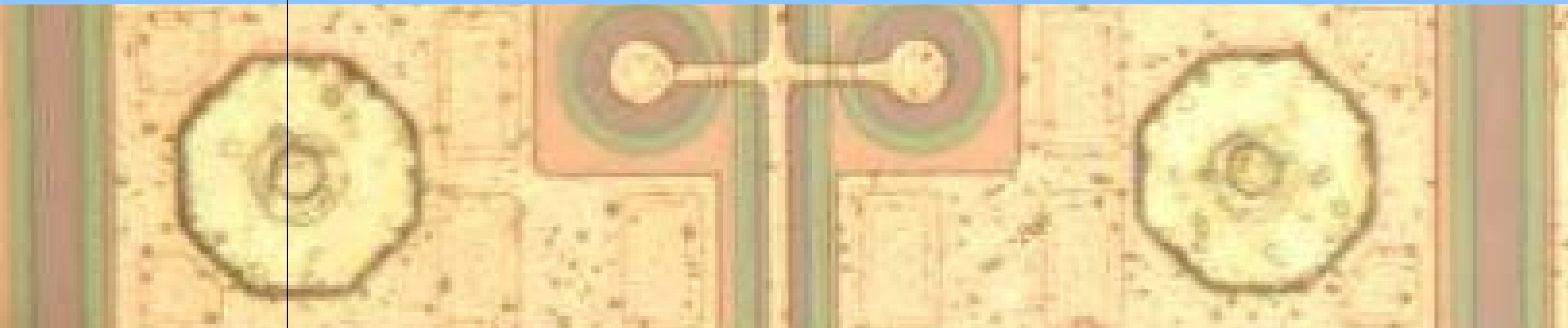


Wir schaffen Wissen – heute für morgen


Paul Scherrer Institut

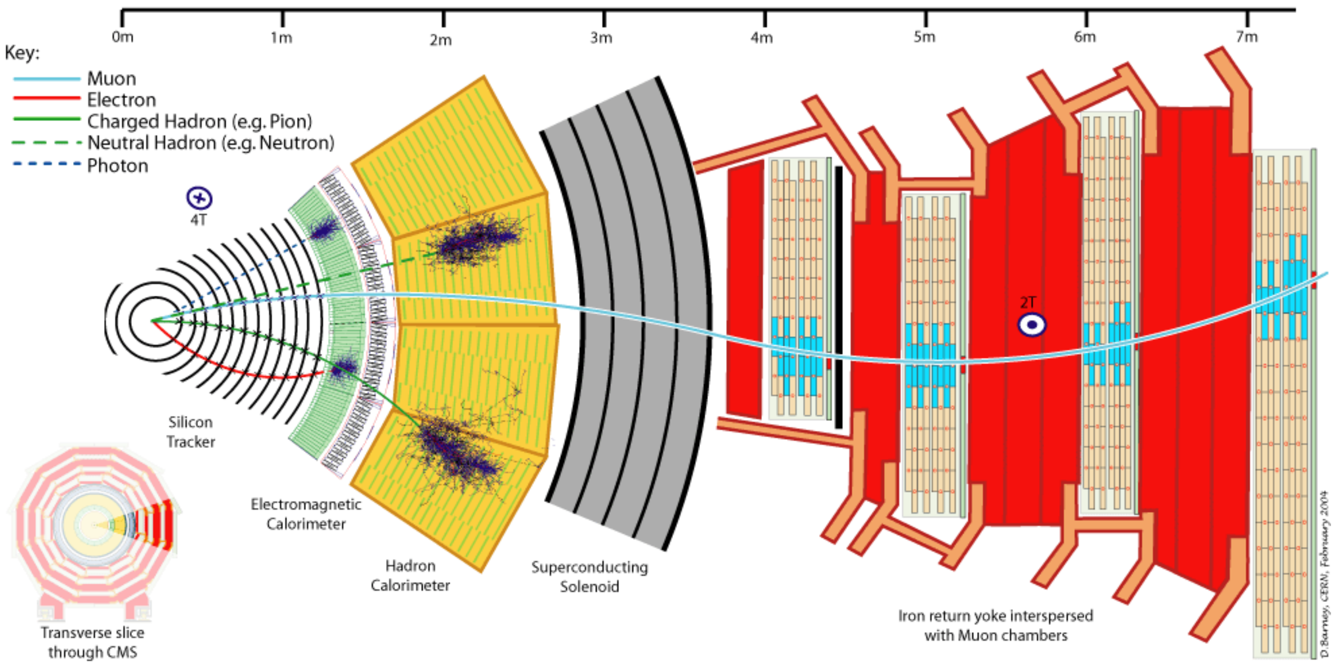
Tilman Rohe


# Silicon Tracking Detectors in High Energy Particle Physics

# Introduction

Innermost part of most HEP Experiments are the tracking systems

- Outer parts for momentum measurement
- Inner parts for vertexing, and (if pixels are used) for track seeding




Most vertex detectors are based on silicon

- Suitable properties (signal, carrier life time, can be doped …)
- Low Z (material budget)
- Good availability in high quality, sufficiently cheap
- Well know processing technology (on principle)

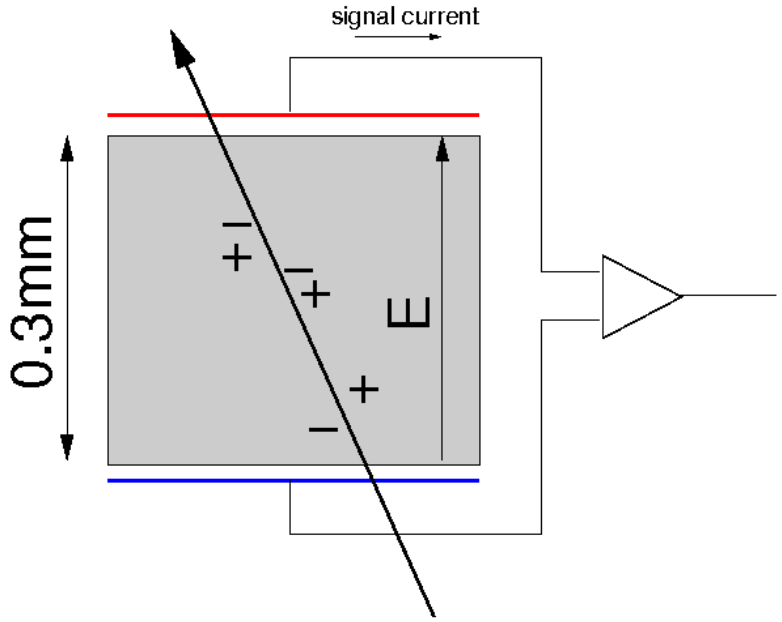
Competitors

- Compound semi conductors: Not sufficiently radiation hard (high Z attractive for X-ray detection)
- Diamond: Expensive, not easily available (esp. single crystal) but very attractive features → R&D ongoing

# Particle detection in Silicon

## Principle of most tracking devices

- A particle (or a photon) ionizes the detection medium
- The charge carriers are separated by an E-field
- Their drift induces charge on the collection electrodes
- If collection electrons are segmented, a spatial information is obtained
- Ionization energy needed for electron – ion separation
  - Argon: ~26 eV
  - Silicon: 3.6 eV




## "Ohmic" detector

- Assume a piece of silicon: area 1cm$^2$ thickness 0.3mm
- Charge released from a m.i.p.: ~25000 e$^-$ ~ 4fC
- Mobility (electrons): ~1400cm$^2$/Vs, targeted collection time: 10ns
- Signal current I = 4 fC/10ns = 400 nA (easy to detect)
- To achieve 10ns collection time an electric field of E=v/m=0.03cm/10ns/1400cm2/Vs~ 2100 V/cm is needed or a bias of 60V

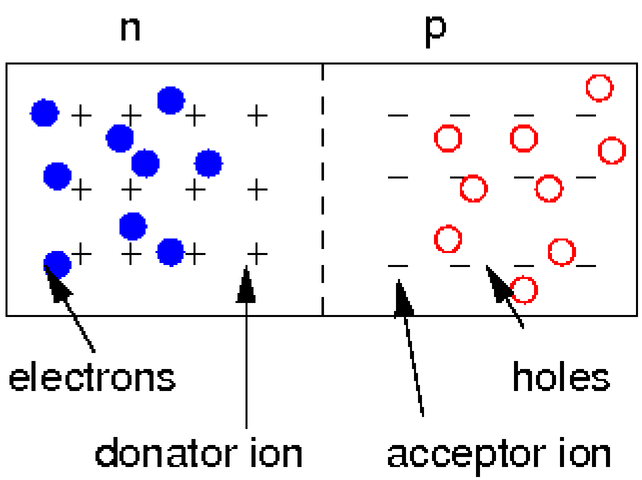
## But:

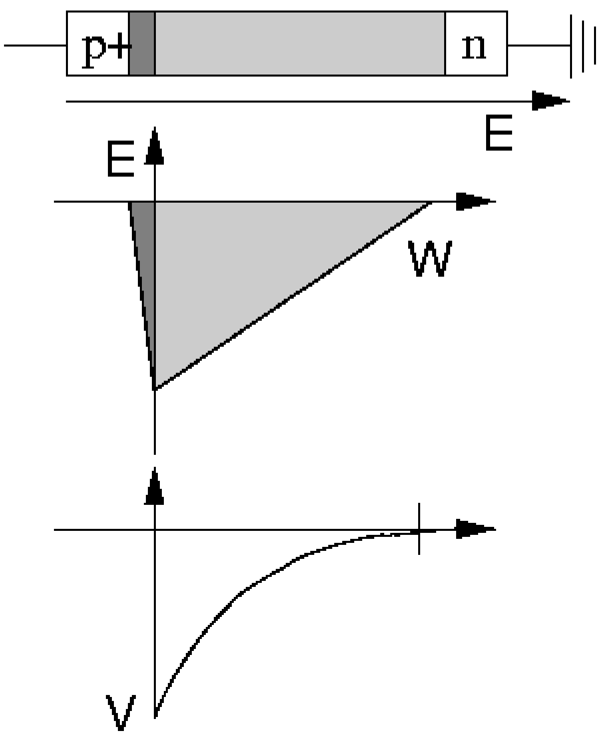
- Silicon is a semiconductor
  - Highest practical resistivity: 10k$\Omega$cm → 300$\Omega$ (our piece)
  - Current at 60V: 200mA
  - For very small cells (pixels) A~10$^{-4}$cm$^{-2}$ good S/N possible but overall power consumption prohibitive (12W/cm$^2$)
  - Large band gap materials (diamond) work in this regime
- For "high" temperature Silicon: suppress leakage current → pn-junction

# pn-junction

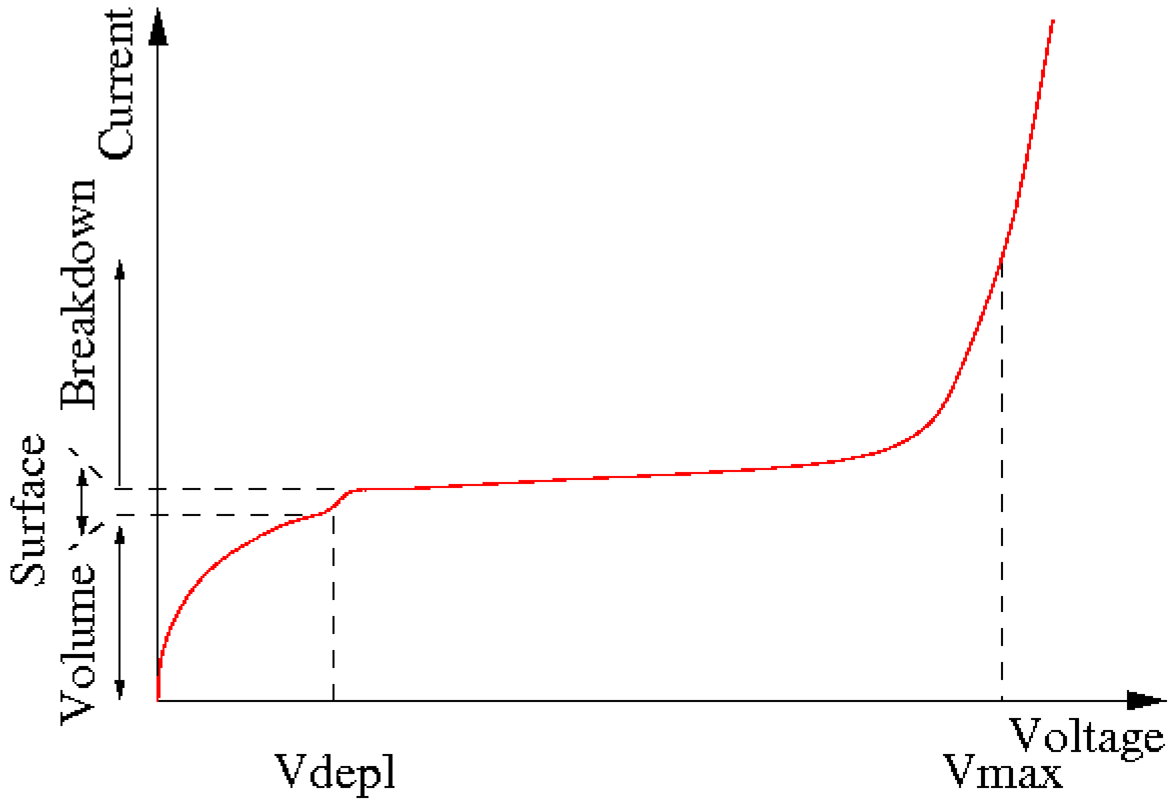
A diode is formed by an interface between p- and n-doped silicon:

- Majority carriers diffuse to the other side
  $J_{diff} = -D_n \nabla n$ or $J_{diff} = D_p \nabla p$
  with $D = kT\mu/e$ (Einstein relation)
- Recombine with “local” majority carriers → zone with reduced concentration of free carriers (depletion zone)
- Remaining acceptor/donor ions cause electric field
  $J_{drift} = -e\, n\, \mu_n\, E$ or $J_{drift} = e\, p\, \mu_p\, E$
- Both currents cancel each other → relation field vs. position
- Forward bias → exponential IV curve
- Reverse bias
  - Depletion zone is increased
  - Current is suppressed (only thermal generation)
- In case on side of the junction is much heavier doped than the other and the junction is abrupt:
  - $W = \mathrm{sqrt}(2\varepsilon_0\varepsilon_{Si}V/eN_D)$ → depends only on bulk doping
- Constant bulk doping → linear field



# IV curve




- Dark current by thermal generation of e-h-pairs in the space charge region (volume)
  - Effected by defects in the crystal
  - Heavily increased by radiation
- Exponential Temperature dependence
  $J_{vol} \sim T^2 \exp(-E_g/2kT)$ or factor 2 every 8K

Other sources of leakage current

- Thermal generation at interfaces/surfaces
  - Segmentation
  - Process quality
  - Radiation
- Charge multiplication (break down)

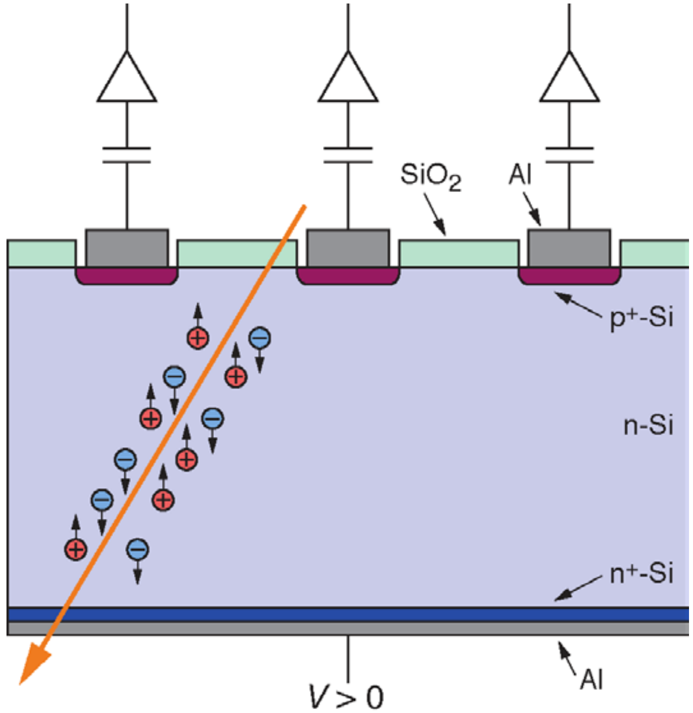
# Strip detector (DC-coupled)

Simplest way to create diodes

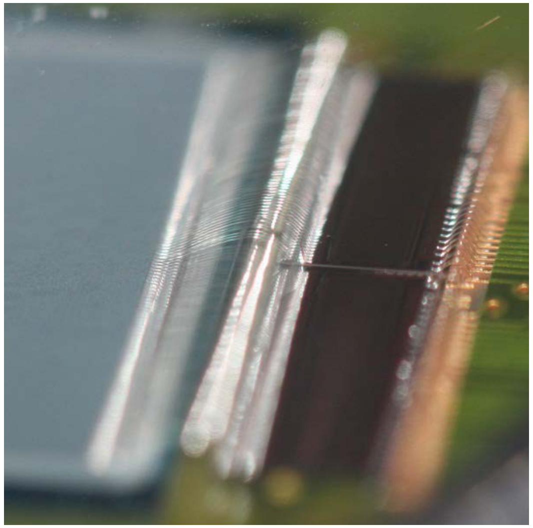
- Implant Boron over a photoresist pattern into high resistive n-type silicon
- Electrodes typically have the shape of strips are connected to the read out electronics by wire bonding

Features:

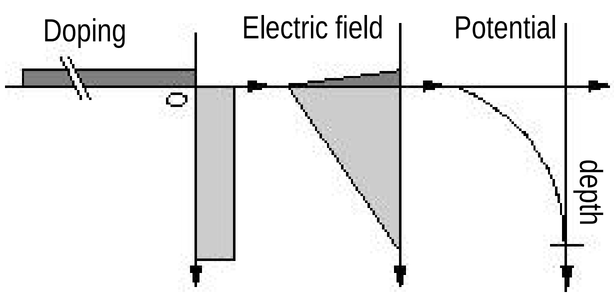
- $W = \mathrm{sqrt}(2\varepsilon_0\varepsilon_{Si}V/eN_D)$ → depends only on bulk doping
- Full depletion for 300µm and $n=10^{12}cm^{-2}$ ~ 70V
- Constant bulk doping → linear field
- Strip implant forms junction → peak at strip
- High dose implant on back side (ohmic contact, break down)



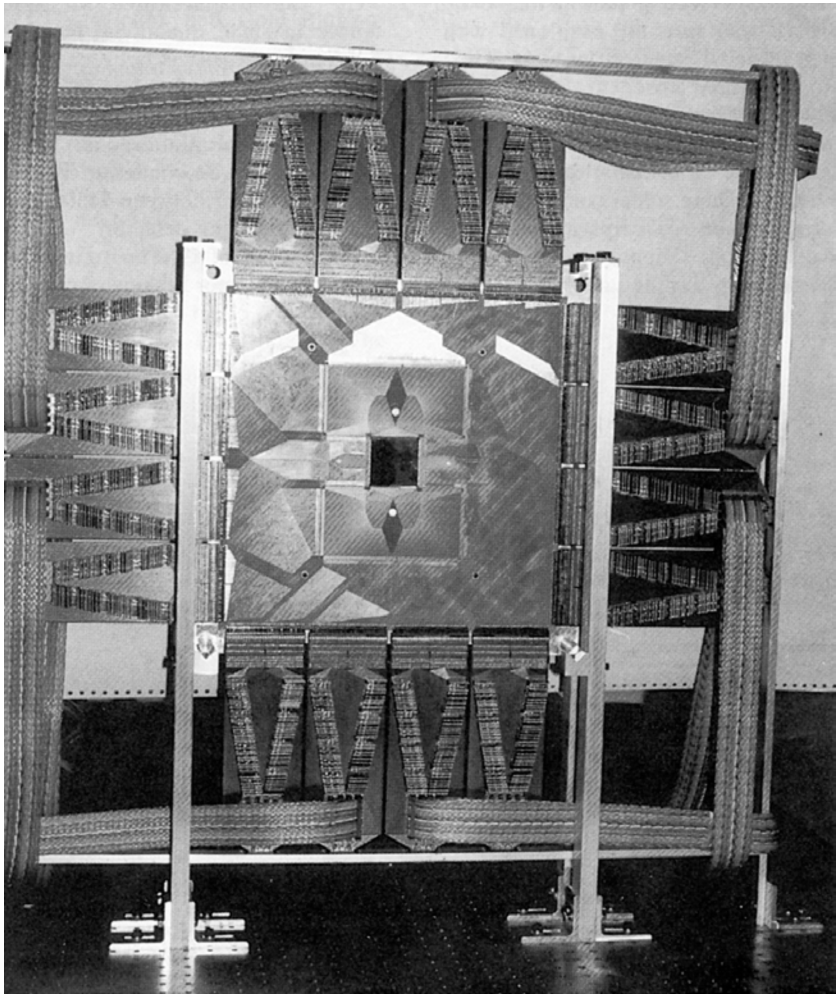

Sensor

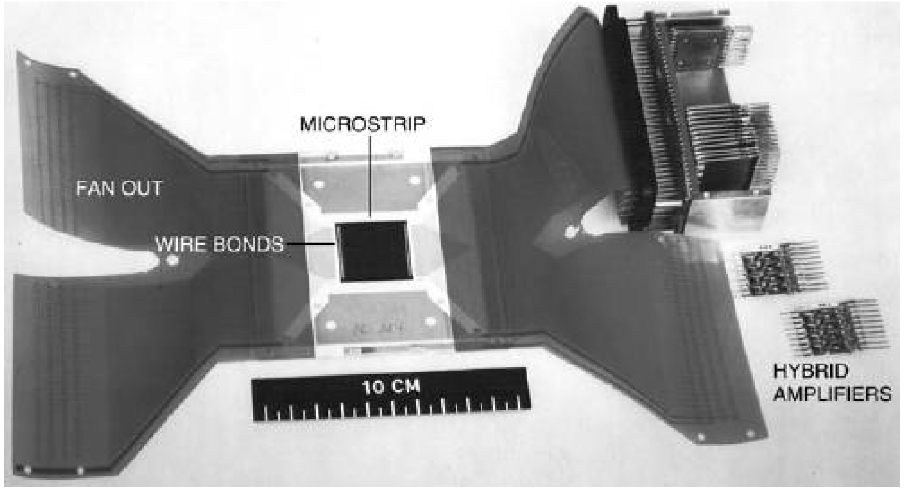


Readout electronics



# 1st strip trackers






Left: 1st strip tracker at FNAL-E706 (around 1980)

- Signals were still routed to crates using flat band cables

Top: CERN WA82 (1986)

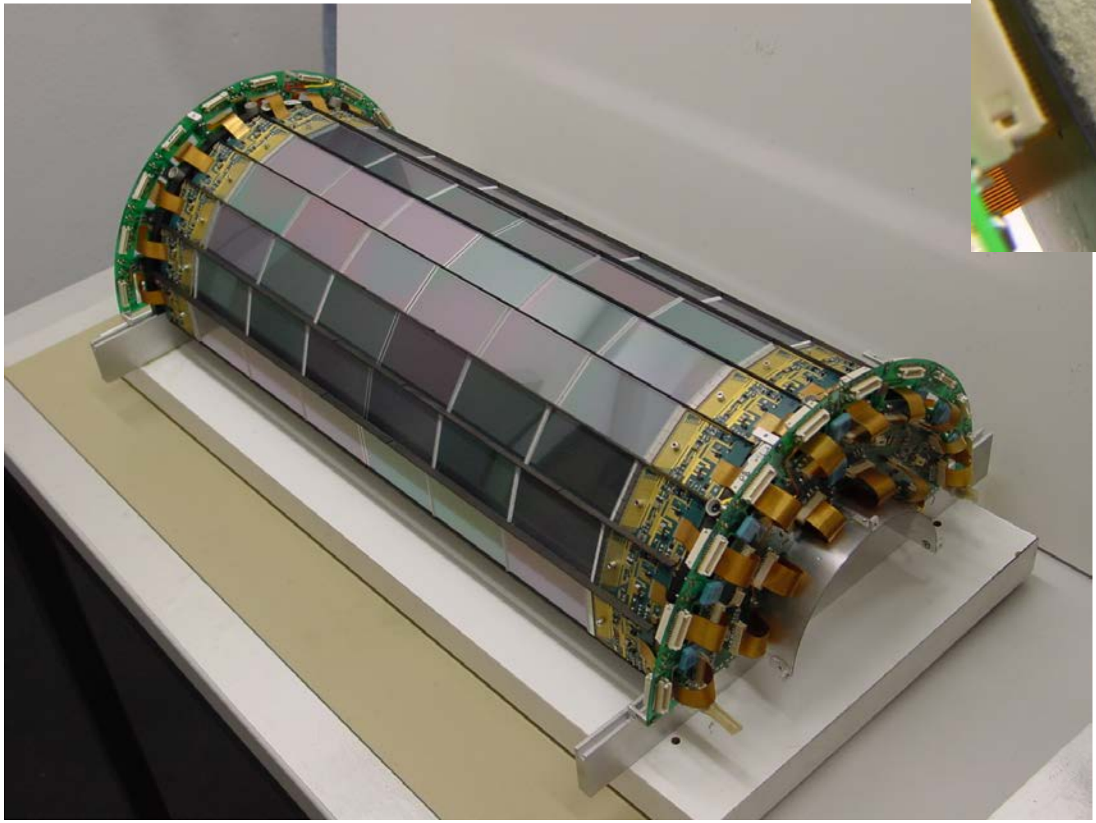
- Signal amplifiers built with discrete components

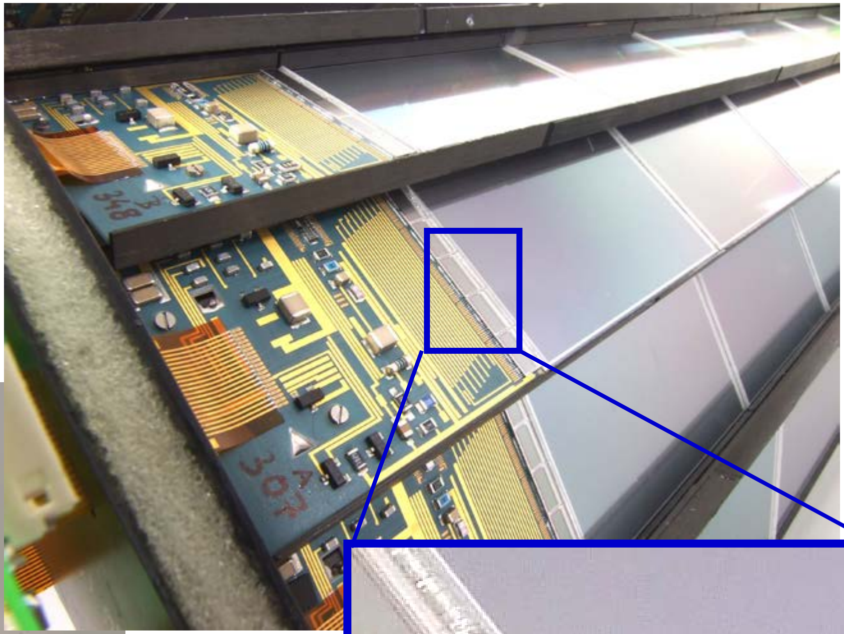
Due to the bulky readout electronics only used in fixed target experiments

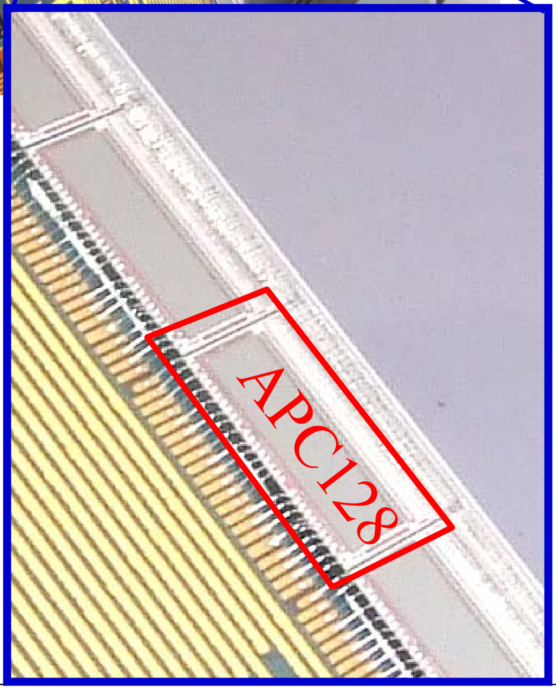
ASIC readout → Collider experiments (LEP, HERA)

# HERA -CST

- Designed and built at PSI (1992-96)
- Read out with ASIC (apc128)
  - Readout electronics placed in small hybrids
  - 128 channels 50µm pitch
  - Digital controlled analogue signal processing
  - Very universal (e.g. now used for telescope)

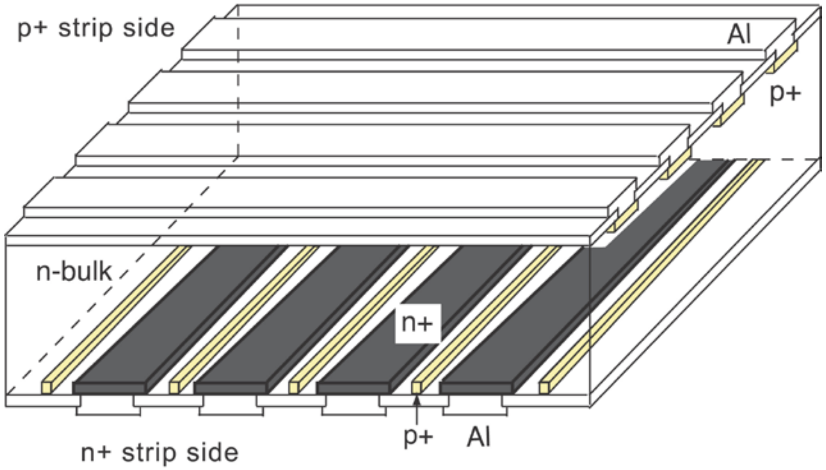


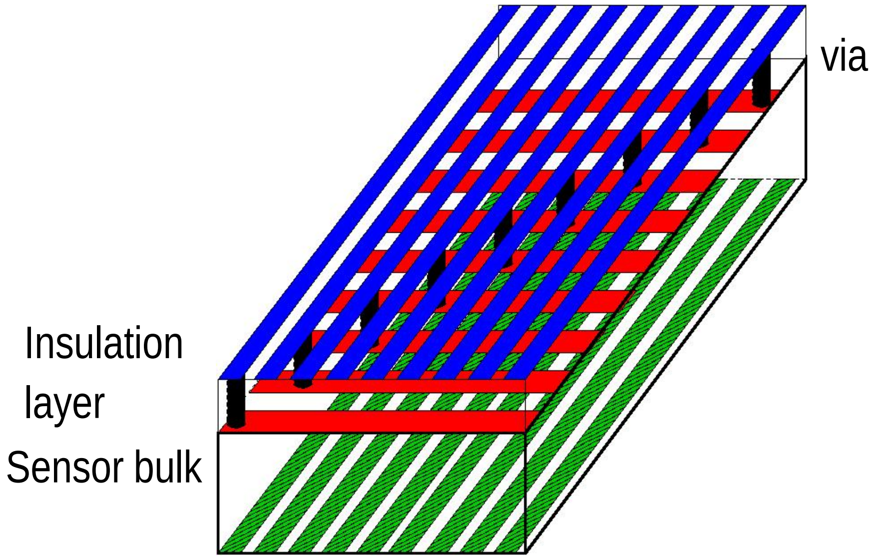


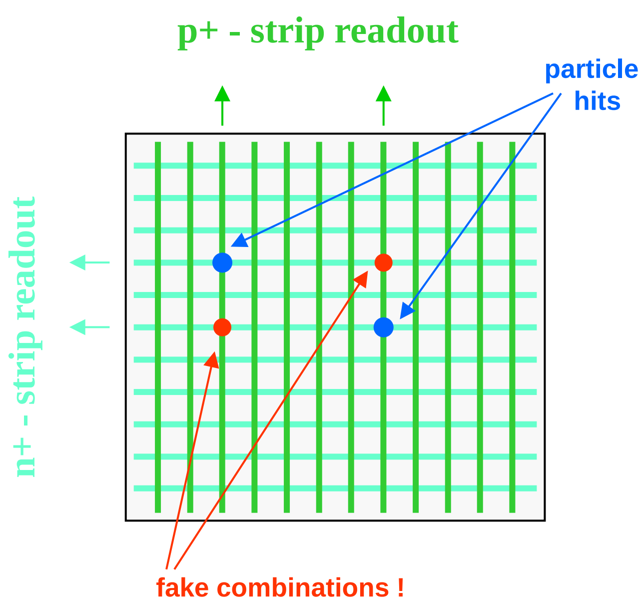


# HERA -CST

- Double sided read out
  - N-side isolation
  - Ground of electronics (one side on HV)
    - Readout via optical fibers
    - Control signals coupled in via capacitors
- Luminosity at HERA was small
  - 3 sensors daisy chained
  - 90 degree stereo angle
    - Double layer metal on n-side
      → Large capacitance → high noise

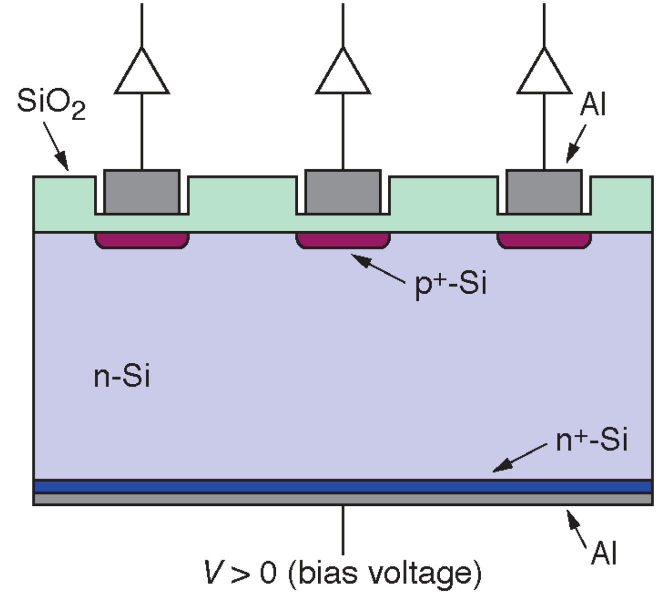


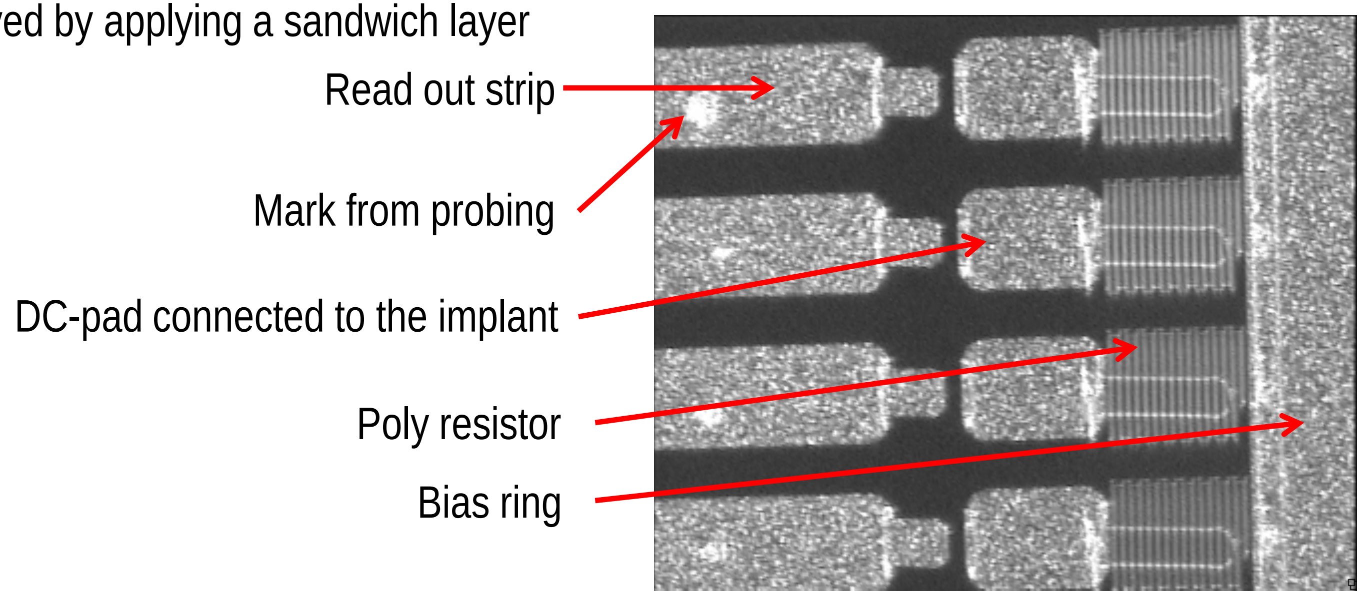



# AC-coupled strip detector

- Bias resistor and coupling capacitor are difficult to implement on an ASIC
- Implementation on sensor is possible
  - Capacitor: SiO2 layer
    - Due to large strip size, a few 100nm thick layer possible
    - Can be very stable up to 100V
  - Long poly resistor (R> 1M$\Omega$)
- Yield of capacitor is cost driving
  - Every capacitor/strip has to be tested
  - Yield can be improved by applying a sandwich layer of $Si_3N_4$



CDF

Pioneering in 2 respects

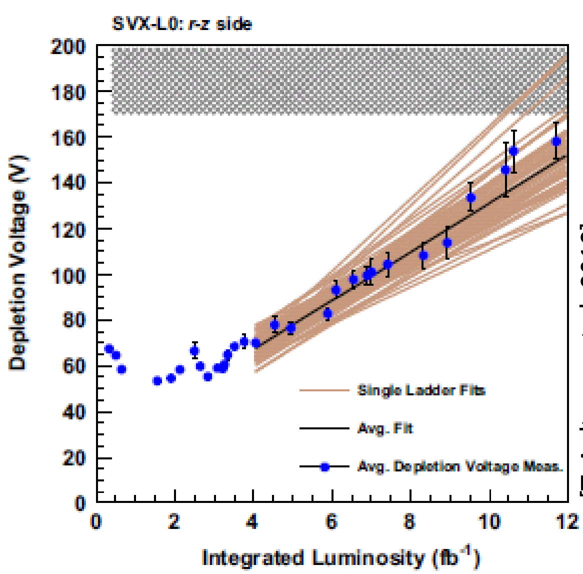
- 1st “large area” application: several m$^2$
- 1st strip sensors which suffered substantial radiation induced degradation

Sensor choice: Double sided AC coupled sensors, both readout electronics on GND:

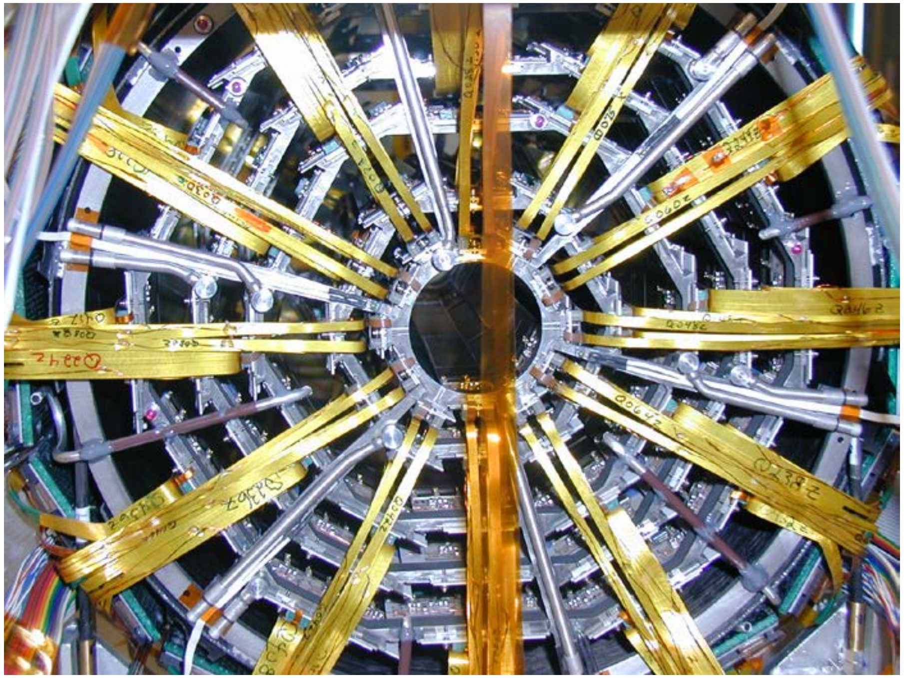
- Voltage drop over coupling capacitor
- Limit of max. bias to 170V

Solution: Insertion of “layer00”:

- Single sided, stable > 600V




[T. Aaltonen et al. 2013]

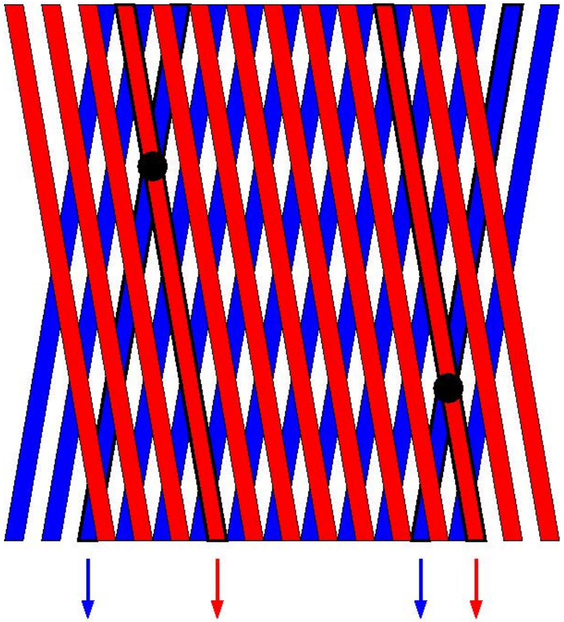


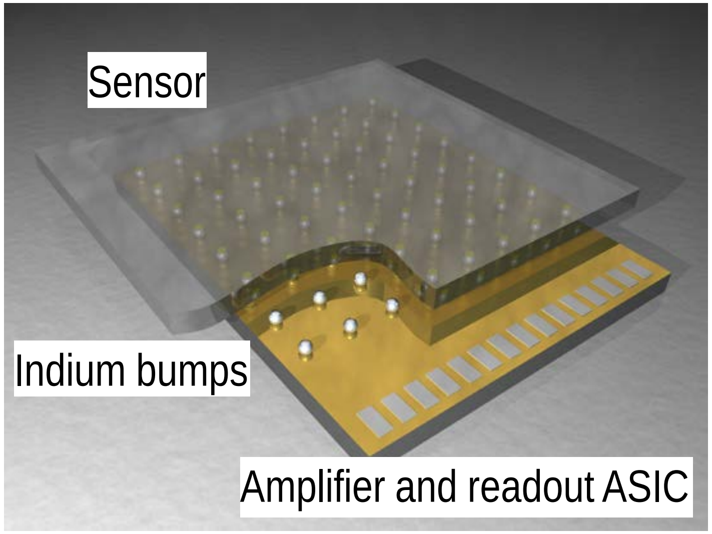
# LHC-Experiments (e.g. CMS)

The requirements to CMS tracker

- Intermediate and outer regions (r>20cm)
  - "Moderate" radiation hardness required
    - Can be archived with "standard" sensors
    - Small stereo angle
      - Less ambiguities
      - No double metal required to mount ASICs at "stave" end
      - Loss in z-resolution
  - Very large area (~200m$^2$) → cost
    - Single sided p-on-n sensors
    - Double sided → 2 sensors back-to-back
    - Large wafers (150mm instead of 100mm)
- Inner region (r< 20cm)
  - High track density
    - No ambiguities
    - Zero suppression and local data storage
  - Radiation induced degradation (sensor and ROC)

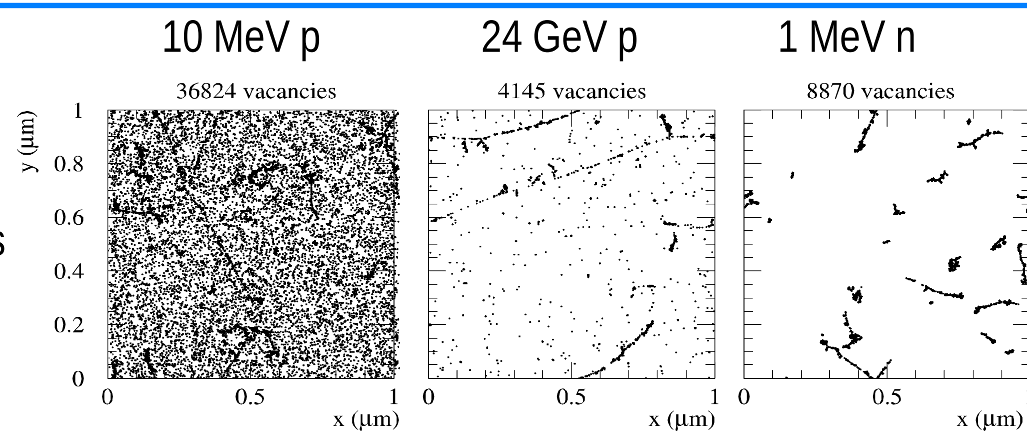
→ Pixels





# Radiation damage in Silicon

- Surface damage
  - Mainly by ionisation in the covering layers
  - Built up of positive surface charge
  - Danger of breakdown close to n-side electrodes
  - → careful choice of n-side isolation
- Crystal damage by displacement
  - Leakage current increase proportional to $\Phi$
    $\Phi$ ~ ?? (depending much on T)
    - power load (cooling), power
    - Preamplifier (if DC coupled)
  - Change of internal electric field
    $\Phi >$ a few $10^{14}\ N_{eq}/cm^2$ ($\int L >$ ~100/fb)
    - Bias voltage has to be
    - Charge is focused → spatial resolution degrades
  - Reduced signal (trapping)
    $\Phi >$ ~$10^{15}\ N_{eq}/cm^2$ ($\int L >$ ~250/fb):
    - Possibly charge amplification > 1kV → RD50
    - High voltage is presently limited by connectors, cables and power supplies

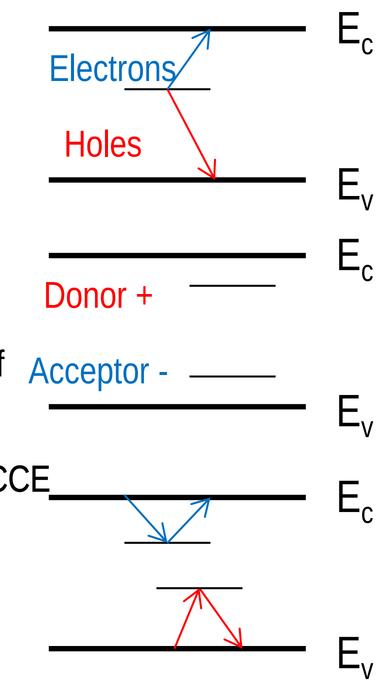



[Mika Huhtinen NIMA 491(2002) 194]

generation
⇒ leakage current
Levels close to midgap most effective

charged defects
⇒ $N_{eff}$, $V_{dep}$
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h) ⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping



# Leakage current

Leakage current was measured with a very large number of small diodes with the guard current separated

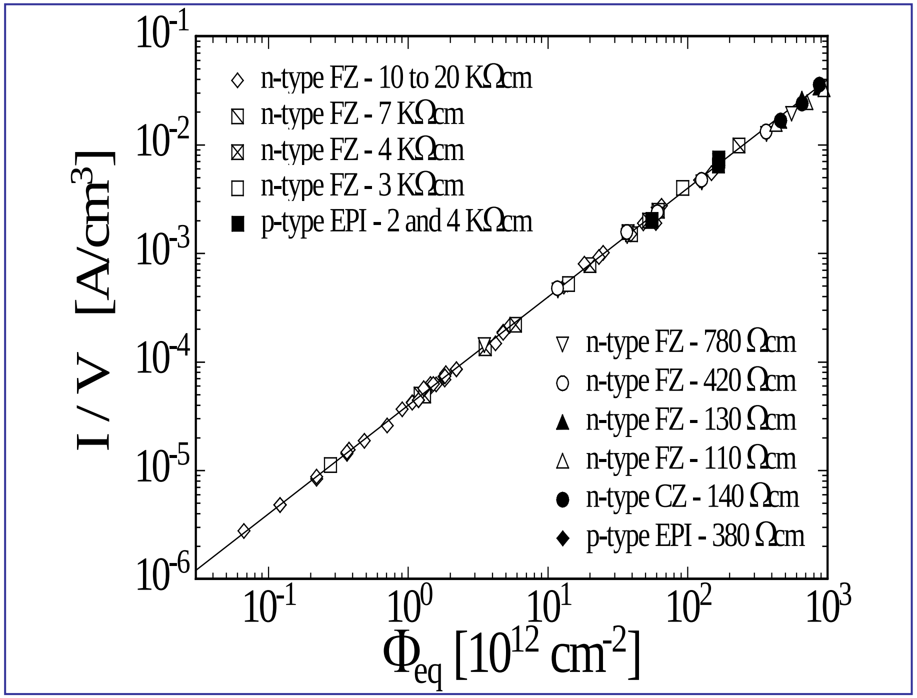
- Volume current only
- Segmented sensors might be different

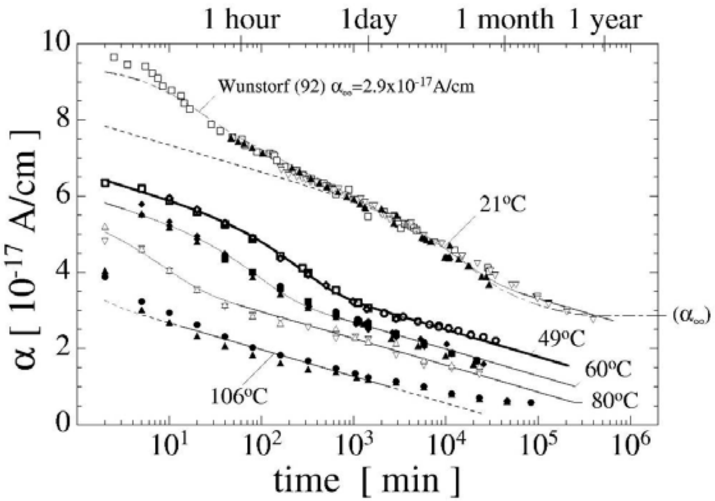
Result

- Current density is proportional to the Fluence
- Damage constant $\alpha = \Delta I / (V\ \Phi_{eq})$ independent of
  - Kind of particle
  - Fluence
  - Growth method of the crystal
  - Impurities of the crystal

  → NIEL hypothesis correct for $I_{leak}$
- Leakage current of diodes is used for fluence calibration or as measurement of $\kappa$

- Annealing

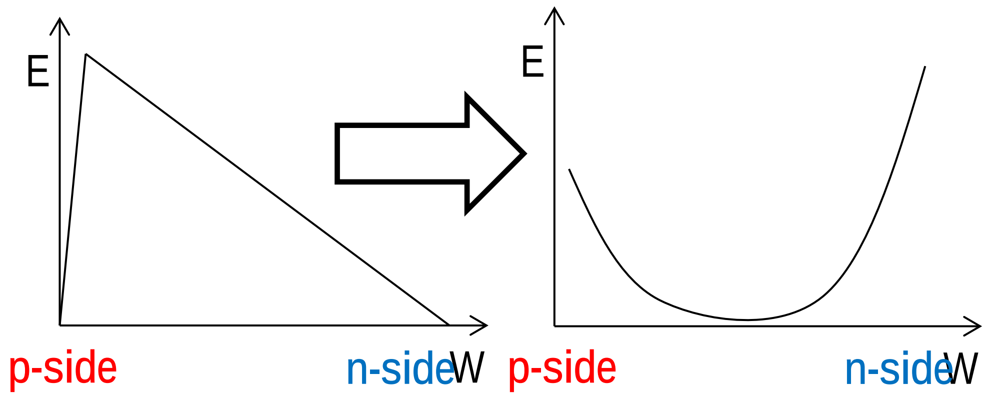


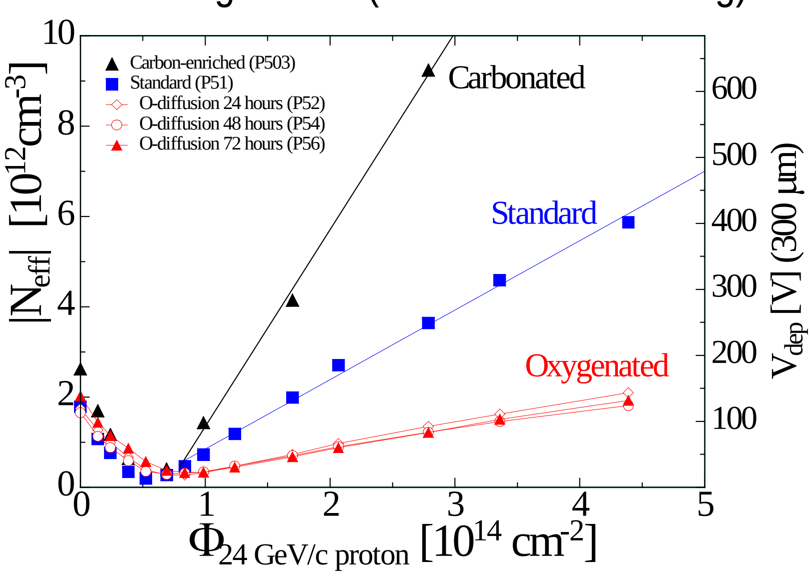




[M.Moll PhD thesis]

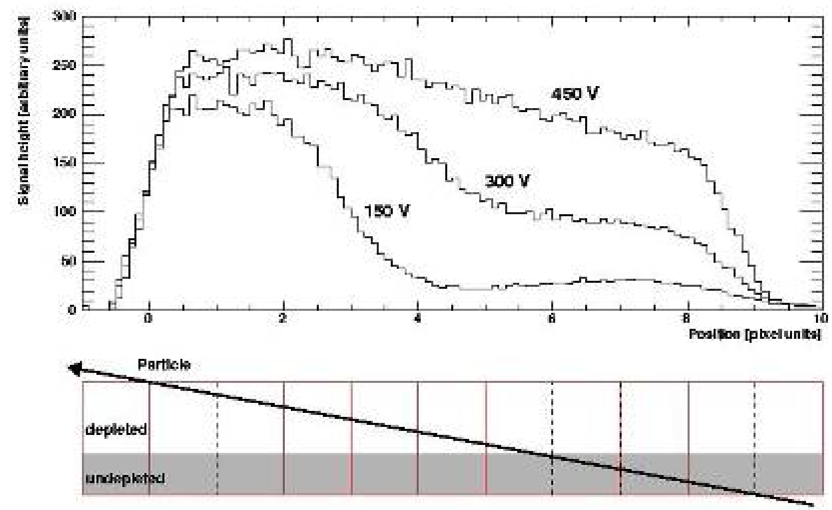
# Internal electric field

- Highest electric field moves from p-side to n-side (“type inversion”)
- Double peak field builds up
- Total amount of space charge increases
  - Minimum bias voltage increases
  - Depends on
    - material choice
    - kind of radiation (even compensating effects with proton/neutron irradiation)
  - Effective doping (“average”) described by Hamburg model (creation and anneling)



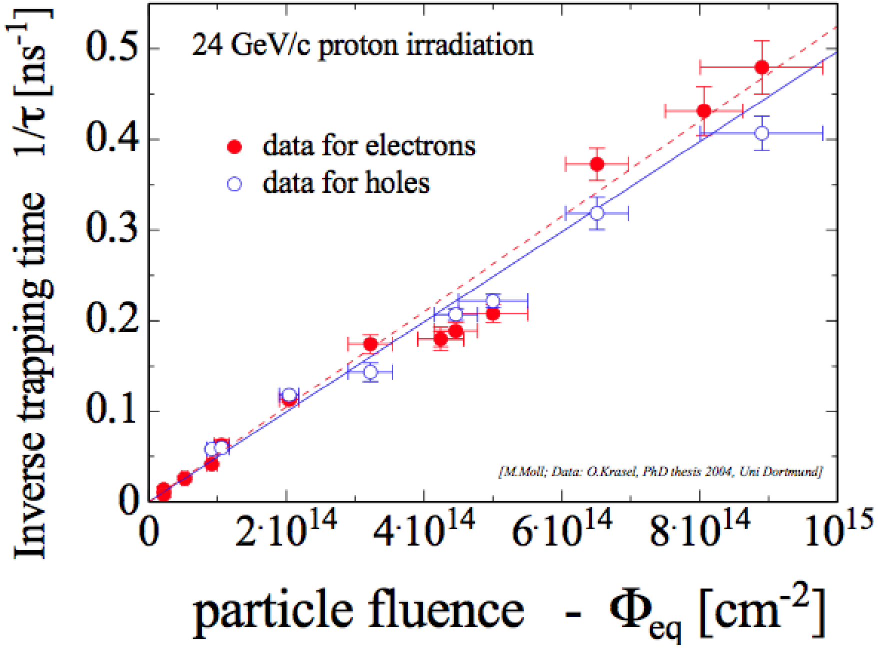

[ROSE-Report]

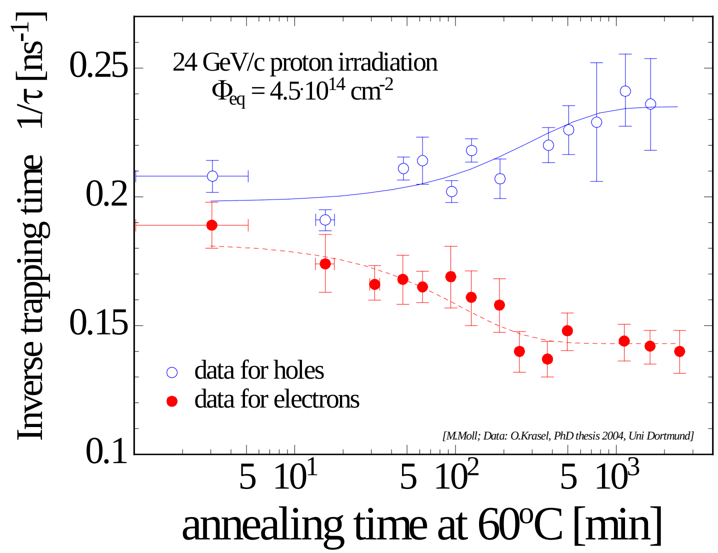


# Trapping

Charge trapping displays presently the absolute operational limit

- Not dependent on material properties (present status)
- Decreases anti proportional to fluence
- Presently measured only up to $10^{15}N_{eq}/cm^2$
- Holes and electron have about same inverse trapping time
- Annealing is different for electrons and holes
- Electrons are 3$\times$ more mobile, their collection is of advantage (→ n-in-n/p sensors)
- Collection distance after $10^{15}N_{eq}/cm^2$ ~ 200µm



# CMS pixel sensor concept

## Collect electrons (n-side readout)

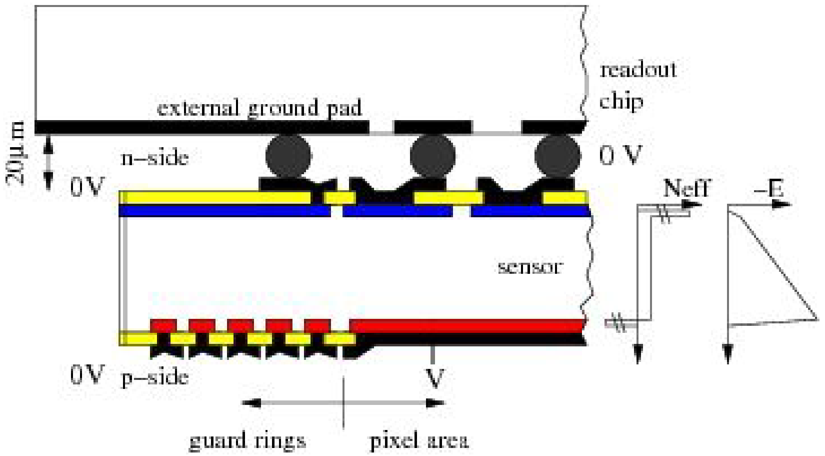
- Less prone to trapping
- Larger Lorentz angle
- n-side isolation required

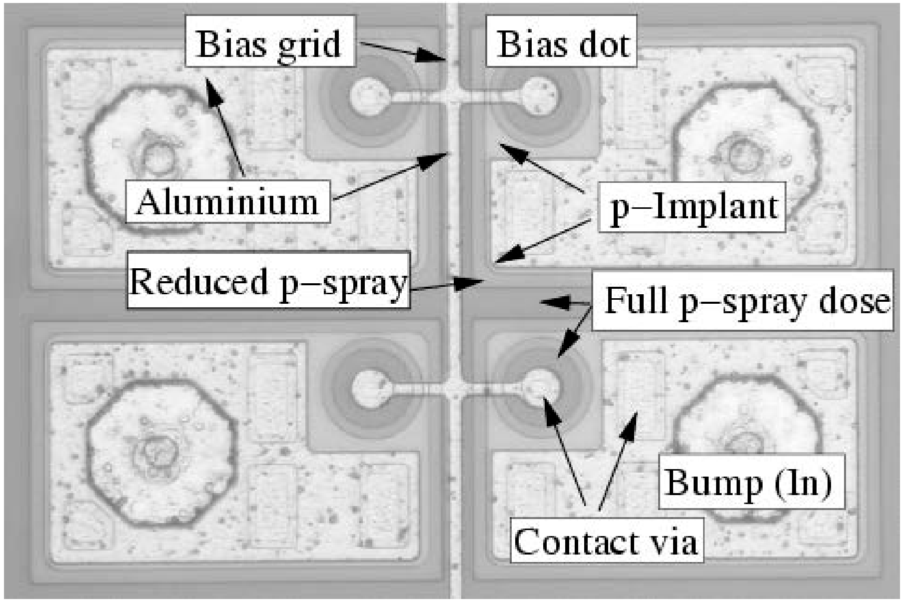
## Avoid problems in module design

- N-Substrate
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing

## Pixel cell layout

- Moderated p-spray with bias grid
  - Reliable IV measurements prior to flip chip procedure
  - Only moderate over depletion necessary
  - Small partly insensitive area of the order of 2% (not effect on efficiency in CMS)
- Small gaps between implants
  - homogenous drift field
    - Minimize effect of field separation on charge sharing
    - Avoid flied peaks (high voltage capability in irradiated state)
  - higher C ~ 80fF (Not critical for performance)

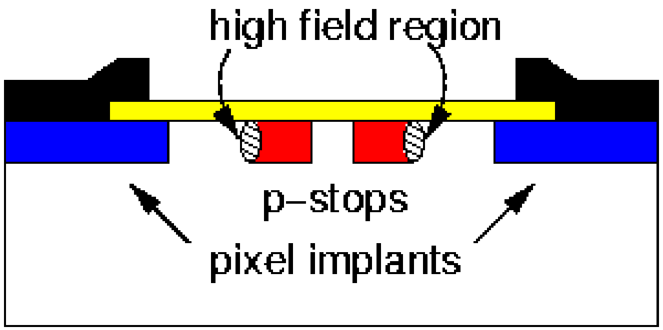


# Excursion: N-side isolation

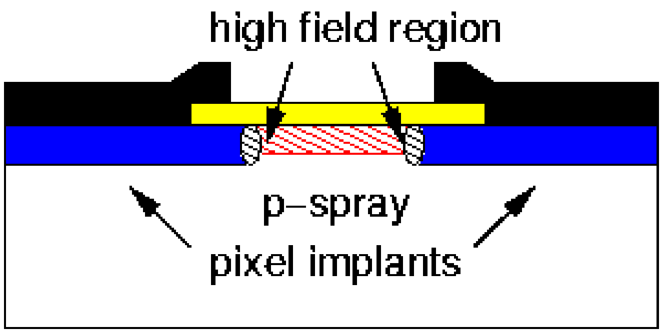
## Fixed oxide charge

- Creates a conducting channel between n-electrodes
- Determines the electrical field in the critical area close to the surface
- Technology parameters (dose of the isolation implant has to be adjusted)



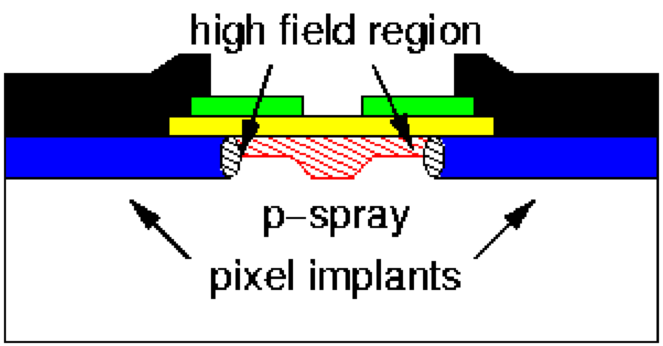

## P-Stops (FPix)

- High boron dose (adjustment uncritical)
- Alignment important
- (Breakdown after irradiation if dose is too high)




## P-Spray, mod. p-Spray (BPix)

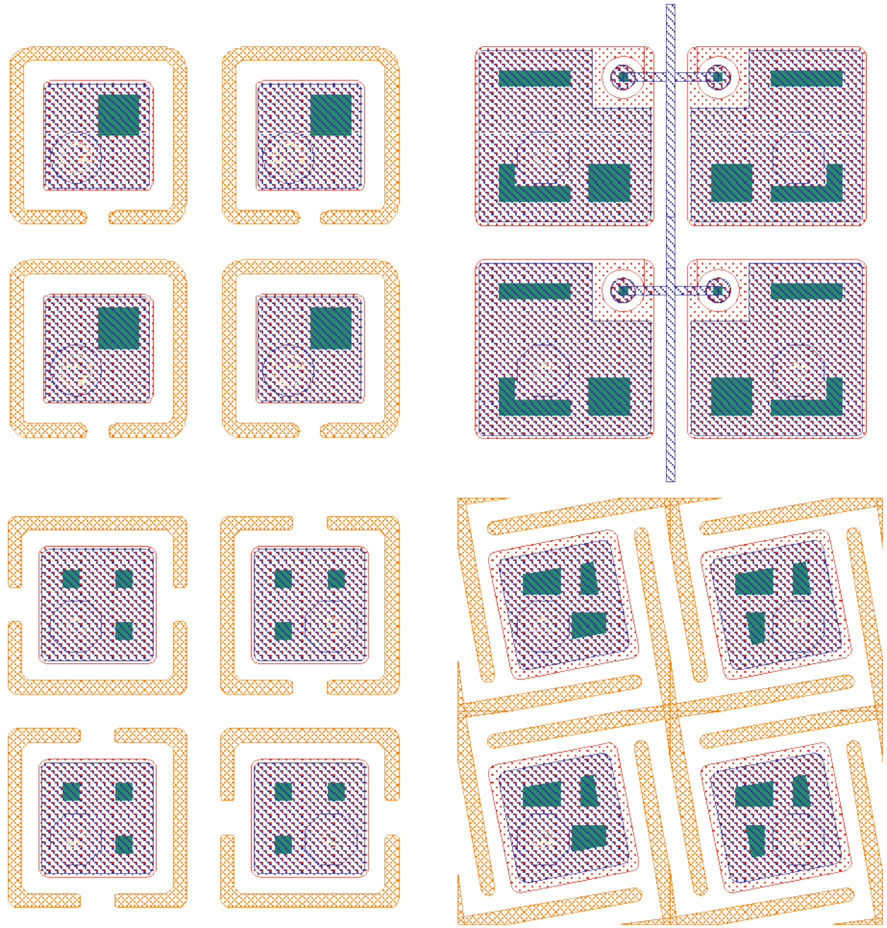
- HV-stability of un-irradiated device critical
- Boron dose to be adjusted
  - High enough to provide isolation
  - Low enough to enable HV operation of new devices (e.g. during module production)
- Narrow gaps possible (without moderation)
  - Punch through structures
  - Homogenous drift field at high voltages



# Different pixel designs in 2003

Sintef (Ring):
- Only 1 un-irradiated (measured at 300V)

CiS (Ring)
- 1 un-irradiated (measured at 300V)
- Each 1 irradiated to 3 and $8\times10^{14}$ measured between 100 and 600V



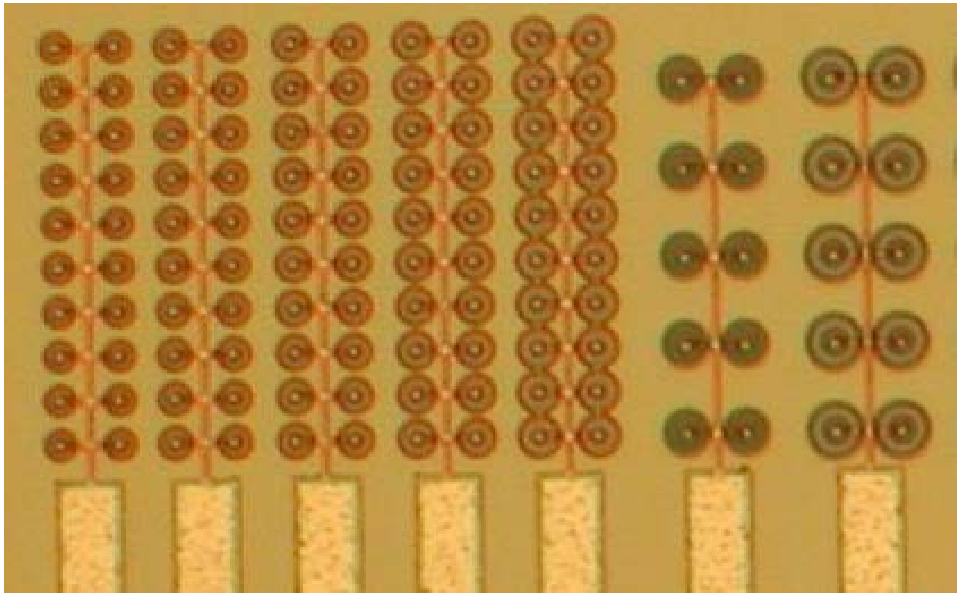
CiS (Spray)
- 3 unirrad (Gap 20,15 & 30)
- 2 (gap 20) irradiated to 8 and $11\times10^{14}$ measured between 100 and 600V

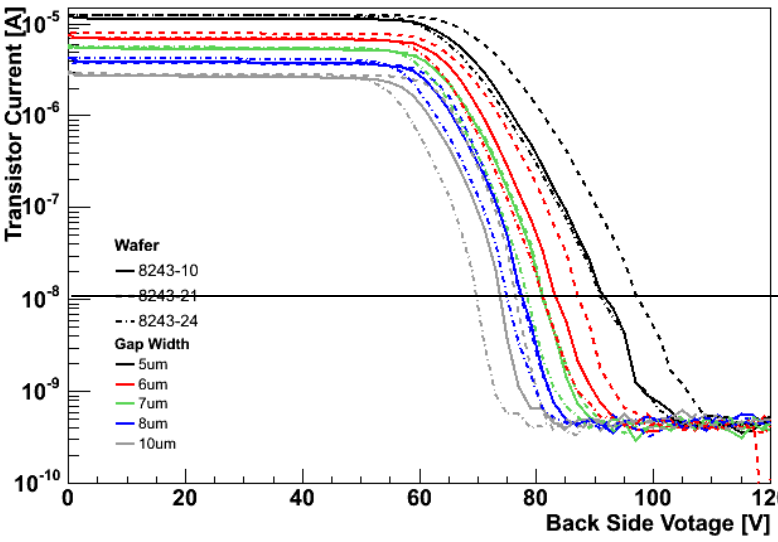
CiS (Cross)
- 1 un-irradiated
- 1 irradiated to $8\times10^{14}$ (bad bump-yield)

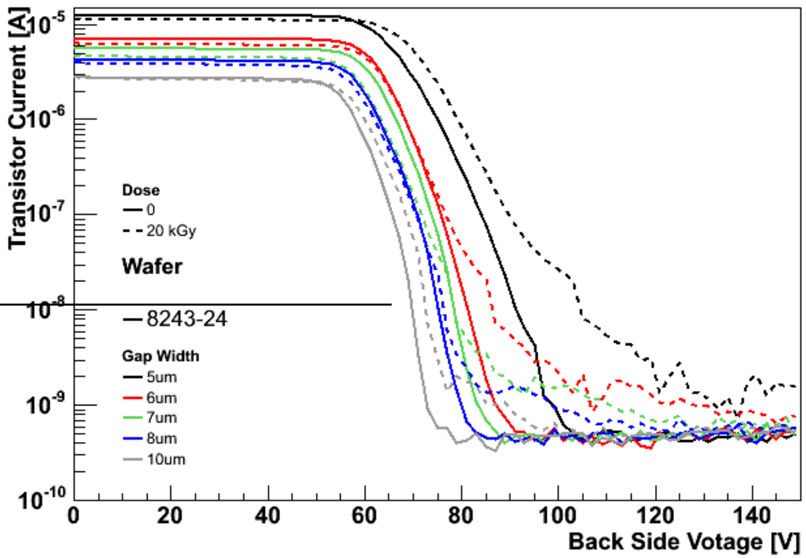
After many test beam and lab measurements we decided for the p-spray design

# Check of pixel isolation

- Use special test structure which "imitates" the biasing structure
- Applied 0.6V (~0.5 * $V_{ana}$)
- Measured the current as function of the back side voltage
  - Some over depletion needed to separate bias grid from pixels
  - No dramatic change with radiation
- Chosen gap of 7 µm





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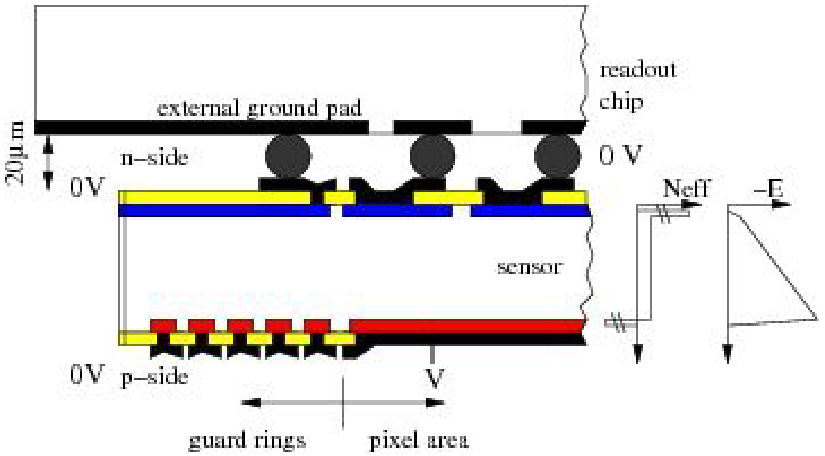


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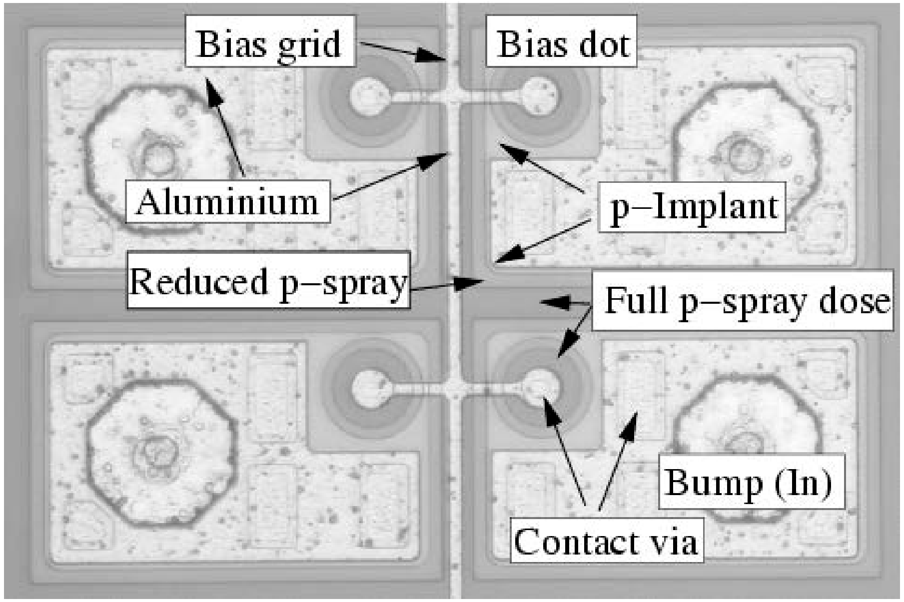
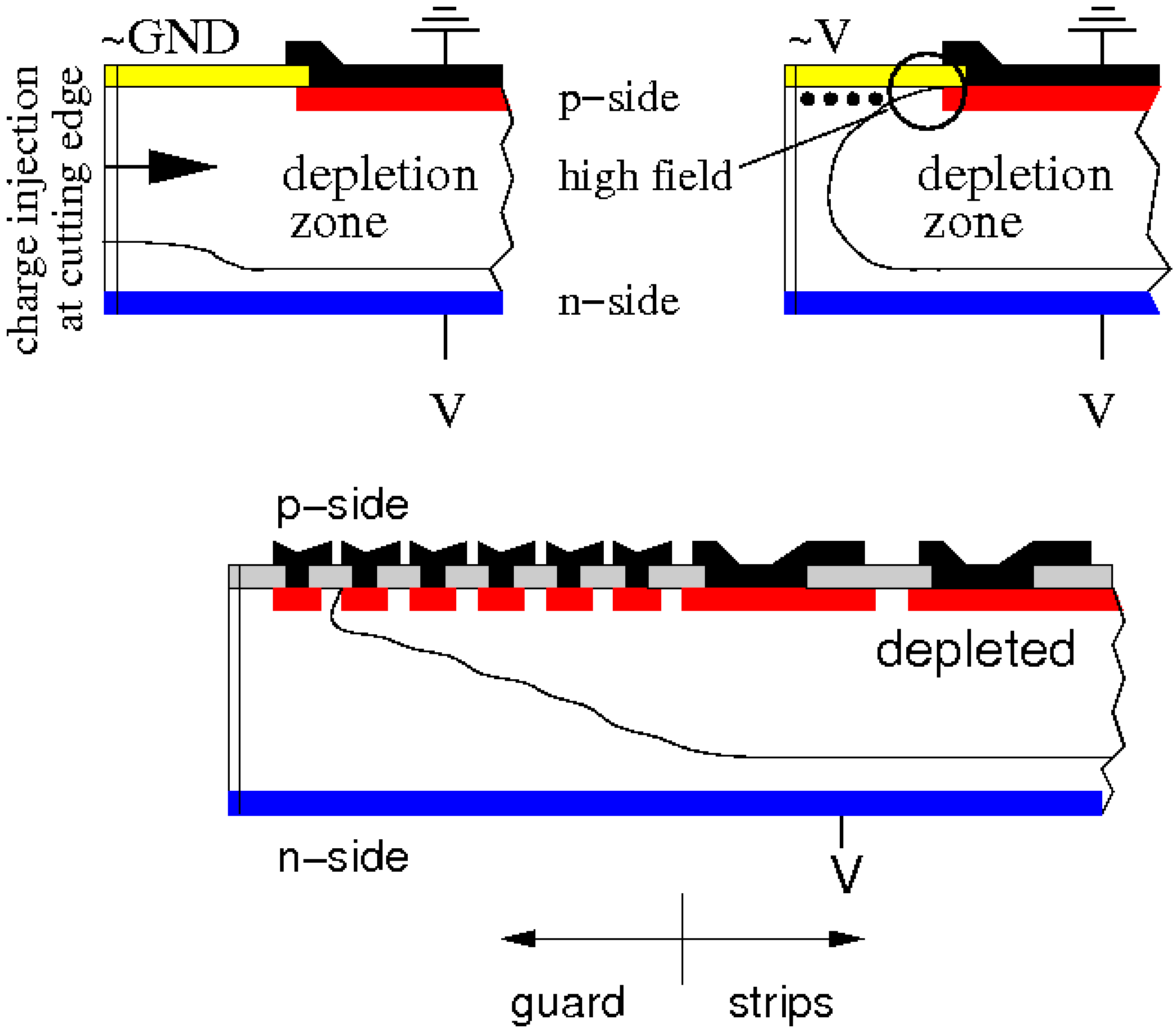


# Excursion 2: guard rings

Prevent

- Edge break down by gently reducing the potential between diode and edge
- Current injection by preventing the space charge region from reaching the edge



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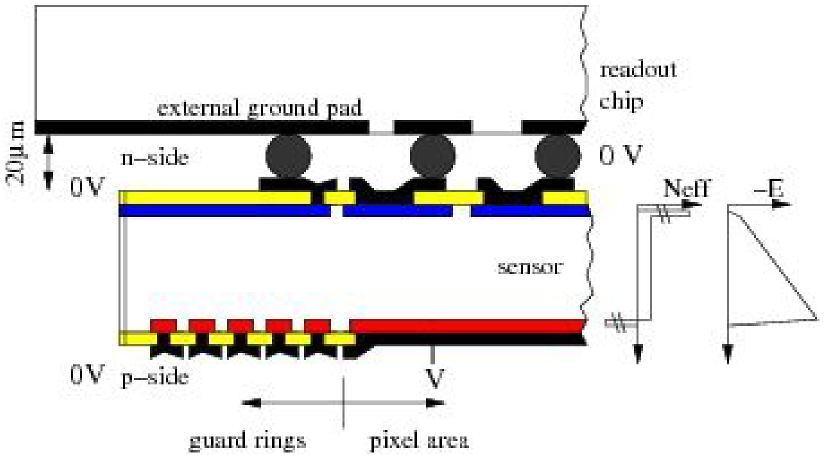
- Larger Lorentz angle
- n-side isolation required

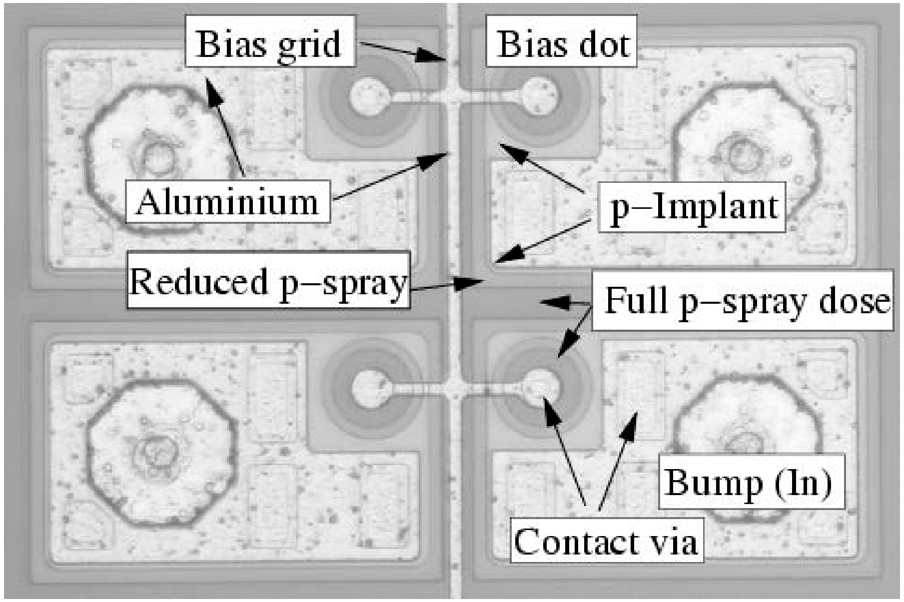
## Avoid problems in module design

- N-Substrate
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing

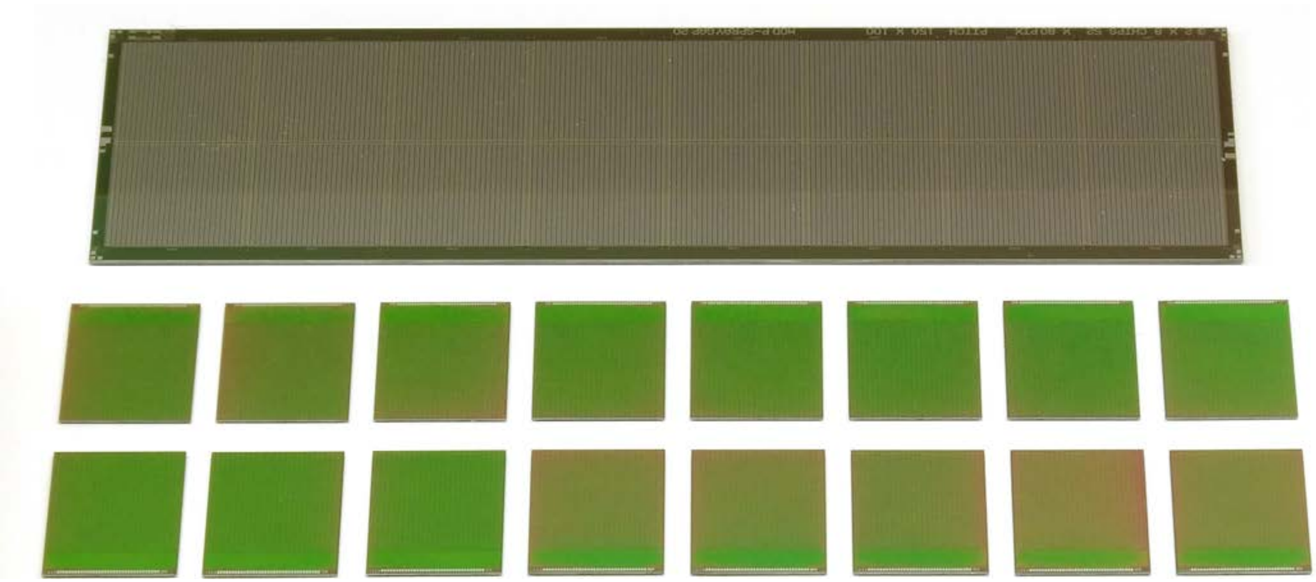
## Pixel cell layout

- Moderated p-spray with bias grid
  - Reliable IV measurements prior to flip chip procedure
  - Only moderate over depletion necessary
  - Small partly insensitive area of the order of 2% (not effect on efficiency in CMS)
- Small gaps between implants
  - homogenous drift field
    - Minimize effect of field separation on charge sharing
    - Avoid flied peaks (high voltage capability in irradiated state)
  - higher C ~ 80fF (Not critical for performance)



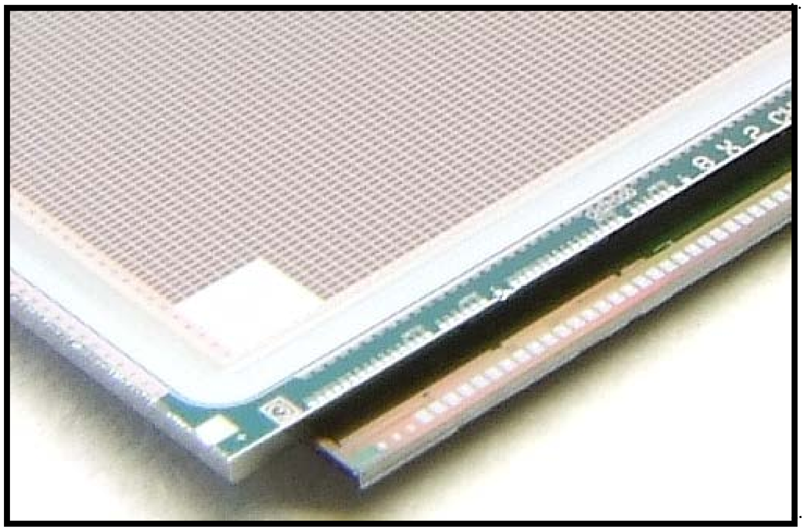



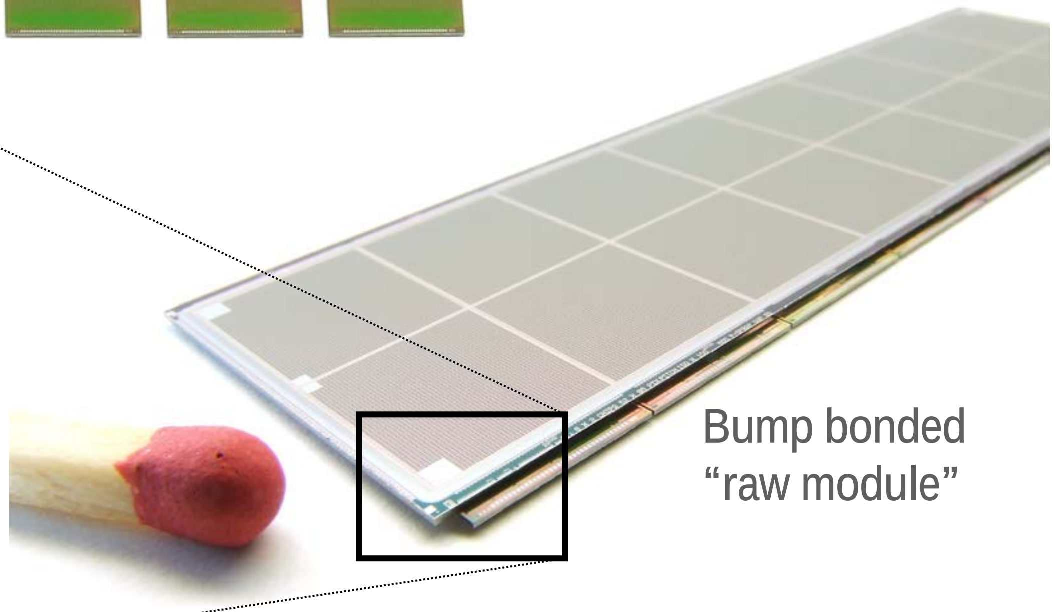
# Bare module



Pixel Sensor with
UBM & Indium balls

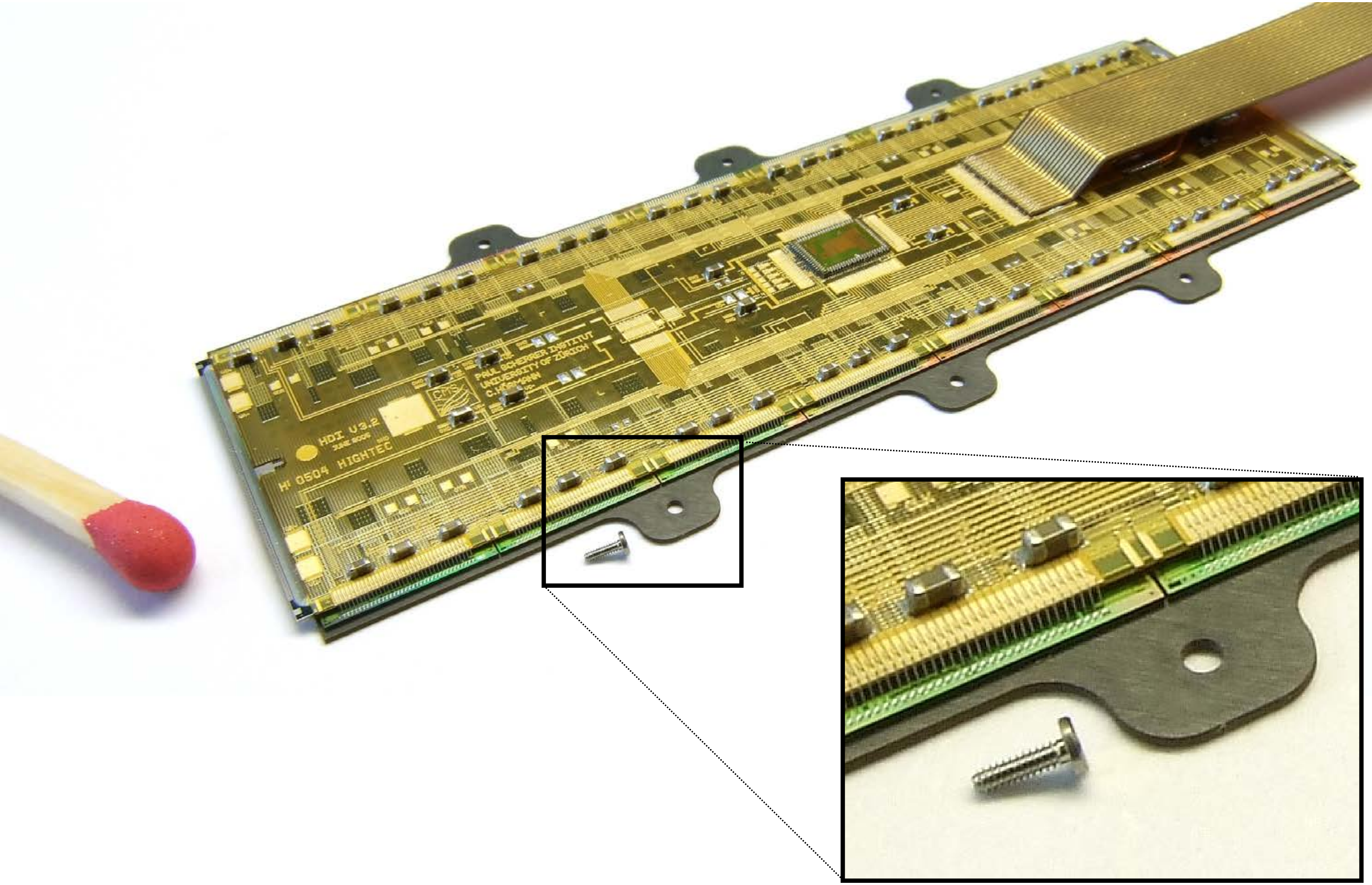
16 tested CMOS ROC chips with
UBM & Indium



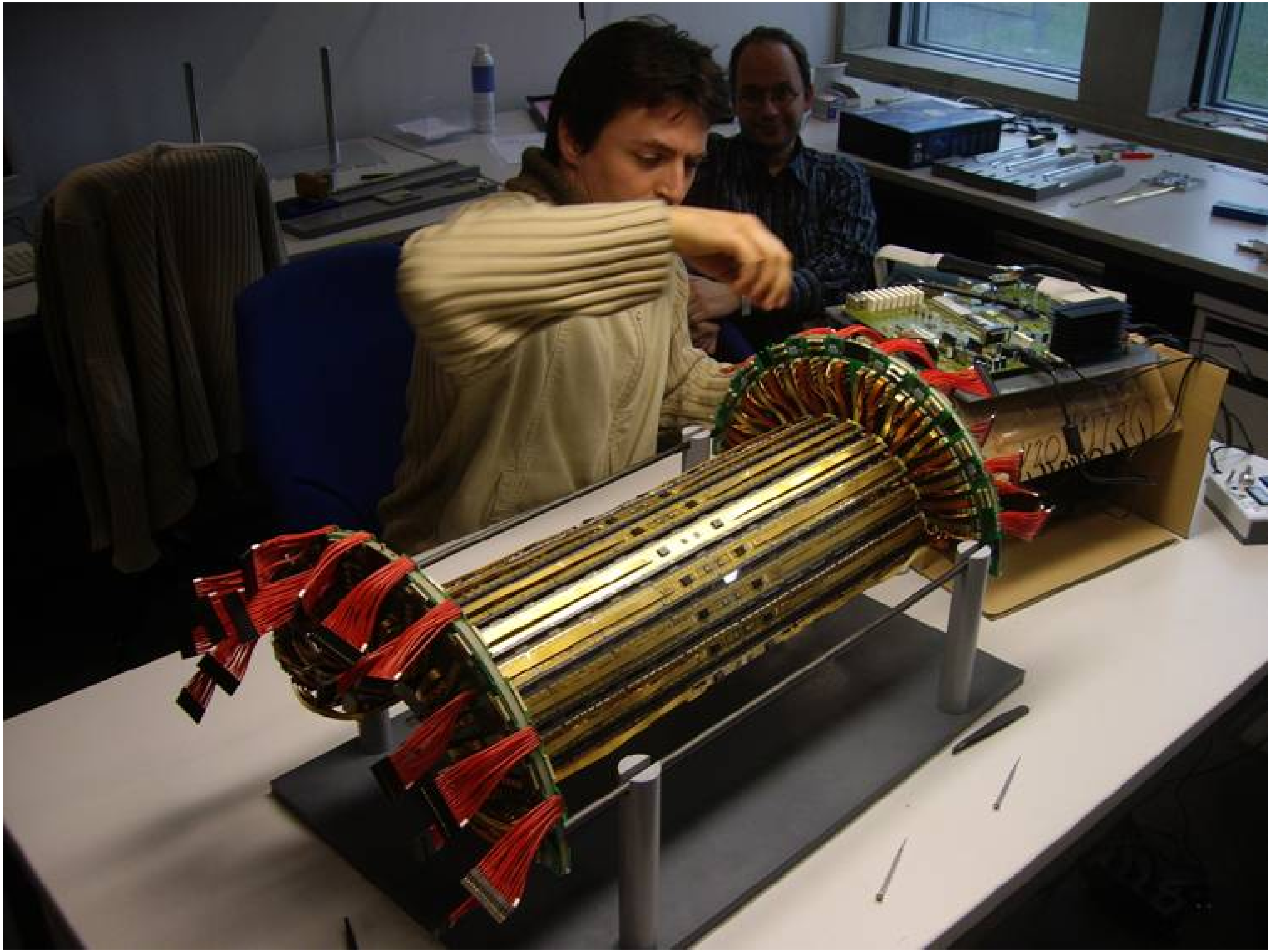


Bump bonded
“raw module”

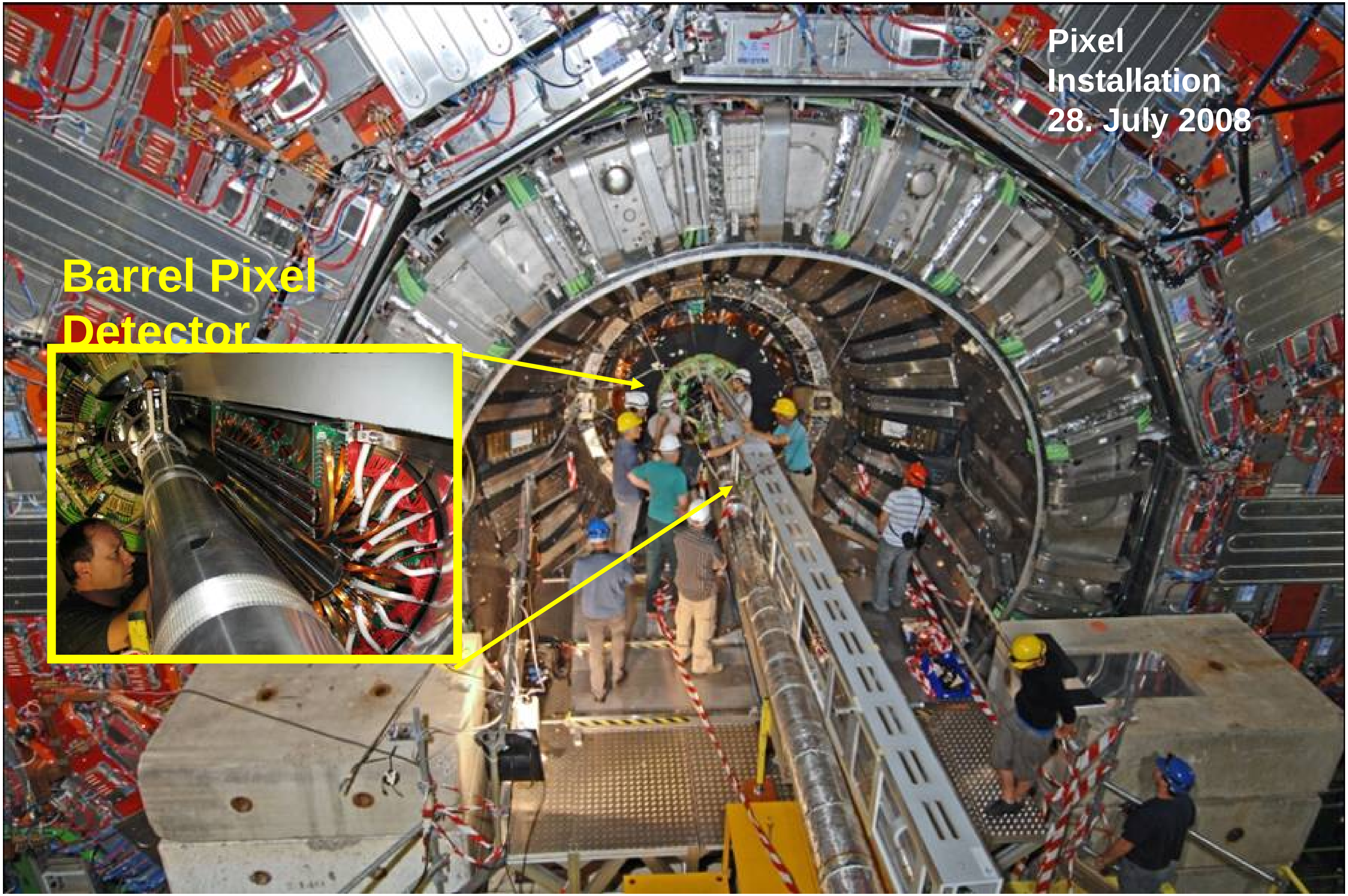
# CMS barrel pixel module



# Half shell of the detector



# Insertion in CMS



# Development of signal height

## CMS

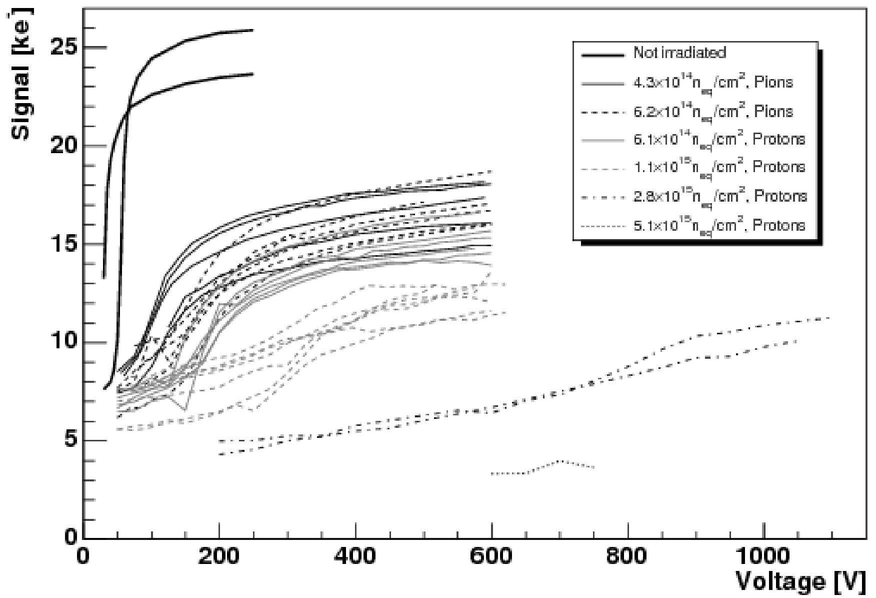
- Performance fully satisfactory
- Radiation level is still low but above the point of space charge sign (“type”) inversion

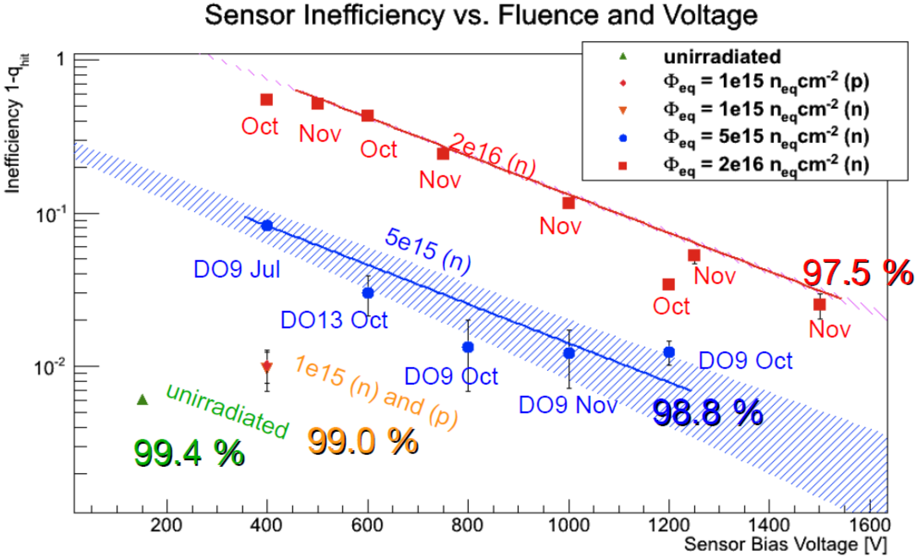
## Radiation hardness studies

- Up to ~$1.2 \times 10^{15} N_{eq}/cm^{-2}$:
  – Several test beam studies in the years 2002-06
  – Including tilt angle, B-field, and threshold
  – Summarized in NIM A 583 (2008) 25-41
- Higher fluences up to ~$3 \times 10^{15} N_{eq}/cm^{-2}$
  – Source tests. Dac settings and trimming procedure not 100% settled
- Fluences up to ~$5 \times 10^{15} N_{eq}/cm^{-2}$
  – ATLAS IBL (same sensor concept and vendor)

Signal height and detection efficiency fully sufficient for the targeted radiation level of $1.5 \times 10^{15} N_{eq}/cm^{-2}$ (~250fb$^{-1}$ in layer 1 at 3cm)

Increase of bias voltage increase the live time



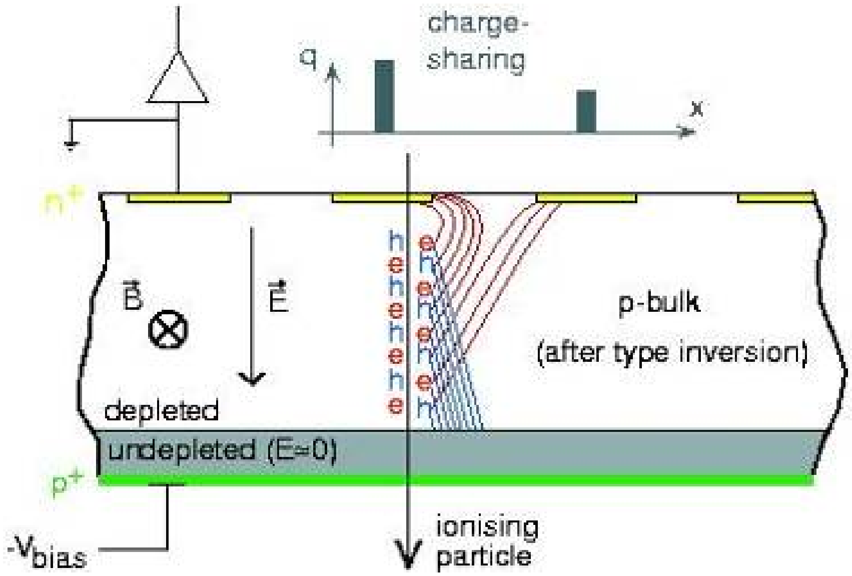



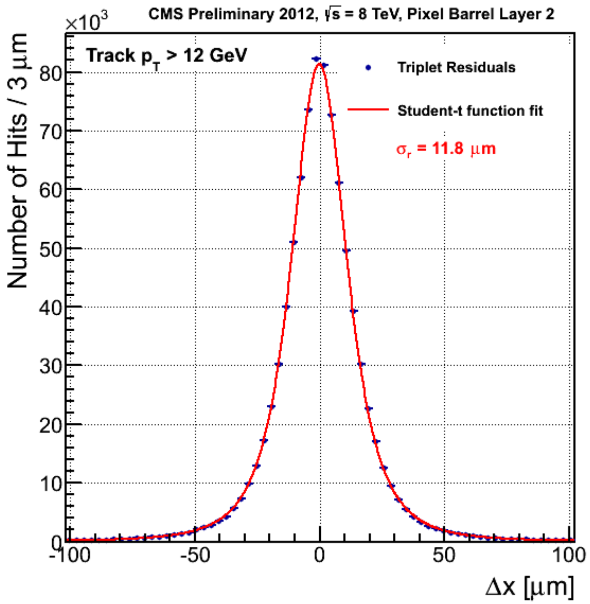

[G. Troska, TU Dortmund, PhD thesis 2012]

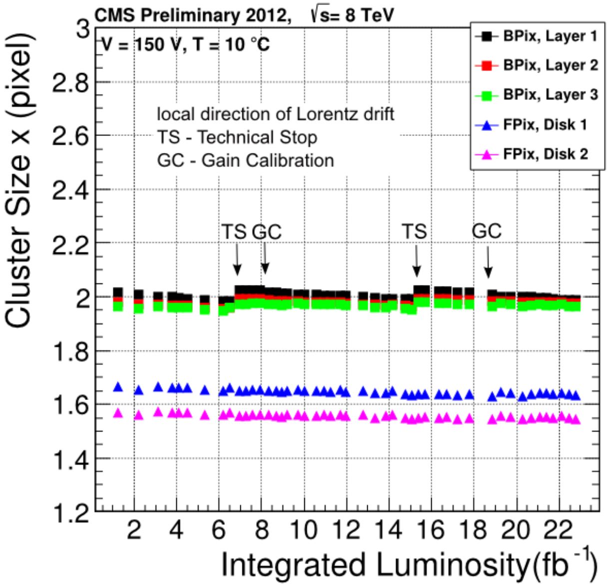
# Spatial resolution

## Value in rϕ: ~9 µm

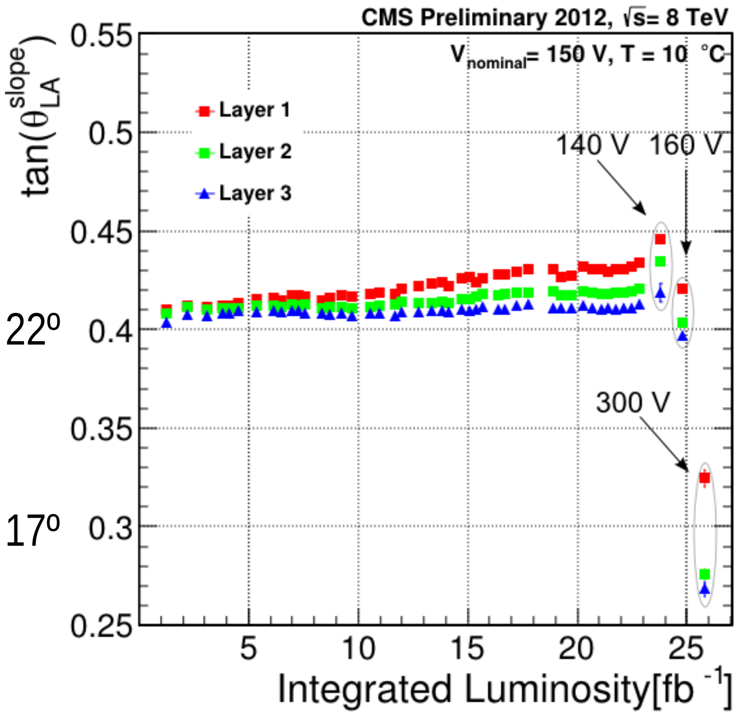
- Cluster size in rϕ-direction ~ 2
  - Lorentz angle presently about 22º
  - High mobility of electrons
  - “Small-gap” implant geometry

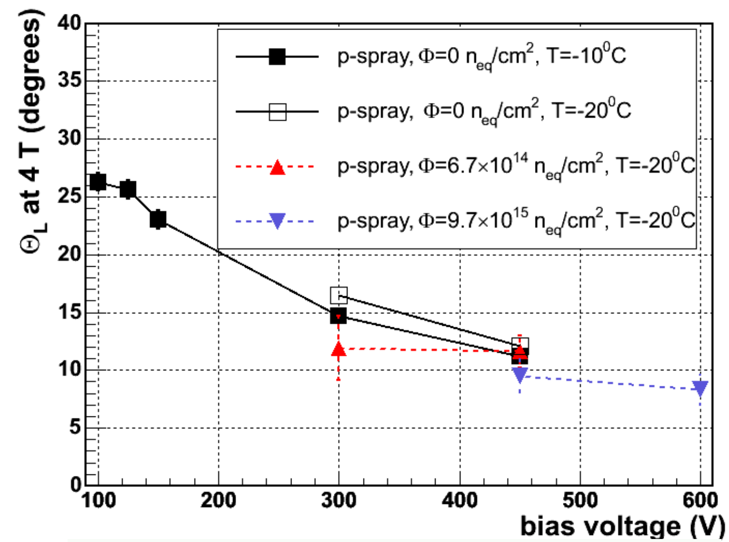


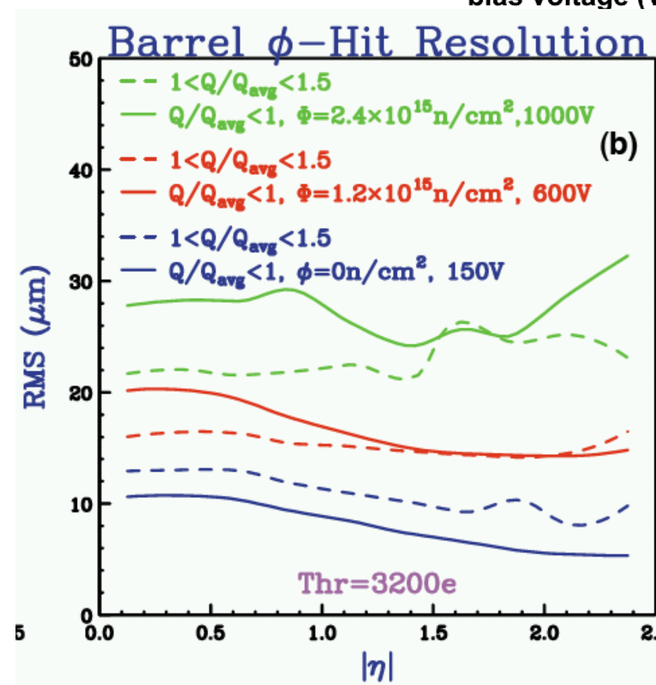



# Development of spatial resolution




A. Dorokhov NIM A530 (2004) 71-76




[Morris Swartz, JHU, taken from the draft TDR]

## Perpendicular to the beam axis

- Lorentz angle is reduced by higher bias voltage
- Process is slow and steady
- Well understood and measured since many years
- No way to prevent this
- Better focusing of charge onto one channel leads to better detection efficiency

# Spatial resolution parallel to beam axis

New detector:

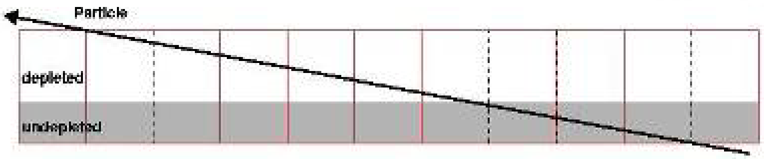
- Very low $\eta$ (cluster length: 1): ~150µm $\times$ sqrt(12)~40µm
- "optimum" (cluster length 2): best interpolation possible ~15-20µm
- Larger $\eta$ (cluster length >2): Interpolation more difficult.
  Fluctuations in the centre of the cluster do not contain information.
- Reach in average ~28µm (overlap studies)

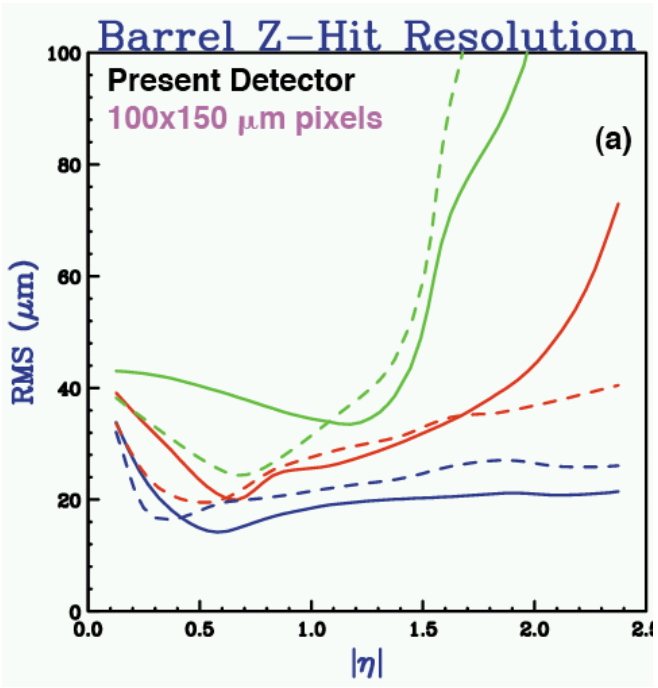
In irradiated sensor:

- Shape of cluster has to be taken into account "template algorithm")
- If fluence is too high/signal too low:
  - level is low (pitch is smaller than thickness)
  - fluctuations might lead to "hole" in the clusters
  - present software cannot "glue" to clusters together
  - large errors in position determination
- Smaller pitch makes things worse

Need

- lower threshold (digital ROC will reach below 2000e)
- powerful software tools to "reconnect" broken cluster, which is difficult in multi track environment inside jets



# Outlook

Needs of LHC-experiments are fulfilled by sensors presently available:

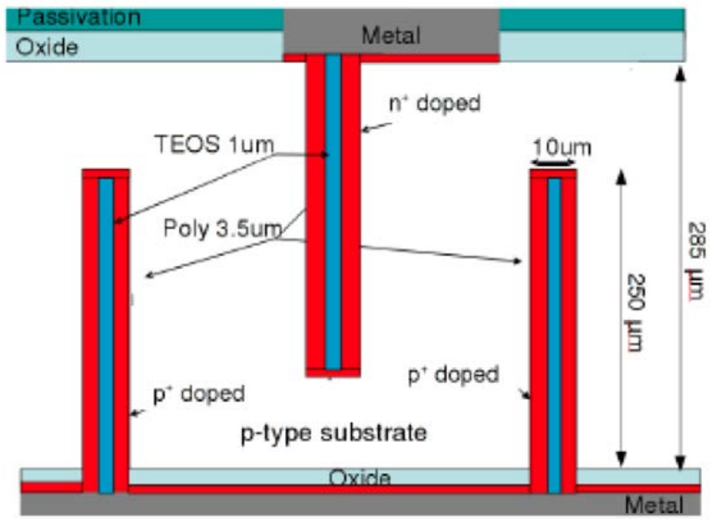
- Large areas: p-in-n strips
- Vertexing: n-in-n pixel

Future projects (e.g. LHC upgrade 2) require

- “Outer” layers: improved radiation hardness at same price level → n-in-p sensors
  - High resistive p-material available
  - Same level of radiation hardness as present pixels
  - Might profit from mixed radiation environment ($\pi$/n) in the outer tracker regions
- Pixel layers
  - Level of ~ $5 \times 10^{15} N_{eq}/cm^{-2}$ or above achieved with present technologies
  - Should consider radiation hardness of read out electronics
  - Easily exchangeable “standard” detector might be the cheapest solution

Other candidate technologies

- 3D sensors
  - Reduce drift distance
  - Proven to deliver high signal at $10^{16} N_{eq}/cm^{-2}$
  - Not attractive for small pixel size (dead area, capacitance)
- Diamond
  - Used in beam monitors at ATLAS, CMS, GSI
  - Polarization effects to be understood
  - Availability of single crystals



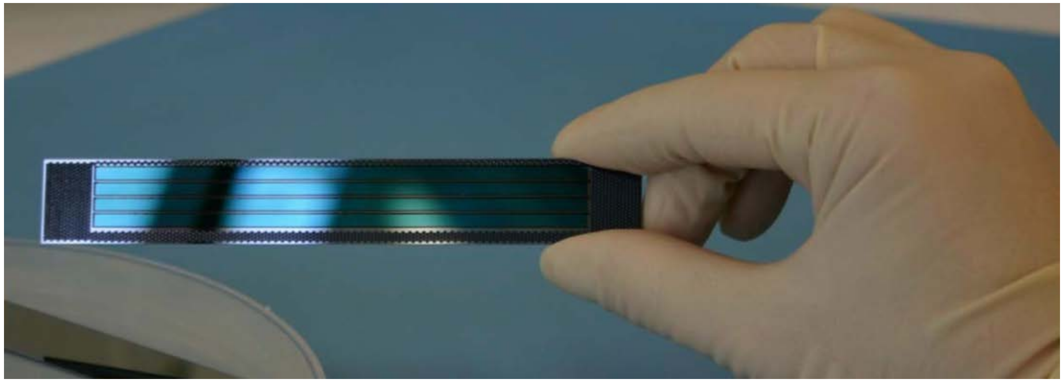
# Linear Colliders

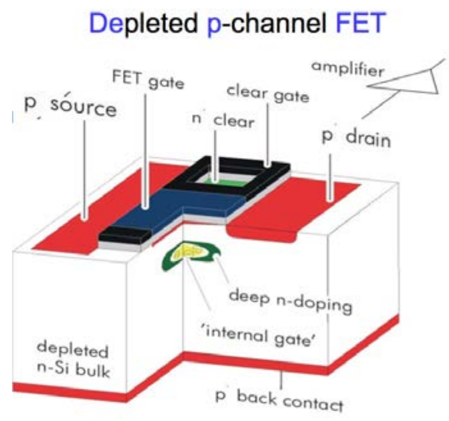
Here an extremely thin tracker is required

- Very thin
- Little power (air cooling)

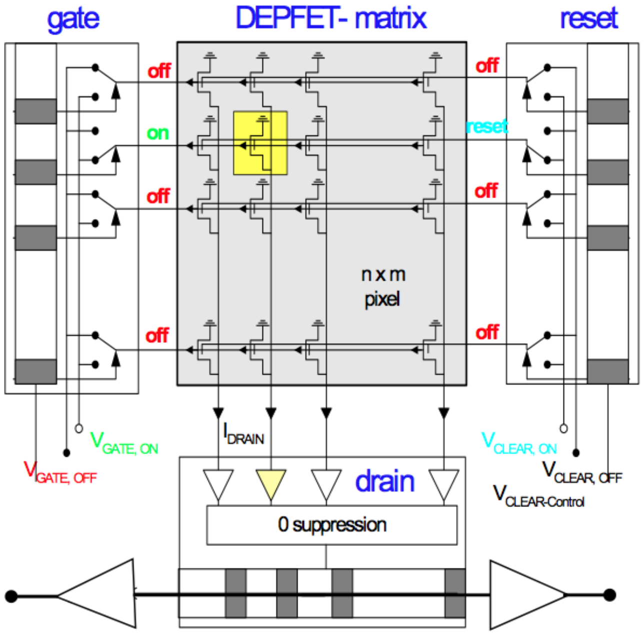
One prototype: BELLE II Vertex Detector

- 2 layers at radii = 1.4, 2.2 cm
- Based on DEPFET principle
  - Sensor can store charge
  - 1st amplification on sensor
  - Also used for X-ray astronomy
- monolithic sensor thickness 75µm
- pixel size ~50 x 50 $\mu m^2$
- rolling shutter mode , 100nsec → S/N=17/1






Ch. Kiesling (MPI, Munich)




**Final device 75um thick → $X/X_0$ = 0.18% !!**

(self supporting, no extra mechanics in sensitive region)

Silicon sensors are an interesting and active field

- Requirements to sensors are very different depending on the experiment
- Up to now all requirements were met
- Development is ongoing with high speed