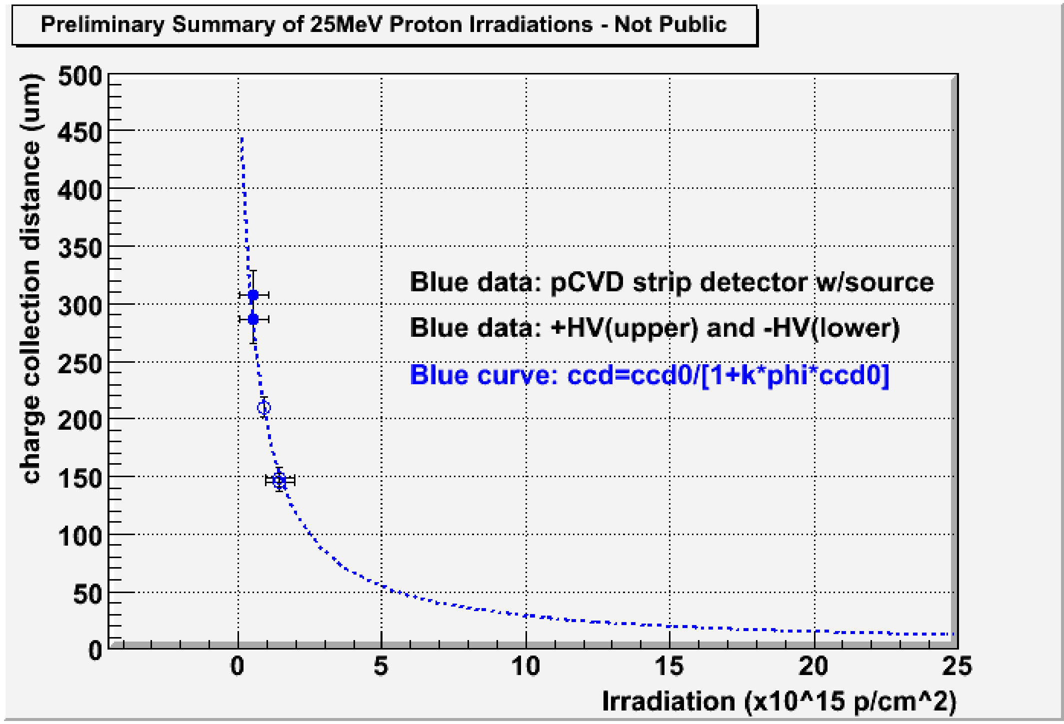
Preliminary Test beam Results

Diamond Radiation Tolerance: 25MeV protons

Recent Irradiation with 25 MeV protons at Karlsruhe Facility in Karlsruhe, Germany

- Result: 25 MeV protons 5x more damaging than 24GeV protons

  $k \sim 3.3x10^{-18}\ \mu m^{-1}cm^{-2}$
- NIEL prediction 15x
  - NIEL violation ?!
- Work in progress



Preliminary Test beam/source Results

Diamond Radiation Tolerance

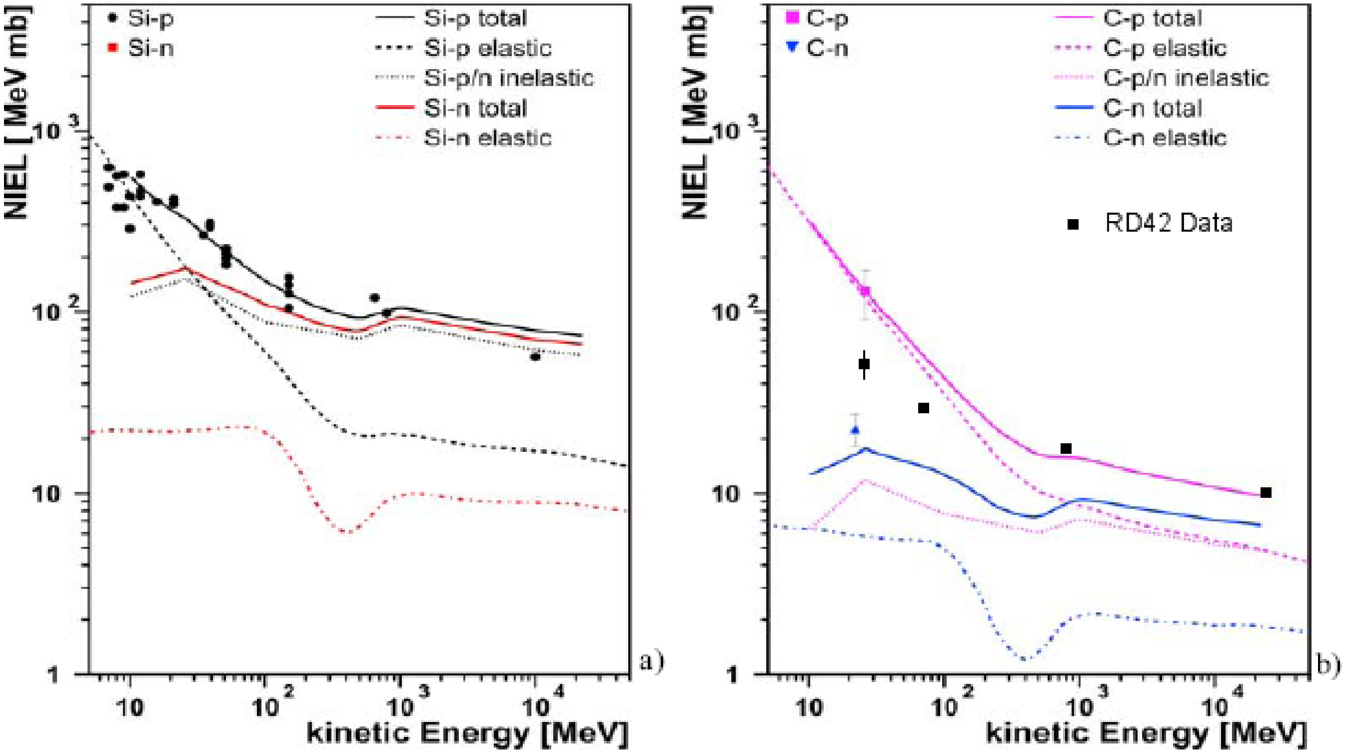


Fig. 4 (online colour at: www.pss-a.com) NIEL damage cross section of a) Si and b) diamond for pro-

- New results from low energy irradiations
- Deviation from calculated NIEL at low energy? NIEL violation? or is the theory incorrect?

Understanding Diamond and Silicon data

For high fluences trapping is the major effect for both diamond and silicon

In general:

$$ccd = d_e + d_h = (\mu_e\tau_e + \mu_h\tau_h)E$$

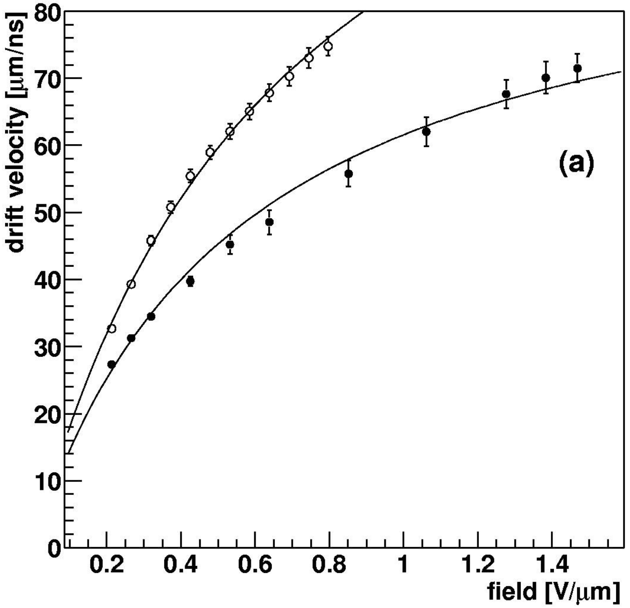
$$= v\tau = \mu E\tau \quad \text{where } \mu=\mu_e+\mu_h \text{ or } v=v_e+v_h$$

$$\text{then } \tau=(v_e\tau_e+v_h\tau_h)/(v_e+v_h)$$

$$ccd \;\alpha\; \tau$$

For diamond: $v/ccd = 1/\tau = v/ccd_0+vk\phi$

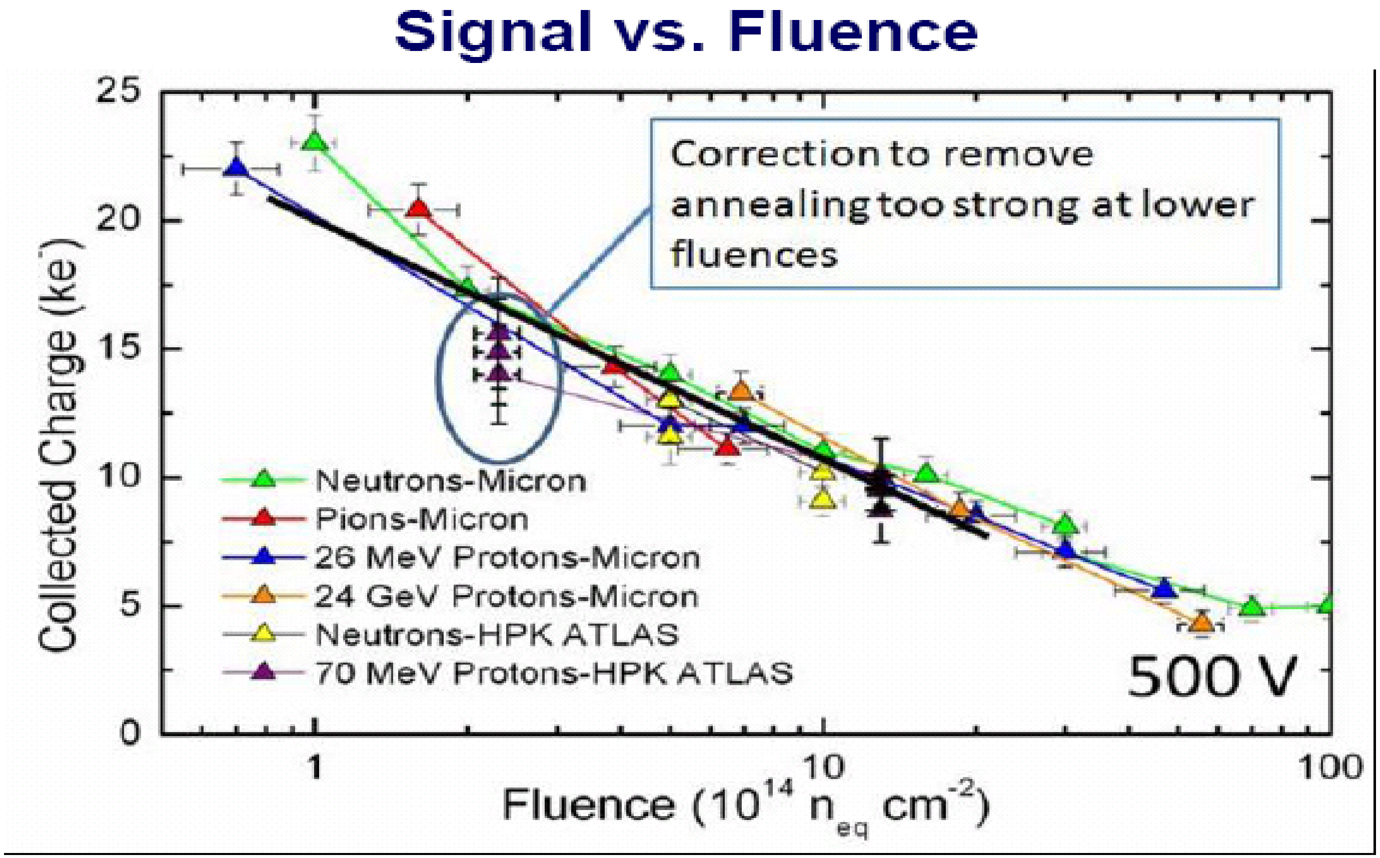
For silicon: $1/\tau_{e,h} = \beta_{e,h}\phi$



Work in trapping distance (ccd) space rather than τ space

So turn silicon irradiation data into ccd

Silicon Data – Affolder et al.



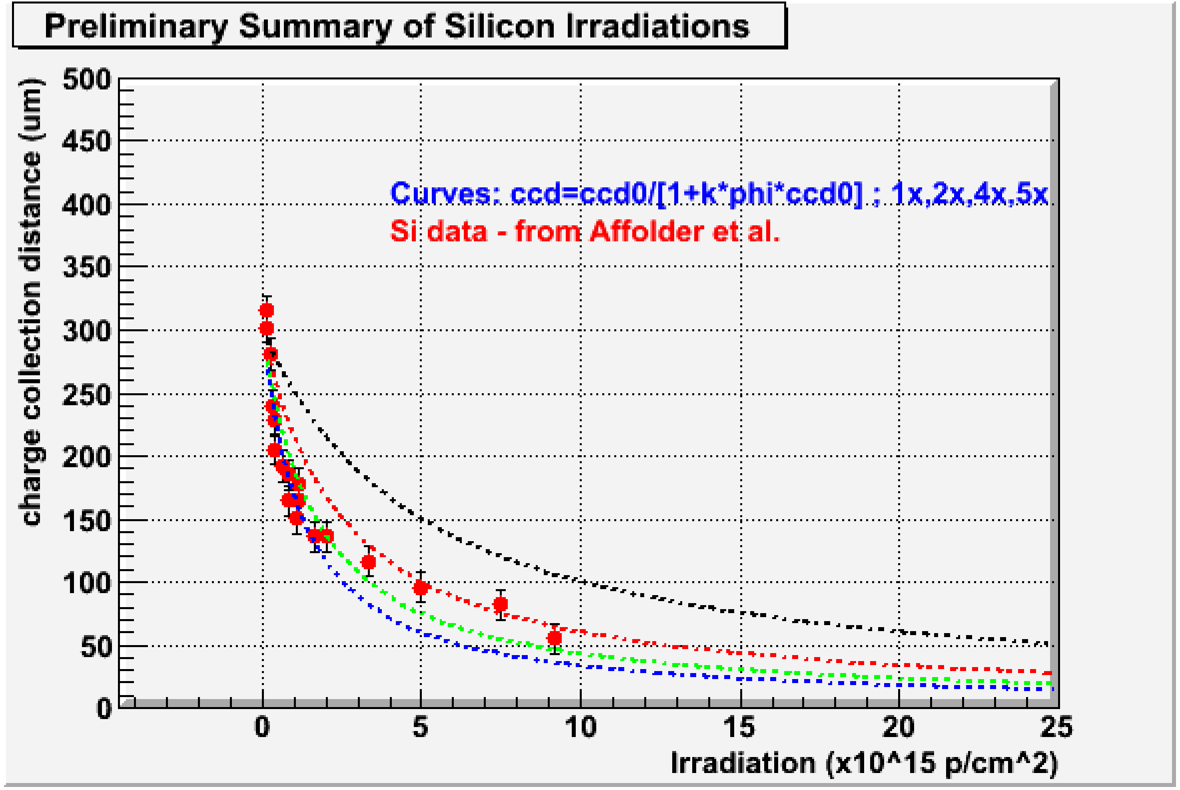
Signal vs. Fluence

Correction to remove annealing too strong at lower fluences

Measured signal (ke-) as a function of fluence for 500V bias (cables!)
for Micron [9] and Hamamatsu [10] miniature n-in-p FZ devices.
The devices are either not annealed (neutrons, 26 MeV protons, 24 GeV protons)
or corrected for annealing during the irradiation (pions) or shipping (70 MeV protons).

Hartmut F.-W. Sadrozinski, Layout Limits RESMDD10

Silicon Data - Affolder et al. - in ccd space



- Black curve diamond damage constant
- Red curve 2x more damage; Green curve 4x; Blue curve 5x
- At all energies silicon has larger damage constant than diamond
- So why does NIEL appear to work for silicon and not for diamond?

More irradiations – n, π

- pCVD (2) with reactor neutrons up to 1.3x10^{16} n$_{eq}$/cm^2 (6steps)
  - k ~ 3-5x10^{-18} μm^{-1}cm^{-2}
  - Discrepancy between source and test-beam data
  - Source overestimates damage
- Samples tested in CERN test beam – results soon

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

- CVD with PSI 300MeV π up to 6x10^{14} p/cm^2
  - k consistent with ~1-3x10^{-18} μm^{-1}cm^{-2}
- pions up to 1x10^{15} π/cm^2
  Samples tested in source and CERN test beam – results soon

Remaining Diamond Issues

Perhaps the largest obstacle to using diamond is the number of manufacturers: 1

- E6/DeBeers
- Need to develop additional manufacturers and capacity

E6 diamond quality nearly in steady state

- Recently have made some progress!!
- Grow a wafer thicker
- Still need to work on slower growth

New manufacturers will help both issues!

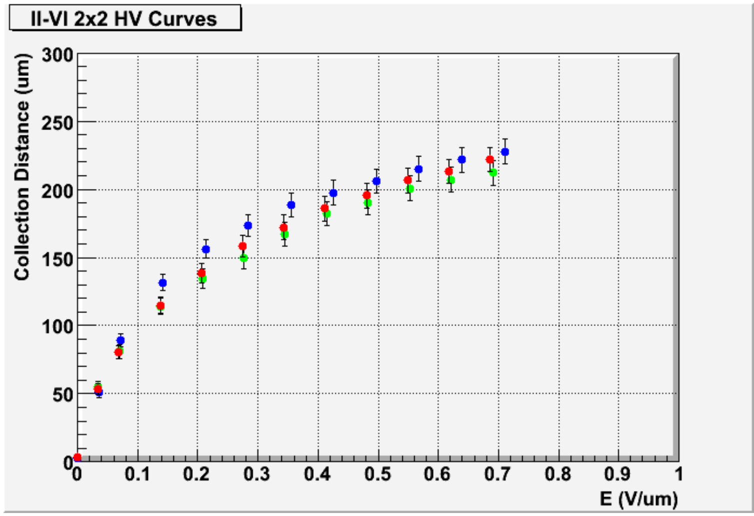
New Diamond Manufacturer: in the US

New manufacturer II-VI Inc.

- Fairly large company in the U.S.
- Vertically integrated manufacturer of crystalline compounds
- II-VI recently sold eV Products

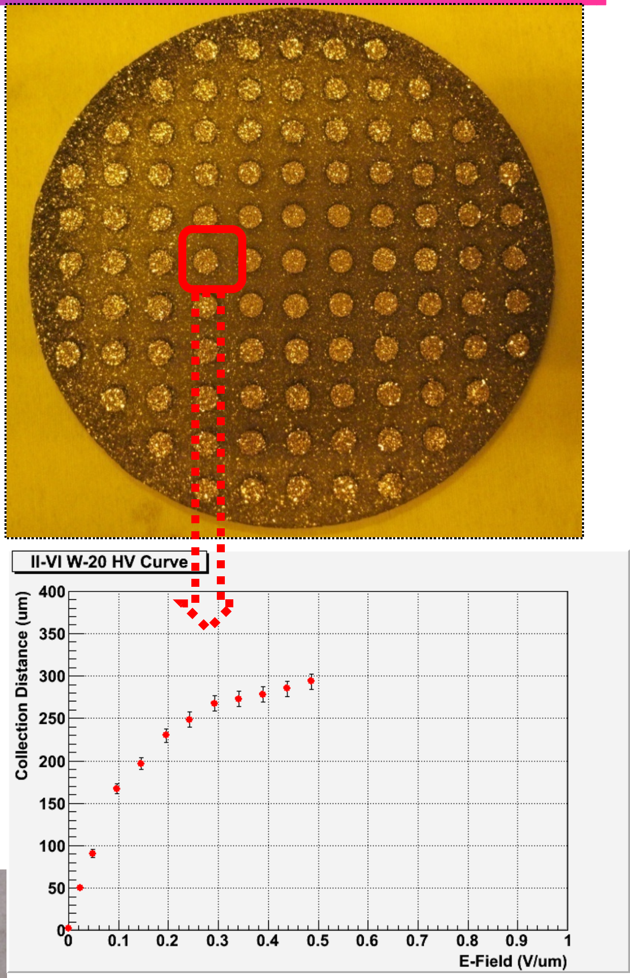
II-VI has a development project in electronic grade CVD diamond

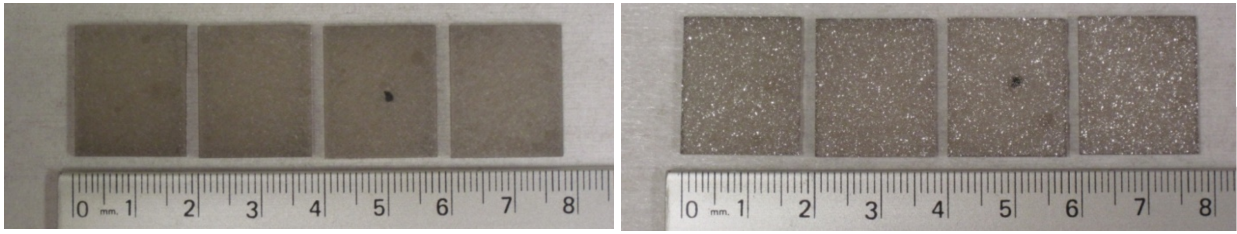
- Have measured > 30 samples – the best compare well with the state-of-the-art
- Nice uniformity of samples. Will make a "tuned growth" to maximize the charge collection distance next.



Results from II-VI Inc.

- Delivered many samples so far
  - Produced a 1.5 mm thick 5" wafer in their "normal" process
    - Not tailored to HEP applications at all – but ccd reached 300μm
  - 4 FE-I4-shaped pieces being made for testing
    - As grown – processing now





Summary

- CVD Diamond cn be used for high energy radiation and particle detection
  - Beam condition monitors in BaBar, CDF, ATLAS, CMS, LHCb, Alice.
  - ATLAS, CMS and LHCb are preparing proposals for diamond inner tracker upgrades.
- Radiation Hardness of CVD diamond is nearly quantified
  - pCVD and scCVD have the same damage constant.
  - Dark current decreases with current.
  - Problems with NIEL?
- pCVD and scCVD material is available.
  - Still need to measure quality of each sample.
  - Would like pCVD with larger ccd; large scCVD
- New manufacturers entering the field

- Backup slides