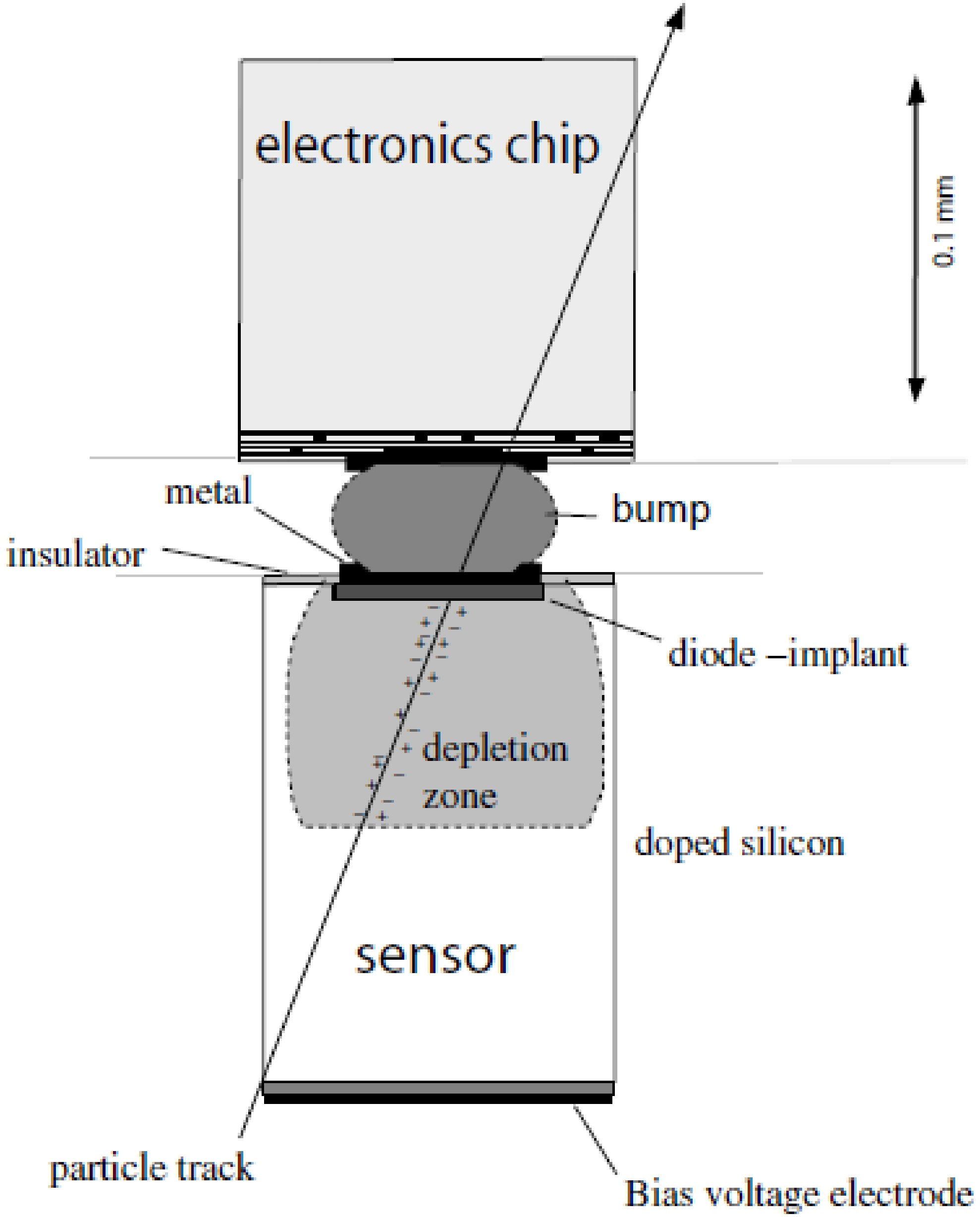
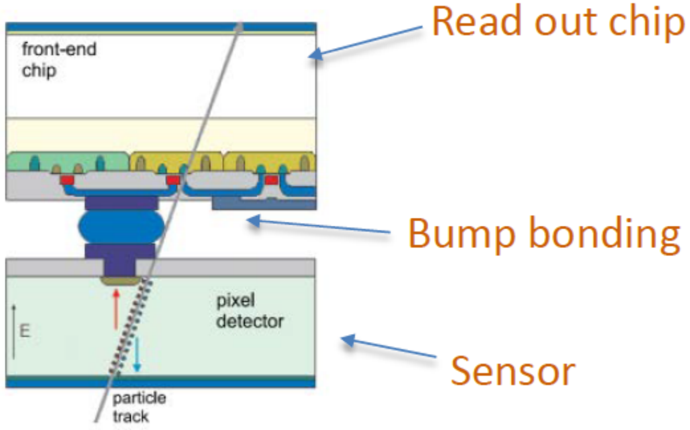
Rivelatori e Apparati

Slides_8 – Pixel, immagini ed esempi

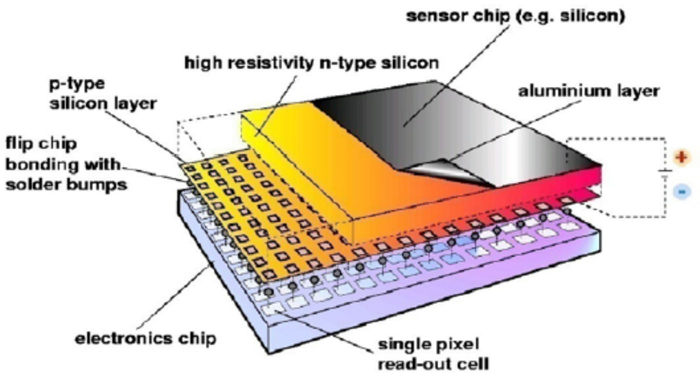

electronics chip
0.1 mm
metal
bump
insulator
diode –implant
depletion
zone
doped silicon
sensor
particle track
Bias voltage electrode

Pixel detectors

- usually **inner layers** of trackers
- **Hybrid pixel** detectors instrument all major LHC detectors



Hemperek (U. Bonn)



Hibrid pixel detectors

Separate sensor and ASIC

- each pixel connected to a readout channel in the ASIC → flip chip + bump bonding and wire bonding

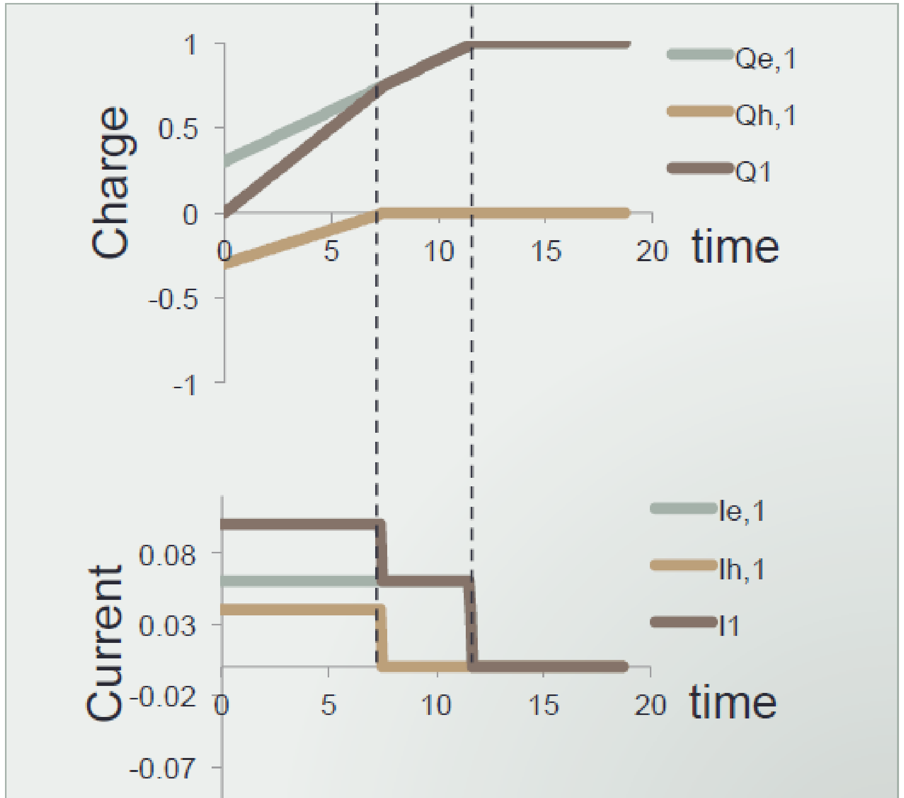
Pros

- Fast
- radiation hard (full depletion, high voltage)
- high S/N
- fully depleted sensor
- complex read out electronics possible (zero suppression)
- **optimize sensor and read-out chip independently**

Cons

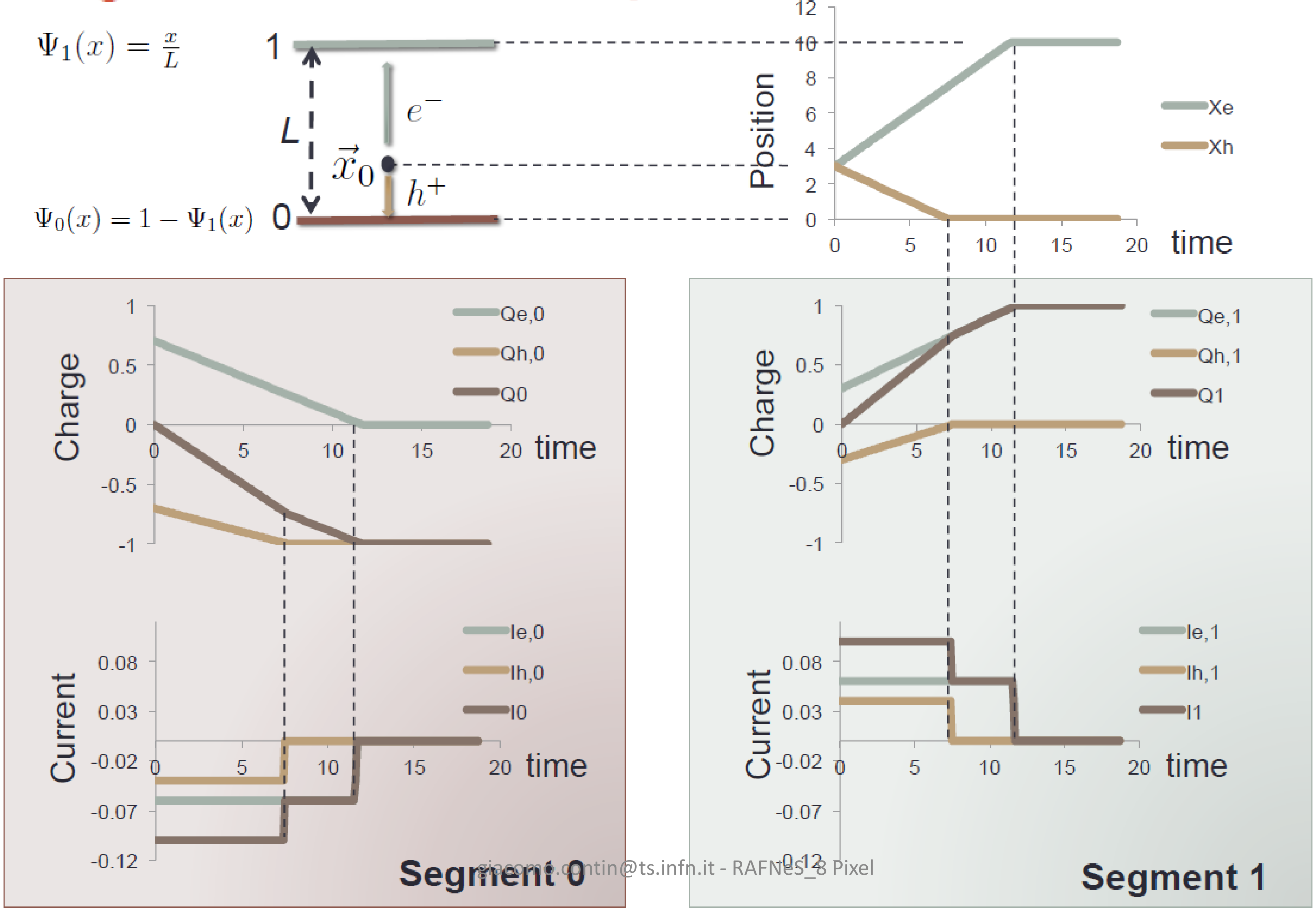
- complex assembly
- ‘thick’
- granularity and power limitations
- costly

Signal formation: planar detector

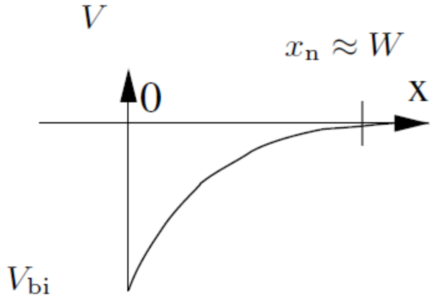


- (Assumed constant drift velocities)
- Electrons and holes are created in equal amounts, at equal positions: Charge signals always start from 0.
- When all charges are collected, the charge signal has the amplitude equal to the collected charge, but with opposite sign of the collected charge (but it is not a collection process)
- Steepest slope method:
  The change in slope can be used to calculate the collection time and thus

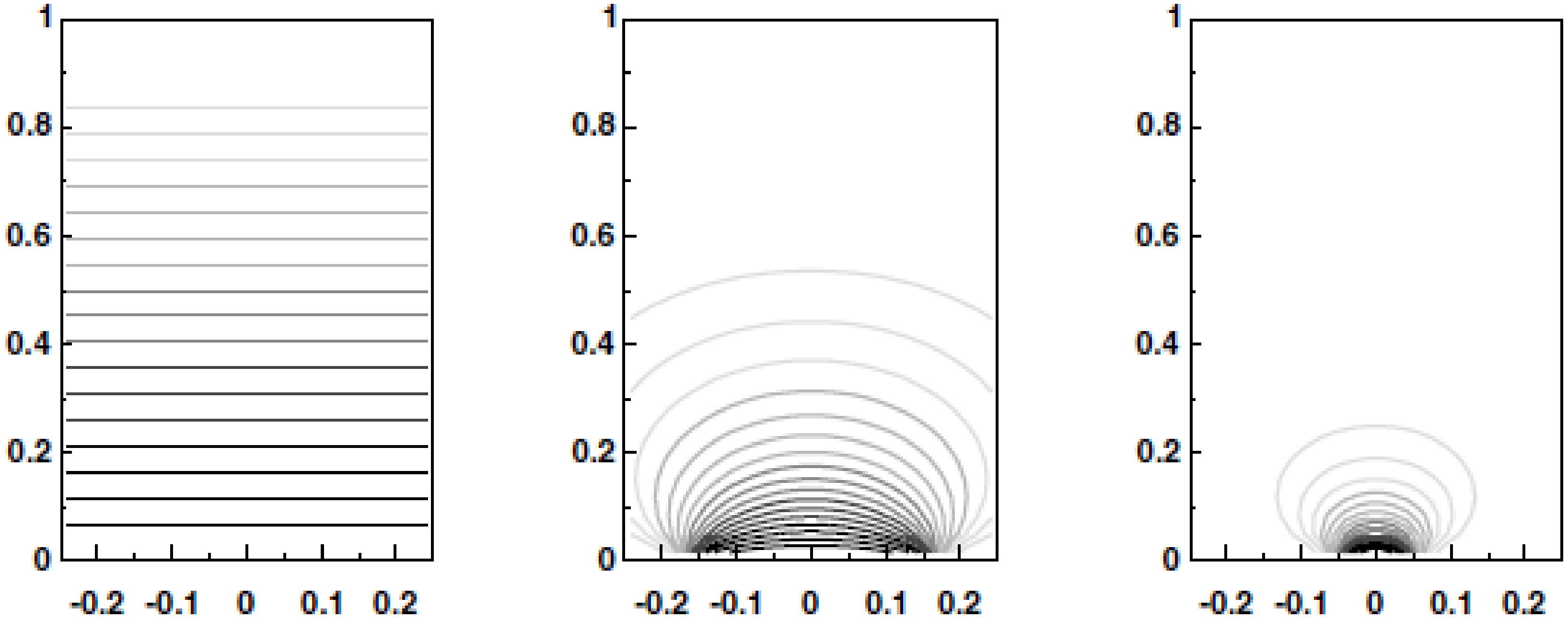
Signal formation: planar detector



Potenziale peso (weighting potential)



Campo di deriva



Giunzione piana

Elettrodo largo 1/3 dello spessore

Elettrodo largo 1/10 dello spessore

Campo peso

Il potenziale peso e' lineare con la profondita (distanza linee indica gradiente);
Il potenziale di deriva ha forma parabolica (cambia velocita' di raccolta)

Tutto il percorso contribuisce allo stesso modo alla carica indotta (anche se con velocita' diverse, ovvero con diversa corrente):

- Se la carica e' generata a meta' percorso, l'elettrone che si avvicina all'elettrodo induce Q/2, le buca che si allontana da esso altrettanto

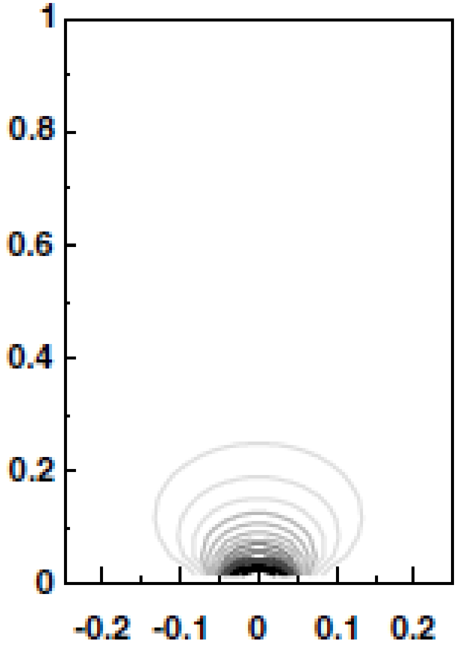
Il potenziale peso non e' lineare, si concentra vicino al pixel, spec. se piccolo

La carica e' indotta solo vicino all'elettrodo ed equivale all'integrale sul percorso

- Le cariche verso l'elettrodo opposto non contano molto
- I pixel vicini inizialmente vedono un signale indotto, che poi cambia segno → integrale nullo

Effetto di piccolo pixel *(small pixel effect)*

- Le differenze piu’ grande tra un sensore a pixel molto segmentato e un pad detector a grande area sono:
    - La maggior parte del segnale e’ indotto nell’ultima parte del cammino di deriva della carica
    - I portatori di carica che derivano verso il piano opposto non contribuiscono al segnale in maniera significative
- Effetto importante in caso di sensori irraggiati quando una parte importante della carica rimane intrappolata e non deriva piu’:
    - Se la probabilita’ di intrappolamento e’ uniforme sul sensore, vuol dire che la maggior parte della carica si ferma prima di riuscire a indurre qualunque segnale sull’elettrodo di raccolta
    - I sensori a pixel piccolo quindi e’ molto piu’ sensibile all’**intrappolamento di carica** dei rivelatori a grandi pads



Risoluzione con lettura binaria (a soglia) e analogica

- Binaria: il segnale viene registrato solo quando passa una certa soglia
  - Soglia abbastanza alta da eliminare il rumore
  - Soglia abbastanza bassa da prendere anche frazioni di segnale

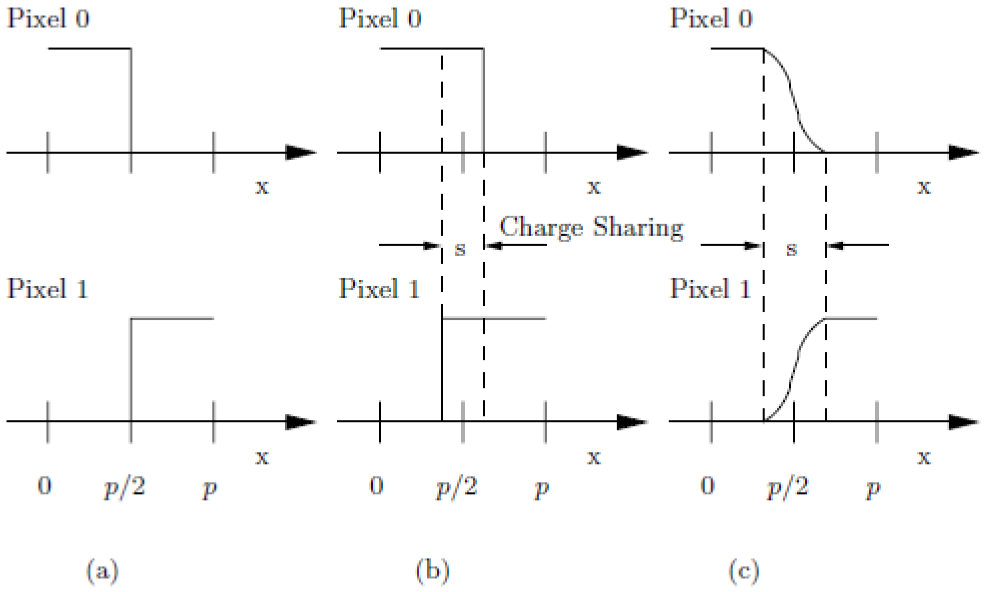
- Cluster in funzione del punto di impatto x della particella:

a) Senza divisione di carica
   - Tra –p/2 e p/2 si accende il pixel0, tra p/2 e 3/2p si accende pixel1

b) Con divisione di carica
   - Tra p/2-s/2 e p/2+s/2 si accendono pixel0 e pixel1

c) Con lettura analogica
   - L'ampiezza indica dove ha impattato la particella

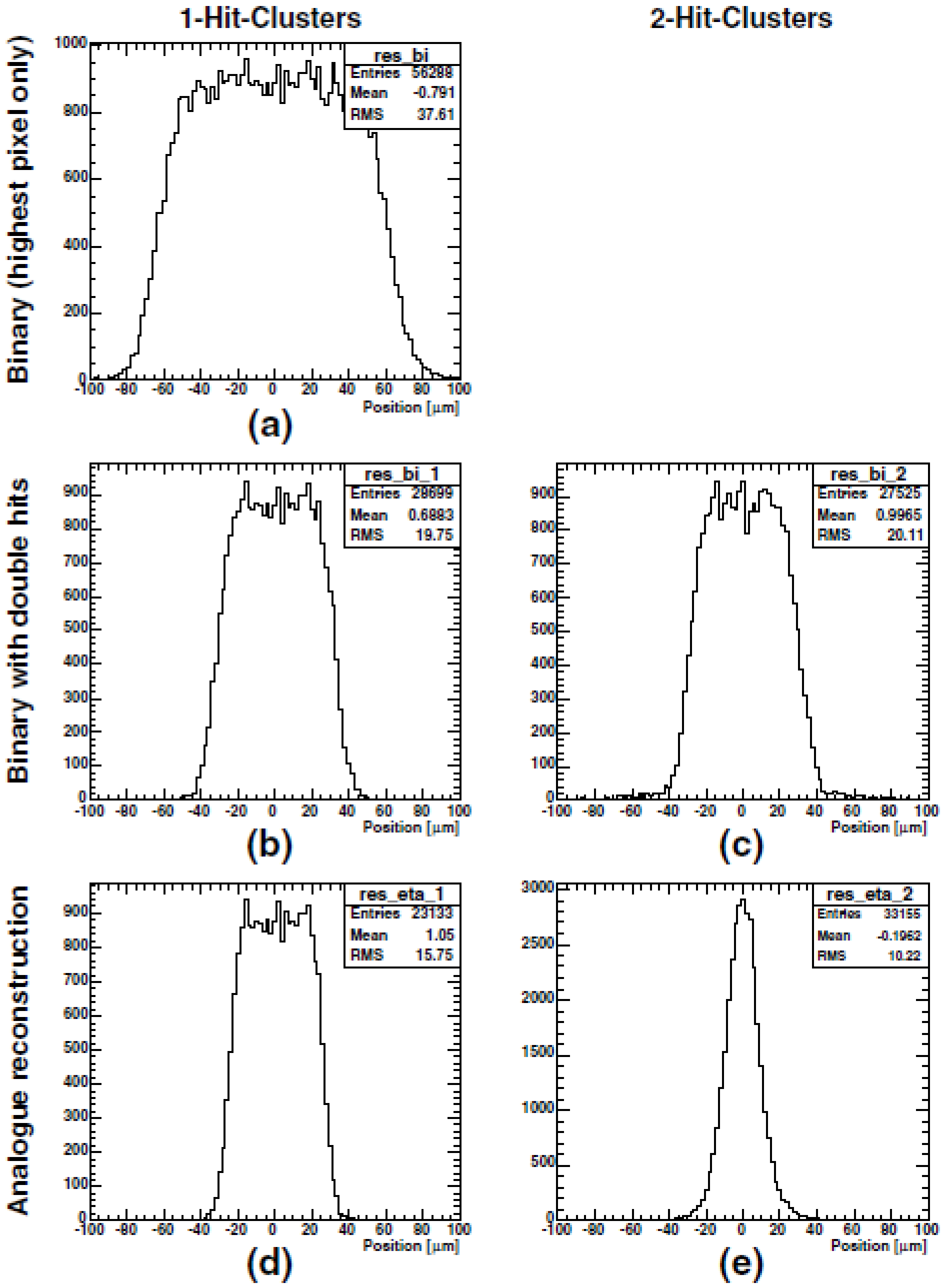
- Condizione ottimale: condivisione s=p/2
  → risoluzione raddoppiata in maniera uniforme



Effetto sulla risoluzione

- Residuo: distanza tra punto effettivo di impatto e posizione ricostruita

a) Equiprobabile sul passo
b) Equiprobabile sul passo
c) o sulla zona di condivisione
d) Analogico pesato su uno
e) e due pixel



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Effetto del campo magnetico

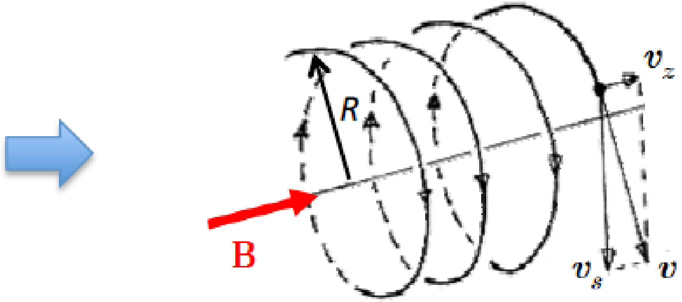
Almost all High Energy Physics (HEP) experiments with accelerators make use of magnetic spectrometers to determine the momentum of charged particles

If a particle with mass m_0 and charge q traverses a magnetic field **B** with velocity v

$$\frac{mv^2}{R} = qvB \qquad \boxed{R = \frac{mv}{qB}}$$

Lorentz force $\boxed{\frac{d\bar{p}}{dt} = \bar{F} = q\bar{v} \times \bar{B}}$

In case of homogeneous magnetic field the trajectory is given by an helix



In experiments at hadronic colliders the emphasis is on the measurement of the transverse momentum p_T

$$\boxed{p_T[GeV/c] = 0.3B[T] \cdot R[m]}$$

Use layers of position sensitive detectors before and after or inside a magnetic field to measure the trajectory and determine the bending radius R

$$\boxed{\frac{\delta p}{p} = \frac{p}{0.3BL^2} \sigma \cdot \sqrt{C_N}}$$

The relative error on the momentum is:

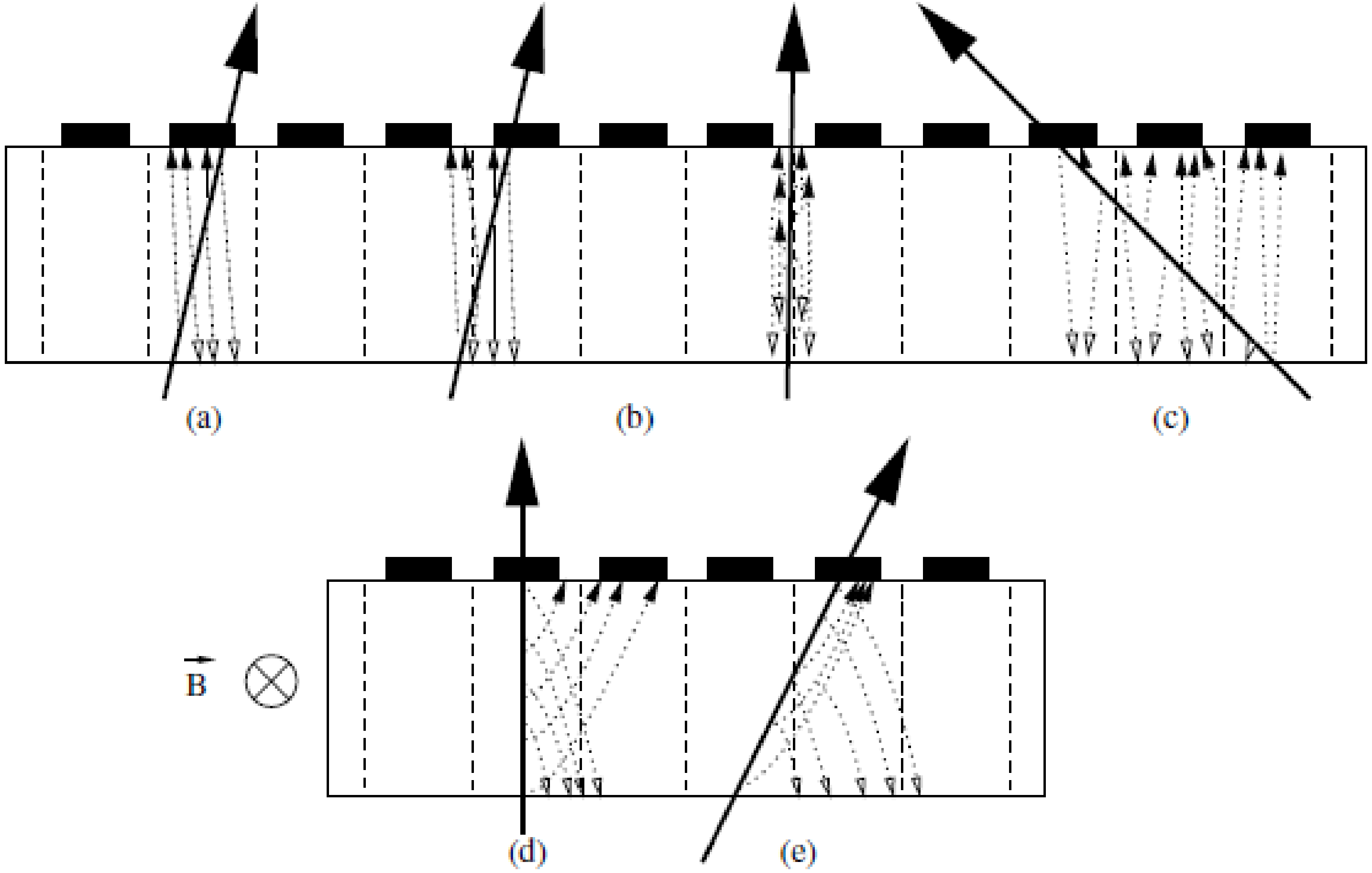
- proportional to p
- inversely proportional to B
- inversely proportional to L^2
- proportional to the detector spatial resolution σ

BL^2 = bending power

Cluster: gruppo di pixel adiacenti «accesi» da una particella

- Senza campo magnetico
  a) Cluster da 1 pixel – traccia obliqua
  b) Cluster da 2 pixel – traccia obliqua/perp.
  c) Cluster da 3 pixel – traccia molto obliqua

- Con campo magnetico
  a) Traccia perpendicolare – cluster allargato
  b) Traccia obliqua – cluster ristretto



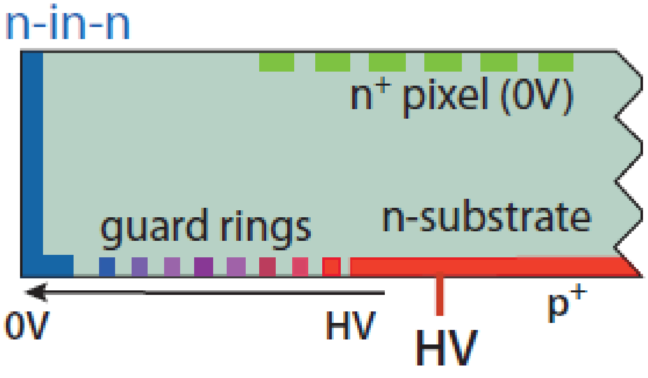
Si puo’ sfruttare il campo magnetico per ottimizzare la dimensione del cluster in base all’obiettivo (risoluzione spaziale)

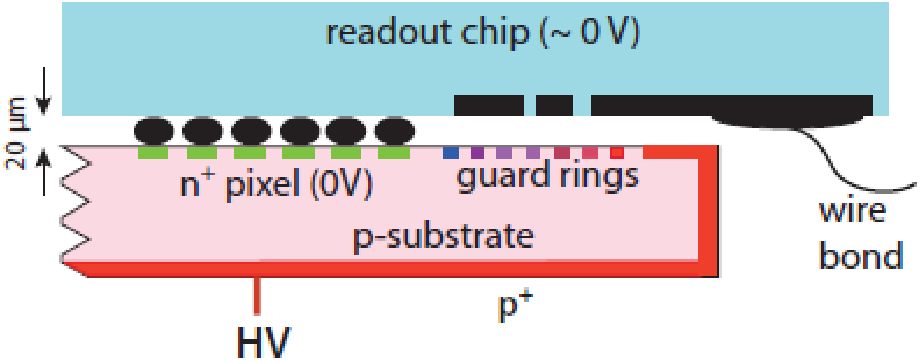
Pixel Planari (simili alle giunzioni viste)

- **n-in-n** richiede:
  - processamento di entrambi i lati
  - guard rings sul lato opposto
  - leggero drogaggio p tra gli impianti n+
  - inversione substrato

- **n-in-p** ha:
  - solo un lato processato
  - guard rings sul lato degli impianti
  - raccolta della carica (e-) piu' veloce
  - maggiore resistenza alle radiazioni

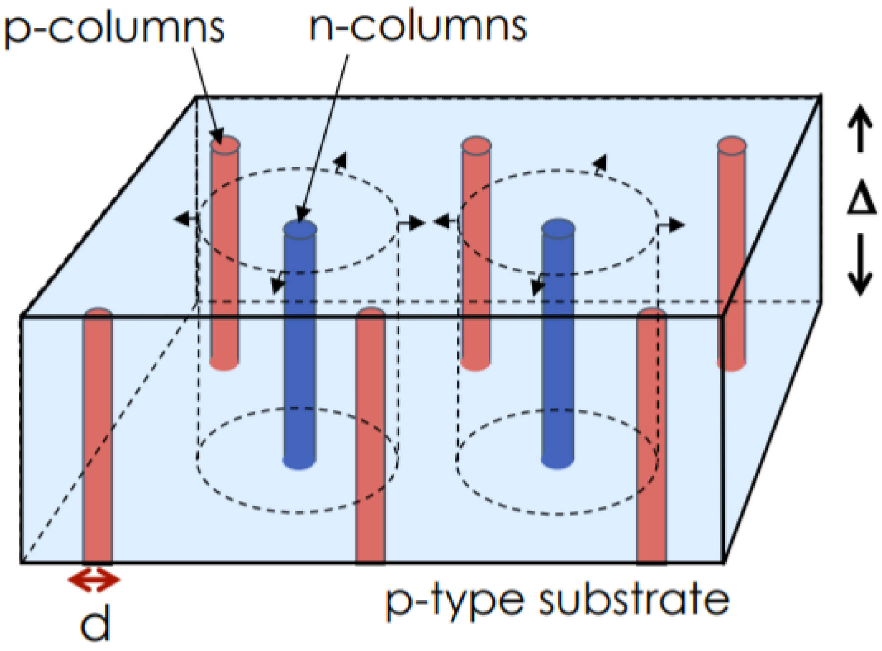
- **possono essere assottigliati**
  - aumenta tolleranza a radiazioni
  - perdita carica generate e segnale





Sensori a pixel 3D

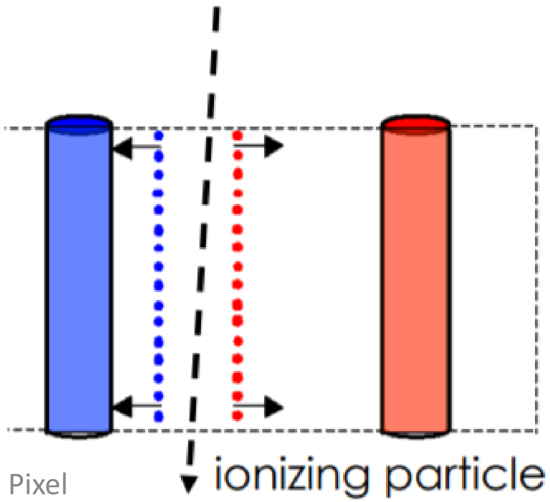
- Tecnologia innovativa ma gia’ ben radicata
- Sfrutta processi di microlavorazione moderni usati per sistemi micro-elettromeccanici (MEMS) come il DRIE
- Realizzazione di elettrodi verticali a colonna che penetrano il substrato di silicio



Δ ~ 200 µm
d ~ 10 µm

Modo per avvicinare l’elettrodo senza diminuire spessore attivo

- Veloce raccolta
- Segnale piu’ grande



- **Non uniform spatial response**
  - Electrodes are inefficient regions

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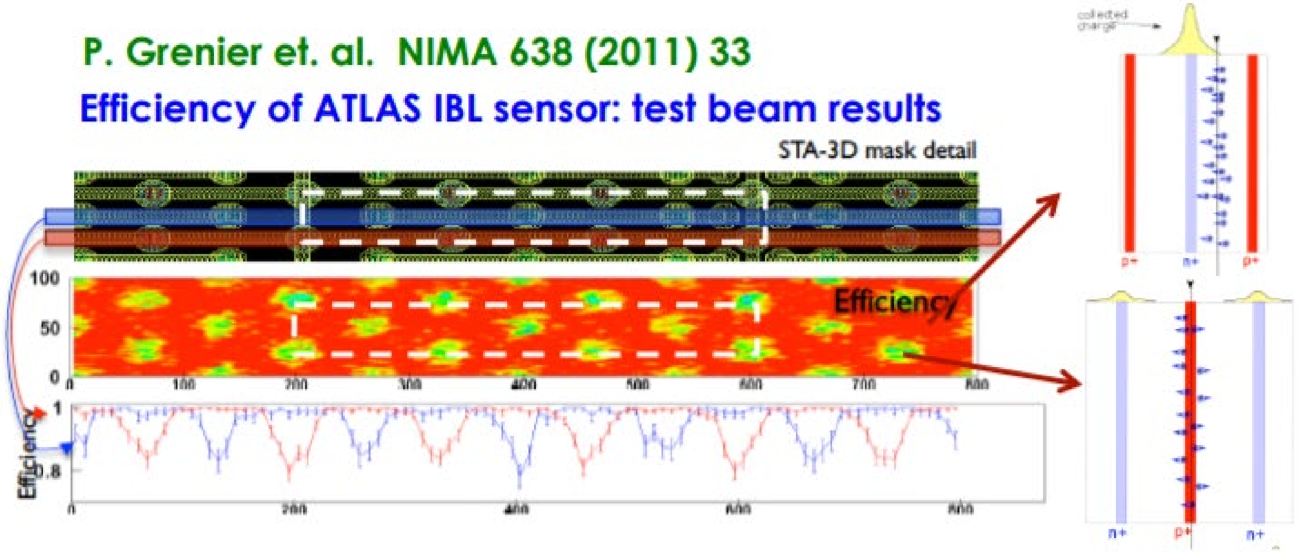
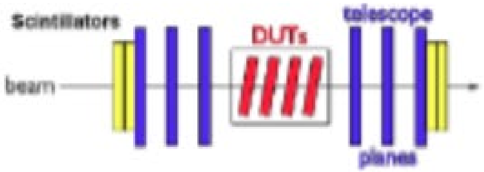
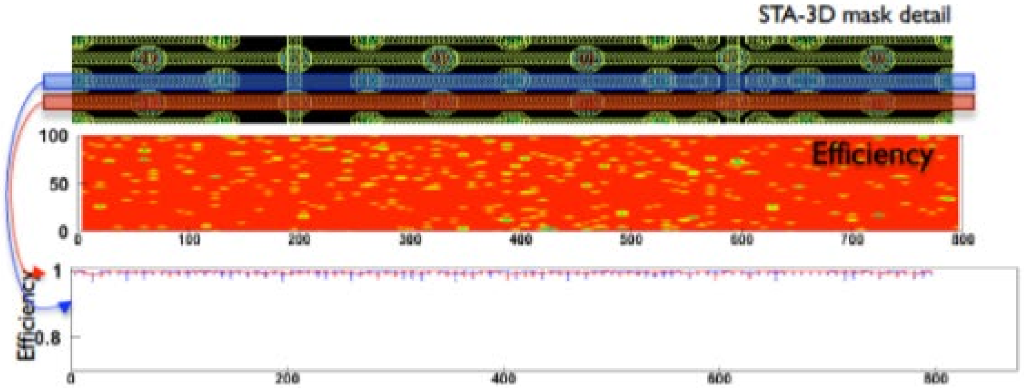
Efficiency of ATLAS IBL sensor: test beam results

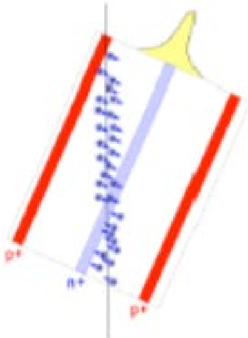




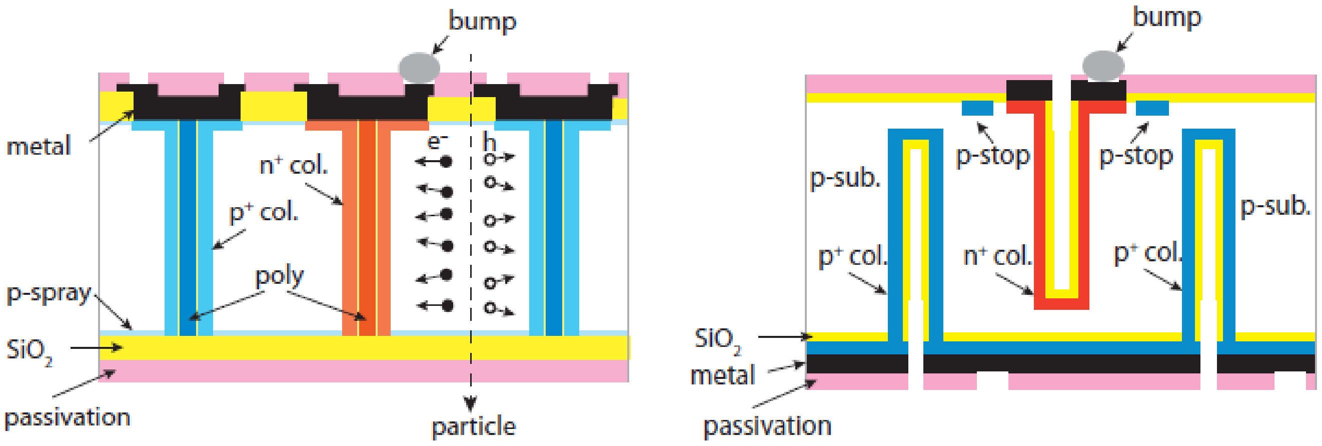
Efficiency recovered by tilting sensors

→ Efficiency >99.8% with ~10° angle

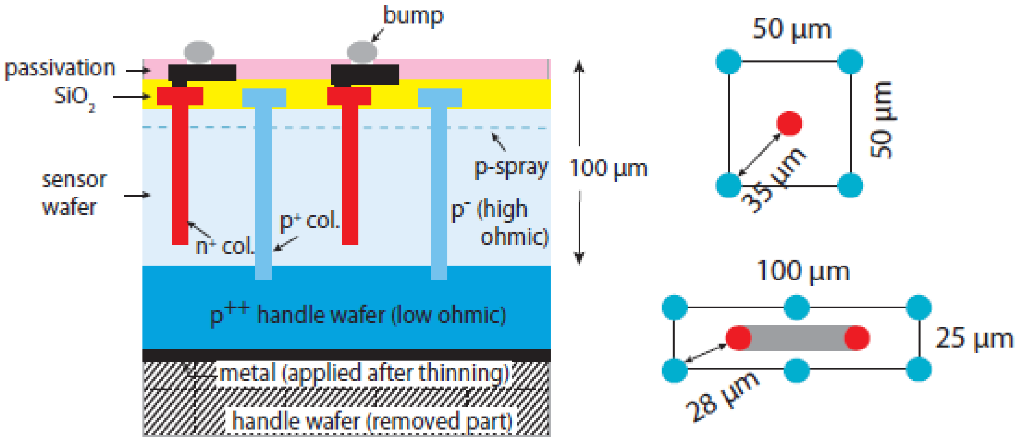




Pixel 3D



(a) 3D-Si: penetrating columns (b) Partial 3D-Si (double sided)

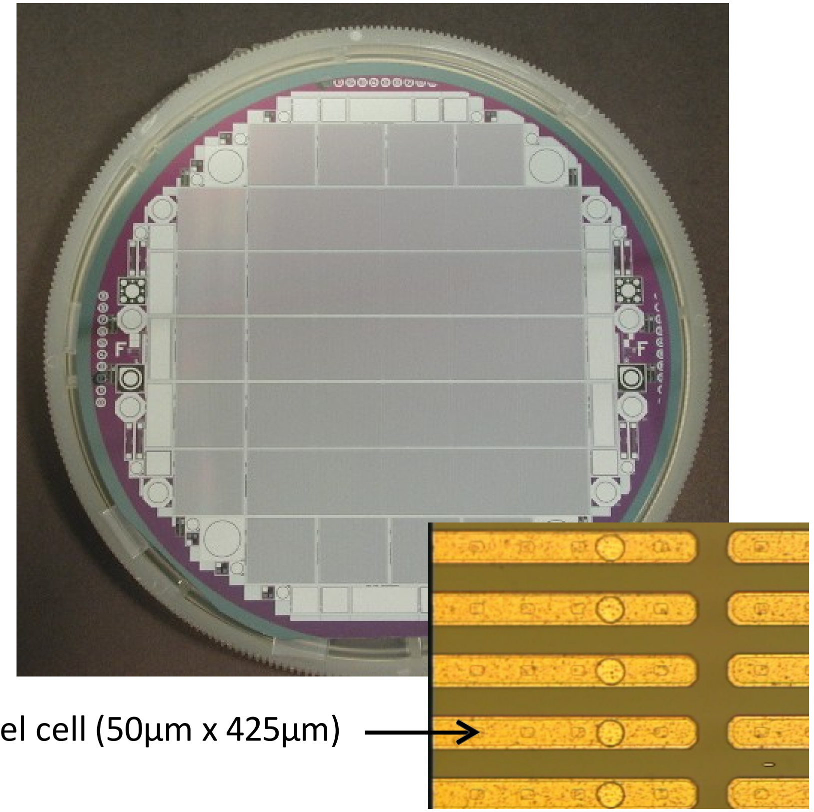


(c) HL-LHC design

Figure 11: 3D-Si sensors: (a) Design (single sided) with columns going completely through the sensor bulk [59]; (b) double sided design with columns entering from both sides, but not reaching through (adapted from [63]); (c) thin design optimized for HL-LHC (adapted from [64]) with two top view sketches for 50 × 50 μm^2 and 25 × 100 μm^2 pixel sizes, respectively [65].

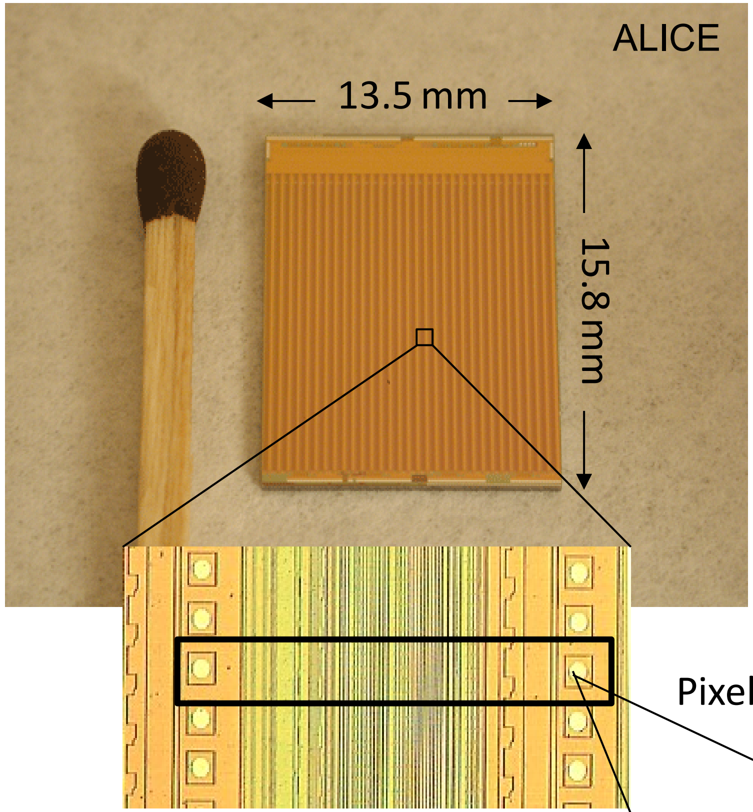
Hybrid Pixel Detectors

1. Pixel Sensor

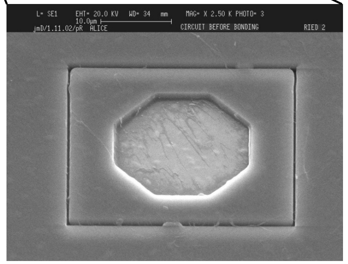


Pixel cell (50µm x 425µm)

2. Readout Chip (ASIC)

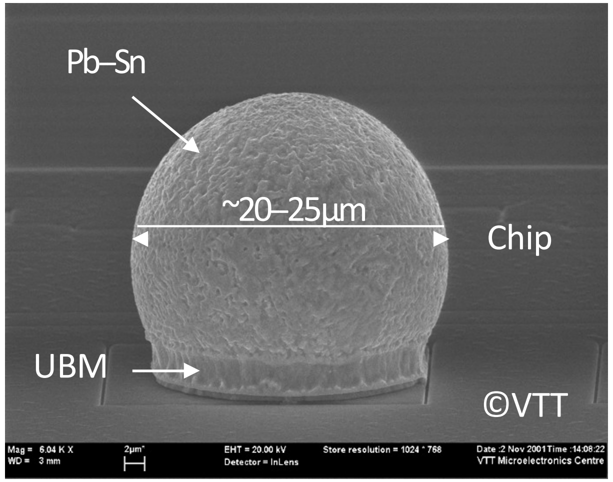


Pixel cell (e.g. 50 µm x 425 µm)



Bump bonding pad

3. Bump Bond



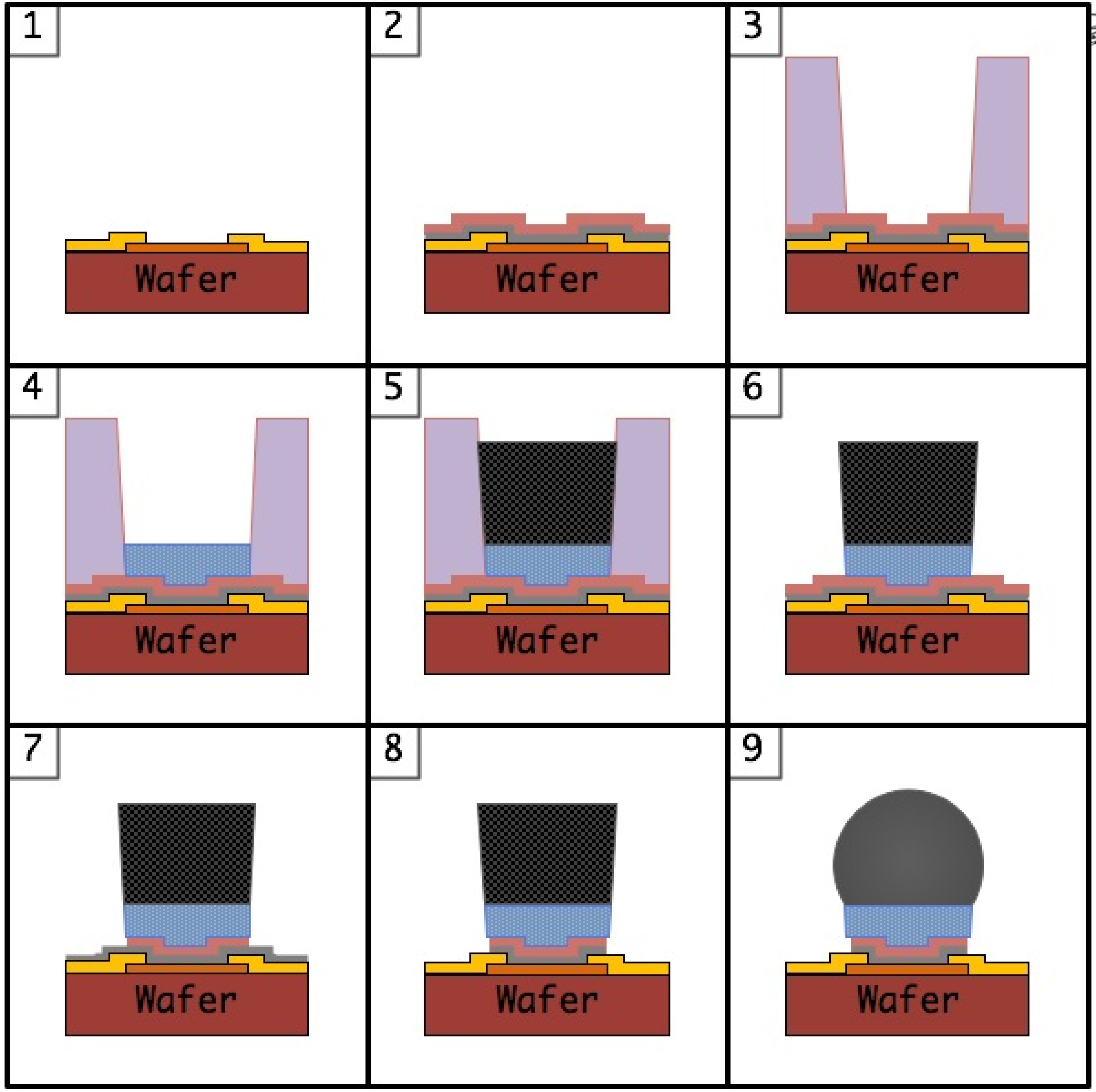
SEM picture of one bump bond

Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond

Usually several readout chips are connected to a single sensors

Processo Bump bonding

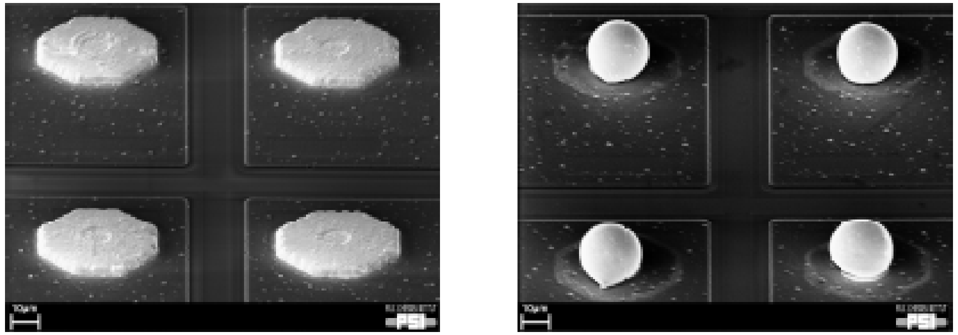
1. Pulitura wafer
2. Deposito degli strati adesivo (Ti:W) o iniziale
   - Adesivo Ti:W, anche barriera per atomi rame
   - Iniziale: base Cu o Au depositata elettrochim.
3. Applicazione spesso fotoresist
4. Deposizione elettrolitica UBM
   - Underbump metallization
5. Deposizione elettrolitica materiale saldante
6. Rimozione meccanica fotoresist
7. Rimozione eccesso strato iniziale (etching)
8. Rimozione eccesso strato adesivo (etching)
9. Riflussaggio materiale saldante
   - Assume forma sferica
   - Facilita riallineamento dei sensori



*etching = incisione

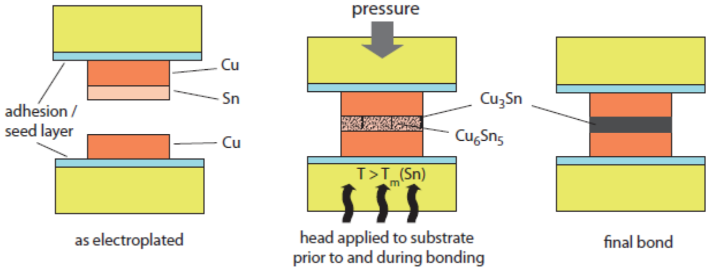
Altri Bump Bonding

In-In bonding



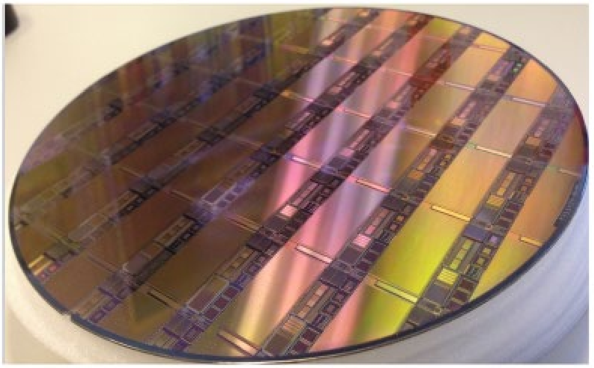
- Indio-Indio bonding
  - Deposito di vapore di indio attraverso finestre
  - Bump piatti e sottili, Saldato via termocompressione a 100C
  - Vantaggi: bassa temperature e facile da implementare-Svantaggi: bond fragile e resa bassa (90%)
  - Puo essere riflussato per fare assumere forma sferica ai bump
- Bonding adesivo
  - Strato di materiale adesivo e accoppiamento capacitivo tra pads dei due sensori
  - Richiede ottimo allineamento e planarita’, economico, connettivita’ non provata
- Bonding diretto Cu-Cu
  - Le pad vengono messe in contatto con forze adesive. Atomi di Cu si diffondono tra le pad
  - Termocompressione e’ semplice ma richiede troppo alte temperature
  - Attivazione di superficie a temperature ambiente con trattamento chimico
  - Vantaggi: passo molto piccolo e’ possibile 4um
  - Svantaggi: richiede livelli di pulizia e planarita’ elevatissimi

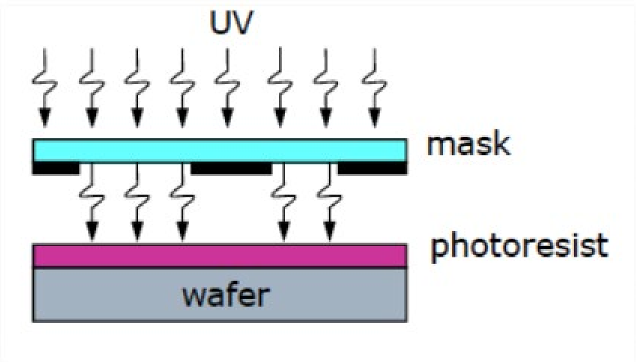
SLID



Connessione, assottigliamento, cucitura

- Bonding Ossido-Ossido
  - A temperatura ambiente i wafer sono rivestiti con strato di ossido che si lega all’acqua.
  - Richiede estrema pulizia e connessioni elettriche aggiuntive (tipo “through silicon vias”-TSV)
- SLID: Interdiffusione solido-liquido di Stagno e Rame
  - Si legano a 240-320C, non reversibile
- Assottigliamento (thinning)
  - Wafer partono da spessori piu’ spessi (700-250um) per arrivare allo spessore desiderato (300-150um)
  - Substrato sul lato inattivo viene grattato via per sfregamento con dischi con superficie a grana via via piu’ sottile, da 20-80um a 1-8um
  - Il lato attivo e’ protetto da adesivo che viene poi lavato via
  - Resistenza alle rotture, deformazione, incurvamento da tenere sotto controllo
- Cucitura (stitching)
  - Esposizione allineata della stessa maschera ripetuta sul reticolo (25mm*25mm) per coprire grandi superfici





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Primi rivelatori a pixel

- 1984 IEEE Nuclear Science Symposium: circuito integrato per sensori per imaging a piano focale (Hughes Aircraft Co.)
- Accoppiato con bump bonding a matrice di diodi semicondutori per la rivelazione e localizzazione di raggi X
- 4 MOSFETs per pixel
  - Piccole dimensioni di pixel
  - Carica integrate per centinaia di μs su un condensatore per minimizzare il rumore seriale dell'elettronica
  - Lettura multiplex di ogni pixel a turno, a un tempo prefissato.
- Funziona a condizione che:
  - Ogni pixel tiri una corrente molto bassa per non saturare l'amplificatore di lettura e non contribuire al rumore parallelo dell'elettronica
  - La frequenza dei dati e' mantenuta a 1 kHz al massimo
  - Il dispositivo viene interrogato in continuo e non con trigger esterno

Primi rivelatori a pixel

- Limitazioni compatibili con applicazione imaging ma non per particelle cariche
- Evoluzioni seguenti negli anni ’90 in sviluppi per SSC e LHC
- Applicazioni a esperimenti a bersaglio fisso
  - Grazie al boost di Lorenz la maggior parte delle tracce si concentra in un cono, basta un piccola superficie coperta dal sensore
  - Tutti i servizi (cavi e raffreddamento) possono essere posti fuori dal volume sensibile
  - Si puo’ accedere al rivelatore frequentemente e facilmente, vista la configurazione degli esperimenti a b.f.
- Prime applicazioni sono state le collisioni tra ioni pesanti
  - L’alta molteplicita’ di particelle prodotte puo’ essere gestita bene da questi rivelatori ad altra granularita’ e con informazione 3D
- R&D specifico per rivelatori per raggiungere prestazioni estreme in vista di LHC
  - OMEGA Pixel Detectors

OMEGA pixel detector

- Matrice del sensore attivo
  - Pixel size 75 × 500 μm^2
  - 1024 pixel (16 colonne e 64 righe)
- Solder bump bonding
- CMOS readout chip in 3μm feature size
  - Preamplificatore sempre attivo
  - seguito da comparatore asincrono
  - ritardo digitale in attesa di trigger esterno:
  - quando il trigger arriva, tutti i pixel con un segnale sulla linea di ritardo vengono letti.

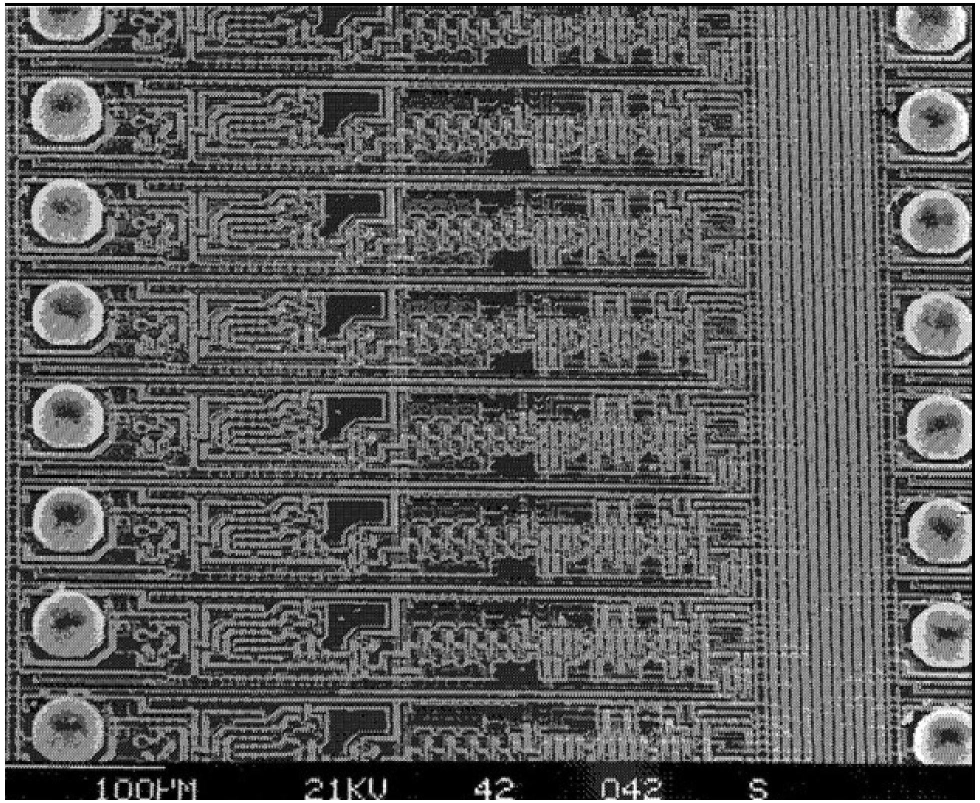


Foto SEM di OmegaD chip

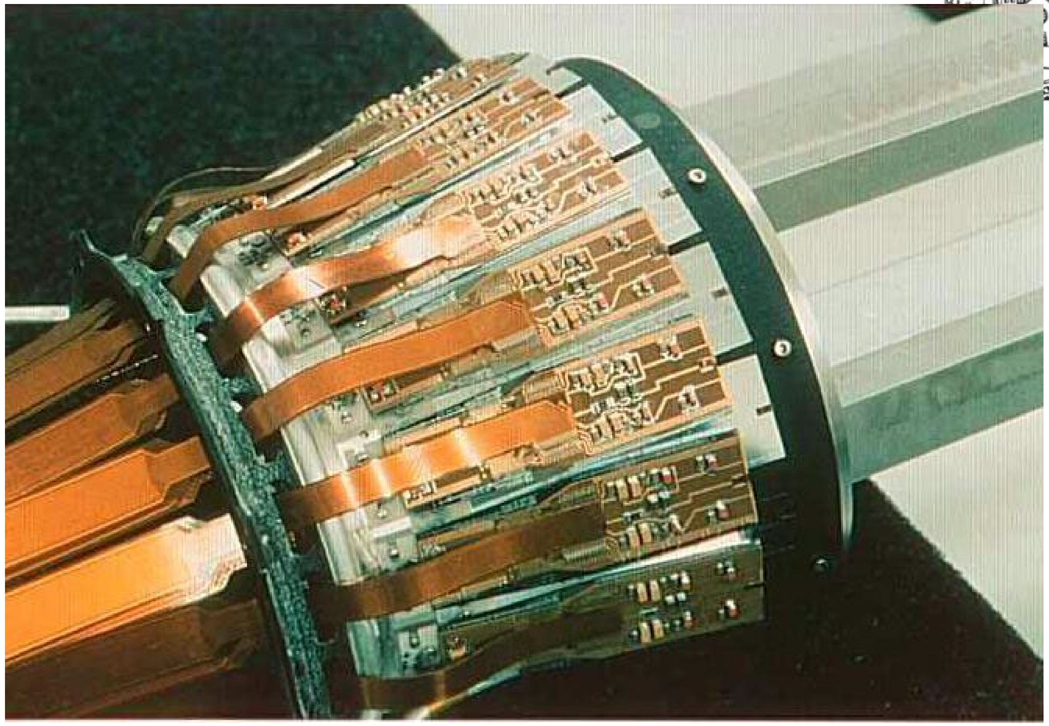
- Prestazioni prima versione
  - 30 μW per pixel (i.e. ≈1mW/mm^2);
  - Rumore elettronico circa 100 e− rms
  - Variabilita' soglia tra canali attorno a 500 e− rms
  - Disuniformita' da pixel a pixel
  - Limitazioni tecniche (variazioni lungo l'area)
  - Scelte di design (sensibilita' a cadute di potenziale)

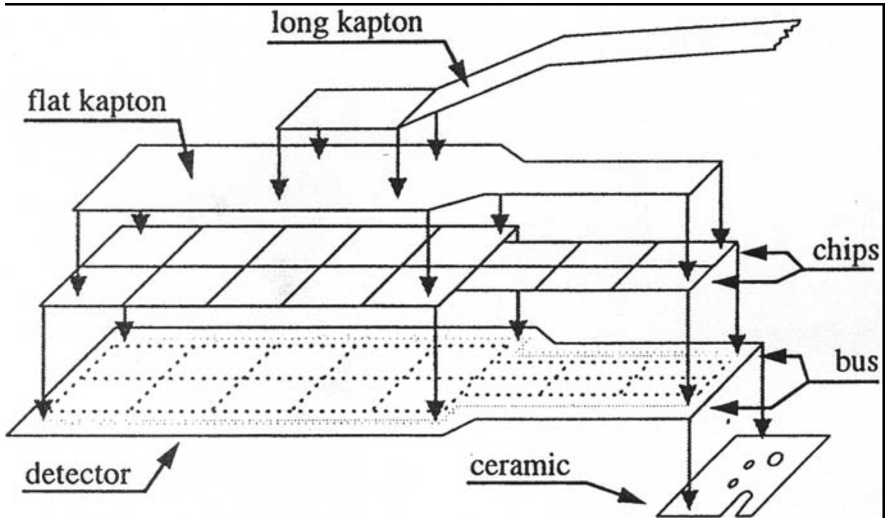
OMEGA – versioni successive

- Feature size da 3 a 0.25 μm
  - da 80 a 500 MOSFET per pixel
  - Strati di ossido piu' sottili
  - Meno danni da radiazione (tollera 300 kGy, fattore 1000)
- Dimensioni wafer cresciuto da 4 a 8 pollici
- Da 3 chip singoli a 84 ladders con un sensore e 6 chip ciascuno
  - 73k pixels per ladder, 29 cm^2 di area
  - Yield basso: 35%
- Ultima versione: ALICE1 per l'esperimento ALICE

PIXEL di DELPHI (LEP)

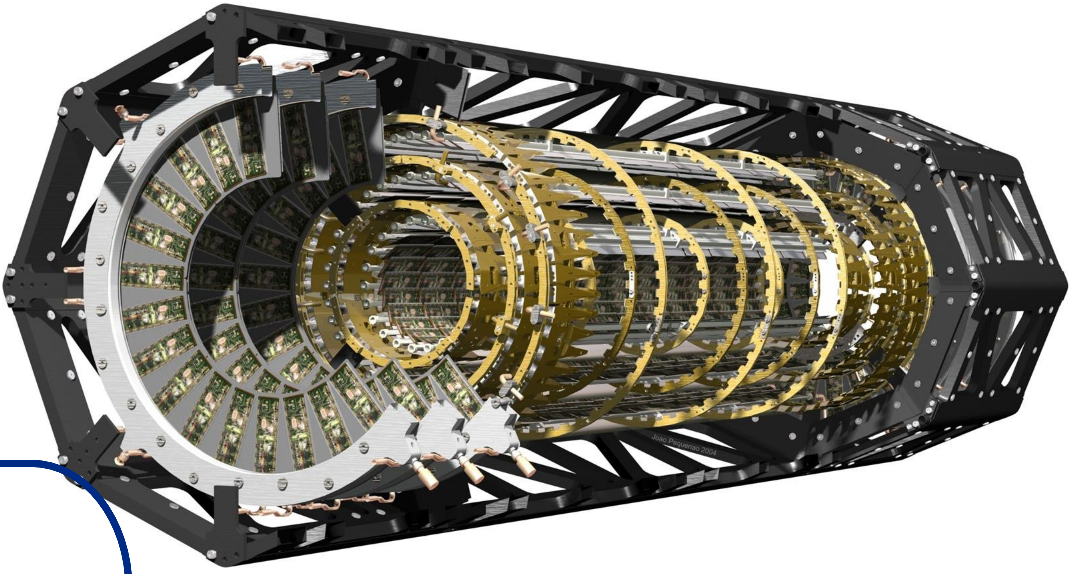
- Corona per estendere accettanza in avanti e indietro
- 1.2 M pixel su 0.15 m^2
- 0.03 W/cm^2 electronics
- Poco materiale inattivo
  - singolo condotto di raffreddamento dentro la corona (gradiente 10C)
  - Scelta di materiali leggeri
- Matrici 24x24 e 16x24 per superficie che si restringe
- 330× 330 μm^2
- Primo tentativo di implementare readout bus sul sensore (ma alta caduta di V richiese aggiunta)
- Rumore: qualche 100e-
- TH: 10 ke- → efficienza > 99%
- 0.3% pixel troppo rumorosi e mascherati
- Raddoppia l'efficienza di ricostruzione di traccia in quella accettanza
- Resa moduli: 36%





The ATLAS Pixel Detector

- 3 hit system up to angular coverage of |η| < 2.5
- 3 barrels and 2 x 3 endcap disks
- C_3F_8 evaporative cooling (10kW/m2, serve T=0C contro rad)
- 1.7 m^2 of silicon
- 1744 pixel modules (tutti uguali)



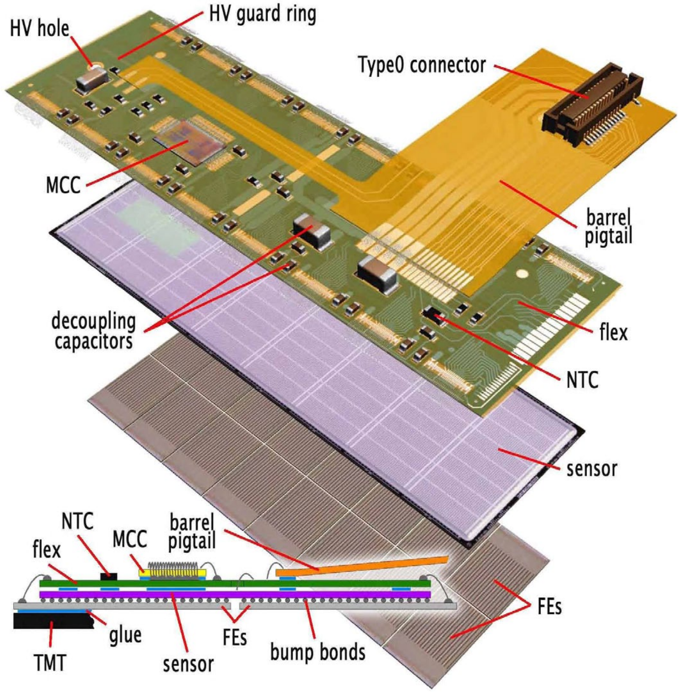
Each pixel module consists of:

- 1 planar n+-on-n (per poter operare parzialmente svuotato dopo inversione da radiazione) sensor 60.8 x 16.4 mm active area, 250 µm thick, 46080 pixels
- 16 guard rings per operare ad alto V
- 50x400 area, rettangolari per migliore risoluzione nella direzione di curvatura (per misurare momento)
- 16 FEI3 front-end chips plus one controller (0.25 µm CMOS)
    - Front-ends are bump-bonded to the sensor.
    - Charge measurement using 8-bit **ToT** information.
- 1 flex that provides electrical connections
- Data rate per module: 80-160 Mbps

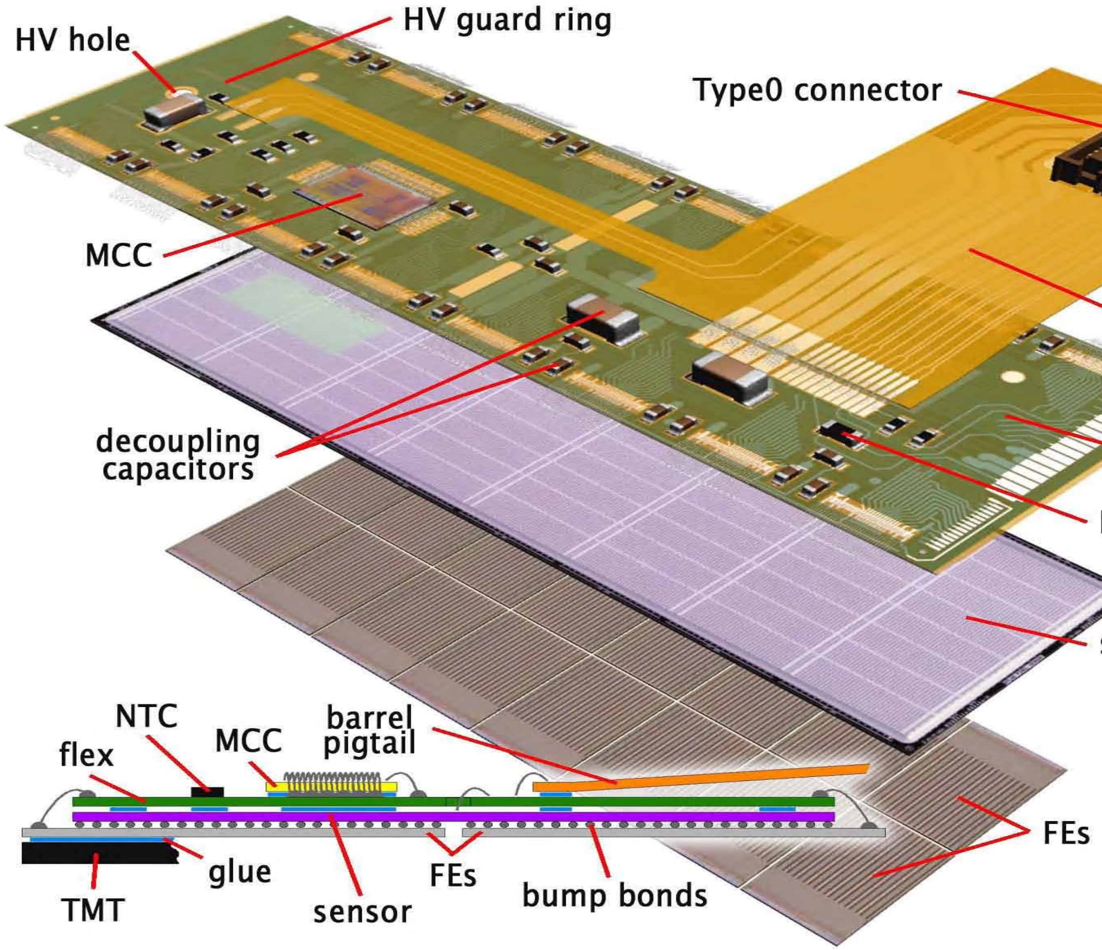
Radiation-hard

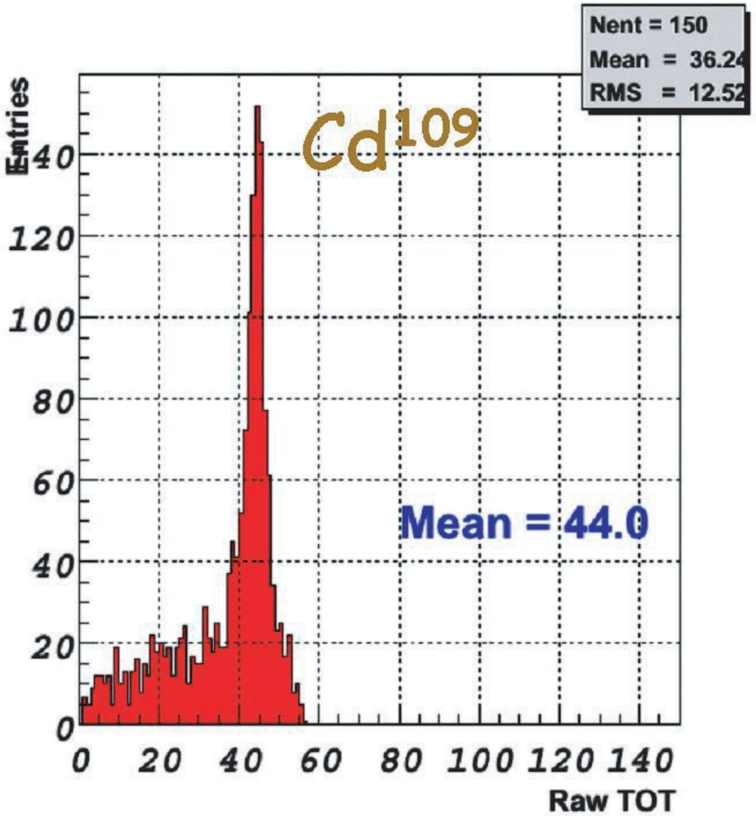
1 x 10^{15} MeV n_{eq} cm^{-2}

50 Mrad



Time over threshold calibration
Module sketch



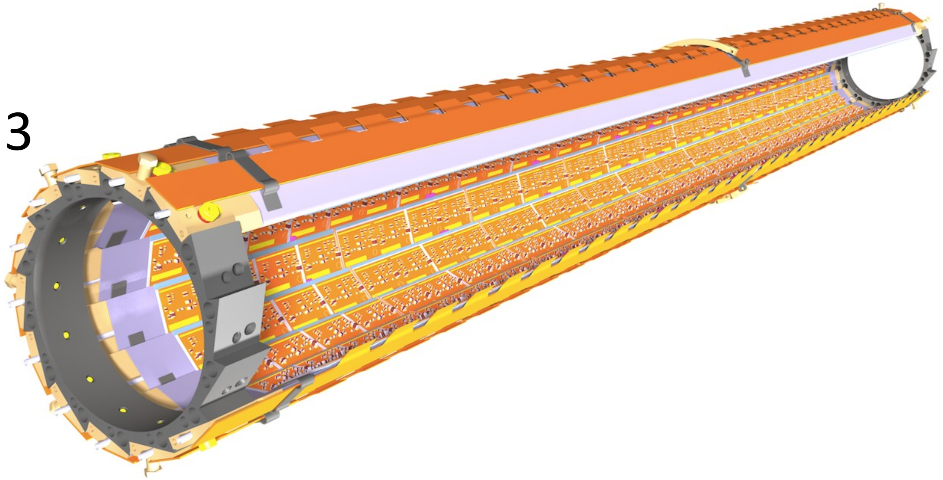


TOT: con una risoluzione di 25ns, il tempo di sailta e di discesa del segnale sopra soglia vengono misurati. Piu' grande e' l'impulso piu' tempo resta sopra soglia (registro a 7 bits)

Fig. 5.6. Pulse height distribution resulting from ^{109}Cd photon conversions inside an ATLAS pixel assembly. The measurement is performed using the correlation between the charge collected by one pixel and the time-over-threshold (TOT) of the output of its amplifier. The 22.3 keV ^{109}Cd photopeak is measured with an energy resolution of ≈5%.

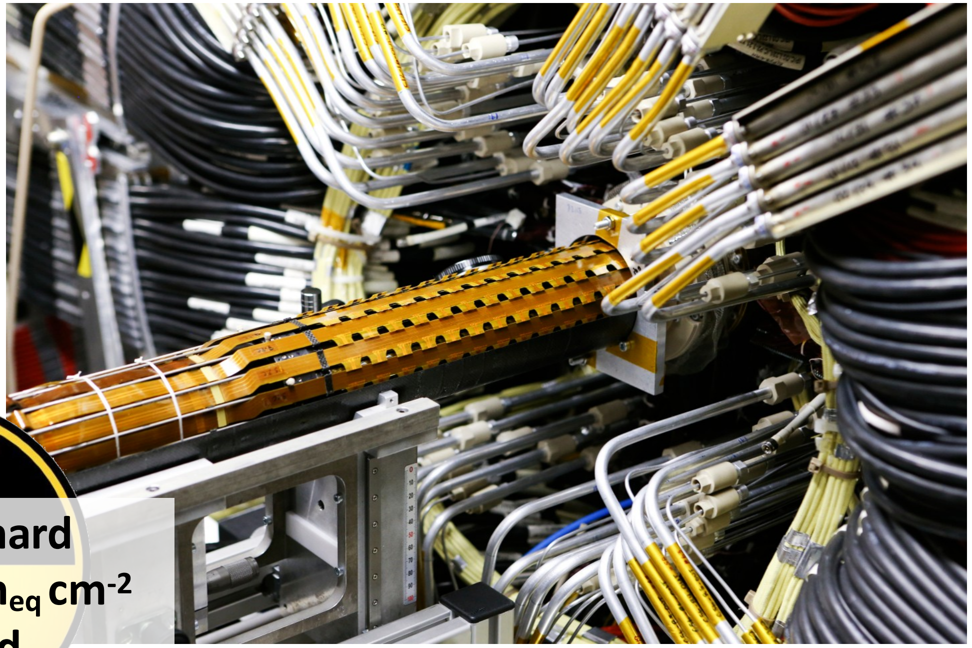
IBL – Insertable B-Layer

- Innermost layer of the pixel detector, coverage of $|\eta| < 3$
- New in LHC Run 2, installed in 2014
- 14 staves, 0.2 m^2 of silicon
- CO_2 evaporative cooling
- 280 IBL modules
- Planar sensors (central) and 3D sensors (forward)



Each IBL module consists of:

- Sensor:
  - Planar slim edge n-on-n sensor, 200 µm thick
  - 3D n-on-p sensor with 2 electrodes per pixel, 230 µm thick
- 2 or 1 FEI4 front-end chips (0.13 µm CMOS)
  - Front-ends are bump-bonded to the sensor.
  - Charge measurement using 4-bit ToT information
- 1 flex that provides electrical connections
- Data rate: 160 Mbps



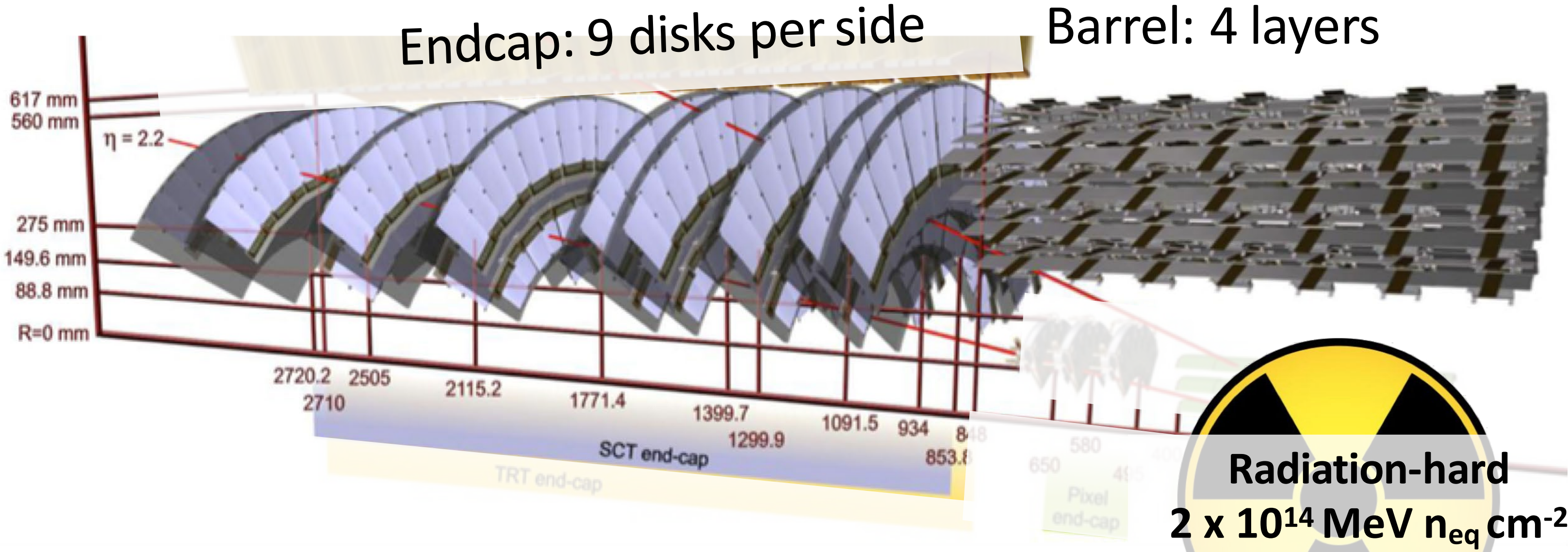
Radiation-hard

5×10^{15} MeV n_{eq} cm^{-2}

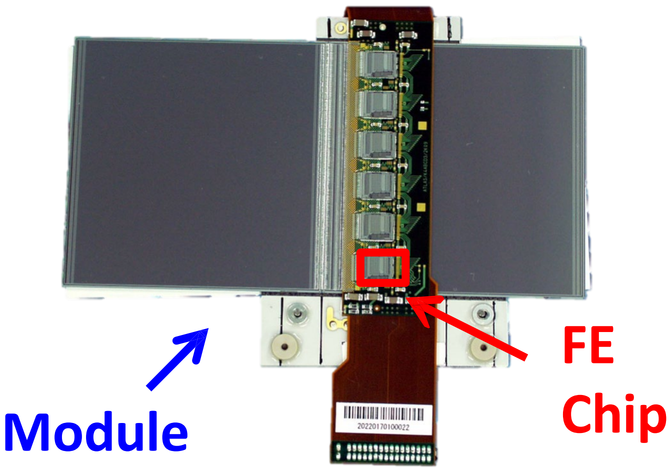
250 Mrad

SCT- Semi Conductor Tracker

- 8 hit system
- Angular coverage: $|\eta| < 2.5$
- C_3F_8 evaporative cooling
- 61 m^2 of silicon
- 4088 modules



Radiation-hard
2×10^{14} MeV n_{eq} cm^{-2}

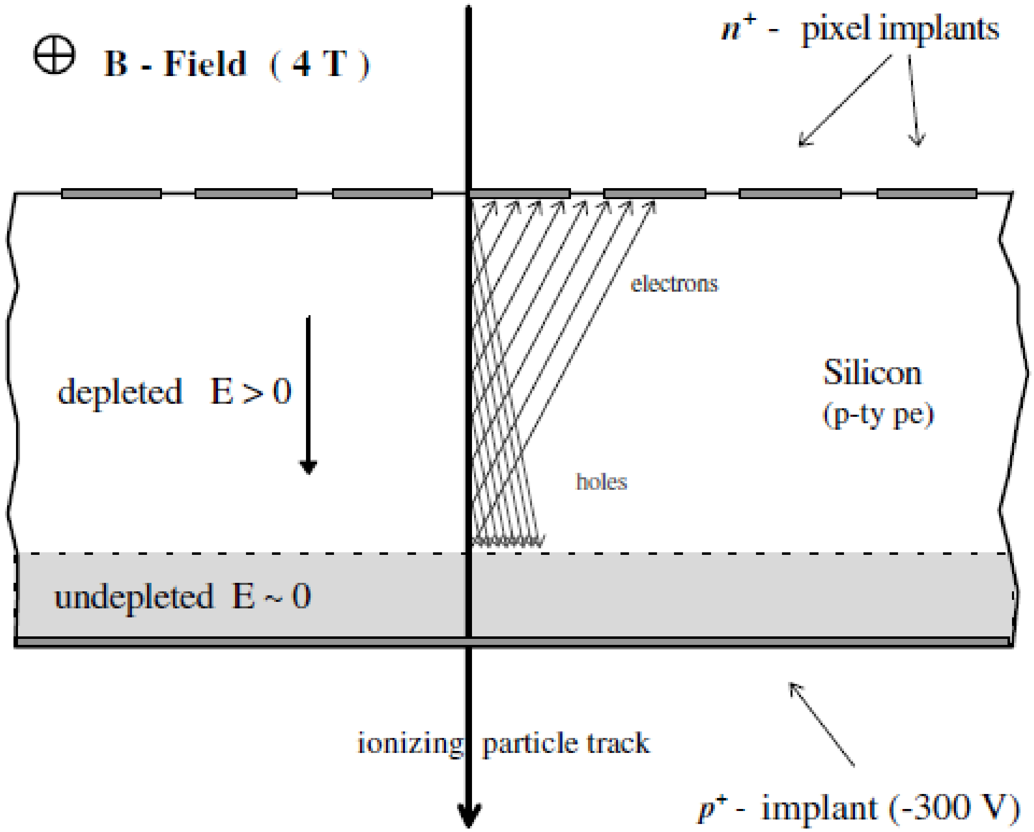


Each SCT module consists of:

- Two strip sensors crossing at 40 mrad
- Single-sided p-in-n sensor, 285 μm thick, 768 strips
- 2 x 6 ABCD front-end chips (0.8 μm biCMOS)
  - Binary readout: hit = signal > threshold
  - 3 consecutive time bins sampled per trigger
- Data rate: 40 Mbps

CMS Pixel

- 100umx150um per avere risoluzione spaziale simile in entrambe le direzioni; usa interpolazione di carica per trovare il centroide
- La carica deve essere sempre condivisa
  - Approfittare del forte campo magnetico
  - Non inclinati nel barile centrale, inclinati nell’endcap
- La risoluzione sulla carica deve essere alta
  - Lettura analogical della carica di ogni pixel
  - Salvata in condensatore in ogni pixel e nella periferia
  - Soglia bassa (2500e-)



CMS Pixel phase-1 detector

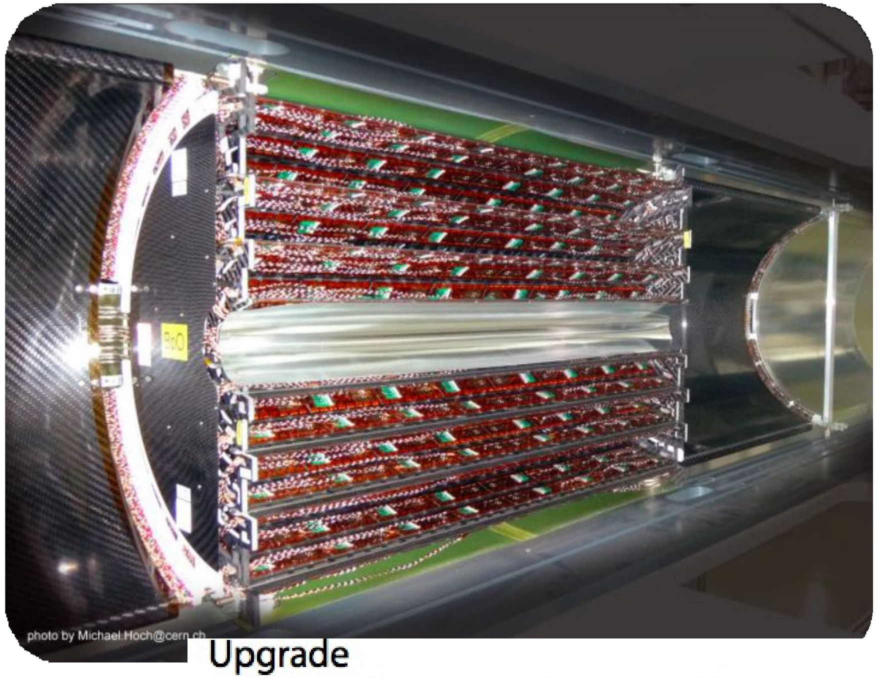
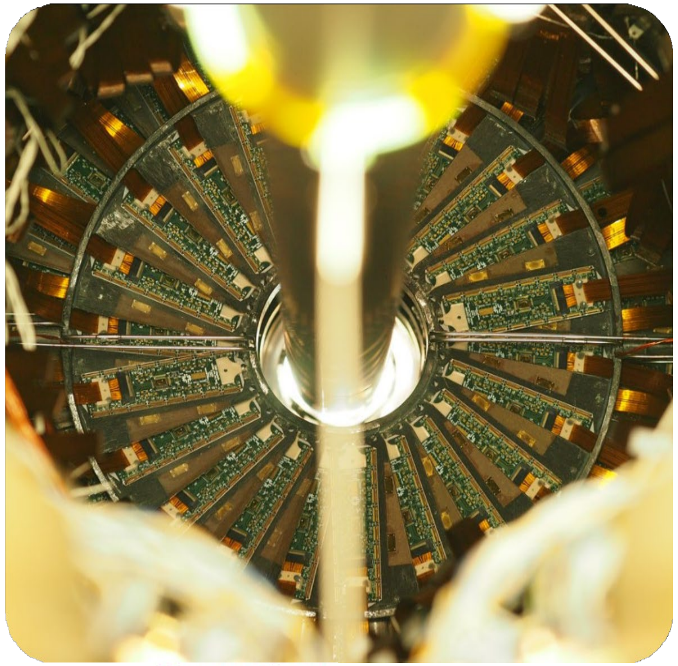
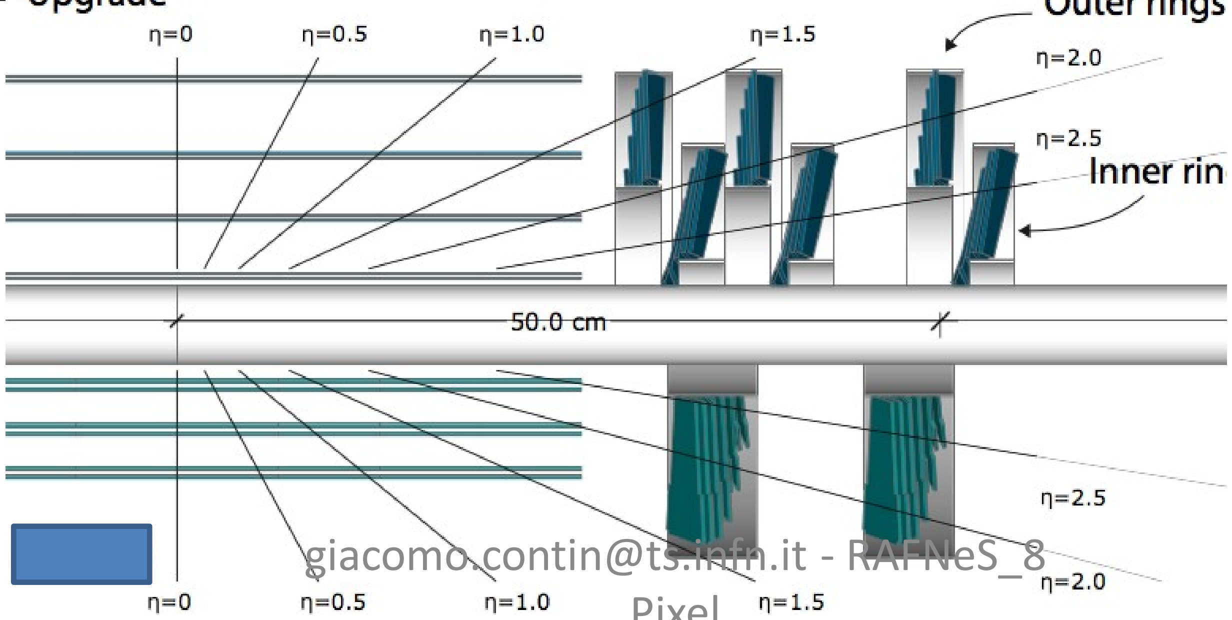


photo by Michael Hoch@cern.ch

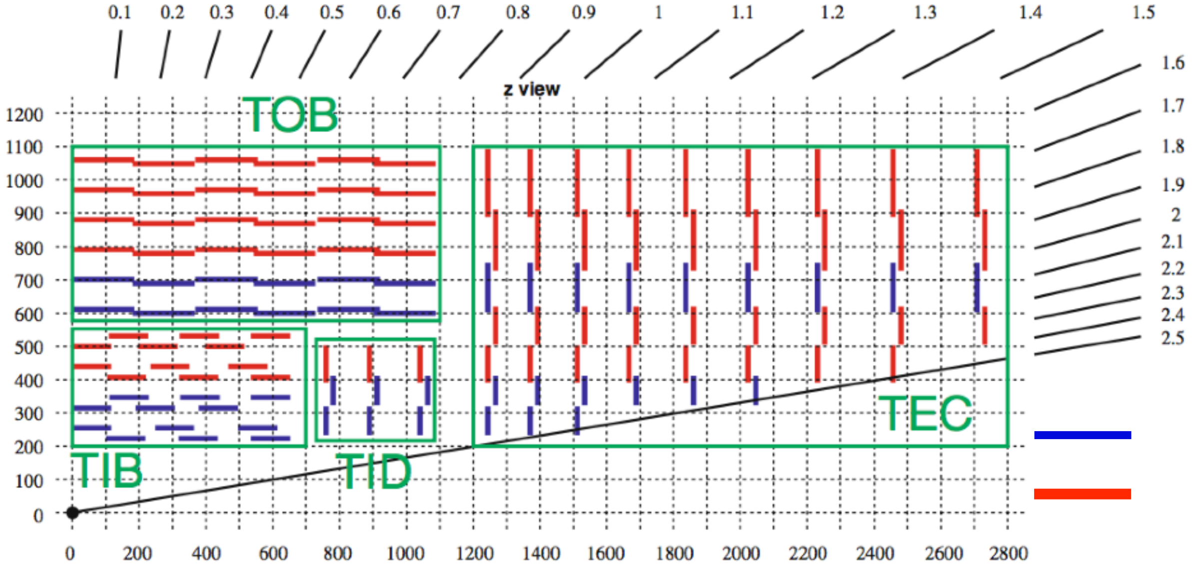




4 barrel layers
(BPIX)

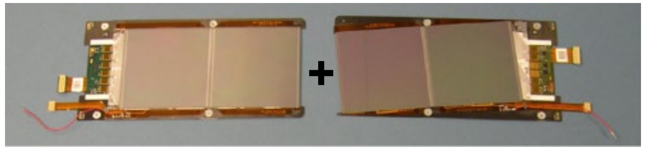
3 forward disks (FPIX)

CMS silicon strip detector

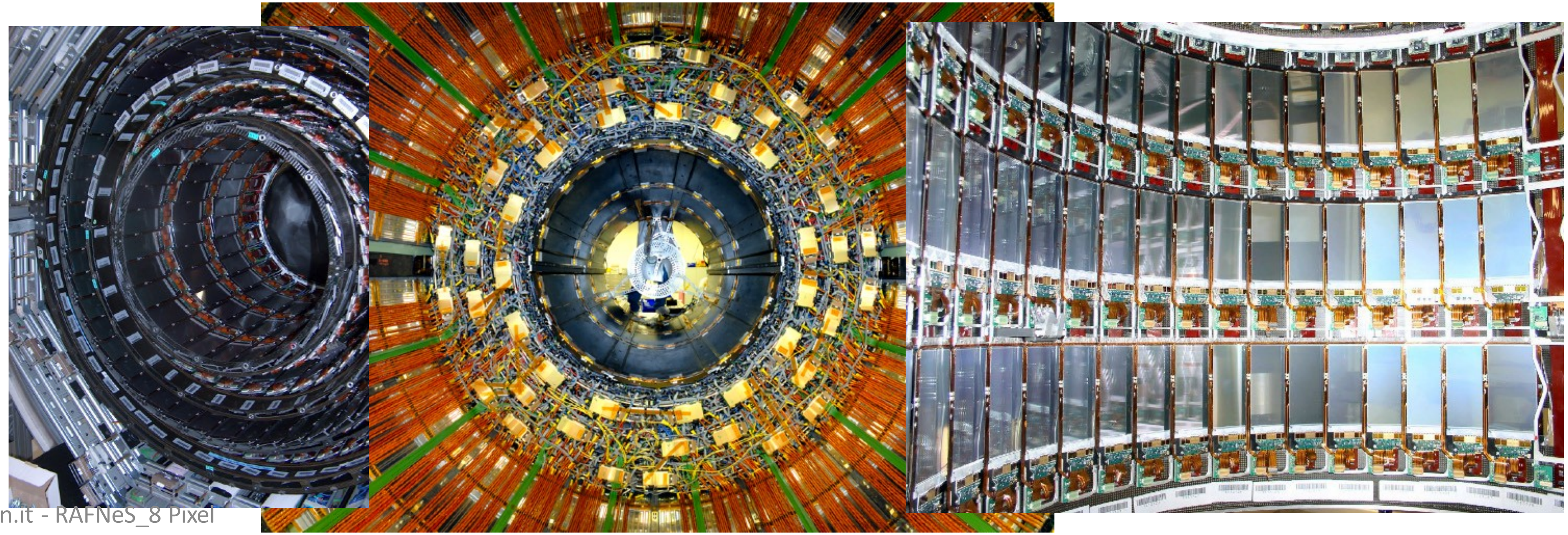


🟦 double sided

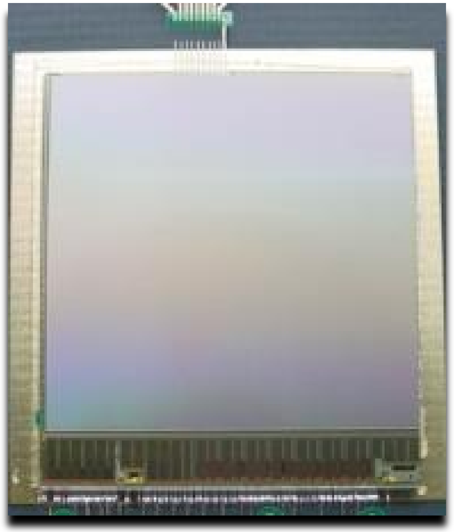
🟥 single sided

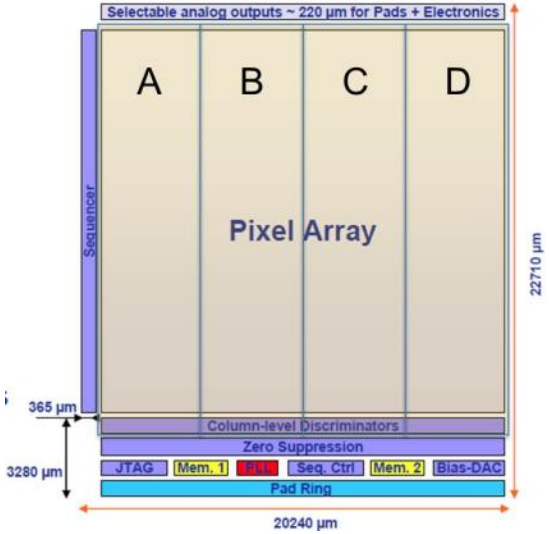


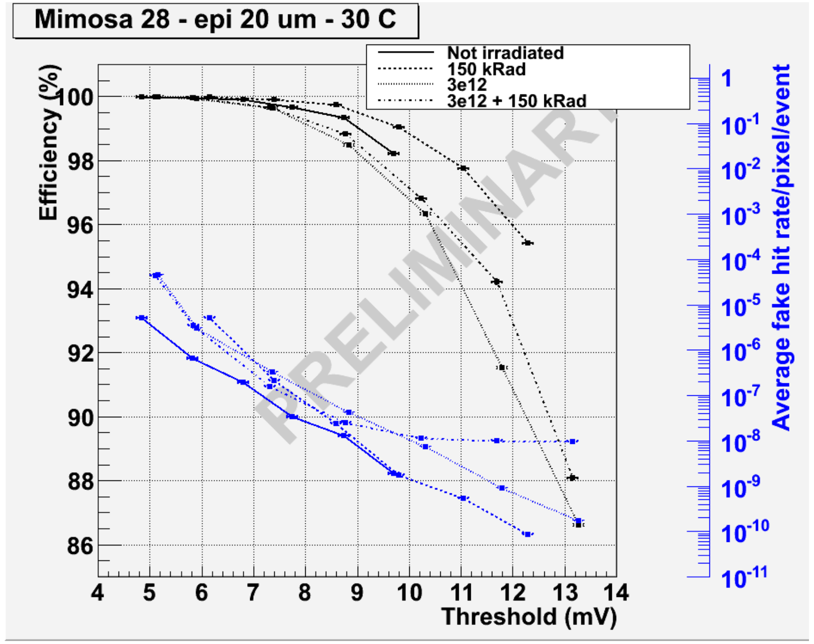
9.3 million strips, 198 m^2 active silicon area, 15148 modules 5 m long, 2.5 m diameter



MAPS *Ultimate-2* Sensor







3rd generation sensor developed for the PXL detector by the PICSEL group of IPHC,Strasbourg, optimized for the STAR environment

- Monolithic Active Pixel Sensors
- Reticle size (~ 4 cm²)
  - Pixel pitch 20.7 µm
  - 928 x 960 array
- Power dissipation ~170 mW/cm² @ 3.3V (air cooling)
- Short integration time 185.6 µs
- Sensors thinned to 50 µm

- In pixel CDS
- Discriminators at the end of each column
- Column-parallel readout
- 2 LVDS data outputs @ 160 MHz
- Integrated zero suppression (up to 9 hits/row)
- Ping-pong memory for frame readout (~1500 words)
- 4 sub-arrays to help with process variation
- JTAG configuration of many internal parameters

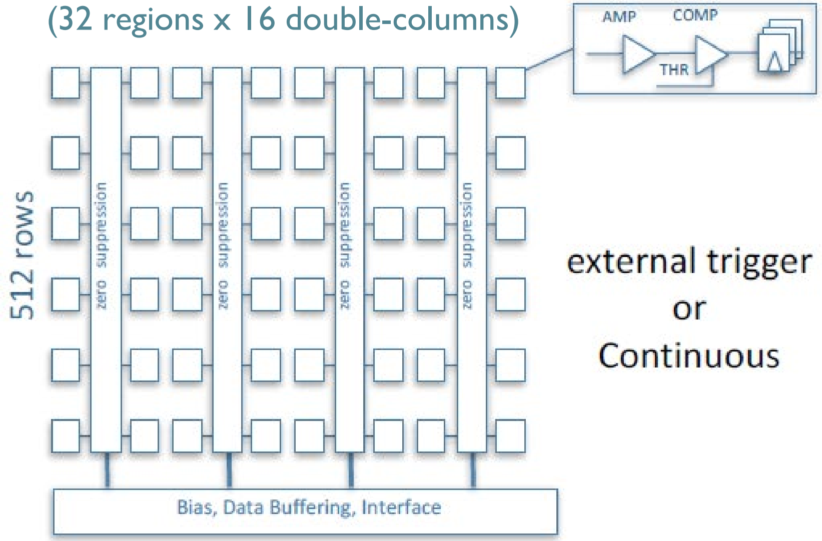
MAPS – ALPIDE sensor

Priority Encoder (AE-RD)

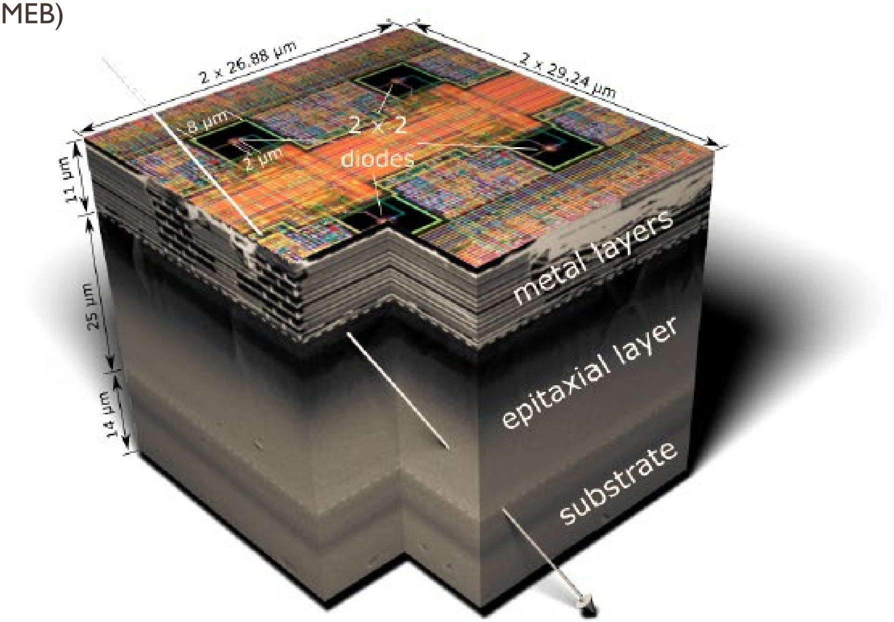
1024 pixel columns

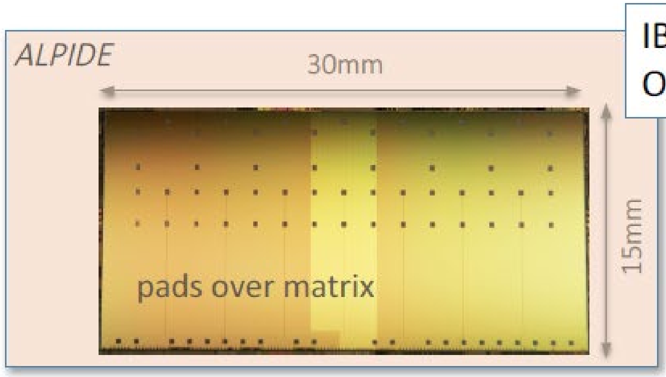
(32 regions x 16 double-columns)

In pixel:
- Amplification
- Discrimination
- 3 hit storage registers (MEB)



external trigger
or
Continuous





IB: 50μm thick
OB: 100μm thick

Power: 40 mW/cm^2
Trigger rate: 100 kHz
Integration time: < 20 μs
Read out up to 1.2 Gbit/s.

130,000 pixels / cm^2 27x29x25 μm^3

spatial resolution: ~ 5 μm (3-D)

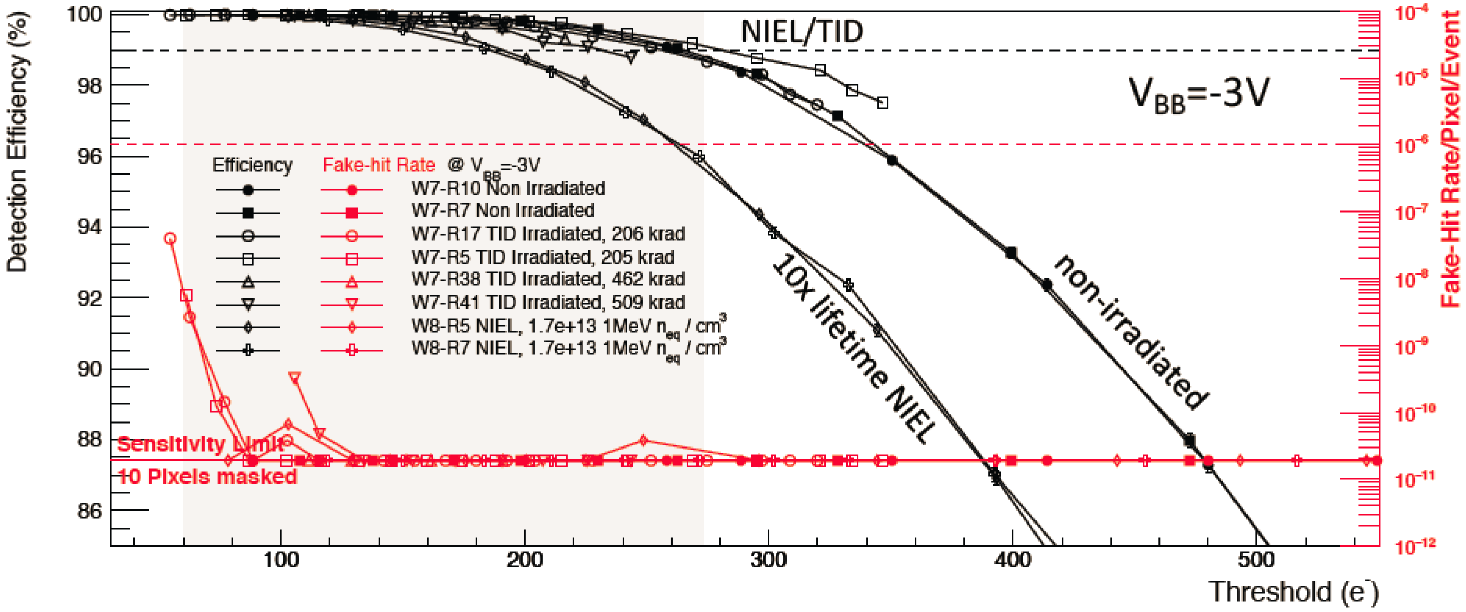
Max particle rate: 100 MHz / cm^2

fake-hit rate: ~ 10^{-10} pixel / event

power : ~ 300 nW /pixel

ALPIDE performance

Detection Efficiency and Fake-Hit Rate

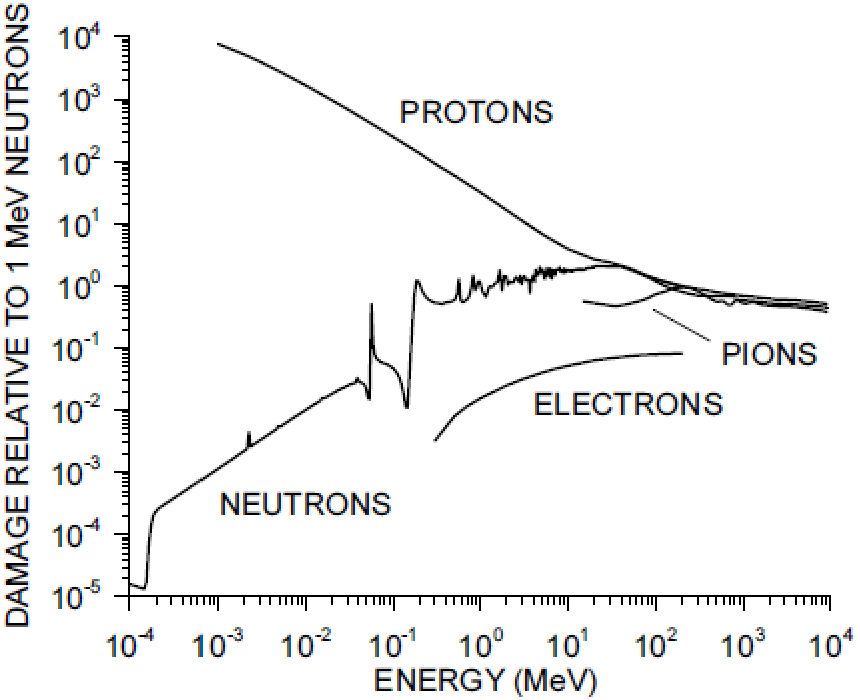


- Big operational margin with only 10 masked pixels (0.002%)
- Chip-to-chip fluctuations negligible
- Non-irradiated and NIEL/TID chips show similar performance
- Sufficient operational margin after 10x lifetime NIEL dose

From ITS Upgrade Talk @ QuarkMatter17, February '17

Danno da radiazione (grafici)

- Dislocazione (riferito a neutroni da 1Mev)



Annealing and anti-annealing

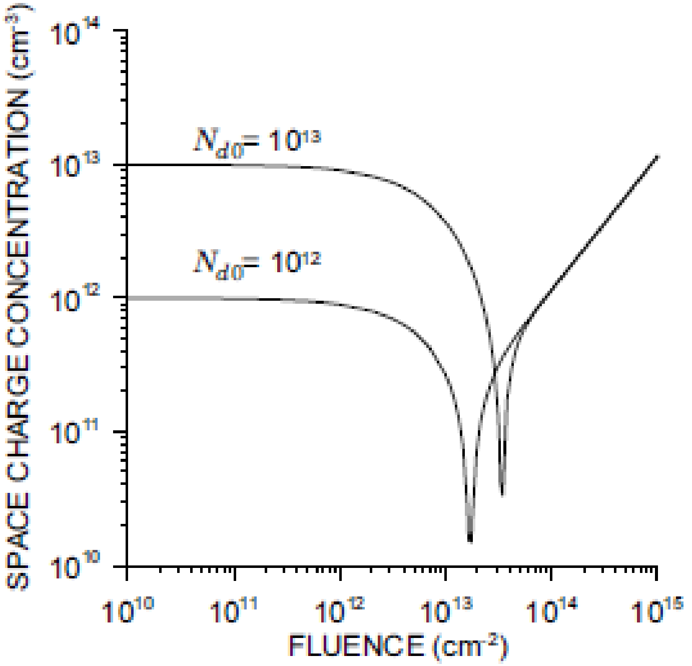


FIG. 7.4. Calculated space charge *vs.* high-energy proton fluence for silicon with initial donor concentrations N_{d0} of 10^{12} and 10^{13} cm^{-3}. With an infinitely fine calculation grid both distributions would dip to zero.

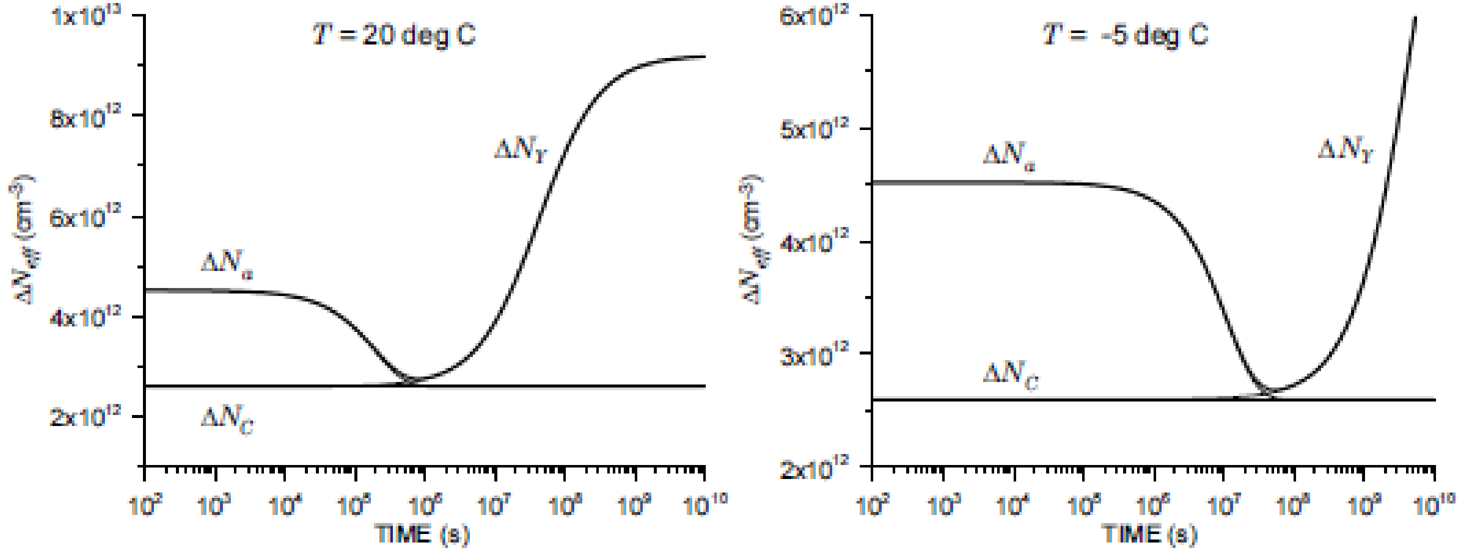
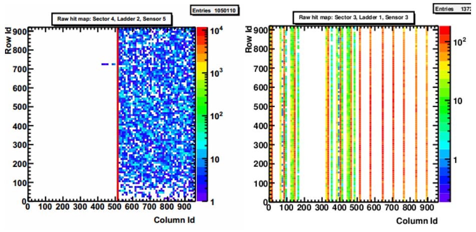


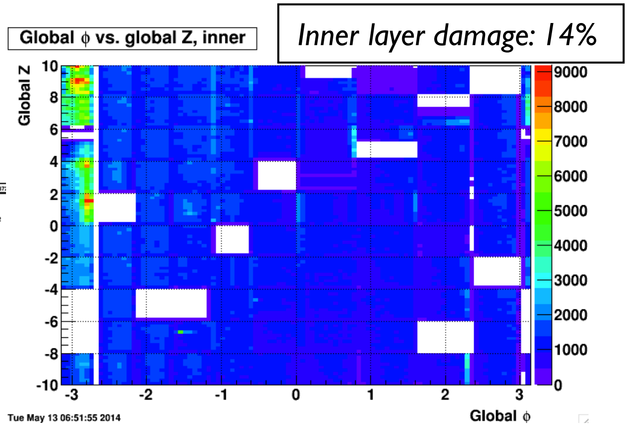
FIG. 7.5. Evolution of beneficial annealing ΔN_a and anti-annealing ΔN_Y vs time at 20 °C and -5 °C after a proton fluence burst of 10^{14} cm^{-2}.

Operational issues: Latch-up damage

- Unexpected damage seen on 15 ladders in the STAR radiation environment in 2014 Run first 2 weeks
    - Digital power current increase
    - Sensor data corruption
    - Hotspots in sensor digital section
    - Correlated with *latch-up* events
    - Limited with operational methods



Inner layer damage: *14%*

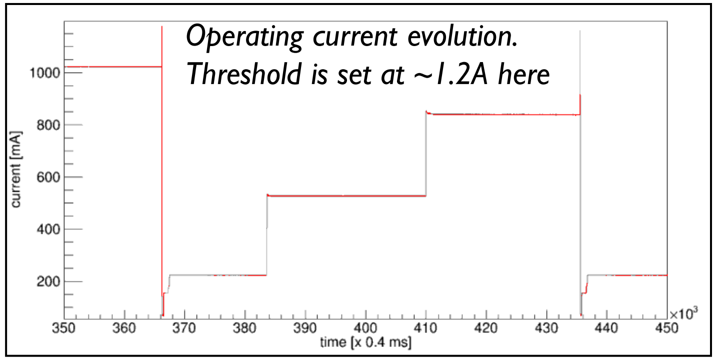


- Latch-up tests at *BASE facility* (LBL) to measure latch-up cross-section and reproduce damage
    - 50 μm & 700 μm thick, low and high resistivity sensors; PXL ladders
    - Irradiation with heavy-ions and protons

Latch-up phenomenon:

- Self feeding short circuit caused by single event upset
- Can only be stopped by removing the power

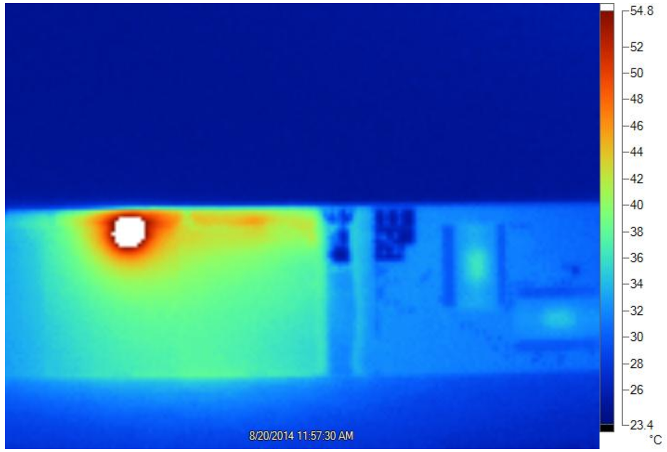
- Results and observations
    - Current limited latch-up states observed (typically ~300 mA)
    - Damage reproduced only with HI on PXL 50 μm thinned sensors
    - Latch-up protection at 80 mA above operating current
    - Periodic detector reset to clear SEU



Operating current evolution.
Threshold is set at ~1.2A here

Latch-up test damage analysis

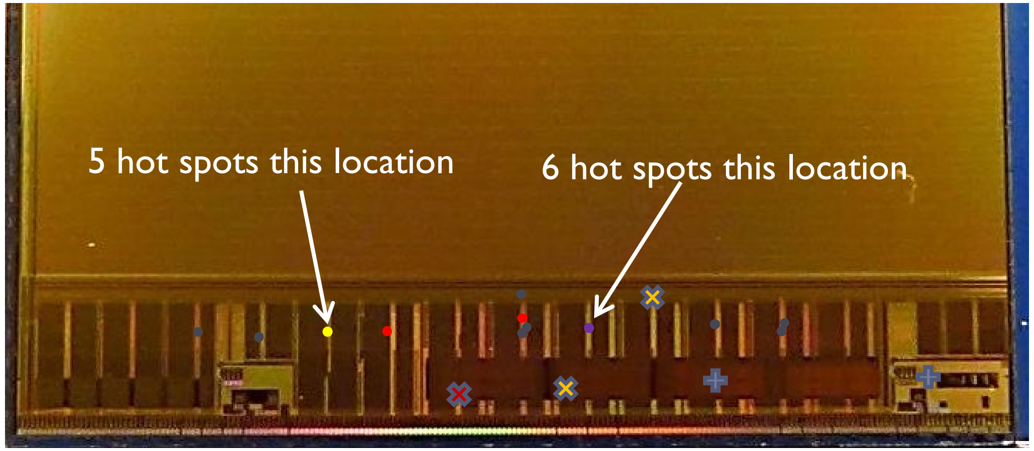
Hot spot showing damage to sensor #2 on run 14 ladder

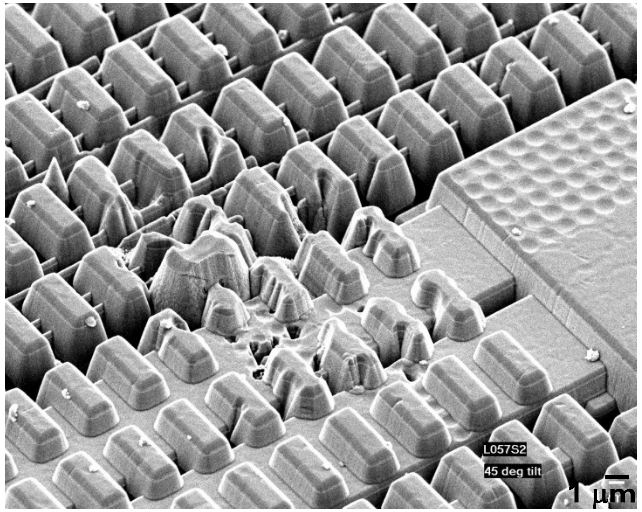


50 um thinned silicon
Temperatures from 55-100 C

- **Full thickness sensors were tested** for LU during development: measured cross section consistent with LU events recorded on the detector
- **Damage cross section is too low** to easily measure with individual sensors based testing

Hotspots tend to favor particular structures (isolated buffers with specific structure pitch)





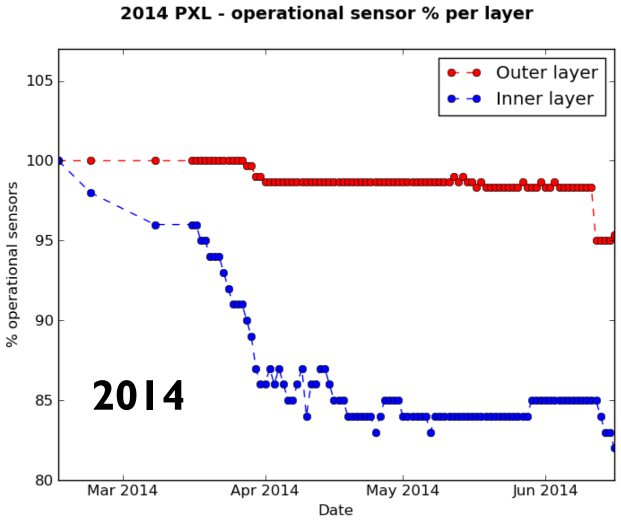
PXL sensor layers deconstructed (plasma etching technique) and viewed with SEM (@BNL Instrumentation Division)

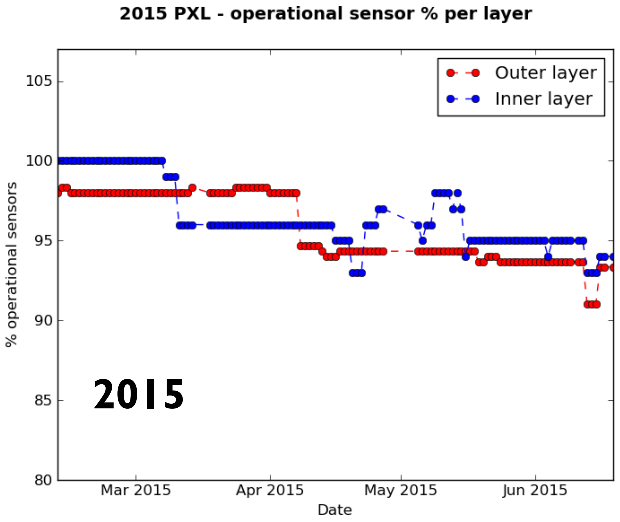
The layers appear to be melted

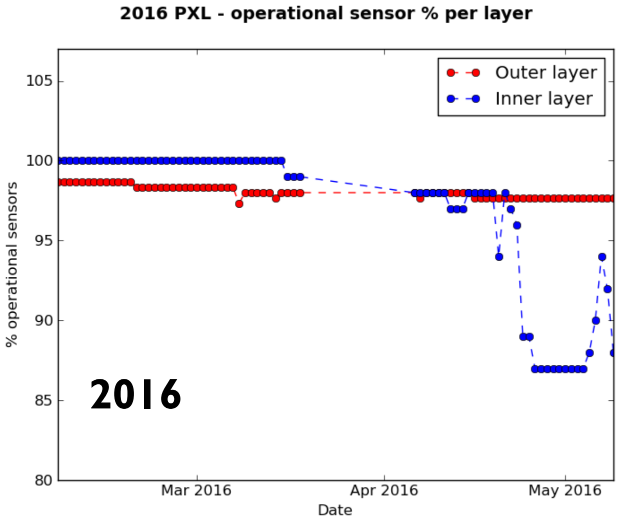
Latch-Up Damage evolution

Run	Good sensors on Inner Layer		Good sensors on Outer Layer		*Comment*
	installation	**end of run**	installation	**end of run**	
2014	100%	82%	100%	95%	LU damage, most of it in the first 15 days of operations
2015	99%	94%	98%	96% *(93%)**	* = Lost control of an outer ladder (10 good sensors off)
2016	100%	95% *(87%)*$^+$	99%	98%	$^+$ = Current instability on inner ladder (8 good sensors off)

Good sensor = sensor with >95% active channels and uniform efficiency


2014 PXL - operational sensor % per layer

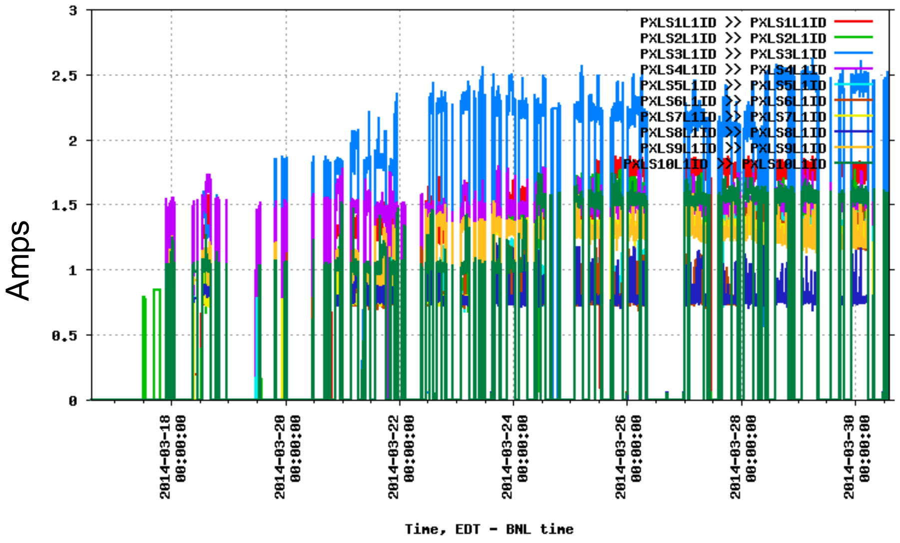

2015 PXL - operational sensor % per layer


2016 PXL - operational sensor % per layer

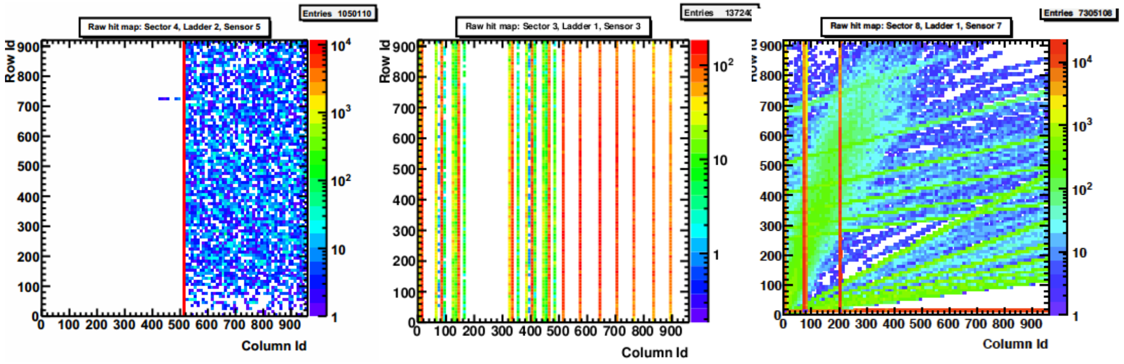
Radiation damage

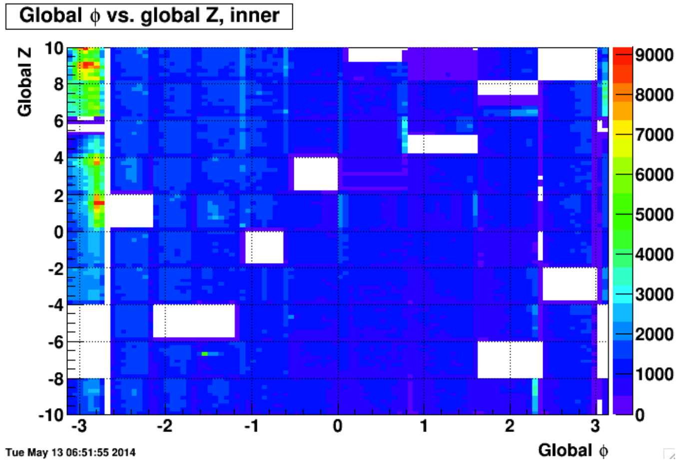
- First damages observed at the end of 15 GeV run:
  - Observed after several beam loss events (seen by STAR as TPC Cathode trips): efficiency loss and increase of current consumption in 2 ladders
- Damage continued into 200 GeV Run
  - Most PXL sensor damage appears to be radiation related damage possibly due to latch-up events in thinned sensors and takes on many forms: increased digital current, loss of or damaged columns, damaged JTAG registers, loss of full or partial sub-arrays, etc.

Digital current on the inner ladders during initial period of 200 GeV/c Au+Au Run



Sensor damage examples

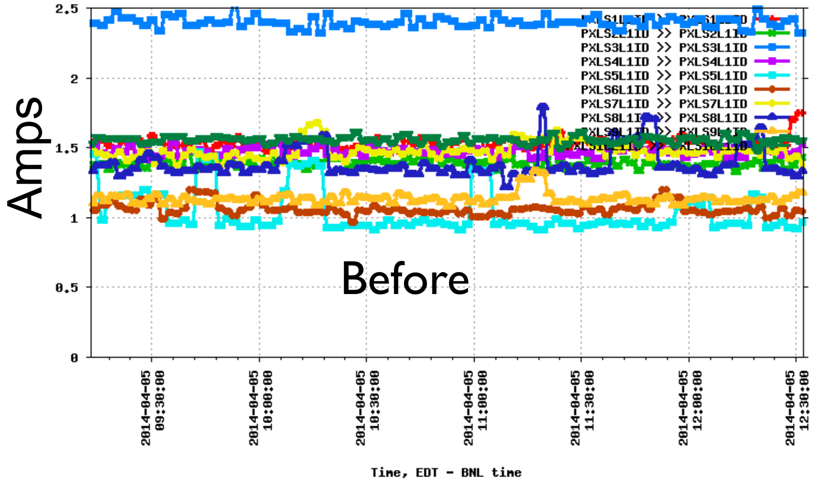


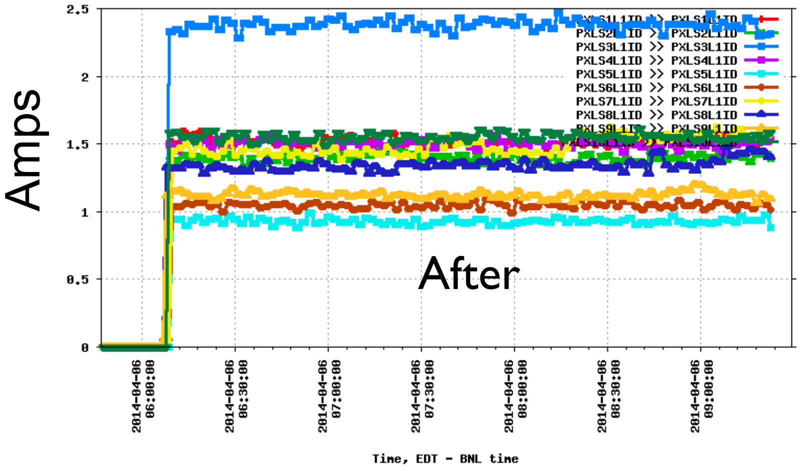


Inner Layer: 14% damage
(Outer layer: 1% damage)

Remediation

Digital current stability on Inner ladders





Remediation in place:

- PXL and IST are only turned on when collision rate < 55 kHz
- Cycle digital power and reload configuration automatically every 15 minutes
- Latch-up thresholds now 120 mA above measured operational current for each ladder

Next actions:

- The failure mechanism extensively investigated by exposing existing PXL ladders and thinned sensors on testing cards to heavy ion beams at the 88” Cyclotron BASE facility at LBNL
- In Run15, LU current thresholds set very close to the ladder running current in order to limit the energy available to a latch-up event

Digital current on the inner ladders after implementing remediation