



---

# Test beam measurements of the performance of the ATLAS Pixel Detector production modules

**Attilio Andreazza**  
**Università di Milano and I.N.F.N**  
**for the ATLAS Pixel Collaboration**



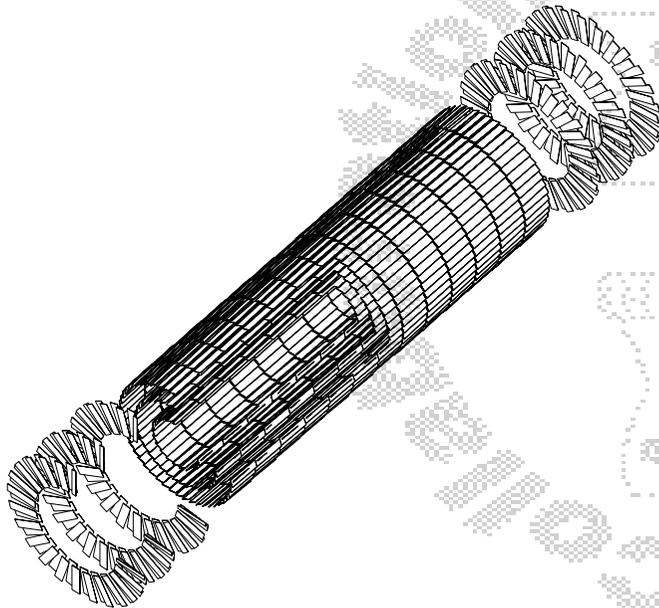
---

## Outline

- The ATLAS Pixel detector and modules
- Test beam setup
- Overall performance (timewalk effects)
  - detection efficiency
  - **spatial resolution**
- Measurements in high intensity beam (validation of read-out architecture)
  - **efficiency vs. occupancy in LHC-like conditions**



# The ATLAS Pixel Detector

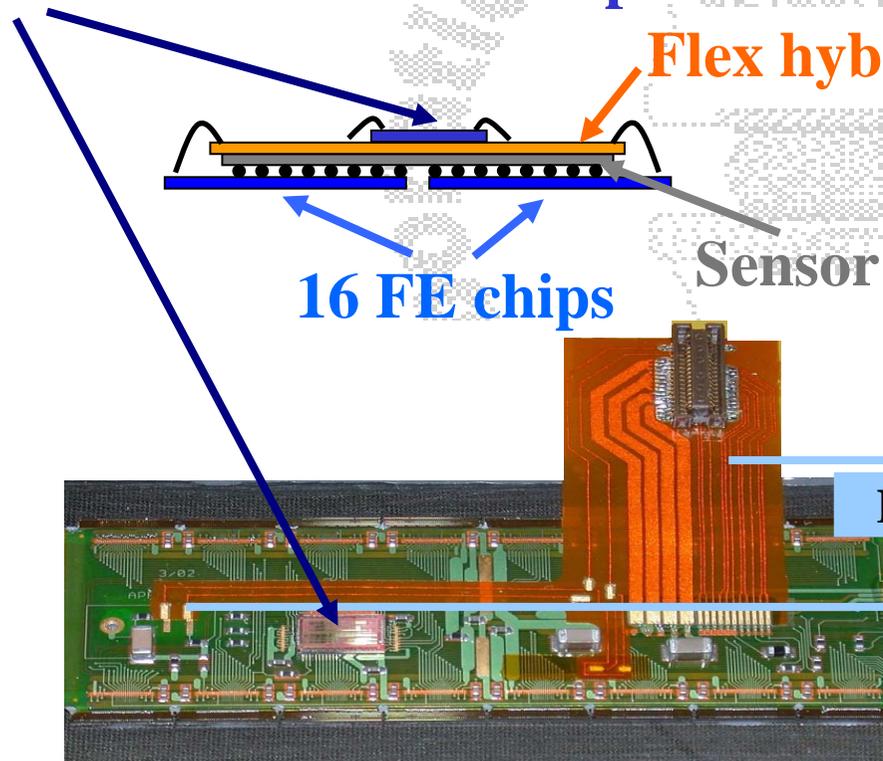


- The Pixel Detector is the vertex detector for the ATLAS experiment.
- It consists of three barrel layers and six disks, covering with three precise measurement points the region up to  $|\eta| < 2.5$ .
- Innermost layer (B-layer) at  $R=5$  cm
- There will be 1456 barrel modules and 288 forward modules, for a total of 80 million channels and a sensitive area of  $1.6 \text{ m}^2$ .
- Modules will operate in an environment temperature below  $0^\circ\text{C}$  and within a 2T solenoidal magnetic field.
- Barrel modules are tilted by  $20^\circ$  in the  $R\phi$  plane to overcompensate the Lorentz angle.

# Module concept

- **Self-consistent detector unit.**
- **Sensor (Oxygenated FZ Silicon):**
  - active area  $60.8 \times 16.4 \text{ mm}^2$
  - $250 \mu\text{m}$  thickness
  - pixel cell  $50 \mu\text{m}$  (R $\Phi$ )  $\times$   $400 \mu\text{m}$  (Z)
  - extended cells (ganged and long pixels) to cover the otherwise dead region between FE chips.
- **Front-end electronics:**
  - 16 FE-I3 chips,  $0.25 \mu\text{m}$  IBM technology, with rad-hard design;
  - 46080 channels/module
- **Interconnection by bump-bonding:**
  - Solder (IZM, Berlin)
  - Indium (Selex, previously AMS, Rome)
- **Flex hybrid:**
  - Module Controller Chip to perform communication and event building;
  - local decoupling and temperature monitoring.

## Module Controller Chip





# Specifications

## Radiation hardness:

- $\text{NIEL} > 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$
- 500 kGy

## Technical Design Report specification were:

- $R\phi$  resolution 13  $\mu\text{m}$ ,
- efficiency better than 97% at end of lifetime,
- analog information was a high priority option.

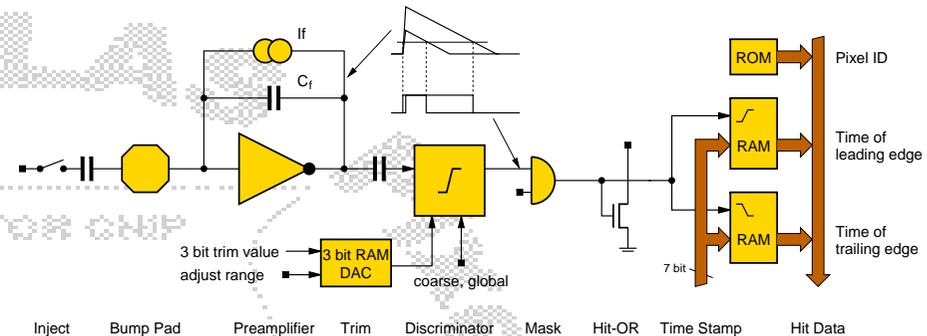
## Given the 25 ns beam crossing rate at the LHC:

- must be able to assign each hit to the proper bunch crossing;  
(measurements of timewalk effects on efficiency and resolution)
- must be able to store the hit information during the trigger latency time of  $\sim 100$  beam crossings.  
(measurements of rate capability of the readout system with high intensity beam)

2004 testbeam with production modules, 7 irradiated to maximum dose.  
**90% of plots refers to irradiated devices**

# Front-end electronics concept

- Fast charge amplifier with constant current feedback.
- Fast discriminator with tunable threshold (7-bit DAC)
- Storage of hits during the trigger latency time in 64 “End of Column” memory buffers for each column pair of  $2 \times 160$  pixels
- Timestamps of trailing and leading edges



## – LVL1:

**the clock cycle/bunch crossing in which the discriminator goes above threshold.**

This is the only timing information on the leading edge available from the detector, and must be exactly associated at the beam crossing, otherwise the hit is attributed to an incorrect event.

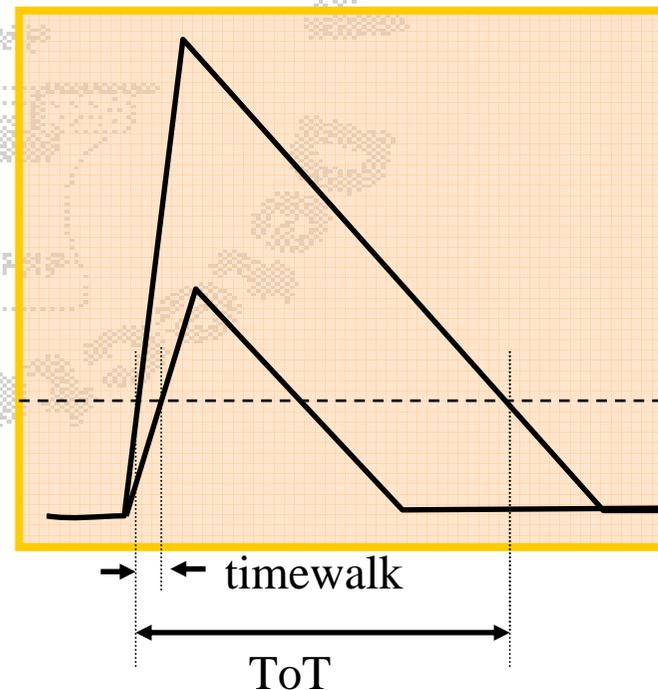
## – Time over Threshold (ToT):

**the length of the discriminator pulse.**

It is proportional to the deposited charge and measured in discrete clock cycles

## – timewalk:

**the variation of the delay between the charge deposit in the detector and the time at which the discriminator goes above threshold..**





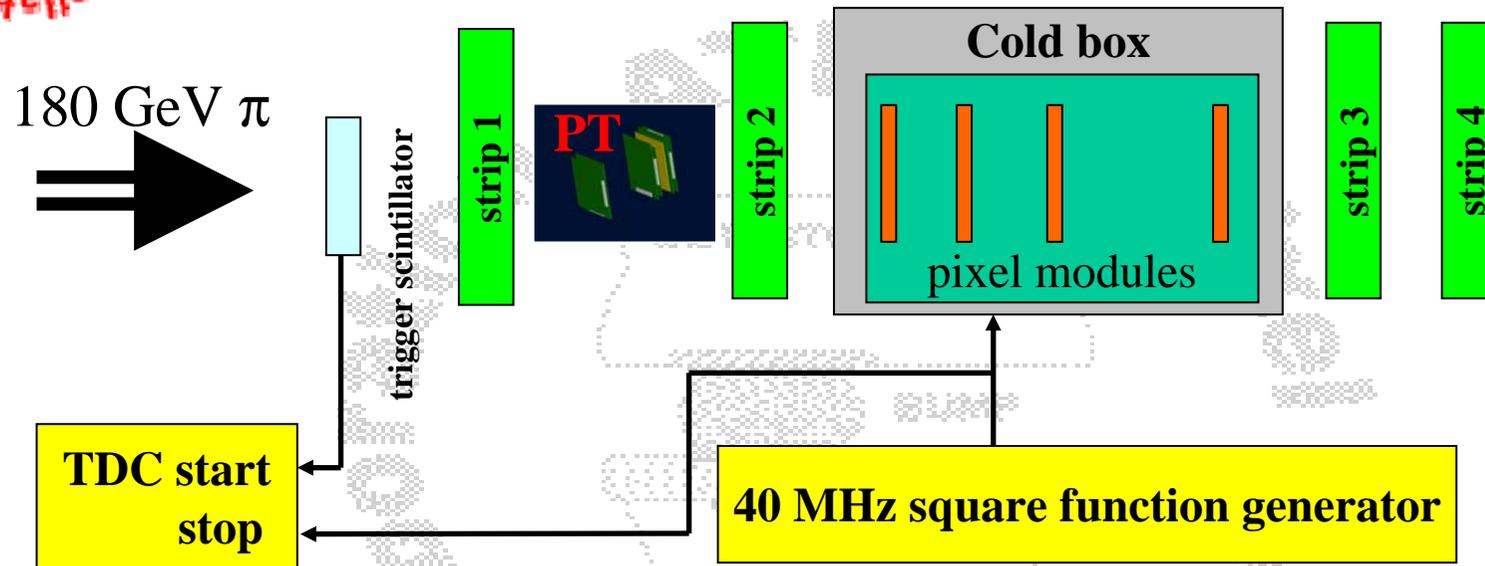
---

# Measurement of detector performance

Timing measurement in testbeam  
Timewalk effect on efficiency  
Timewalk effect on resolution  
and hit duplication

---

# Test beam setup



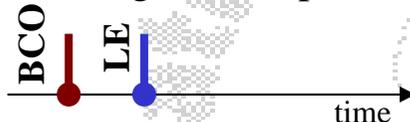
- H8 beam line providing 180 GeV/c hadrons.
- Reference track provided by 4 microstrip plane with  $\sim 6 \mu\text{m}$  extrapolation error.
- Small Pixel Telescope
- **Beam is asynchronous w.r.t. the 40 MHz clock: for each event the time between the scintillator trigger and the clock edge is measured.**
- Devices under test are placed in a cold box (essential for irradiated assemblies), with  $x$  and  $y$  movement capability.
- For each scintillator trigger 8-16 consecutive triggers are sent to pixel devices, **collecting data in a 200-400 ns window about the trigger.**

# Timing and performances

- Because of timewalk, leading edges reach threshold at different times after the beam crossing.

Some examples:

- All charge in one pixel:



- Charge equally shared

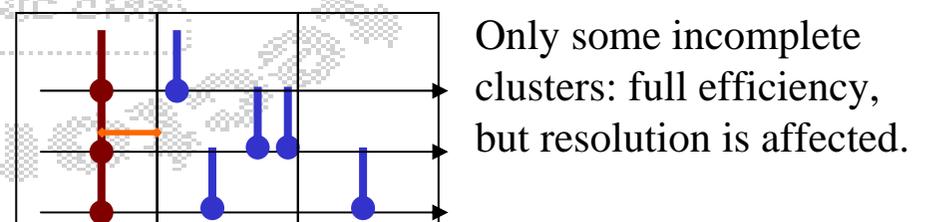
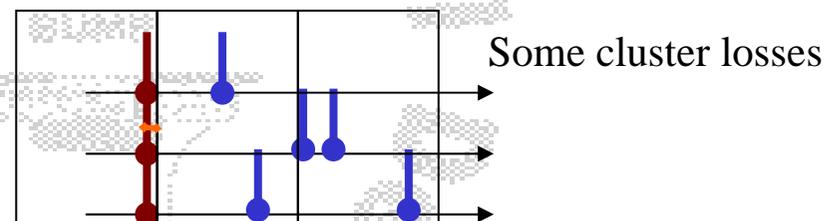
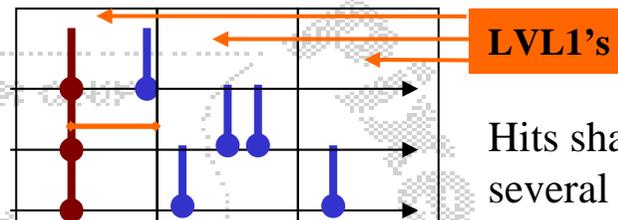


- Charge unequally shared.



- In test beam setup beam crossing is asynchronous with clock cycle.
- The TDC information is used to retrieve the relative phase between trigger (=BCO) and clock edge (=LVLI)

- Classifying events according to TDC reading (orange bar) is a scan over BCO-Clock phases:



- find optimal conditions;
- find stable operation range.



# In-time efficiency: irradiated

FE-13 irradiated

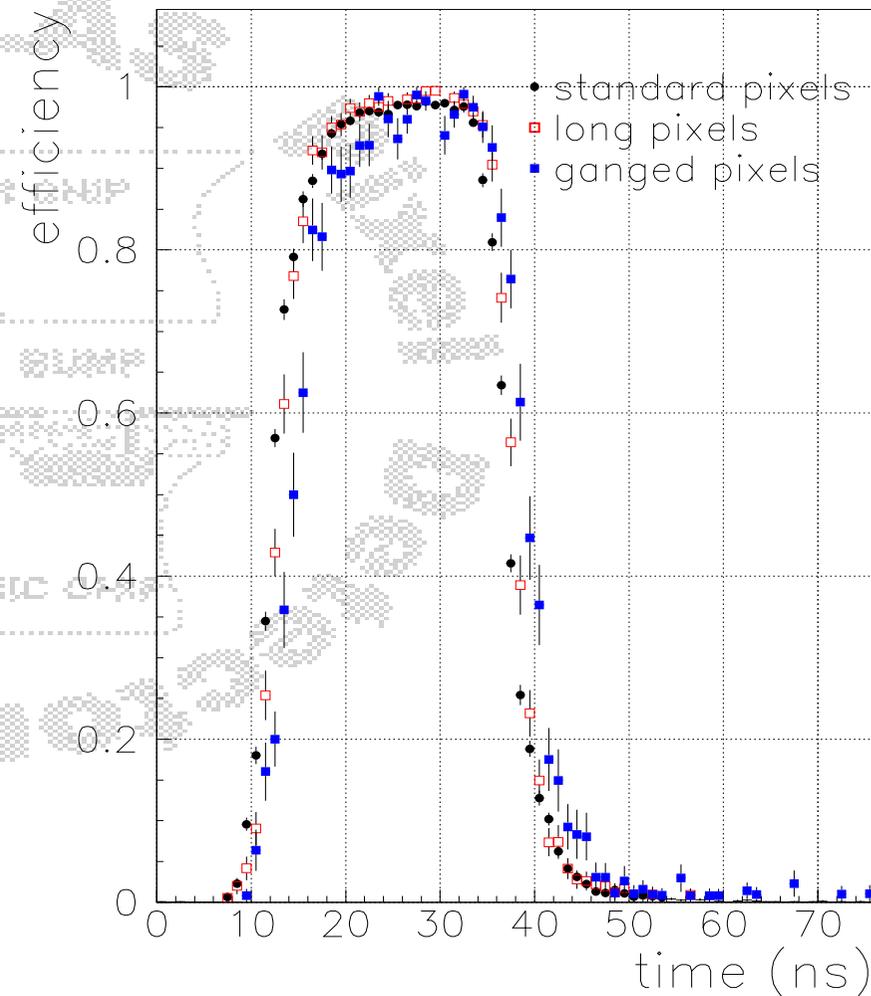
- 7 irradiated production modules have been tested in 2004.

---

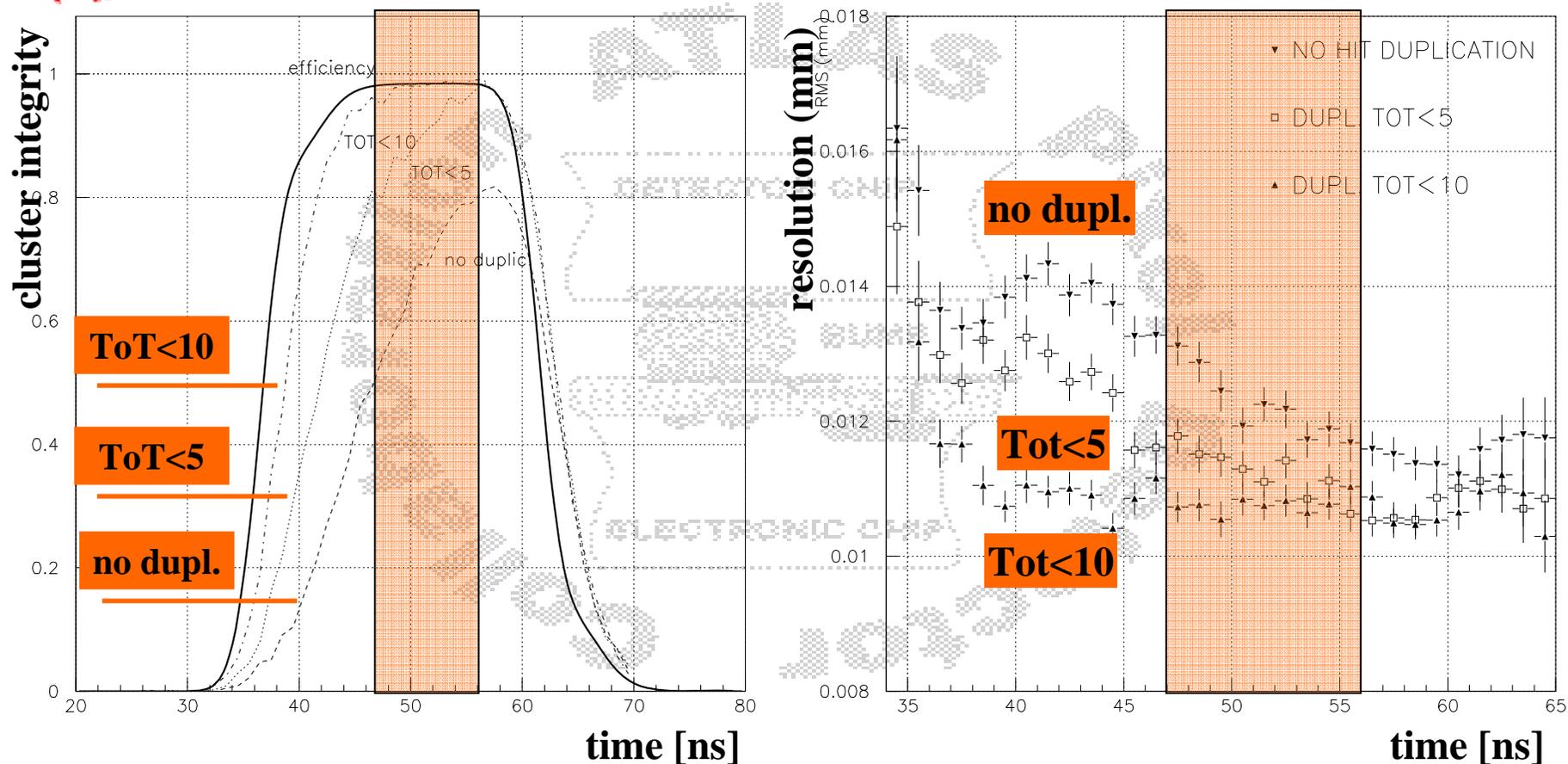
efficiency	97.8	$\pm 0.7$ %
no hits	1.5	$\pm 0.4$ %
timewalk losses	0.7	$\pm 0.3$ %
plateau size	9.7	$\pm 1.1$ ns
masked	O(10 <sup>-4</sup> )	

---

- Efficiency is above the requirement**  
( $\geq 99.9\%$  before irradiation)
- Plateau size is acceptable**  
(2 ns time jitter among different FEs)



# In-time resolution



Low charge hit of a cluster may be late → **loss of resolution**  
 FE feature: duplicate low ToT hits in earlier LVL1  
 → **restore cluster integrity**

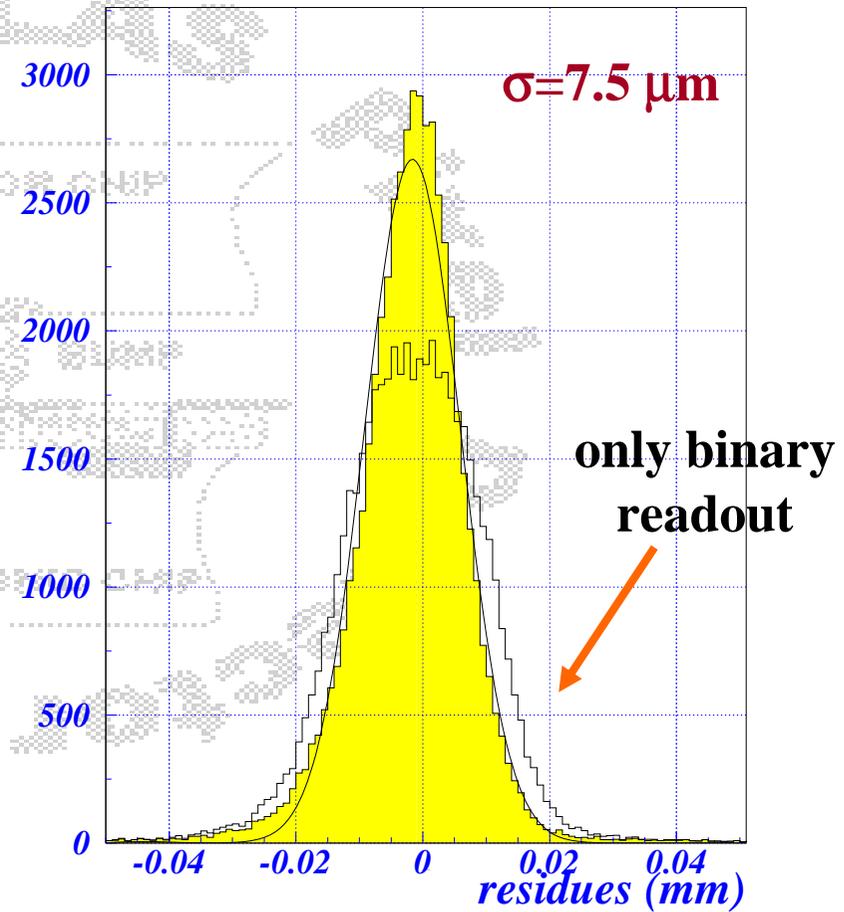
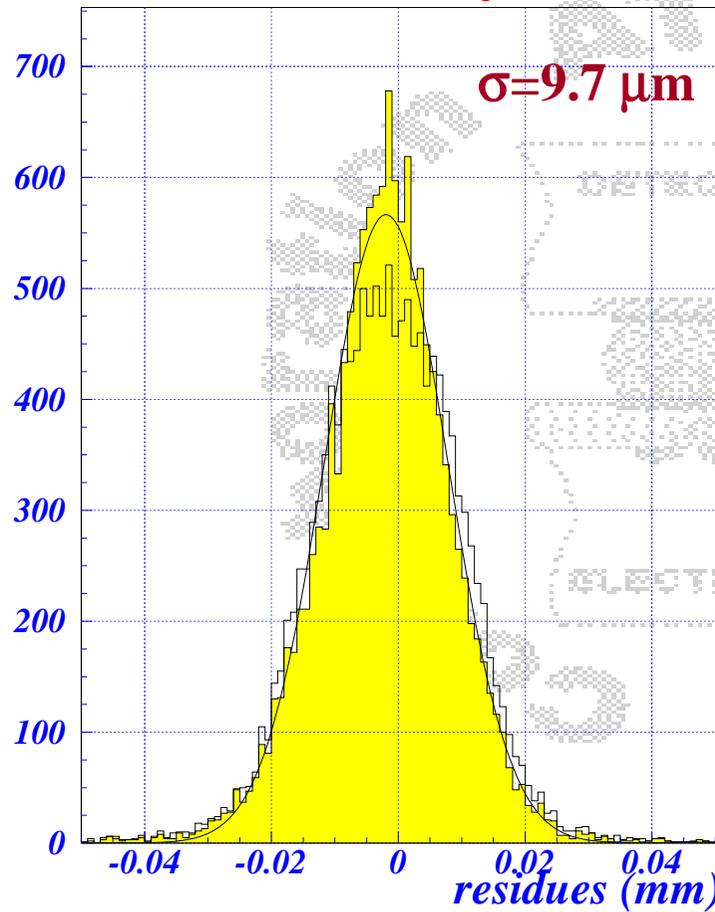
**Almost full resolution can be obtained with  
 duplication at 1/6 of m.i.p.  
 with only 10% occupancy increase**



# Analog resolution (at 15° incidence)

500 kGy

Not irradiated





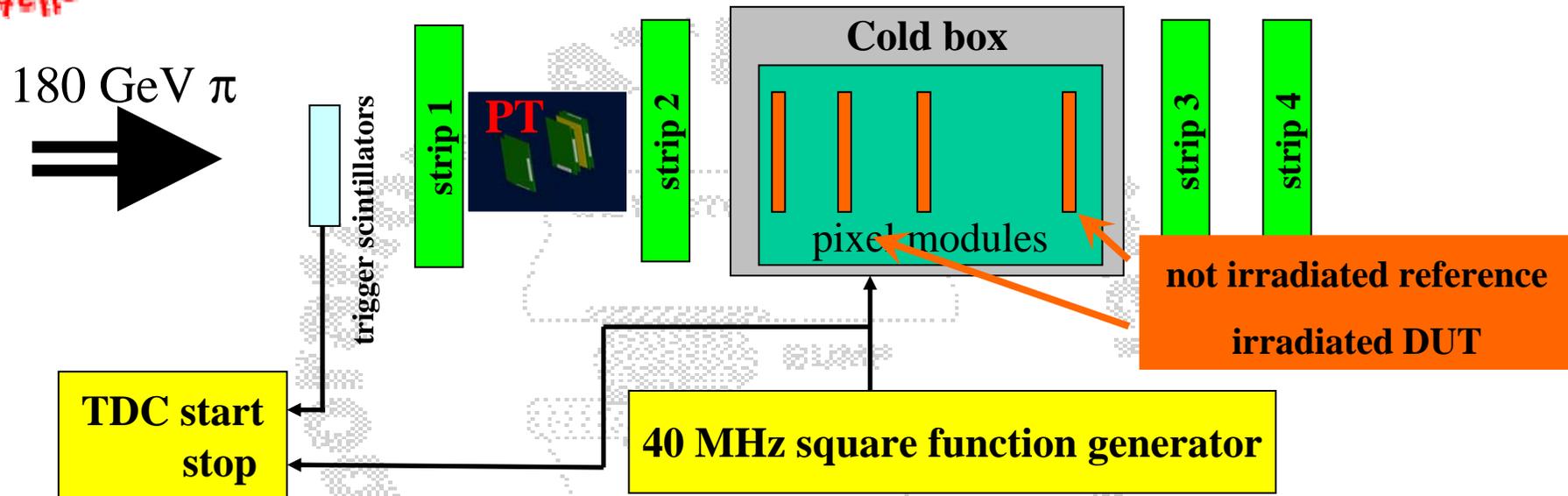
---

# Measurements with high intensity beam

Modification of setup  
Efficiency vs. Occupancy

---

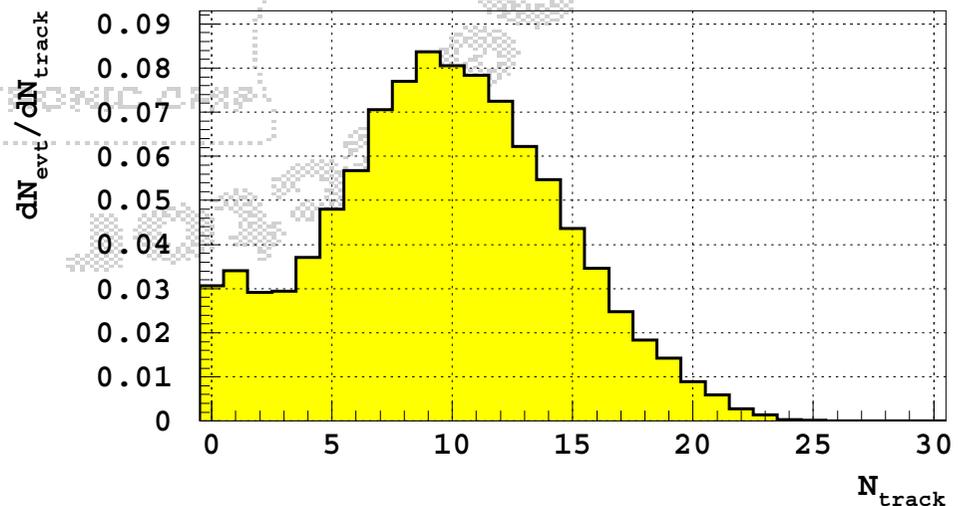
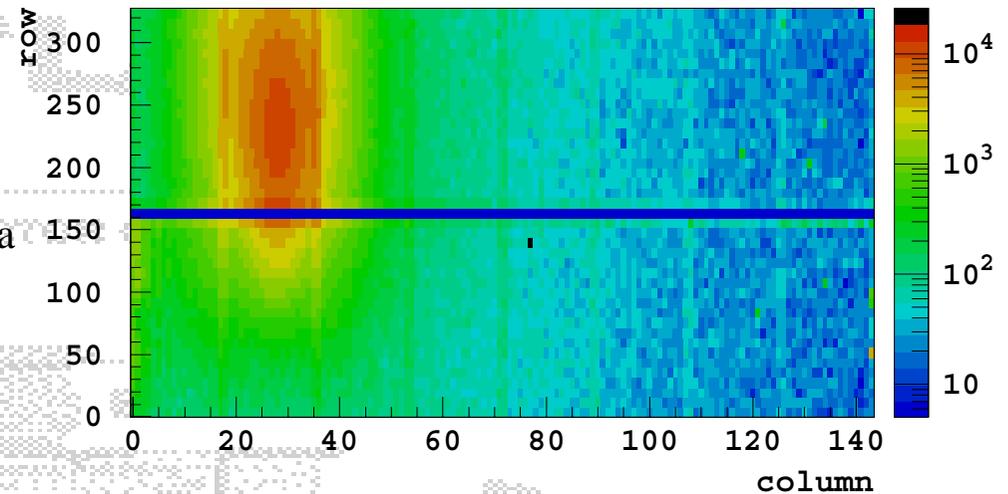
# Test beam setup (2)



- In 2003 and 2004 the SPS team delivered to ATLAS a beam with
  - LHC-like intensity
  - ~3 mm gaussian width
- measurement of efficiency dependence upon occupancy in realistic conditions.
- Trigger scintillator not able to cope with the rate:
  - ☞ **intensity high enough to use random triggers!**
- Strip detectors not able to cope with the rate:
  - ☞ **stand alone pixel telescope!**

# Data analysis

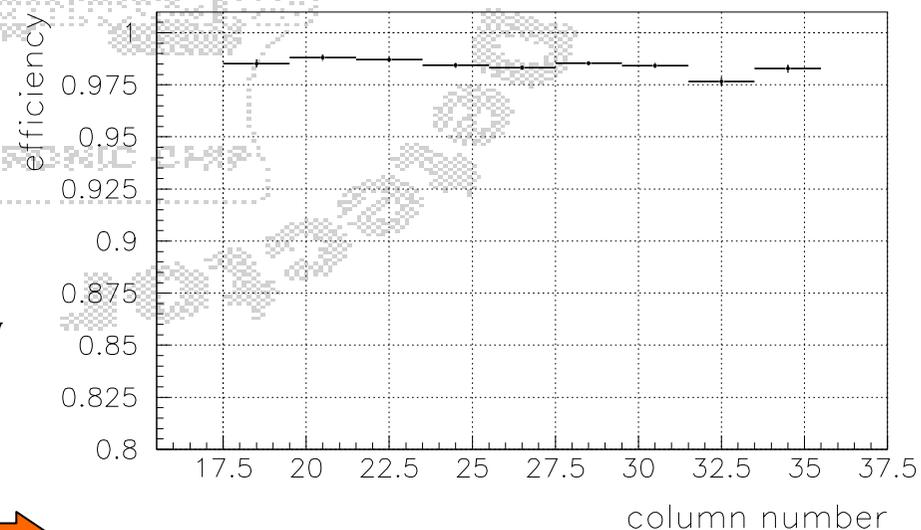
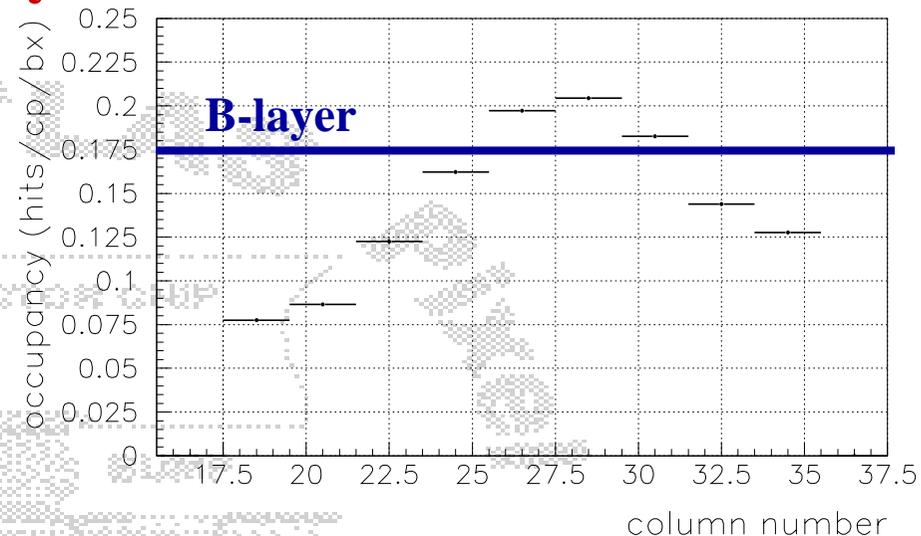
- **Occupancy** computed from the average number of hits of each **column pair**:
  - in one chip the occupancy has a spread of a factor 2.
- **Tracks** fitted from 3 modules:
  - digital resolution
  - $\chi^2$  probability  $> 2\%$
- **Efficiency** determination:
  - extrapolation within the most populated chip;
  - search for hits within
    - 400  $\mu\text{m}$  along the long pixel direction
    - 200  $\mu\text{m}$  along the short pixel direction



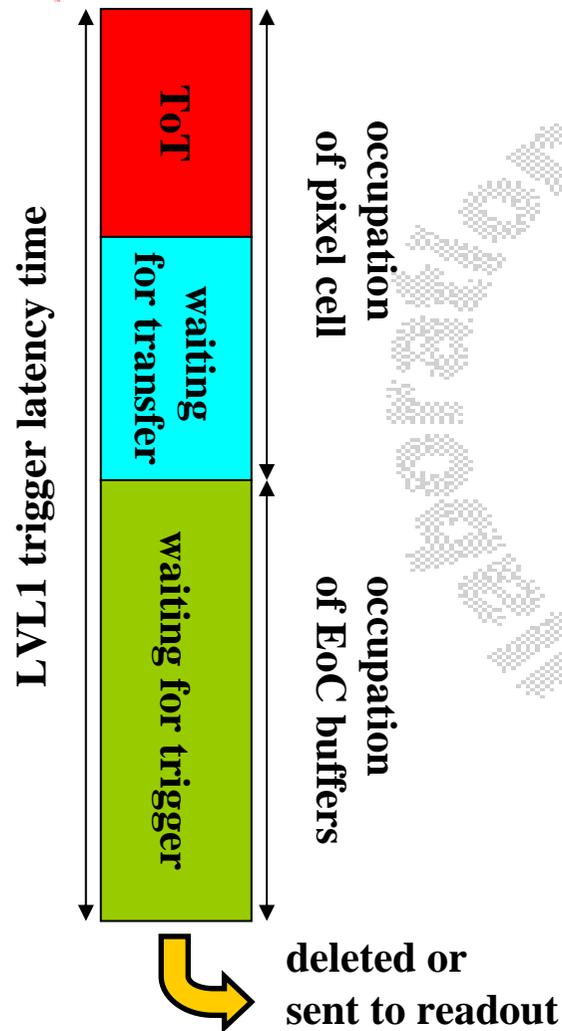


## Efficiency vs. Occupancy

- Default (realistic) running conditions
- Nominal tilt angle of 15 degrees.
- Max occupancy 0.20 hits/cp/bx
- **B-layer: 0.17 hits/cp/bx**  
or  $10^8$  hits/cm<sup>2</sup>/s  
with 1.5 hits/track
- **Efficiency:  $98.2 \pm 0.4\%$**   
( $\sigma$  is the spread over 3 devices)
  - consistent with the detection efficiency
  - independent on the hit rate.
- **But how much room is left?**
  - No possibility to increase intensity of SPS beam;
  - Other tricks to stress the system



# Efficiency vs. Occupancy



Besides the detection efficiency hits can be lost if:

- the hit arrives when the pixel cell is busy processing a previous hits (dead time):
  - tuning of the feedback current to set the ToT**  
 default:  $ToT = 15 \text{ bx/mip}$   
 $\Delta\epsilon = A \times \text{occupancy} \times \Delta\langle ToT \rangle$   
 $A = -0.78 \pm 0.17$  (expected  $A = -1$ )  
 less than 1% at B-layer luminosity.
  - clock frequency for the sparse scan logic  
 default: 40 MHz  
 if set at 20 MHz losses are visible above 0.14 occupancy.  
 threshold for this effect at max speed is 0.28 occupancy
- the on-chip memory is full when the hit is transferred from the pixel cell to the EndOfColumn region.
  - trigger latency  
 default: 130 bx  
 increase up to 250 bx (hits wait longer in the EoC)
  - hit duplication  
 (increase number of hits in EoC without increasing dead time)
  - This is the most relevant effect:  
 additional 1% losses at 0.21 occupancy  
 additional 3% losses at 0.30 occupancy



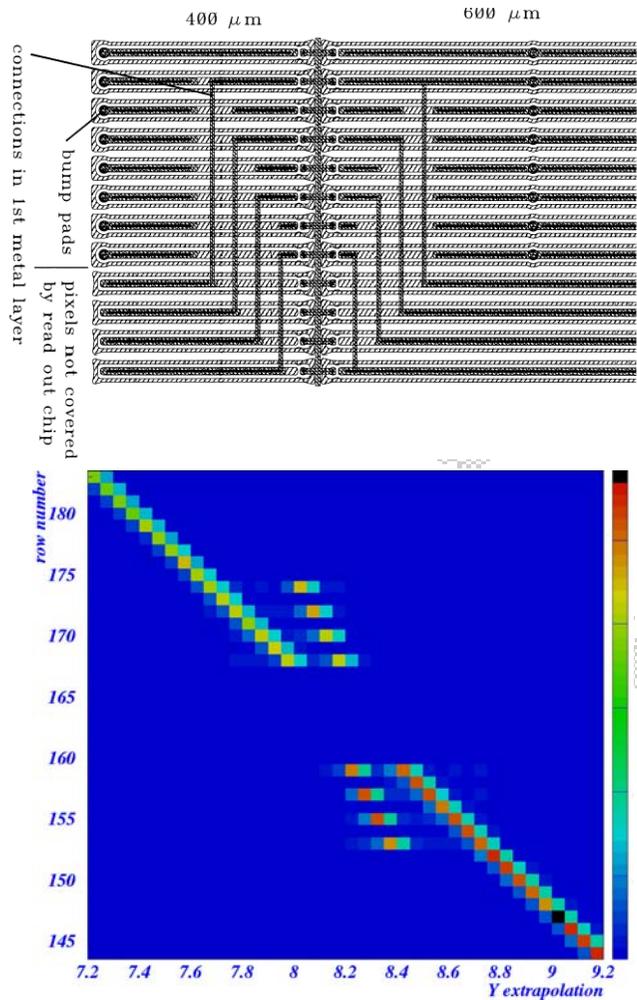
# Conclusions

- **Production modules have been tested after irradiation to:**  
NIEL =  $10^{15}$  1 MeV  $n_{eq}/cm^2$ , dose = 500 kGy
- **Device properties tested in the standard H8 beam:**
  - efficiency (TDR requirement >97%):
    - >99.9% before irradiation
    - 97.8% after irradiation
  - resolution (TDR requirement < 13  $\mu m$ ):
    - 7.5  $\mu m$  at 10° incidence before irradiation,
    - 9.7  $\mu m$  at 15° incidence after irradiation,
    - requires hit duplication (10% increase in occupancy)
- **Efficiency of irradiated detectors has also been measured in an LHC-like particle flux:**
  - **the readout architecture is verified**
  - **efficiency is not affected by occupancy even at B-layer rate**
  - **different sources of losses start to show up above 0.21 hits/cp/bx (+23% with respect to the B-layer occupancy)**
  - **onset of inefficiencies is gradual and it does not exceed 3% even at an occupancy 65% higher than B-layer.**

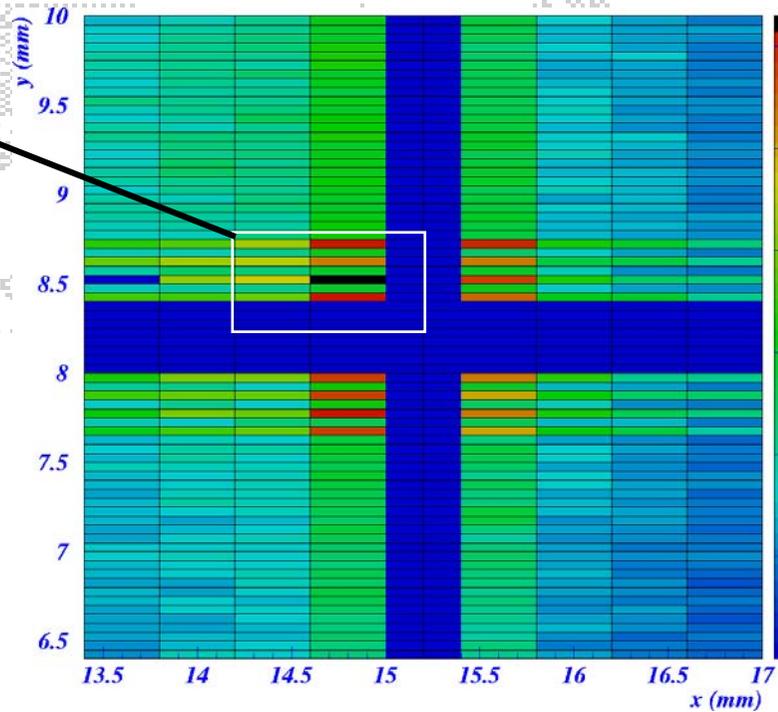


## Back-up slides

- Ganged and long pixels
- Effects of radiation damage
- Timing on not-irradiated modules
- Detailed efficiency vs. occupancy plots



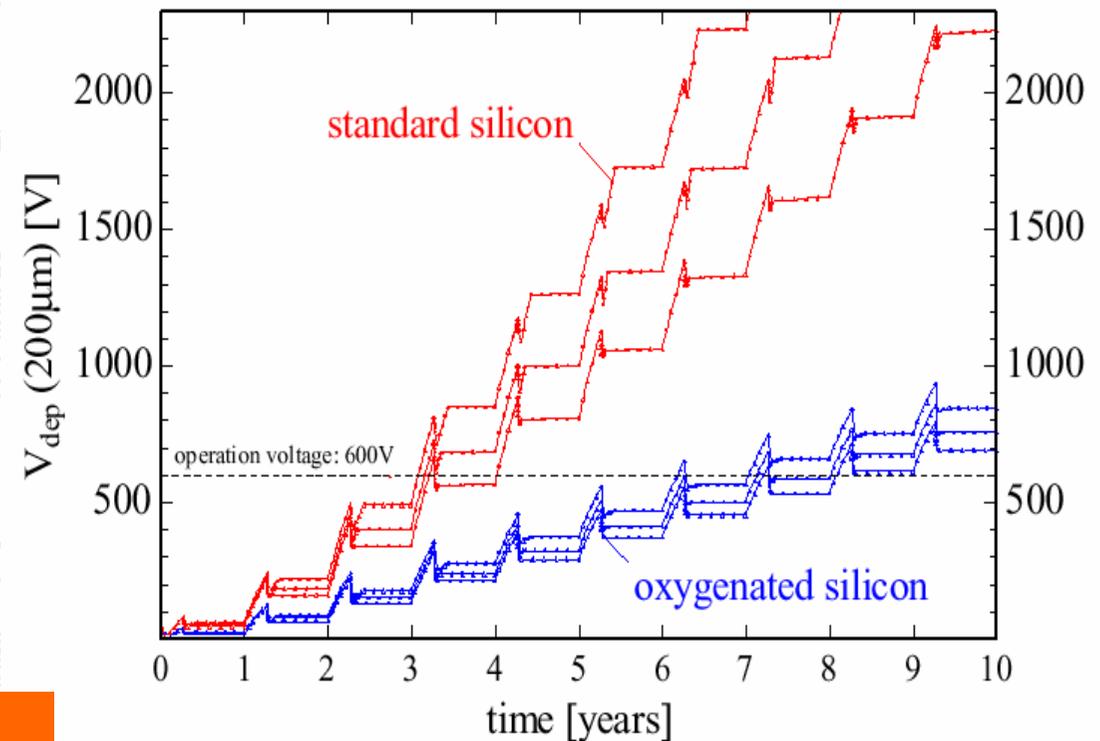
- Operation of “special” pixels in the inter-chip region can be clearly seen both from the hitmap and the hit position vs. track extrapolation correlation.



# Constraints: radiation hardness

- External pixel layers will receive a yearly damage from NIEL corresponding to a fluence of  $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
- B-layer at  $R=5.5 \text{ cm}$  will be a factor two more.
- Initial specification were:
  - external layers must withstand 10 years of operation at the LHC
  - B-layer must withstand at least 5 years of operation

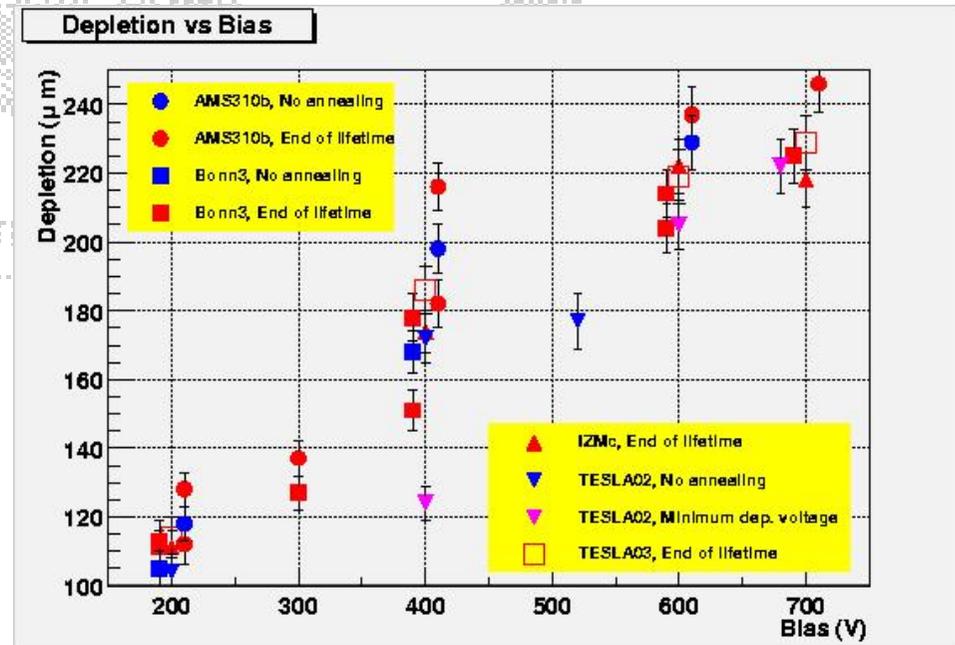
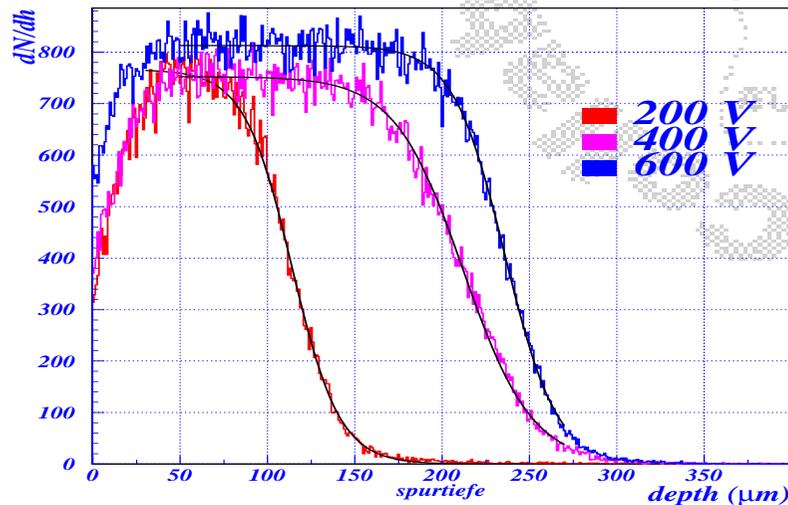
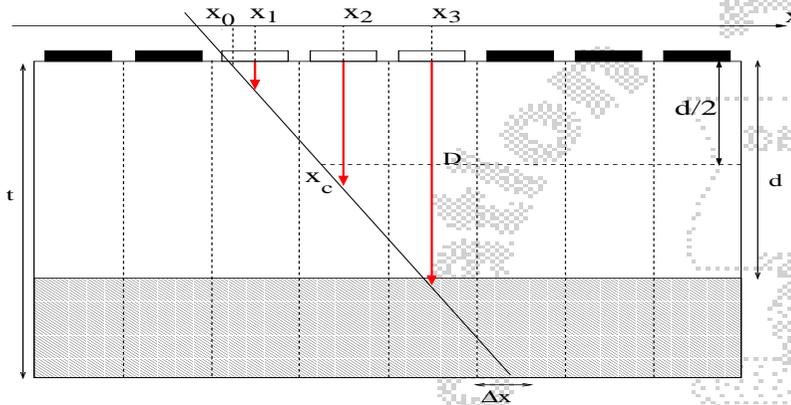
- That means:
  - $\text{NIEL} > 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
  - dose  $> 500 \text{ kGy}$



**Oxygenated FZ silicon was chosen because of improved hardness to charge particle irradiation.**

# Effective depletion depth

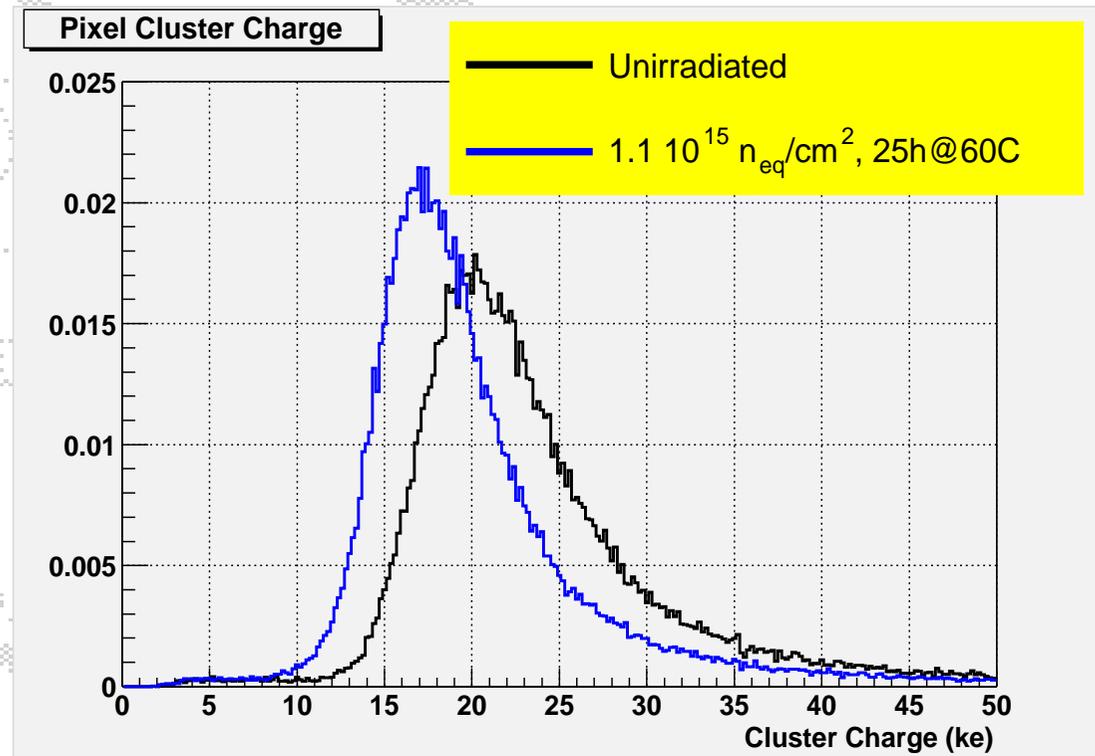
- Tilted tracks cross pixels at different depths.
- The depth of collected hits shows an edge:  
*effective depletion depth*  
⇒ depends on the detection threshold.
- **maximum effective depletion depth is reached at 500V**



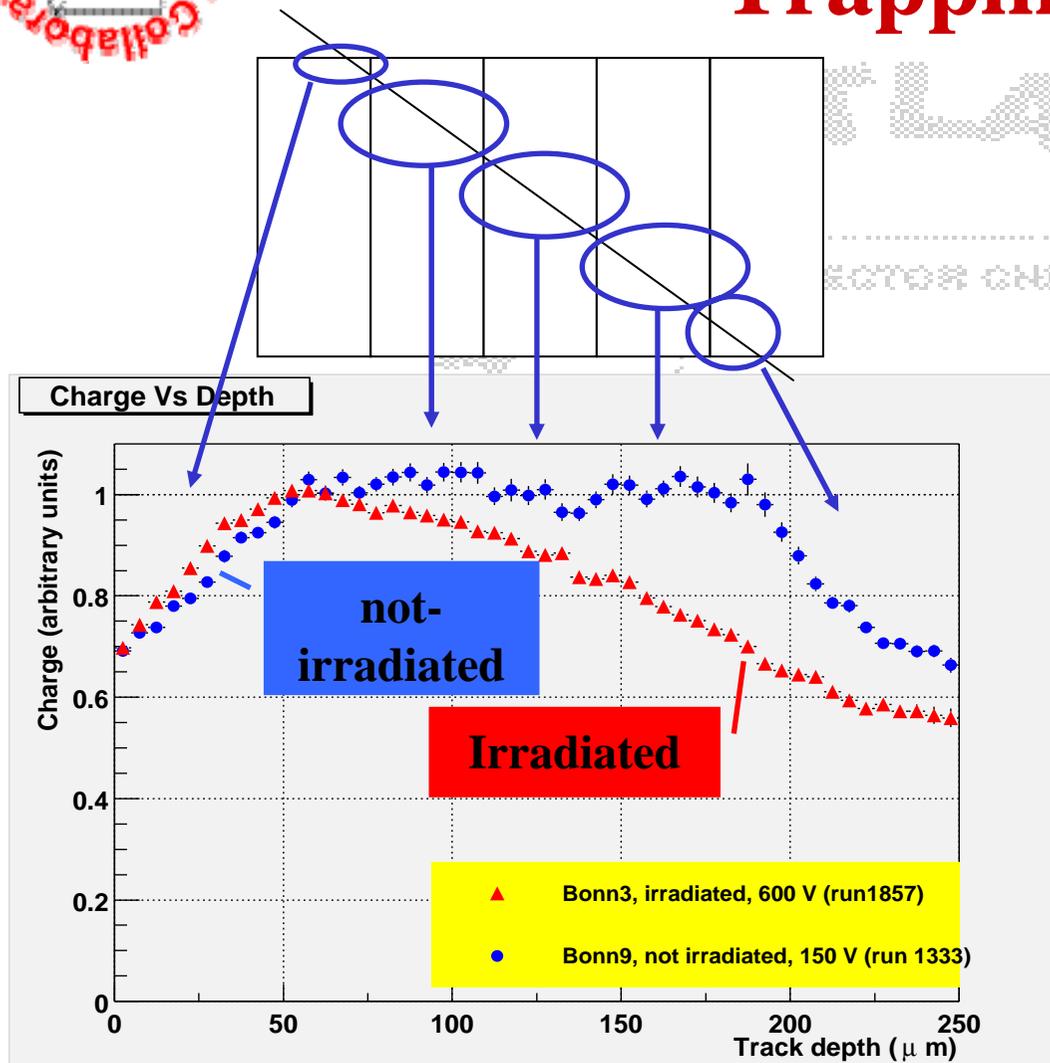


# Charge collection

- Average collected charge:
  - 25 ke ( $\pm 10\%$ ) before irradiation
  - 20 ke ( $\pm 10\%$ ) after irradiation
- **80% charge yield after irradiation at nominal dose.**
- Losses are due to:
  - low efficiency regions near the bias grid;
  - charge trapping



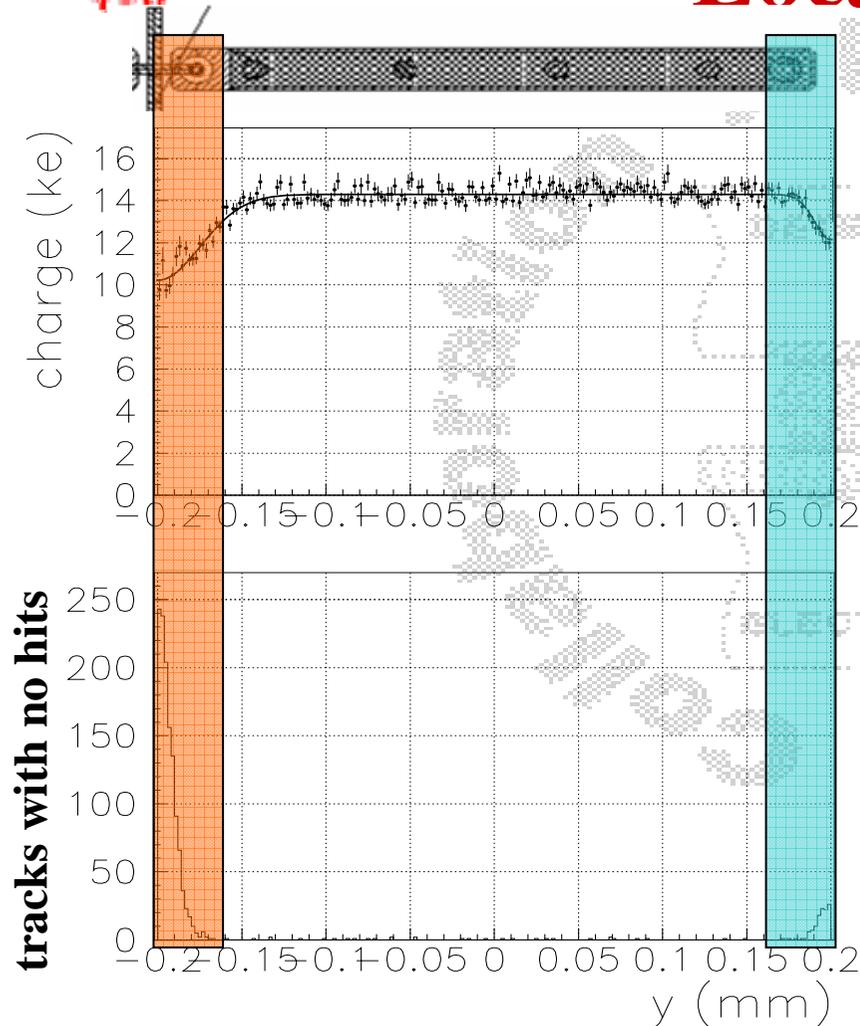
# Trapping



- The same technique of tilted tracks used for the depletion measurement can be applied to measure the trapping of the charge carriers.
- For not irradiated sensors, the collected charge is uniform along the depth.
- For irradiated sensor, the yield as a function of the depth can be translated, via the drift velocity, in a carrier lifetime:  

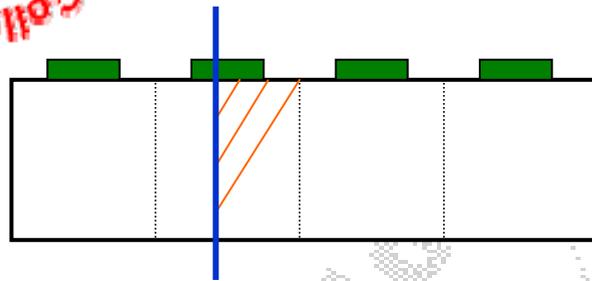
$$\tau_e = 4.1 \pm 0.3 \pm 0.5 \text{ ns}$$

## Local losses

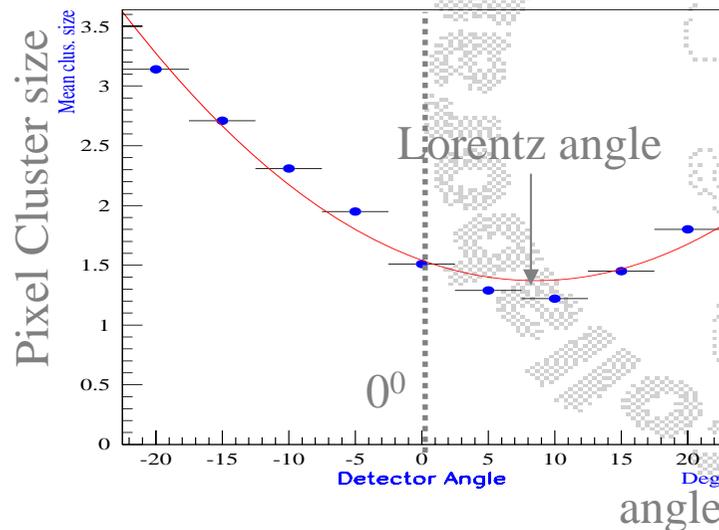


- After irradiation there are regions of low charge collection:
  - near the bias grid (**orange**), which is necessary for the sensor test before bonding;
  - in the edge region between two columns (**blue**).
- In these regions is also localized the tracking inefficiency.

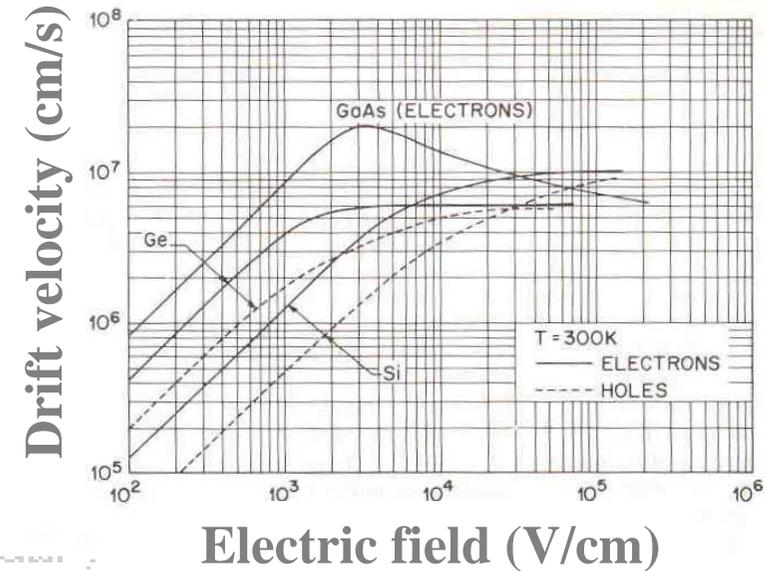
# Lorentz angle



ST2 Non Irradiated - 150 V



**Measurement method:** number of pixel hits is minimum when incidence angle is equal to the Lorentz angle  $\gamma_L$ .



$$\tan \gamma_L \propto \mu_d = \frac{v_s/E_c}{[1 + (E/E_c)^\beta]^{1/\beta}}$$

As bias voltage is increased to cope with irradiation, the Lorentz angle decreases:

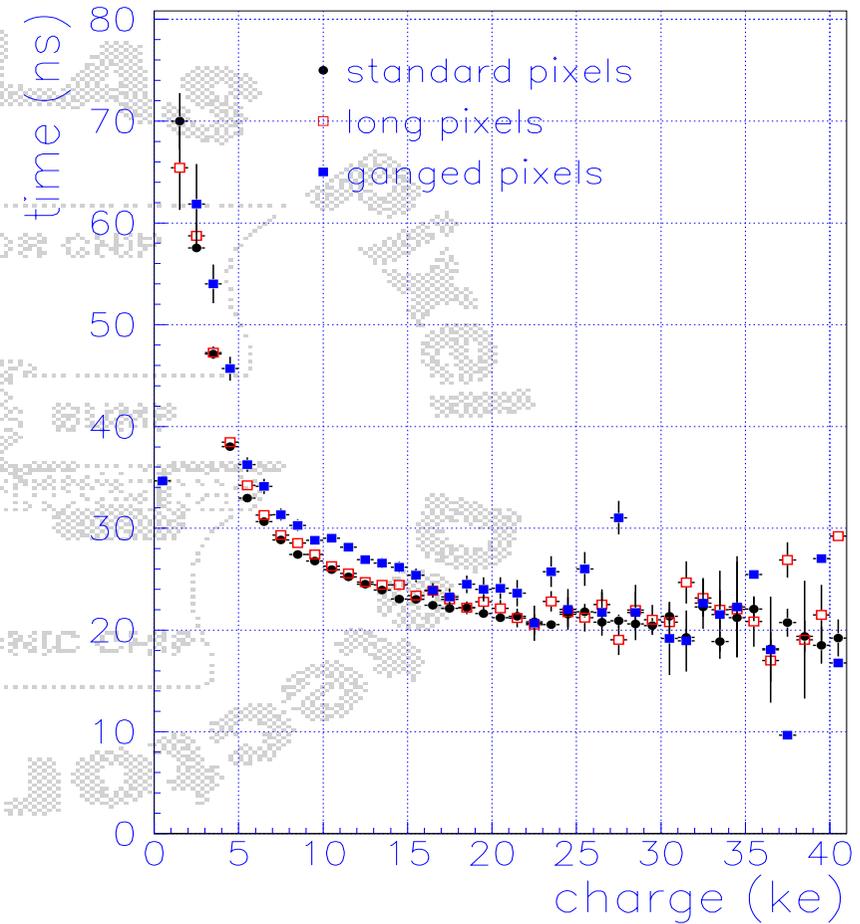
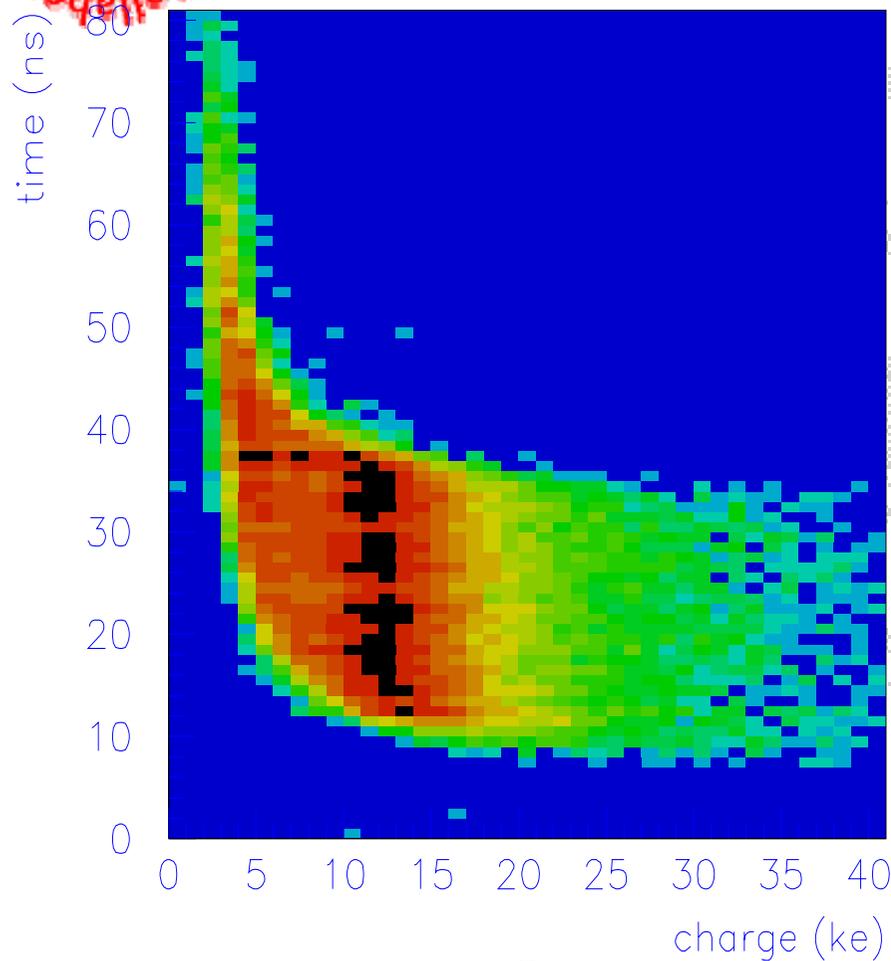
Lorentz angle @2T, 150V = -15°

Lorentz angle @2T, 600V = -5°

Pixel modules tilt in ATLAS=20°

**Effective incidence angle = tilt angle + Lorentz angle**

# Timewalk



**hit time = TDC time + 25 ns × LVL1 #**

# In-time efficiency: not irradiated

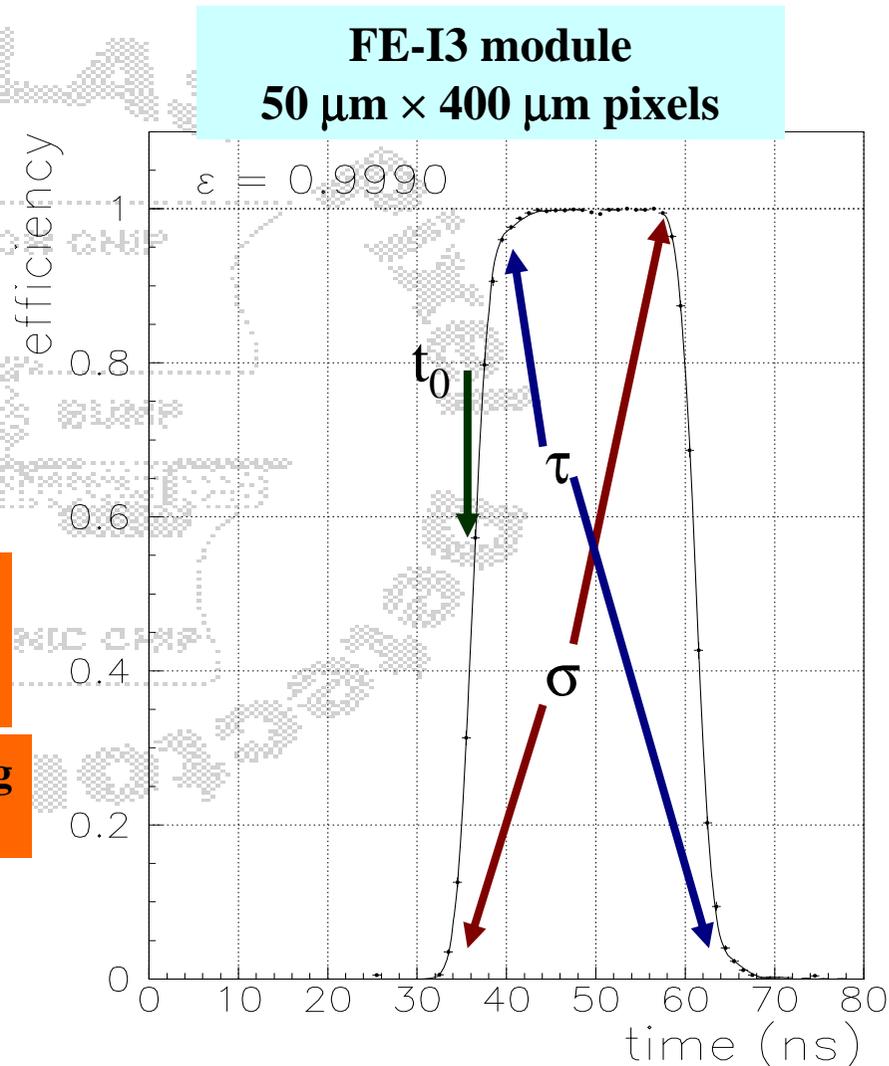
- Reference track from microstrip telescope.
- Associated hits as a function of the hit time.
- The fit function is the convolution of an exponential and a gaussian (*no special reason, it just looks fine...*)

- For not irradiated modules:

– plateau efficiency	99.9%
– no hits	0.1%
– timewalk losses	0.0%
– plateau size	14 ns
– $t_0$ uniformity	<2 ns

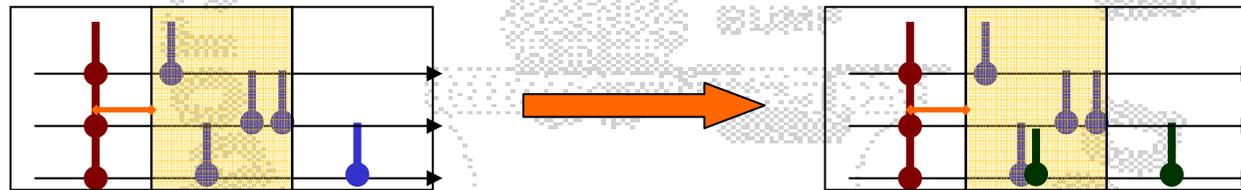
**Includes  
masked  
pixels**

**no tuning  
problem**



# Hit duplication

- For irradiated modules, which will have a  $15^\circ$  effective incidence angle:
  - lower total collected charge
  - a lot of charge sharing
- it is likely the low charge hit of a cluster will be lost:



- **FE feature:**

**hits below a selectable ToT value can be duplicated in the previous LVL1**

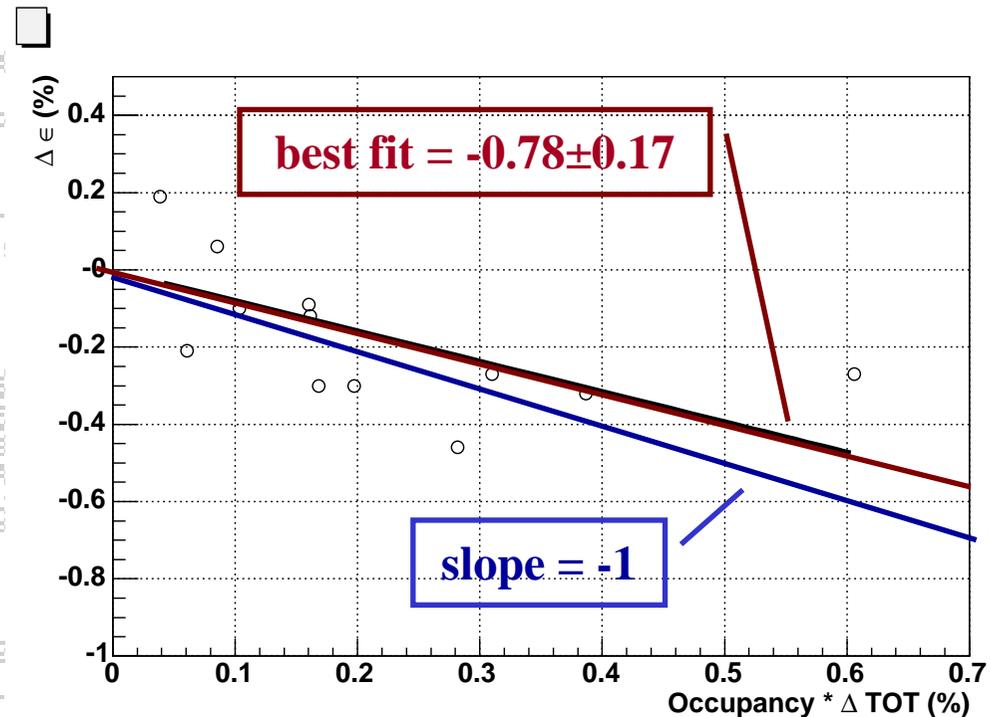
- The cluster is seen anyhow:
  - **no loss of detection efficiency**
- The fraction of cluster to perform charge interpolation is smaller:
  - **loss of resolution**
  - **dependence of resolution on clock phase**

- **restore integrity of clusters for charge interpolation**

- **increase occupancy**

## ToT

- Losses due to the dead-time of the pixel cell are expected to be:  
 $pixel\ occupancy \times \langle ToT \rangle$
- It can be verified by changing the ToT tuning and checking the efficiency change:  
 $\Delta\epsilon = occupancy \times \Delta\langle ToT \rangle$
- From the spread of the observed point, the best fit line has a slope of  **$-0.78 \pm 0.17$** , well compatible with the expected slope -1.



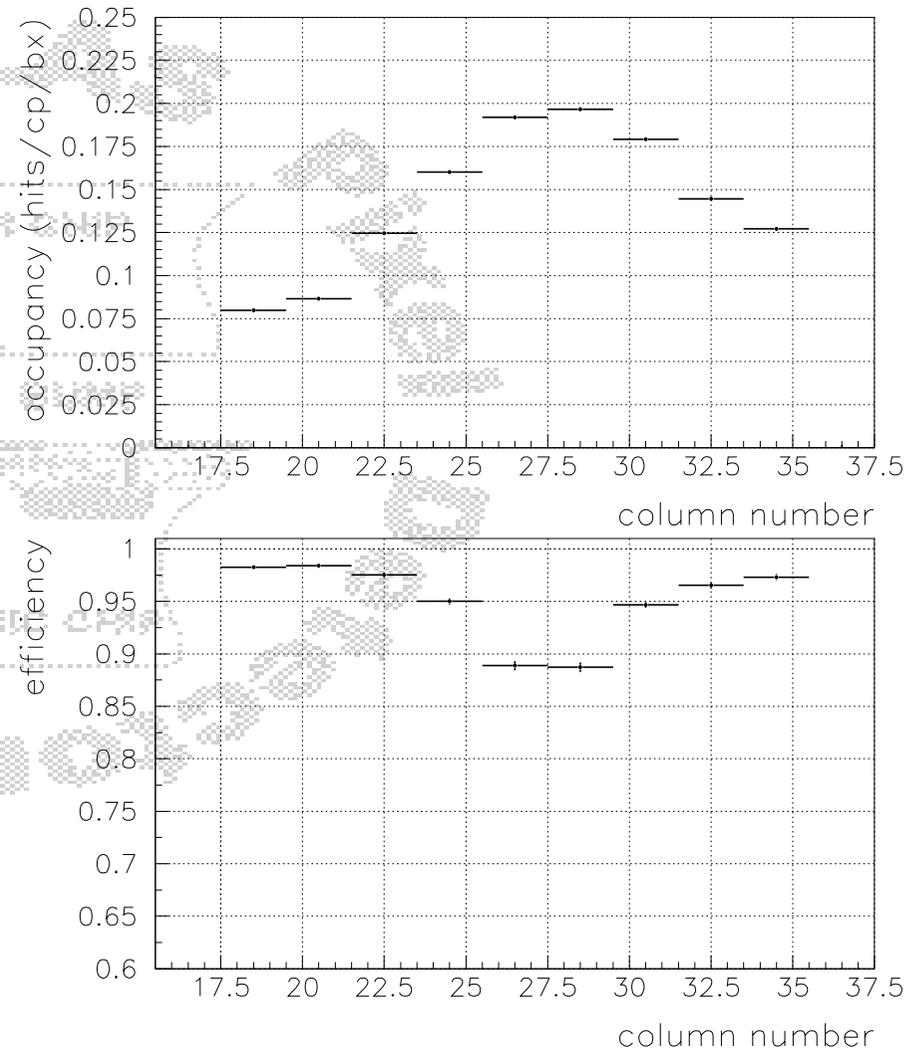
- **Even at B-layer occupancies, this effect is below the 1% level.**



## Sparse scan

- The clock used for the sparse scan may have a frequency reduced with respect to 40 MHz.
- This introduces an additional dead time in the pixel cell due to the increase of transfer time from the cell to the EoC buffers.
- Reducing it to 20 MHz results in an efficiency drop:  
98.2% → 91.3%
- losses start at occupancy of 0.14

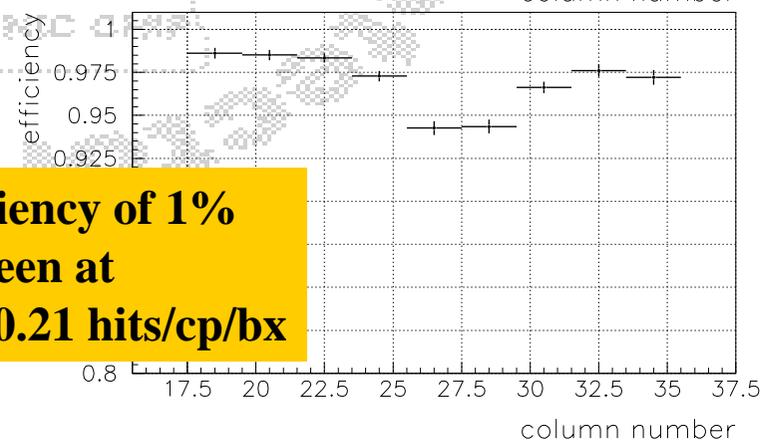
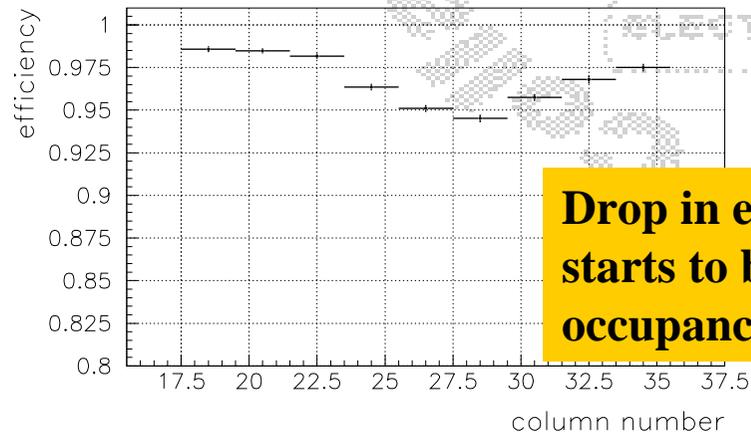
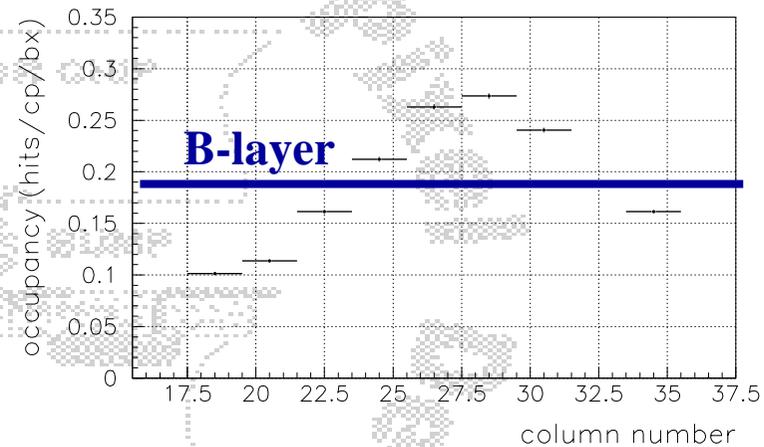
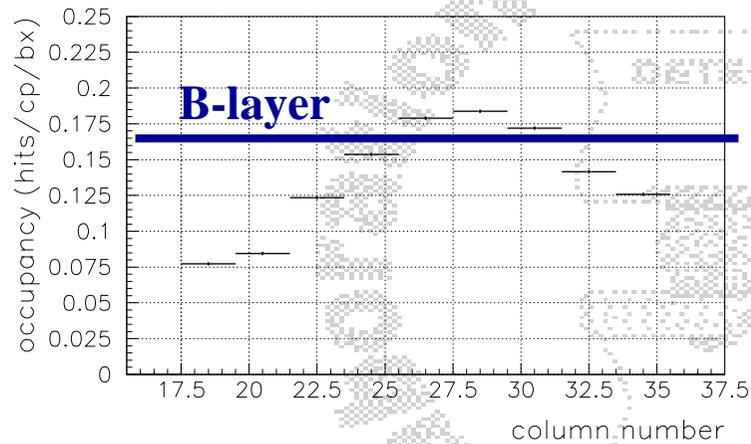
- **At normal readout speed the losses are expected to start at occupancy >0.28 hits/cp/bco.**





## Occupation of EoC buffers

- scales with latency.
- Latency 130 bx  $\rightarrow$  250 bx
- efficiency 98.2%  $\rightarrow$  95.4%
- can be increased by choosing a high level of hit duplication
- hits/cp/bx 0.20  $\rightarrow$  0.28
- efficiency 98.2%  $\rightarrow$  95.8%



**Drop in efficiency of 1% starts to be seen at occupancy  $>0.21$  hits/cp/bx**