# Silicon Detectors for Precision Tracking

**LTP Seminar**

**Paul Scherrer Institute**

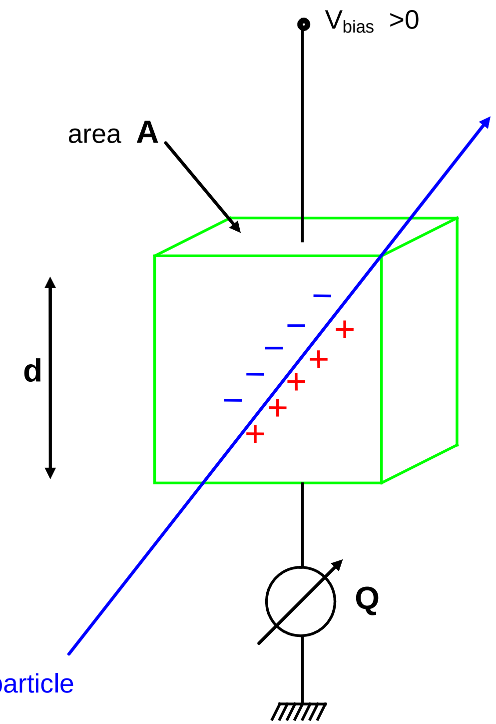
**10. July 2017**

**Roland Horisberger**

# „Ohmic“ Particle Detector

(Gedankenexperiment)

**Ohmic material : Resistivity r**




- **E-field** :

  $E = V_{bias} / d$

- **Carrier velocity** :

  $v = \mu E = \mu ( V_{bias} / d )$

- **Signal collection time** :

  $\tau = d / v = d^2 / (\mu V_{bias} )$

- **Resistance** :

  $R = \rho (d / A)$

- **„leakage current“** :

  $i_{leak} = V_{bias} / R = (V_{bias} A) / ( \rho d )$

- **„leakage charge“** :

  $Q_{leak} = i_{leak} \tau = d A / \rho \mu$

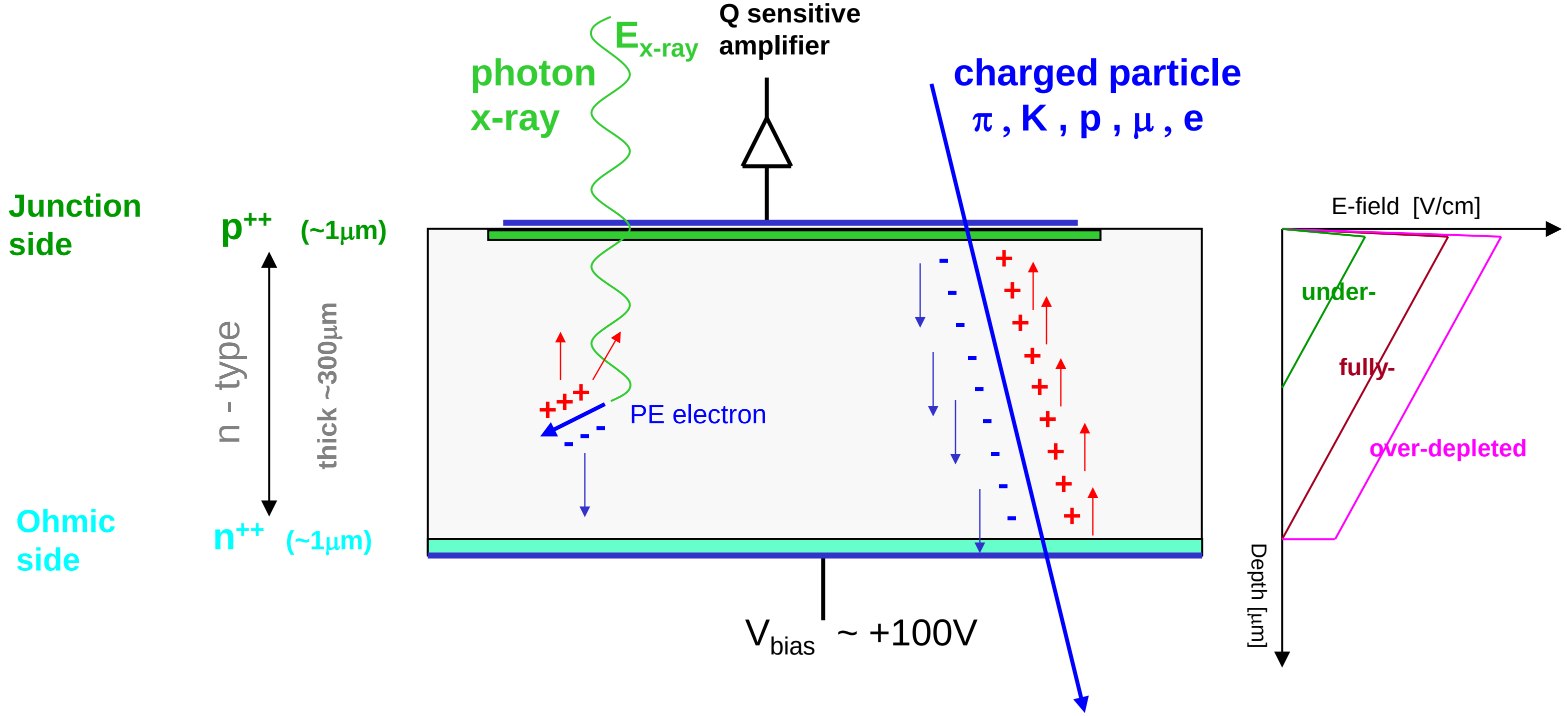
  $Q_{leak} = \text{Volume} / \rho \mu$

**Example :** Silicon $\rho$ = 20 k$\Omega$cm d = 300$\mu$m , Signal charge = 4fClb = 24'000 e

Pad detector : A = 1 $cm^2$ $Q_{leak}$ = $10^{-9}$ Clb → Poisson → $\sigma$ ~ 80'000 e → S/N ~ 0.3

**For Silicon sensors at room temperature need another trick !**

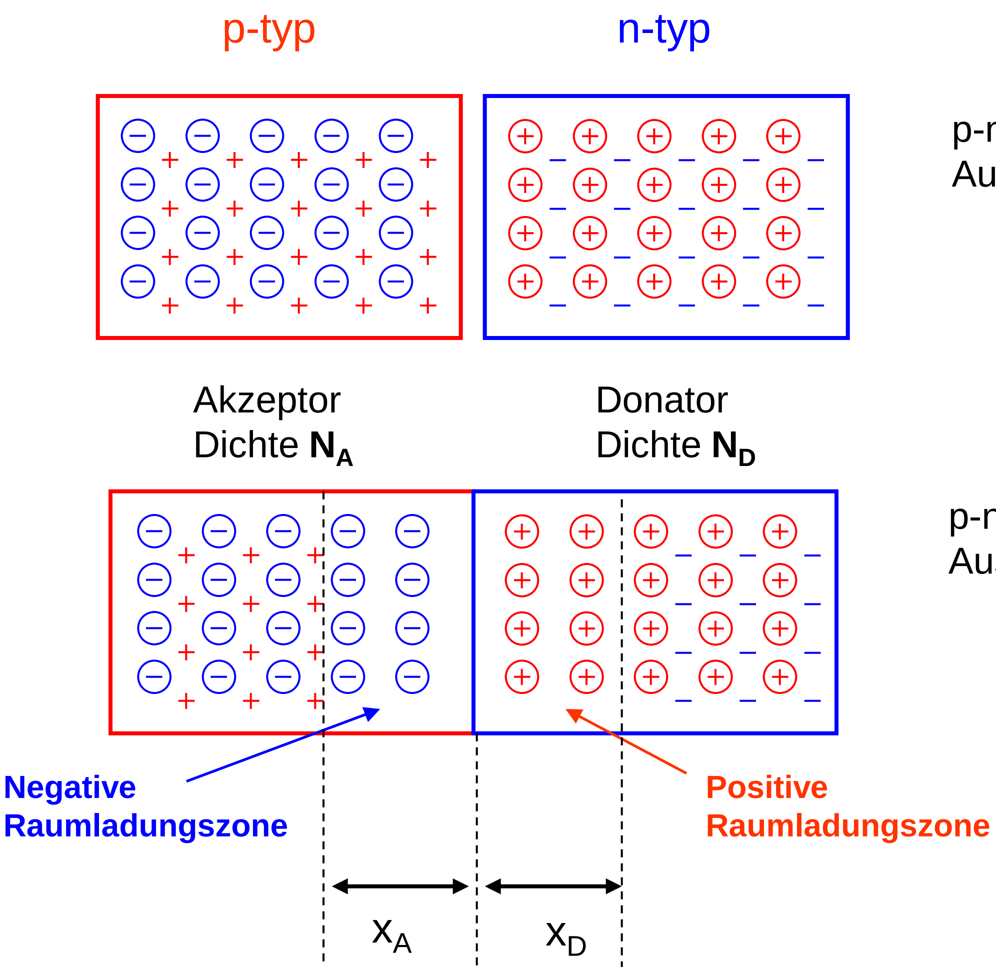
# Use of reverse biased diode as particle detector



# p-n-Uebergang  und Raumladungszone

Feste Ladungen : ⊖ ⊕

Mobile Ladungen: + –




p-n-Uebergang **vor**
Ausgleich der Ferminiveaus

p-n-Uebergang **nach**
Ausgleich der Ferminiveaus

**Ladungsneutralität →**

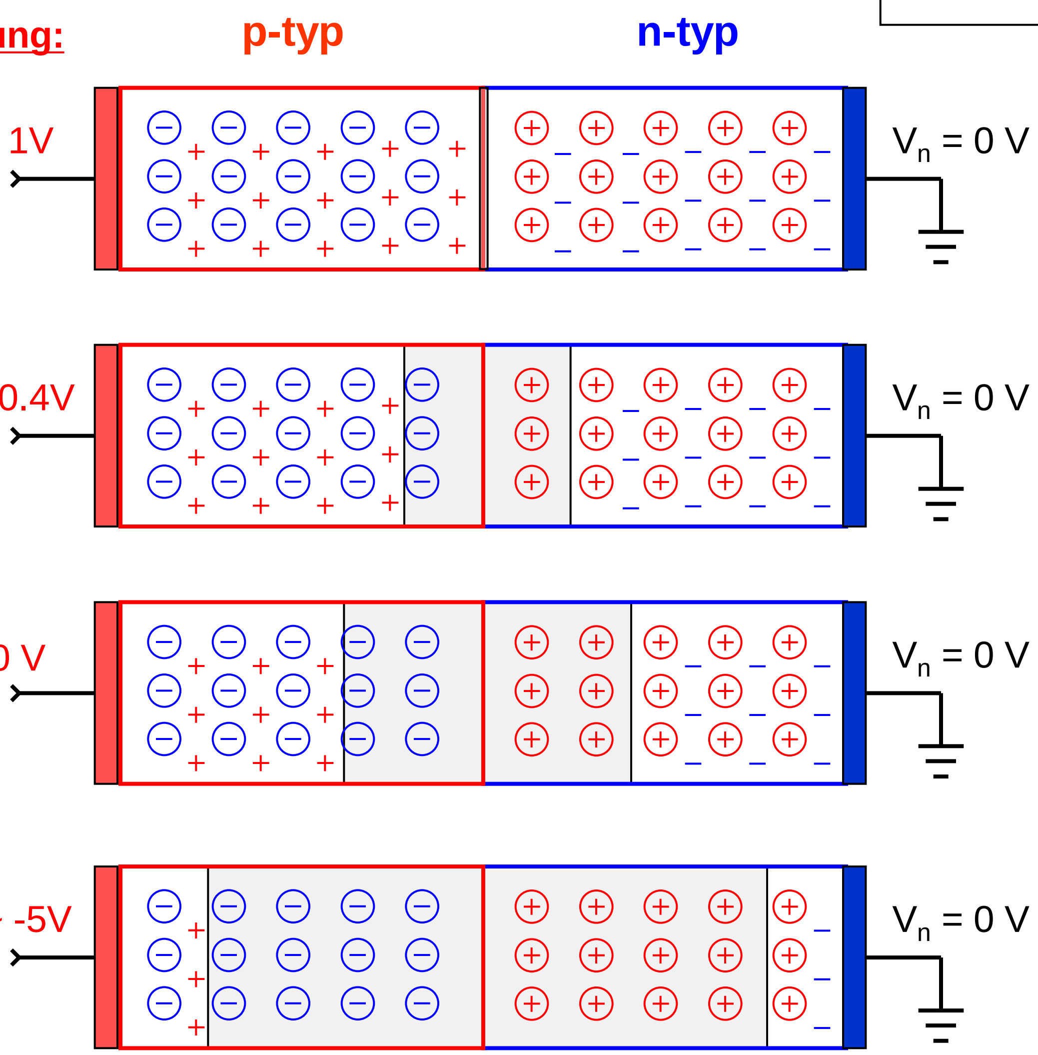
$$N_A \cdot x_A = N_D \cdot x_D$$

# Spannungsabhängigkeit der p-n-Raumladungszone

Fest: ⊖ ⊕

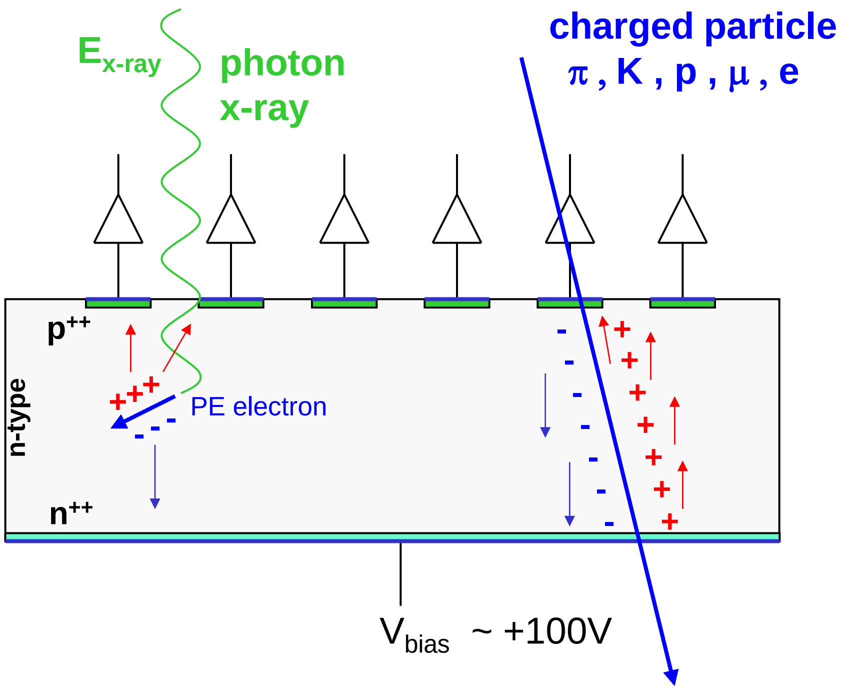
Mobil: – +

| p-n-Diode: | $C_{diode}$ | Spannung: |
|---|---|---|
| stark leitend | nicht definiert | $V_p$ ~ + 1V |
| schwach leitend | gross | $V_p$ ~ +0.4V |
| nicht leitend | nat. | $V_p$ = 0 V |
| sperrend (Leckstrom) | klein (minimal) | $V_p$ ~ -5V |




Raumladungszone (depletion layer)

# Segmented Silicon Diode Sensors for Particle Detection




Shared Charge collection on segmented electrodes due to:

- Diffusion during drift time
- Lorentzangle due to presence of B-field
- Tilted tracks

Individual readout of charge signal on electrodes allowes **position interpolation** that is better than pitch of segmentation.

carrier drift velocity **$v = \mu E$**

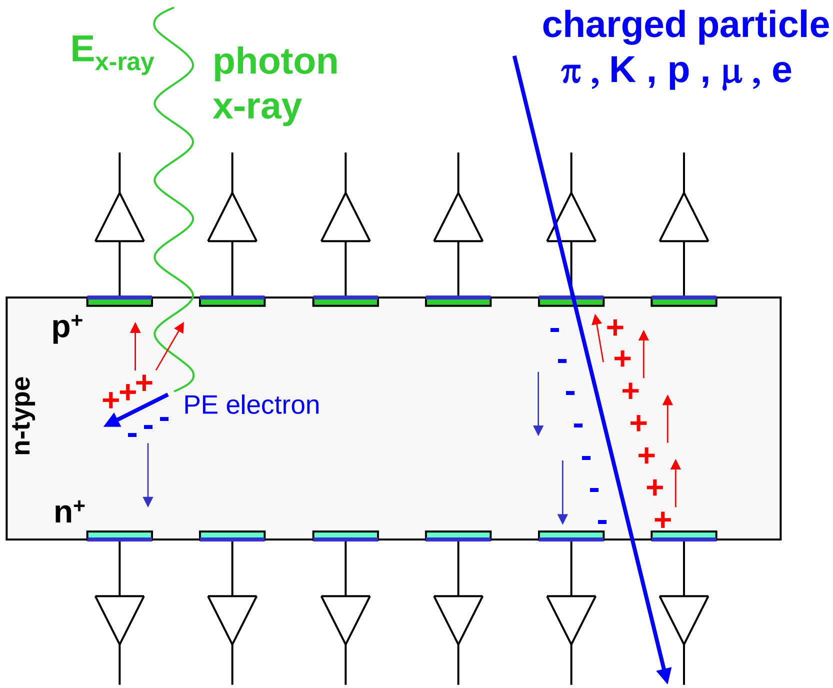
E = electric field [V/cm]
$\mu_e$ ~ 1200 $cm^2$/Vsec mobility electrons
$\mu_h$ ~ 480 $cm^2$/Vsec mobility holes

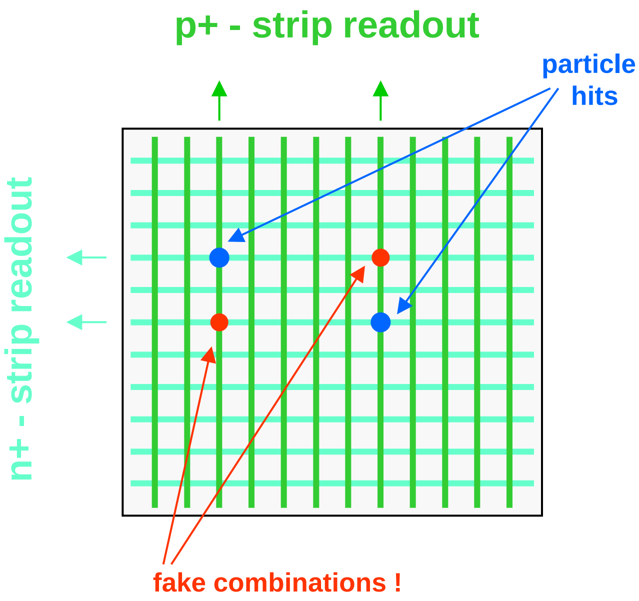
Charge diffusion **$\sigma^2 = D\,t$**

$D = \mu\, kT$ Fick-Einstein relation

Silicon microstrip detectors in HEP with pitch = 50μm have achieved in beam tests a position resolution of ~1.3 μm

# Double Sided Silicon Strip Detectors



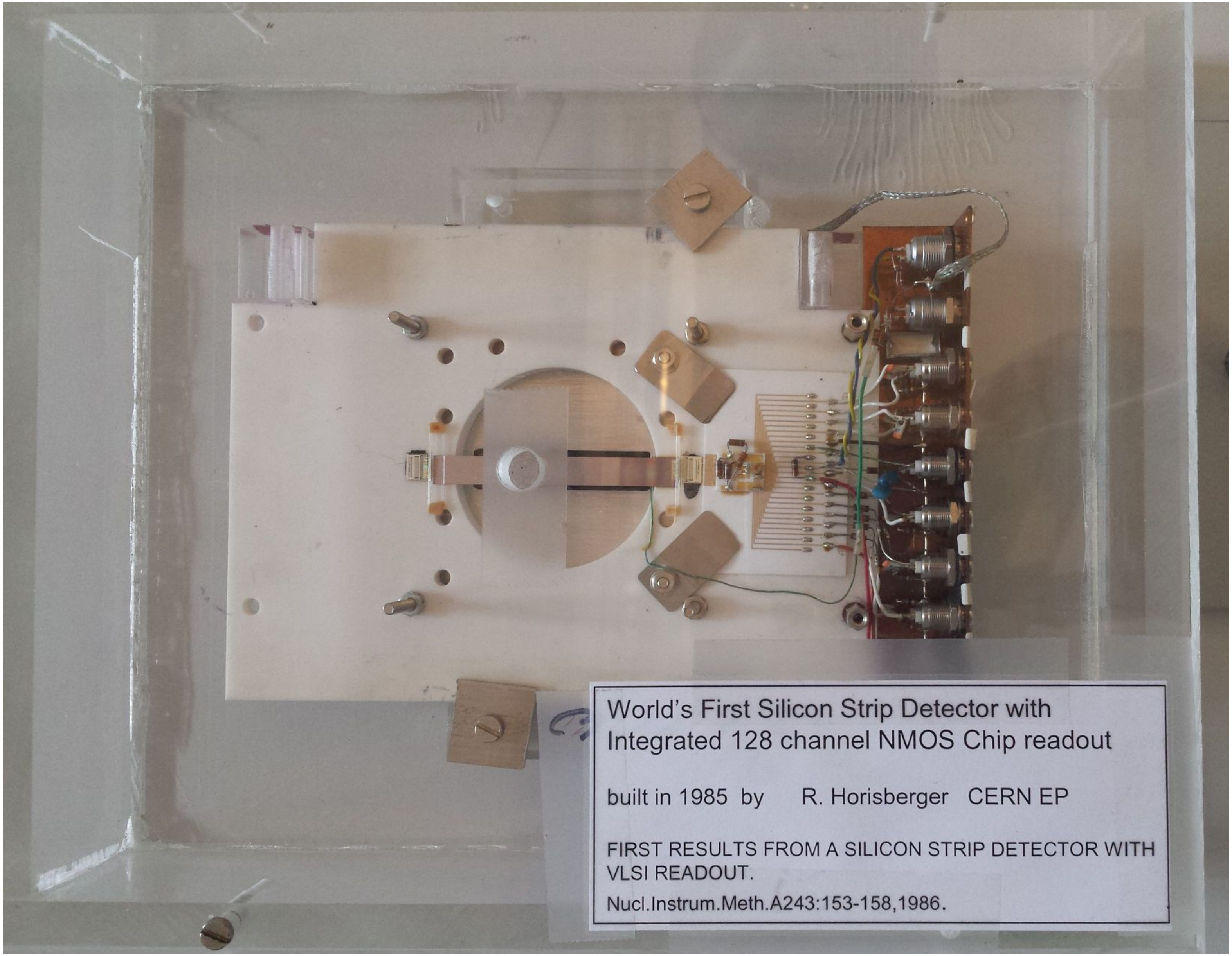




Crossed p-strip and n-strips allows readout of x & y coordinate of particle !

→ But **ambiguity problem** for many hits !

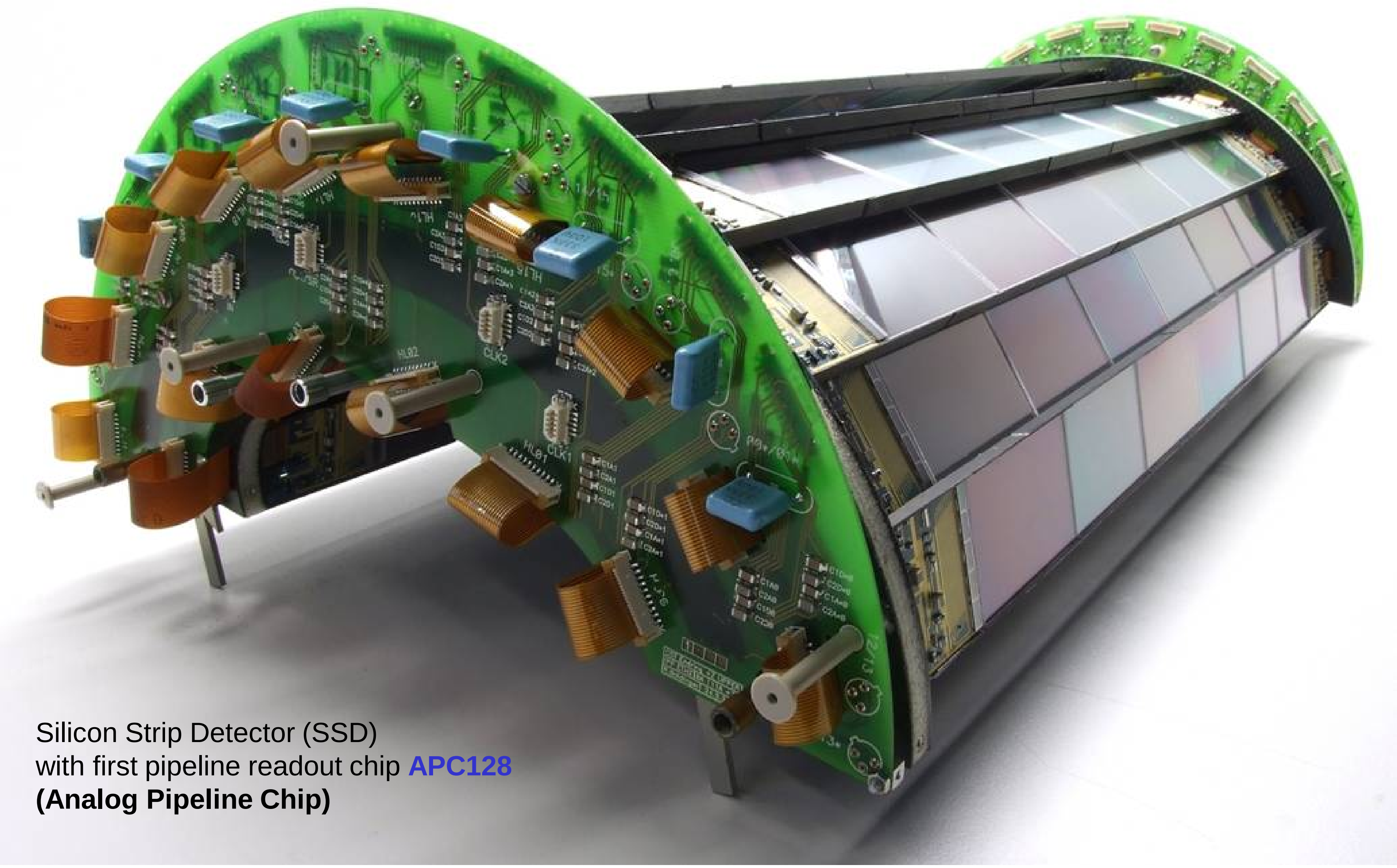
→ solved by **pixel segmentation**

# First Silicon Strip Readout with ASIC



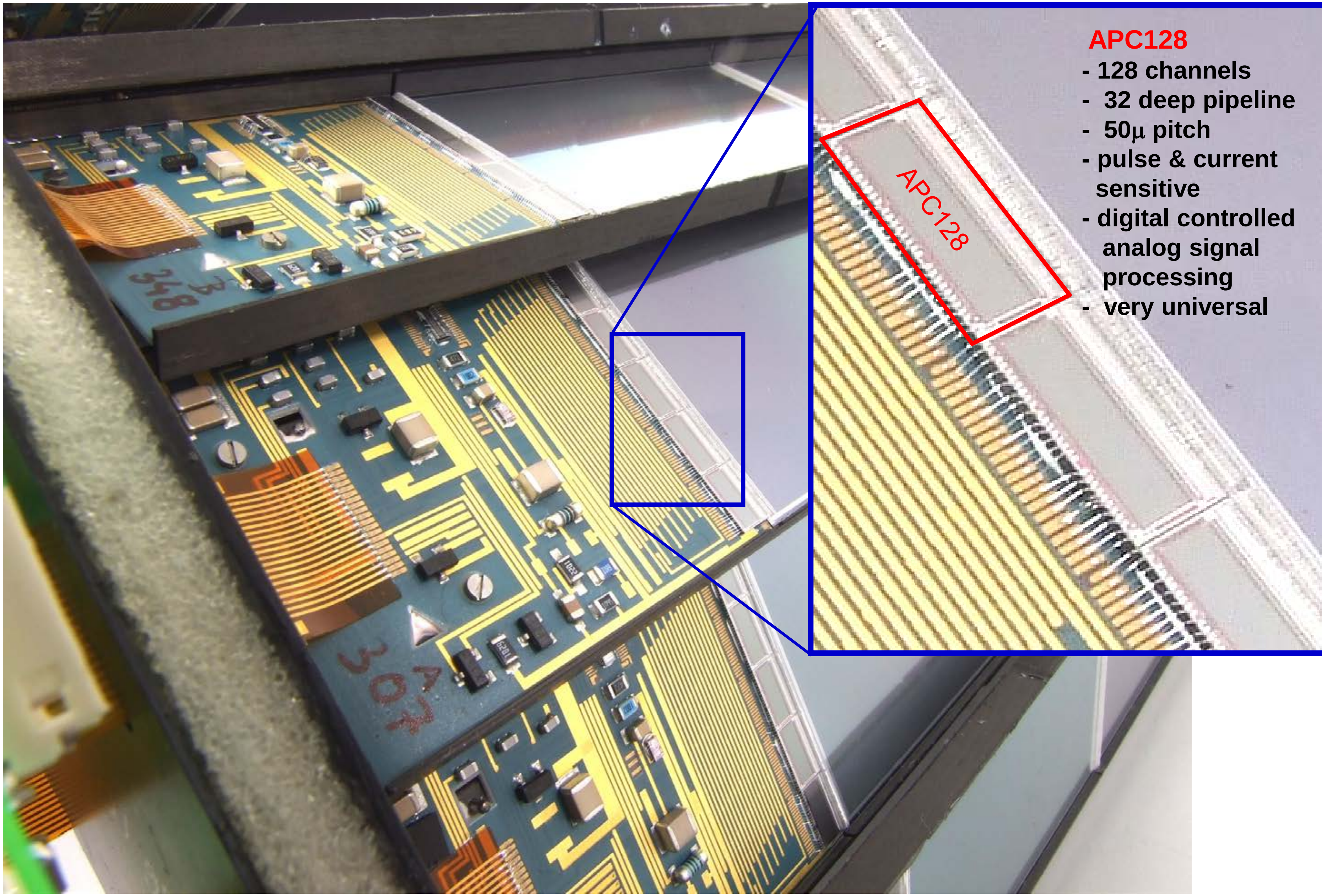
# H1 Central Silicon Vertex Detector

Completely designed and built at PSI (1992-1996)



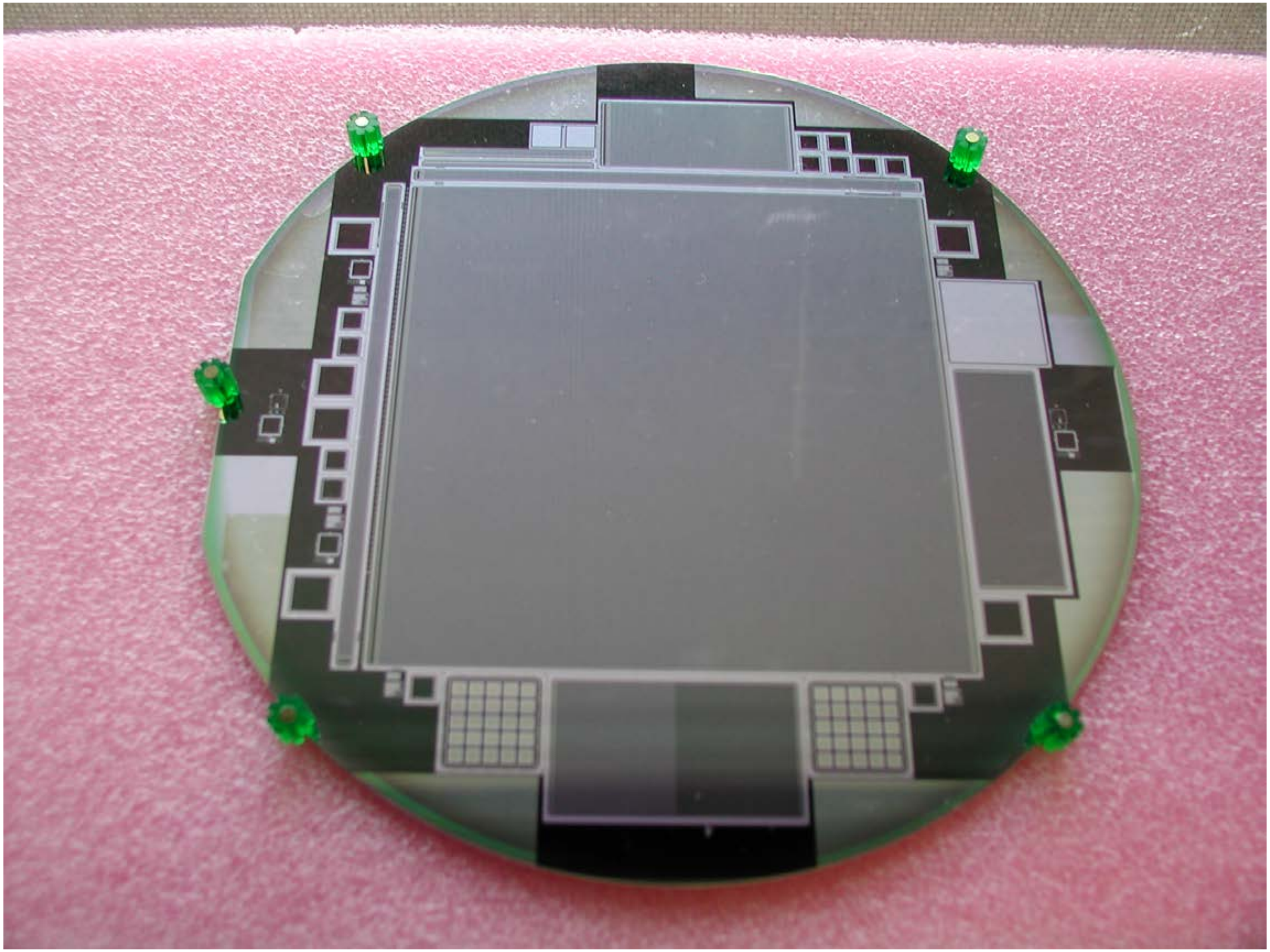
Silicon Strip Detector (SSD)
with first pipeline readout chip **APC128**
**(Analog Pipeline Chip)**

# Analog Pipeline Chip for Si-Strips



# Wafer eines Silizium Streifen Detektors

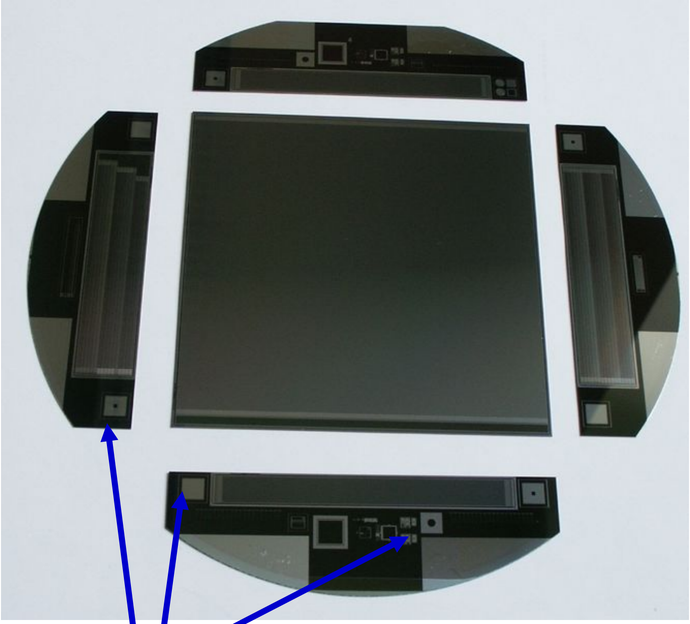
Typ. 6"  ~ 150mm Durchmesser



# Silizium Streifen Detektoren für Teilchenphysik Experimente

**Wafer gesägt mit Diamant Säge**

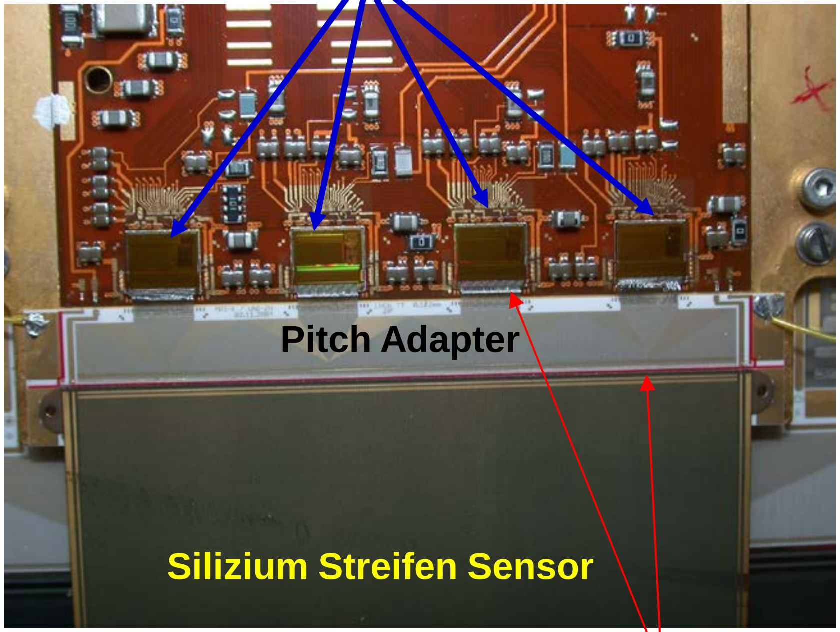
Z.B. 30μmBlatt Breite



Test-Strukturen zur Messung der Wafer Parameter
z.B. Implantationsdosis, Flächendioden, Oxidkapazitäten, Poly-Si-Widerstände

**Streifen Detektor mit CMOS Auslese-elektronik auf Interconnect-Hybrid**

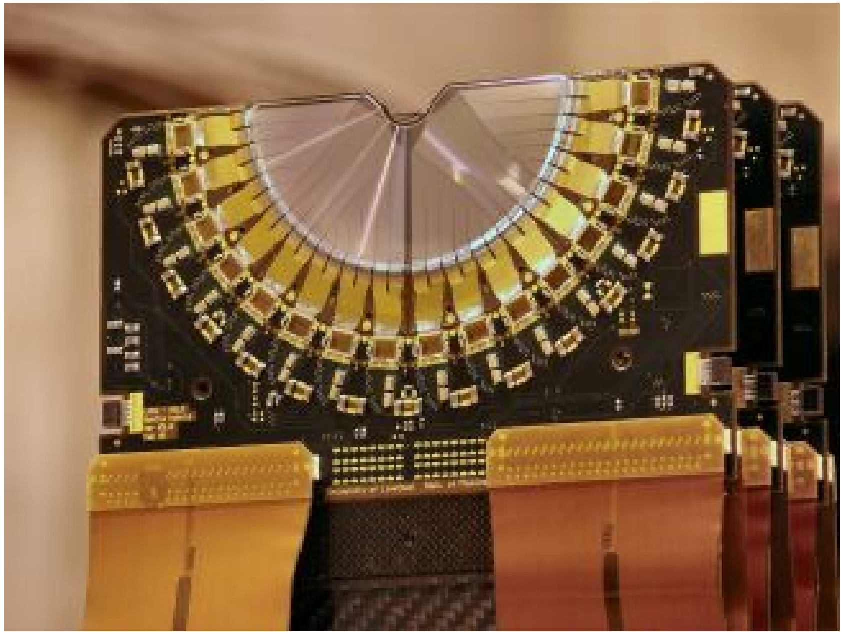
CMOS Elektronik Chips (128 Kanäle / Chip) zur Auslese der Signalladungen jedes Streifens




Ultraschall Draht-bonding
(typ. 25mm Al-Draht)

# Silizium Streifen Detektoren für Teilchenphysik Experimente

TT-Station LHCb   (Uni ZH)
(CMS Streifen Detektoren)



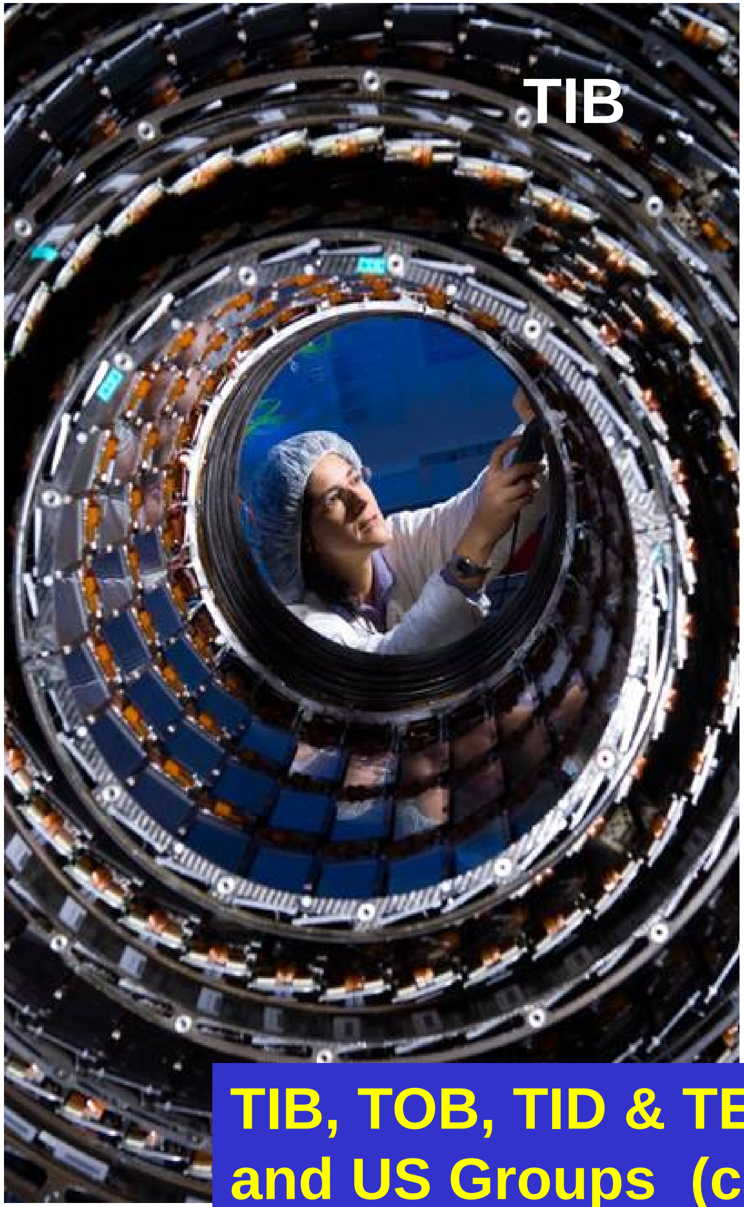
Vertex Locator (Velo) Detektor von LHCb
(Univ. Liverpool)

Benutzung von nicht orthogonalen Geometrien

Detektor mit Mini-Streifchen in Polar-Koordinaten

# Silicon Strip Tracker

**~ 12 Million Readout Channel**

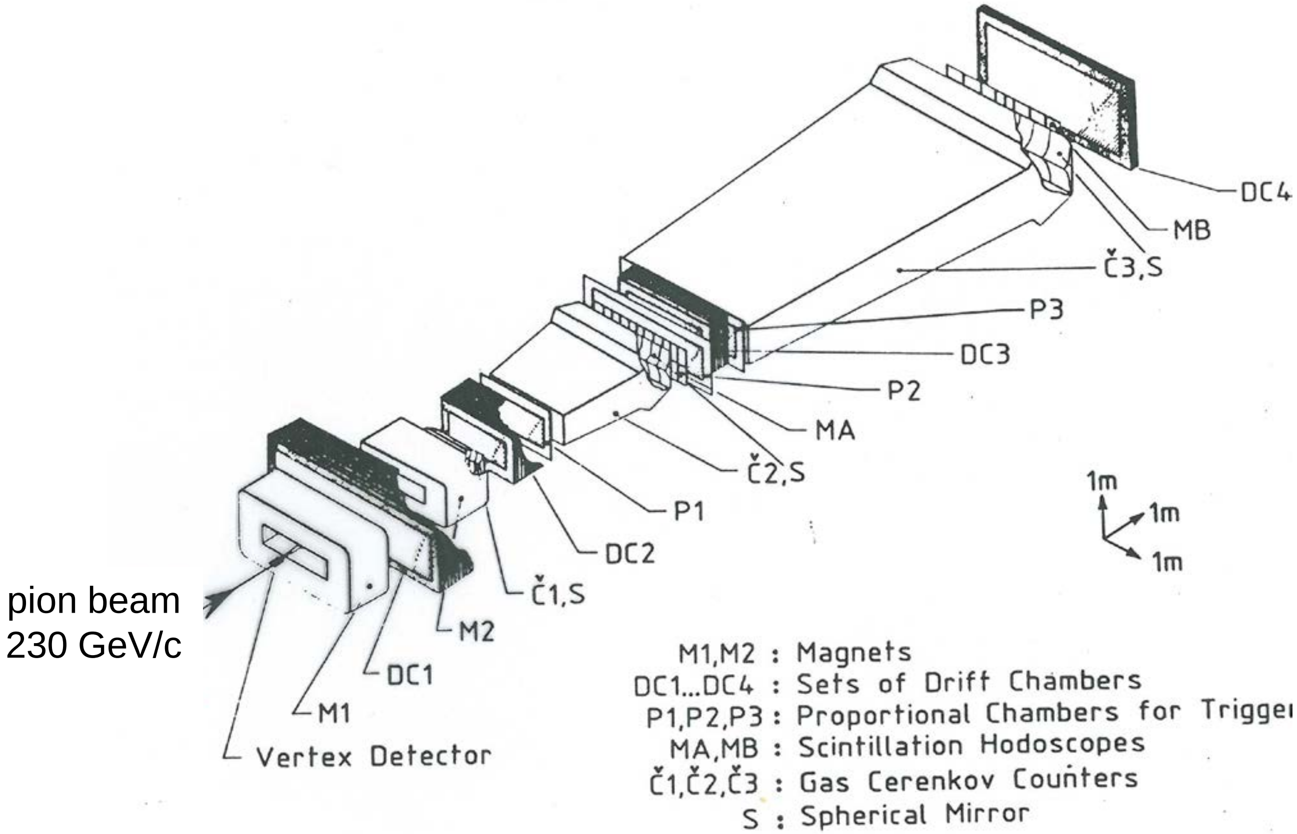




**TIB, TOB, TID & TEC build by European and US Groups (ca. 400 physicists)**

# NA11 experiment searches hadronic charm

experimental observation of hadronic produced charm particle is rather difficult

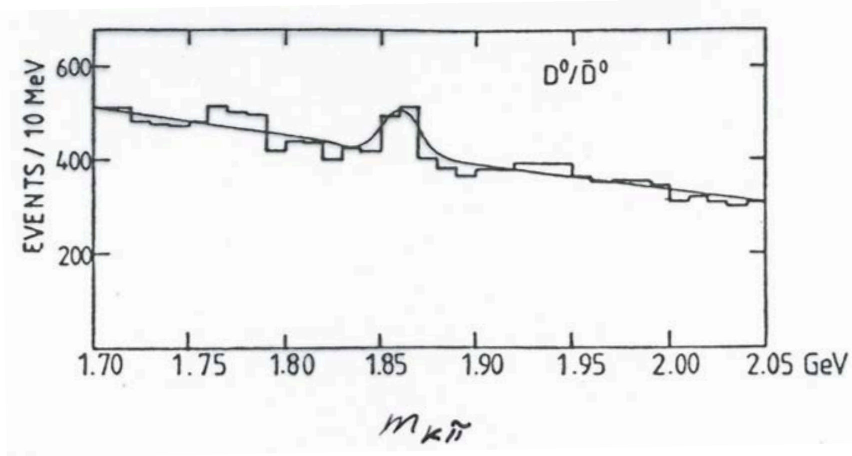



NA11 experiment is rather complex and quite a big effort in hardware and people

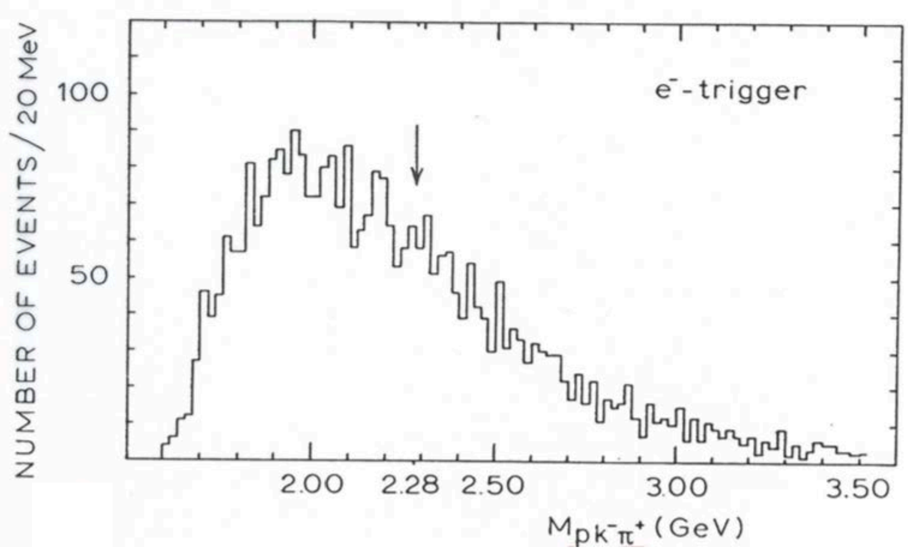
# NA11 experiment searches hadronic charm

experimental reconstruction of hadronic produced charm particle is not easy

$D^0 \rightarrow K\pi$




$\Lambda_c \rightarrow p K^- \pi^+$




experimental observation of easier channels worked, but seldom produced charm particles and lower branching ratio decays were not possible.

→ overwhelming, high rate hadronic backgound processes

→ selection of charm events by very precise livetime tagging should help !

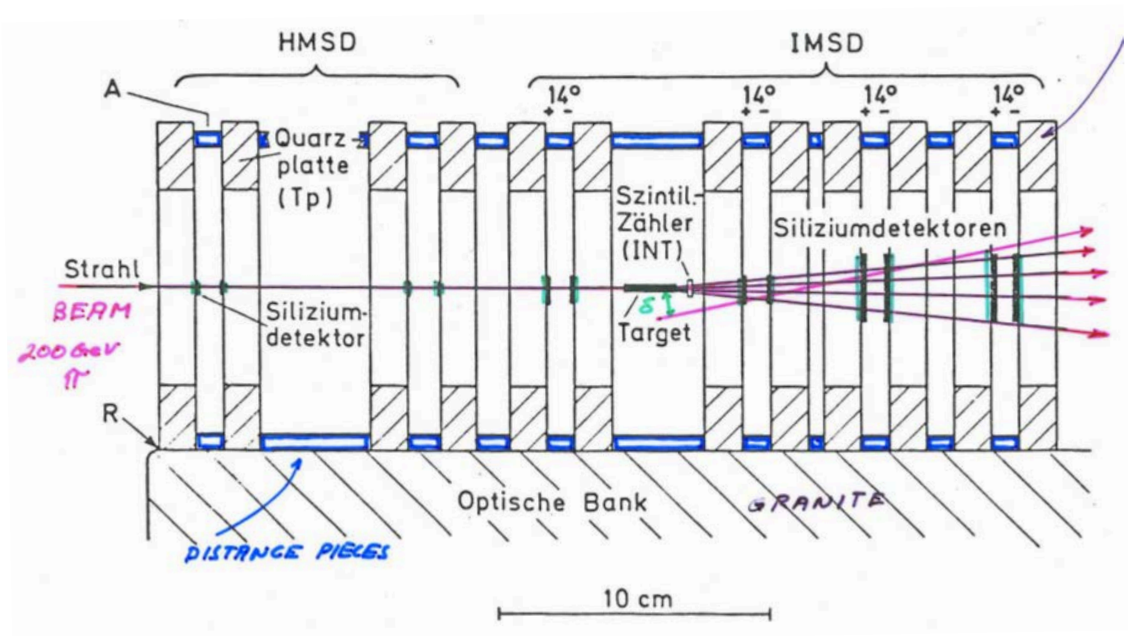
→ improve experiment by adding novel, very precise silicon vertex detectors

# Silicon detectors boost NA32 experiment

Several groups of ACCMOR collaboration develop novel silicon detector technologies

**NA11/32 becomes breeding ground of today's silicon precision vertex detectors**

## Silicon micro strip detectors in NA32




$\Lambda_c \rightarrow p\,K^- \pi^+$

*with* Si-strip detectors

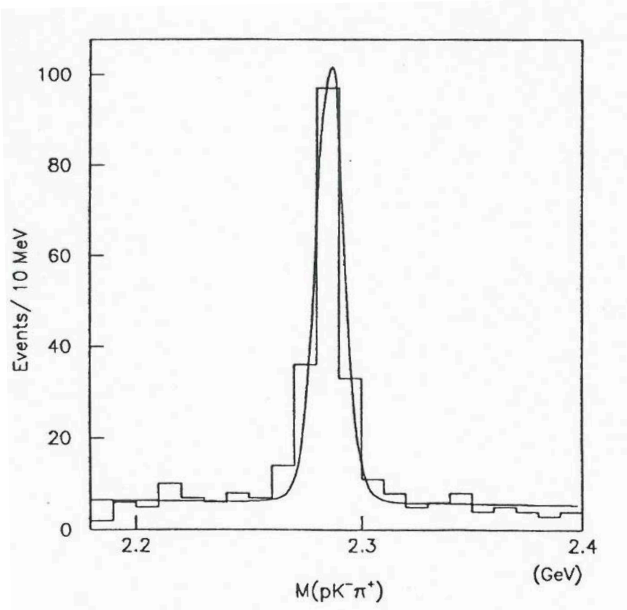



Fig. 1. pKπ invariant mass spectrum.

**The addition of silicon micro strip detectors made a huge difference !**

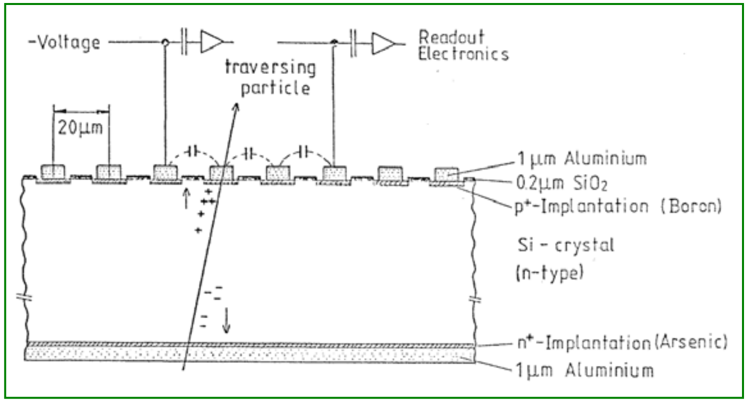
# Silicon strip detectors developed for NA32

PAUL SCHERRER INSTITUT

Small group pioneered and developed silicon micro strip detectors for NA32

*A wealth of innovation:*

- analog pulse height readout
- precision by interpolation
- capacitive charge division
- AC-coupled low noise electronics
- system & integration




*Strip detector:* resolution

| | | |
|---|---|---|
| 20μ strip pitch | | |
| 60μ readout pitch | → | 4.5μ |
| 120μ readout pitch | → | 7.9μ |


Nuclear Instruments and Methods 205 (1983) 99–105
North-Holland Publishing Company




## A SILICON COUNTER TELESCOPE TO STUDY SHORT-LIVED PARTICLES IN HIGH-ENERGY HADRONIC INTERACTIONS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Received 5 July 1982



A telescope consisting of six silicon microstrip detectors achieving 5 μm spatial resolution for minimum ionizing particles has been built. The design and fabrication of the counters, electronics, and mechanical set-up is described, and first results of its performance in a 175 GeV/c beam are reported.


### 1. Introduction

The telescope described in this article has been built for an experiment to study the production and properties of charmed particles in 100–200 GeV hadronic interactions in a beryllium target at the CERN Super Proton Synchrotron (SPS) **. The lifetime of charmed particles of a few times $10^{-13}$ s, their production cross-sections of a few microbarns, and the general features of hadronic interactions in this energy range, such as the charged multiplicity of ~ 10 and the concentration of most of the particles in a narrow forward cone, have defined the required performance of the counters:

– spatial resolution of ⩽ 10 μm;

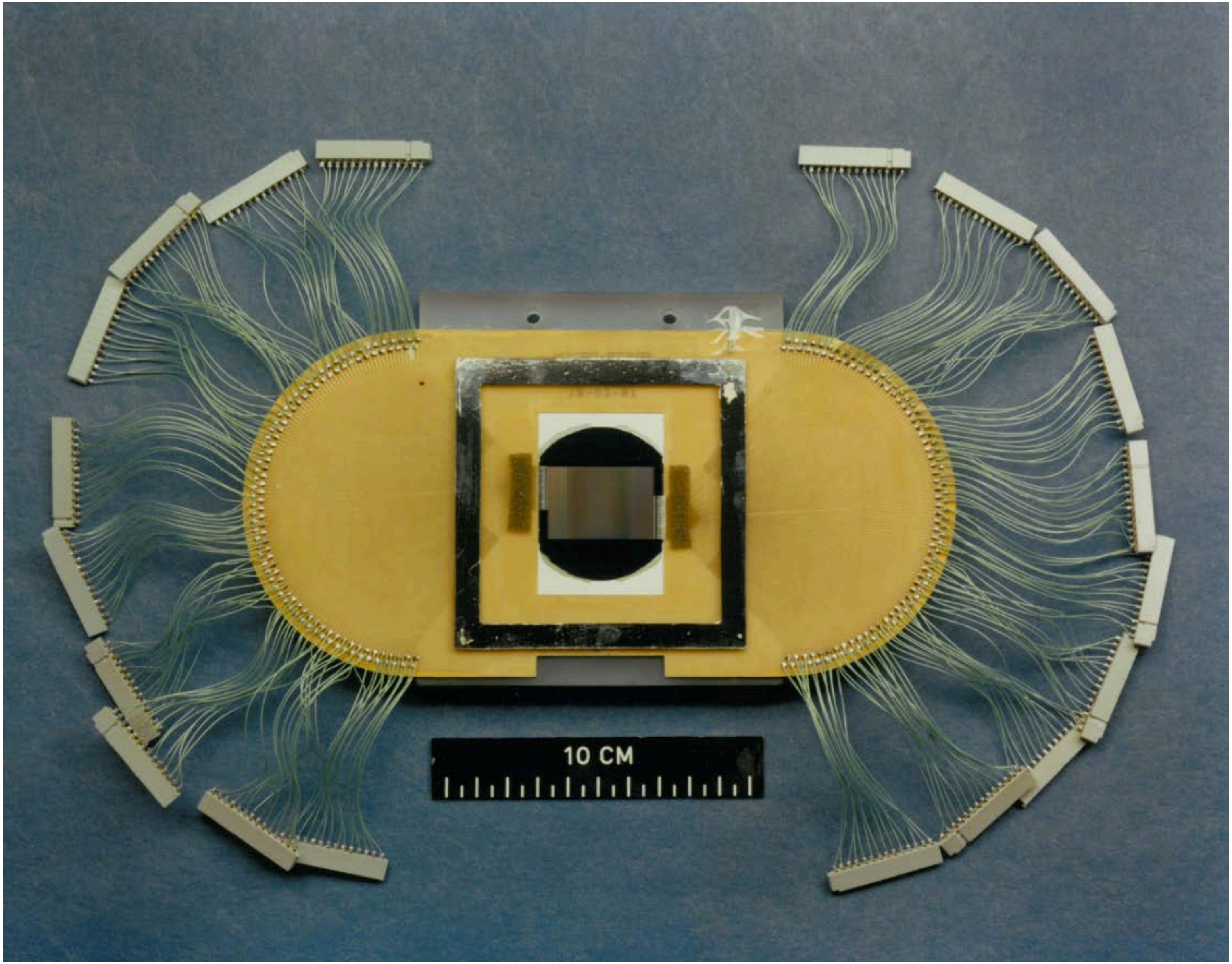
### 2. The silicon microstrip detectors

#### 2.1. Principles of operation

Fig. 1 shows schematically a cross-section of the detector. The basic material is a high-ohmic (~ 2 kΩ · cm) n-doped silicon crystal, 2 inches in diameter and 280 μm thick. One face of the crystal in aluminized. On the other face, the sensitive area of the counter (a rectangle of 24 mm × 36 mm in our case) is covered with $p^+$ implanted diode strips (1200 strips of 12 μm × 36 mm and 20 μm pitch) and Al contacts. Connecting the strips to a negative voltage of 160 V depletes the n-doped silicon crystal of free charge carriers, leaving

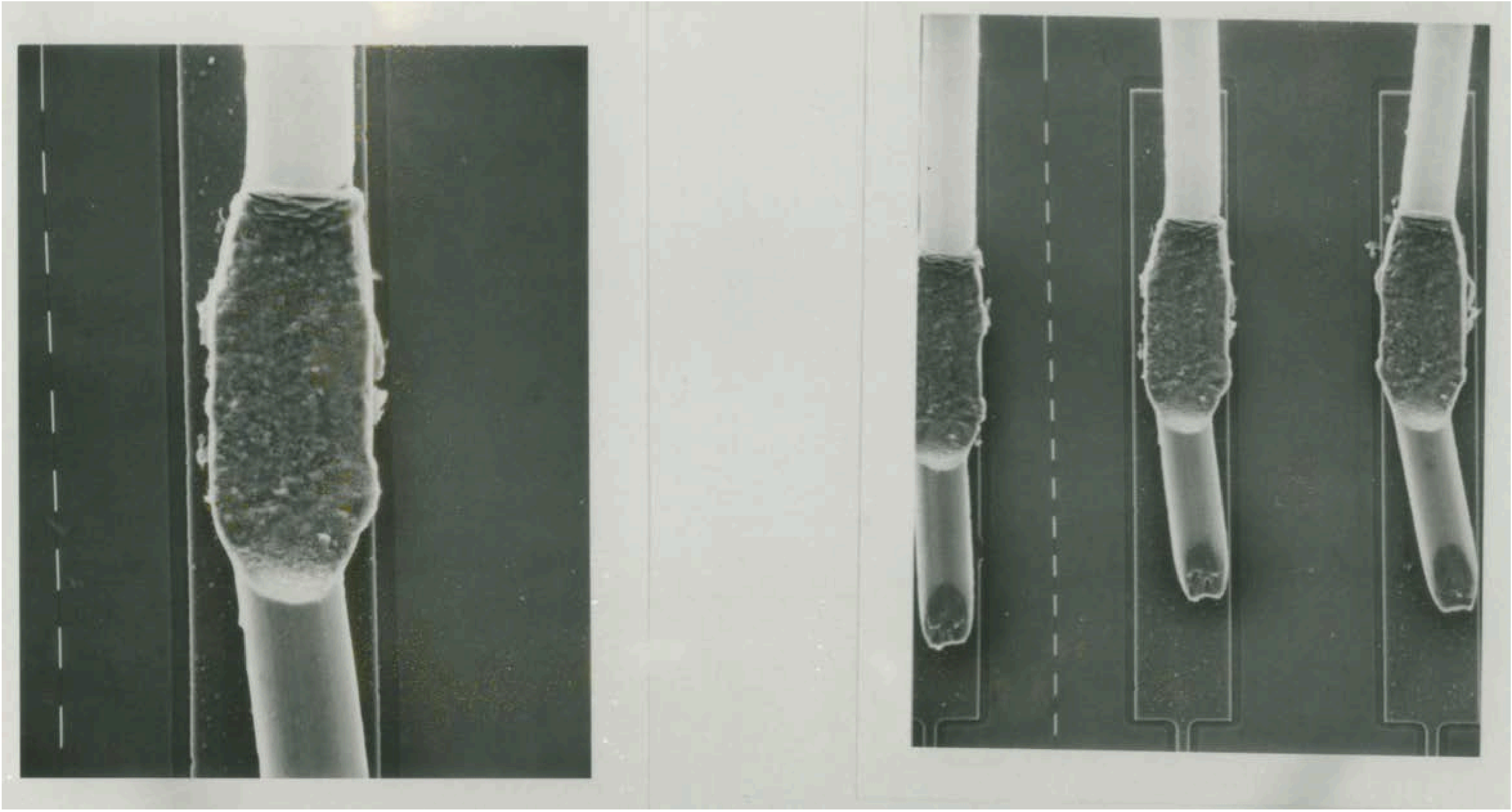
# Silicon strip detectors developed for NA32





# Silicon strip detectors developed for NA32

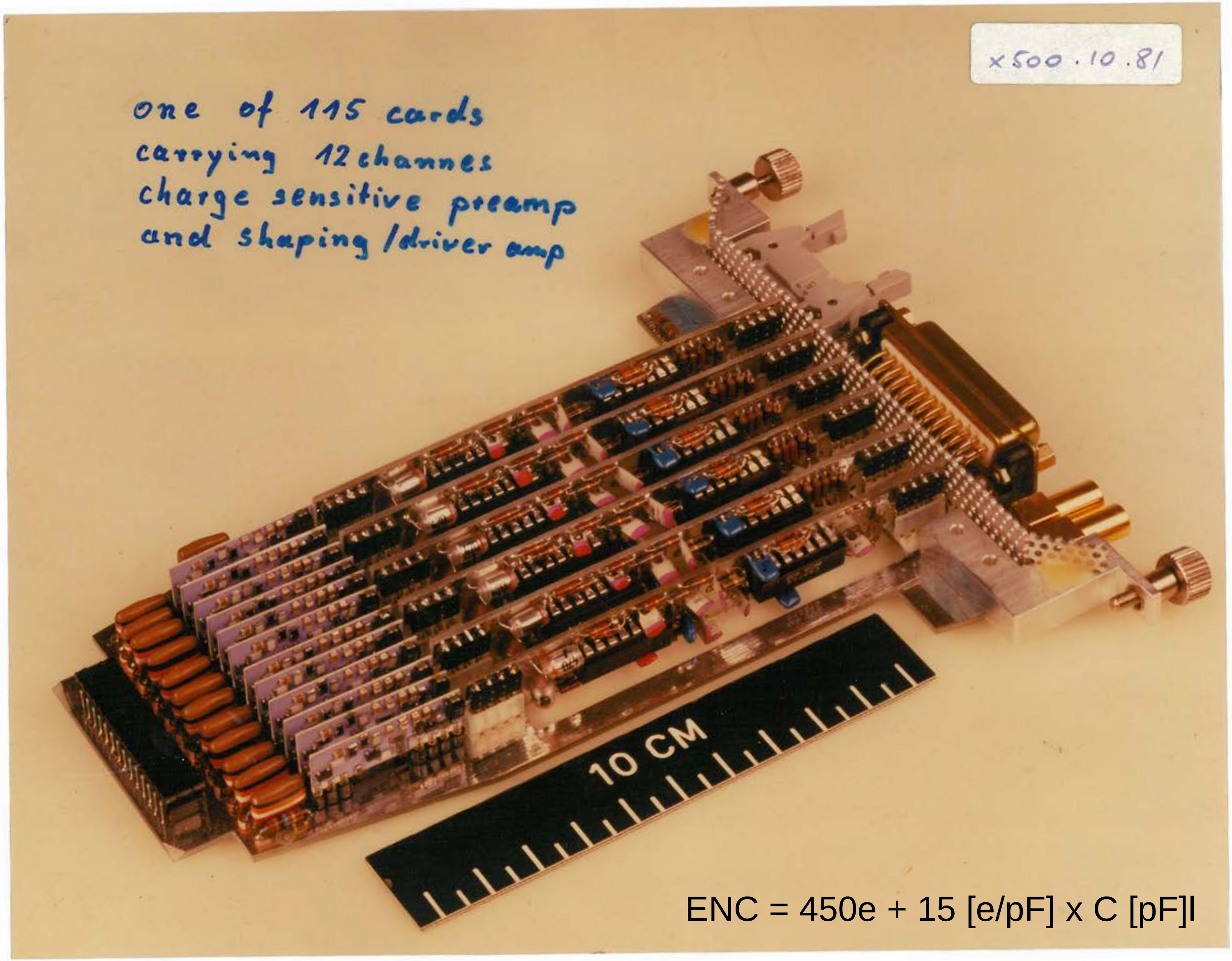
In HEP ultrasonic wire bonding was at the time pretty exotic !



# Silicon strip detectors developed for NA32

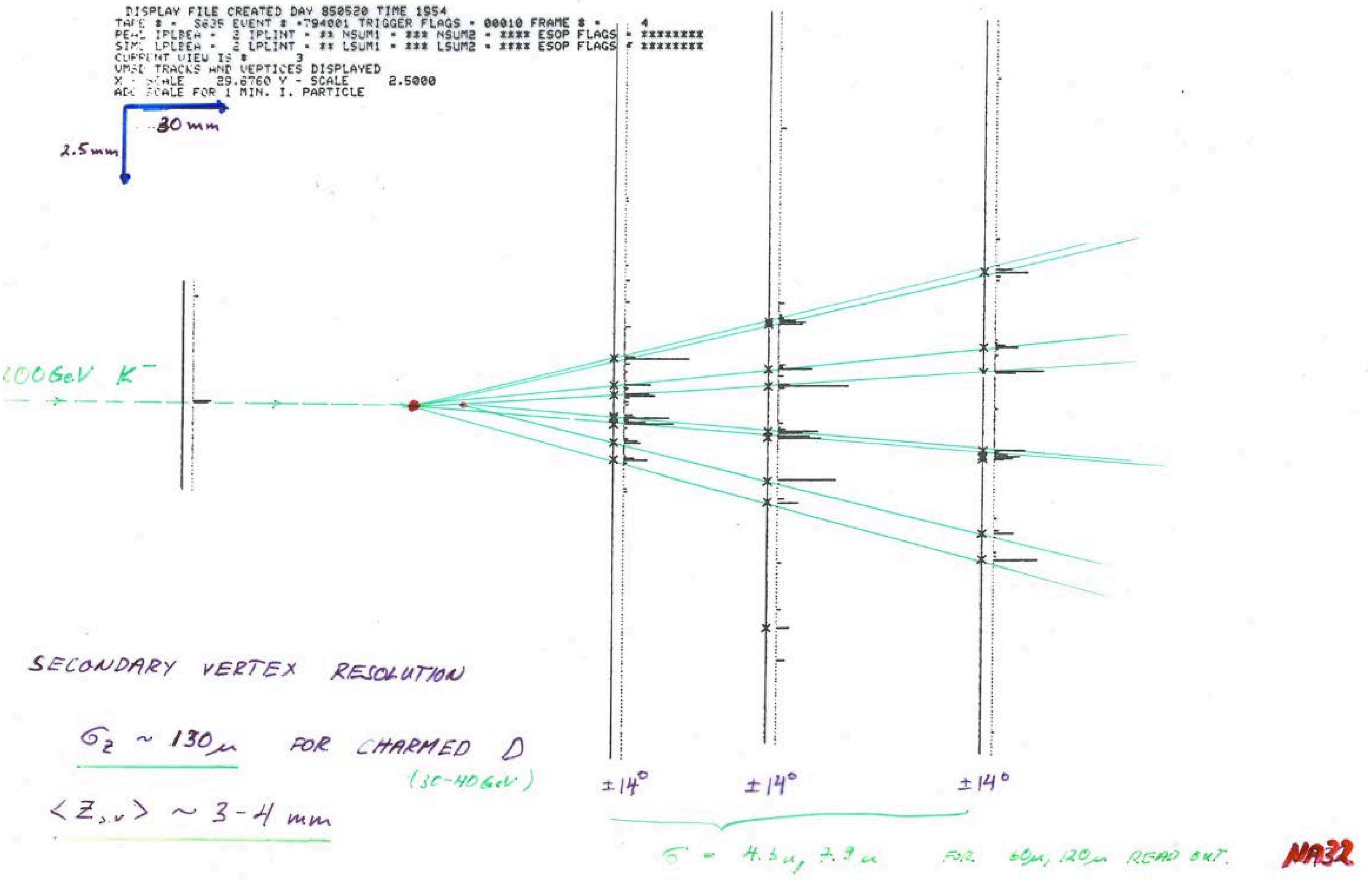
PAUL SCHERRER INSTITUT

cost per electronic channel was the limit for larger applications (~100-200 CHF/channel)




ENC = 450e + 15 [e/pF] x C [pF]l

# Secondary charm vertices with NA32



# Signal interpolation in Si-strip detectors

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the “classical” paper on how to obtain the best resolution with charge interpolation

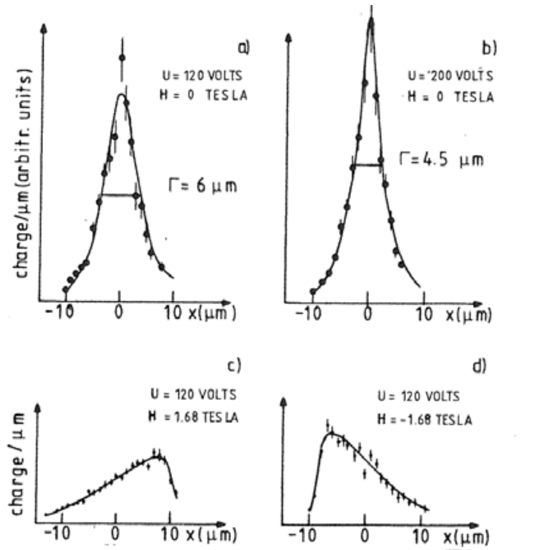


Fig. 6. The charge distribution collected by the diode strips: a) $U = 120$ V, $H = 0$ T; b) $U = 200$ V, H = 0 T; c) $U = 120$ V, $H = 1.68$ T; d) $U = 120$ V, $H = -1.68$ T.

CHARGE COLLECTION IN SILICON STRIP DETECTORS


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NIM 214 (1983) 253-260



The charge collection in silicon detectors has been studied, by measuring the response to high-energy particles of a 20 μm pitch strip detector as a function of applied voltage and magnetic field. The results are well described by a simple model. The model is used to predict the spatial resolution of silicon strip detectors and to propose a detector with optimized spatial resolution.


**1. Introduction**

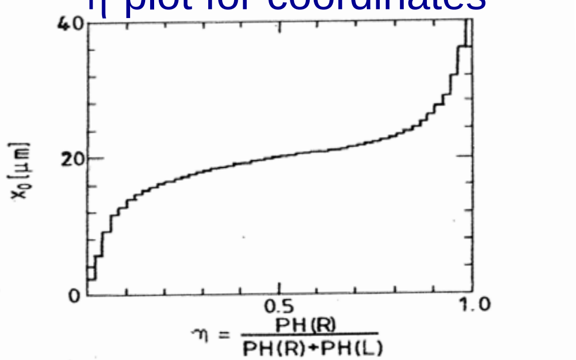
Recently the planar process, developed for producing microelectronics, has been adapted to the fabrication of detectors for ionizing radiation [1]. One of the first applications of this new technology was the development of microstrip detectors with high spatial resolution as a vertex telescope for elementary-particle inter-

**2. The experimental apparatus**

*2.1. The microstrip detector*

A high-ohmic (~ 3 kΩ cm) n-doped silicon crystal, oriented in the 1,1,1-direction, 2 inches in diameter and 280 μm thick, is used as base material. One face of the crystal is aluminized. On the other face the sensitive area of the counter (2 mm × 32 mm) is covered with p+

η-plot for coordinates

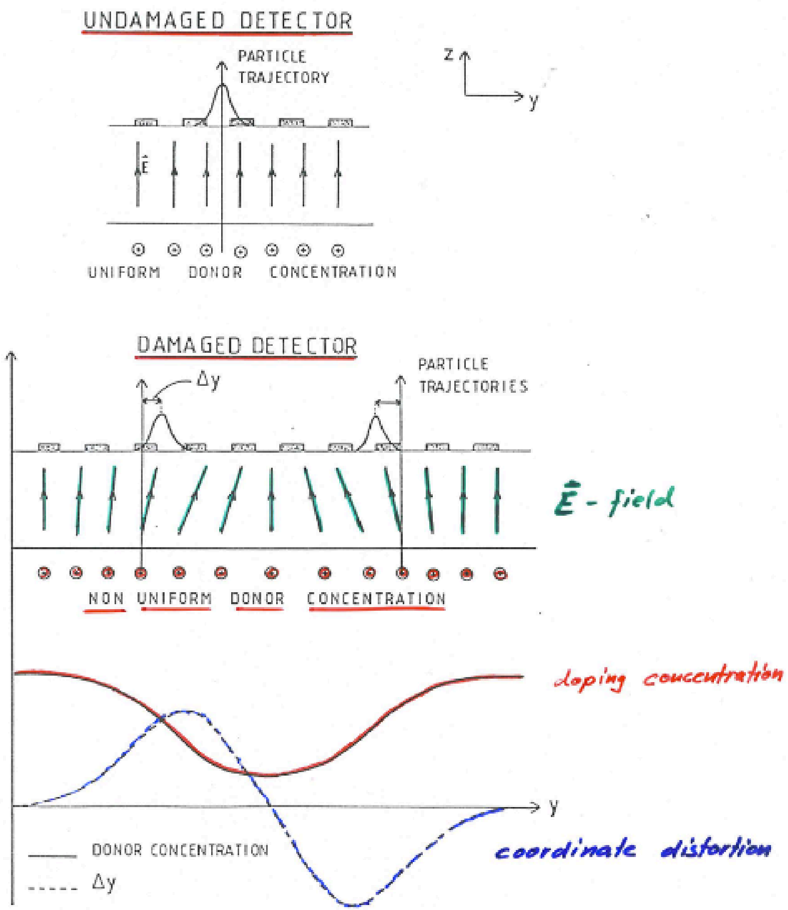



η-algorithm is now used everywhere in silicon detectors

test beam 1994: 25μ strip readout → 1.3μ resolution
(P. Weilhammer et. al.) → HE-LHC, FCC

# Silicon detectors damaged by π beam

after running several years in the pion beam small coordinate shifts showed up.




RADIATION DAMAGE IN SILICON STRIP DETECTORS

H. Dietl[3], T. Gooch[1], R. Klanner[2], M. Pepé[4] and F. Wickens[4]

The high resolution silicon strip detectors of the ACCMOR collaboration [1] have been used during 1982-1984 to measure production and decay of charm particles in hadronic interactions. During this time, they have been exposed to $2.3 \cdot 10^{12}$ hadrons, focussed onto a spot of $\Gamma_x \times \Gamma_y$ = 12 mm x 0.5 mm. The following effects have been observed [2]:

(i) an increase in leakage current approximately proportional to the number of particles traversing a detector element $I_{leak} = I_0 + \alpha \cdot N \cdot d$ ($\alpha = 1.3 \cdot 10^{-8}$ nAmp/cm, N . . . number of particles traversing the detector element of thickness d, $I_0$ . . . leakage current without radiation damage)

(ii) a voltage current characteristic, deviating from the $V^{1/2}$-dependence of an undamaged detector (Fig. 1). This is interpreted as a result of an increased bulk resistivity due to radiation damage

(iii) a systematic shift of the measured coordinate (Fig. 2) of up to 10 µm. It can be explained by the transverse electric field inside the silicon crystal due to the change in resistivity from radiation damage. It is found that 0.05 doping centres are removed per one cm path of a minimum ionizing particle in the crystal.

References


[1] B. Hyams et al., NIM 205 (1983) 99;
E. Belau et al., NIM 214 (1983) 253.

[2] H. Dietl et al., Radiation Damage in Silicon Strip Detectors, paper submitted to this conference.


Figure Captions

Fig. 1 Current voltage characteristics for detector elements with strong (#25) and little (#8) radiation damage.

Fig. 2 Systematic shift in measured coordinate as function of position. The beam, which caused the radiation damage, was centred at 0 with a full width of 400 µm.

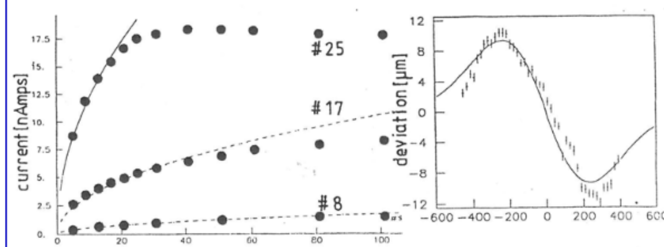



Fig. 1 voltage [Volts]

Fig. 2 position [µm]


1) Bristol University, Bristol, U.K.
2) DESY, Hamburg, Fed. Rep. Germany
3) Max Planck Institut für Physik, Munich, Fed. Rep. Germany
4) Rutherford Appleton Laboratory, Chilton, Didcot, U.K.


Bari 1985

first observation of doping change → type inversion

# Radiation Damage to Silicon sensors

(basic material properties studies by RD50)

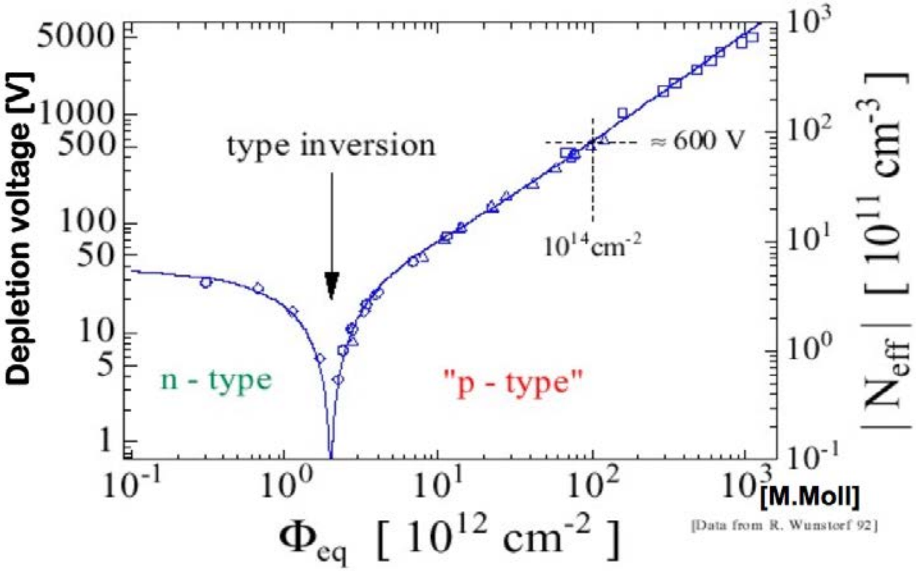
Irradiation in silicon sensors gives :

- Surface damage from Ionizing Energy Loss (IEL) → surface charges ($SiO_2$)
- Crystal damage from Non-Ionizing Energy Loss (NIEL) → energy levels in bandgap

the latter leading to leakage current, trapping centers and doping effects.

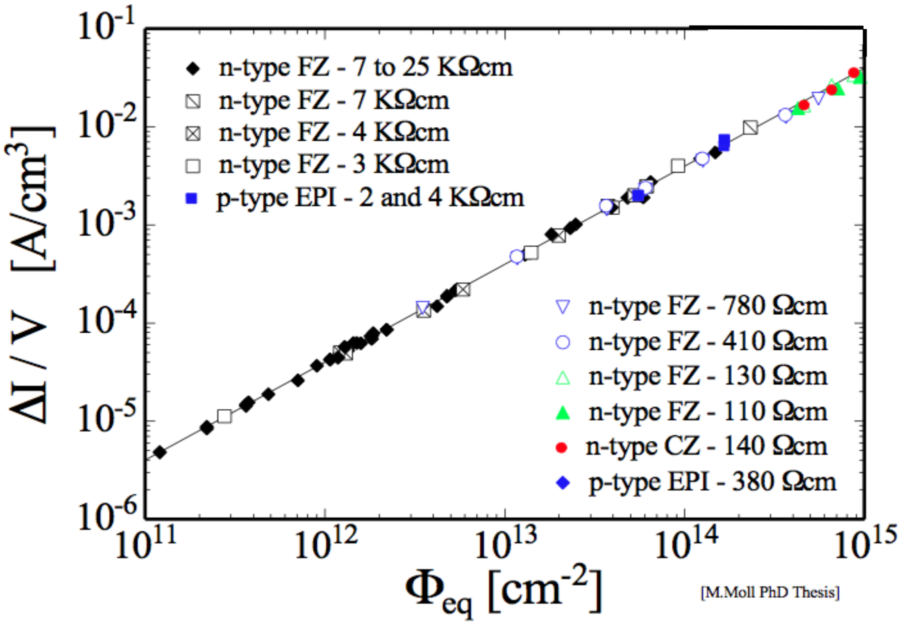
→Type Inversion (doping)

Normalize dose $\Phi_{eq}$ to damage of 1-MeV-neutrons

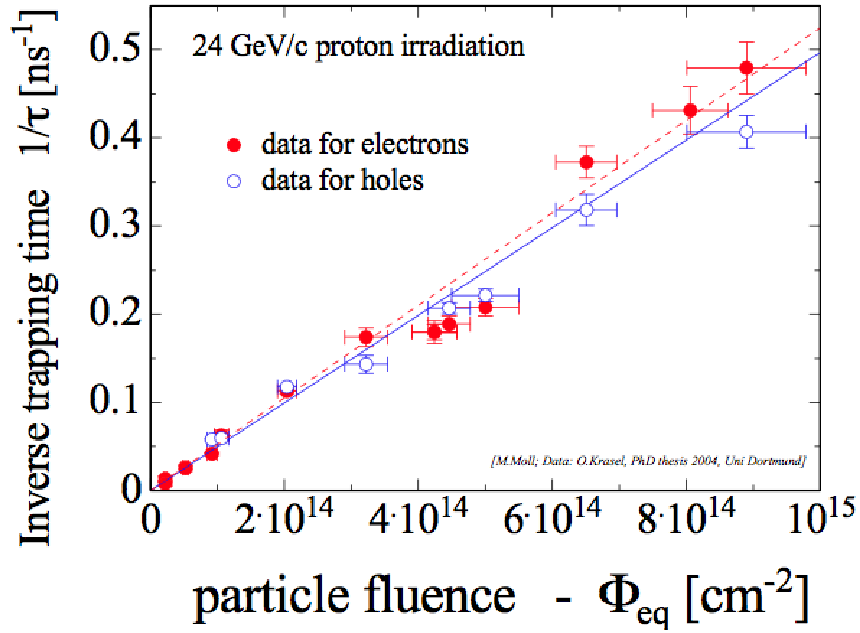


Observe the generation of universal, device doping independent

**leakage currents**




**charge trapping times**



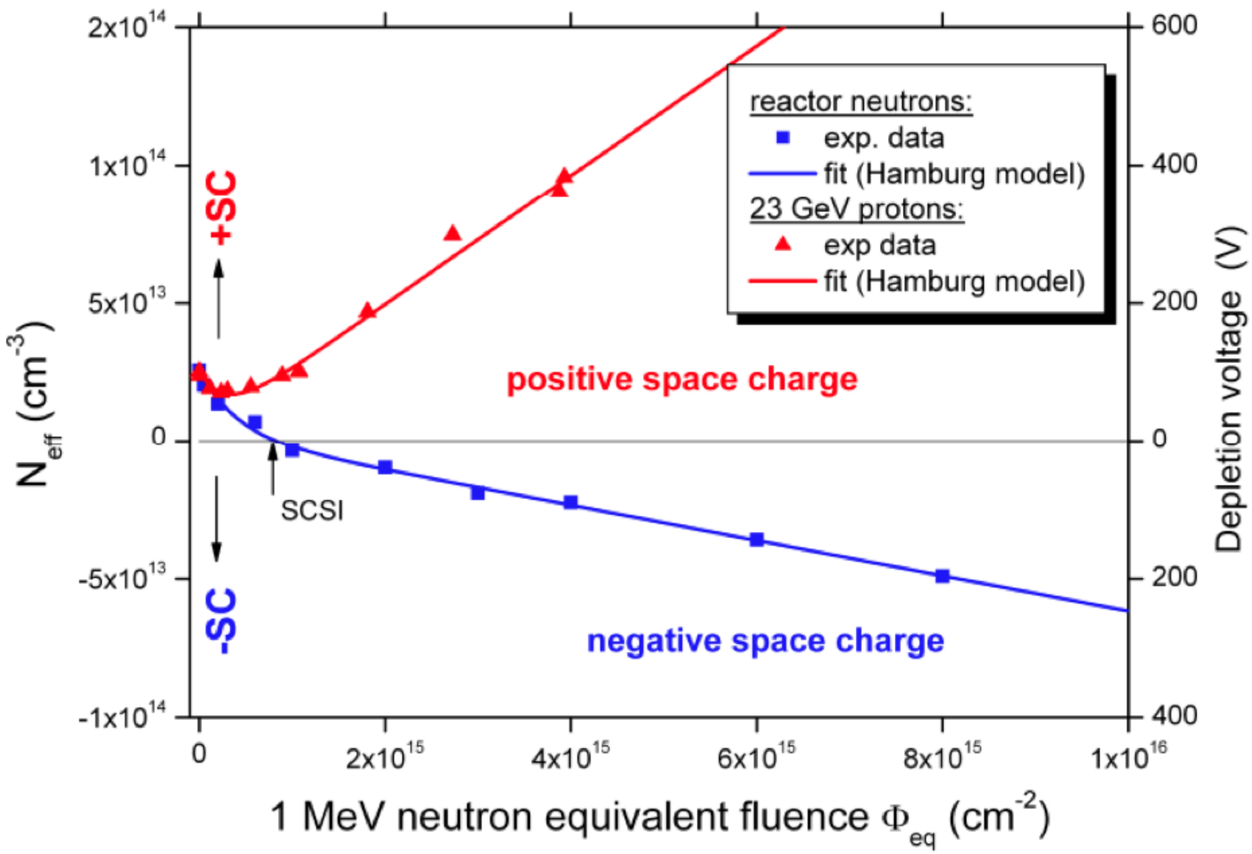

Signal charge trapping is **dominant** effect of irradiation at $10^{15} n_{eq}$ and above !

$$\tau_{eff}(10^{15} n_{eq}) = 2ns \qquad w = v_{sat}\tau_{eff} = 200\mu m$$

$$\tau_{eff}(10^{16} n_{eq}) = 0.2ns \qquad w = v_{sat}\tau_{eff} = 20\mu m$$

charge collection distance

Effective doping concentration $N_{eff}$ depends on radiation activated defects:




Epitaxial silicon diodes irradiated with:

**23 GeV protons**

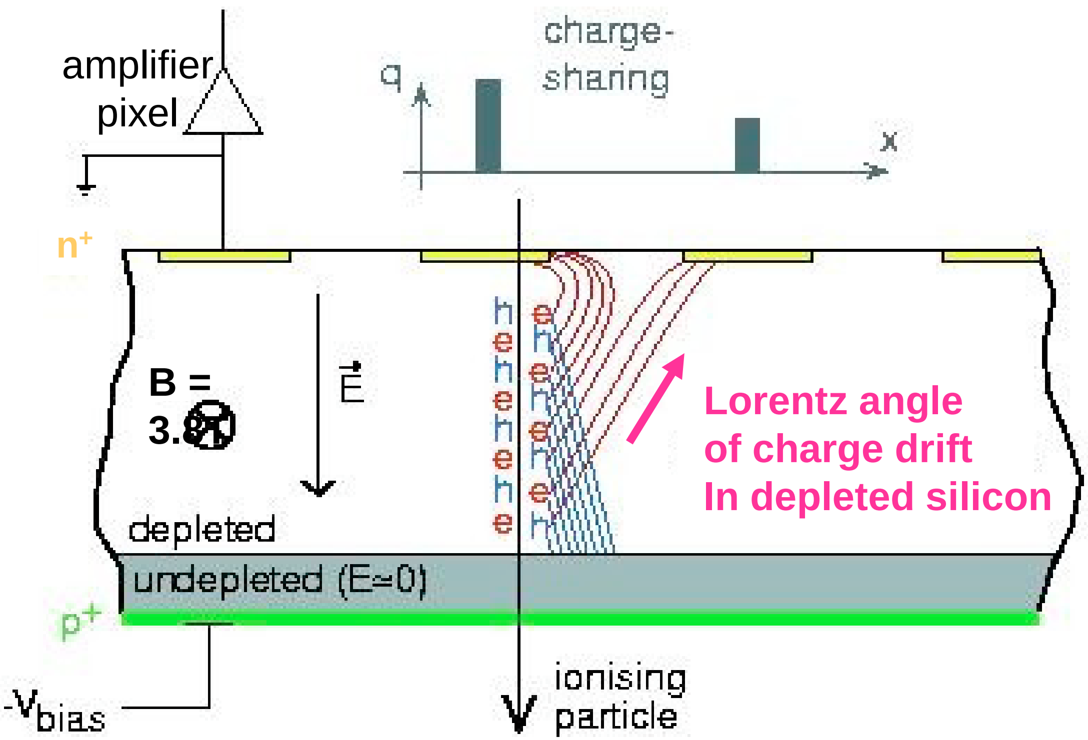
**reactor neutrons**

**Depending an radii, HL-LHC experiments will expose their silicon sensors more to charged hadrons or neutrons** → pixels (more hadrons) & strips (more neutrons)

# Pixel Sensor: Precision by Sharing

Charge sharing of collected signal charge

→ **precision coordinates ~10-20μ**
in both directions r-φ & z



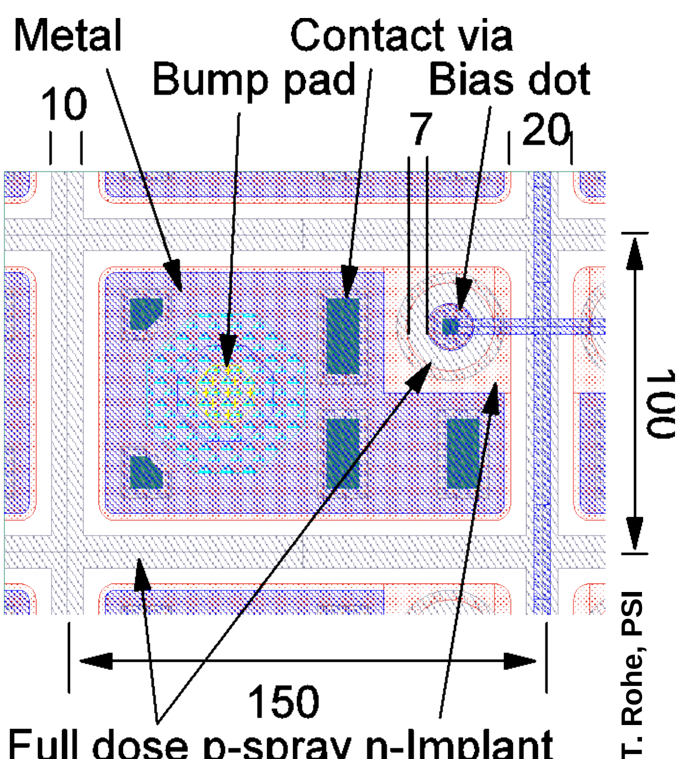

**Sensor for LHC conditions**

- work after large π-fluences
- $n^+$-pixel on n-silicon design
- silicon type inversion n → "p"
- good signal at LHC fluences
- graceful degradation
- resolution by charge sharing
- track angle dependence
- Lorentz angle dependence
- low pixel capacitance
- robust HV behavior

# Pixel Sensor Design & Development

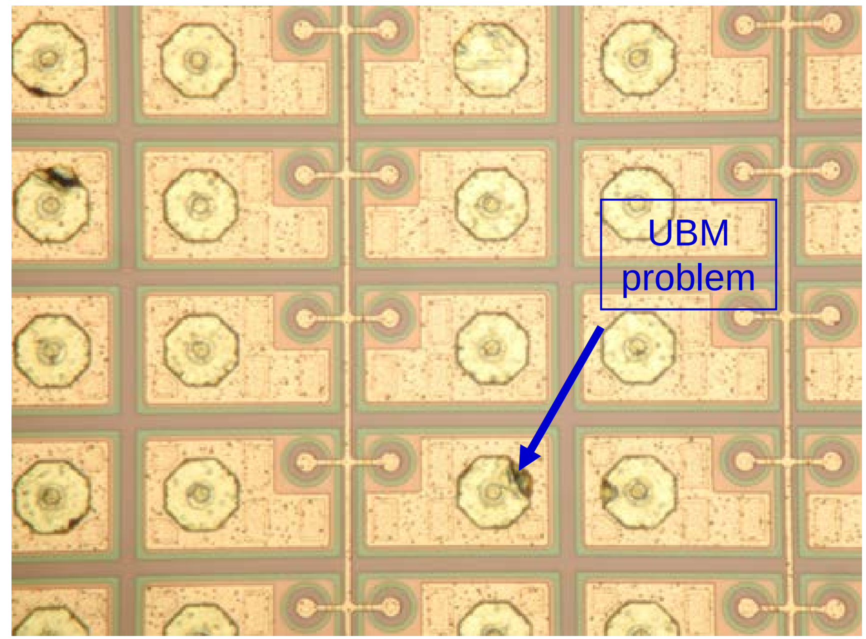
**Design of sensor masks at PSI**

- optimize position resolution ~10-15μ
- minimize pixel capacitance ~80fF
- optimize HV robustness ~600V




**<u>Final Choices</u>:**

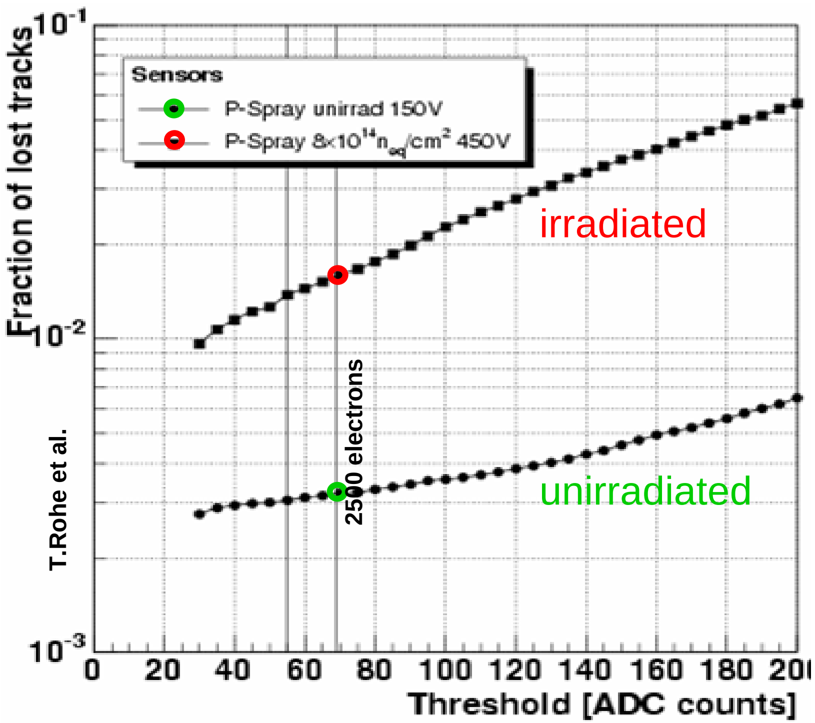
- $n^+$-on-n - Silicon (285μm thick)
- Size: 150μm × 100μm



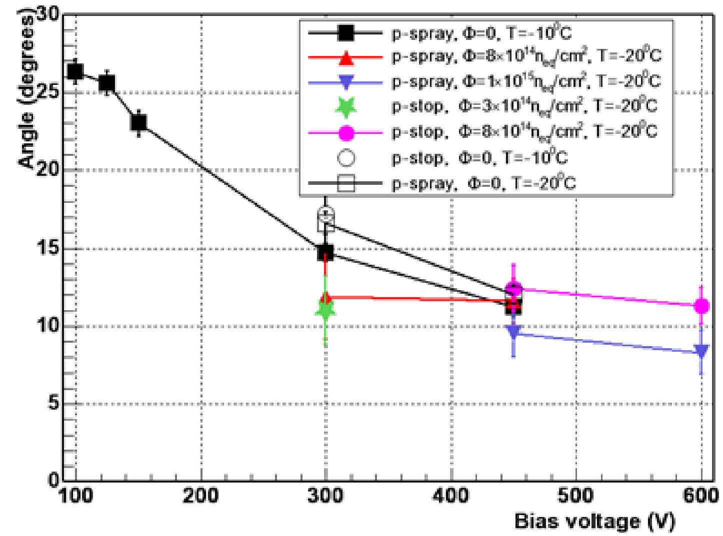

Si-Sensor - ROC systems detect MIP particles at fluence well up to $5 \times 10^{15}$ /cm$^2$ → SLHC

# Pixel Sensor Beam Tests & Tests & . . . .

## Signal charge after 8 x $10^{14}$ $cm^{-2}$




## Lorentz angle at B=4Tesla

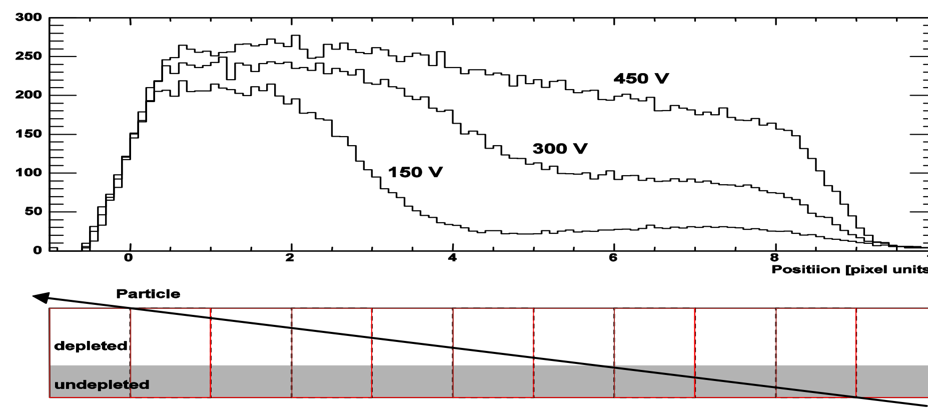



Dorokhov et al NIM A 530 (2004) 71-76

**After many irradiations and beams tests at CERN :**

**→ Sensors are fit for LHC !**

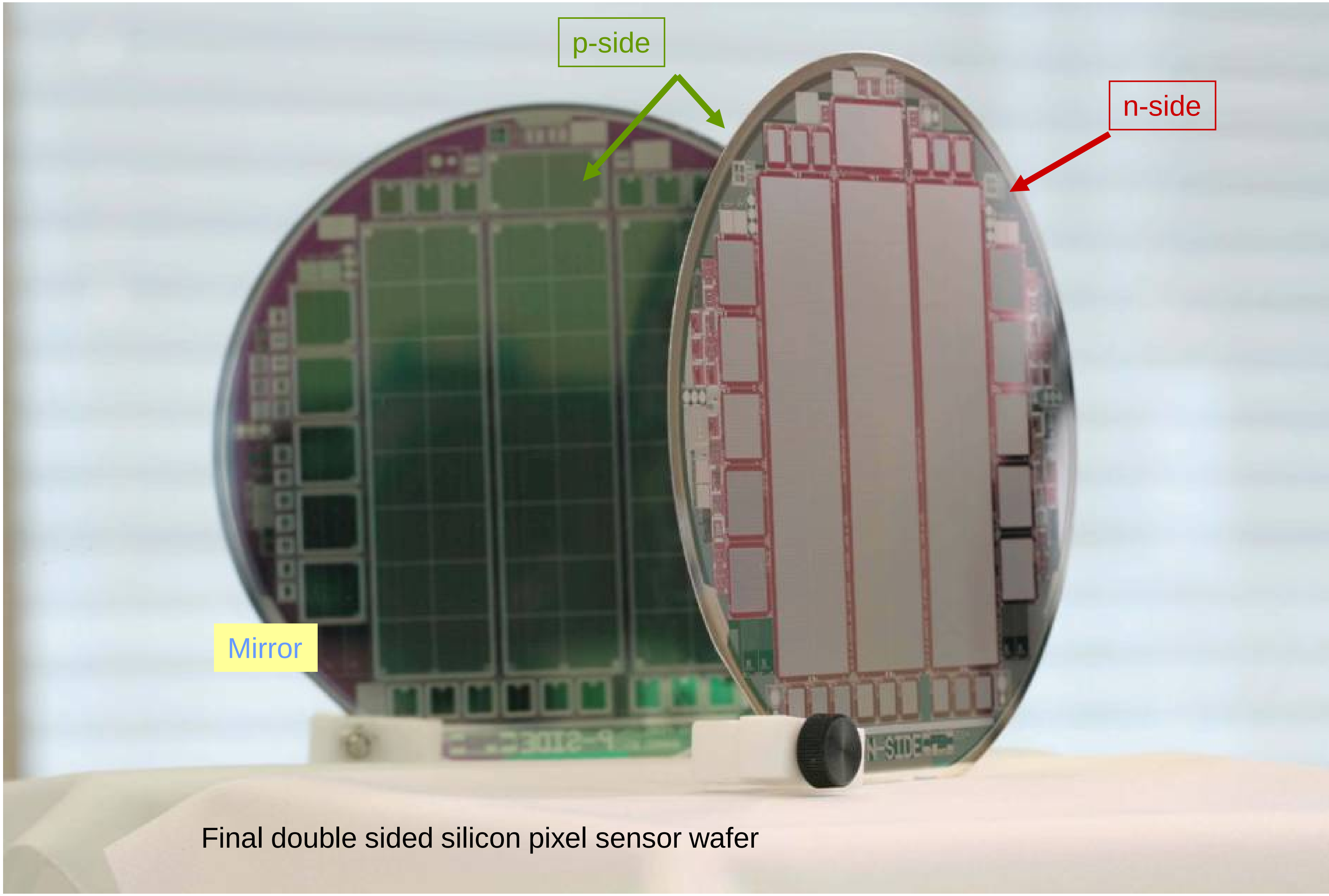
## Depletion depth after LHC fluences




Chiochia, Swartz, Rohe et al

shallow angle technique

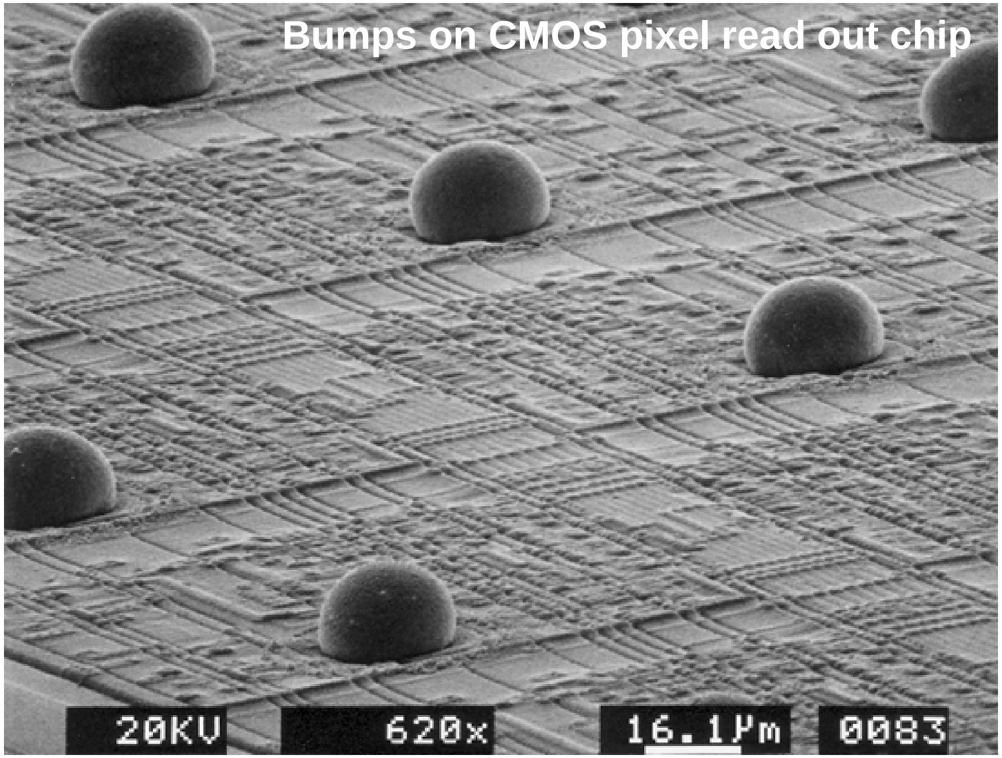
# Now we need good 400 silicon sensor wafers



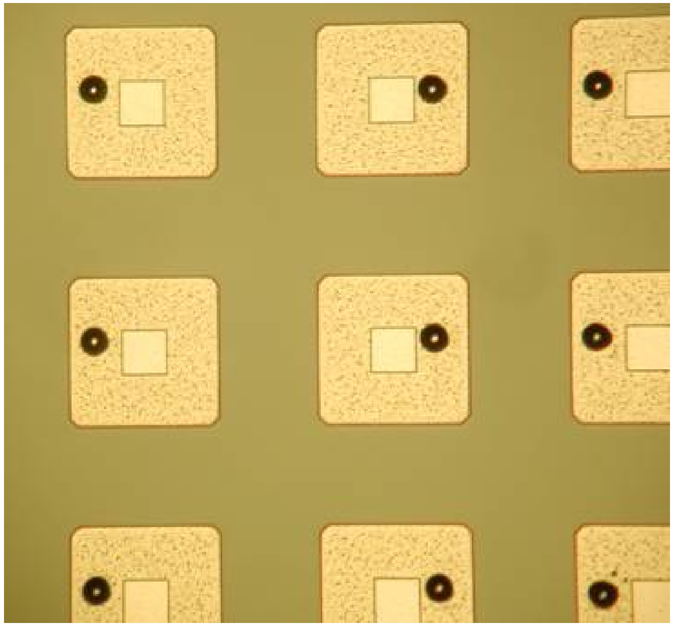

Final double sided silicon pixel sensor wafer

# Micro – Bump bonding at PSI

- very dense 2-dimensional connection technique ( typ. 10’000/cm$^2$)
- **Key technology for Hybrid Pixel Detectors** (In 1996 commercially **not** available)
- 17$\mu$m Indium-bump balls to connect sensor to CMOS-ROC (Read Out Chip)



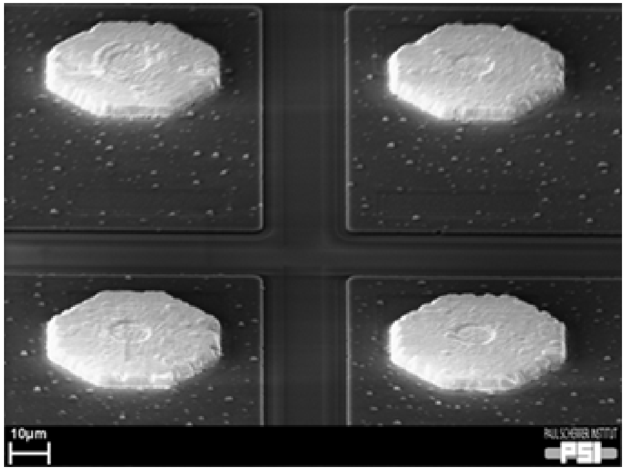

Silicon Pixel Sensor with Bumps



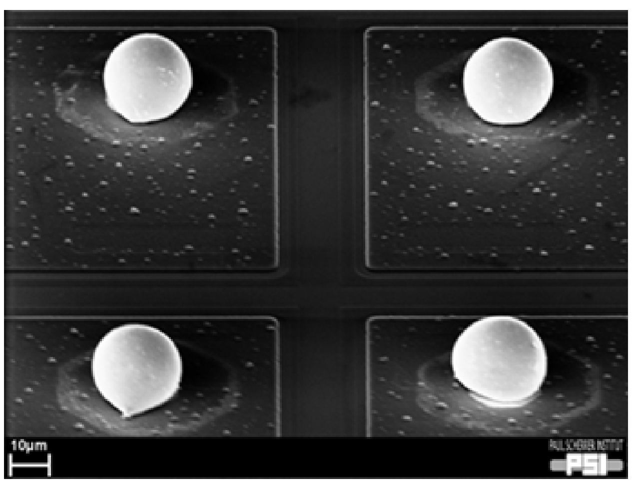
T. Rohe PSI/LTP

# μ – Bump Process Steps

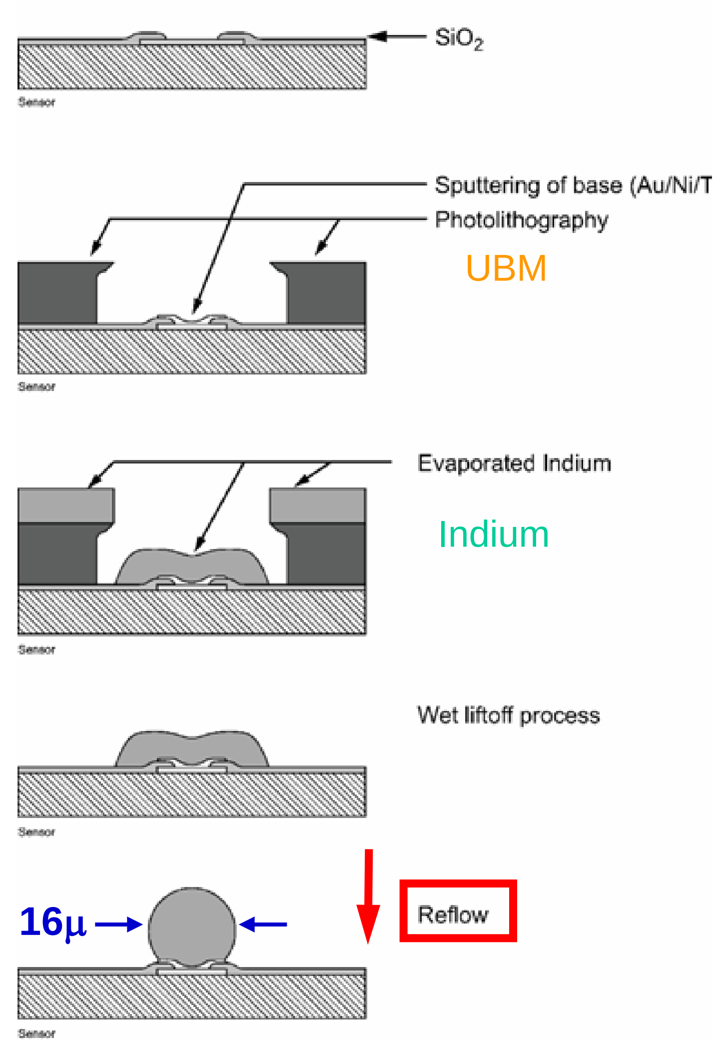
**Indium “cakes” before reflow**




reflow

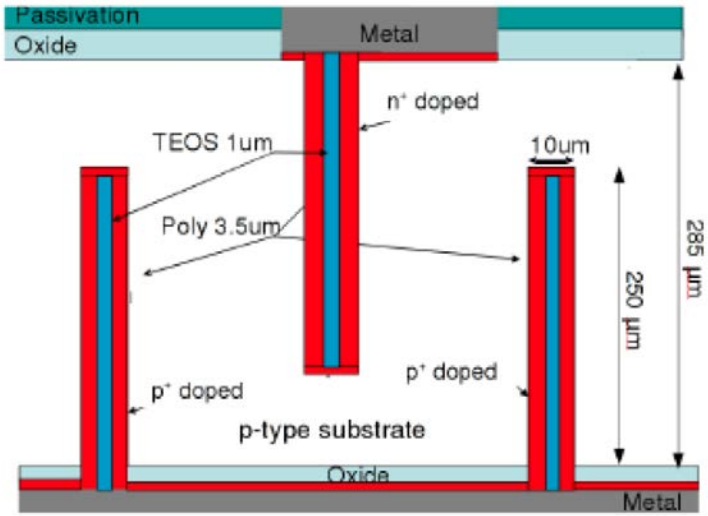


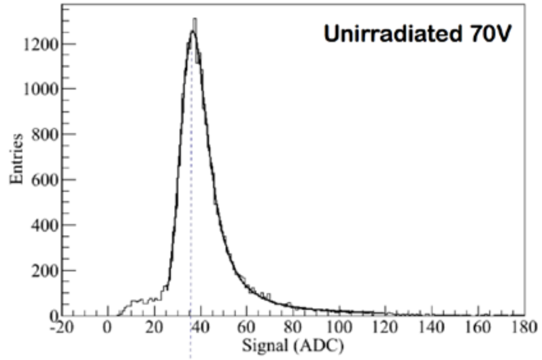

**Indium balls after reflow**

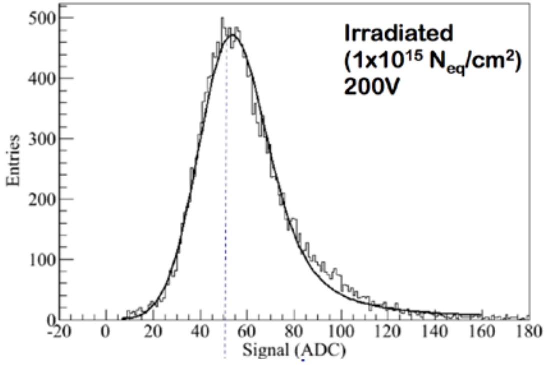



Developed at PSI with help of LMN (F.Glaus, J. Gobrecht)

# Charge Collection in 3D Detectors

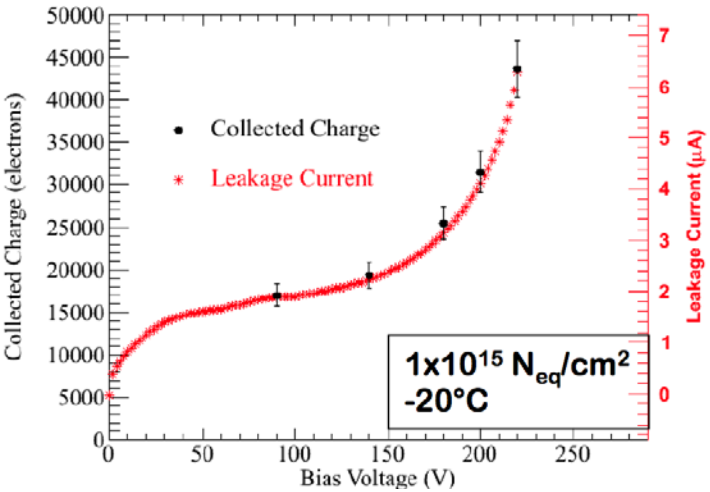



- short charge collection distance
- insensitive regions for tracks passing through electrode pillars. e.g. $90^0$ tracks
- interleaved electrode pillars → capacitance !
- 3D sensors show avalanche charge multiplication after irradiation. (seen also in planar)

  → non gaussian sensor noise in read out




3D-silicon sensors planned in ATLAS ILB pixel upgrade

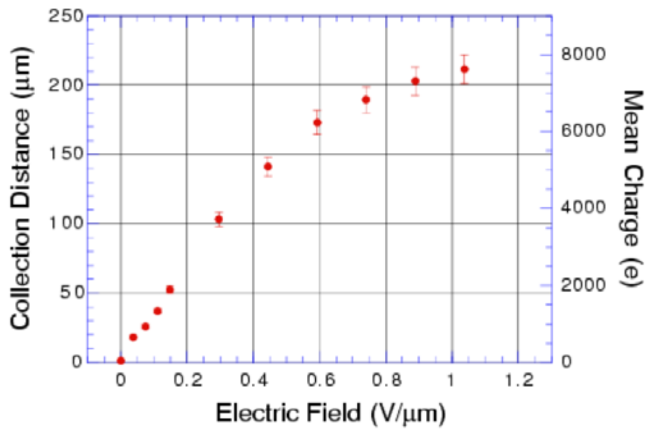
(RD42, ETHZ)

# Diamond Sensors

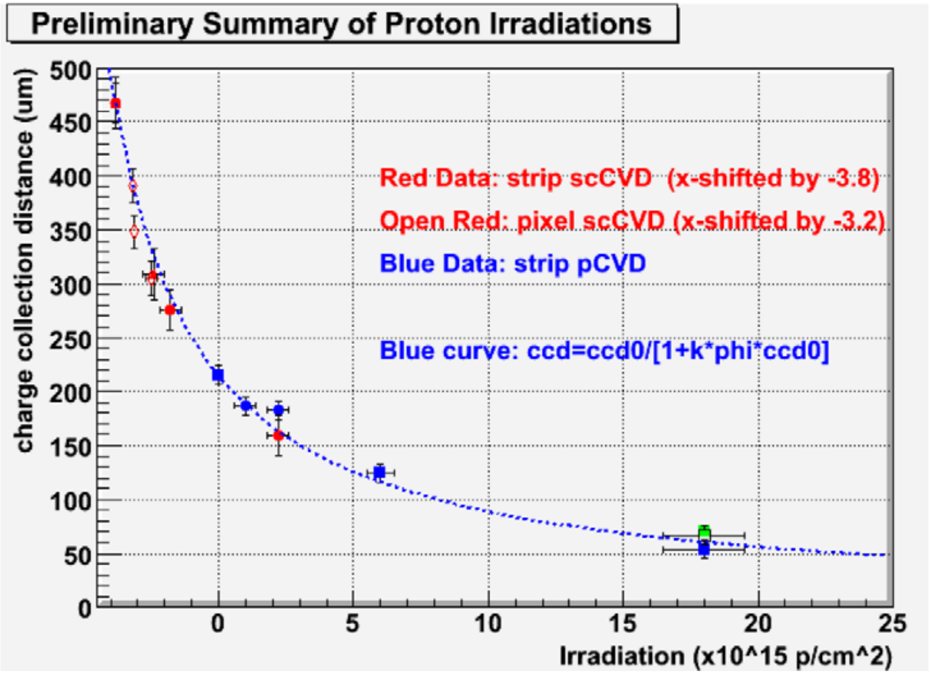
- Diamond pixel sensor can be operated at $300^0$K
- Excellent thermal conductor → heat removal

- Particle detectors from Chemical Vapor Deposited (CVD) Diamond are trapping defect dominated.

- Mono-crystalline diamonds show much better charge collection distances !




## Mono- / Poly-crystalline Comparison




**Poly-crystalline material shifted by ≈ 3.8 × $10^{15}$ p/cm$^2$ to mono-crystalline material**

Running construction projects:

- ATLAS Beam Conditions Monitor
- CMS Pixel Luminosity Telescope
- ATLAS Diamond Beam Monitor