The History of Silicon Detectors for Particle and X-ray Physics

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The Very Early Days of Solid State Detectors

Idea of solid state ionization chamber and first successful realisations:

- 1943: P.J. von Heerden, Utrecht (AgCl)

- 1949: K.G. McKay, Bell (Ge – pn junction)

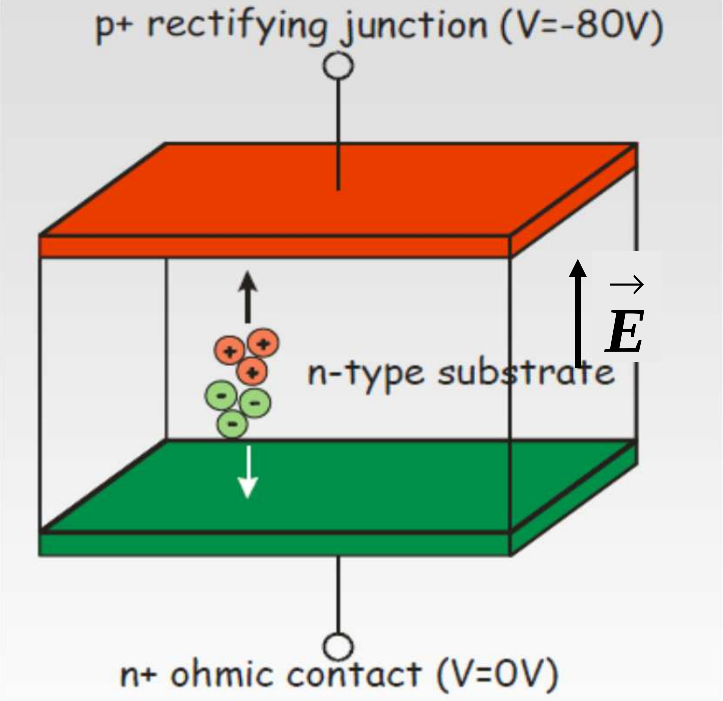
- 1955 – 1965: Si mono-crystals available → surface barrier detectors at several labs. Oak Ridge, Chalk River, CEA, ... main motivation nuclear particle spectrometers

- 1961: G. Dearnaley, Harwell: first segmented detector a pixel detector !

- 1970: first strip detectors – Argonne, Fermilab, Karlsruhe, Southampton; for nuclear physics and nuclear medicine

- 1970: CCD: W.S. Boyle and G.E. Smith, Bell

Several companies in the US and Europe for detector fabrication (> 7 in 1975)



Typical values for Si:

- voltage: 50 – 500 V
- thickness: 0.05 – 1 mm
- signal: 1e/h-pair/3.6 eV
  → mip 25000 charges/0.3 mm
- collection time: 5-50 ns
- diffusion: few µm
- sensitive to light ≲1 µm, X-rays 0.2 - 20keV, charged particles

The Very Early Days

Si-detectors can also be used to detect minimum ionizing particles !

(J.E.Bateman, NIM71(1969)256)

- **surface barrier detector**
- **area: 2 cm^2**
- **thickness: 500 µm**
- **resistivity: 8 kΩ•cm**
- **voltage: 400 V**
- **noise: ~ 4000 e (rms)**

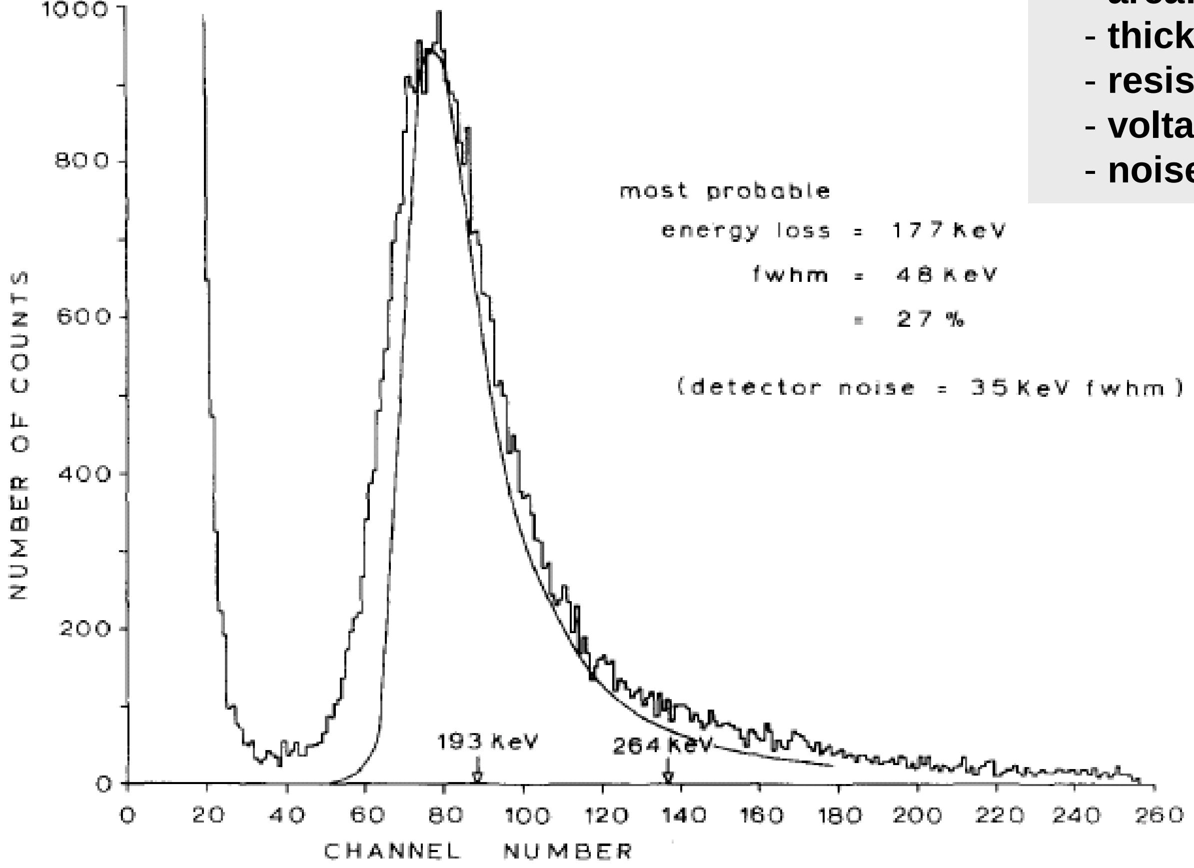


Fig. 4. Energy distribution produced in C56 by electrons of energy 150 MeV (momentum resolution ≈ 2%). The solid curve is given by Landau's theory.

Early Realization of Double Sided Strip Detector

S. M. Gruner BSC-thesis (1972):

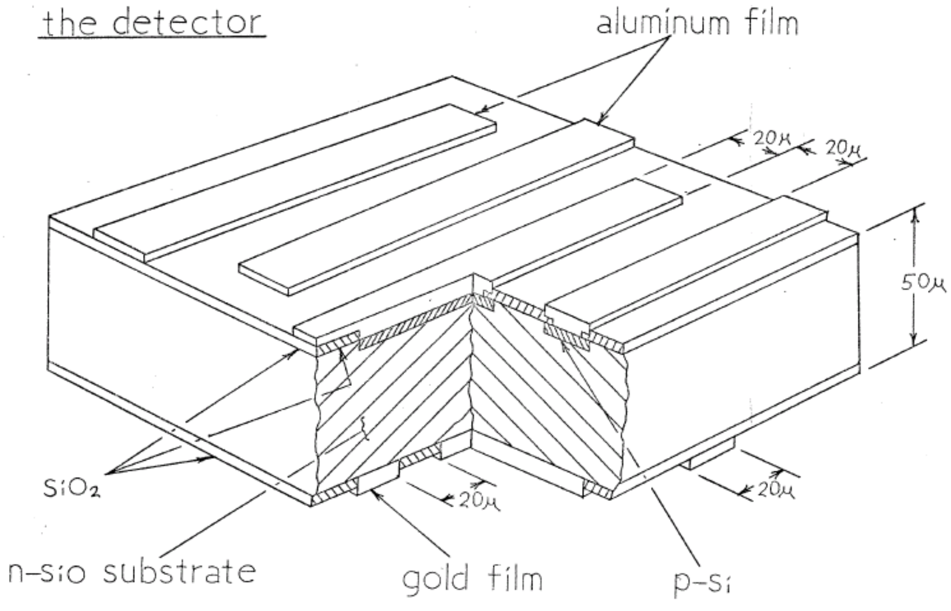
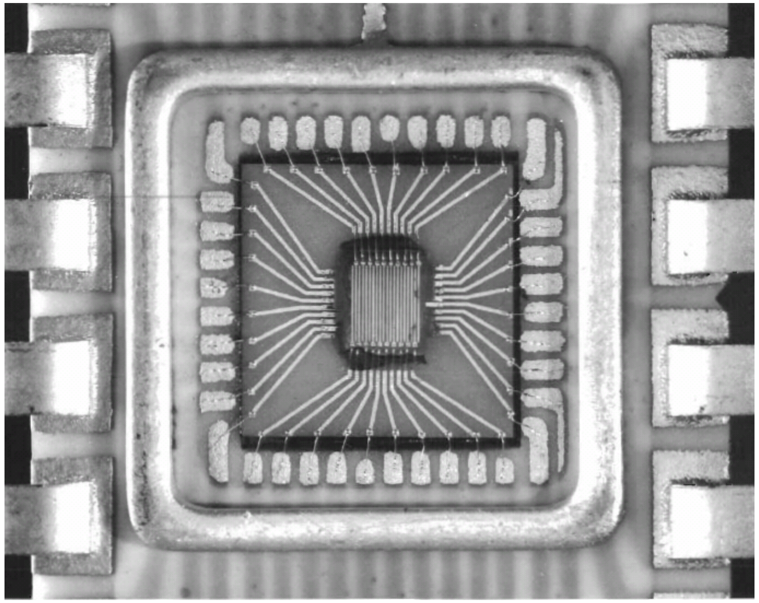
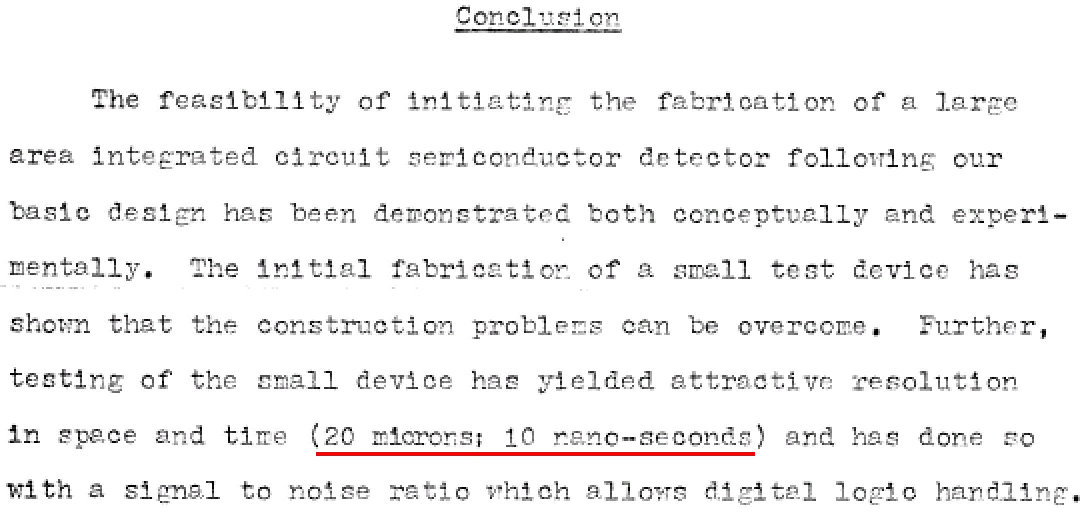


figure 3



- (.6×.6) mm^2 × 50 μm n-type Si
- B-diffused (+Al): p$^+$n-junction
- Au strips: np-junction
- test with ^{90}Sr source + amplifier + scope + scope camera

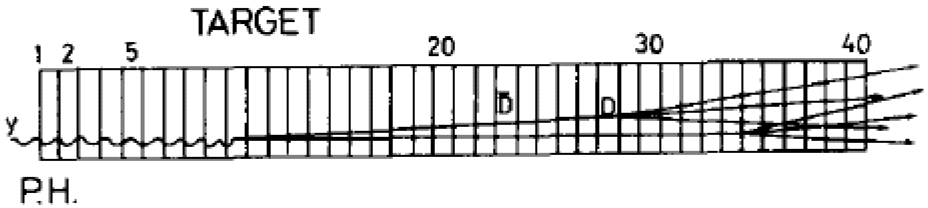


Conclusion

The feasibility of initiating the fabrication of a large area integrated circuit semiconductor detector following our basic design has been demonstrated both conceptually and experimentally. The initial fabrication of a small test device has shown that the construction problems can be overcome. Further, testing of the small device has yielded attractive resolution in space and time (20 microns; 10 nano-seconds) and has done so with a signal to noise ratio which allows digital logic handling.

The Very Early Days of Si Detectors in hep

Segmented active target 1973 (G. Bellini et al., NA-1 CERN Coherent production π+Si → 3π + Si; and later for charm)



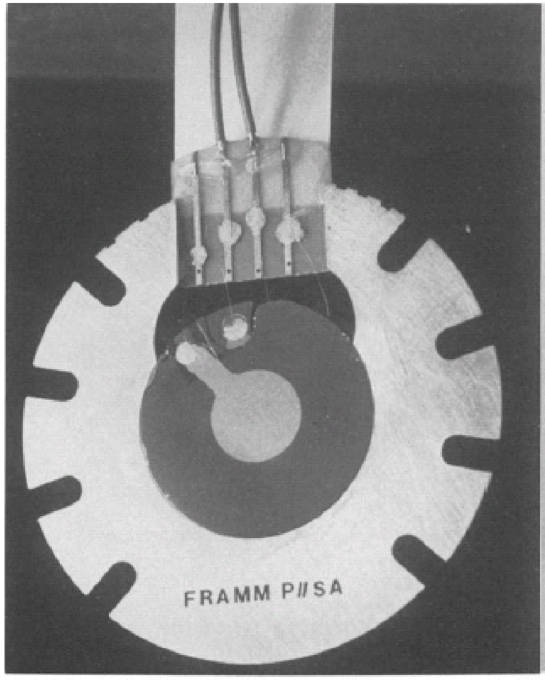


Fig. 3. Silicon disk.

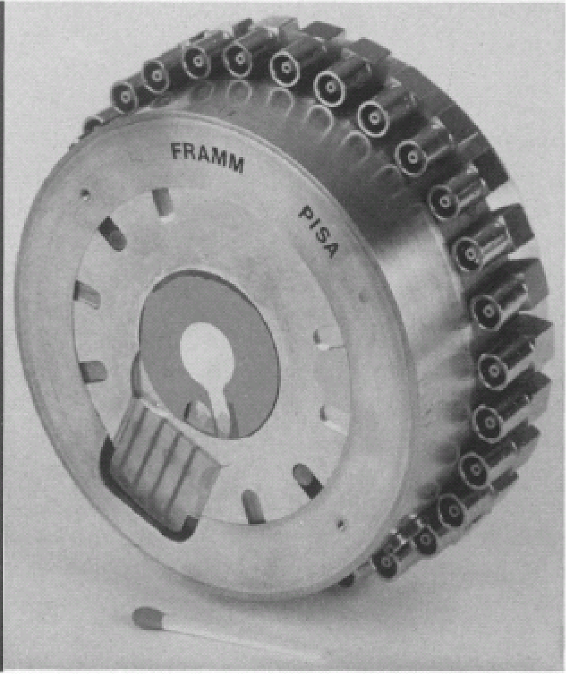


Fig. 5. Assembly of the whole telescope.

Surface barriers: a "mystic" art

- reliability not guaranteed
- but successful experiments and great potential realised

→ however, limited use

In 1974 with the

- discovery of J/ψ
- paper by Gaillard, Lee und Rosner on charmed particles
- discovery of charm (1975) (lifetime $c\tau \sim 100$ μm)
- discovery of τ-lepton
- discovery of beauty

→ Hunt for high position resolution electronic detectors

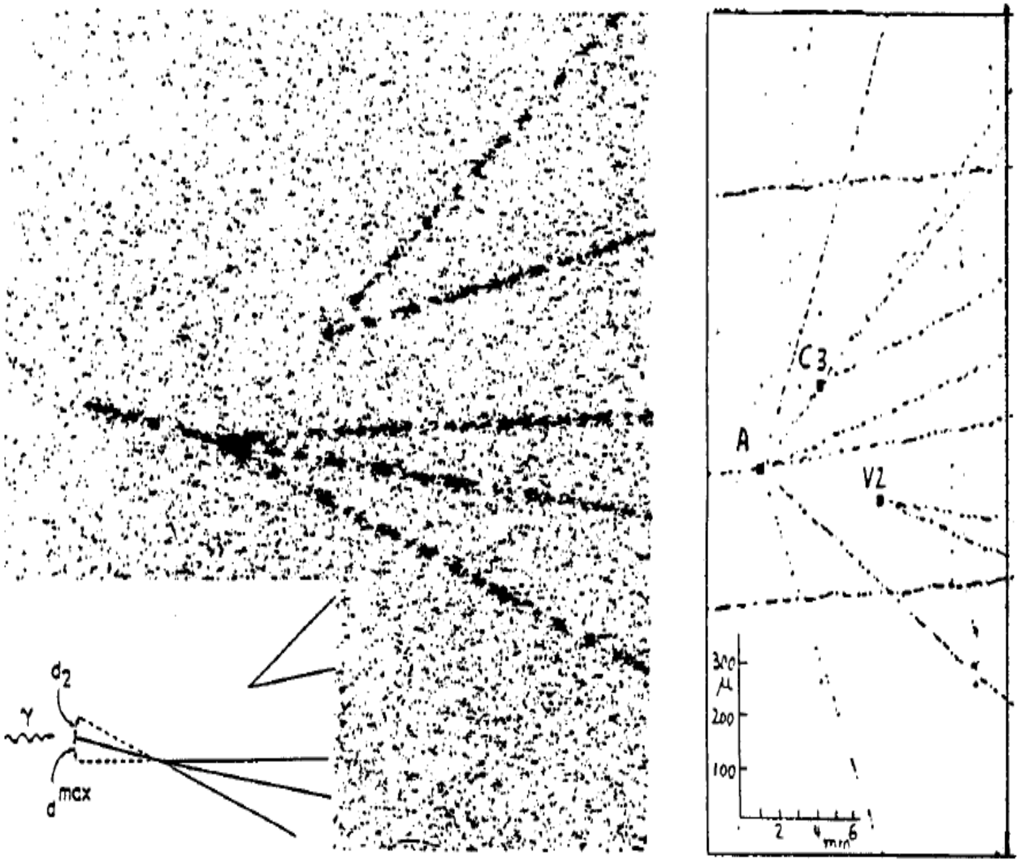
(a friendly competition between gaseous and solid state approach, e.g. in the MPI group)

The Hunt for High Resolution Electronic Detectors

There are **3 reasons** why the development of high position resolution Si-detectors took off in the late seventies:

- discovery of short-lived particles; lifetime $c\tau \sim 100\ \mu\text{m}$ defines required resolution; $\langle\text{decay length}\rangle = \beta\gamma \cdot c\tau$, and $\langle\text{impact parameter}\rangle \approx c\tau$
- highly developed Si-technology for electronics (crystals + the planar process)
- development of miniaturized electronics (thick film hybrids → VLSI) generally available

→ Several hep groups started to learn the art of silicon sensors and micro-electronics (in close collaboration with industry)

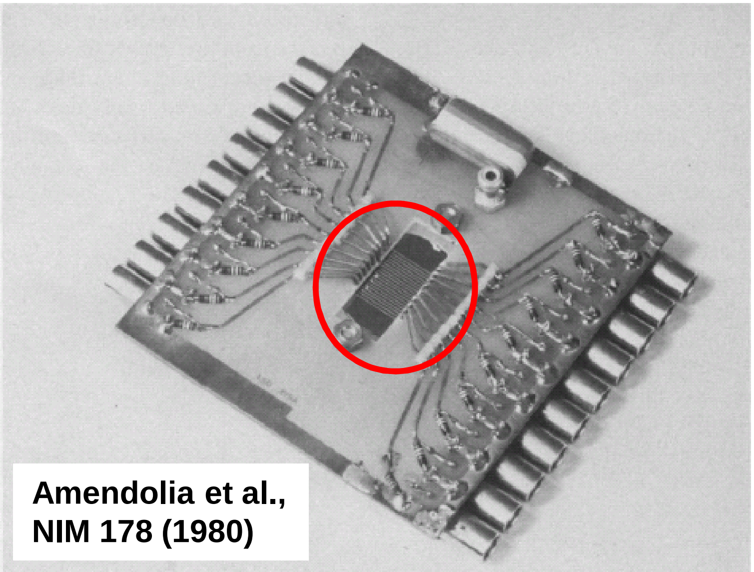


High-resolution bubble chambers: SLAC - CERN (production charm-anticharm)

The Early Days of Si Strip Detectors in hep

Still surface barrier technology:

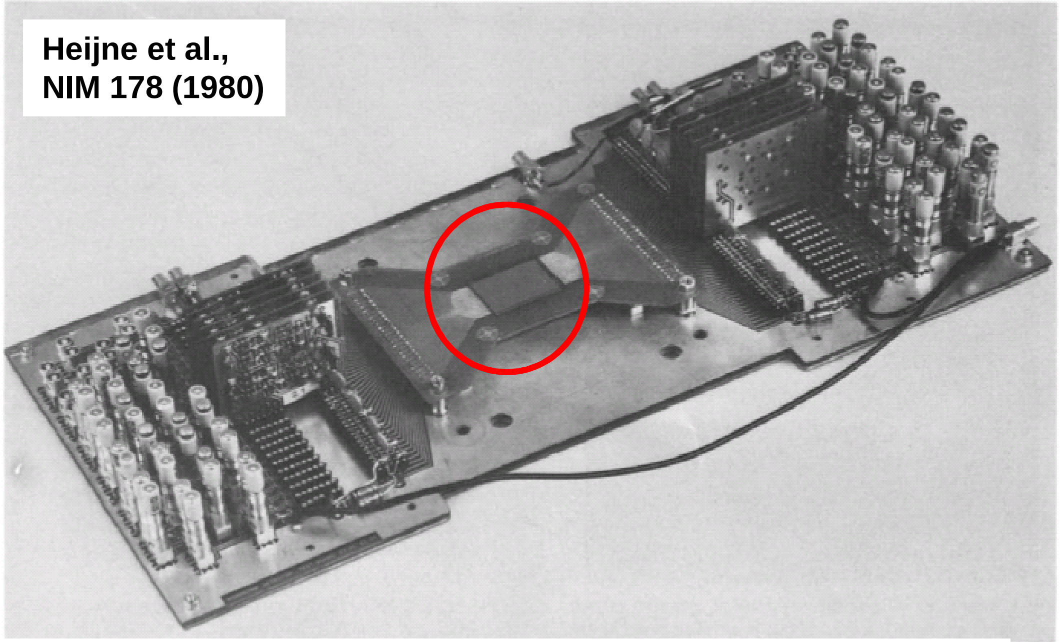
PISA group (Amendolia et al. 1980)
→ Si-strip sensor with 600 µm pitch



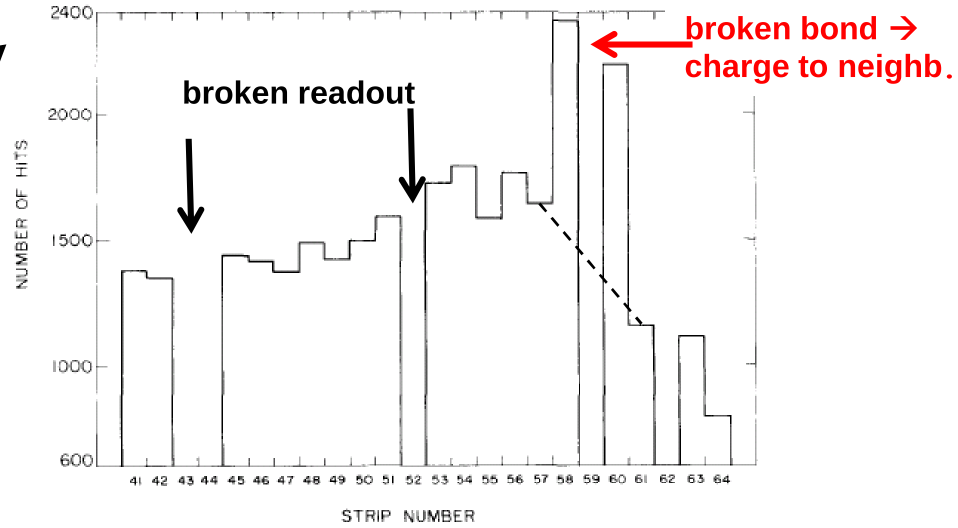
**Amendolia et al.,
NIM 178 (1980)**

CERN group (B. Hyams et al. 1980)
Si-strip sensor with 300 µm pitch

- demonstrate vertex reconstruction (within the NA-11 experiment)
- demonstrate capacitive charge division (thanks to broken channels)



**Heijne et al.,
NIM 178 (1980)**



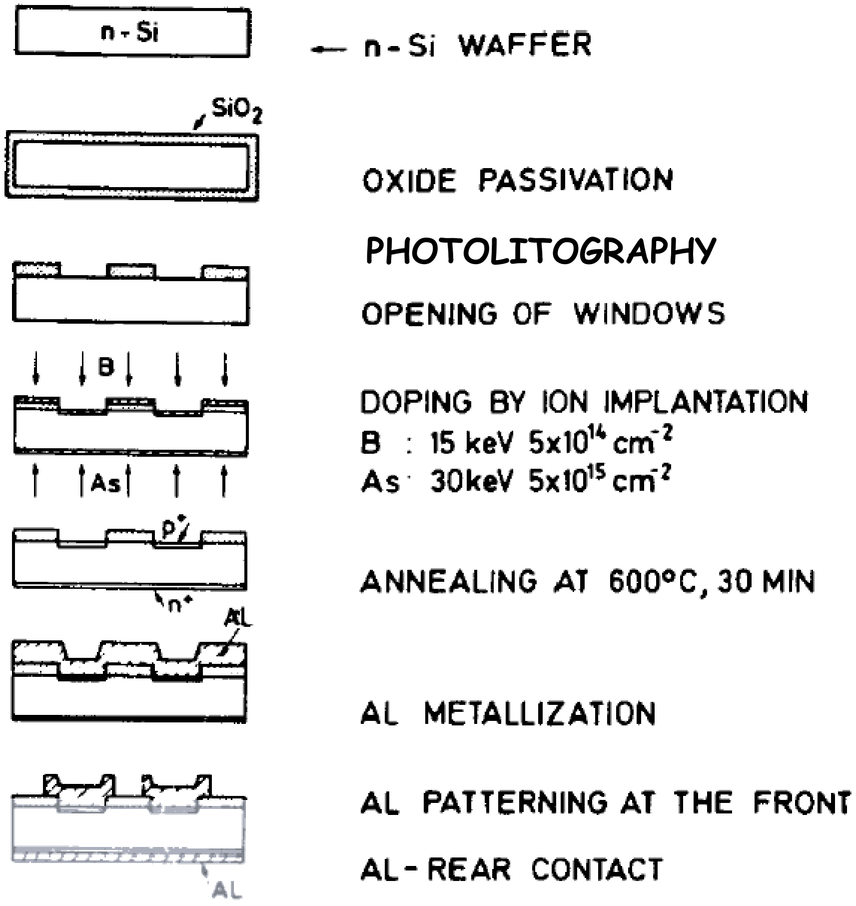
broken readout

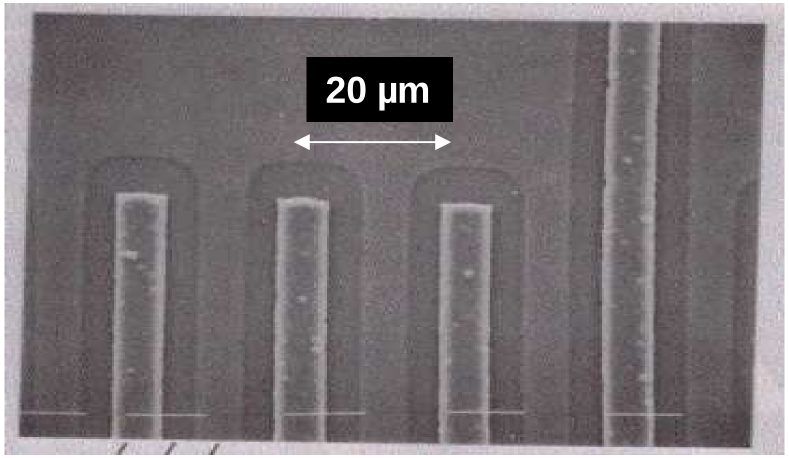
broken bond → charge to neighb.

Fig. 10. Hit distribution over 24 strips in the 10 GeV beam. Amplifiers on strips 43, 44, 52 and 62 were not working. Strip 59 has a broken contact, but its signals are collected on either 58 or 60.

Transfer of the Planar Process to Detector Fabrication

Kemmer 1979, TU-München, transferred the highly developed Si-technology for electronics to detector fabrication + industry (P. Burger – Enertec/Canberra)



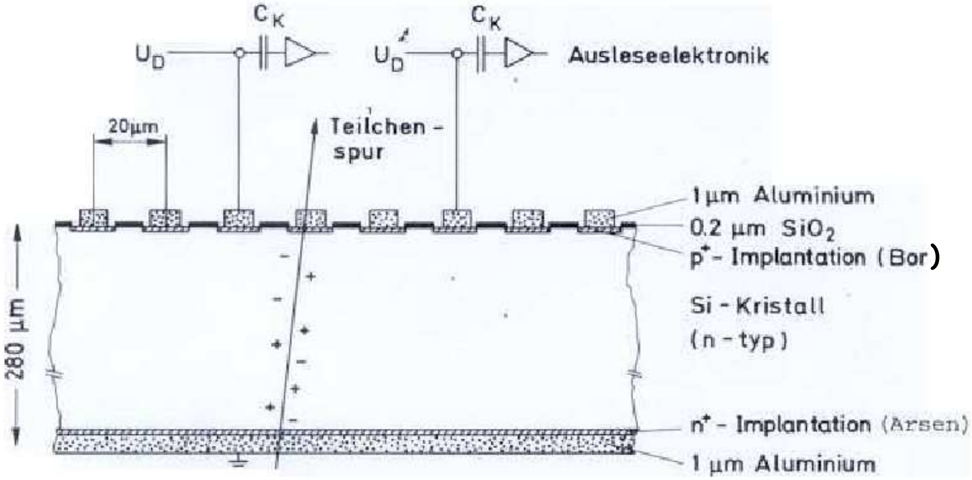


J. Kemmer, NIM 169(1980)499 and NIM 226(1984)89

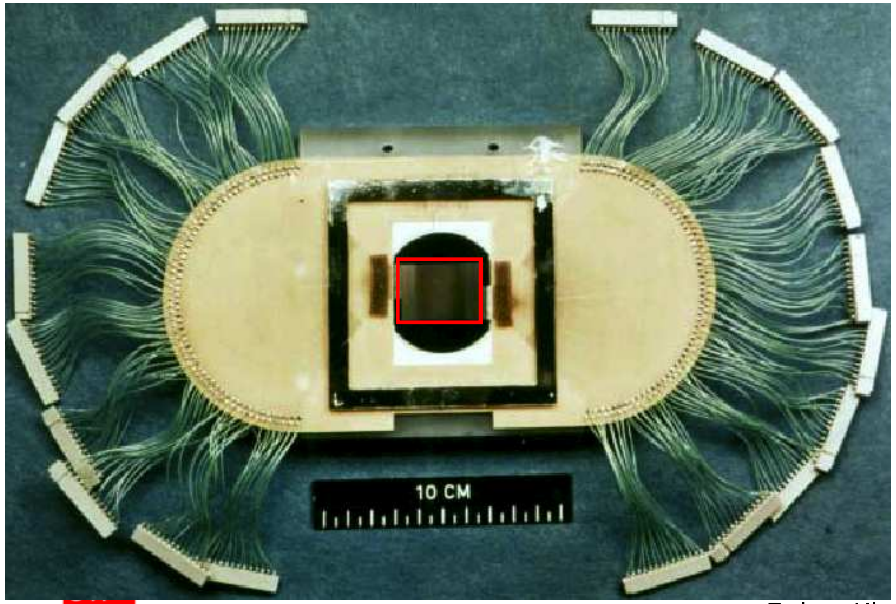
Si-strip Detector Telescope in CERN NA11 Experiment

NA-11/32 experiment:

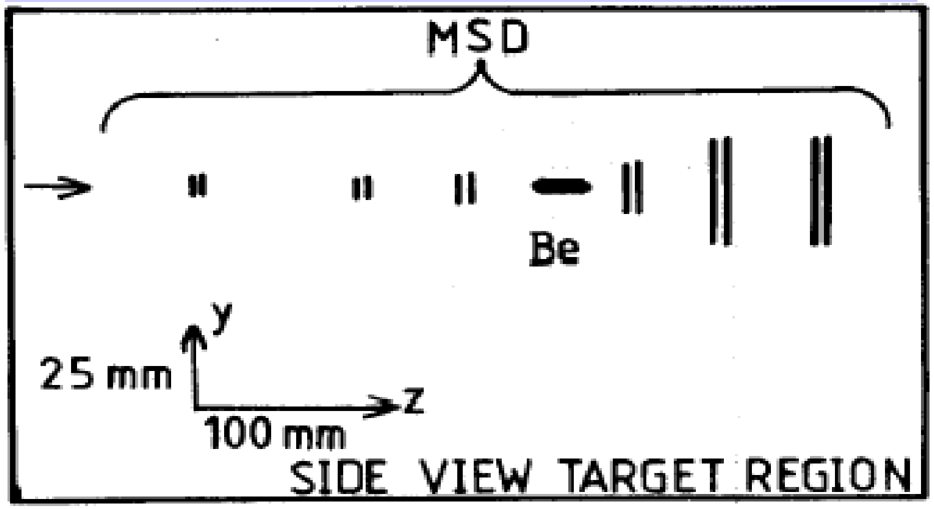
- spectrometer for the study of hadronic reactions eg π+Be->charm+X
- **1981**: 6 planes Si-strip detectors
  - **24x36mm^2, 1200 strips/sensor**
  - **strip pitch 20 µm, 280 µm thick**
  - **60 µm readout → σ = 5.4 µm**
  - **120 µm readout → σ = 7.8 µm**
  - **total < 2000 channels**
  - **100 % efficiency (all channels working!)**



B.Hyams et al., NIM 205(1983)99



NA-11 target region



Results from the NA11/32 Experiment

NA-11/32: Charm physics results

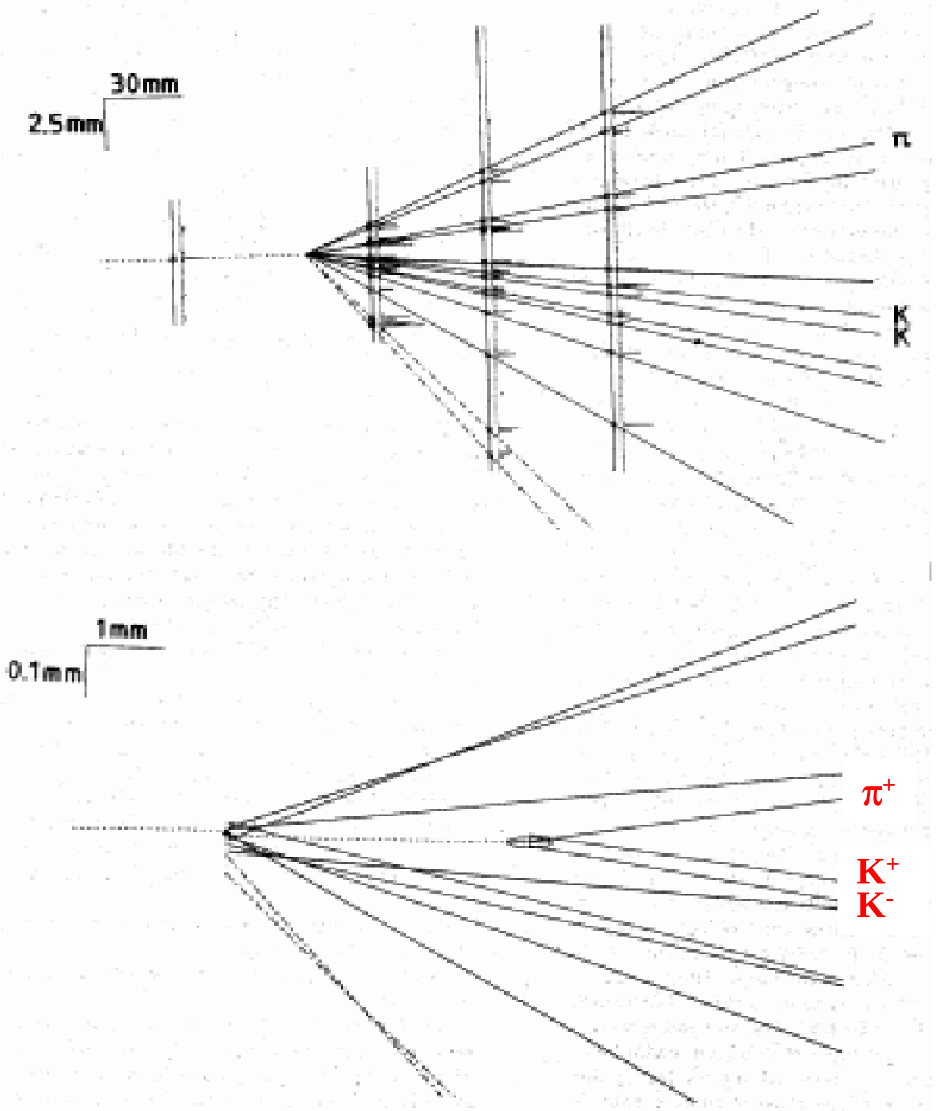
- lifetimes D^+, D^0, D_S, Λ_c, ...
- observation and mass of $D_{S,}$
- hadronic production of charm particles (QCD)

Impact of NA11/32:

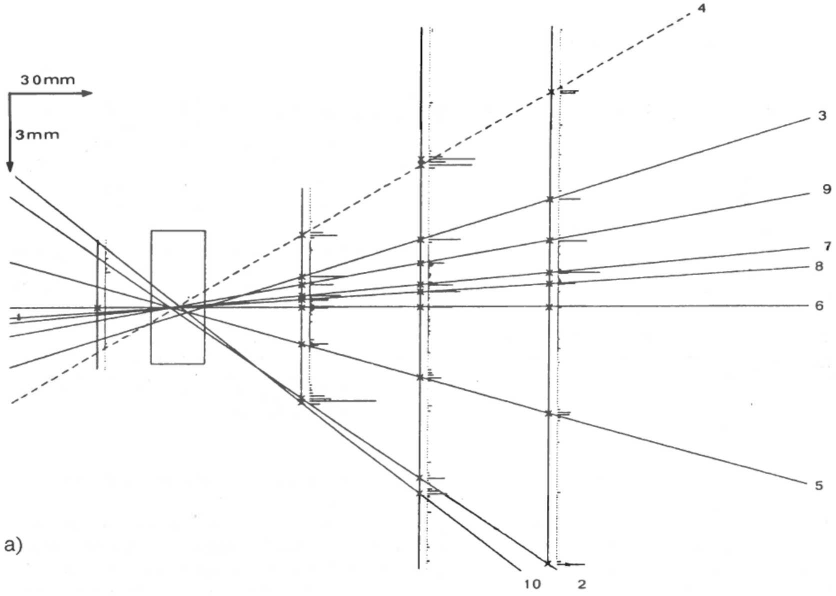
- demonstrated excellent performance of **Si-strip** detectors
- demonstrated excellent performance of **Si-pixel** detectors (→ CCDs added in NA32)
- testing ground for new ideas and concepts (→ Si drift ch.)
- **learning- + communication-environment for junior and senior Si-experts**

(R.Horisberger, D.Dorfan, S.Parker, U.Kötz, V.Lüth, E.Gatti, P.Rehak + many more)

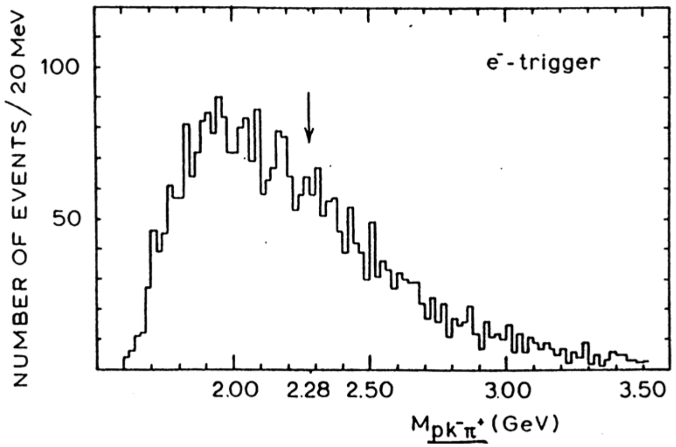
Observation of $D_S \rightarrow \Phi\pi$



Si telescope of NA11/NA32 (ACCMOR-Collaboration)

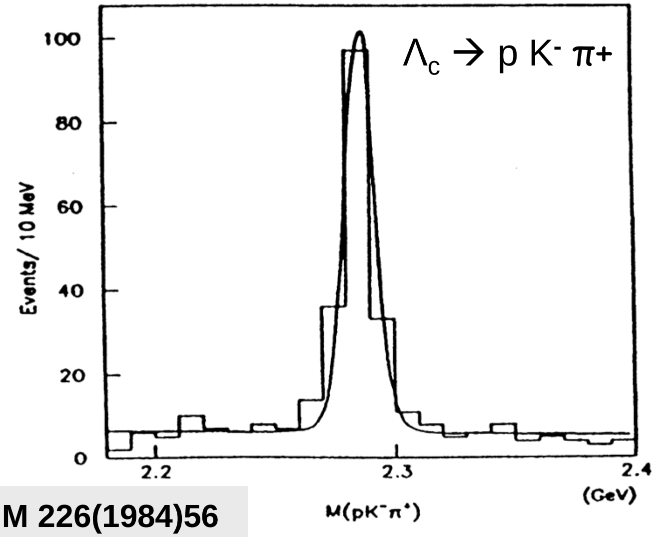


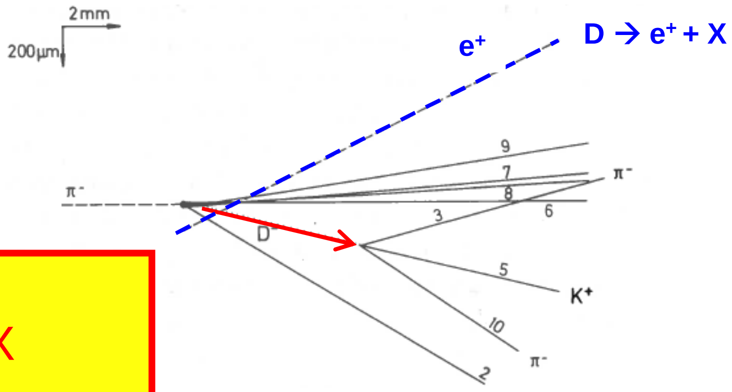
Before



Background rejection by lifetime cut

after installation of the Si-telescope





A NA11 event

$\pi^- + Be \rightarrow \mathbf{D} + \mathbf{D^-} + X$

$\quad\quad\quad\quad\quad\quad \hookrightarrow e^+ \hookrightarrow K^+\,\pi^-\,\pi^-$

ACCMOR Collab.: R. Bailey et al., NIM 226(1984)56

Event displays and plots, which convinced the hep community → start of Si success story

Si Detectors: Well-understood Performance

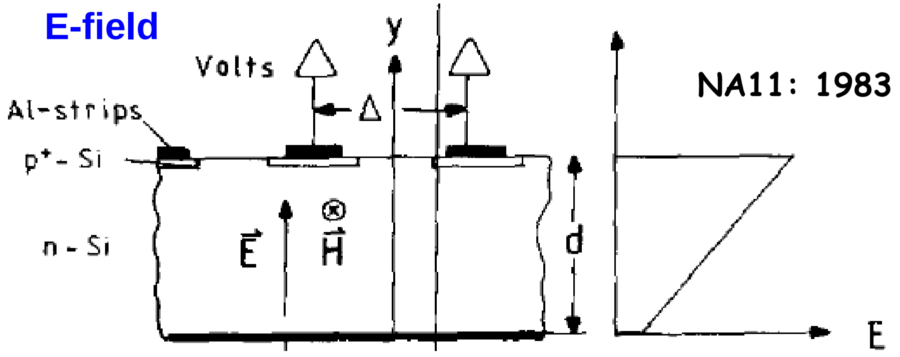
From the beginning, performance of (non radiation damaged) Si-sensors was well understood + experimentally verified:

- **PH distribution → "Landau" dE/dx**
- **position resolution → charge sharing**
  - **charge collection**
  - **charge diffusion**
  - **Lorentz force**
  - **resolution vs. track angle**
  - **effect of δ-rays on resolution**

  + electr. noise + dE/dx fluctuations
- **optimal reconstruction algorithm (η)**

→ Straight-forward optimisation of strip and pixel sensors if there would be no radiation damage !

E-field



Charge diffusion

Lorentz angle

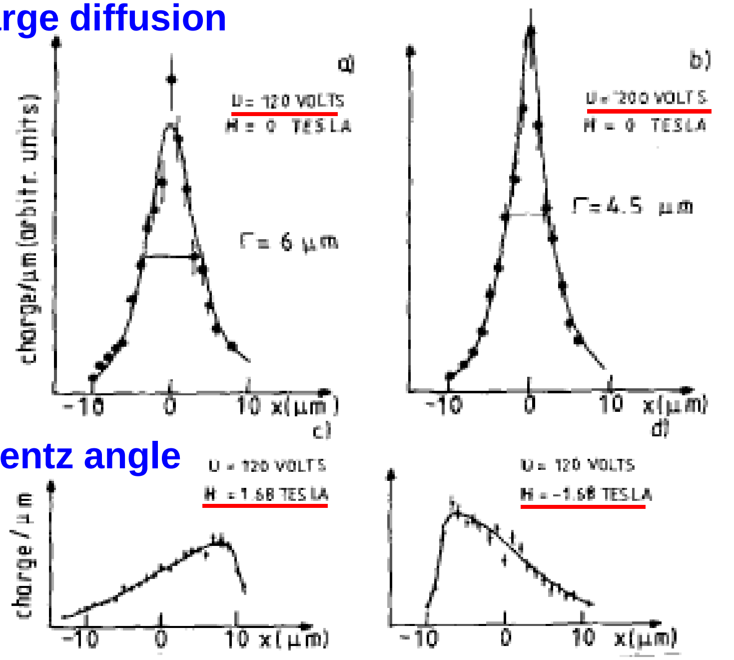


Fig. 6. The charge distribution collected by the diode strips: a) $U = 120$ V, $H = 0$ T; b) $U = 200$ V, H = 0 T; c) $U = 120$ V, $H = 1.68$ T; d) $U = 120$ V, $H = -1.68$ T.

E. Belau et al., NIM 214 (1983) 253

Getting Organized

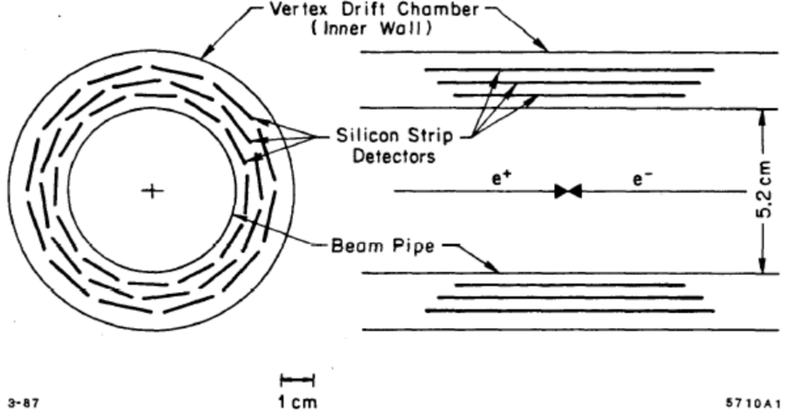
1983: 3rd European Symposium on Semiconductor Detectors at Munich

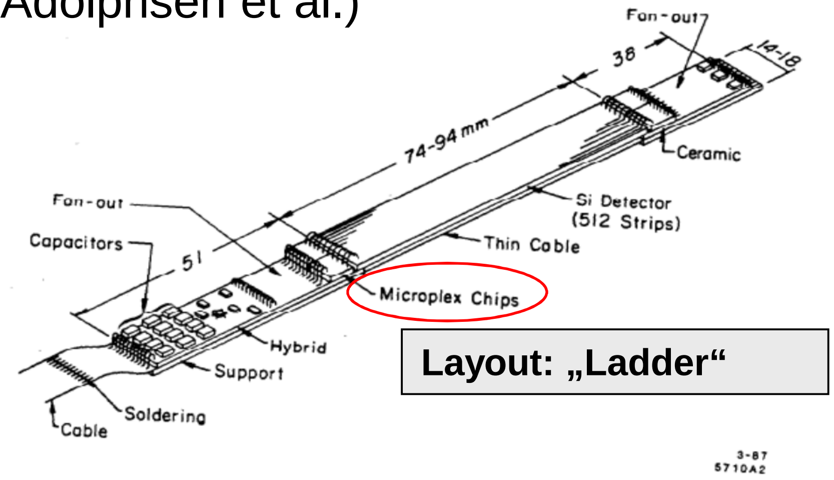
Si Vertex Detector for e^+e^-: SVD at Mark-II at SLC

Parallel to Si-detectors → development of VLSI readout chips
(**CAMEX**: G.Lutz et al., MPI; **Microplex**: Hyams, Walker, Shapiro; ...)

Sept.1985: Proposal to add SVD to Mark-II (Adolphsen et al.)

Layout: „Coke Can“





Layout: „Ladder“

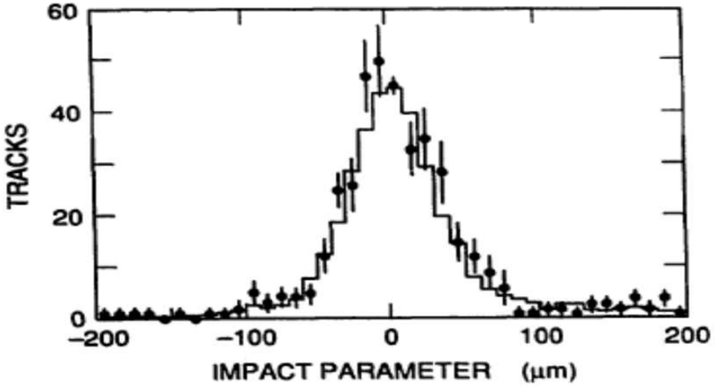
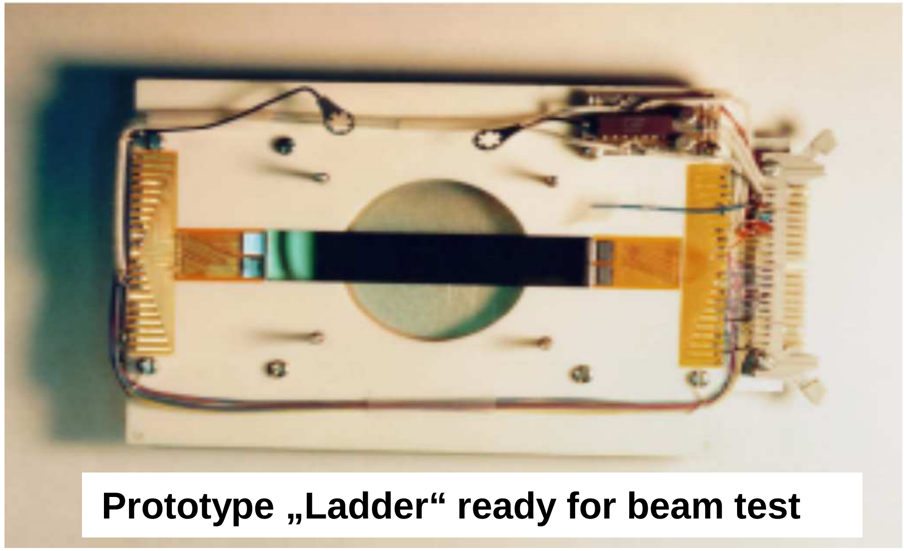


Fig. 40. The impact parameter measurement relative to the single-event vertex, for tracks with transverse momenta above 3.5 GeV/c. The points represent the measured tracks, the histogram shows the results of a detailed Monte Carlo simulation.

Impact parameter resolution ~20 μm



Prototype „Ladder“ ready for beam test

From MARK-II to LHC

Following the pioneering success of MarkII → Si vertex detectors for all 4 LEP-detectors, TeVatron, B-factories, HERA, RHIC and → **LHC**

Example: **CMS Tracker** the largest Si tracker ever built!
precision tracking in the harsh LHC environment for $|\eta| < 2.5$

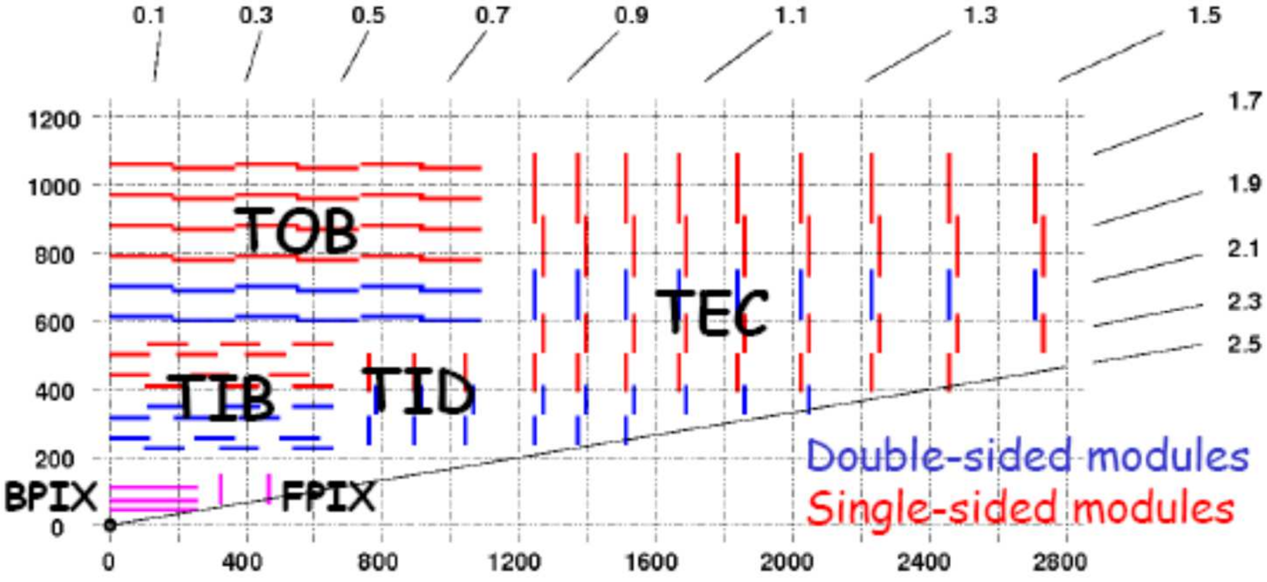
Before Phase I upgrade

Strip detectors:

- **9.3 M channels**
- **210 m^2 sensor area**
- **10 barrel layers**
- **9 (+3) endcap disks**

(Hybrid) Pixel detectors:

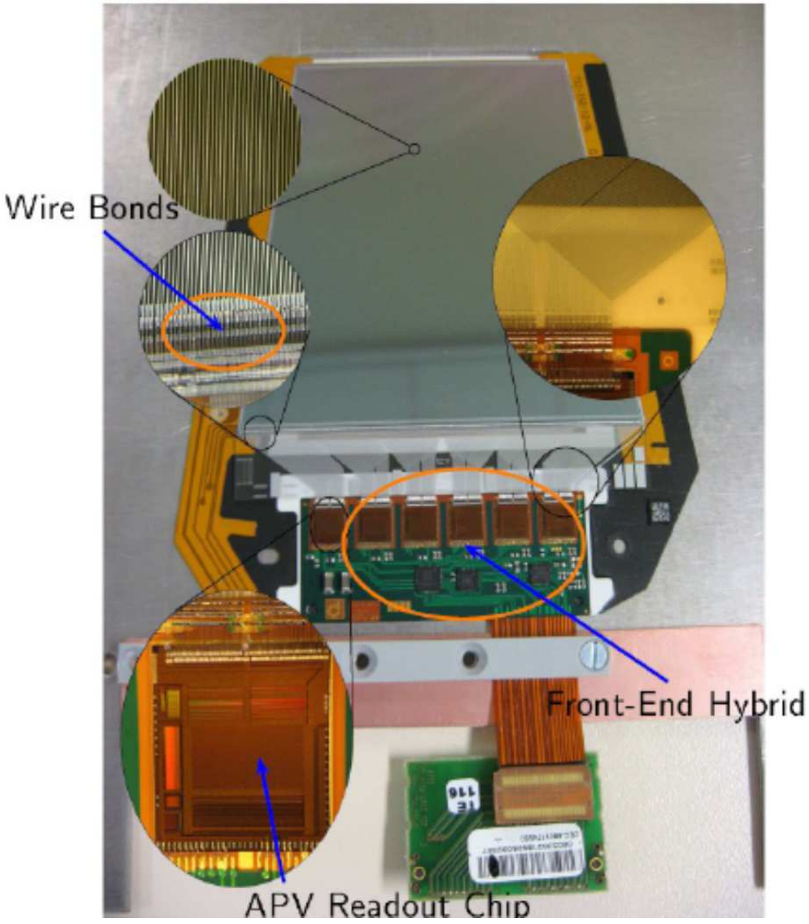
- **66 M channels**
- **~1.1 m^2 sensor area**
- **3 barrel layers**
- **2 endcap disks**
- **innermost layer at r=4.3 cm**

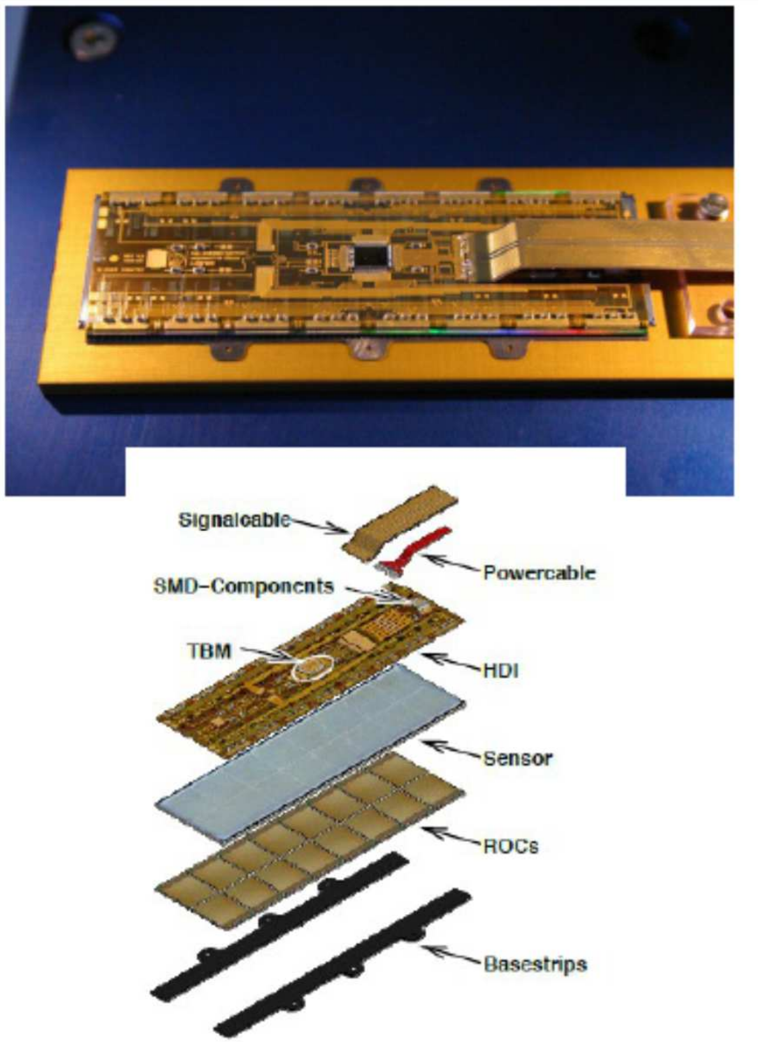


Tracker was running with
97.8 % strips and **96.5 % pixels** operating
at design resolutions and efficiencies

CMS Tracker

The building blocks of the **Si-strip** modules and **Si-pixel** modules

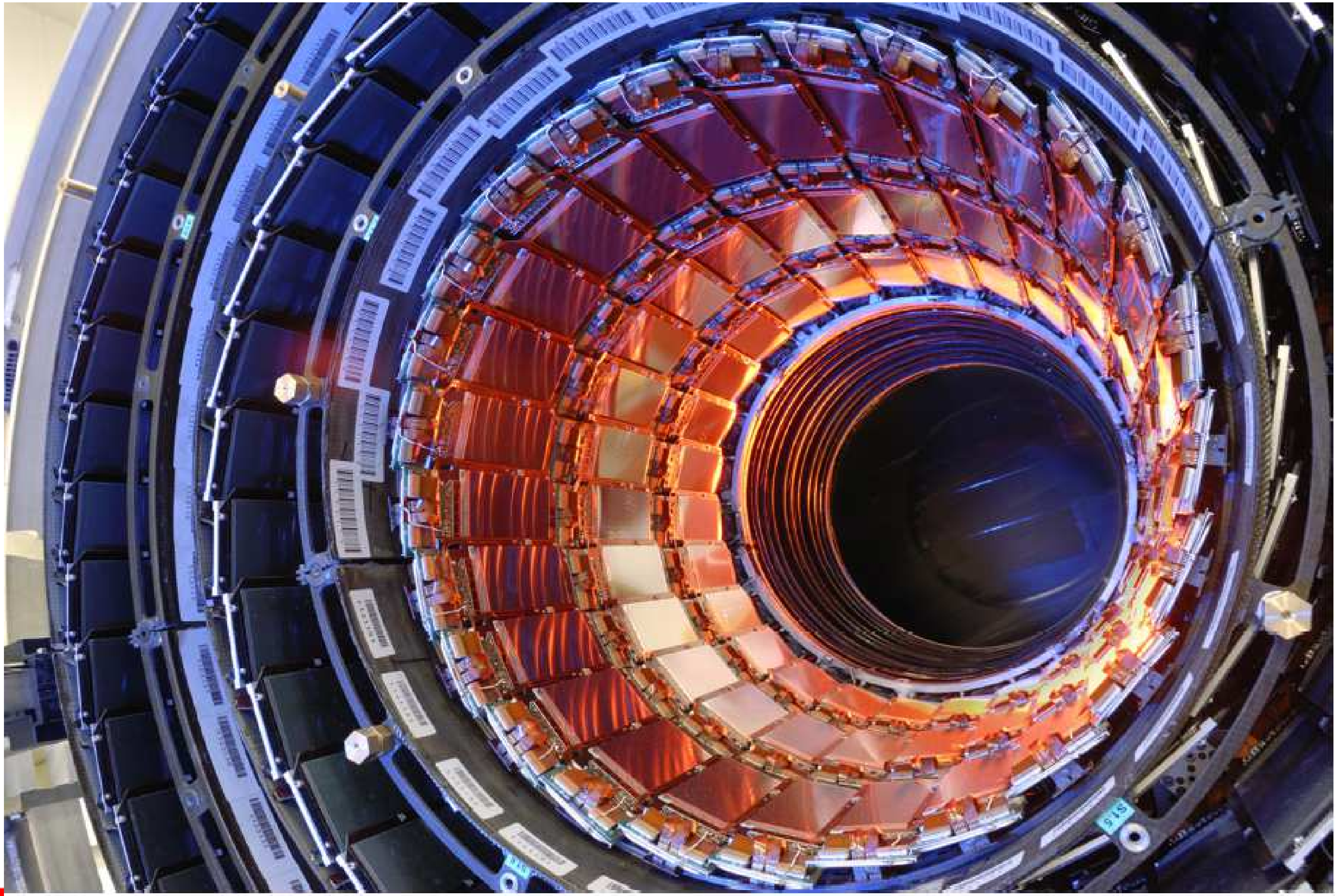




Quasi-industrial assembly (quality control!)

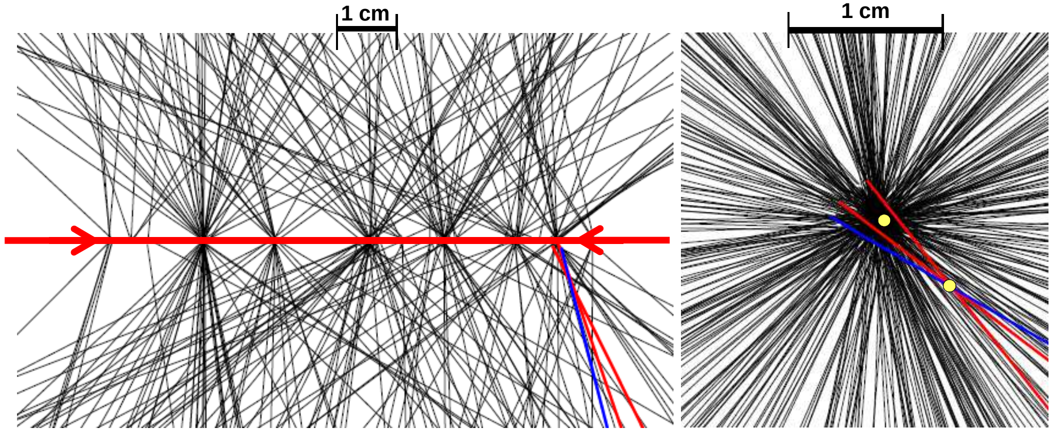
CMS Tracker – “The non-sleeping Beauty”

View of the CMS Tracker during installation in 2007



Silicon detectors and the LHC experiments

Most of the beautiful physics results from the LHC rely on the Si tracker performance



Primary and secondary vertex reconstruction in the presence of **many** interactions per bunch-crossing (CMS)

$p+p \rightarrow B(\rightarrow K+J/\psi(\rightarrow \mu^+\mu^-)) + X$

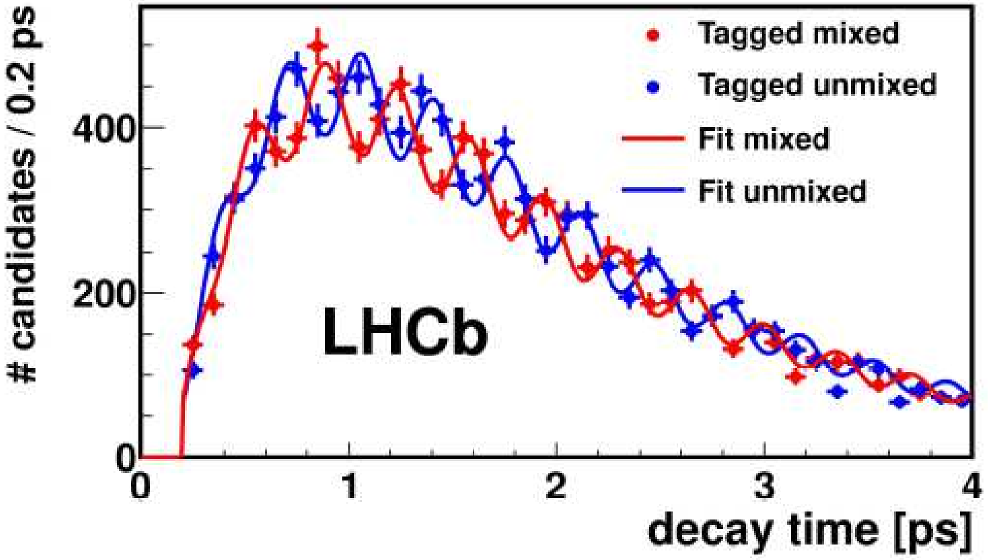
+

43 vertices with >2 primary tracks

(CMS 2017 run; courtsey D.Pitzl, DESY**)**

B_S mass difference with $B_S{}^0 - \overline{B_S}{}^0$ oscillations (LHCb)

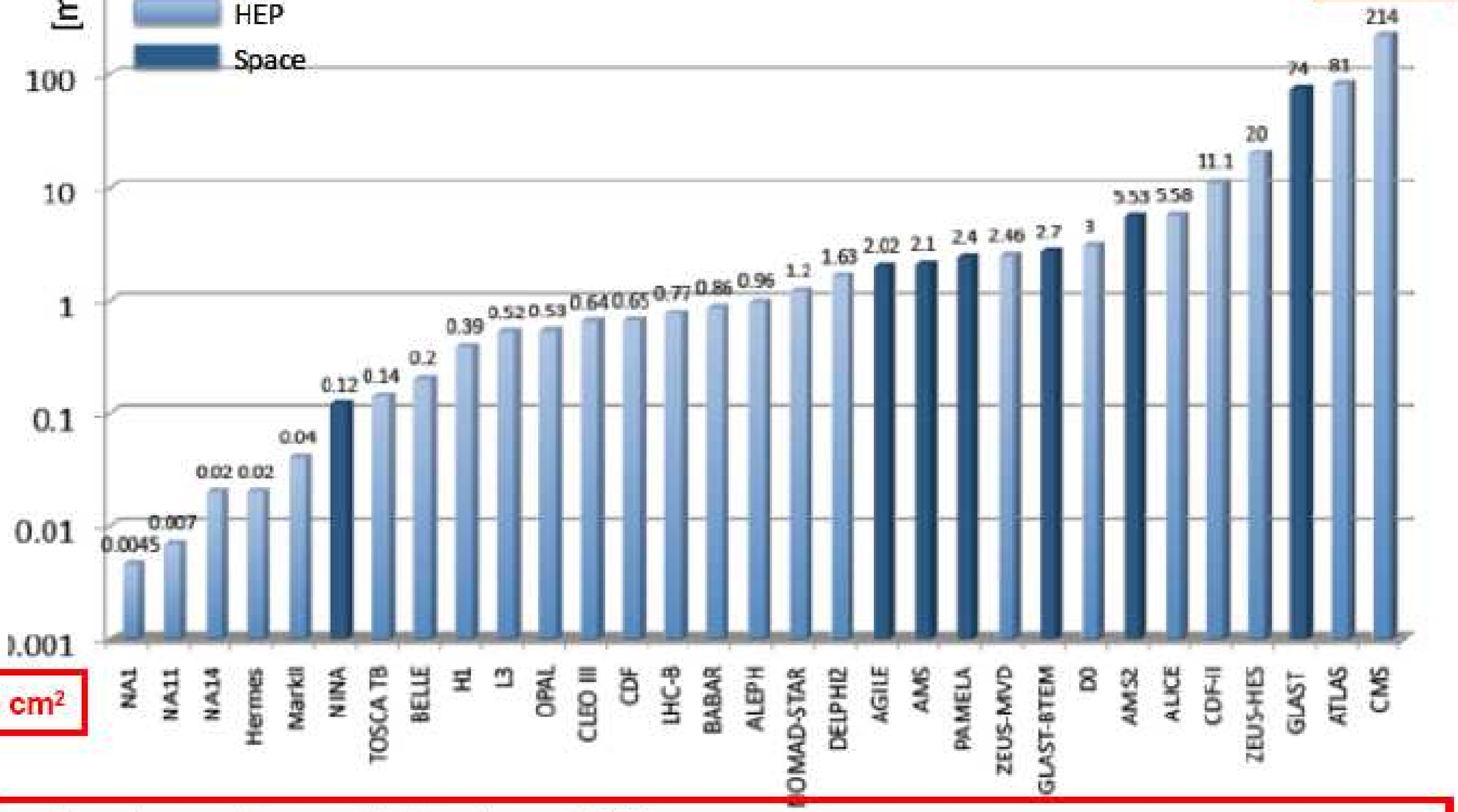
$\Delta M_S = 11 \cdot \hbar/\mathrm{ps}$



Silicon Detectors in hep and Space Experiments

Silicon detector area [m^2] in different experiments: 1981 - now

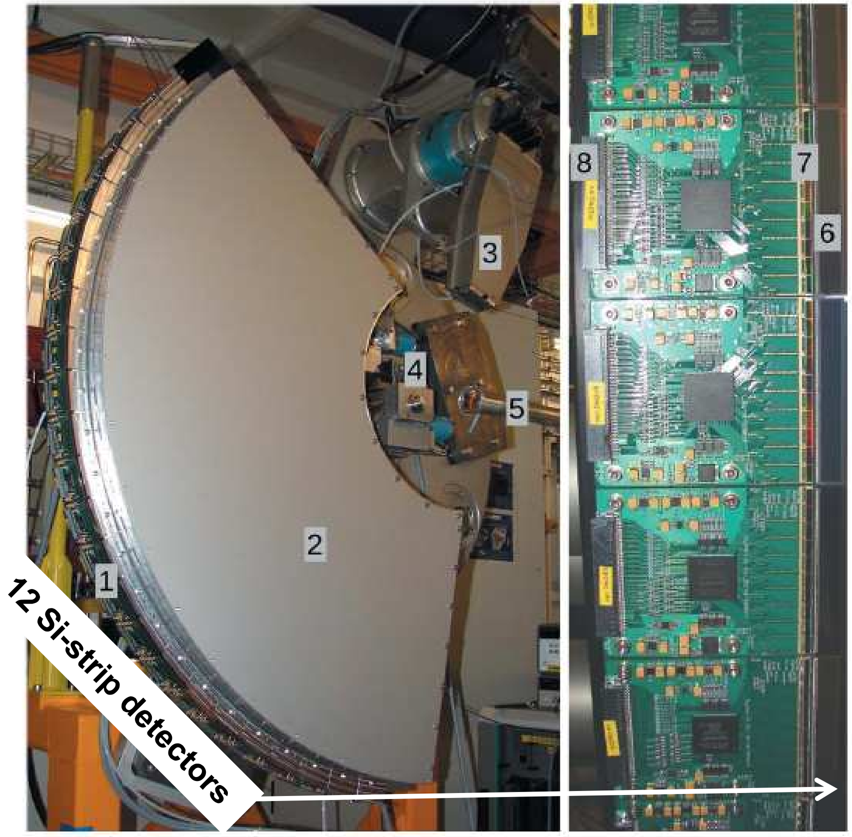
214 m^2



45 cm^2

- ~5 orders of magnitude since 1981
- Si detectors are used in (practically) all hep- and in many space-experiments

Si-Strip Detectors for X-ray Science



(*a*) (*b*)

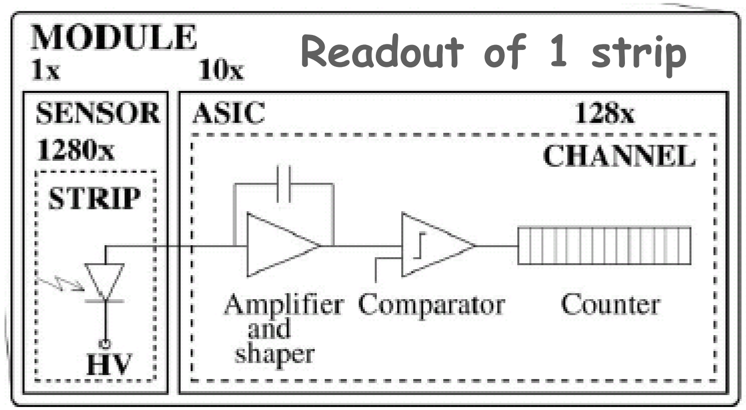
Figure 1
(*a*) Photograph of the MYTHEN detector installed at the powder diffraction station at the SLS and (*b*) a zoom on the modules building the detector. The numbers indicate the main elements of interest: (1) MYTHEN detector layer; (2) He-filled box behind which is fixed the data acquisition system; (3) analyzer crystal detector; (4) center of the diffractometer; (5) beampipe; (6) silicon microstrip sensor; (7) front-end electronics; (8) connector to the data acquisition system.

B.Schmitt et al., NIM-A 501(2003)267

Just one example: **MYTHEN** **(PSI)**

Si-strip sensors: 320 µm thickness
1280 8 mm long strips with 50 µm pitch

- counting rate: > 2×10^6 per strip
- max. no counts 24 bits (16,777,216)
- energy range 5keV (90%) – 30 keV (8%)
- frame rate: 25Hz (24bit) – 500Hz (4bit)



A highly successful example:

- reduction of measurement time for powder diffraction by ~10,000

→ acquire data before radiation damage

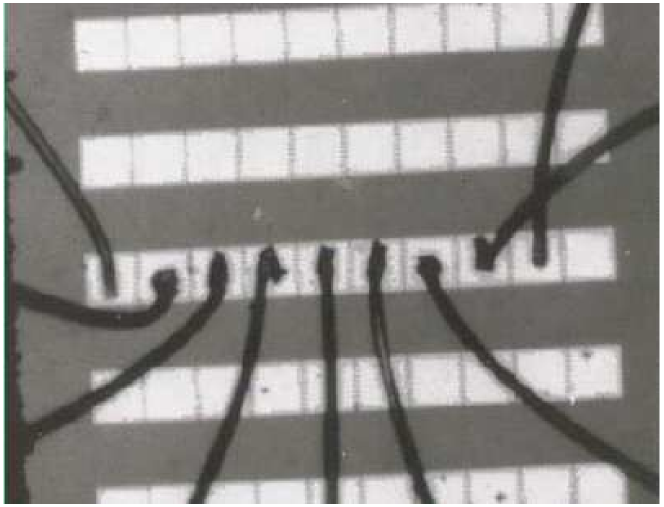
→ time resolved measurements possible

Pixel Detectors: Invention and Principle of CCD

2009 Nobel prize: **W.S.Boyle** and **G.E.Smith**

Invention Charged Coupled Device, the first (practical) solid state imaging device

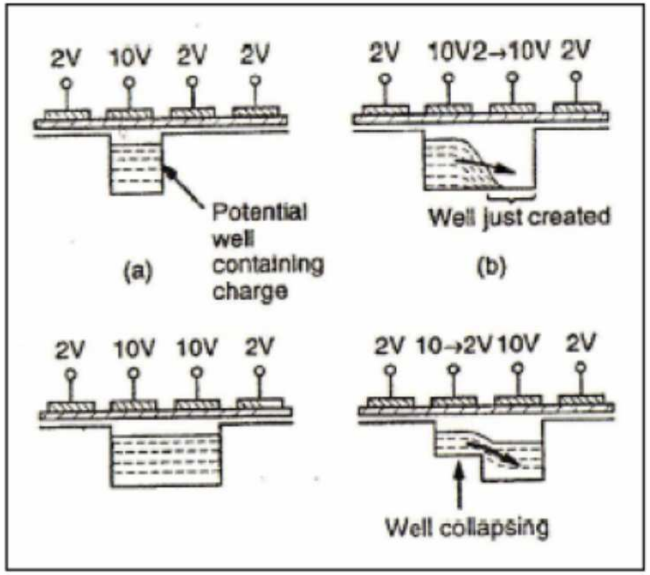
Test device
1 week
after idea!
(1970)



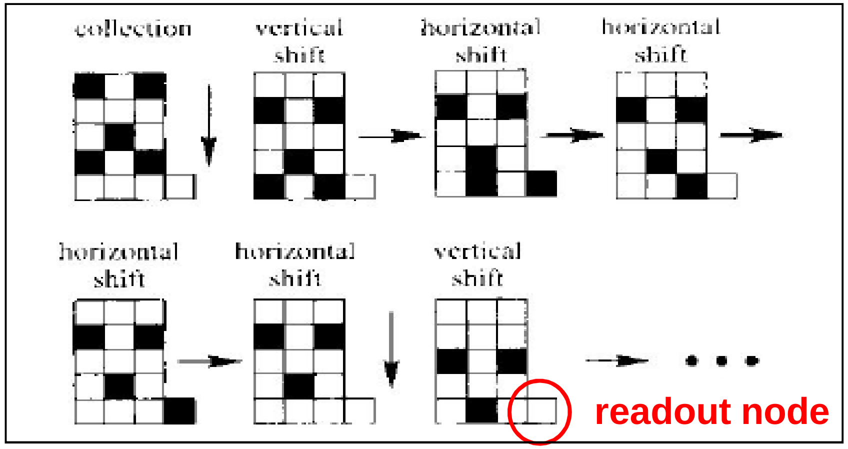
Picturephone
+ CCD inventors

G.E.Smith NIM-A 607(2009)1

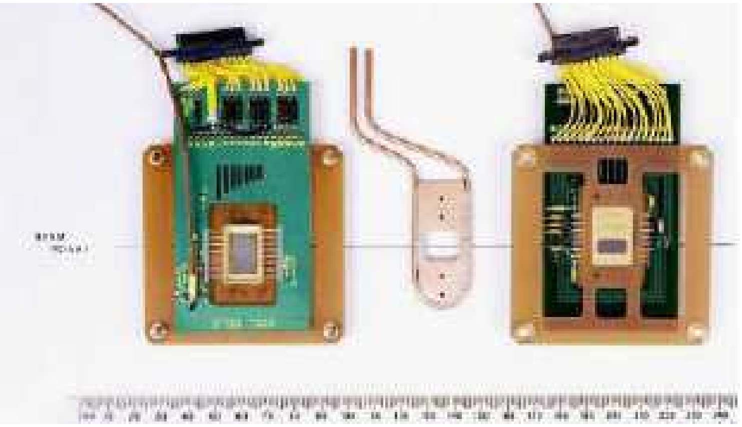
Principle of charge shift

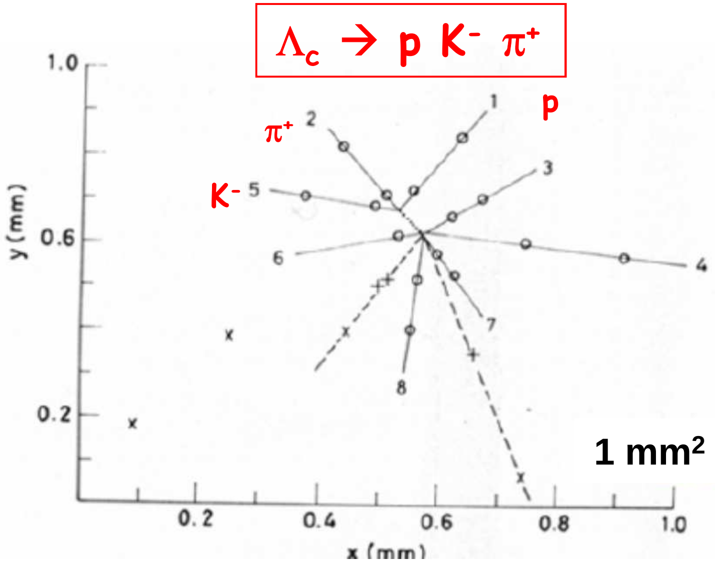


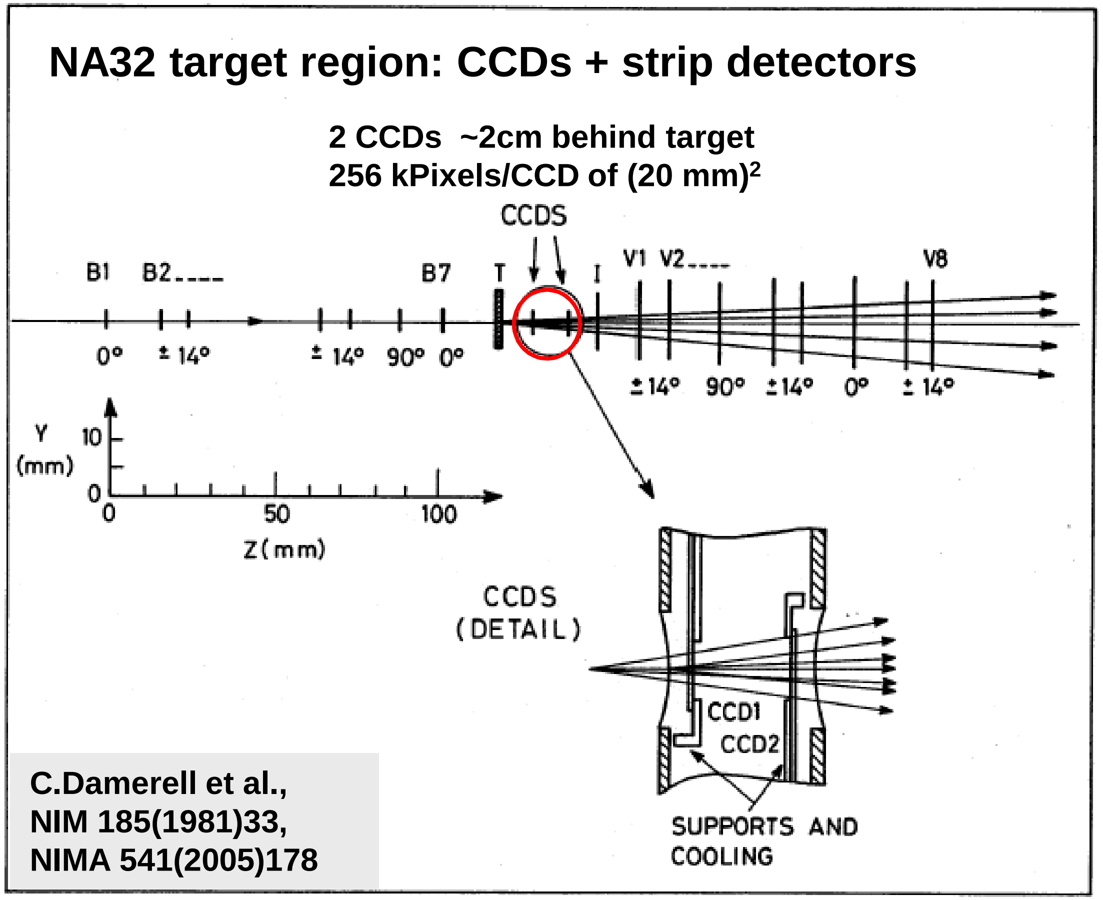
Shift pattern for 2-d CCD



CCDs as Precision Position Detectors in hep







NA32 target region: CCDs + strip detectors

2 CCDs ~2cm behind target
256 kPixels/CCD of (20 mm)^2

C.Damerell et al.,
NIM 185(1981)33,
NIMA 541(2005)178

→ superior pattern recognition convincingly demonstrated

→ C. Damerell et al. join SLD@SLC to build **the best vertex detector** operating so far (with respect to resolution and material budget)

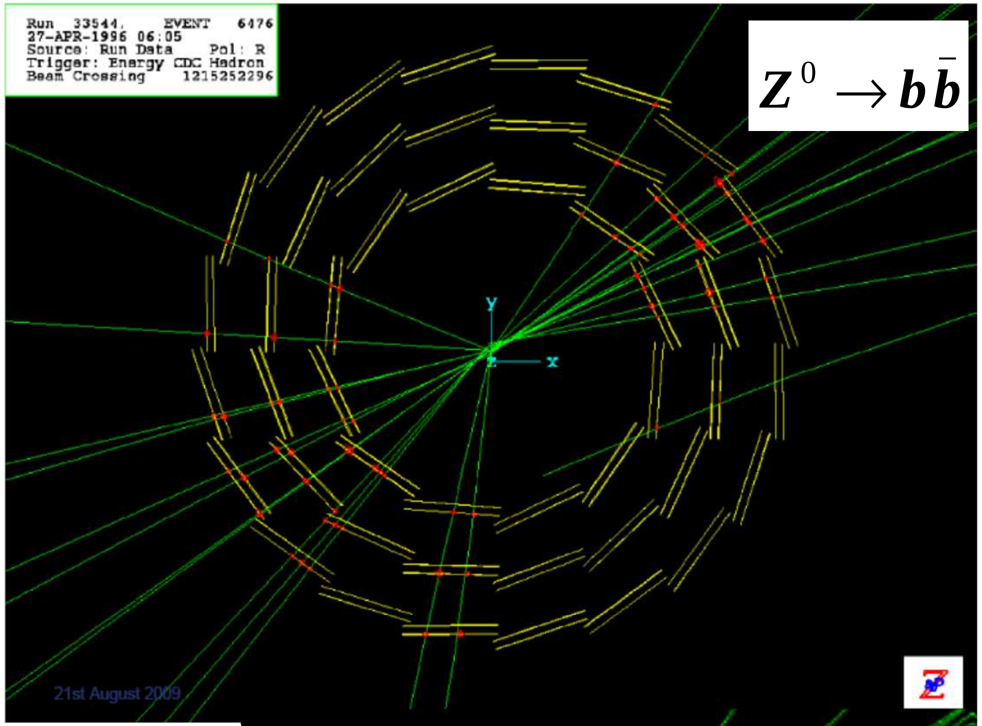
CCDs: VXD3 Vertex Detector for SLD@SLC

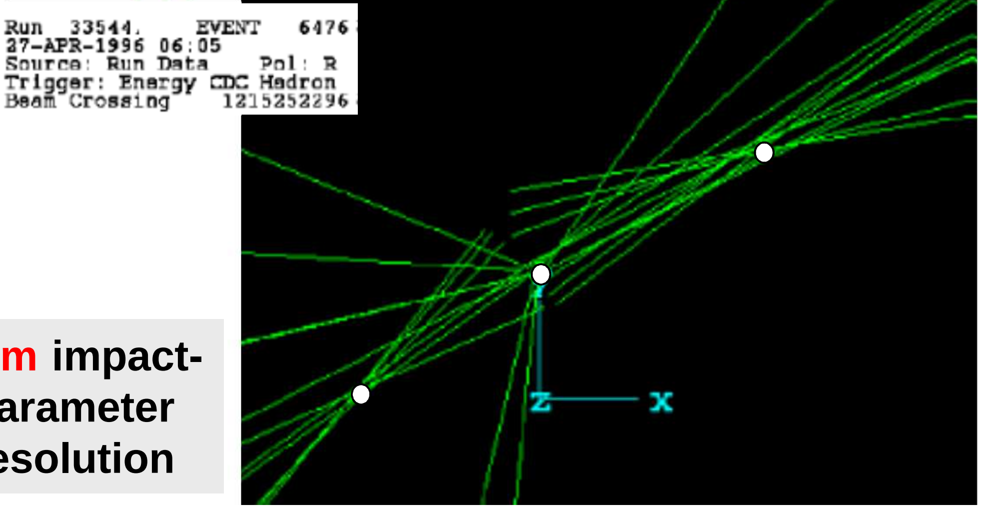
VXD3@SLD

- **installed in 1995**
- **307 MPixels (ATLAS: 80Mpixels !)**
- **0.4% X_0 (multiple scattering)**
- **1^{st} layer < 3cm from beam)**

By far most performing vertex detector in terms of resolution

→ reference point for ILC vertex detectors



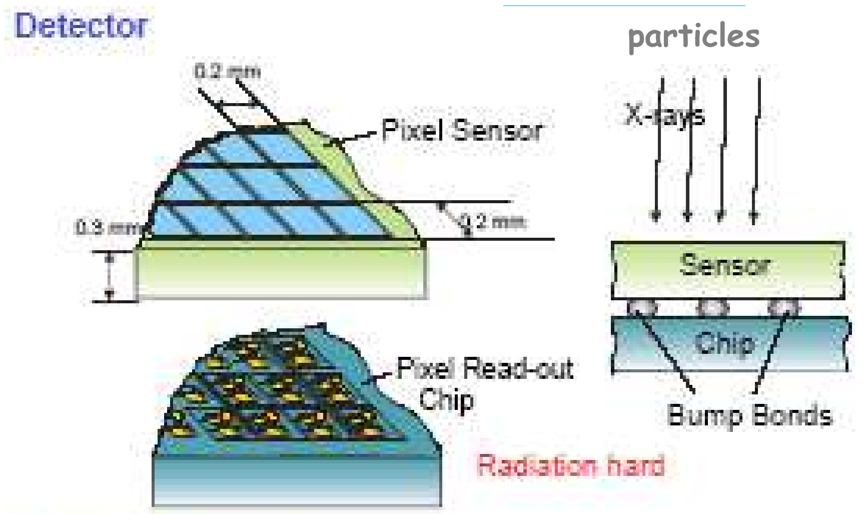


8 µm impact-parameter resolution

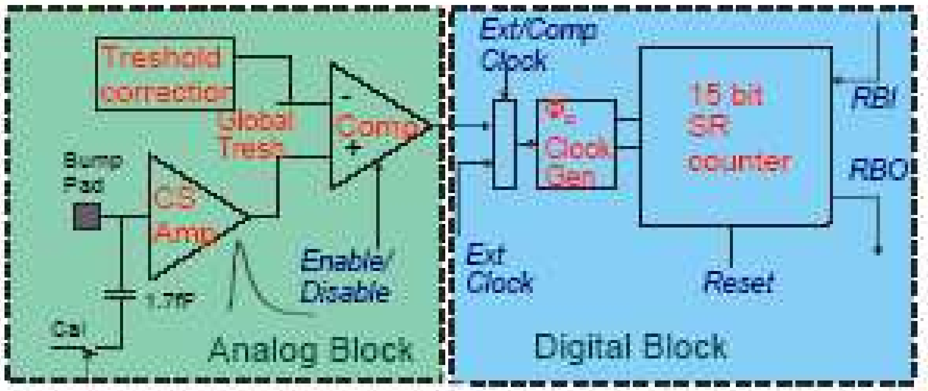
Hybrid Pixel Detectors

Idea: separate sensor and electronic → flexibility **but** additional material

Concept:



Pixel electronics (just one example)



Special features:

- **read-out chip directly mounted on top of detector by bump bonding**
- **every pixel has its own electronics**
- **technology for electronics and sensor can be chosen separately (eg high-Z sensor + Si readout; optimize for radiation hardness,...)**

Limitations:

- **amount of material for precision vertex detector (multiple scattering!) also power dissipation – cooling**
- **read-out speed and dynamic range (in particular for X-ray science)**

Hep experiments using hybrid pixels

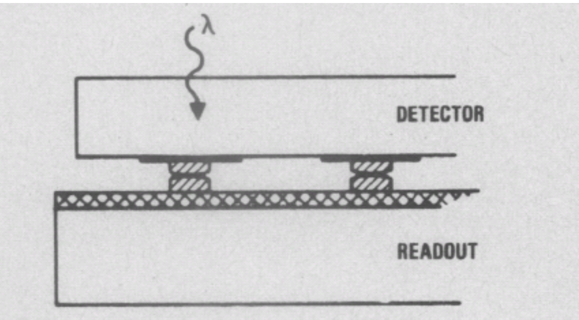
(for LHC-expts. before phase I upgrade):

- **CMS (66 Mpixels of 150×100 μm^2)**
- **ATLAS (80 Mpixels of 40×400 μm^2)**
- **ALICE, PHENIX (BNL), FAIR-expts. (PANDA, CBM, ...) ...**

Early Hybrid Pixel Detector for X-rays

First Ge pixel detector in **1961**
G. Dearnaley

S.Gaalema at 1984 IEEE-NSS



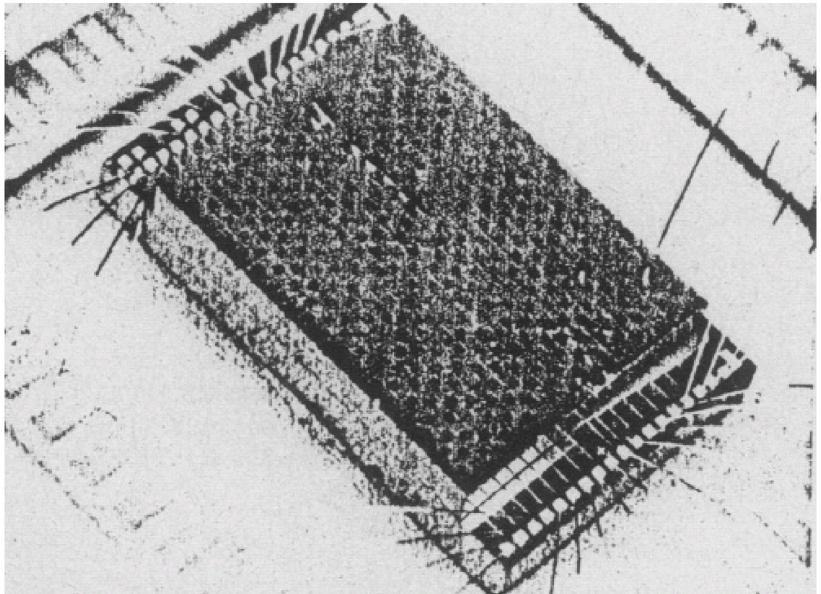
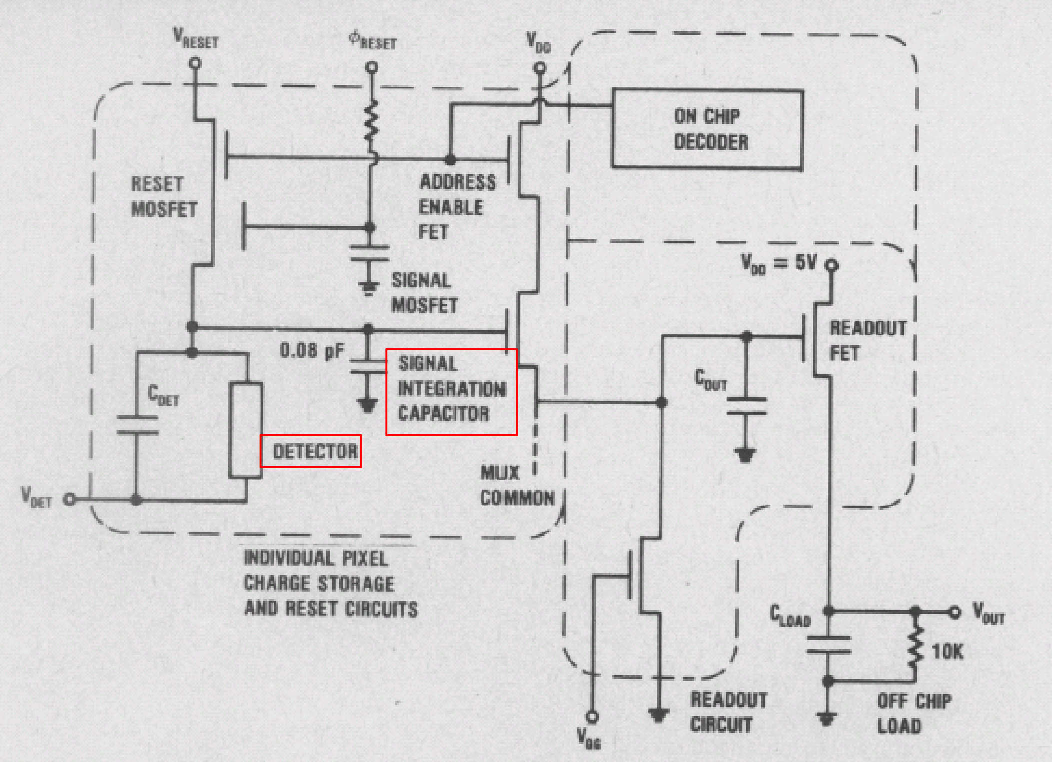


Fig. 2. Typical planar hybrid sensor chips



Performance:
- **600×600 pixels (20 μm)²**
- **50 e (rms) noise**
- **random access to every pixel**
- **average power 1 μW/pixel (for 1kHz readout)**

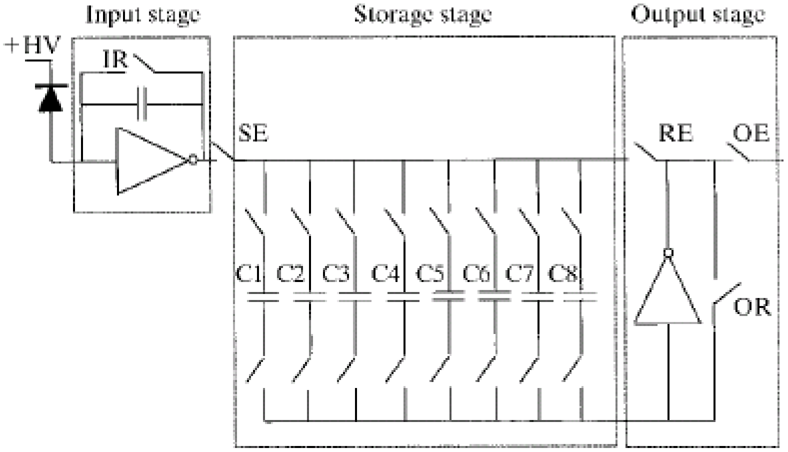
was used to read out Si and Ge detectors

S.Gaalema IEEE Trans. NS-32, No.1(1985) 417

Charge Integrating Hybrid Pixel Detector for X-rays

Task: Fast time resolved imaging with **µs frame rate** → counting not an option
→ **integrating readout**

Single pixel readout architecture (group S. Gruner)



Specifications and performance:

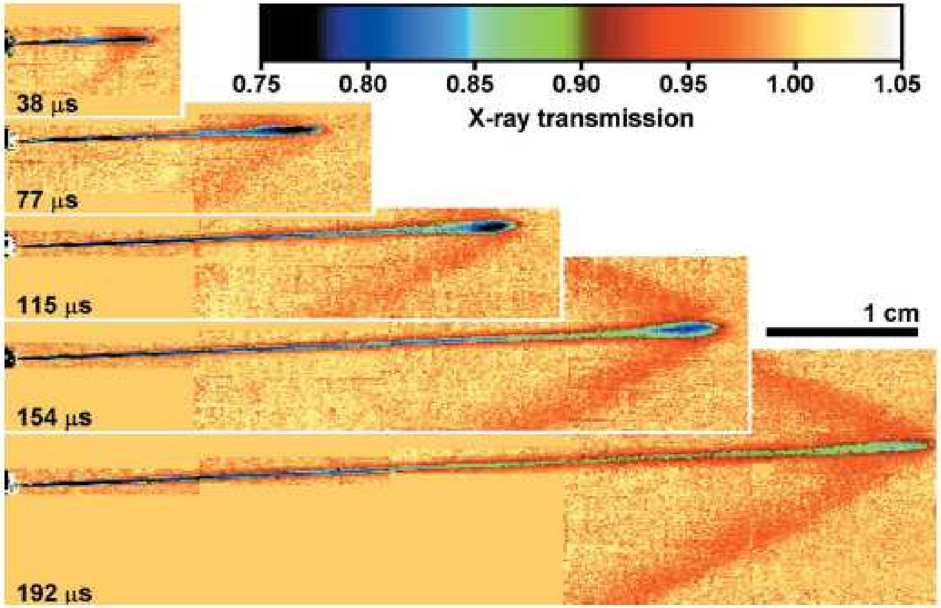
- **Si: 92×100 pixels, (150 µm)^2; 300 µm thick**
- **8 storage cells; min. integration time 1 µs**
- **capacity: 17,000 8.9keV X-rays**
- **non-linearity <0.2% (full range)**
- **noise: ~20 keV (X-rays)**
- **1.2µm HP process; GEC-Marconi bump bond**
- **100 µW power/pixel**
- **limited radiation hardness**

G.Rossi et al J.Synchr.Rad 6(1999)1096

Application:

µs time-resolved x-ray radiography of multi-phase, direct-injection gasoline fuel spray

→ Verify fluid dynamics simulations



Supersonic jet of Diesel fuel spray in 1atm SF$_6$

- **image area (61.7×7.5) mm^2 [built-up from images (13.5×2.5) mm^2]**
- **shockwave: increase in gas density ~15%**

MacPhee et al., Science 295(2002)1261

X-ray Counting Hybrid Pixel Detector(s)

Several examples: **Medipix1, Medipix2, Medipix3, PILATUS1, PILATUS2, ADSC,…**

development chains → continuous improvements + profit from technology advance

Example: PILATUS (PSI) - specifications and performance:

- **pixelsize: (172 μm)^2**
- **max. rate: 1.5 MHz/pixel**
- **dynamic range: 20 bits (1,048,576) no noise !**
- **read-out time: 5 ms**
- **frame rate: 10-100 Hz**

1stgeneration PILATUS module

This image cannot currently be displayed.

B.Henrich et al.,
NIM-A607(2009)247

1stgeneration PILATUS 1M

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PILATUS 6M

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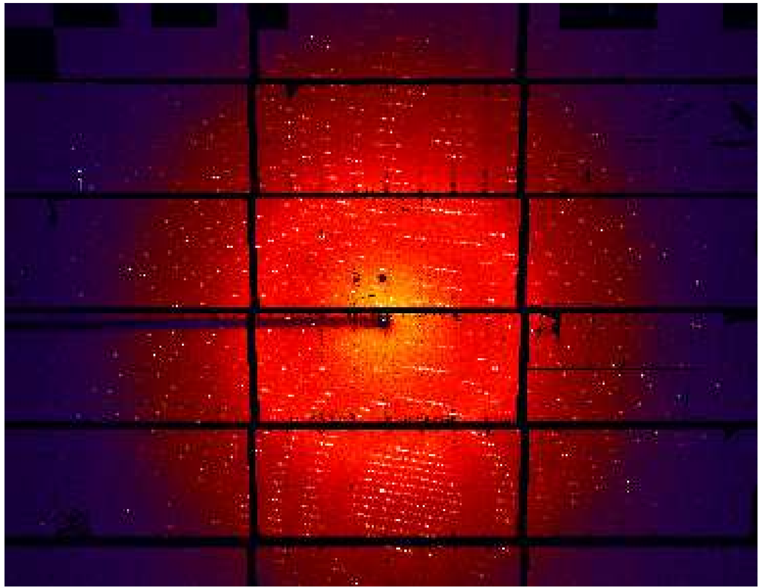
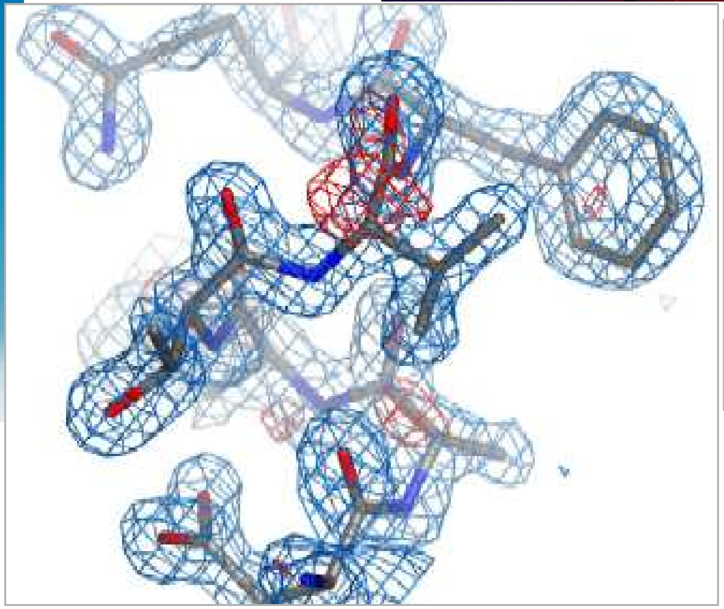
X-ray Counting Hybrid Pixel Detector(s)

Example of an early measurement with PILATUS1





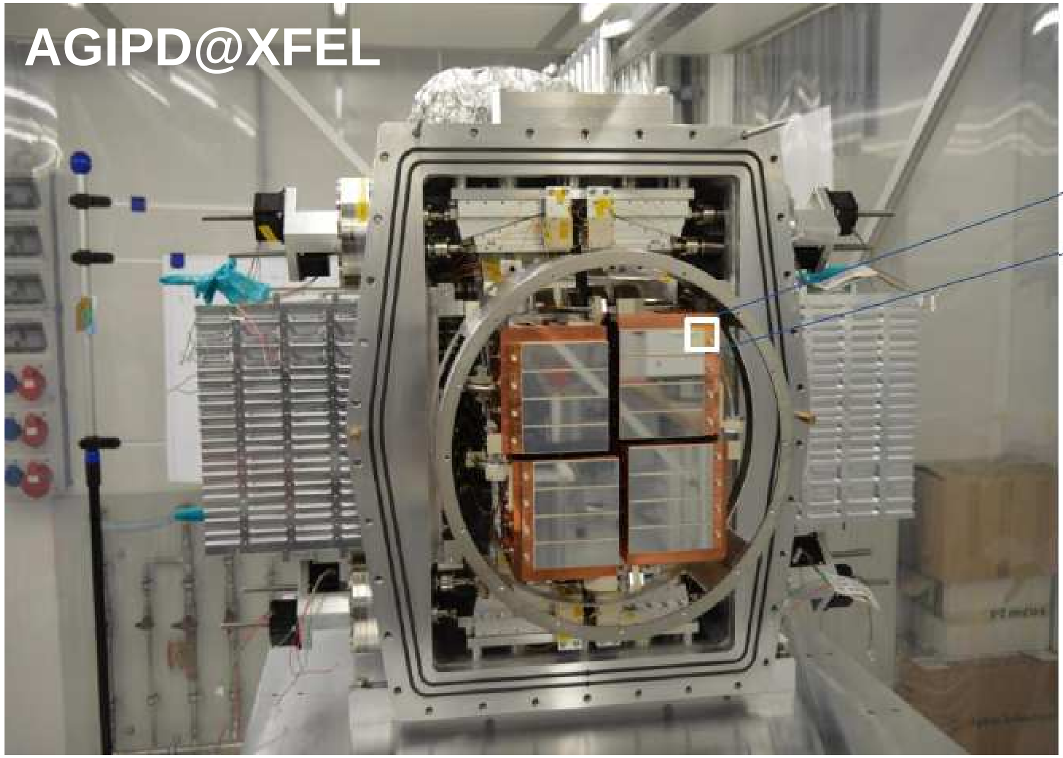
Electron density map of Thaumatin

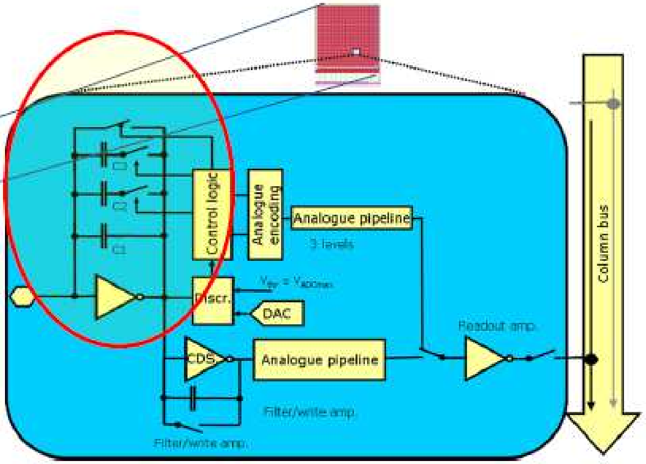
C. Brönnimann et al., J.Sync.Rad.13(2006)120

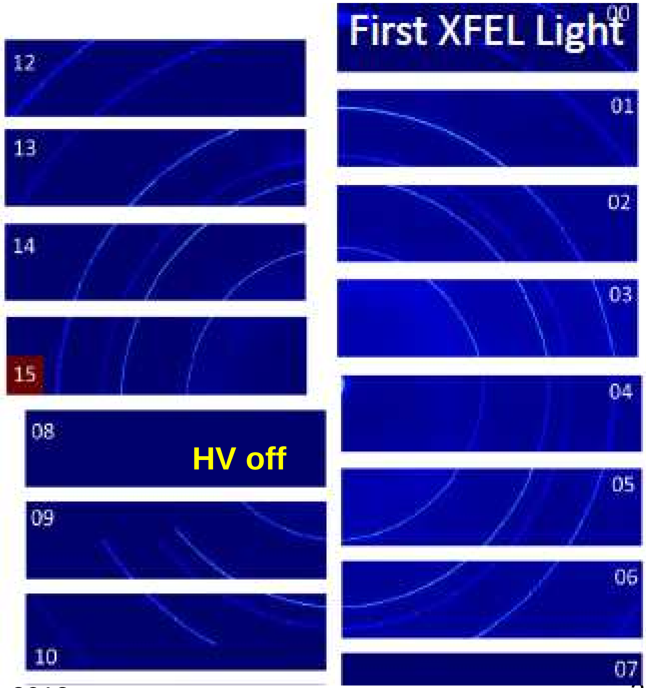
Swiss Economic Award to

DECTRIS

X-ray imaging pixel detectors



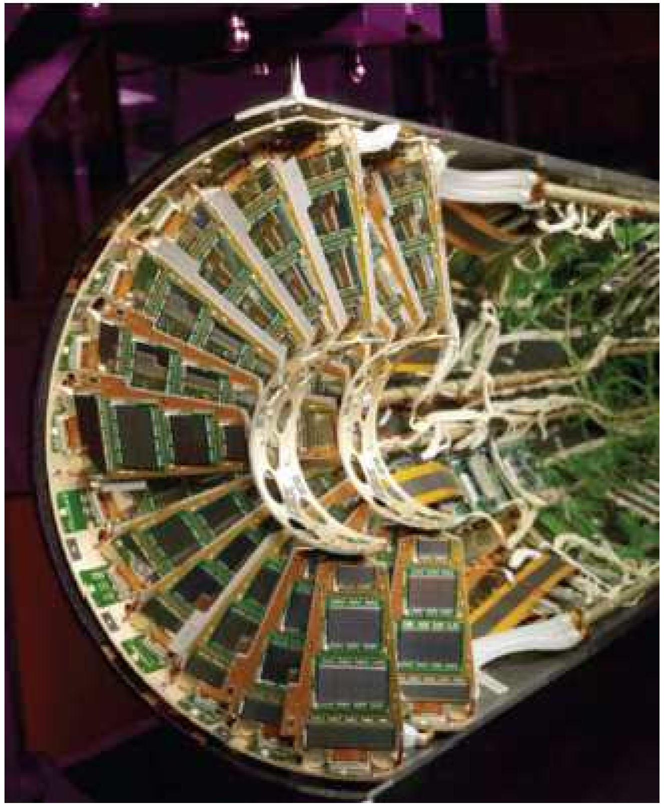




AGIPD = Adaptive Gain Integrating Photon Detector

- 500 µm thick, 200x200 µm^2 hybrid pixel detector
- Sensor designed to work at 900 V up to 1 GGy dose
- XFEL: distance between bunches 220 ns every 100 ms
- Storage of ~350 images
- Dynamic range: 1 → 10^4 ~12 keV photons by “adaptive gain switching”
- Installed and working @ XFEL

Pixel Detectors in hep

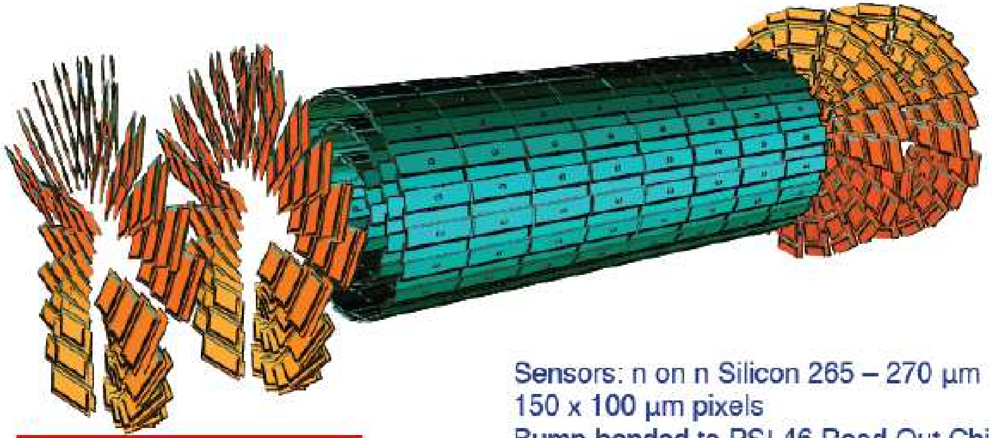


Hybrid-Pixels in use in hep since 1995 **needs micro-electronics because of large no. of channels !**

- **pioneered in fixed target heavy ion expts. at CERN**
- **e^+e^- colliders (DELPHI)**
- **pp- and ion-collider; in particular ATLAS,CMS,ALICE**

CMS Pixel Detector: 124 Mio. pixels

- **4 barrel layers**
- **2 forward disks**



Sensors: n on n Silicon 265 – 270 µm
150 x 100 µm pixels
Bump-bonded to PSI 46 Read Out Chips

Total Area: 0.78+0.28 m²
66 Million Pixels

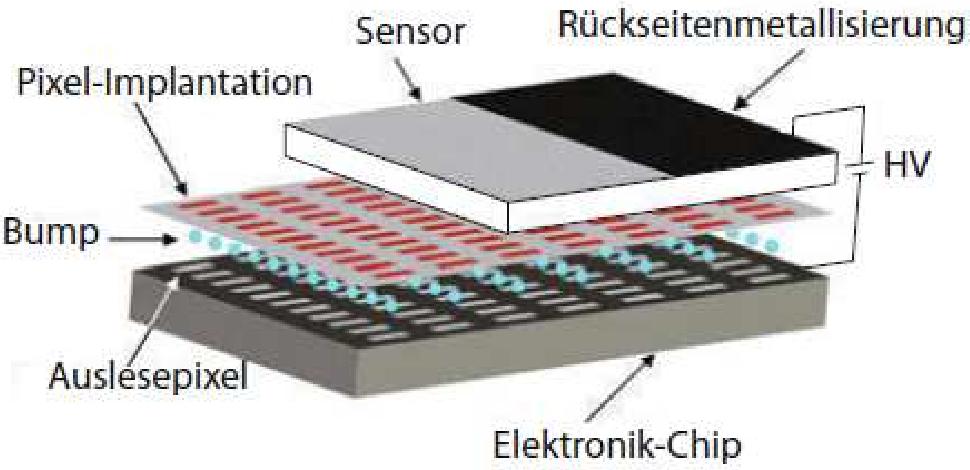
Before phase I upgrade

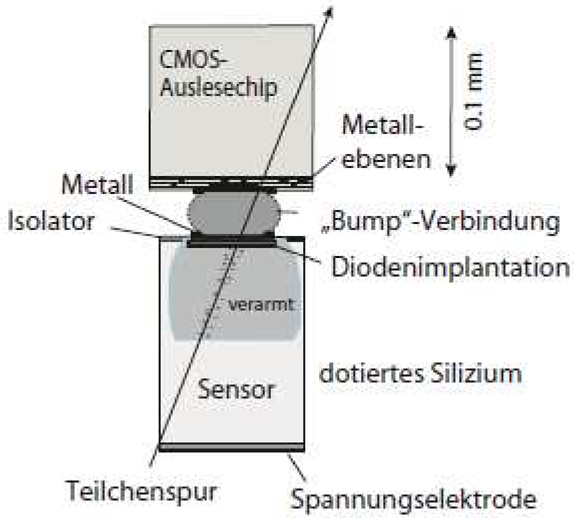
Performance from data: **position resolution $\sigma_x = (12.8 \pm 0.9)$ µm; $\sigma_y = (32.2 \pm 1.4)$ µm**

→ design specifications achieved
→ highly efficient b-tagging / secondary vertex recognition in complex environment
→ essential tool to search for New Physics at the LHC

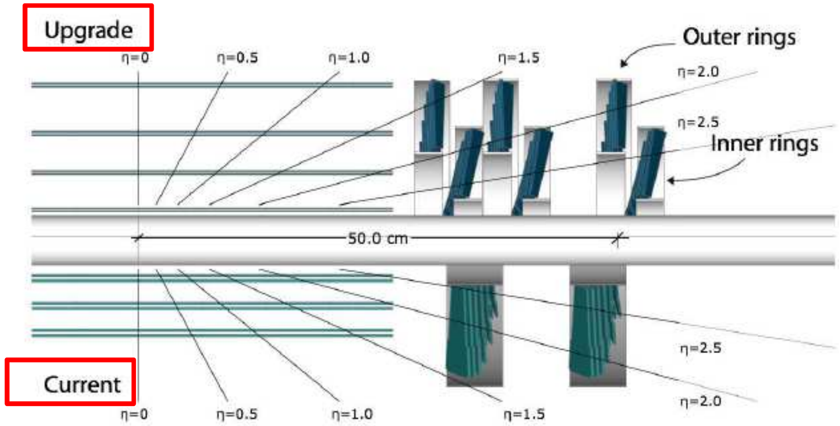
Pixel Detectors in hep

Principle of hybrid pixel detector:





Example: Phase I upgrade CMS Si-pixel detector



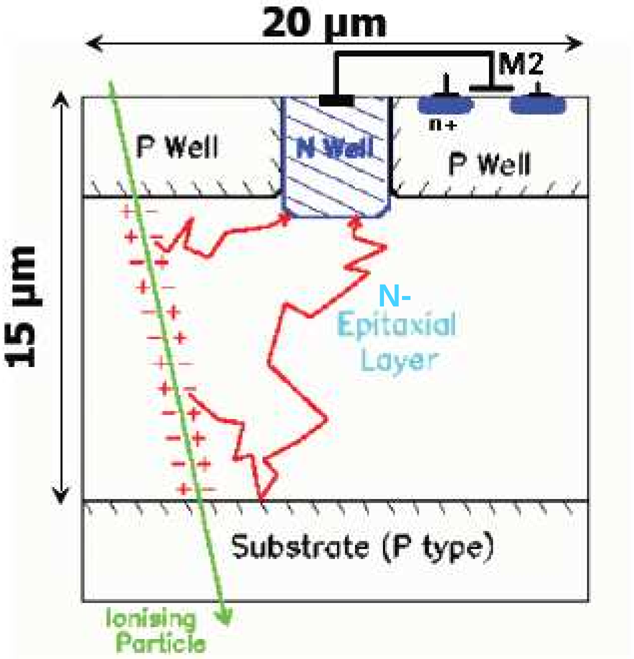
BPIX: 48 → 79 Mpixels **BPIX: 18 → 45 Mpixels**

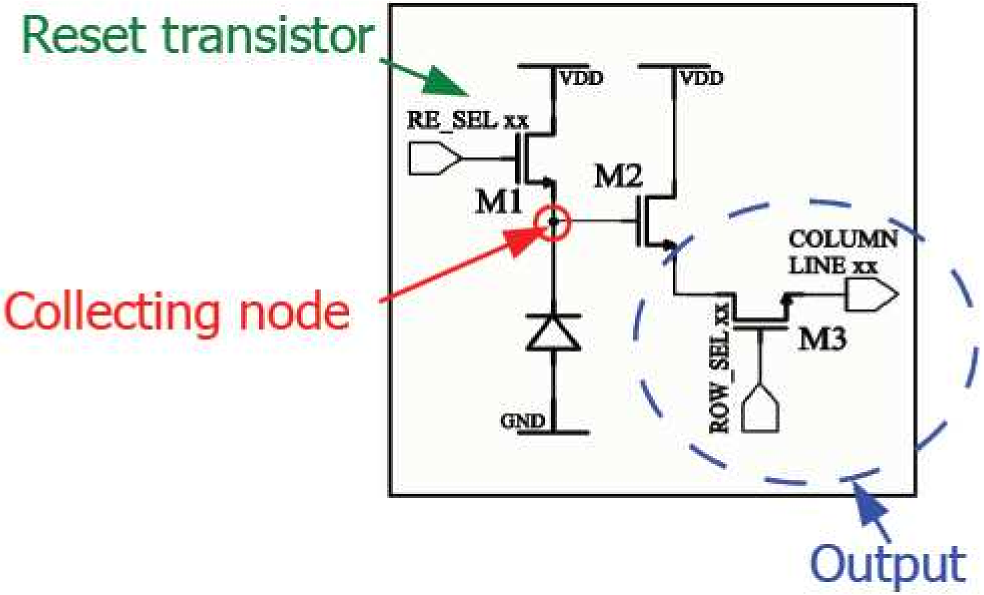
MAPS: Monolithic Active Pixels

For hep: inactive material + sensor thickness → interactions + multiple scattering → degradation of performance (in particular for e^+e^-)

→ monolithic sensor - readout and thinning of substrate

Example: CMOS-MAPS (R.Turchetta et al., NIM-A 458(2001)677)





Outstanding features:

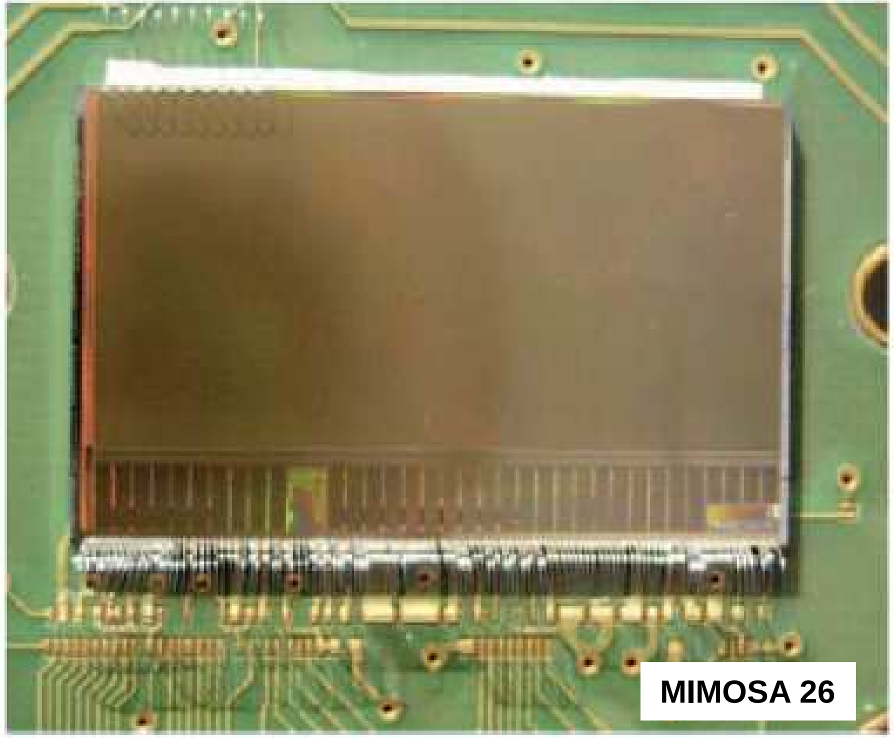
- standard VLSI technology
- small (>10 µm) pixels
- low power
- low noise (5e rms)
- thinned down to 50 µm
- random access

problem: readout time

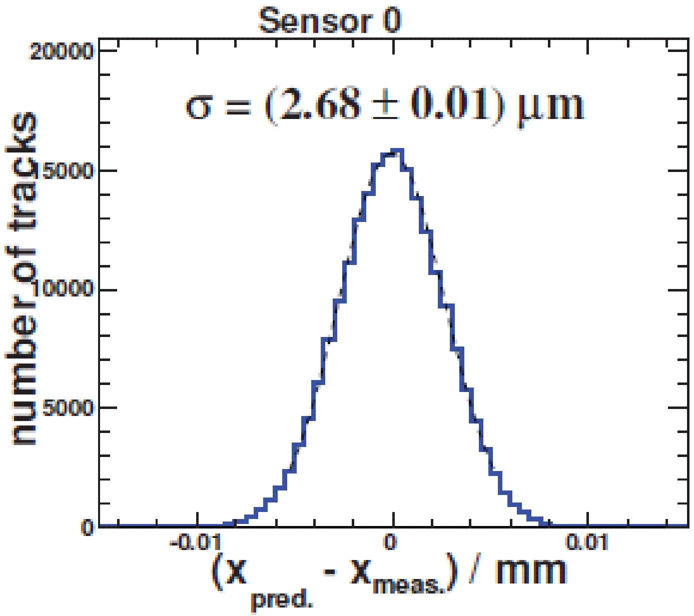
MAPS: Monolithic Active Pixels

State of the art: MIMOSA-26 (EUDET-telescope in DESY test beam)

- **0.35 µm CMOS OPTO process**
- **572×1152 pixels of (18.4 µm)^2 → 10mm×21mm**
- **80 MHz read-out: zero suppressed, binary with data sparsification →**
  reduction of data volume by factor 10 – 1000 (depending on occupancy)
- **112 µs integration time**



position resolution (CERN beam test)
Δx ~ Δy ~ 2.7 µm

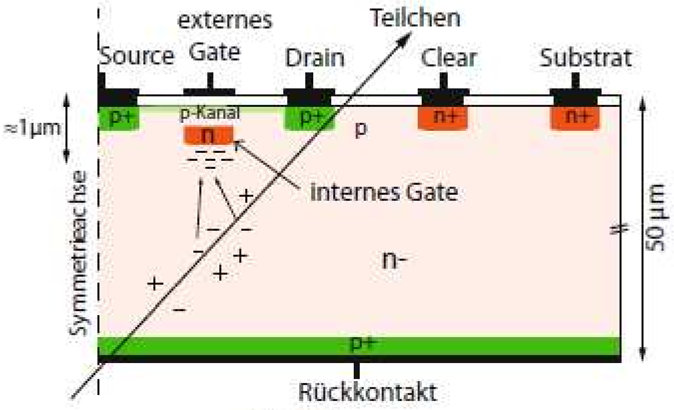


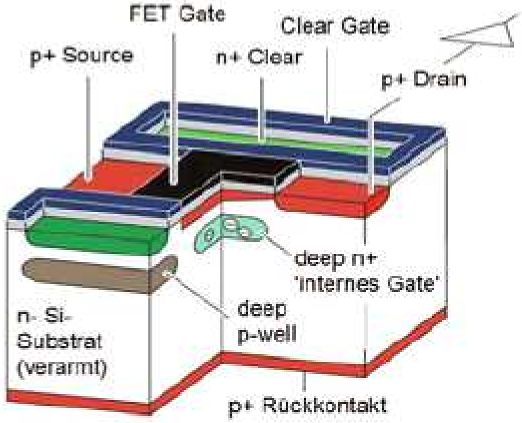
E.Corin, IEEE NS-Conf. N13-118 (2009)816

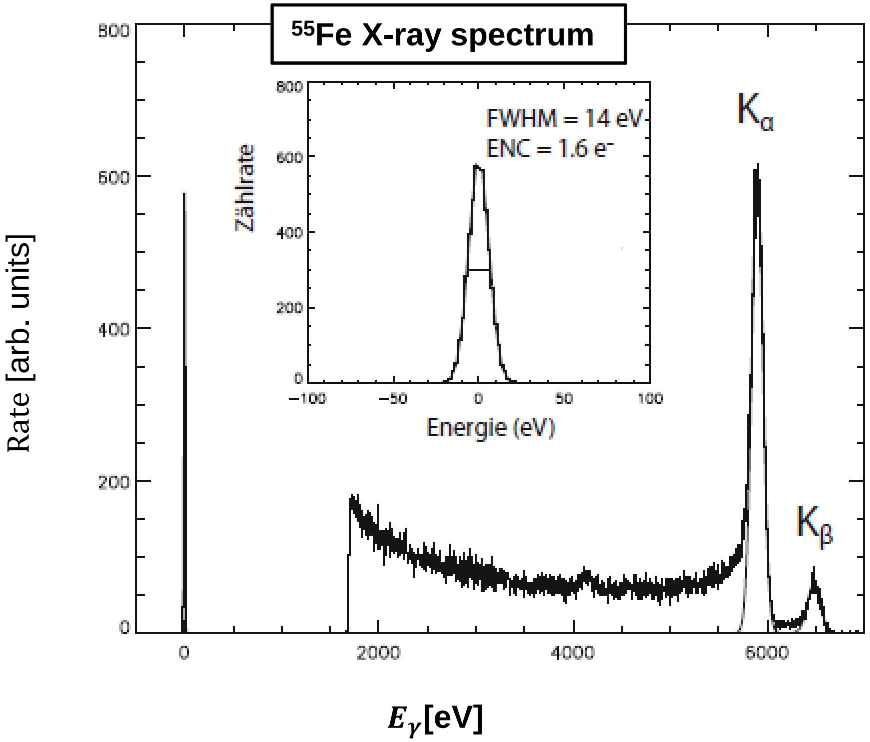
DEPFET pixel sensor

Invented by J.Kemmer and G.Lutz in 1988

- **Charge collected on internal gate → change of internal gate (IG) voltage → change of I_{DS}**
- **Typical values: $g_q = \frac{dI_{DS}}{dq_{IG}} = 400 - 500\ pA/q_0$**
- **Small C_{IG}→ low noise: $1-2\ e$ (µs filter times)**
- **Further noise reduction by multiple reading**



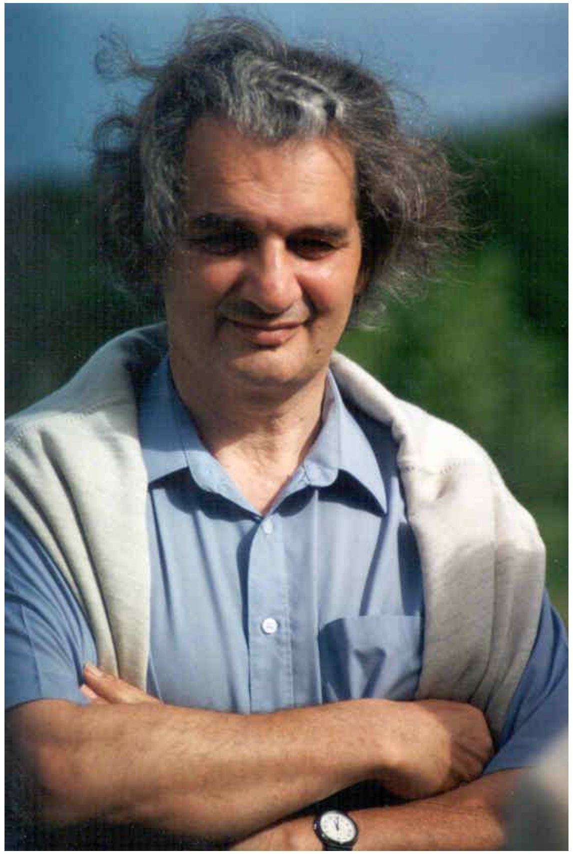



^{55}Fe X-ray spectrum

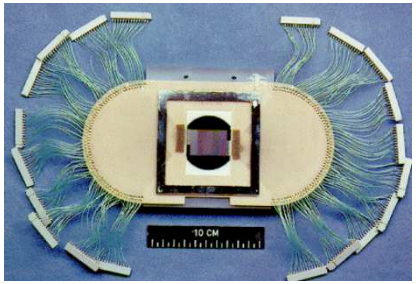
DEPFET: World-record in X-ray resolution at ~ room temperature; used in BELLE II @ SuperKEKB sensors thinned to 75 µm; and X-ray astronomy

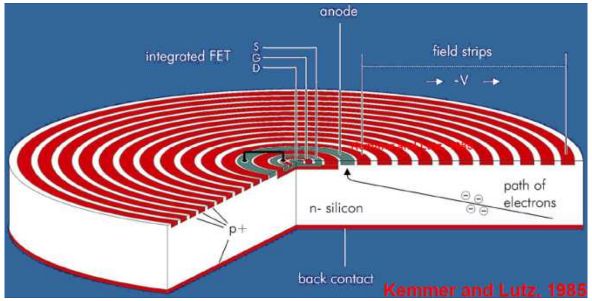
Gerhard Lutz

An outstanding scientist with a clear vision and highly original ideas

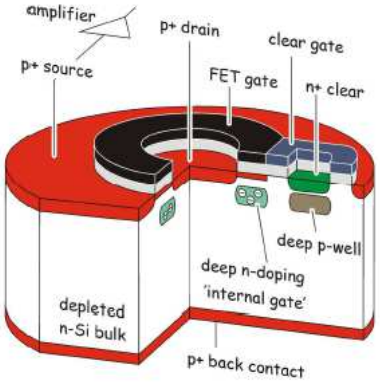


A pioneer and inventor of many Si devices

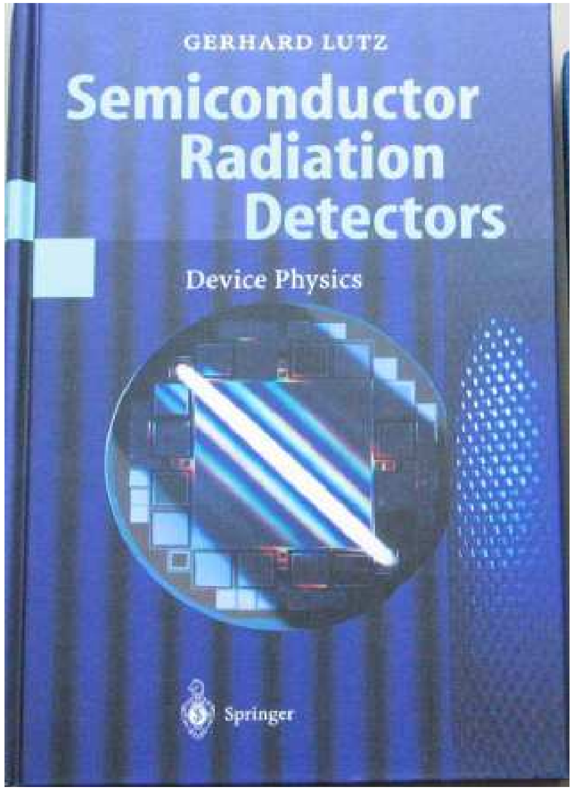




Kemmer and Lutz, 1985



An influential mentor of many junior scientists



GERHARD LUTZ

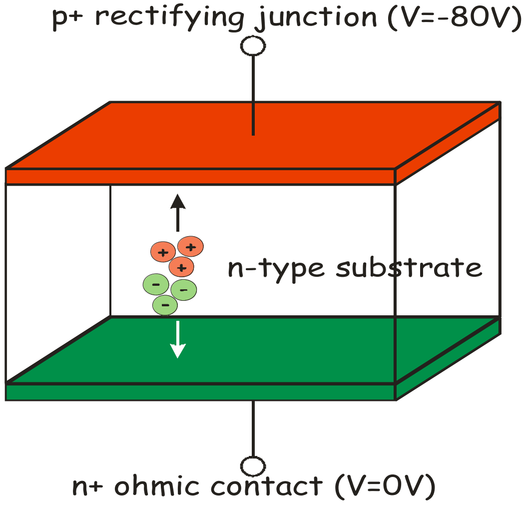
Semiconductor Radiation Detectors

Device Physics

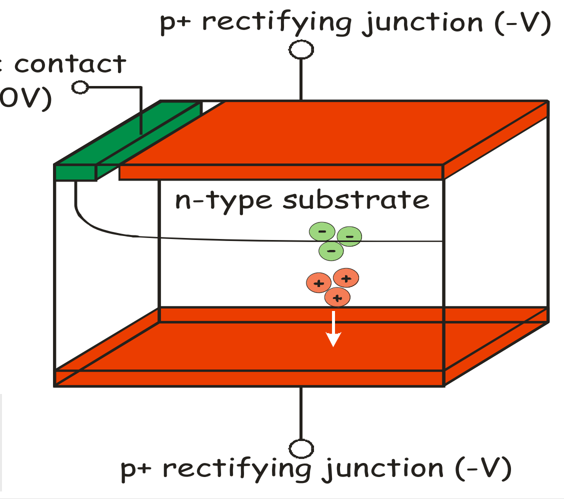
Springer

Drift Detectors: The Principle of Sideward Depletion

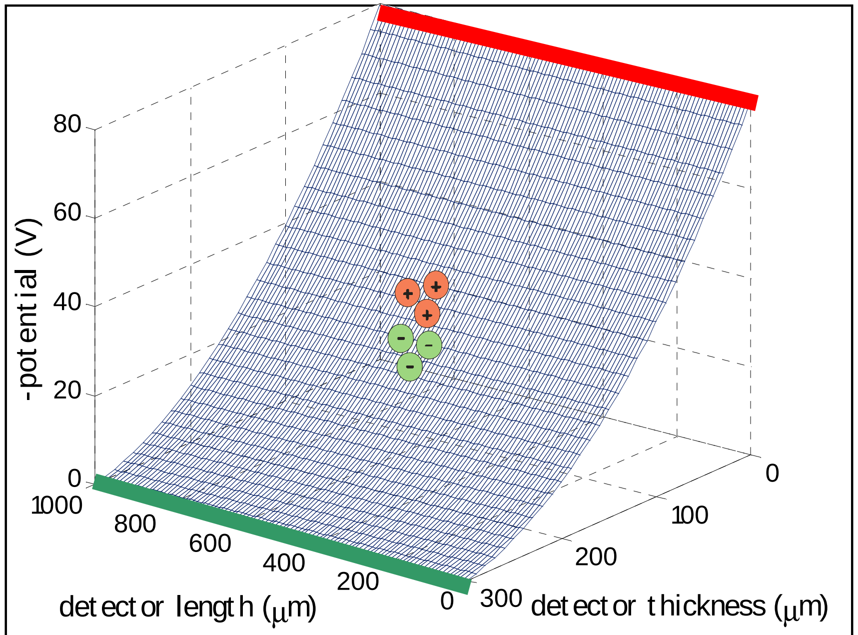
planar pad diode

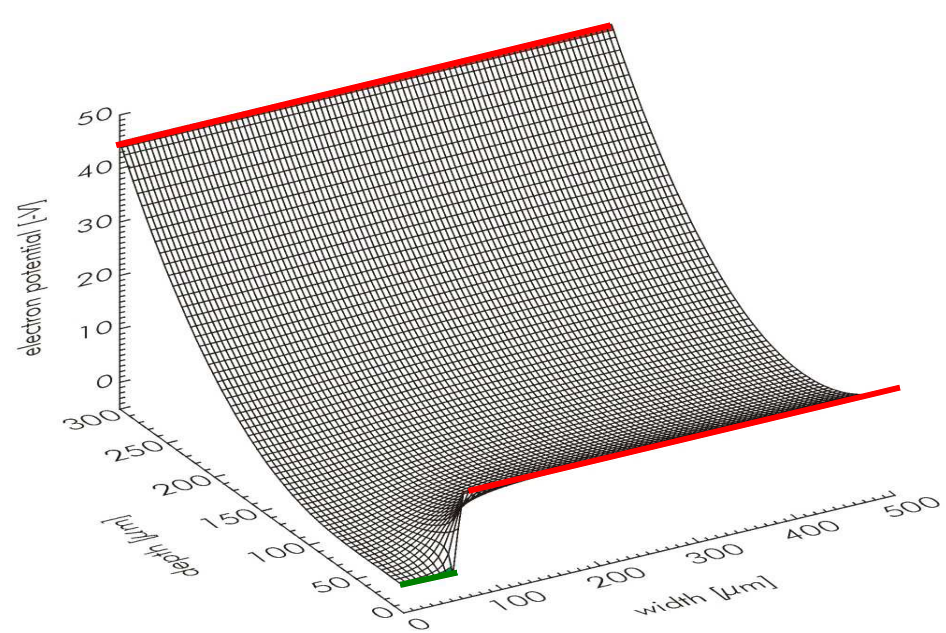


sideward depletion



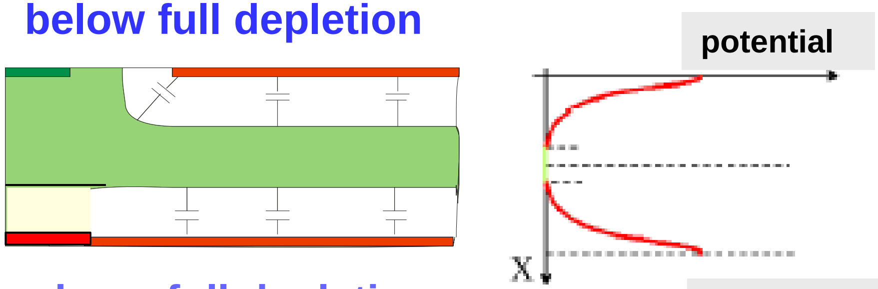
E.Gatti, P.Rehak
NIMA226(1984)608



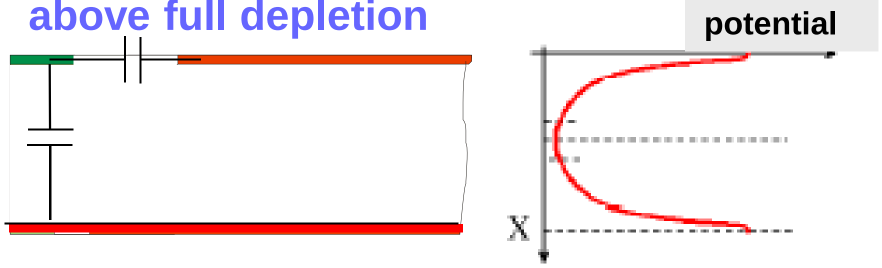


Principle of Sideward Depletion

below full depletion



above full depletion



impact on anode capacitance

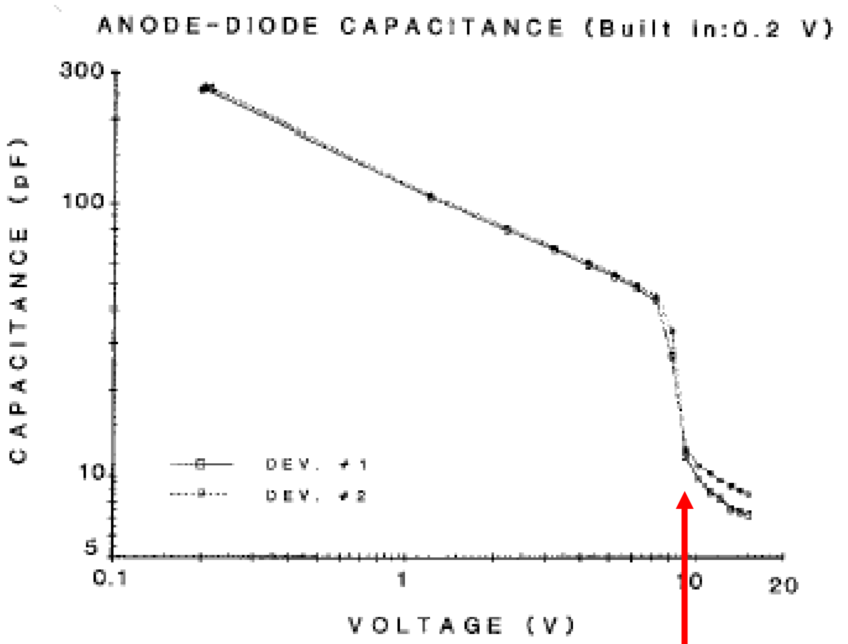


Fig. 12. Capacitance versus voltage plots of two of the test devices provided on the wafer for monitoring its doping uniformity.

P.Rehak et al.,NIMA235(1985)224

full depletion

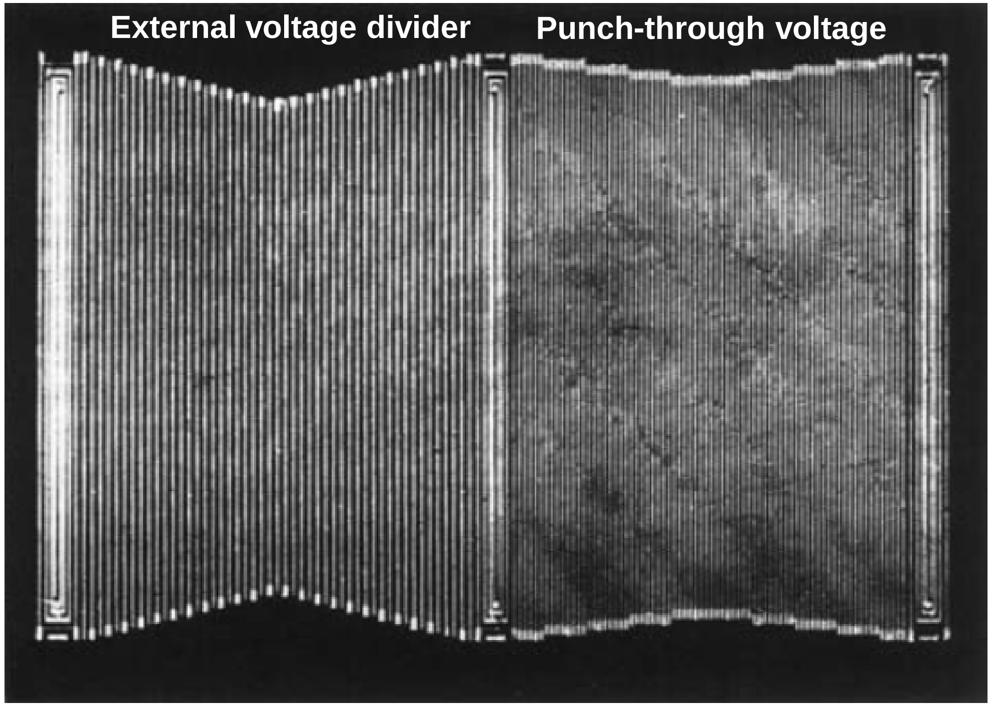
- below full depletion:
  parallel plates
  → C ~ area
- above full depletion:
  - line (or point) - plate
  → C ~ ln(area)

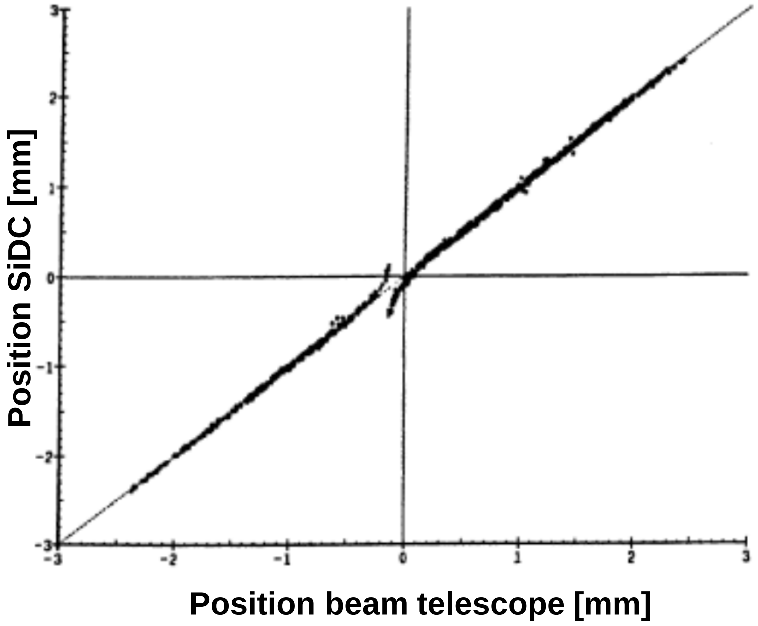
→ collect charge from a large area with minimal capacitance

→ **large area low noise detectors feasible**

Si Drift Detector as 2-D Tracking Detector

Prototype Si-drift chamber SDD built by J. Kemmer (TUM) + MPI – Test in NA32-Expt.

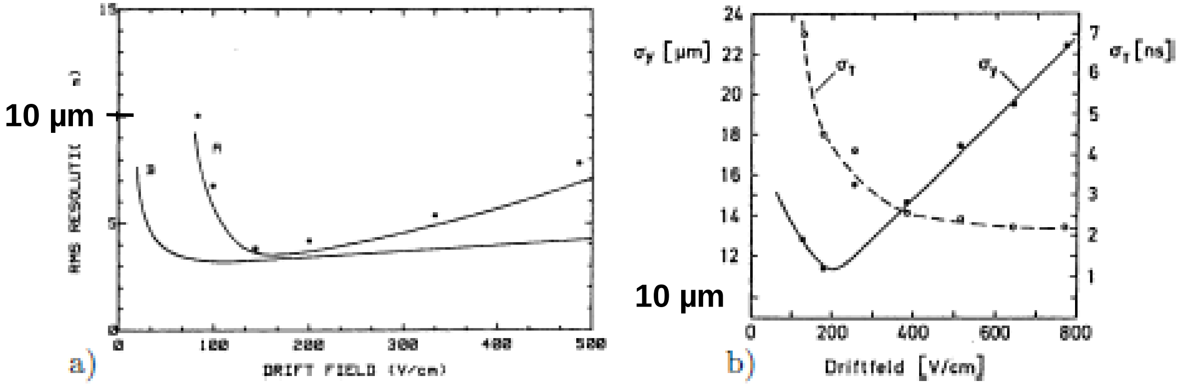




Resolution vs. drift field

Test with laser

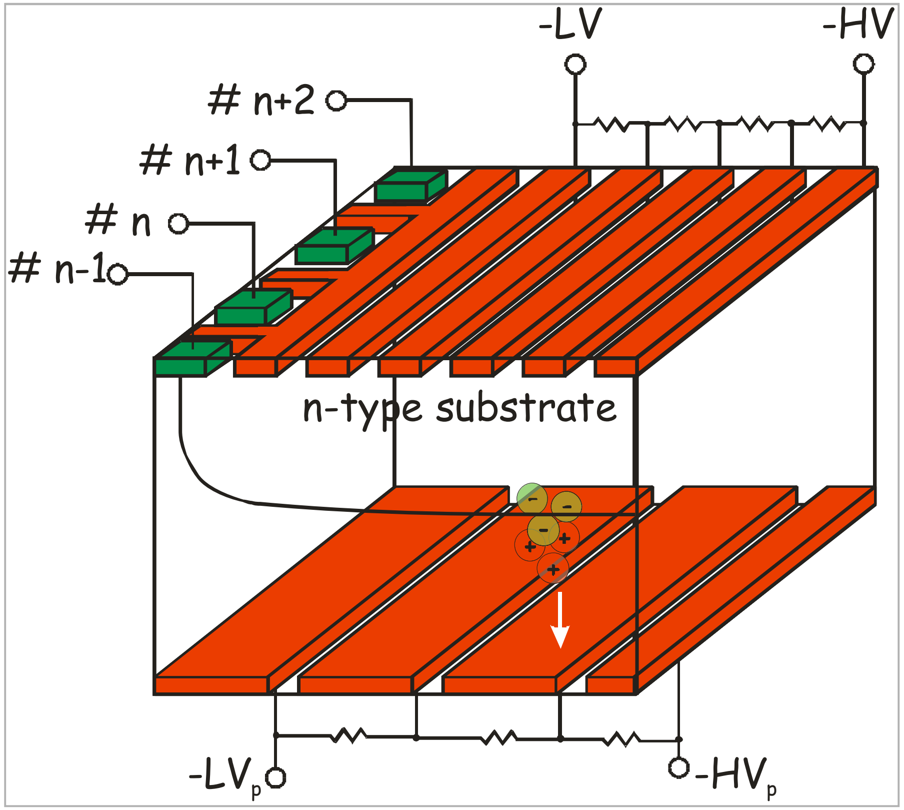
Beam Test

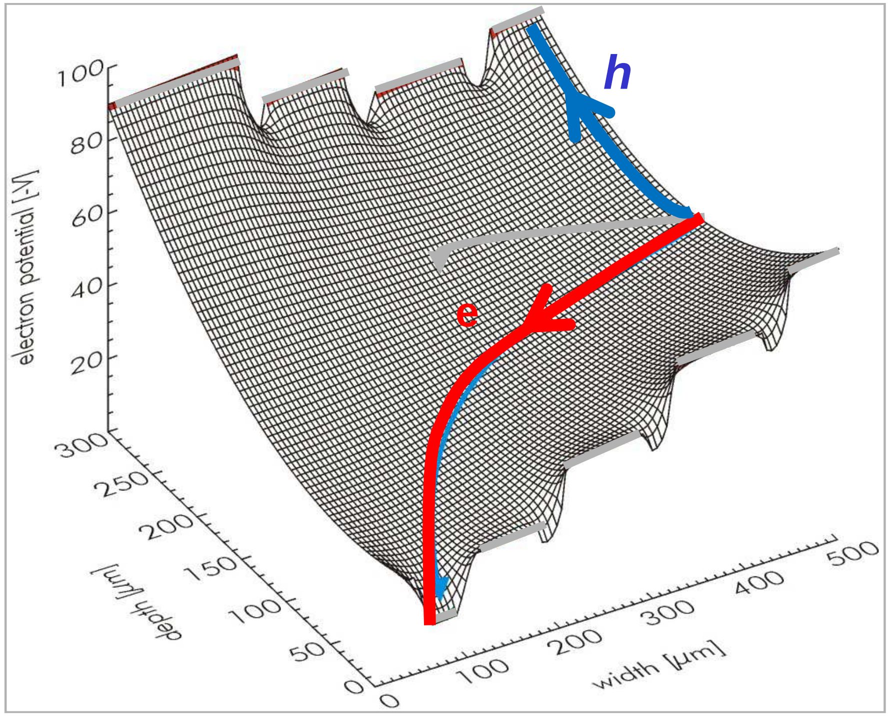


First SDD achieved already 10 µm for minimum-ionising particles → used only in a few experiments

Si Drift Detector as 2-D Tracking Detector

- Cathode strips → drift field
- segmented anode → transverse position – time-of-flight → longitudinal pos.



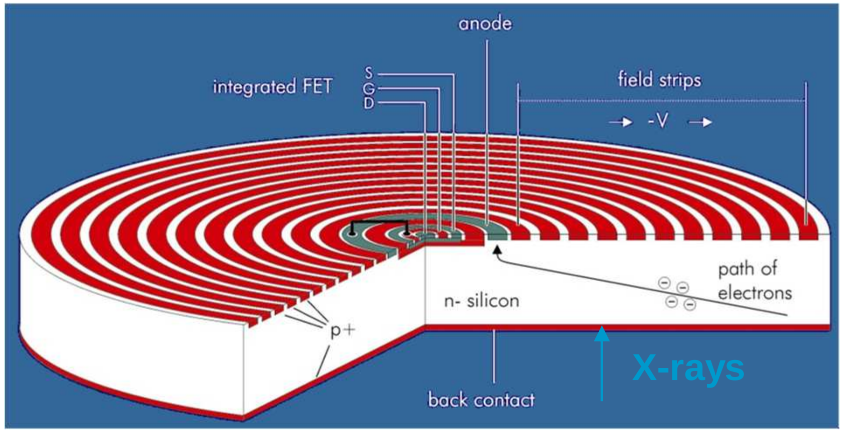


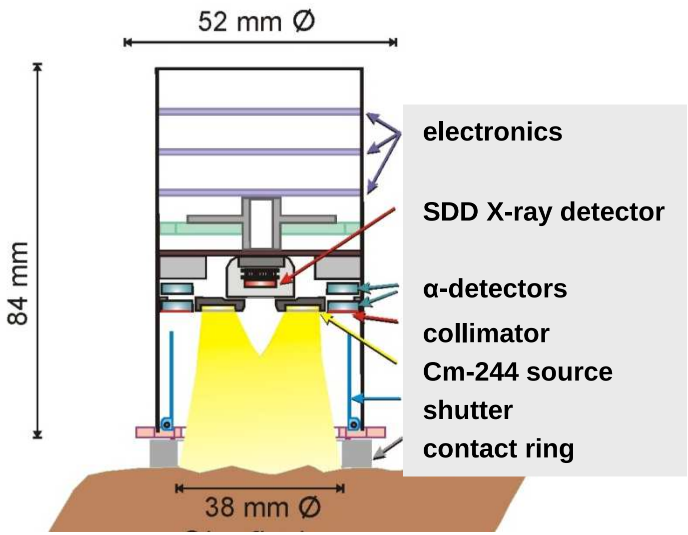
potential (near the anode)…

achieved performance: 2 mm in lab (laser light)
10 mm in test beam
18 mm in actual experiment

Emilio Gatti and Pavel Rehak: Silicon Drift Detector SDD

SDD with integrated JFET→ Low Noise X-ray Detector





electronics

SDD X-ray detector

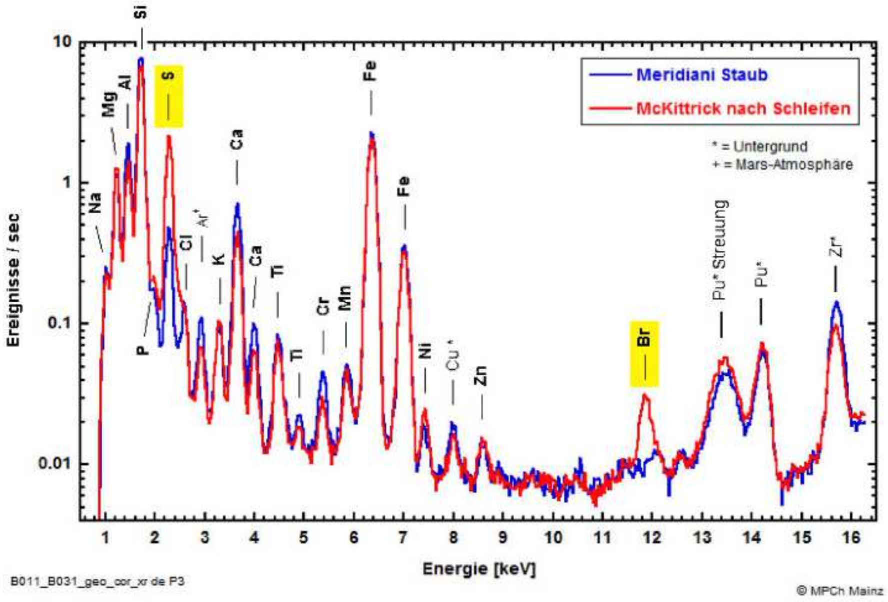
α-detectors

collimator

Cm-244 source

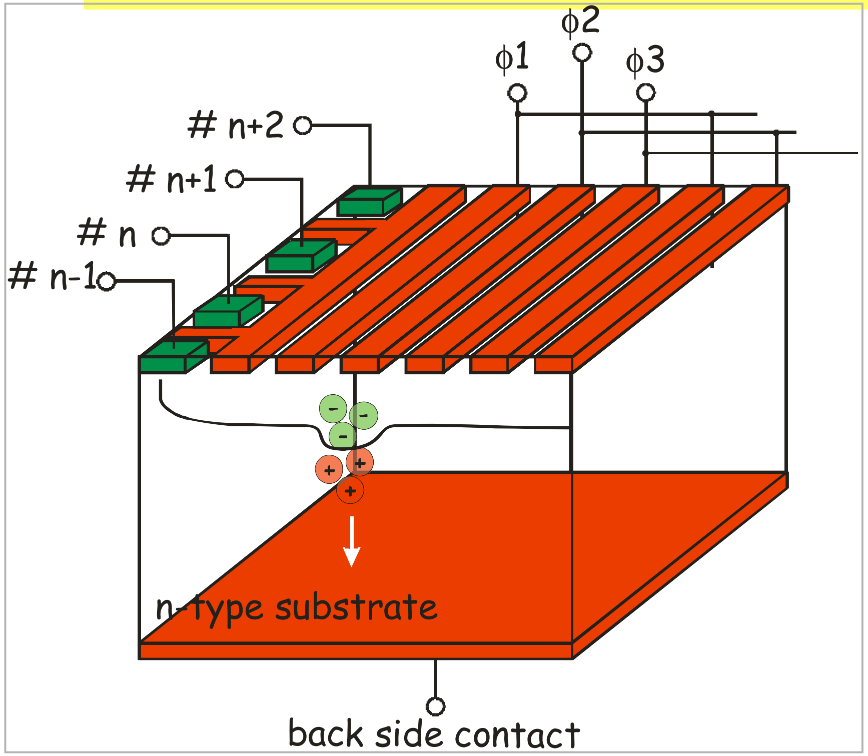
shutter

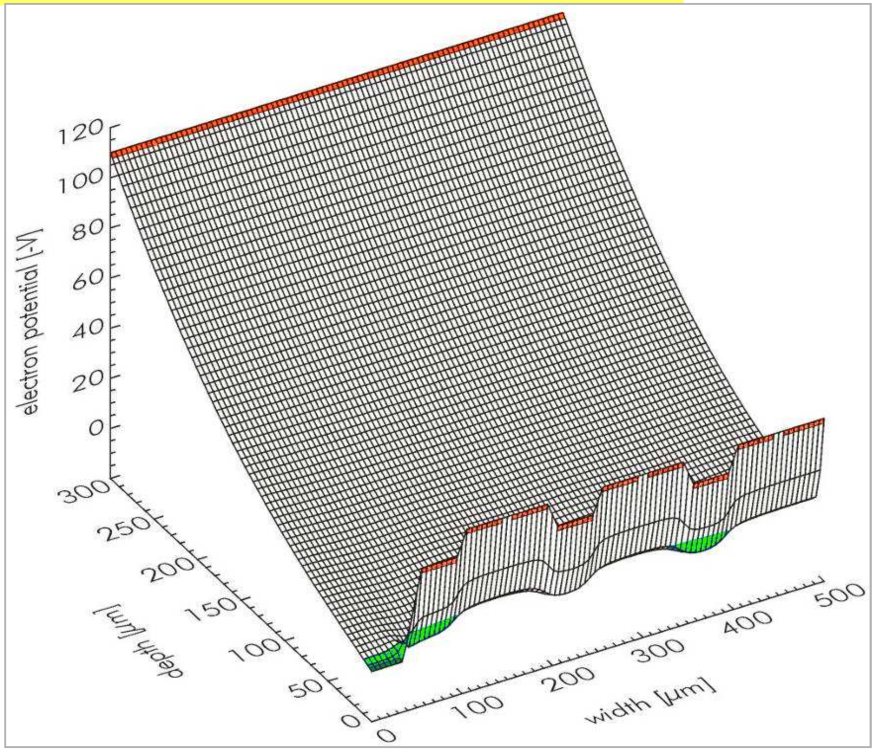
contact ring



L.Strüder,IEEE-NSS Rome 2004,
R.Rieder, MPI für Chemie, Mainz

Fully Depleted pn-CCD (eg EPIC on XMM-N, CAMP,...)





- charge from entire thickness collected and stored in potential trough (below F_2)
- by modulating potentials F_i → transfer charges until they reach read-out electrode(s)
- channel stops prevent that charges spill to neighbouring rows (e.g. from n → n±1)

→ high quantum efficiency for X-rays due to full depletion (CMOS CCDs ~ 20 mm thick !)

→ backside illumination allows for thin entrance window (min. detectable X-ray energy !)

→ high transfer efficiency (uniform response)

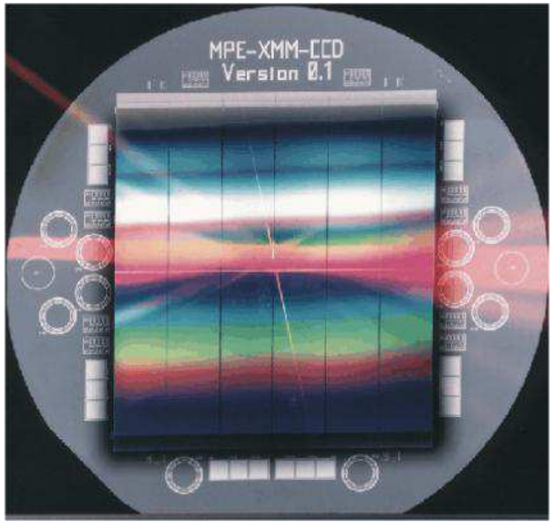
→ pixel size down to ~30 µm

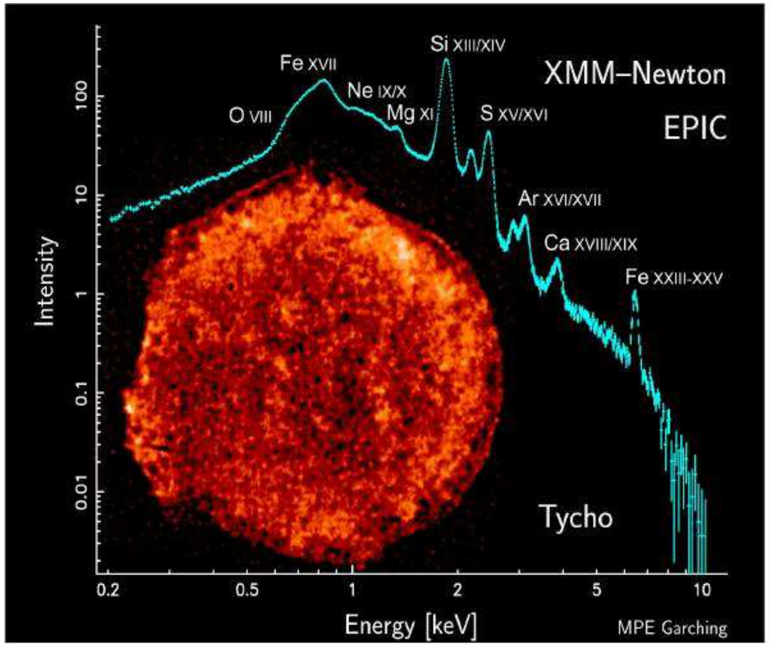
→ good radiation hardness because of pn junctions (no potential steering through oxide)

pn CCDs in Heaven

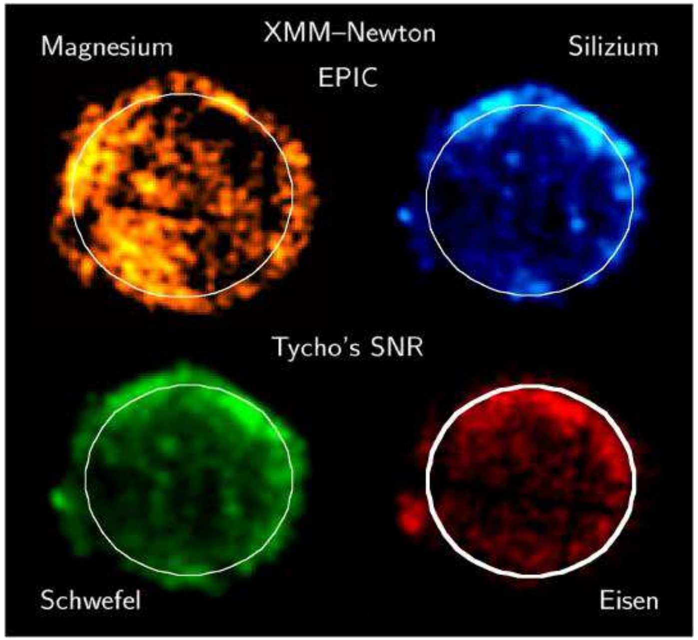
XMM-Newton satellite

pn-CCD





elemental analysis of TYCHO supernova remnant:



L. Strüder, IEEE-NSS 2004

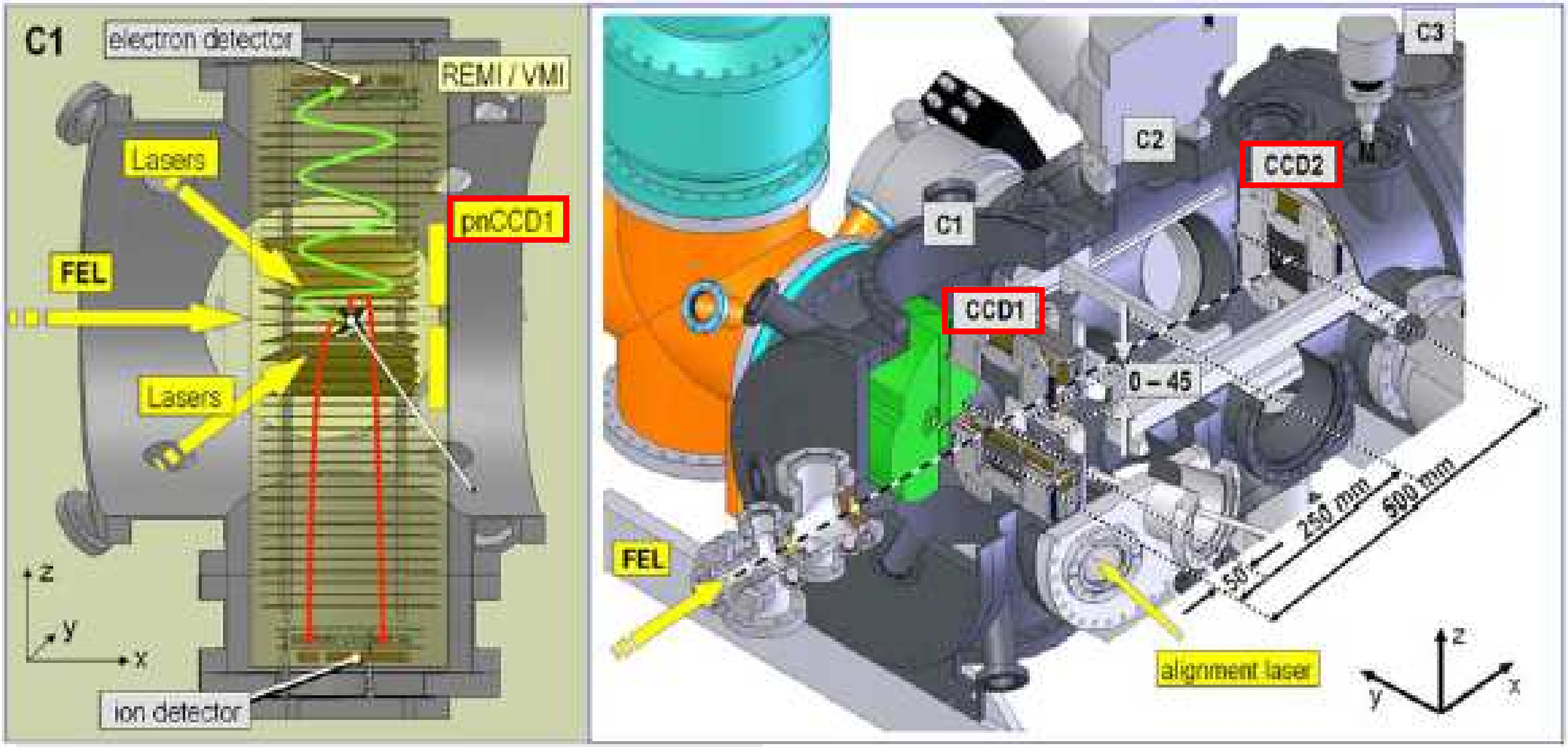
Detectors at the LCLS and other FELs

Experiments at FELs → unprecedented requirements for detectors:

- energy resolution and dynamic range (0 →10^5 photons)
- segmentation and readout-speed
- charge densities and radiation dose (1 GGy @ EXFEL)

Beautiful instruments existing + under developments → **iWoRID13**

Example for a running detector: CAMP (CFEL ASG MultiPurpose) detector



L.Strüder et al., NIMA614(2010)483

Femtosecond X-ray Protein Nanocrystallography

Example: CAMP@LCLS

- Most macromolecules cannot be grown to crystals of sufficient size for conventional crystallography*)

- X-ray dose required to study crystals will destroy them

- can fs pulses at FELs produce diffraction pattern before damage occurred?

- experiment with CAMP at LCLS: 10^{12} 1.8keV γ/pulse of 10, 70 and 200 ns, focused to 7μm (FWHM) → 70 MJ !

record 3M diffraction patterns of 0.2-2μm nanocrystals of photosystem I (structure known)

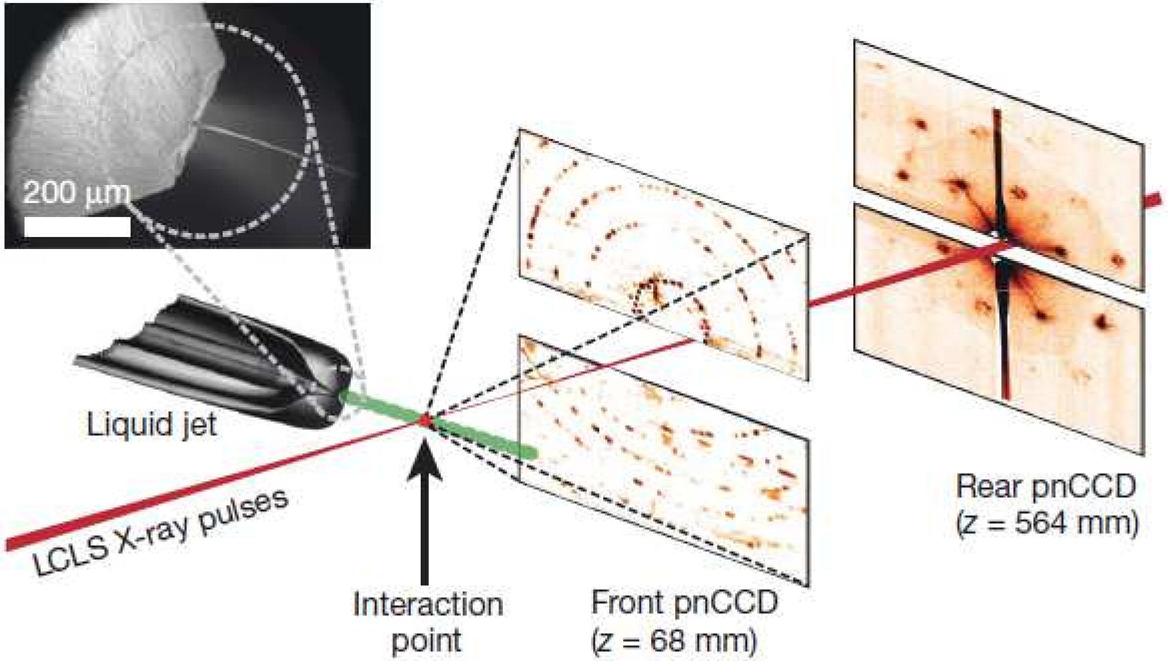


Figure 1 | Femtosecond nanocrystallography. Nanocrystals flow in their buffer solution in a gas-focused, 4-μm-diameter jet at a velocity of 10 m s^{-1} perpendicular to the pulsed X-ray FEL beam that is focused on the jet. Inset, environmental scanning electron micrograph of the nozzle, flowing jet and focusing gas[30]. Two pairs of high-frame-rate pnCCD detectors[12] record low- and high-angle diffraction from single X-ray FEL pulses, at the FEL repetition rate of 30 Hz. Crystals arrive at random times and orientations in the beam, and the probability of hitting one is proportional to the crystal concentration.

H. Chapman et al., Nature 470(2011)73

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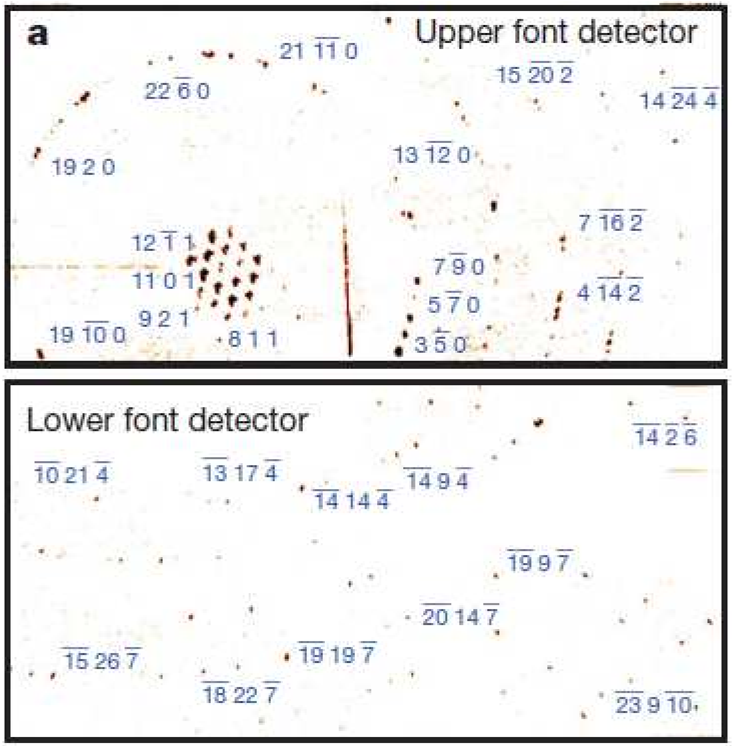
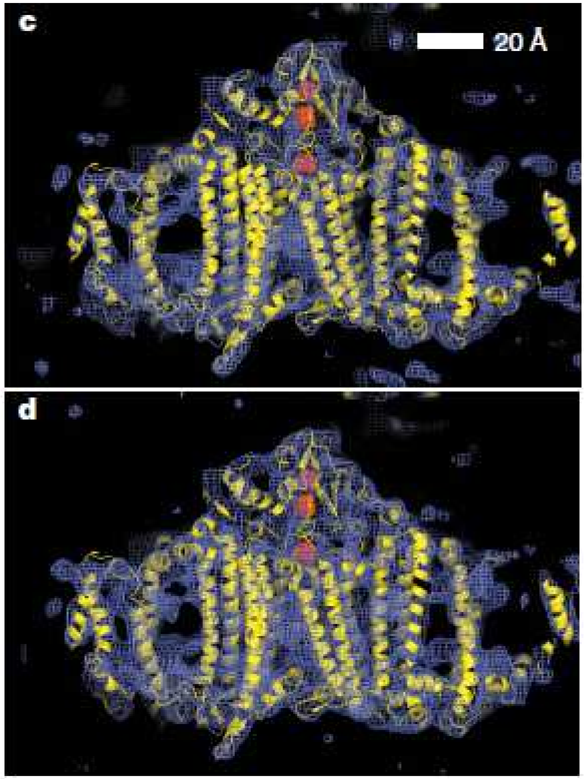
*) so far only 300 unique structures of membrane proteins deciphered !

Femtosecond X-ray Protein Nanocrystallography



Diffraction pattern of single 70 fs pulse



Structure (c) 70 fs pulse; (d) conventional method truncated to 8.5 Å resolution

Single shot femtosecond nano-crystallography demonstrated !

→ excellent Si detectors were necessary for this success

→ further developments are under way and show already first results to meet the challenges of the new X-ray sources

Outlook and Summary (I)

Looking back on > ½ century of development of solid state sensor and detector systems:

- **An exciting story of fascinating developments**
- **Solid state detectors enabled important discoveries + precision measurements (No Si – no Higgs!)**
- **The developments have major impact on industry and science outside of physics**
- **The close collaboration between academia and industry has been important**

Looking forward:

- **Rapidly developing technologies bring new opportunities – they will help solving the many challenges posed by the new science ideas and the new experimental facilities, like Free-Electron Lasers, the High-Luminosity LHC, the International Linear Collider, and many more**
- **I also hope that there will also be completely new ideas, like in the past the CCD, the concept of sideway depletion, the DepFET and more**

My thanks to:

the many students (at UHH and several other places) + colleagues with whom I had (and have) the privilege to collaborate

Summary and Outlook (II): Why work on detectors?

Why work and understand detectors ??? Why invent new methods ???

Albert Einstein 1930 at the opening of the Berlin broadcasting exhibition:

"Verehrte An- und Abwesende!

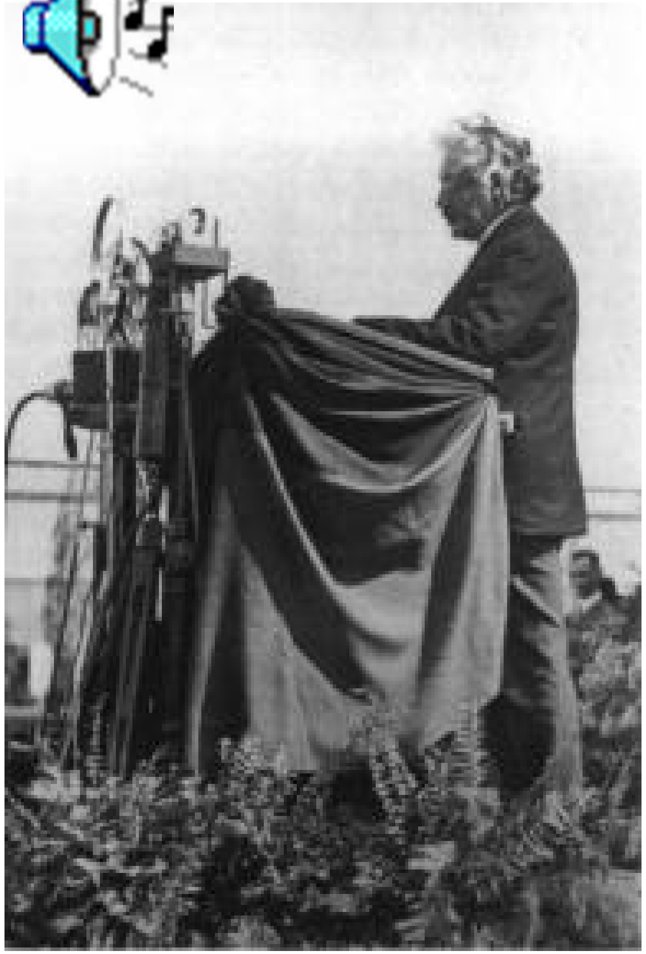
Wenn Ihr den Rundfunk höret, so denkt auch daran, wie die Menschen in den Besitz dieses wunderbaren Werkzeuges der Mitteilung gekommen sind. Der Urquell aller technischen Errungenschaften ist die göttliche Neugier und der Spieltrieb des bastelnden und grübelnden Forschers und nicht minder die konstruktive Phantasie des technischen Erfinders.

Sollen sich auch alle schämen, die gedankenlos sich der Wunder der Wissenschaft und Technik bedienen und nicht mehr davon geistig erfasst haben als die Kuh von der Botanik der Pflanzen, die sie mit Wohlbehagen frisst.“

“Venerated Attendees and Absentees!

When you listen to broadcasting, think also about how we got to own this wonderful tool of communication. The source of all technical achievements is the divine curiosity and the play instinct of the tinkering and pondering scientist, and not less the constructive imagination of the technical inventor.

All should be ashamed, who thoughtlessly use the wonders of science and technology and understand of them as little as the cow does of the botany of plants on which she feeds with pleasure” (translation© R.Klanner – ohne Gewähr)



(http://www.einstein-website.de/z_biography/redefunkausstellung.html)