Development of CVD Diamond Radiation Detectors

The RD42 Collaboration
represented by
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RD42 Collaboration

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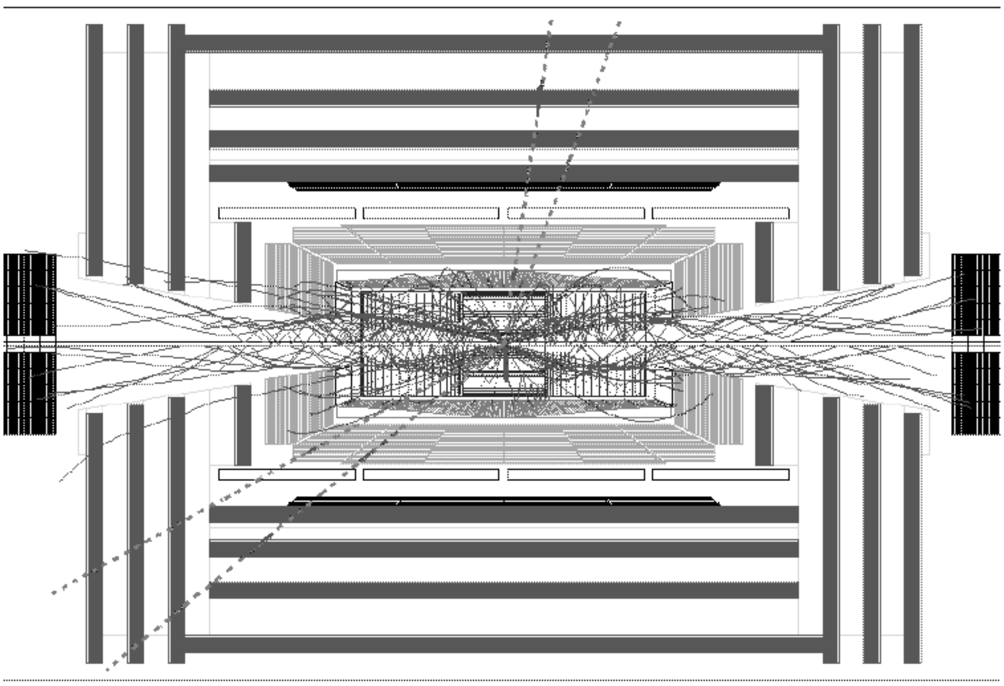
Diamond Detector Application in HEP

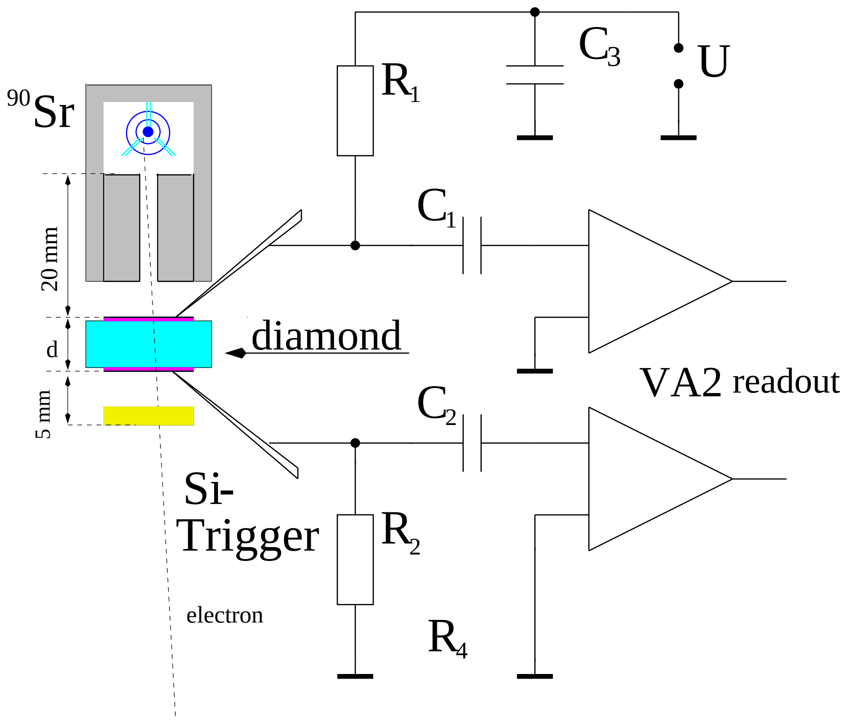
- ... as tracking detector in very high radiation environment.
- **Silicon** strip detectors are used at present for high **precision tracking** with great success (e.g. LEP,TEVATRON CDF). But their **radiation resistance** puts **limits**. Problems with increasing leakage **currents**, increasing **depletion** voltage and charge collection **efficiency**. Probably usable up to 10 MRad or 10^{14} n/cm^2.
- Inner regions at **LHC** experiments, radii $<$ 30 cm, detectors are exposed to **extremly high radiation levels**. At present only Si pixels proposed.
- **Diamond** has good promise to withstand an order of magnitude higher radiation level than present day Silicon.

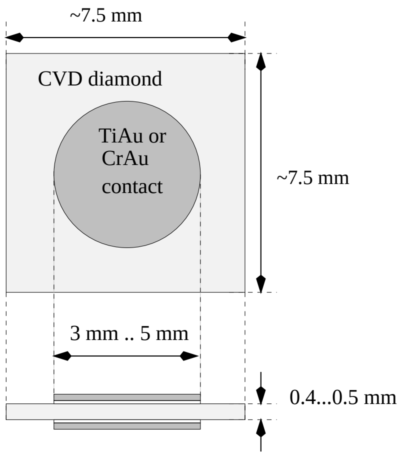


Simulated Higgs→ZZ→4μ event in the CMS detector at the LHC.

Charge Collection, Setup

- Diamond connected (biased) to HV
- Collimated Sr90 β-source illuminates sample.
- One or both sides of diamond coupled to readout chip.
- Readout: VA2-chip, 128 channels, charge integration and signal shaping of 2 μs, measured PreAmpNoise=(80+11/pF)e.
- Silicon diode in line with diamond/source triggers readout.





C_1 = 470 pF/1000V C_3 = 4.7 nF/1000V
C_2 = 470 pF/1000V R_1 R_2 =100 MΩ
d = 100 μm....2 mm U= 0..1 kV

Collection vs. Electric Field

- A *mip* **generates** charge pairs per distance:

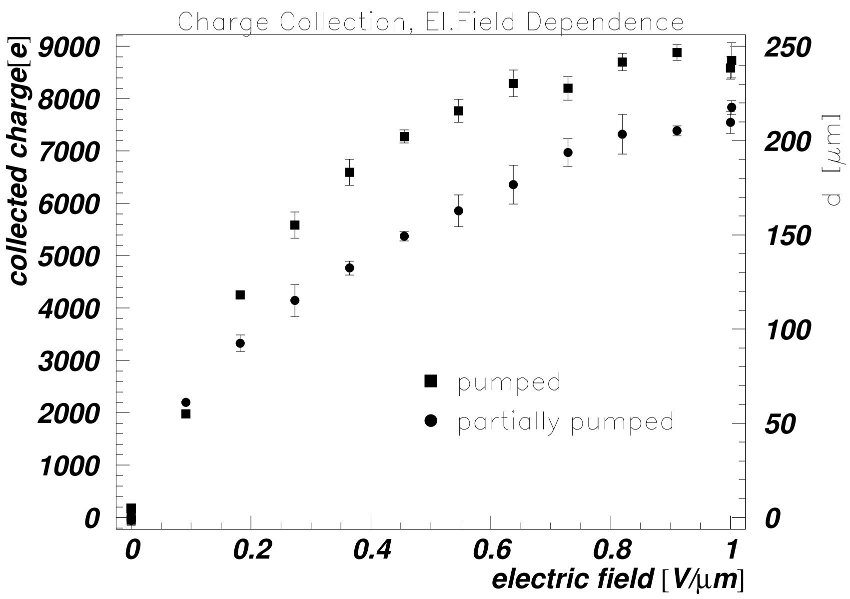
$$\boxed{q = 36\ \mathrm{e}/\mu\mathrm{m} = 10800\ e/300\ \mu\mathrm{m}} \quad (1)$$

- mean charge $\langle Q_{\mathrm{col}}\rangle$ can be **collected**:

$$\boxed{\langle Q_{\mathrm{col}}\rangle = q \cdot d} \quad (2)$$

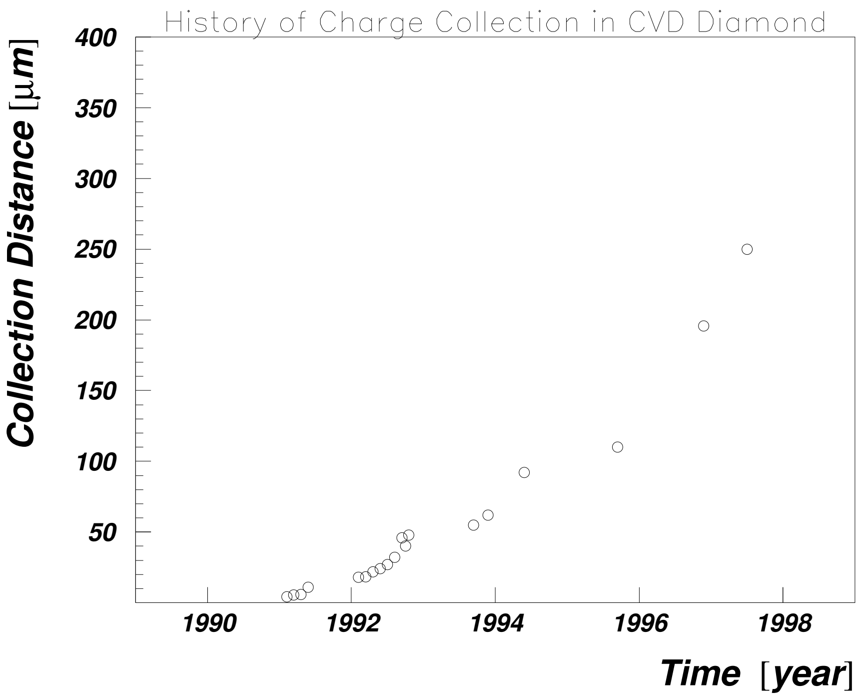
- **Charge collection distance** d, mobility μ, mobility-weighted lifetime τ

$$\boxed{d = \mu \tau E} \quad (3)$$



- $\langle Q_{\mathrm{col}}\rangle = 9000\ e \quad \Leftrightarrow \quad d = 250\ \mu\mathrm{m}$
- saturation velocity $(\mu E)_{\mathrm{sat}} \approx 250\ \mu\mathrm{m/ns}$
- lifetime $\tau \approx 1$ ns

Charge Collection Increase, History

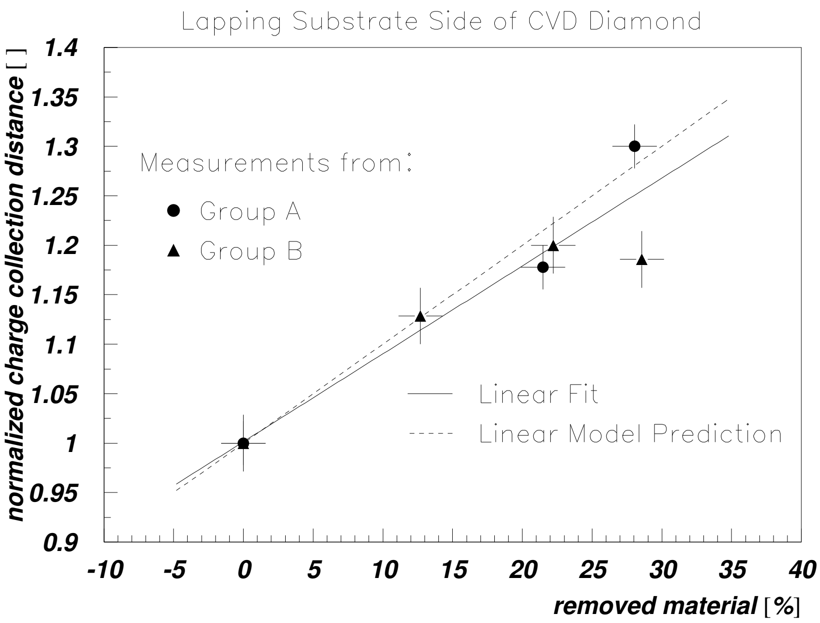


- 1991: few micron material
- 1997: more than 200 μm

Lapping of CVD Diamond

- CVD diamond as grown with thicknes D_{original}
  ... ccd d depends on position x along direction of growth
- **Linear Model** $d(x) = c \cdot x$ predicts $\bar{d}_1$ for $d \ll D_{\mathrm{original}}$
  ... after lapping D_1 from substrate side

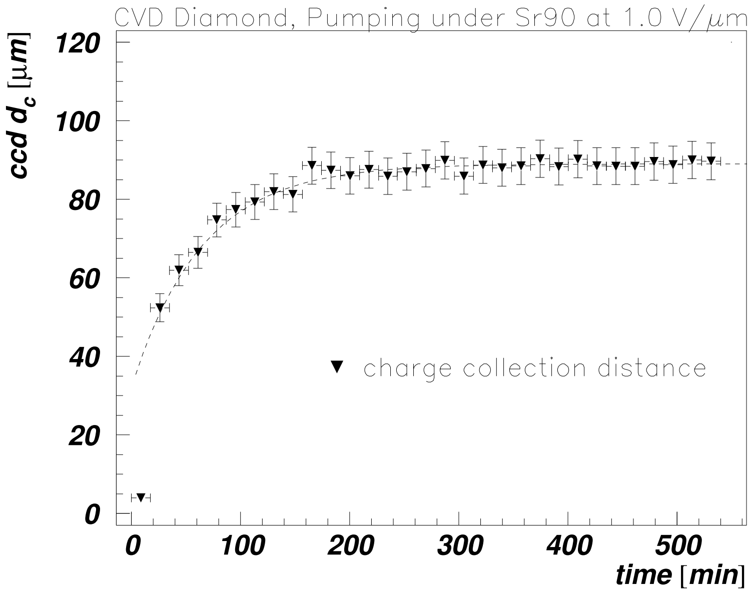
$$\bar{d}_1 = \frac{\int_{D_1}^{D_{\mathrm{original}}} d(x)\mathrm{d}x}{\int_{D_1}^{D_{\mathrm{original}}} \mathrm{d}x} = d_{\mathrm{original}} \left(1 + \frac{D_1}{D_{\mathrm{original}}}\right) \tag{4}$$



- d increases with material removed from substrate side
- Linear Model predicts improvement correctly

Charge Collection Distance, Pumping

- Charge collection at constant field
- illumination with charged particles from ^{90}Sr

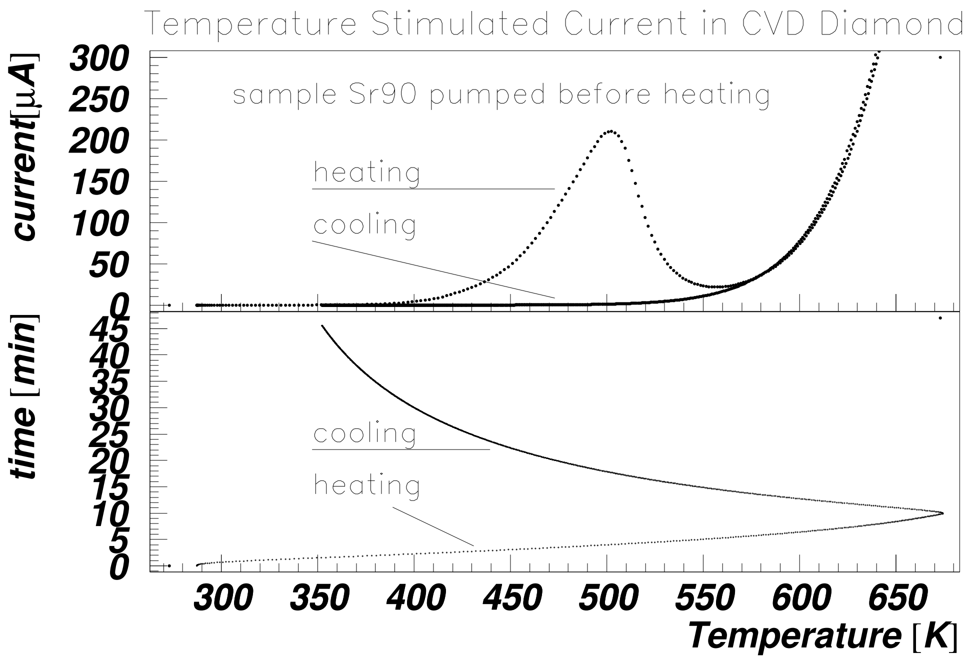


Charge collection distance d ...

- .. increases under irradiation between (1..10) krad, **pumping**
- .. saturates and stays constant above 10 krad, **pumped**
- .. decreases under exposure to fluorescent light, **depumping**

Temperature Stimulated Current

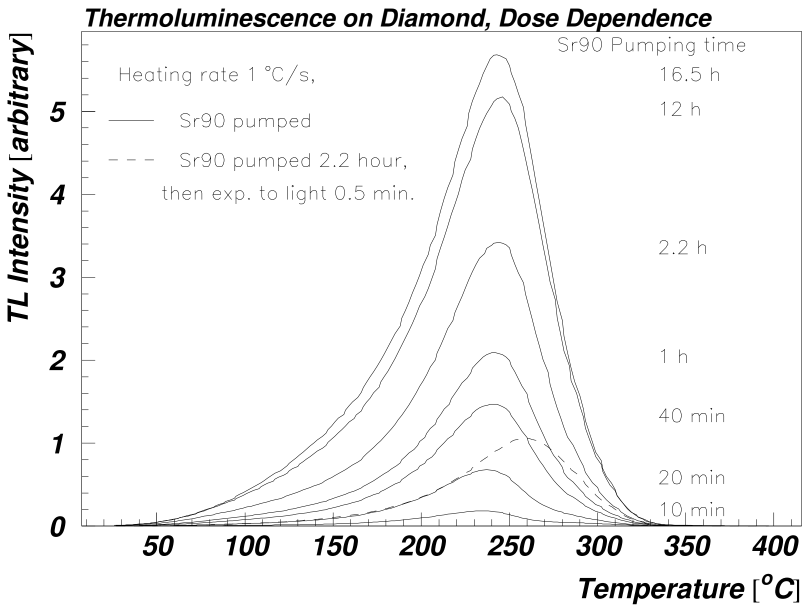
- sample pumped with ^{90}Sr
- biased at 100 V, linear heating to 400°C
- measure current



- current peaks in temperature observed (data presently analysed)
- no peak after annealing or exposure to light

Thermo Luminescence

- sample pumped with ^{90}Sr, different doses
- linear heating to 400°C
- measure light intensity

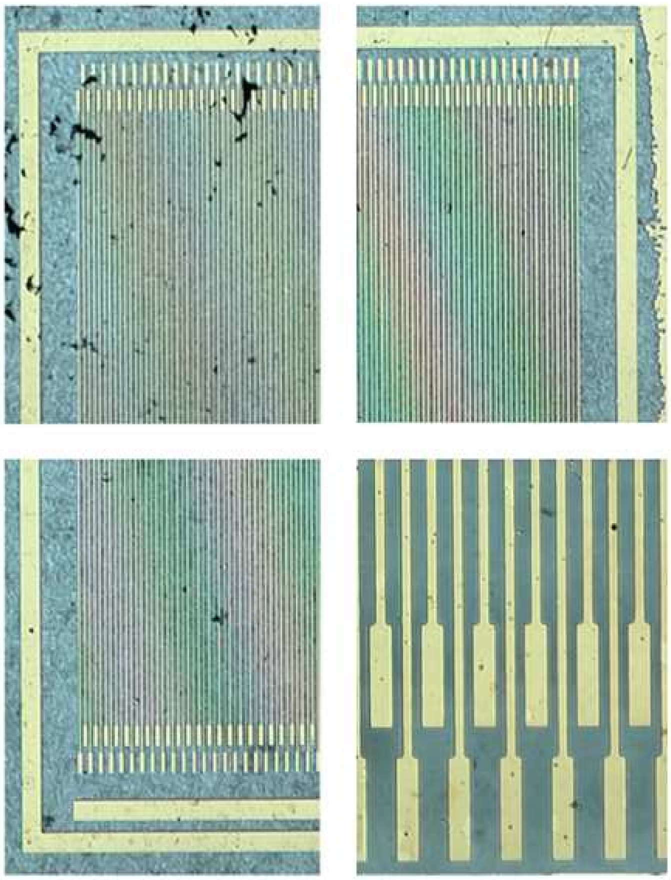


- peaks like in current measurement
- intensity depends on dose
- no peak after annealing or exposure to light

→ pumping with ^{90}Sr: traps are filled
...depumping: heating or light discharges traps

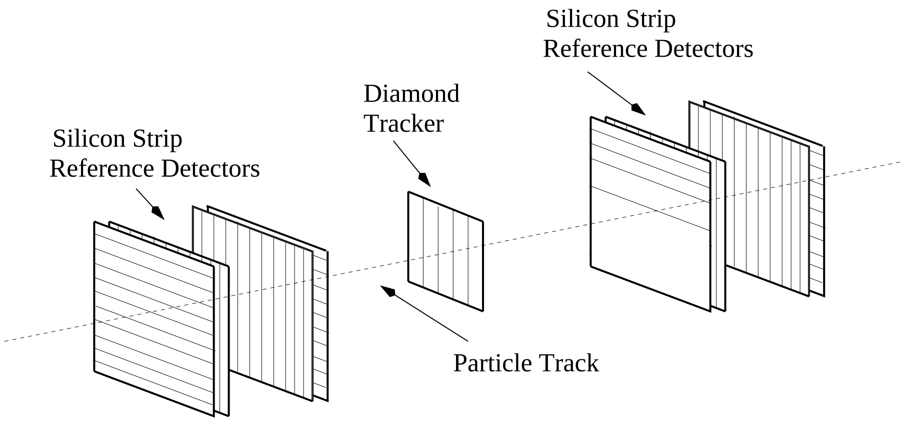
Diamond Tracker

- Diamond strip tracker, 128 strips, pitch 50 μm.
- ... 6.4×6.4 mm^2 active area
- slow readout, VA2, signal peaking time 2 μs.
- .. or fast readout, SCT32A, signal peaking 25 ns.

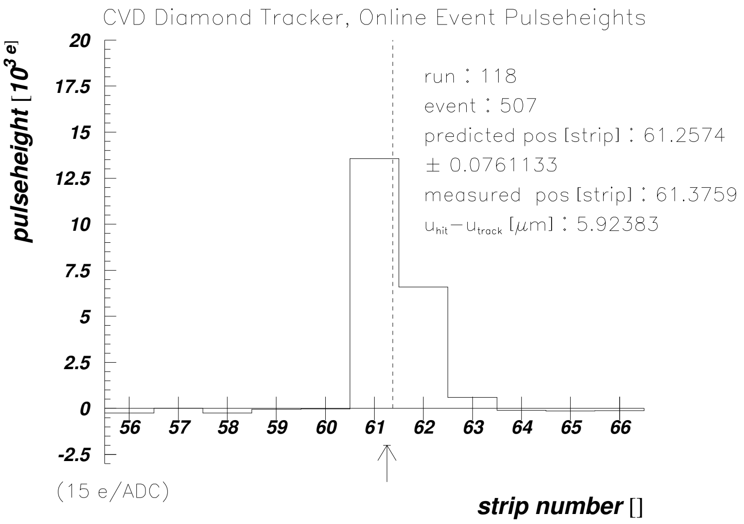


Diamond Tracker in Silicon Telescope

- Silicon strip detectors, 4 horizontal, 4 vertical planes
- ... predict particle track within micron
- Diamond trackers in between silicon planes
- pion beam, 5 to 100 GeV/c, passes telescope
- measure **pulseheight** and **resolution** in diamond tracker

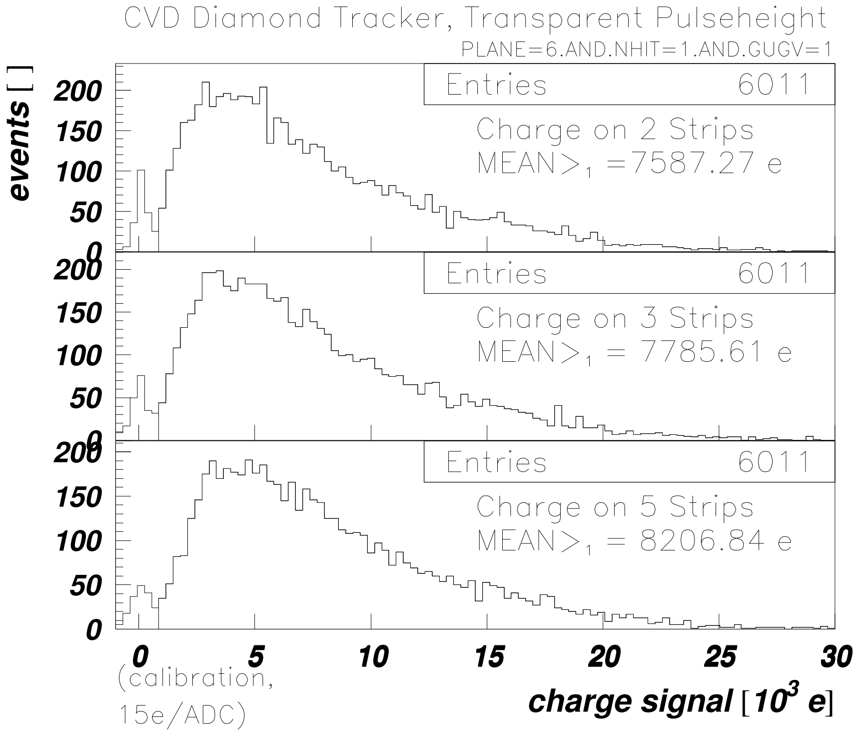


Online event in diamond tracker (example):



Tracking, Pulseheight

- Look for hits around predicted intersection in diamond tracker, ... sum the charge on different number of strips

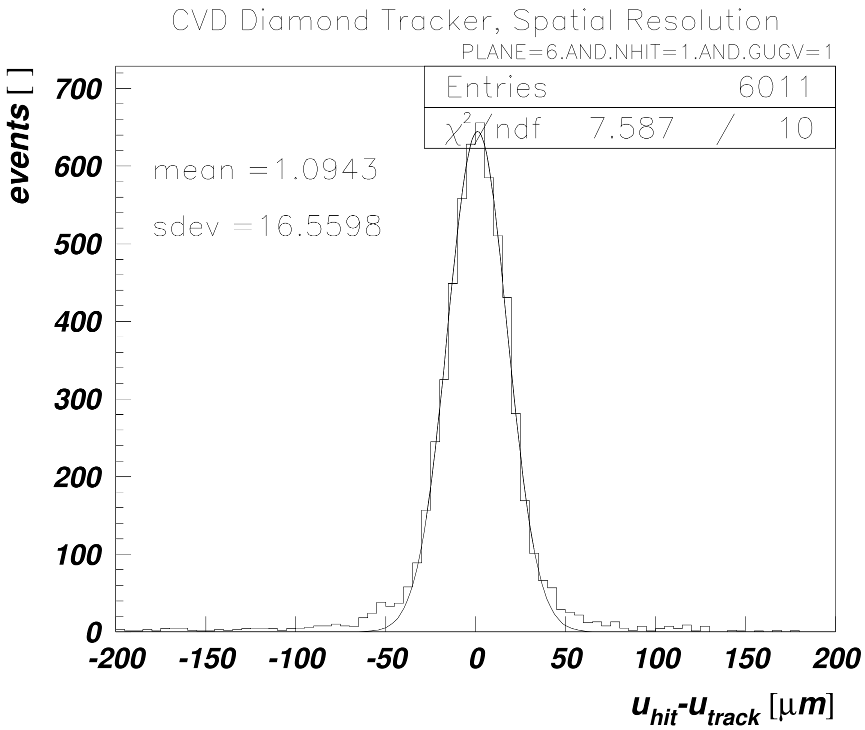


- **average charge** signal 8200 $e \rightarrow d = 230\ \mu$m
- **noise** 150 e
- **signal-to-noise** 55-to-1

Tracking, Resolution

- Look for **predicted** track position x_{track}
- ... and **measured** hit position x_{hit}
- Obtain **spatial resolution** σ:

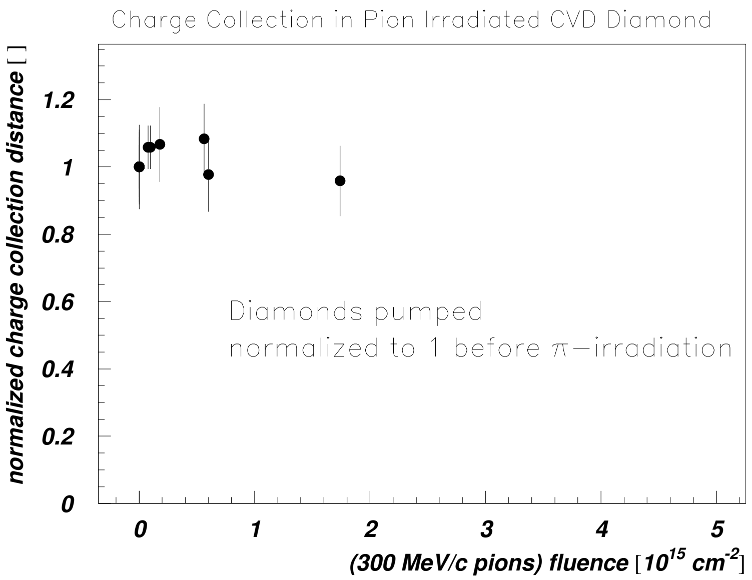
$$\boxed{\sigma = SDEV\left\{x_{\text{hit}} - x_{\text{track}}\right\}} \tag{5}$$



- **resolution** $16.5\ \mu\text{m} \approx 50\ \mu\text{m}/\sqrt{12}$

Pion Irradiation

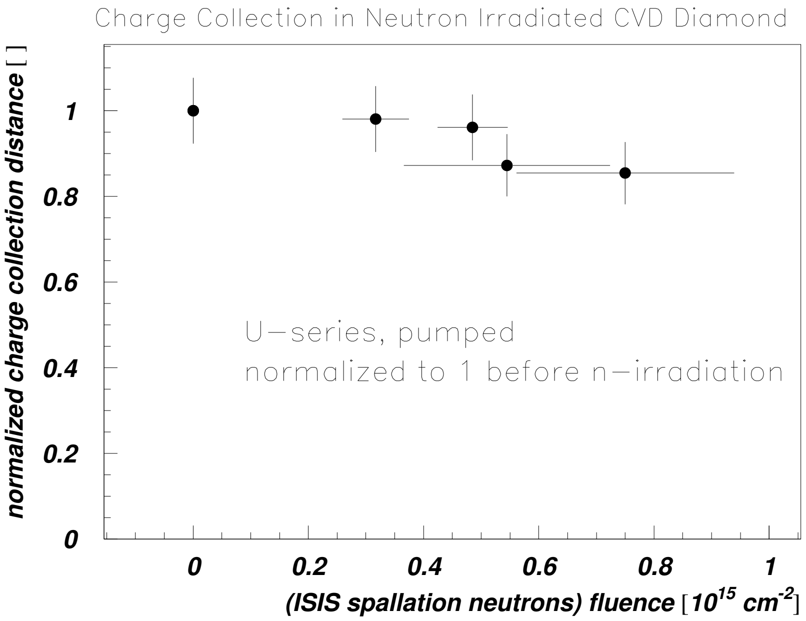
- **pion irradiation** at PSI, Villingen, delivers 300 MeV/c pions
- irradiation up to **fluence** 1.7×10^{15} π/cm^2,
- room temperature, 100 V applied,
- measure **charge collection**,
  ... normalize to pumped value before irradiation:



- 1.7×10^{15} π/cm^2: no decrease in charge collection
- leakage current stays constant or even decreases

Neutron Irradiation, Charge Collection

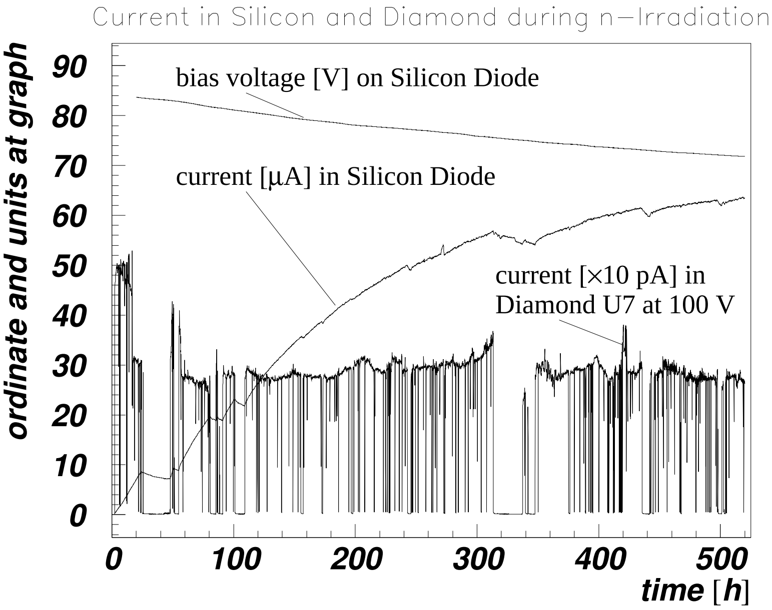
- ISIS **neutron** spallation source at RAL, England
  ... kinetic energy maxima at 1 MeV.
- irradiation above **fluence** $8 \times 10^{14}\ n/\mathrm{cm}^2$,
- at room temperature, biased 100 V.



- up to $8 \times 10^{14}\ n/\mathrm{cm}^2$ no decrease in charge collection
- leakage current stays constant or even decreases (like with pion)

Neutron Irradiation, Current

- current in silicon diode and diamond during n-irradiation
- current in **silicon** is **leakage current**
- current in **diamond** is **particle induced current**



- silicon: increase from few μA to 60 μA in 500 h
- diamond

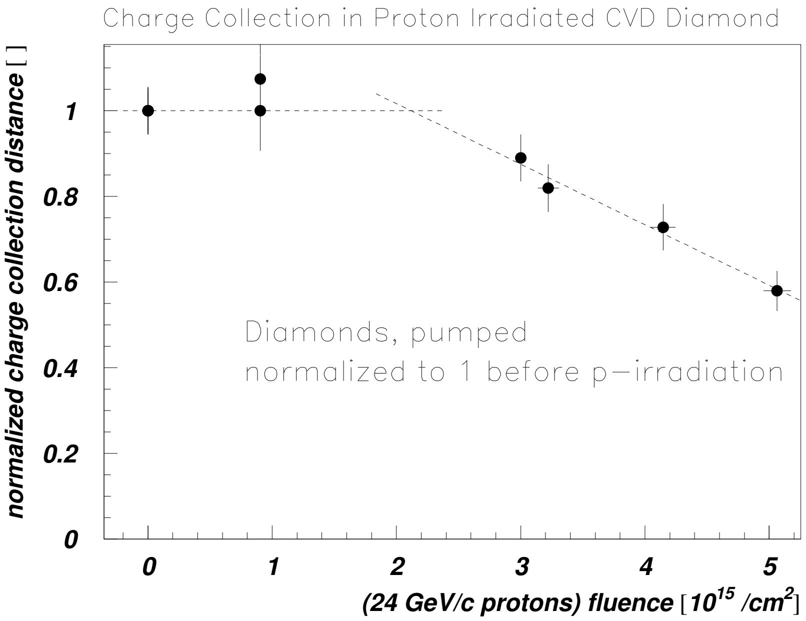
  induced current follows beam structure

  current constant at 24 pA/mm^2 when beam on

  diamond monitors neutron/gamma radiation

Proton Irradiation, Charge Collection

- **Proton irradiation** at PS, CERN, Switzerland
  ... momentum 24 GeV/c
- irradiation up to **fluence** $5 \times 10^{15}\ p/\text{cm}^2$,
- at room temperature, biased 100 V.



- up to $1 \times 10^{15}\ n/\text{cm}^2$ no decrease in charge collection
- above $2 \times 10^{15}\ n/\text{cm}^2$ decrease in charge collection

Summary

- Charge collection distance

  now **250** μm (1997) on 1.1 mm sample

  lapping on substrate side increases charge collection

  explained by **Linear Model** of charge collection distance

  Illumination to charge particles increases (**pumping**)

  .. charge collection, temperature stimulated current and luminescence

- Tracker

  Charge pulseheight above 8000 e ($d \approx 230$ μm)

  Signal-to-noise 55-to-1 on 'slow' readout

  Spatial resolution 16.5 μm

- Irradiation studies, charge collection

  Pions (300 MeV/c): no decrease in charge collection up to 1.7×10^{15} /cm^2

  Neutrons (ISIS): no decrease at 8×10^{14} /cm^2, higher fluence required

  Protons (24 GeV/c): no decrease up to 1×10^{15} /cm^2
  ... decrease above 2×10^{15} /cm^2 up 5×10^{15} /cm^2

$\Longrightarrow$ CVD Diamond is very promising detector substrate
for particle tracking in high radiation environment at LHC experiments