Diamond Strip Sensors & Comparisons with Silicon

Particle Detection and Tracking

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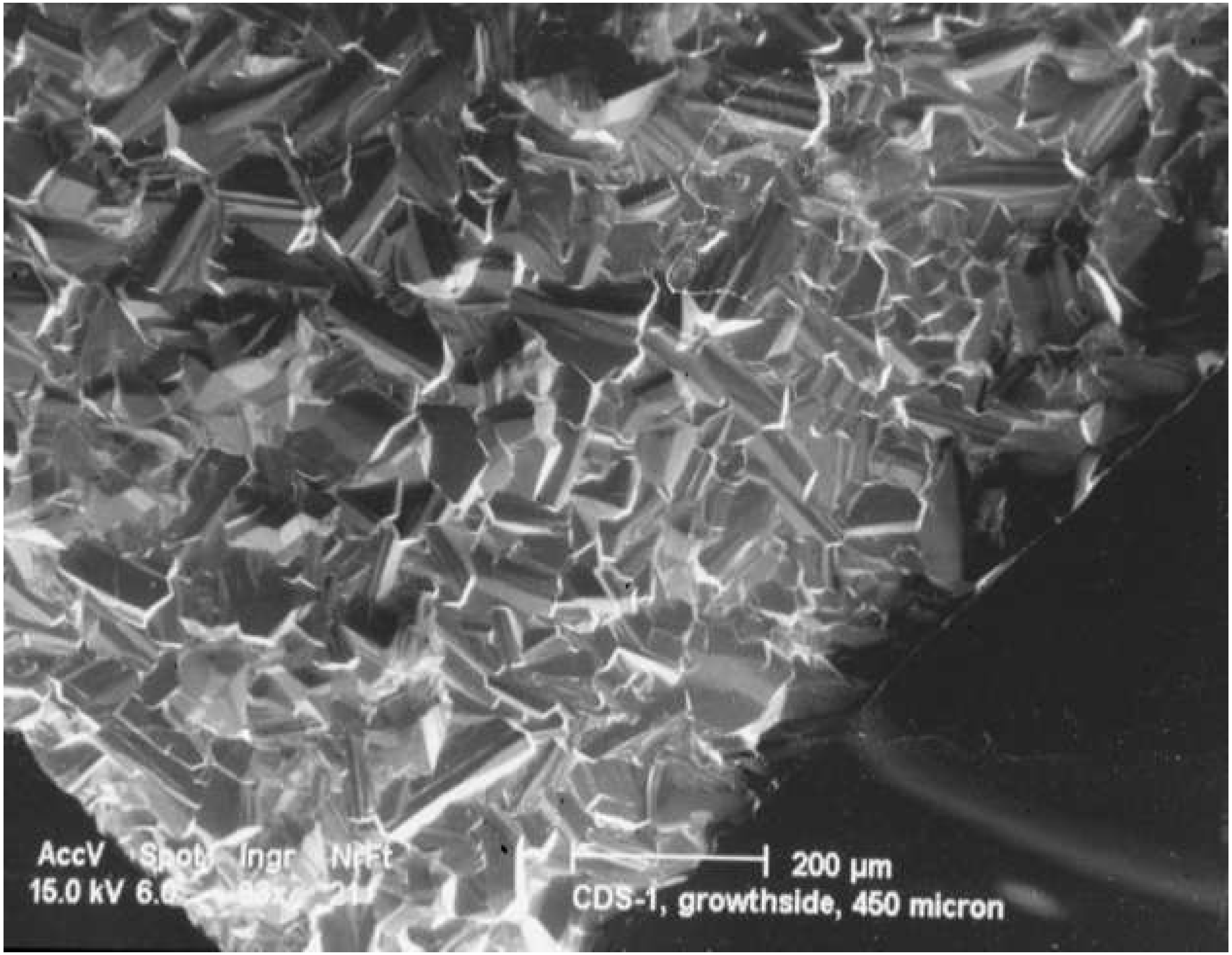
seminar at DESY, Hamburg

- Goal: Study CVD Diamond Sensors
- Electrical Characterization
- Radiation Studies
- Particle Tracking

Diamond Surface, Scanning Electron Micrograph (SEM)



Charge Collection

- A *mip* **generates** in average $36\ eh - \text{pairs}/\mu\text{m}$ in diamond ($\stackrel{e.g.}{=} 10800\ eh/300\ \mu\text{m}$)

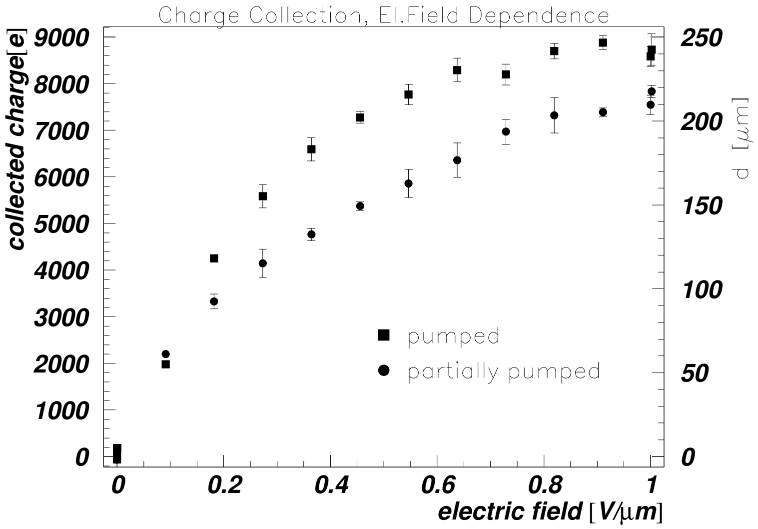
- mean **induced** charge $\langle Q_{\text{induced}}\rangle$ on one electrode

$$\boxed{\langle Q_{\text{induced}}\rangle \approx 36\ eh/\mu\text{m} \cdot d}$$

- **charge collection distance** d

$$\boxed{d \stackrel{\text{def}}{=} |d_+| + |d_-| = \sum_{k=\pm} \mu_k \tau_k E}$$

lifetime $\tau_\pm$, mobility $\mu_\pm$, $\mu = \mu_+ + \mu_-$, ($h$oles '+', $e$lectrons '-')

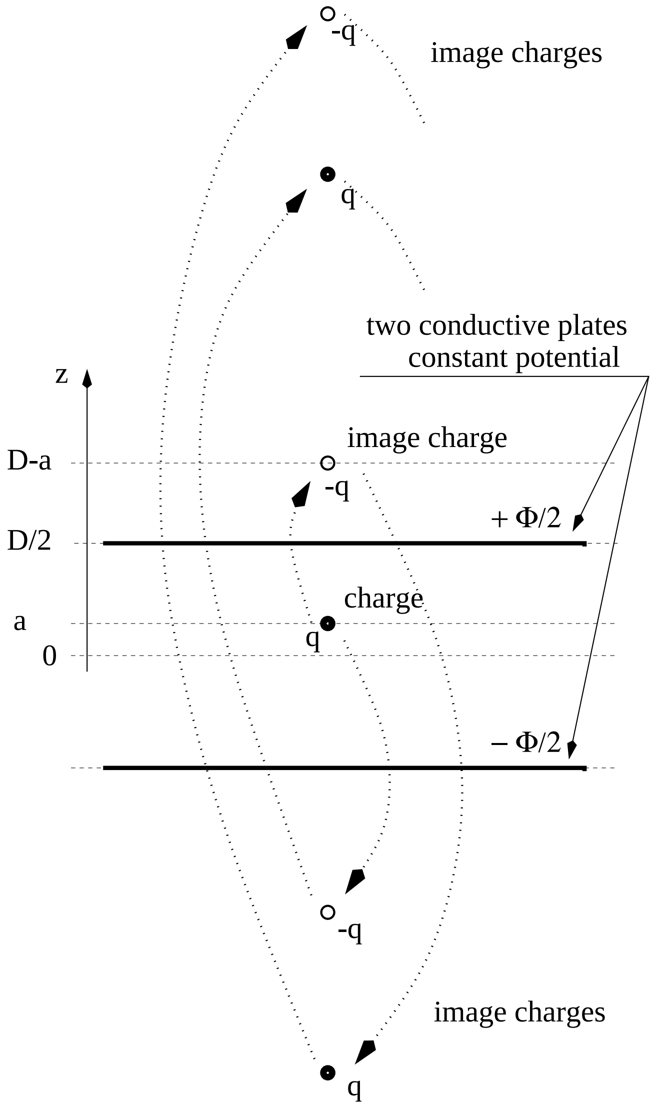


- $\langle Q_{\text{col}}\rangle\Big|_{1\text{V}/\mu\text{m}} = 9000\ e$

  $\Leftrightarrow \quad d\Big|_{1\text{V}/\mu\text{m}} = 250\ \mu\text{m}$

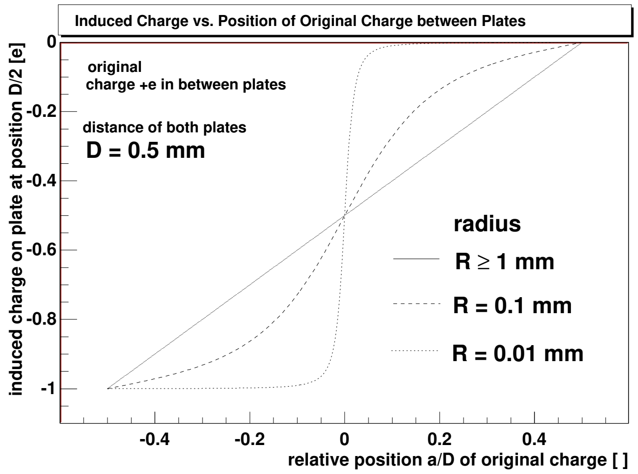
- charge collection pumps (trap filling)

Multiple Image Charge



Induced Charge

$$Q_{\text{induced}}(a; D, R) =$$
$$\frac{q}{2}\sum_{k=-\infty}^{\infty} \frac{2kD-D+a}{\sqrt{R^2+(2kD-D+a)^2}} + \frac{2kD+a}{\sqrt{R^2+(2kD+a)^2}}$$

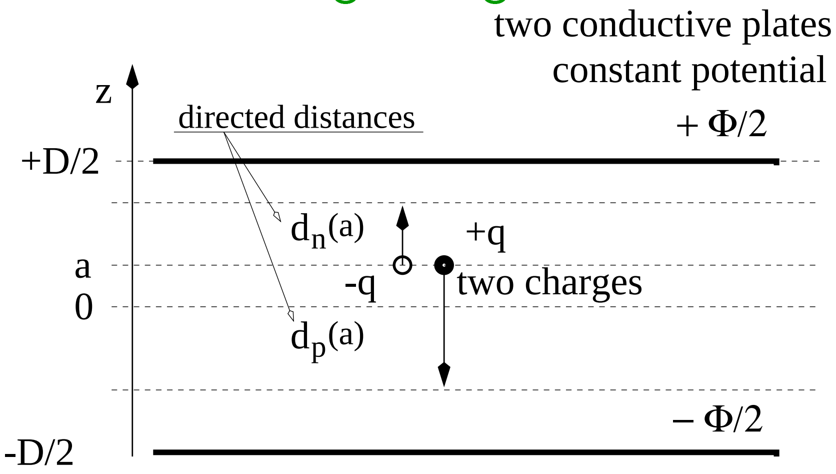


$$Q_{\text{induced}}(a; D \leq R) \approx -q\left(\frac{1}{2} - \frac{a}{D}\right)$$

$$\Rightarrow \quad dQ_{\text{induced}(\mathrm{D}\leq\mathrm{R})} = q\frac{\mathrm{d}a}{D}$$

- linear for 'large contact' (Ramo's theorem)

Moving Charge Pair



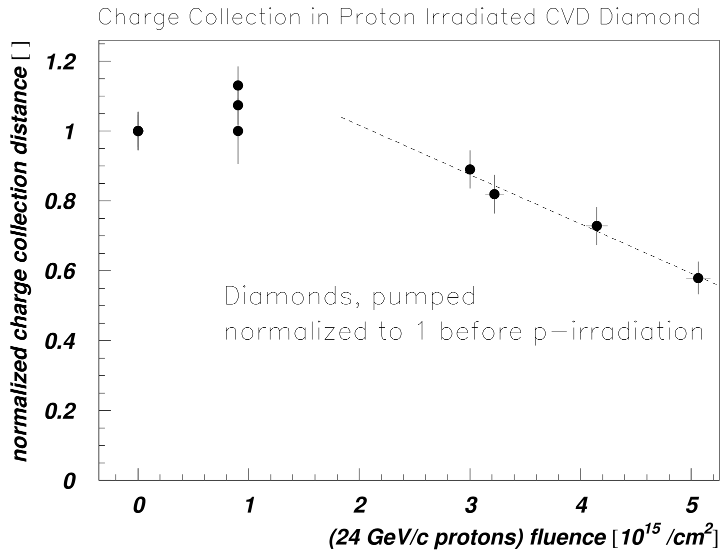
- carriers travel mean distances d_+, d_-

$$Q_{\text{induced}}(a) = \int_a^{d_+(a)} \mathrm{d}Q_+ + \int_a^{d_-(a)} \mathrm{d}Q_- = q\frac{d}{D}$$

Proton Irradiation of Diamond

- proton momentum 24 GeV/c, PS, CERN
- flux up to $2.9 \times 10^{10}\ p/\mathrm{cm}^2/\mathrm{spill}$
- one spill of 300 ms, twice or 3 times in 14 s
- dosimetry with foils
- measured fluence $(0 \text{ to } 5) \times 10^{15}\ p/\mathrm{cm}^2$
- three dot-samples, one tracker at room temperature
- charge collection distance before $\approx 100\ \mu$m

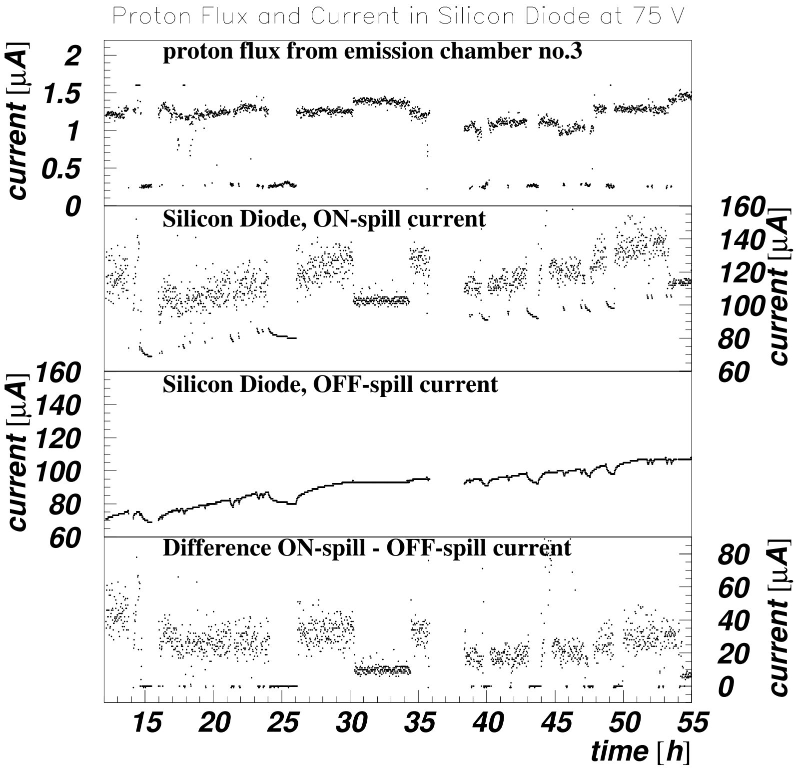
Charge Collection



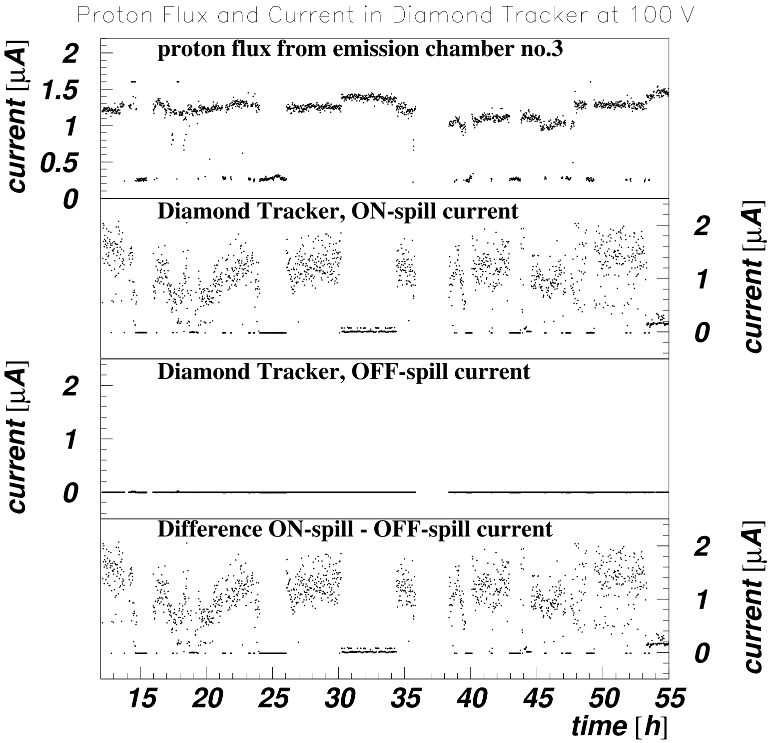
- at $1 \times 10^{15}\ p/\mathrm{cm}^2$ **no decrease**
- **linear decrease** between $(3 \times 10^{15} \ldots 5 \times 10^{15})\ p/\mathrm{cm}^2$
- at $5 \times 10^{15}\ p/\mathrm{cm}^2$ charge collection 60% of before irradiation

Proton Irradiation, Current

Silicon



Diamond



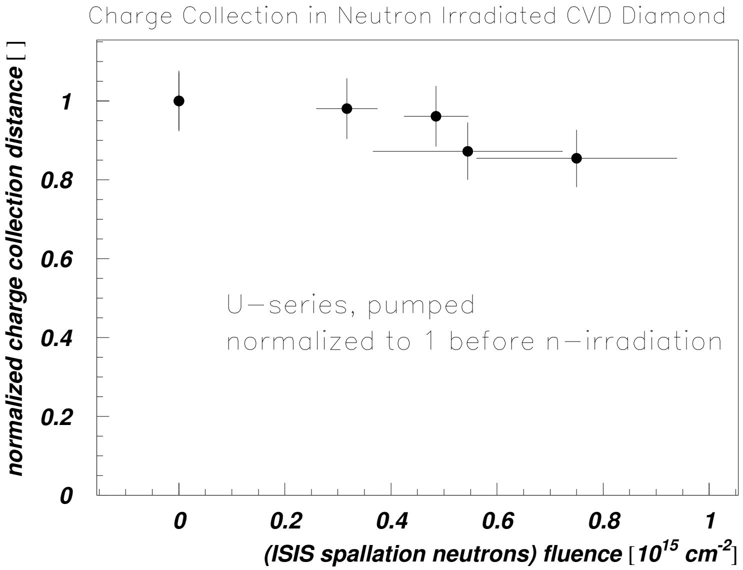
- off spill current increases
- induced current lower than expected

- off spill current constant
- induced current agrees with expectation charge collection distance

Neutron Irradiation of Diamond

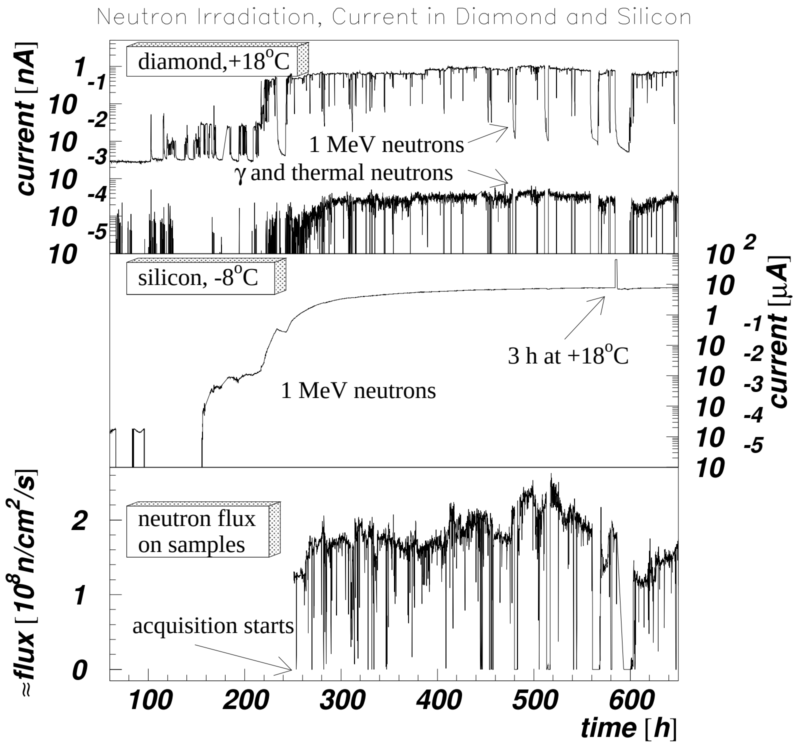
- ‘ISIS/RAL’ neutrons, mean kin. 1 MeV
- flux $\approx 1.7 \times 10^8\ n/\mathrm{cm}^2/\mathrm{s}$, $1/r^2$ dependence
- charge collection distance 50 μm before irradiation

Charge Collection



- decrease by 15% at $8 \times 10^{14}\ n/\mathrm{cm}^2/\mathrm{s}$

Particle Induced Current

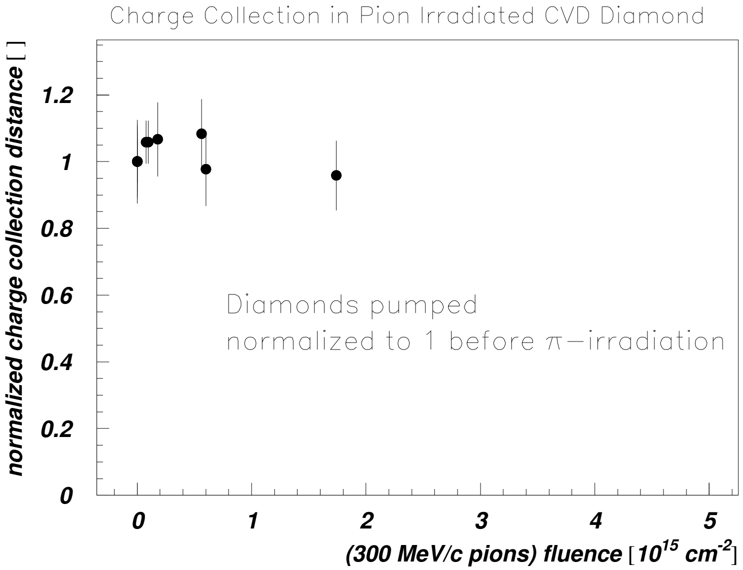


- **diamond**, prompt response, constant
  1 MeV current > at thermal neutrons
- **silicon**, leakage dominates, increase

Pion Irradiation of Diamond

- PSI, 300 MeV pions
- charge collection distance 50 μm before irradiation

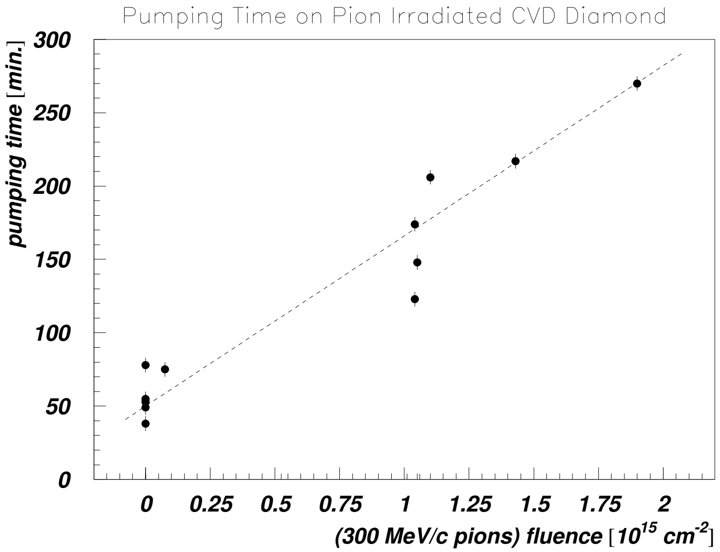
Charge Collection



- No decrease at $1.8 \times 10^{15}\ \pi/\mathrm{cm}^2$

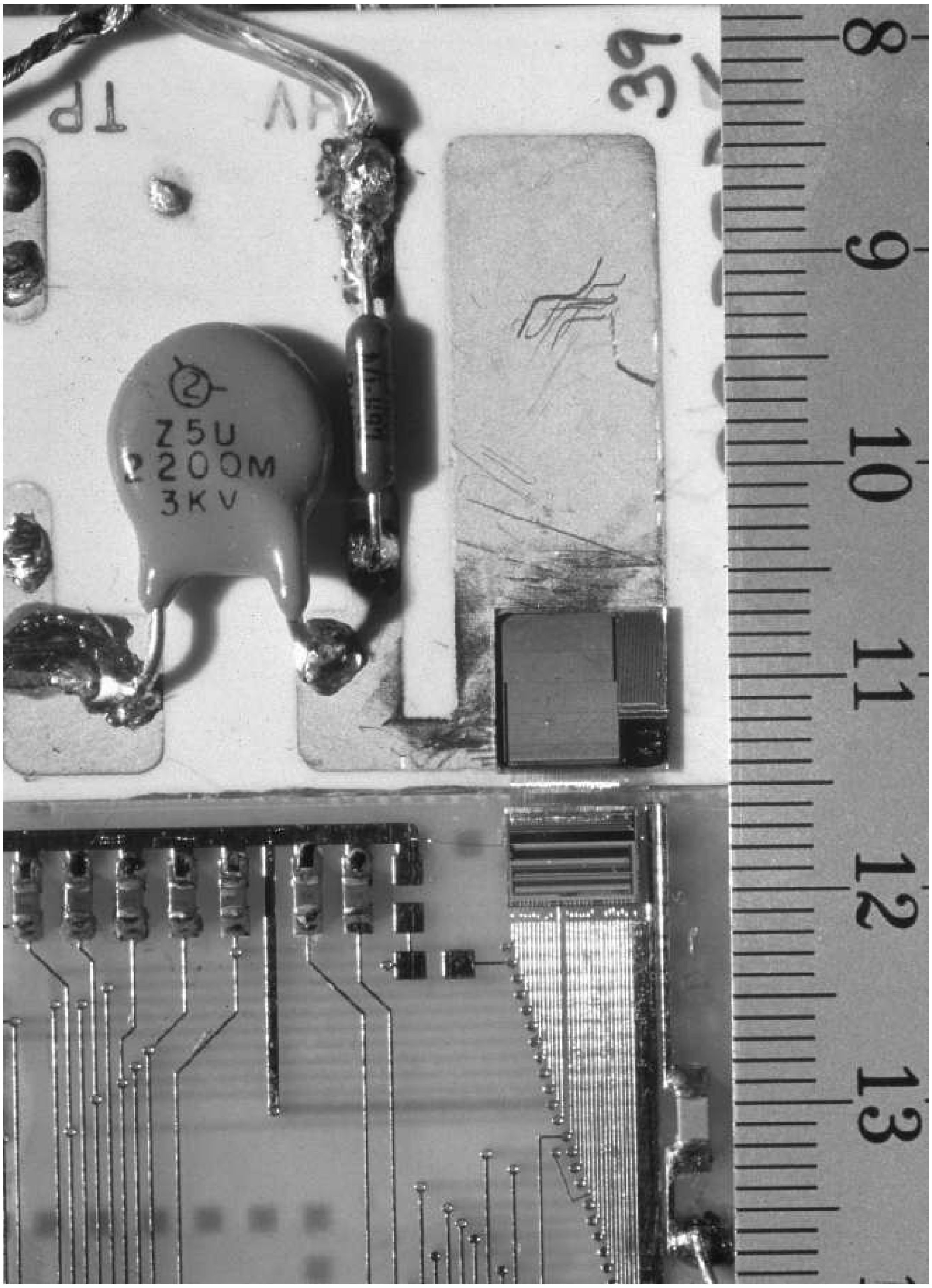
- ^{90}Sr pumping before/after irradiation is exponential
- plot exponential time constant vs pion fluence

Pumping Characteristic



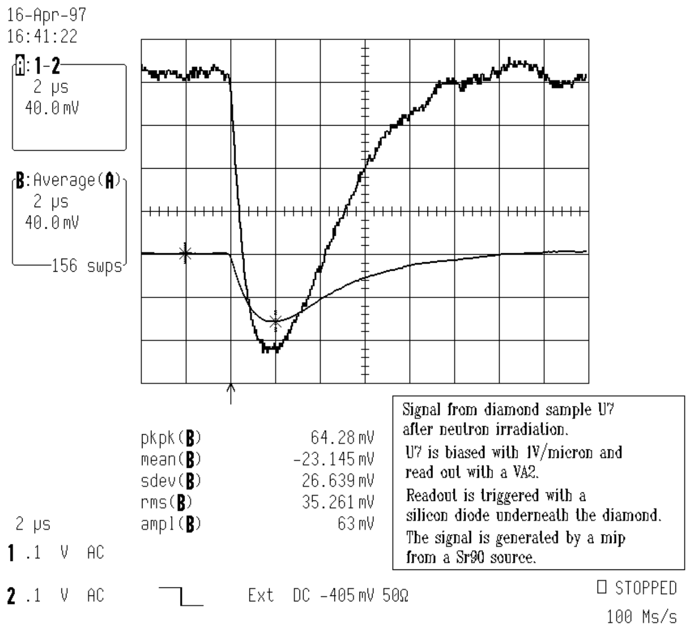
- indication: more traps to fill after pion irradiation
- ^{90}Sr pumping recovers charge collection

Diamond Strip Detector, Picture



- diamond sensor size $8 \times 8\ \mathrm{mm}^2$
- $50\ \mu$m strip&readout pitch

Diamond Signal



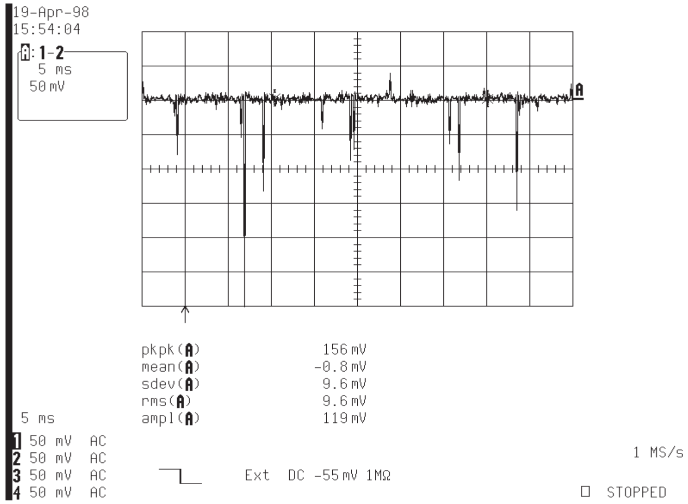
- VA2 readout amplifier, 128 channels,
- charge integration, signal shaping

  $\tau_{\rm peak} = 2~\mu$s,
- low noise (measured)

  ENC$\approx 82e + 14~e/$pF

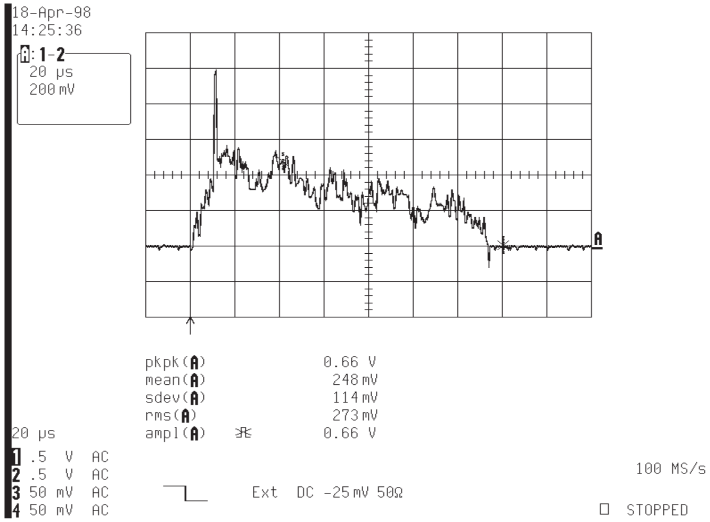
Signal, qualitative check

- ^{90}Sr signals on one strip of diamond tracker



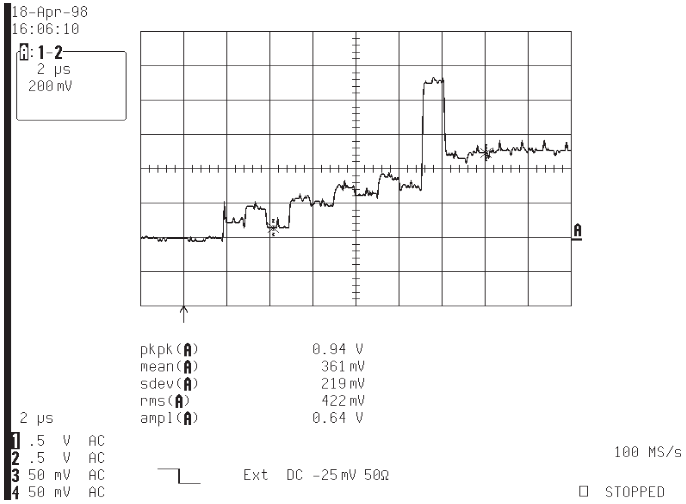
- scope tells: sensor works!

Multiplexed Signals



- 128 channel sequence from VA2

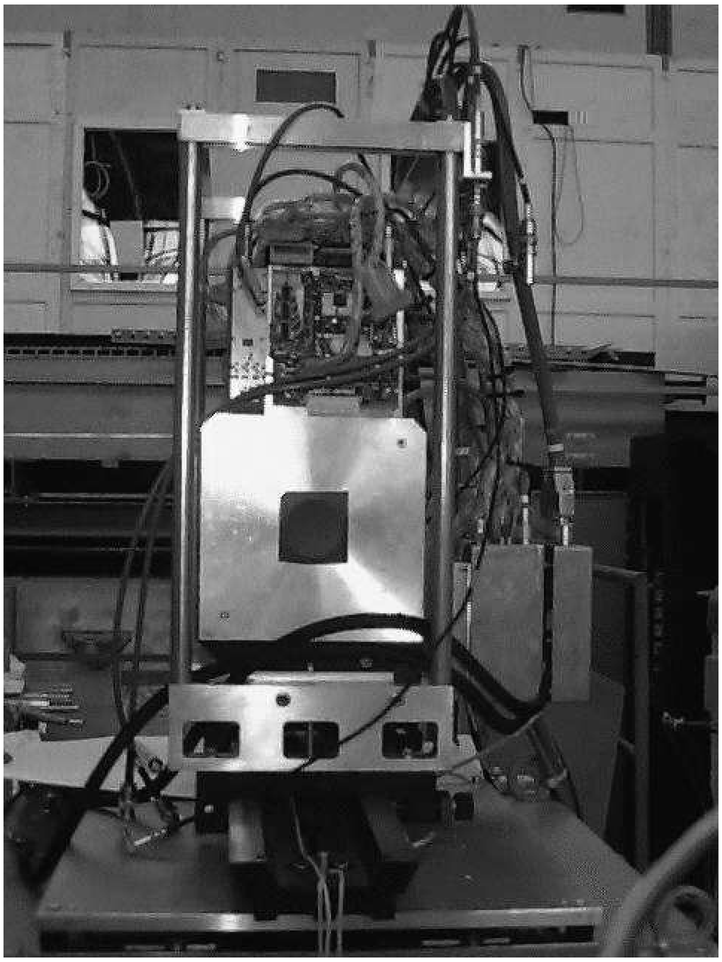
first ≈ 16 channels

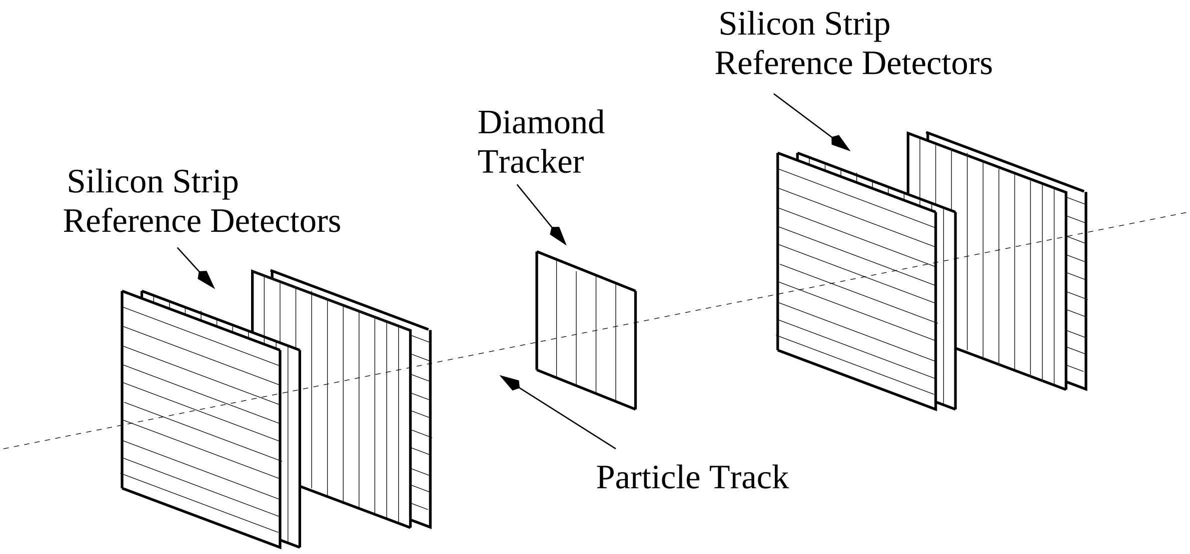


- hold signal from a channel appears 1 μs in sequence

Silicon Telescope, Particle's View

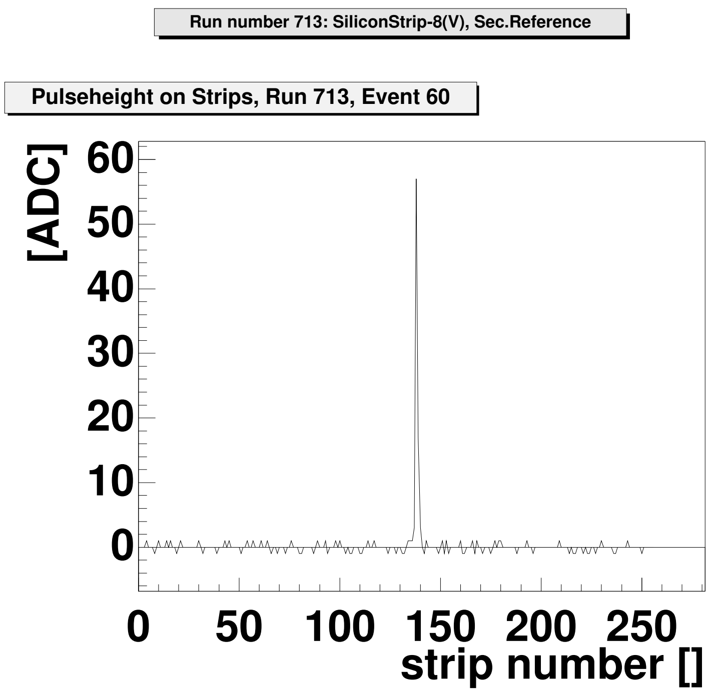
- Front view onto the 'LEPSI' Silicon Beam Telescope



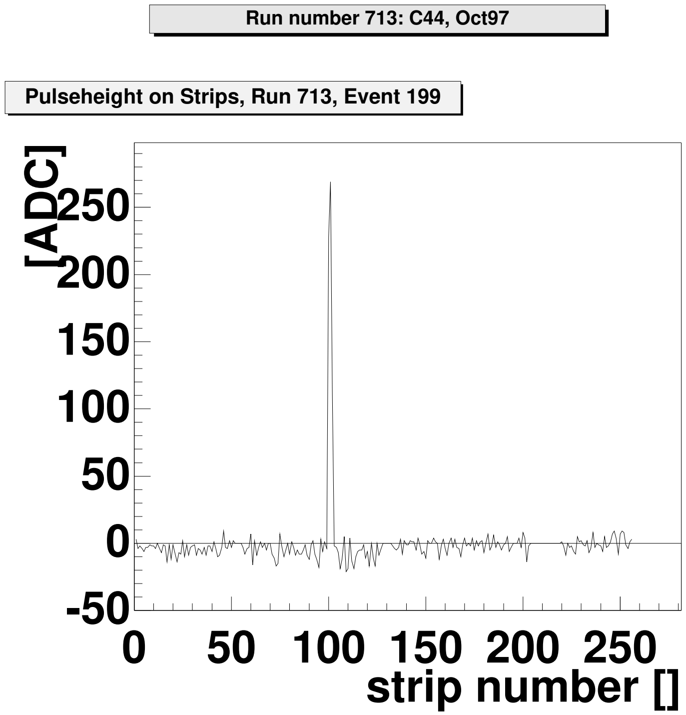


Online Display: Pulseheights on Planes

Hit in silicon plane

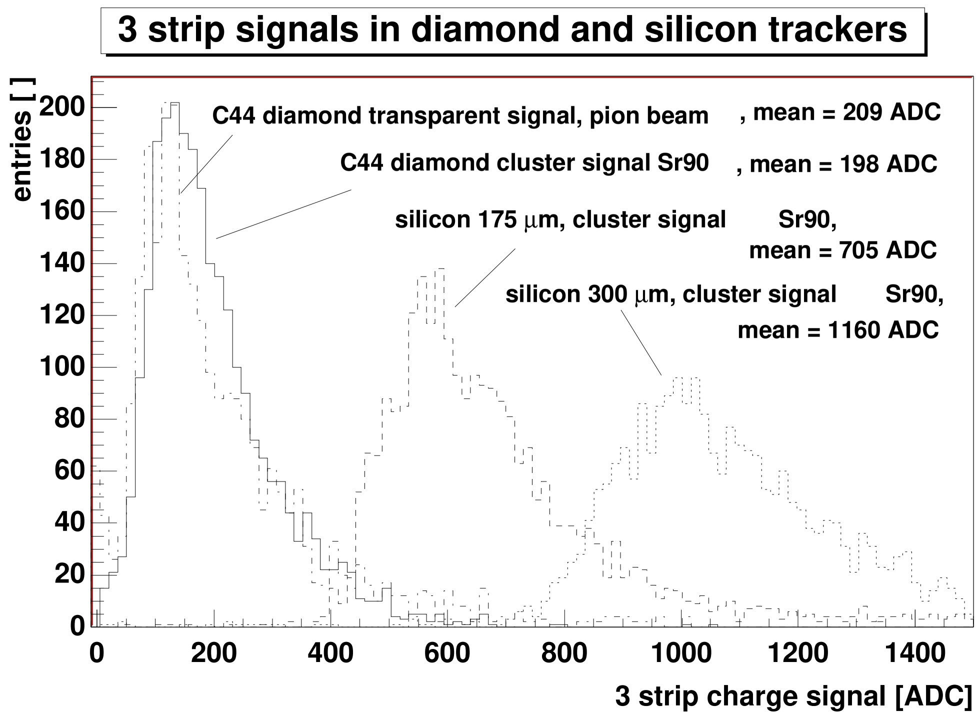


Hit in diamond plane



Diamond/Silicon, Calibration Study

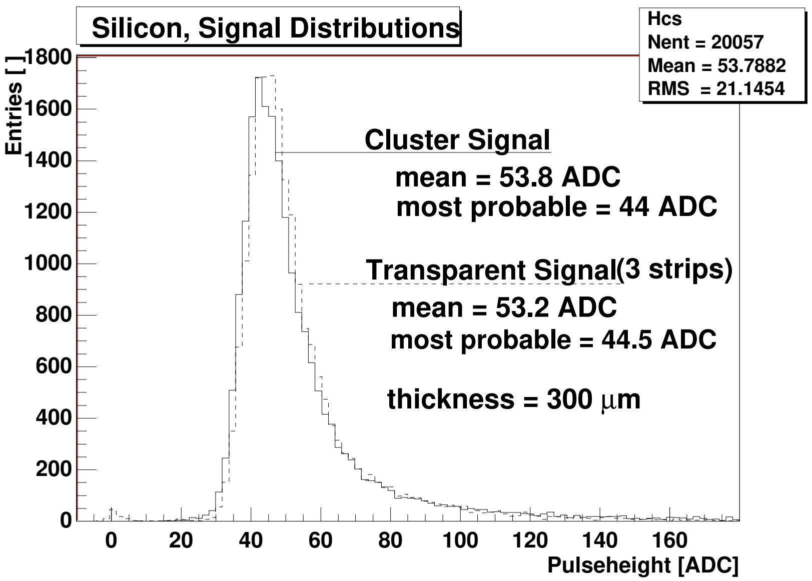
- C44 charge signal (pumped) measured with ^{90}Sr
- .. and silicon strip detectors measured using ^{90}Sr for comparison



- Mean measured charge in 300 μm thick silicon $22500\ e \cdot 1.23 = 27700\ e$
- '175er' Silicon $22.9\ e$/ADC, '300er' silicon $23.8\ e$/ADC
- C44 **charge collection distance** $4600/36\ \mu\mathrm{m} \approx 128\ \mu\mathrm{m}$

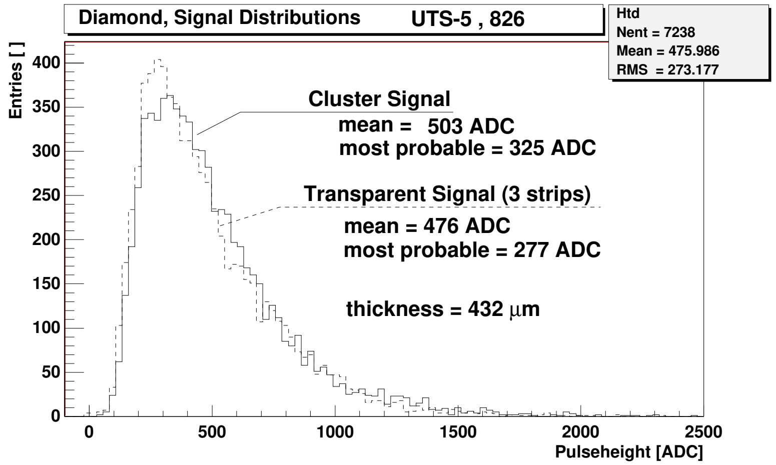
Transparent- and Cluster Signal

Silicon



- transparent and cluster signal overlay
- $\frac{S_{\mathrm{mean}}}{S_{\mathrm{mp}}} = \frac{53.5}{44} = 1.215$
- $\frac{S_{\mathrm{mp}}}{\mathrm{ENC}} \approx 80$
- signal separates from 0, start at $0.7 \times S_{\mathrm{mp}}$

Diamond



- transparent and clustersignal overlay
- $\frac{S_{\mathrm{mean}}}{S_{\mathrm{mp}}} \approx \frac{476}{277} \approx 1.7$
- $\frac{S_{\mathrm{mp}}}{\mathrm{ENC}} \approx 40$ (based on transparent signal)
- signal separates from 0, start at $0.3 \times S_{\mathrm{mp}}$

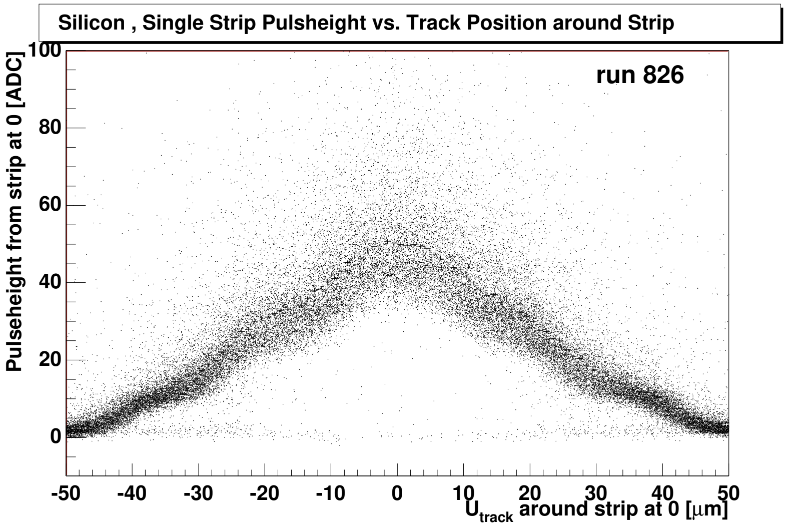
Charge Collection on Single Strip, (Preliminary)

- measured charge $Q_0(u_{\mathrm{track}})$ on single strip at $u = 0$ vs distance between 0 and u_{track}

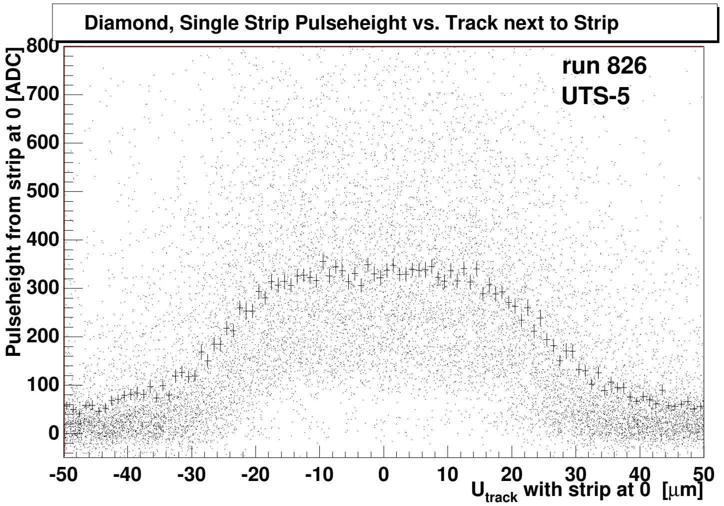
$$Q(u_{\mathrm{track}}) = \int_0^{u_{\mathrm{track}}} q_{\mathrm{profile}}(u)\mathrm{d}u$$

- $q_{\mathrm{profile}}(u) \stackrel{\mathrm{def}}{=} \frac{\mathrm{d}Q(u)}{\mathrm{d}u}$ is ‘unknown’ charge profile

Silicon



Diamond

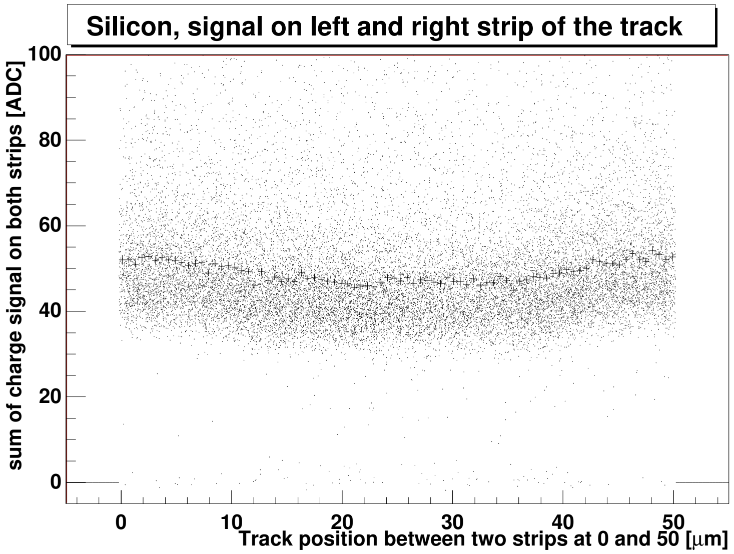


- strip width $\Delta u_{\mathrm{strip}} \approx 6\ \mu\mathrm{m}$
- strip width $\Delta u_{\mathrm{strip}} \approx 25\ \mu\mathrm{m}$

Charge Collection on Two Strips

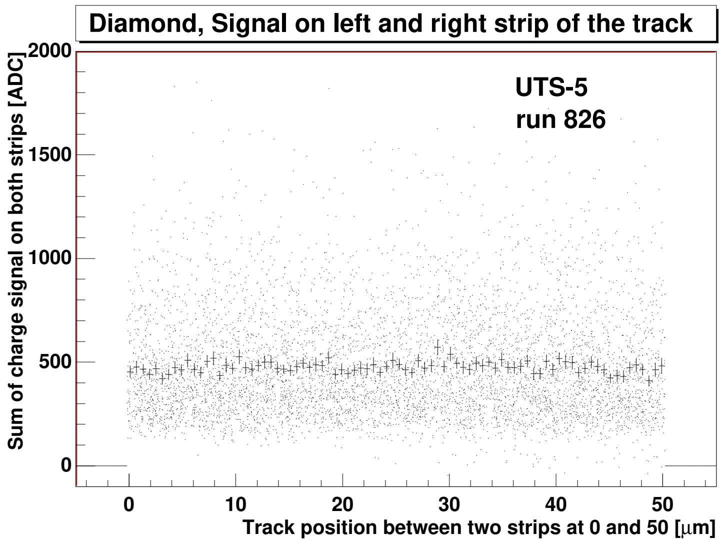
- measured charge $Q_{\text{left}} + Q_{\text{right}}$ on two strips vs. position of track between strips

Silicon



- small loss between strips

Diamond



- no loss between strips

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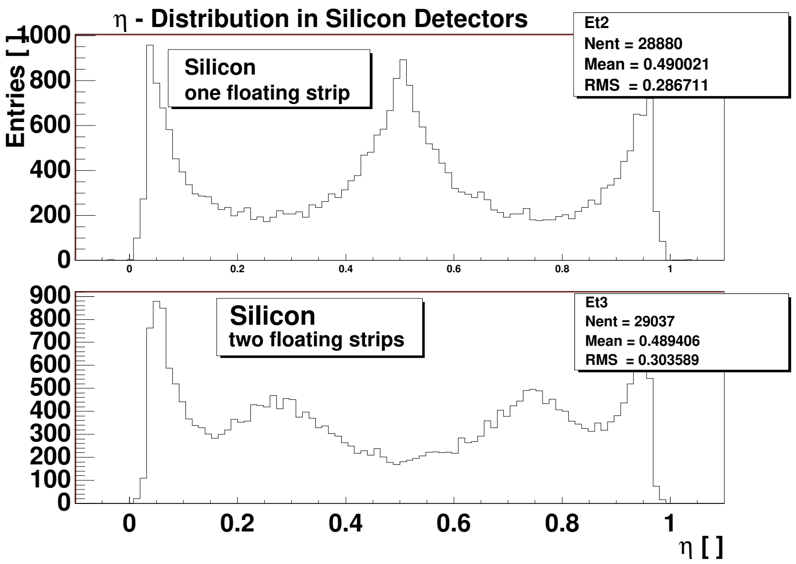
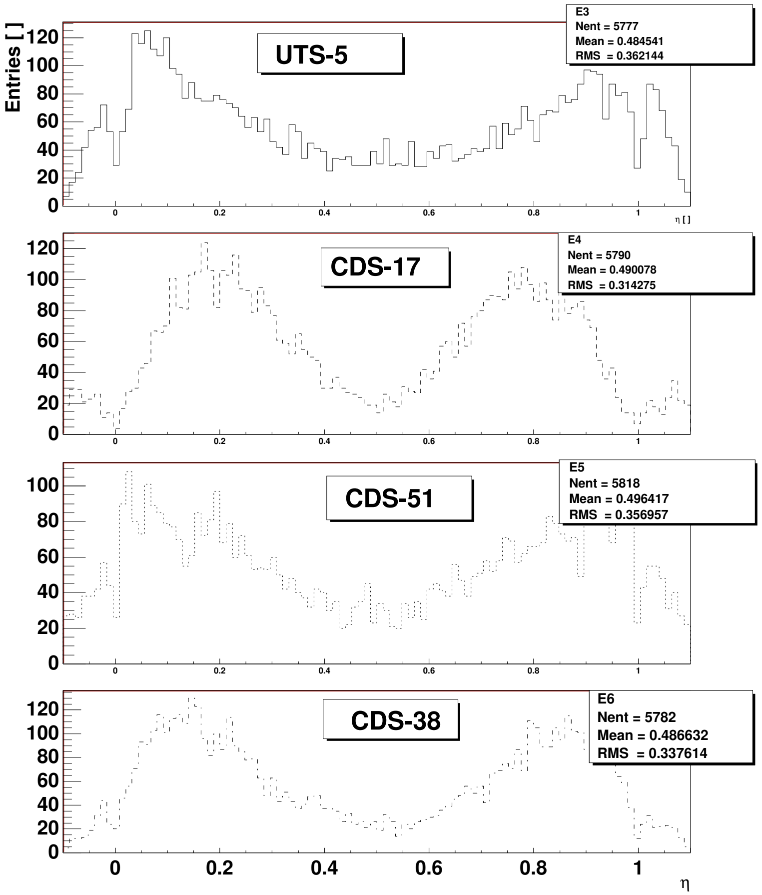
η-Distribution

- biggest and 2nd biggest pulse: one is **right**, the other **left** strip
- Definition: $\eta \stackrel{\text{def}}{=} \frac{\text{Pulseheight}_{\text{rightstrip}}}{\text{Pulseheight}_{\text{rightstrip}}+\text{Pulseheight}_{\text{leftstrip}}}$

Silicon



Diamond



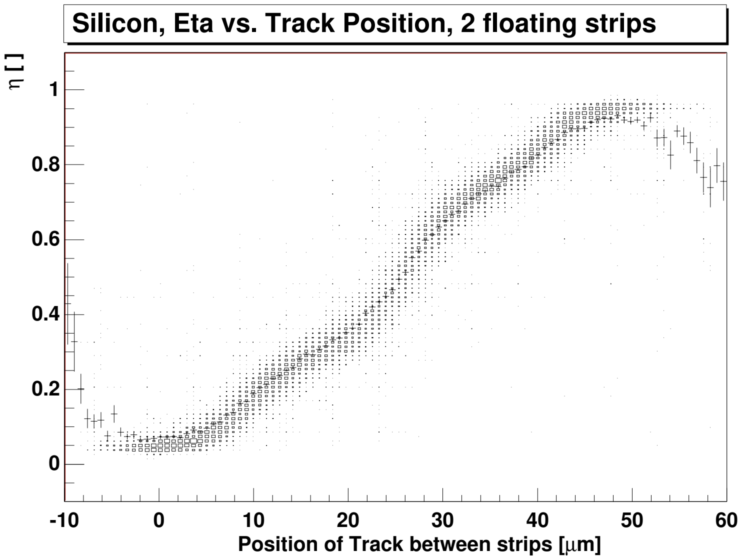
- η within intervall $[0..1]$
- maxima on strips (readout or floating)
- one or two intermediate floating strips

Track with η Correlations

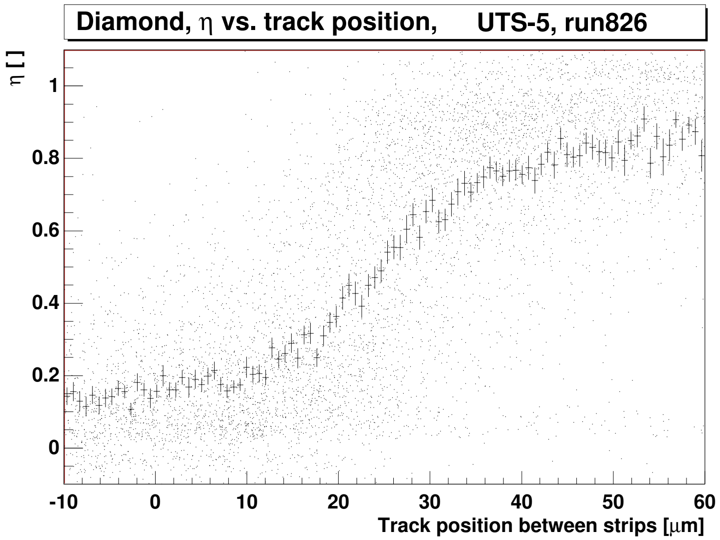
- η correlates with track
- possibilty to improve hit findig, better than center of gravity method

$$x_{\text{hit}} = x_{\text{leftstrip}} + \int_0^{\eta} f(\eta')d\eta'$$

Silicon



Diamond



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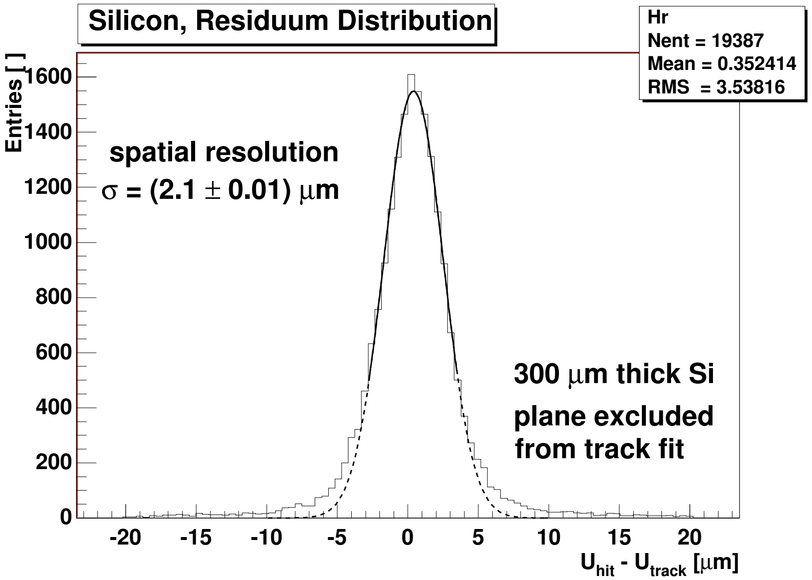
Spatial Track Resolution

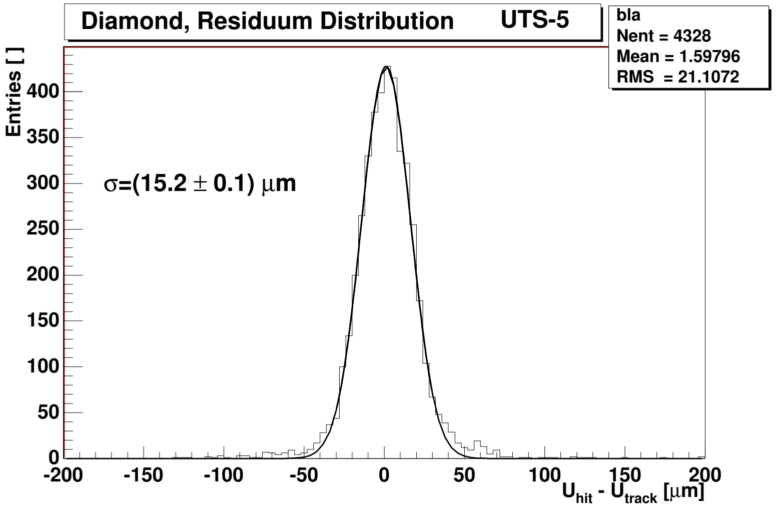
- Definition: Residuum $\stackrel{\text{def}}{=} u_{\text{hit}} - u_{\text{track}}$
- … now distribution of residua

Silicon



- standard deviation = spatial resolution of 2.1 μm
- **intrinsic spatial resolution** 1.5 μm

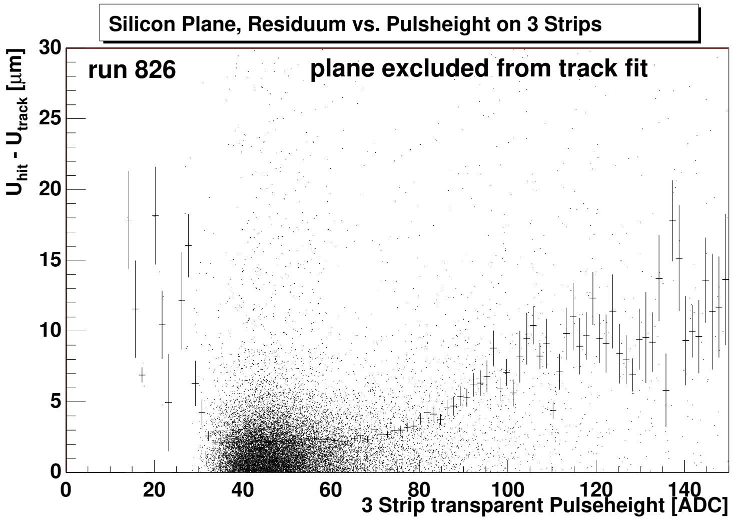
Diamond



- gaussian distribution, $\sigma = 15\ \mu$m
- .. = digital resolution for 50 μm pitch
- other hit finding algorithm under study

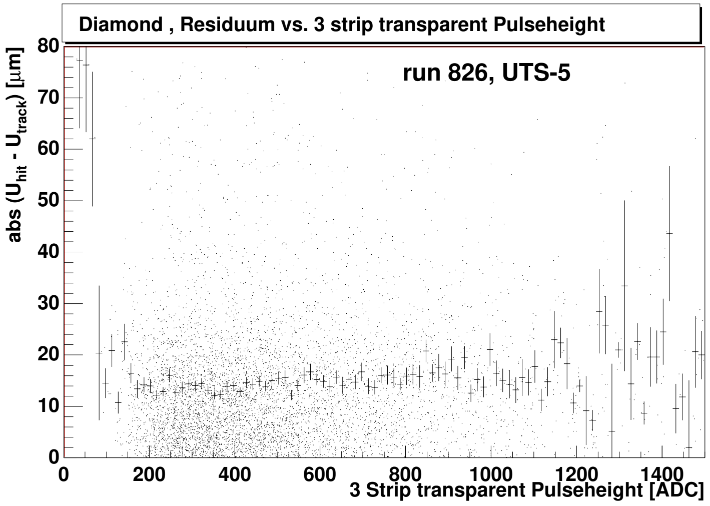
Residuum versus Pulseheight

Silicon



- residuum increases with pulsheight
- resolution decreases with pulseheight
- δ-electron effect

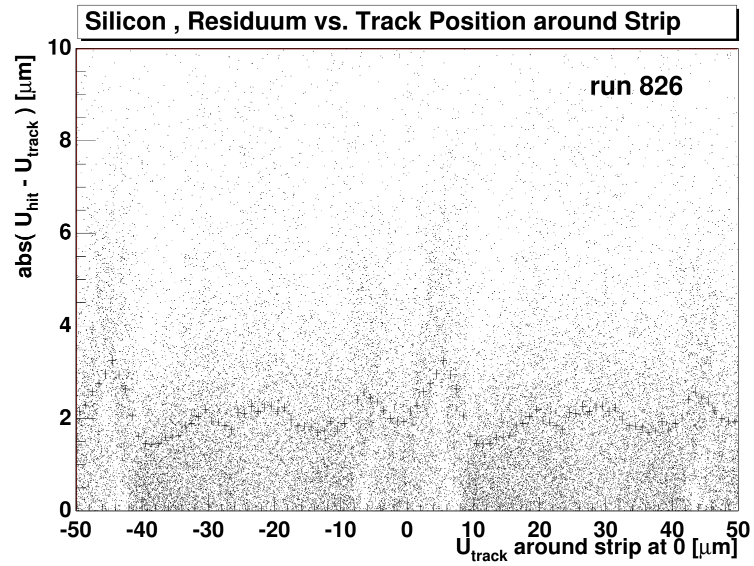
Diamond



- resolution constant with pulseheight
- CG-Method not sensitive to δ's

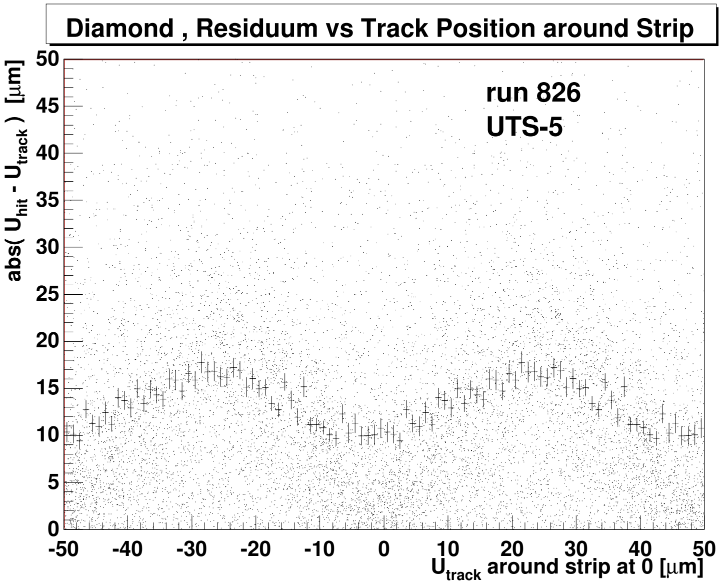
Residuum versus Track Position

Silicon



- mean varies slightly
- .. due to η-hit finding

Diamond

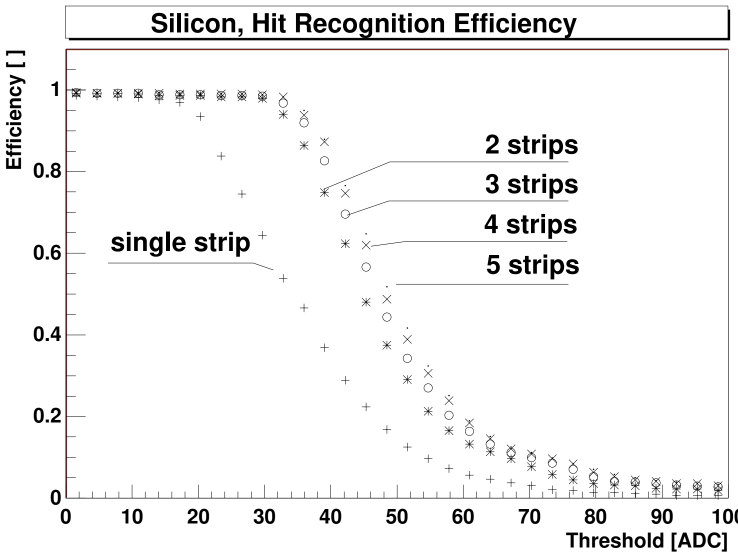


- residuum oscillates
- best at strip position
- $\Longrightarrow$ resolution can improve using hitfinding different from center of gravity

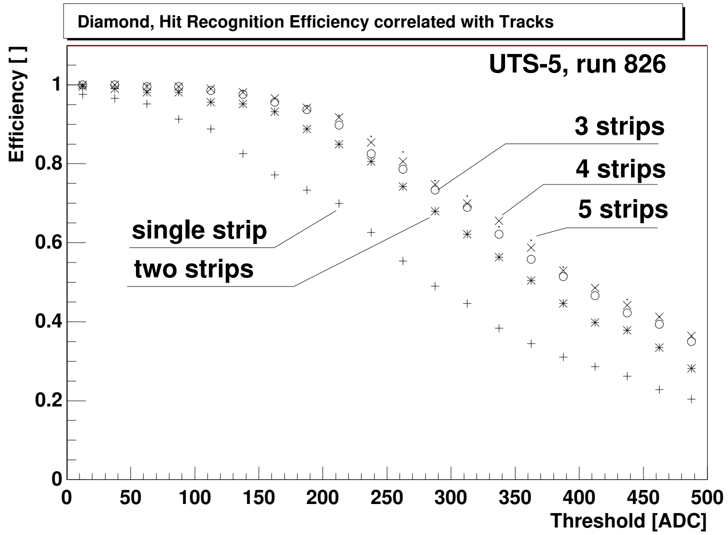
Hit Recognition Efficiency

- **efficiency** $\stackrel{\text{def}}{=} \dfrac{\text{number of hits with ChargeSignalSum above threshold and correlated with track}}{\text{all tracks passing detector}}$

Silicon



Diamond

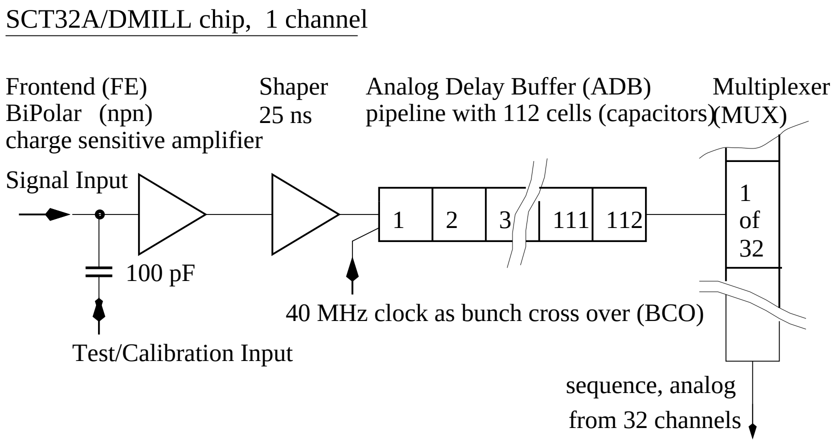


- 99% hit finding efficiency on two strips and threshold below 30 ADC for both strips
- optimal threshold between 100 ADC and 150 ADC
- 99% hit finding efficiency

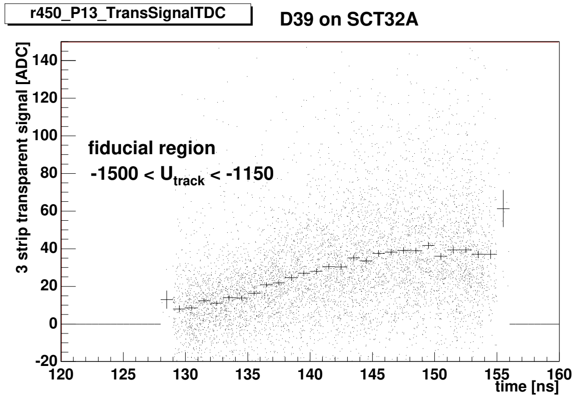
25 ns, SCT/DMILL on Diamond

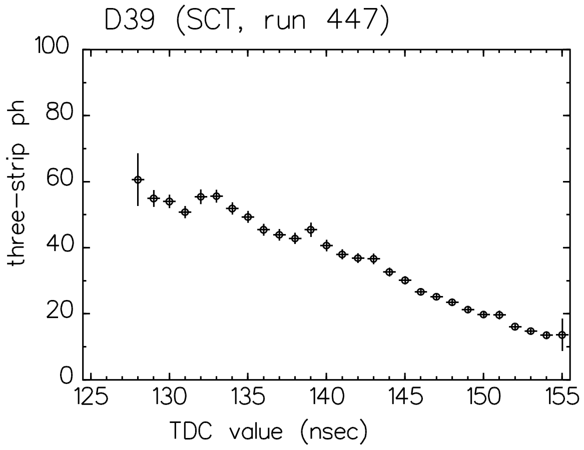
SCT32A/DMILL Chip

- fast shaping (matches LHC BCO)
- radhard DMILL process
- keeps analog information



Signal vs. time from **two cells**

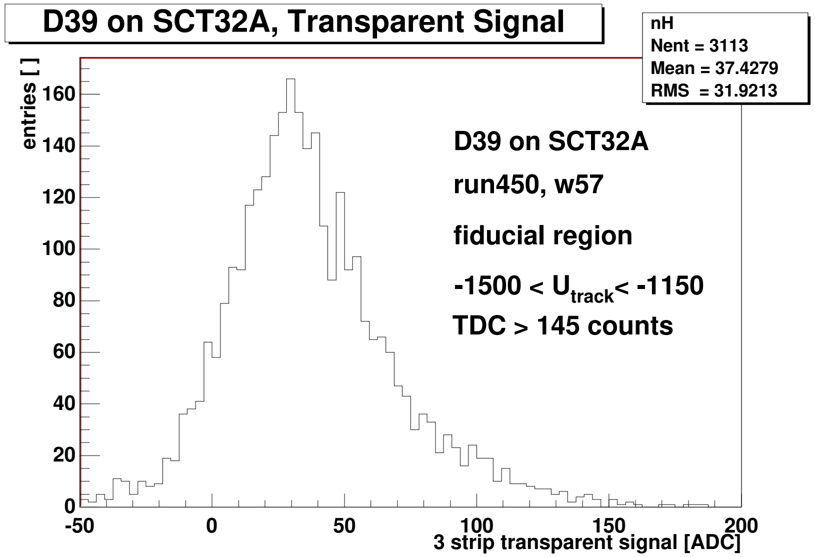




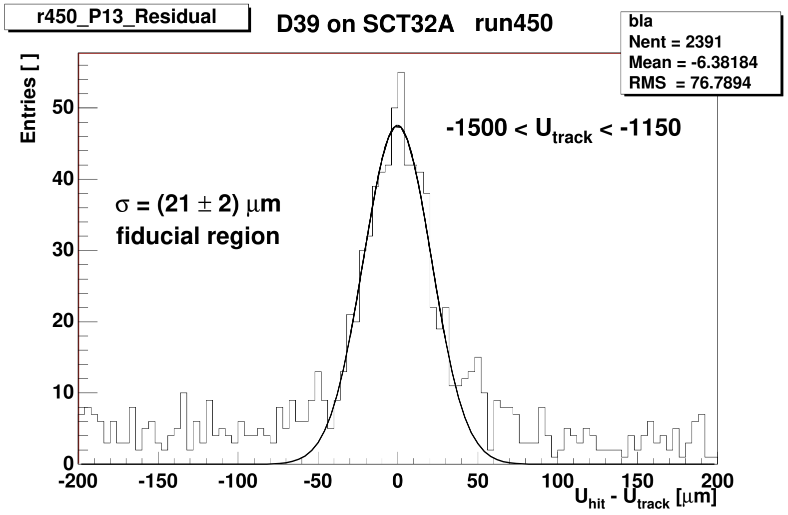
- maximum signal 'between both cells'

25 ns, SCT/DMILL on Diamond

Transparent Charge Signal



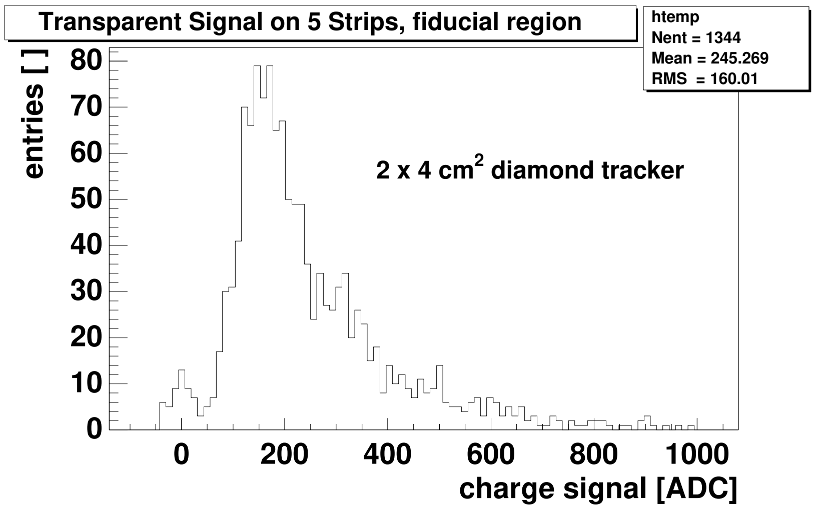
Spatial Resolution



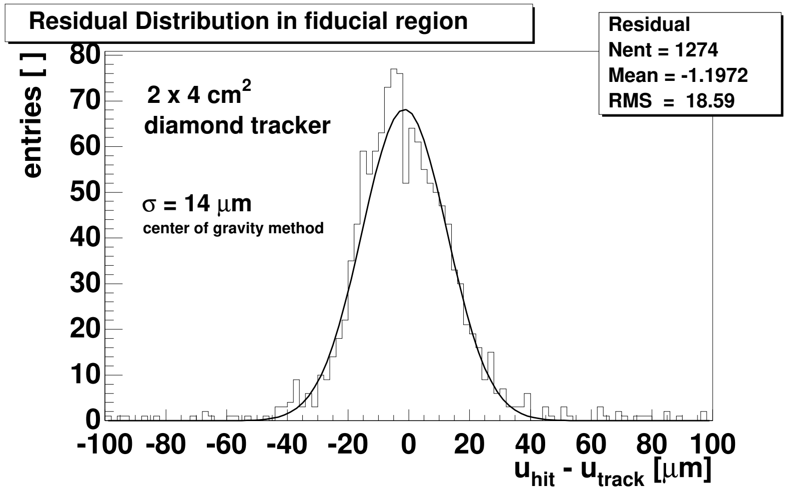
- Resolution 21 μm

Large Diamond Strip Detector

Charge Signal



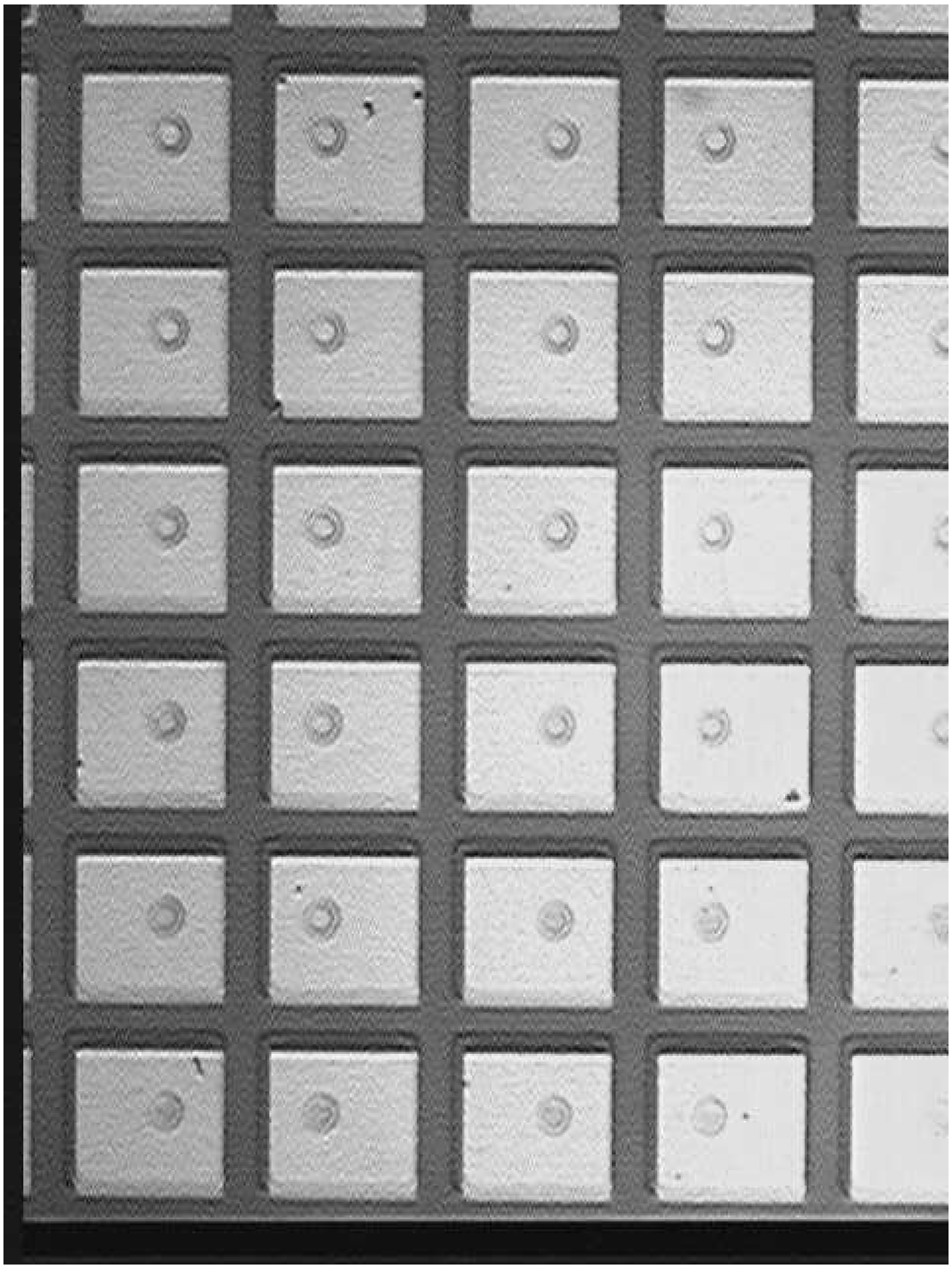
Resolution



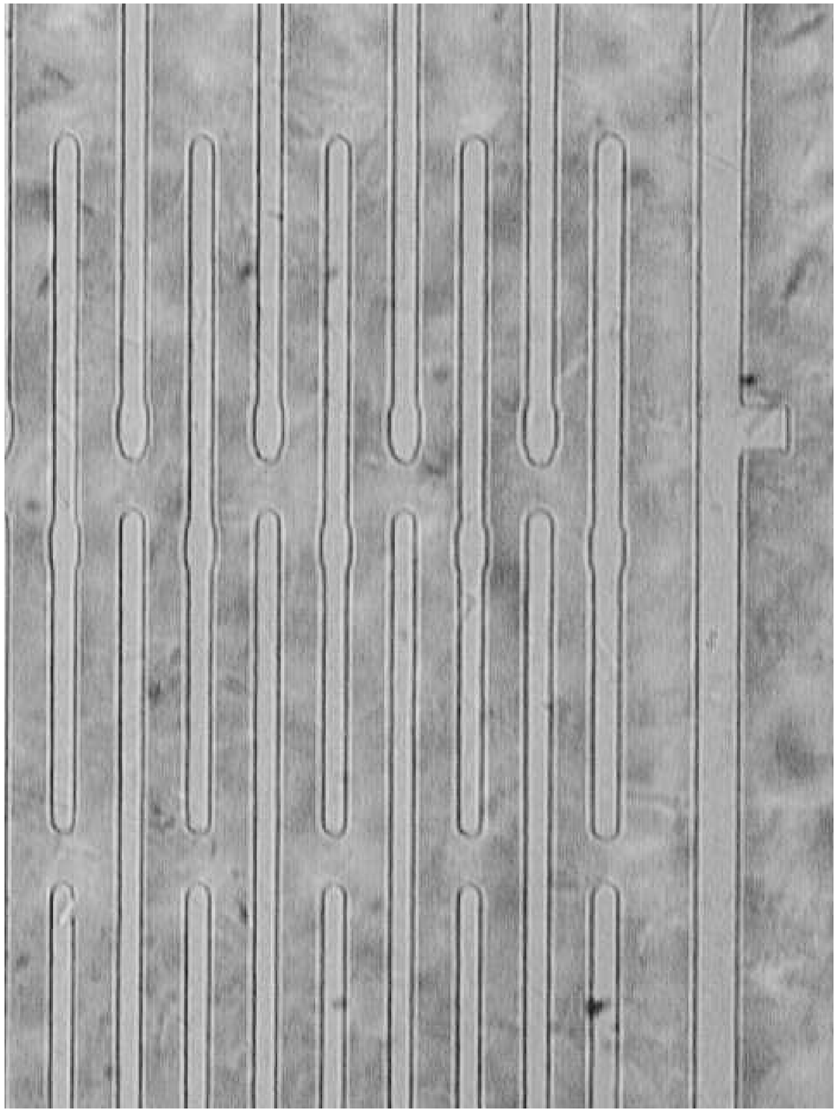
- **mean** transparent signal ≈ 258 ADC
- ratio mean/most probable = 1.5
- Noise ≈ 7 ADC ENC
  $\Longrightarrow S_{\text{mp}}/N \approx$ 23-to-1

- Center-of-Gravity Method:
  spatial resolution ≈ 14 μm
- .. = digital resolution for 50 μm pitch

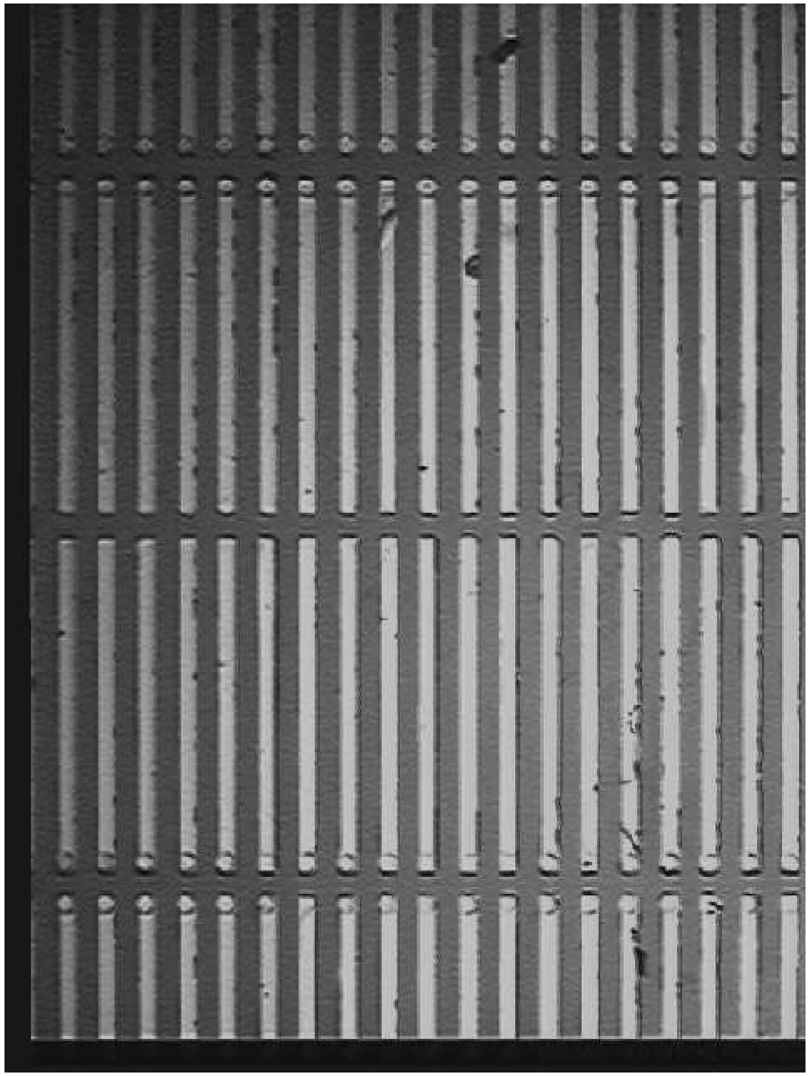
Bump Bonded Diamond Pixels, CMS Version



ATLAS/LBNL



ATLAS/Bonn&Marseille



'along' pixels

- xyz μm inter-digitized pixel pitch
- Resolution 140 μm

'perpendicular' pixels

- 50 μm pixel pitch
- Resolution 15 μm

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Summary

- **Charge Collection**

  Mean signal $\approx$ 8000 e with *mip*'s

- **Irradiation Studies**

  on $100\ \mu$m charge collection samples:

  24 GeV/c p: at $1 \times 10^{15}\ p/\mathrm{cm}^2$ no decrease

  on $50\ \mu$m charge collection samples:

  1 MeV n: at $0.8 \times 10^{15}\ n/\mathrm{cm}^2$ 10%..15% decrease

  300 MeV pions: no decrease at $1.8 \times 10^{15}\ p/\mathrm{cm}^2$

- Diamond, strips on **VA electronics**

  $S_{\mathrm{mp}}/N \approx$ 40-to-1

  Efficiency 99% if threshold below $\approx$ 2000 e

  Large area diamond sensors, $S_{\mathrm{mp}}/N \approx$ 23-to-1

  Digital spatial resolution with Center-of-Gravity

  η-algorithm might improve resolution

- Diamond with **fast radhard SCT/DMILL**

  $S_{\mathrm{mp}}/N \approx$ 3-to-1

  Low capacitance SCT/DMILL will improve

- **Bump Bonded Diamond Pixels**

  ATLAS/design '1' very good TB results

  ATLAS/design '2' in testbeam now

  CMS in preparation