Recent Developments in the ATLAS Pixel Detector

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Fermilab
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Participating Institutes

Canada

- University of Toronto

Czech Republic

- Academy of Sciences - Institue of Physics of Prague, Charles University of Prague, Chzech Technical University of Prague

France

- CPPM, Marseille

Germany

- Bonn University, Dortmund University, Siegen University, Bergische University - Wuppertal

Italy

- INFN and University of Genova, INFN and University of Milano, INFN and University of Udine

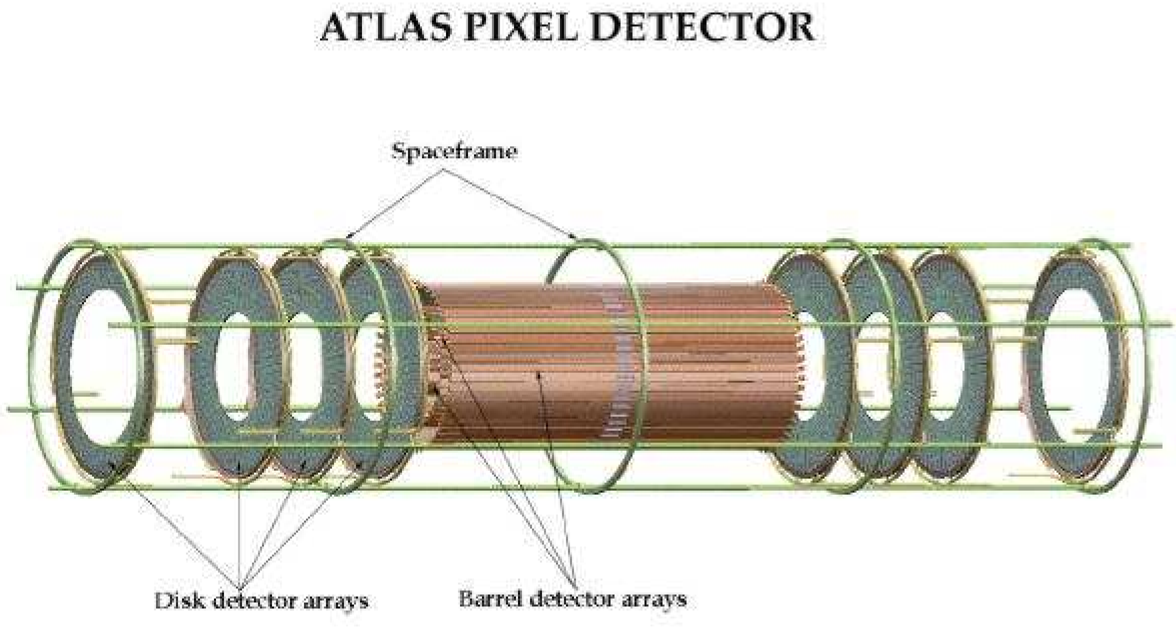
Netherlands

- NIKHEF - Amsterdam

USA

- University of New York - Albany, LBL and University of California - Berkeley, University of California - Irvine, University of New Mexico - Albuquerque, University of Oklahoma, University of California - Santa Cruz, University of Wisconsin - Madison

The ATLAS Pixel Detector



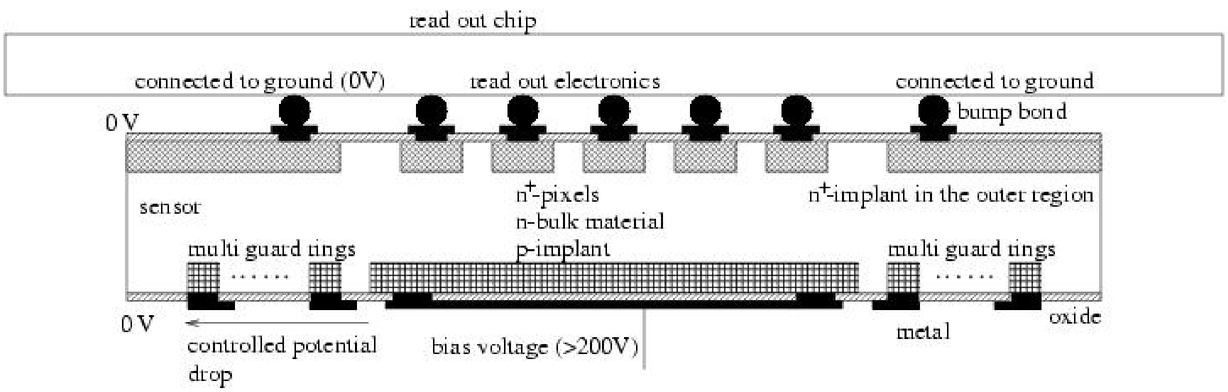
Contents:

- Introduction
- efficiency
- charge collection
- resolution
- modules
- occupancy studies
- depletion depth
- Lorentz angle
- conclusions

Sensor design

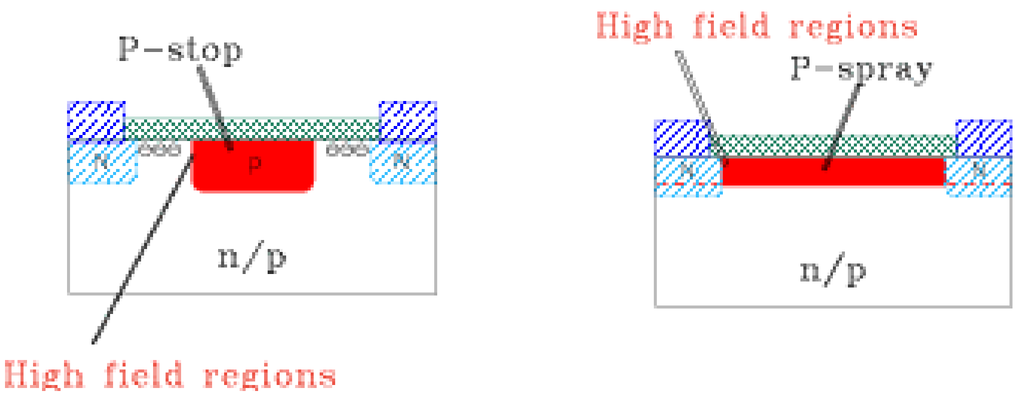
Sensor Concept

- n^+ pixels on n substrate



Pixel insulation needed

- 2 techniques: p-spray and p-stop



p-spray insulation:

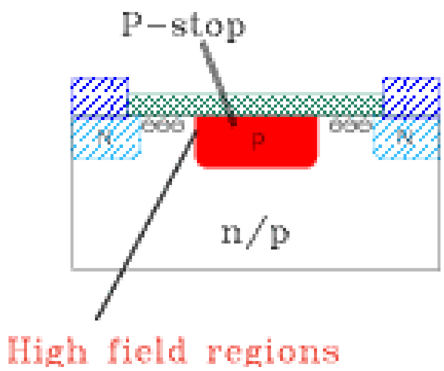
***lowest E-fields** at implant boundaries before and after irradiation*

bias grid allows testing before flip-chip

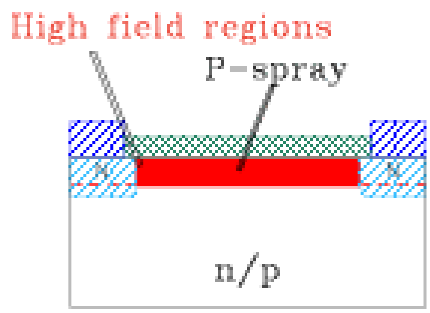
Sensor Design

p-spray vs p-stop

p-stop

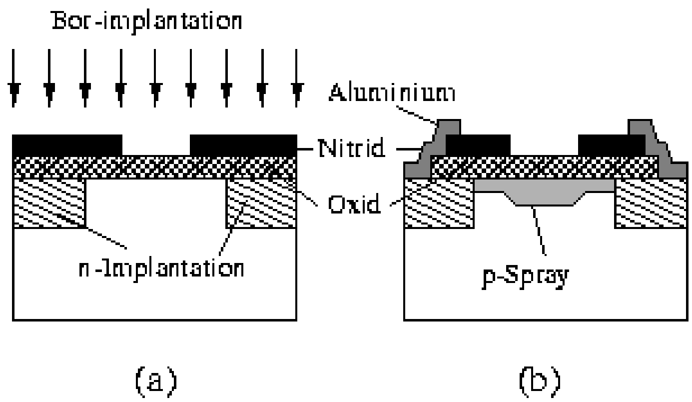


p-spray



	p-stop	p-spray
before irr.:	*low E-field*	*highE-field*
after irr.:	*high E-field*	*low E-field*

Moderated p-spray



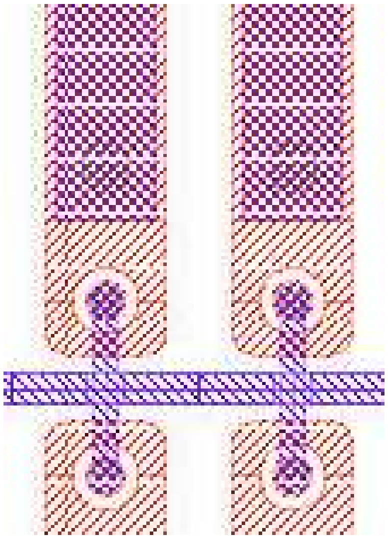
before irr.: *low E-field*

after irr.: *low E-field*

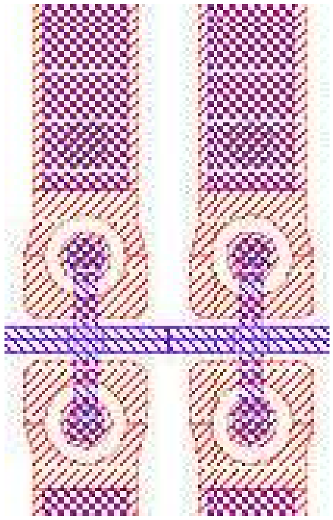
Sensor Design

Bias dot designs

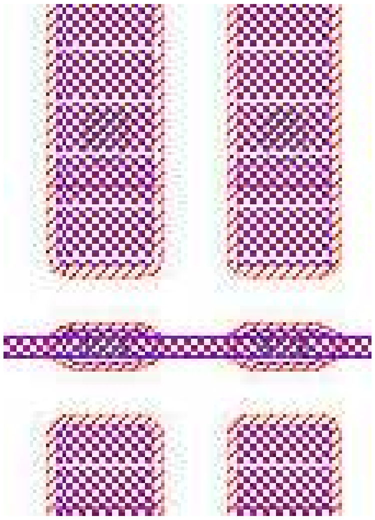
small bias dot



large bias dot



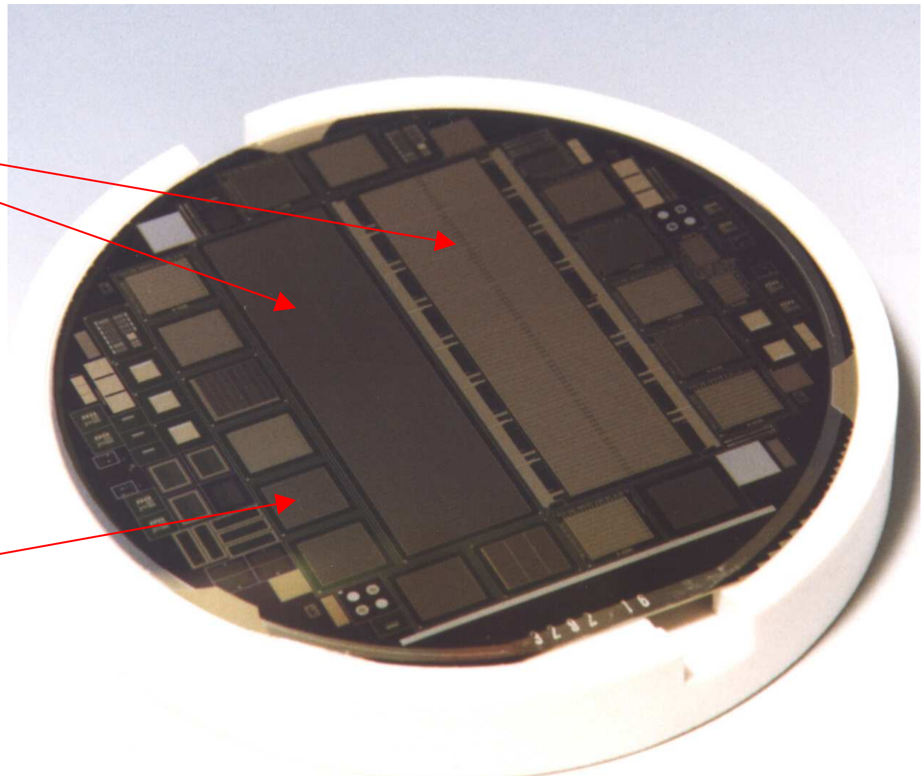
no bias dot



Sensor Fabrication

Wafer structures

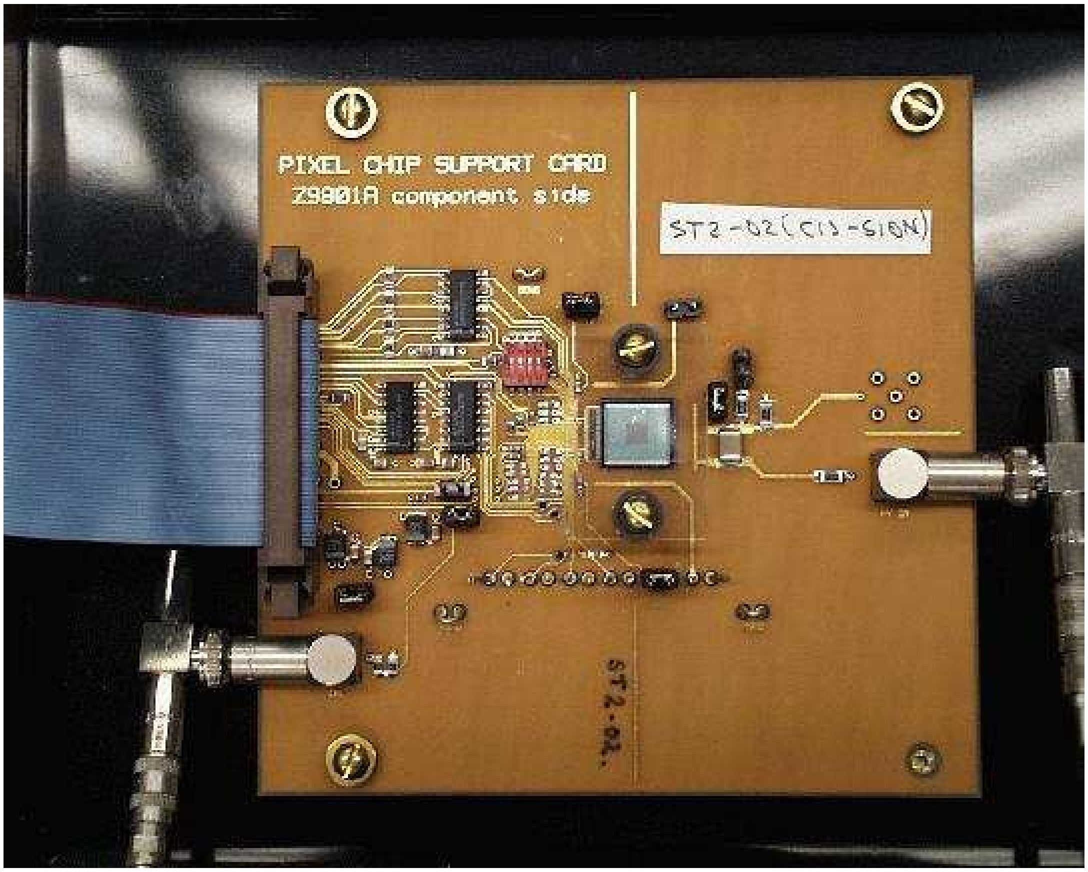
"Tiles"



single chips

- **Tiles** consist in 16 sensors arranged as 2 x 8
- **Modules** are built bonding 16 Front End chips
- **Single chips** have been used in test beam to optimize sensor design

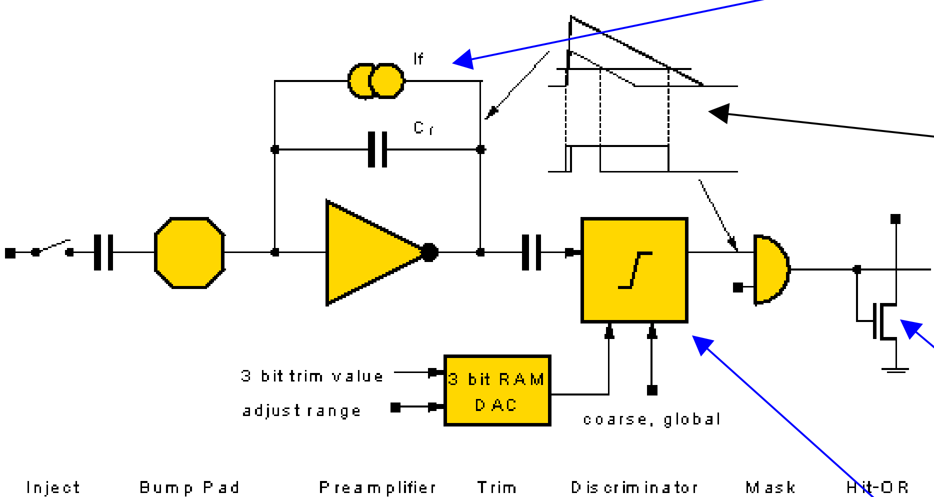
Single chip assemblies



- Single Chip detectors bump bonded to FE electronics
- 18 (or 10) columns
- 160 rows
- Time over Threshold calibrated for every pixel

Front End Electronics

- Cell size: 50 μm x 400 μm
- Pulse height Measurement
- 2 Architectures studied to read -out columns (not discussed here)



DC feedback

Time Over Threshold

Fast or

Adjustable discriminator

dc feedback with current source

- high stability for fast shaping
- tolerates 100 nA leak current
- linear decay for ToT

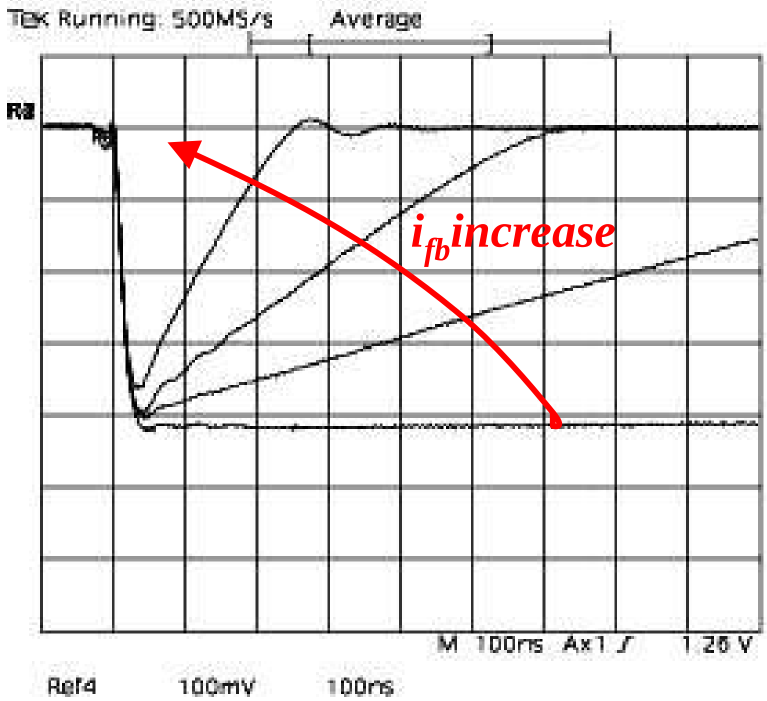
low threshold

- below ~ 3000 e

low noise and threshold dispersion

- below ~ 200 e

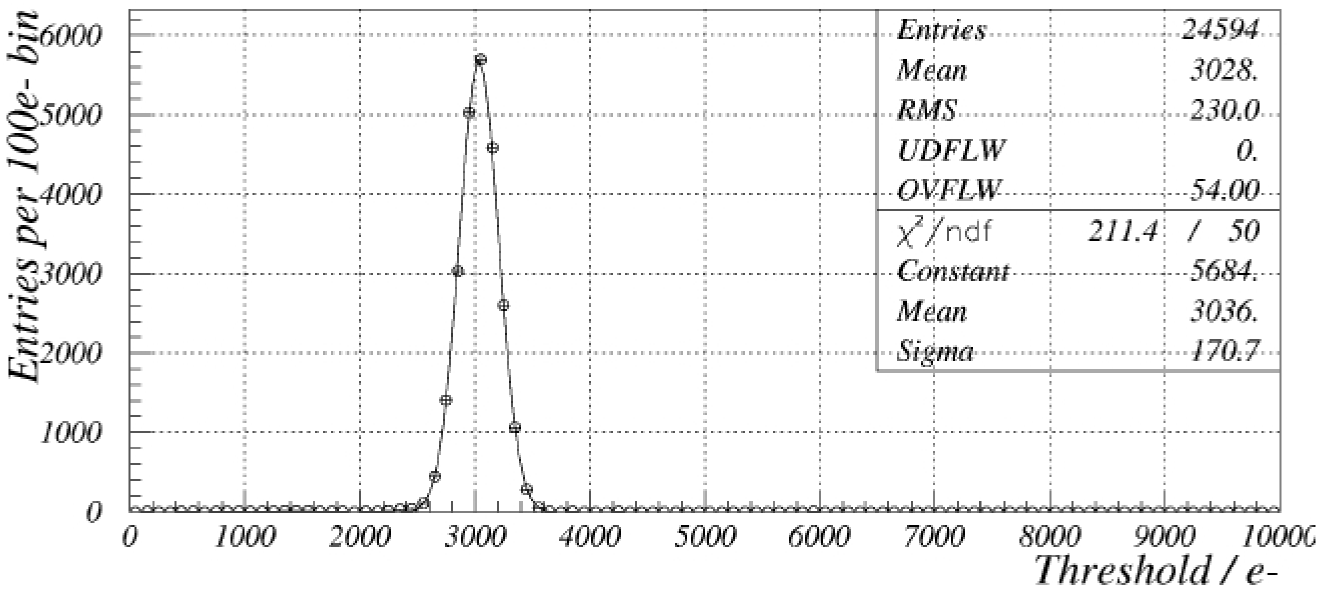
FE electronics settings

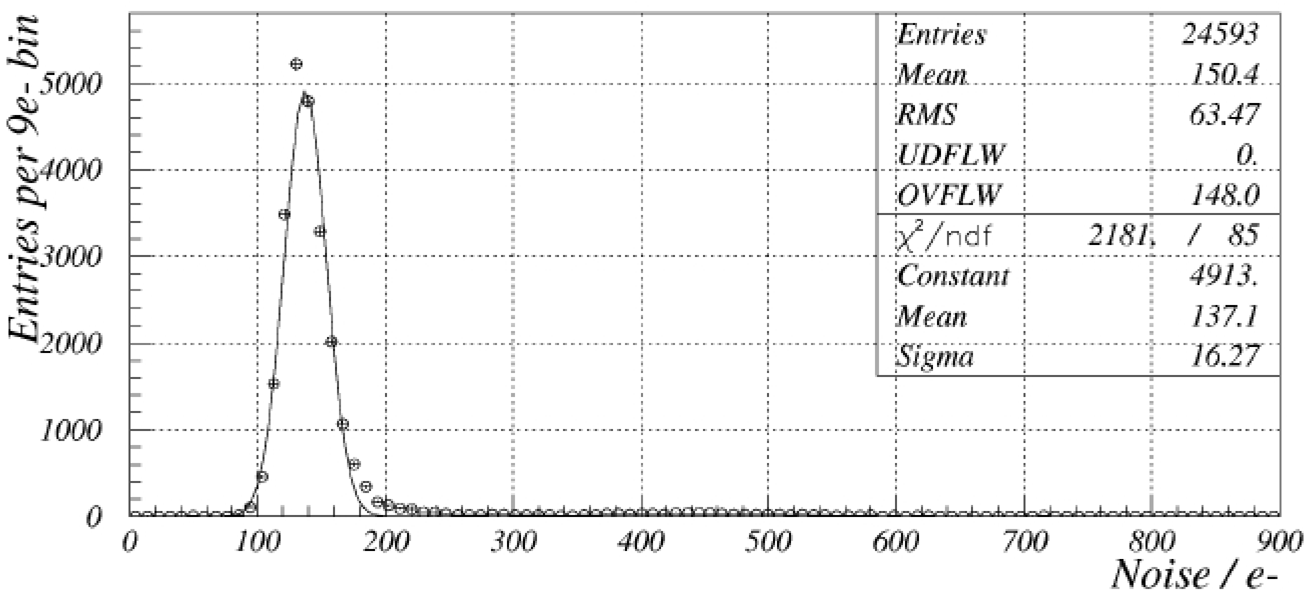


- ***Return to baseline ~ 500 ns***
- ***For charge collection studies:***

  return to baseline ~ 1500 ns to increase TOT resolution
- ***Thresholds settings from 2Ke to 4 Ke***

FE electronics performances

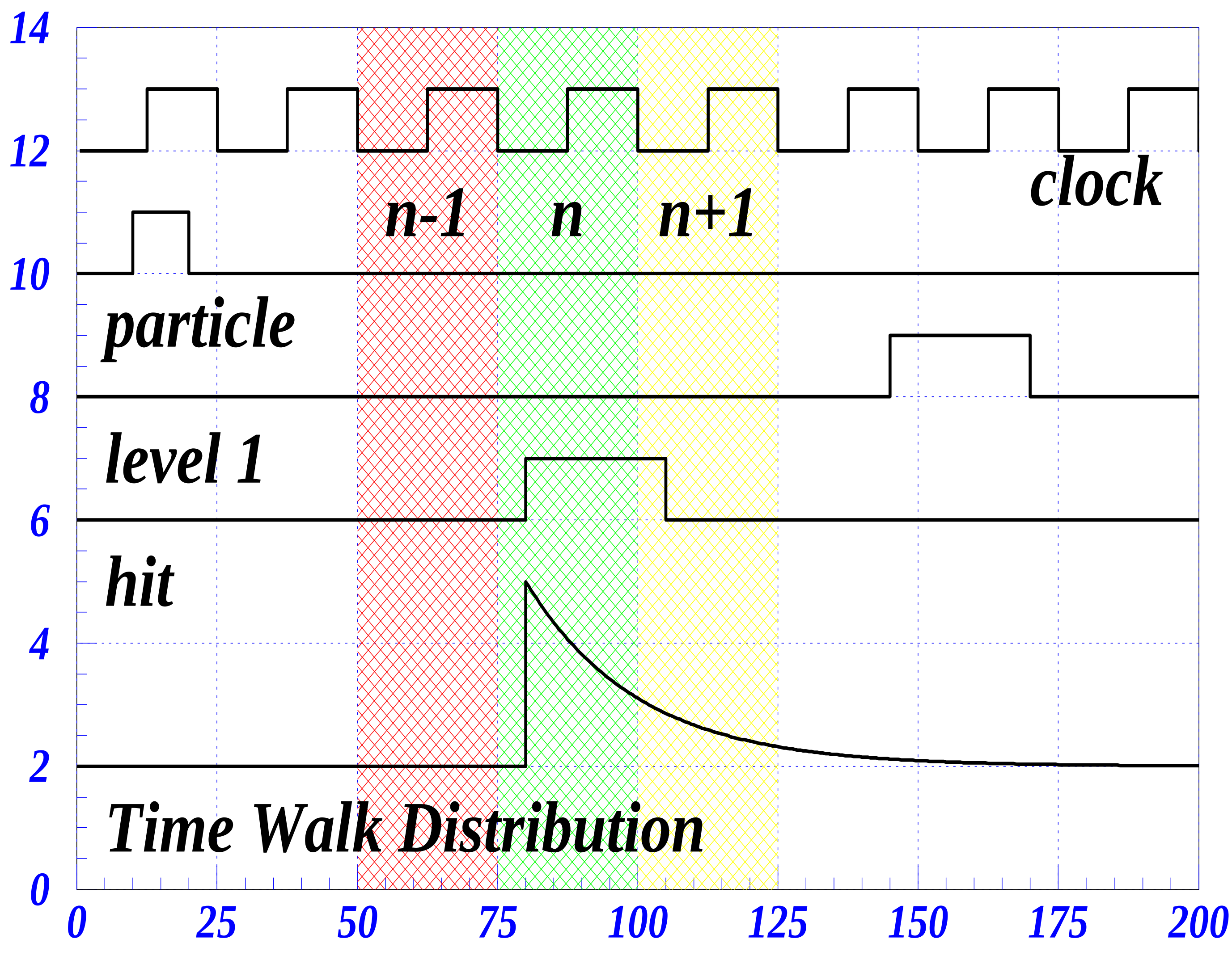




Efficiency

Timing

Definition of Bunch Crossings (BX)



Efficiency

Build Pixel Clusters:

- Contigous Pixel
- Digital Algorithm for Position

Sample Definition :

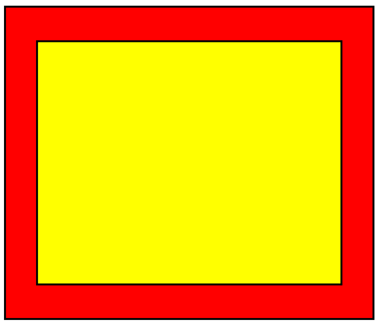
- Tracking quality:

  χ^2 probability > 0.02 in x and y views

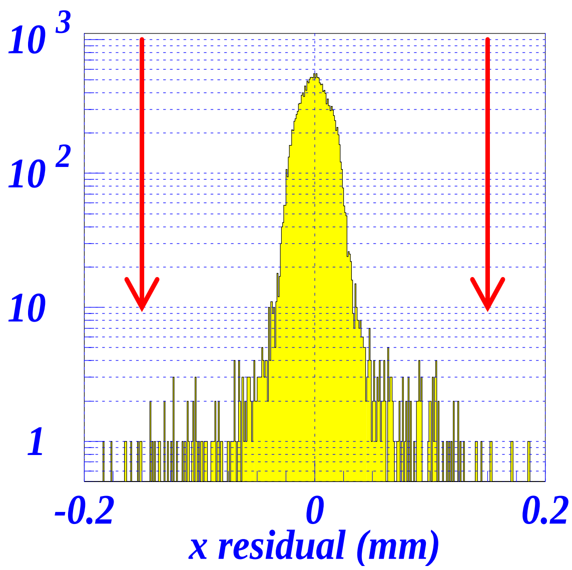
- fiducial cuts:

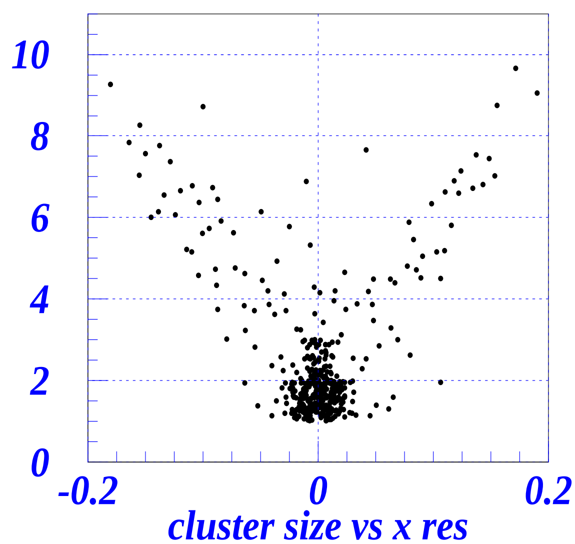
  remove edge of the detector

  to avoid resolution effects



Cluster - Track Matching:





Efficiency vs Time

Tested detectors

- n^+ on n bulk with 2 insulation techniques

- design 1.0

  Single chip Tile 1 ST1

  Single chip Tile 2 ST2

  Single chip Tile 2 ST2 10^{15} n/cm^2

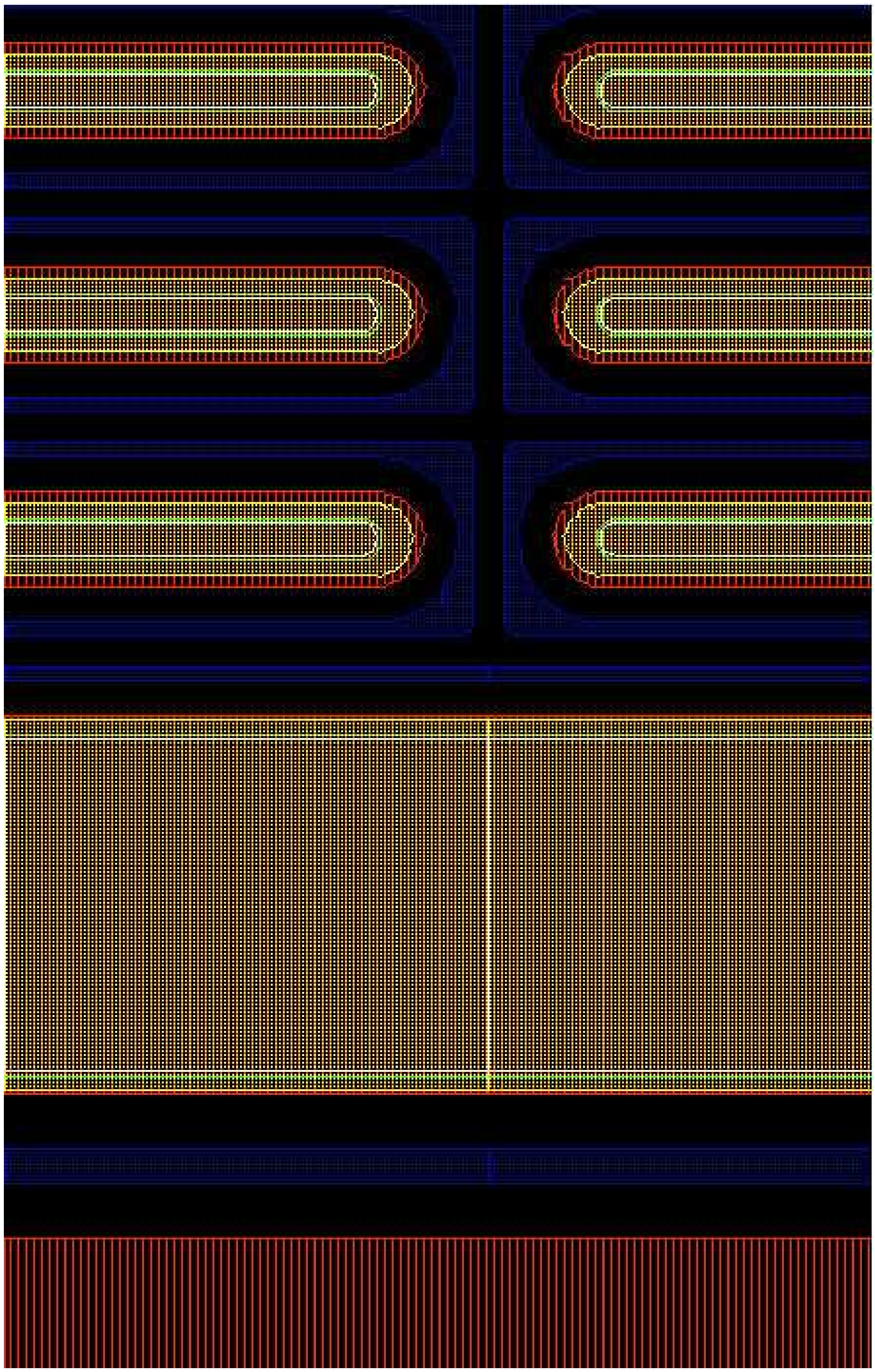
- design 1.b

  Single chip Tile 2 - no bias grid

  Single chip Tile 2 - with bias grid

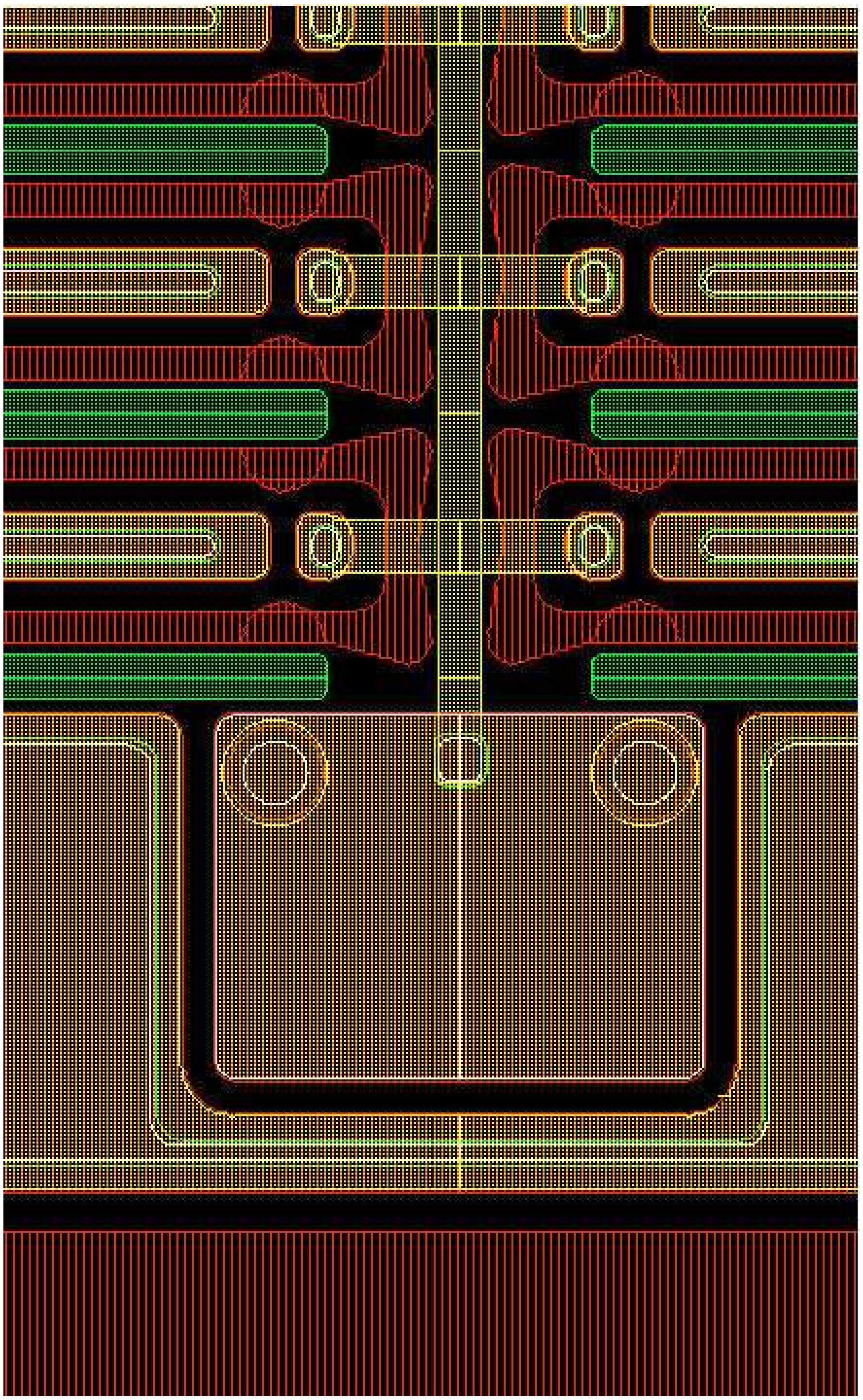
Tile 1 Design

n^+ pixels and p-stop insulation



Tile 2 design

n^+ pixels and p-spray insulation

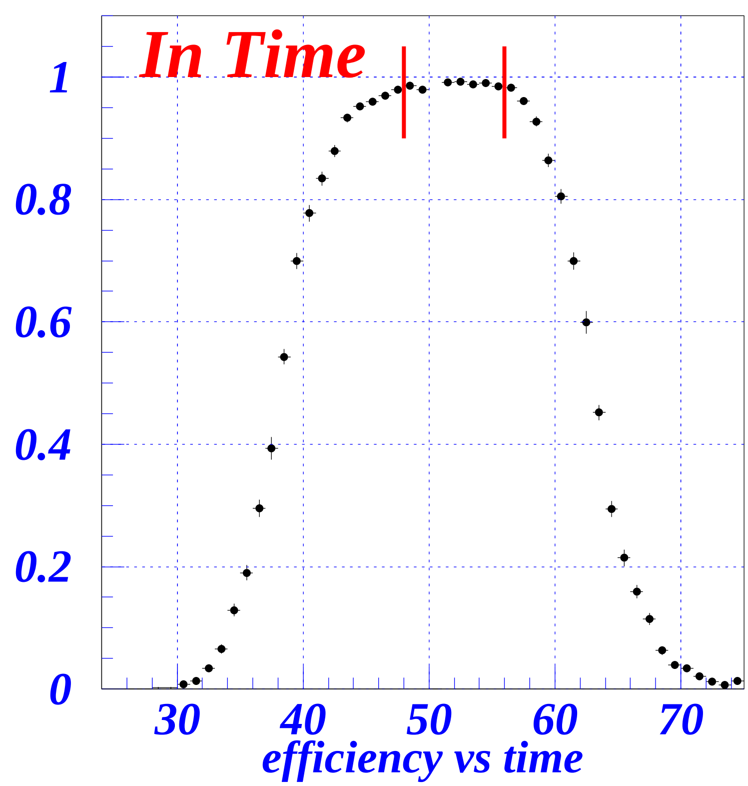


Efficiency vs Time

Efficiency 'In Time'

Detector Tile 2 - not Irradiated - Thr. 3 Ke

efficiency	98.8	Losses	1.2
1 hit	82.0	0 hits	0.4
2 hits	14.6	not matched	0.2
>2 hits	2.2	not in time	0.6

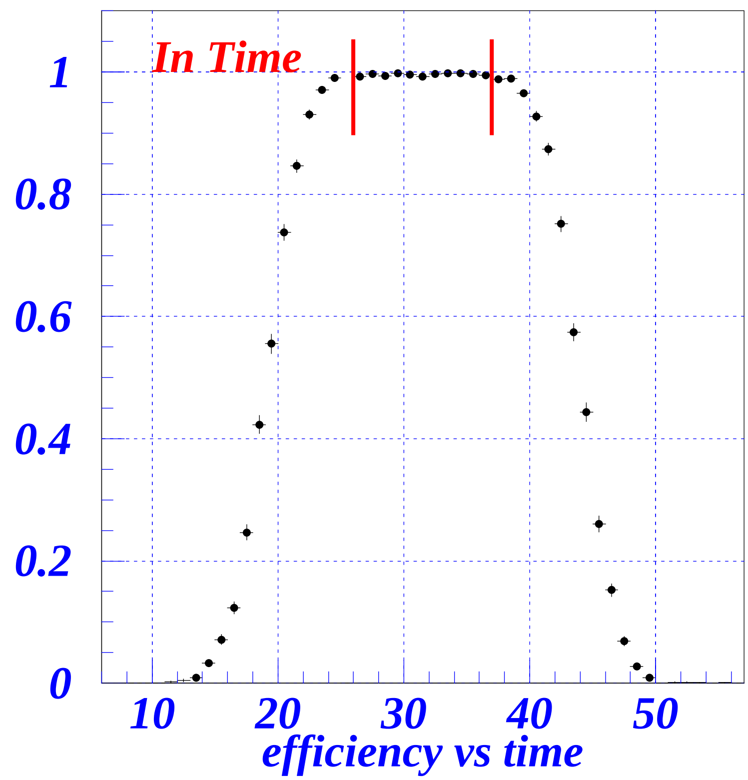


Efficiency vs Time

Efficiency 'In Time'

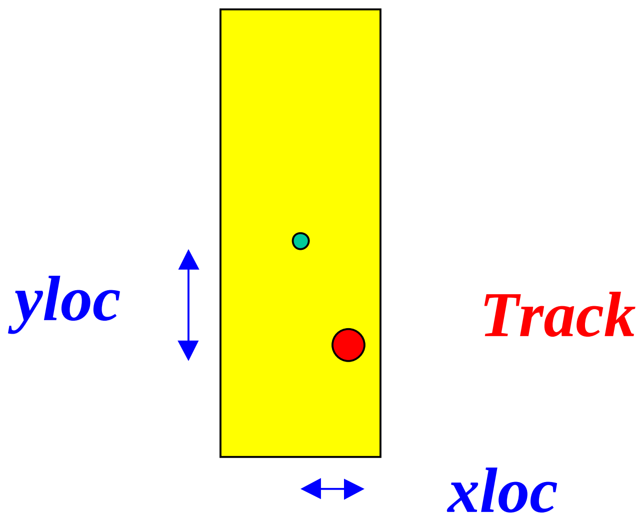
Detector Tile 1 - not Irradiated - Thr. 3 Ke

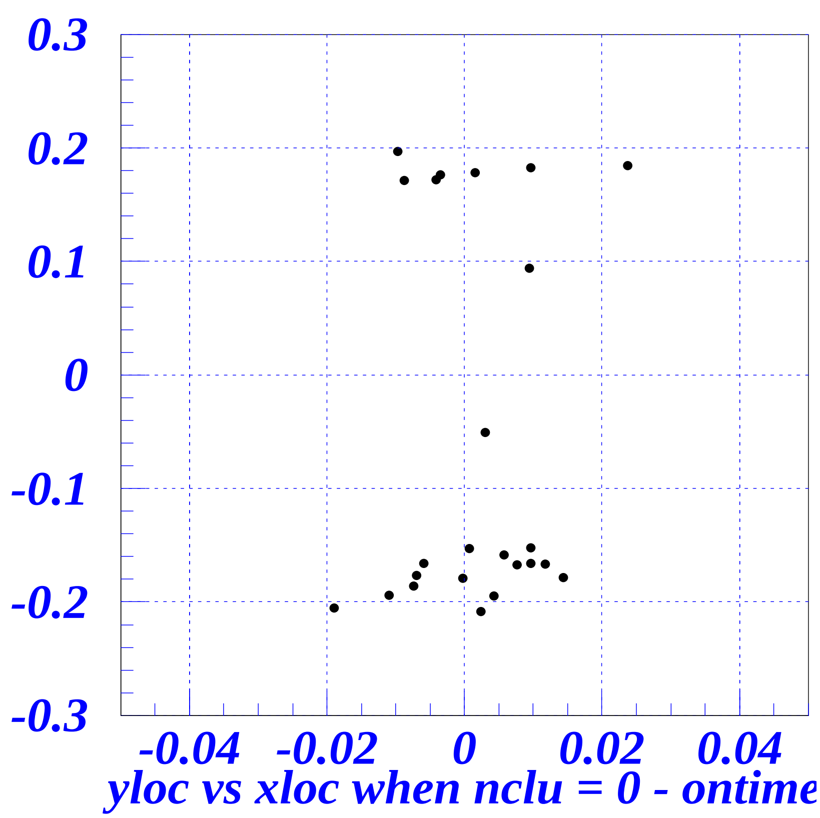
efficiency	*99.6*	*Losses*	*0.4*
1 hit	*72.0*	*0 hits*	*0.1*
2 hits	*25.2*	*not matched*	*0.2*
>2 hits	*2.4*	*not in time*	*0.1*



Efficiency Losses

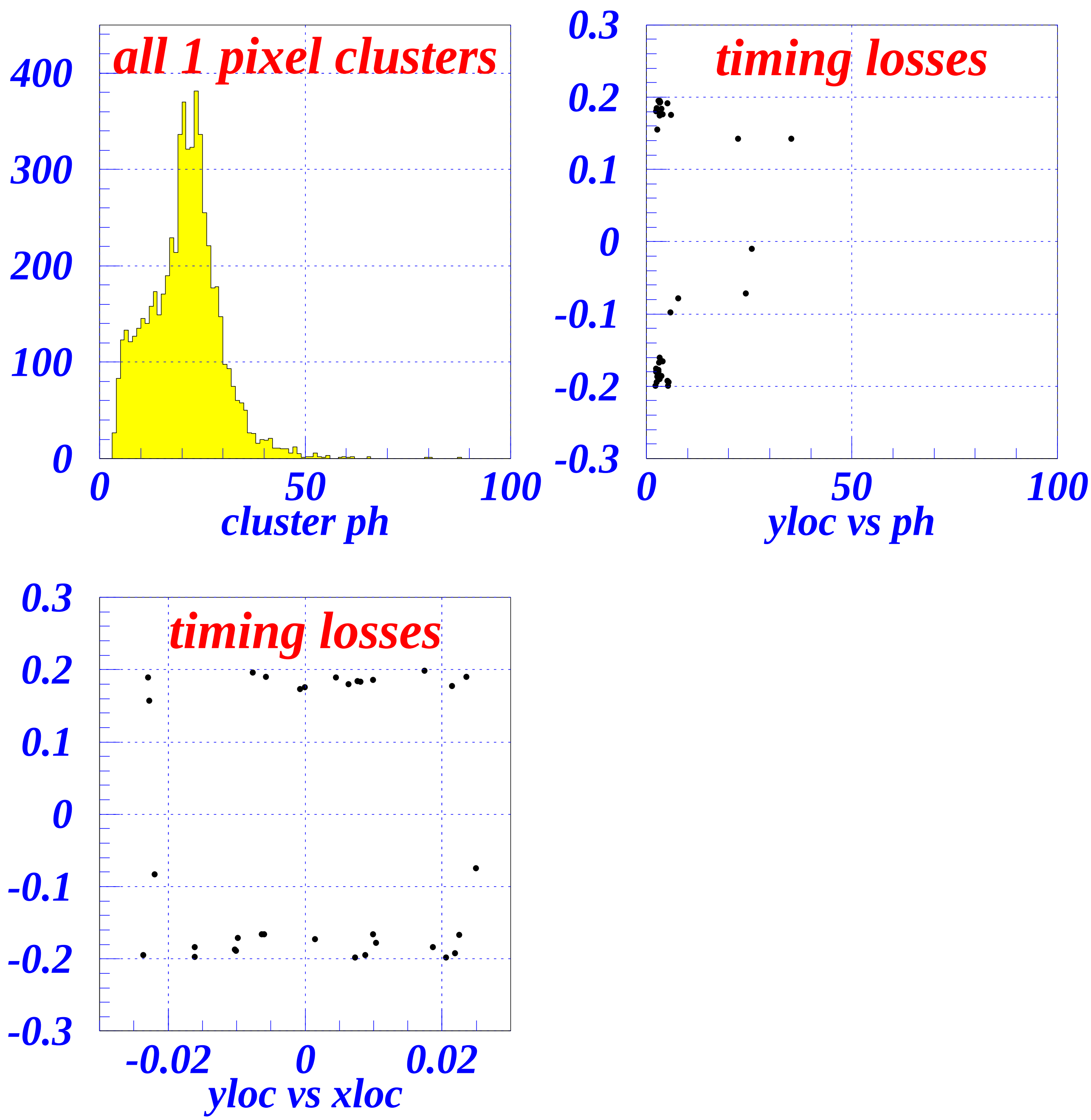
Losses due to missing hits:





Efficiency Losses

Losses due to Timing



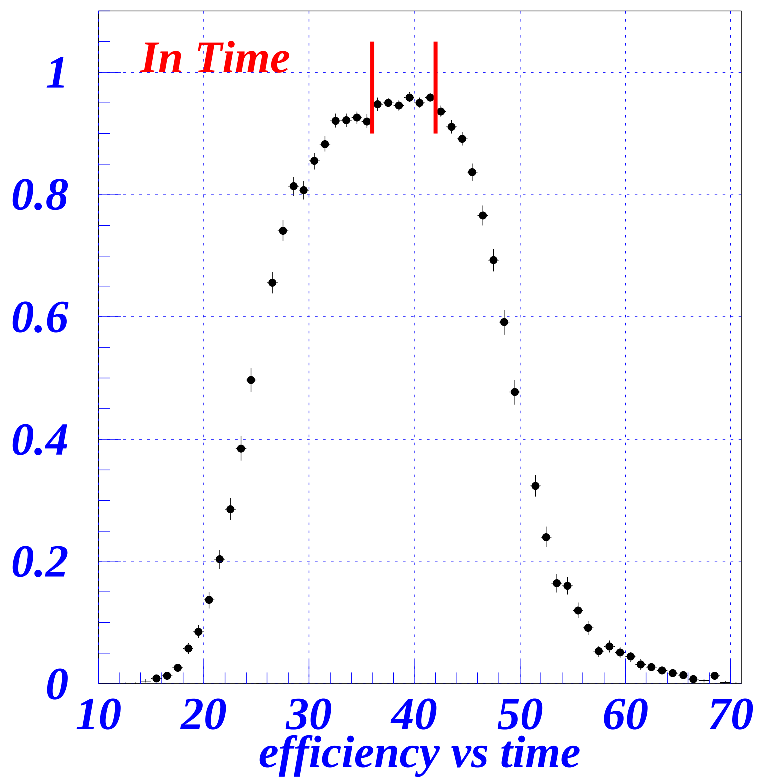
Efficiency vs Time

Efficiency 'In Time'

Detector Tile 2 - Irradiated V_{bias} = 600 V

Fluence 10^{15} n/cm^2 - Thr. 3 Ke

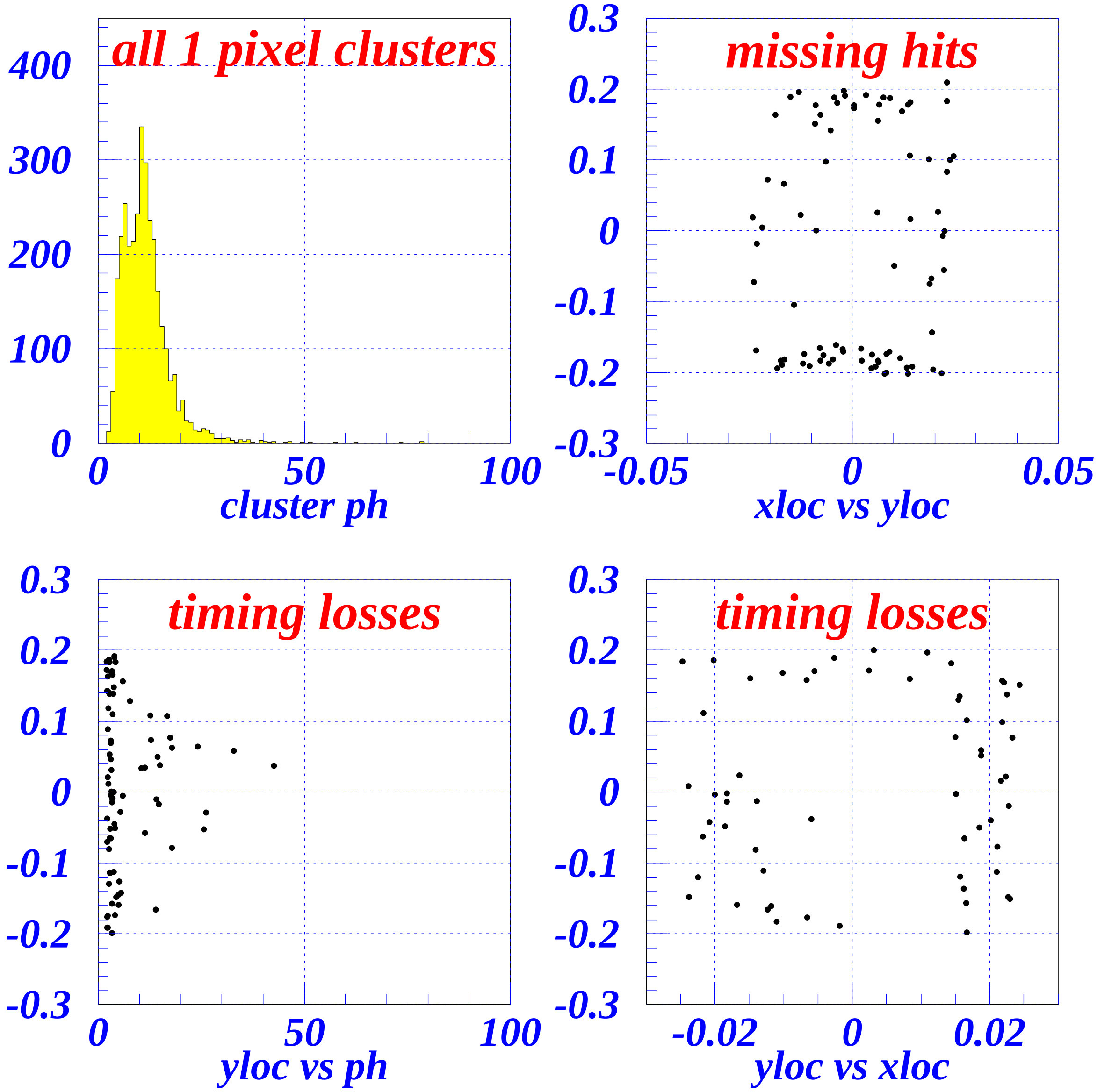
efficiency	**95.3**	**Losses**	**4.7**
1 hit	86.3	0 hits	2.2
2 hits	7.6	not matched	0.1
>2 hits	1.4	not in time	2.4



Irradiated Detectors

Irradiated Detectors Efficiency:

- T2 design -600 V bias
- Fluence 1 x 10^{15} n /cm^2



Efficiency

The Tile 2 detectors shows efficiency losses due to:

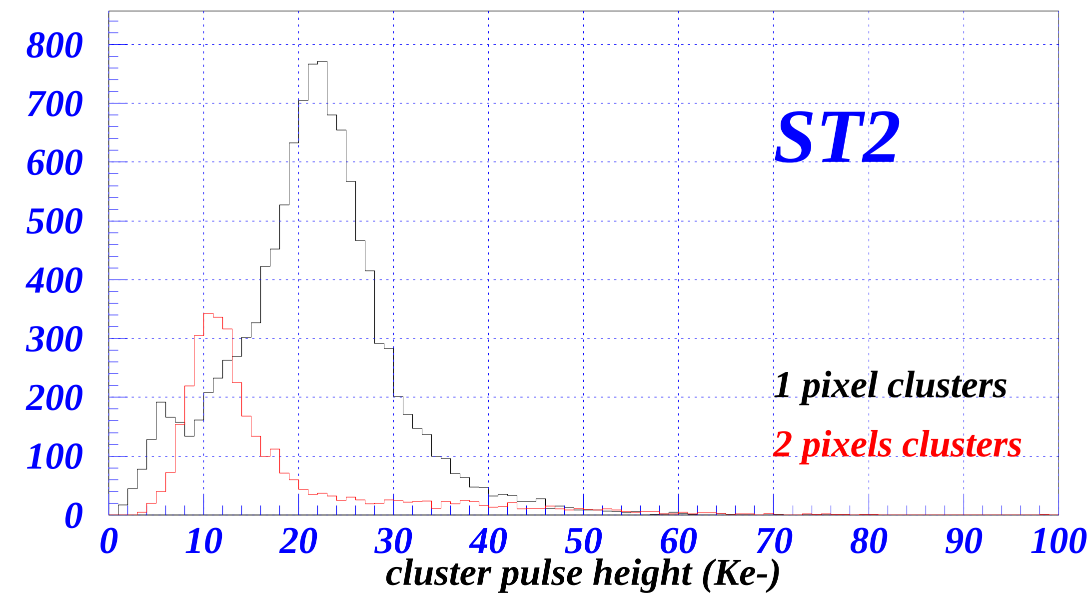
- ***Missing hits***
- ***Timing problems for hits with low Pulse Height***

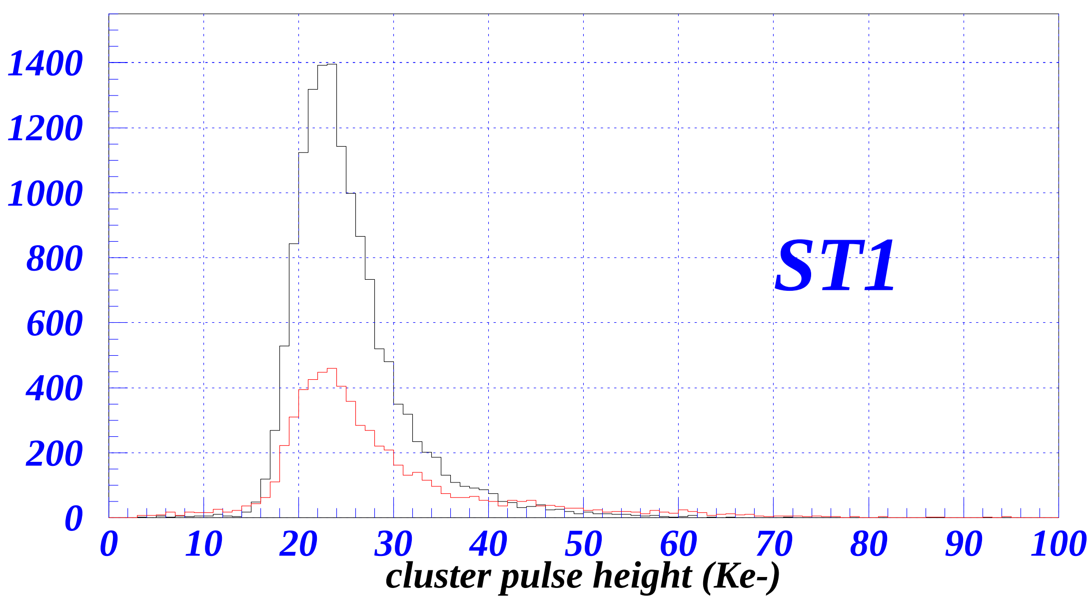
In both cases the losses are localized at the edges of the pixel

Charge Collection

Charge Collection

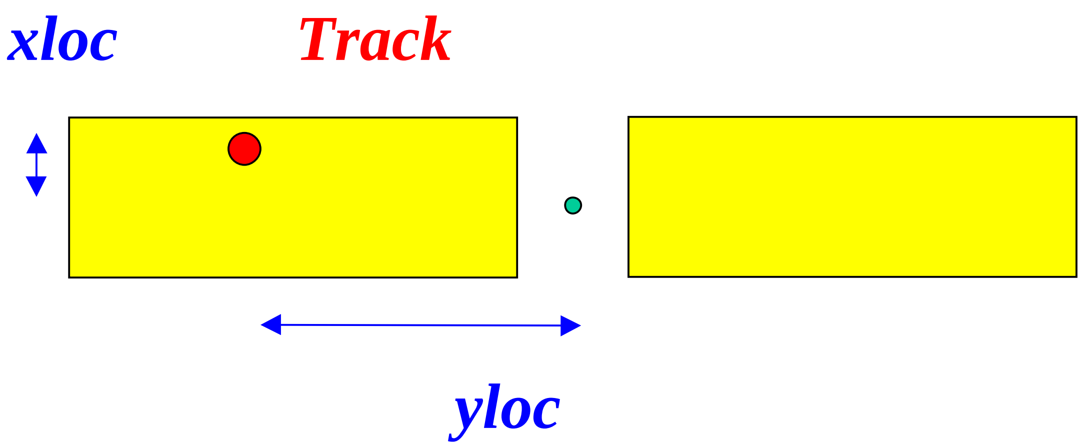
The Landau Distribution for the Tile 2 design shows a problem





Charge Collection

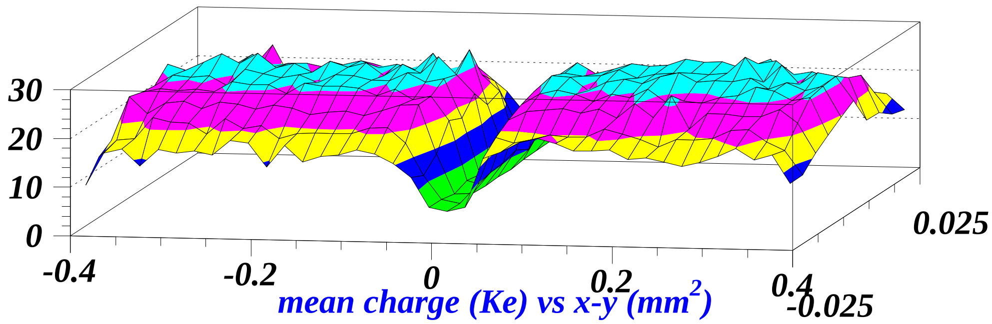
Charge collected vs position

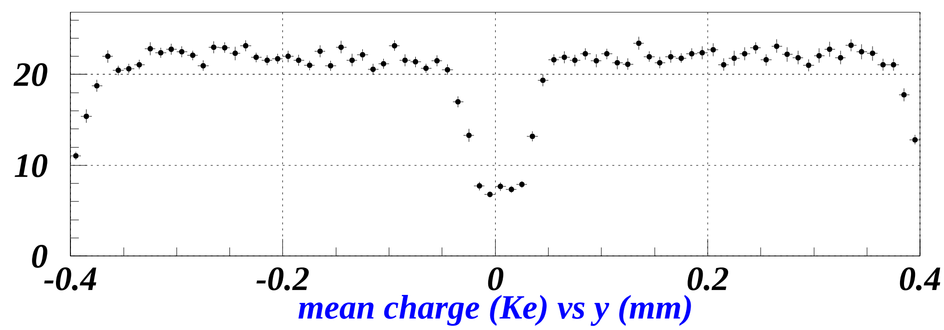


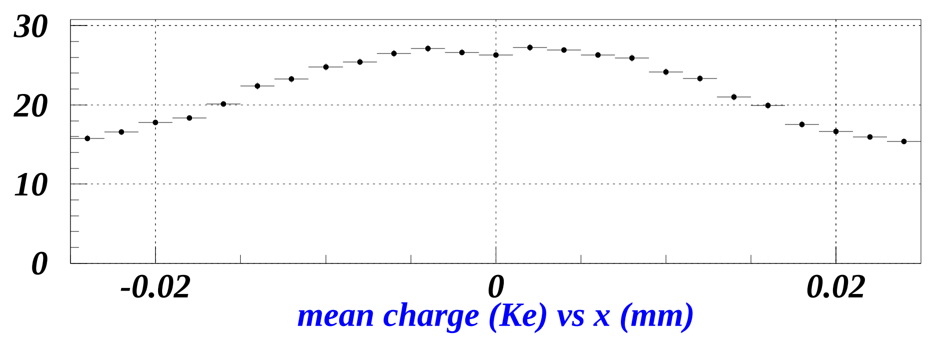
The mean value of the charge is calculated for each (xloc,yloc) bin

Charge Collection

Tile 2 Design   Threshold 2 Ke







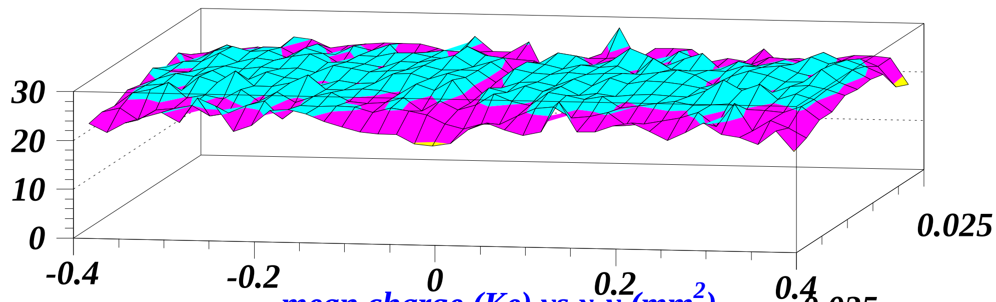
large loss (0.7) near the grid

loss located $\pm$ 30 μm around the grid

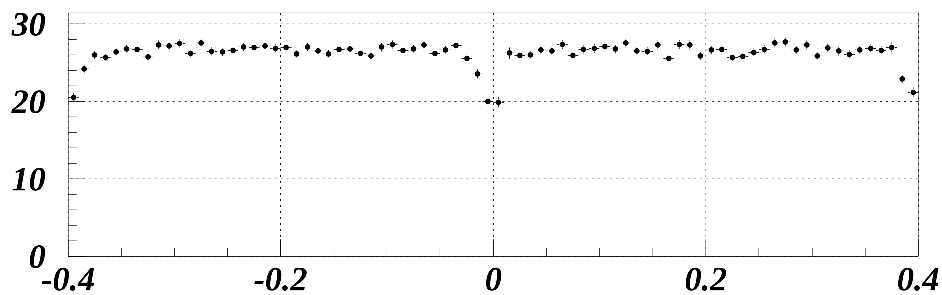
losses at the pixel edges

Charge Collection

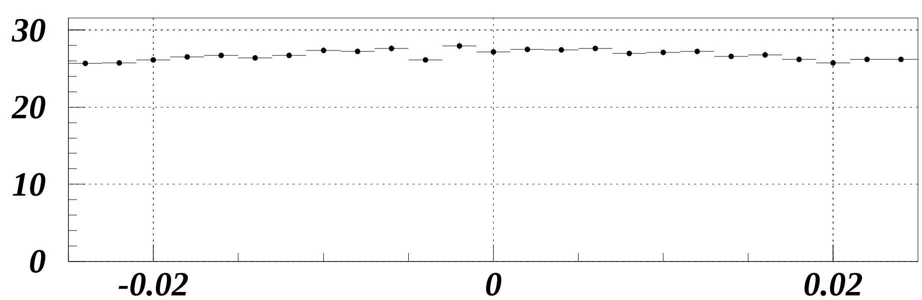
Tile 1 Design   Threshold 2 Ke



mean charge (Ke) vs x-y (mm^2)



mean charge (Ke) vs y (mm)



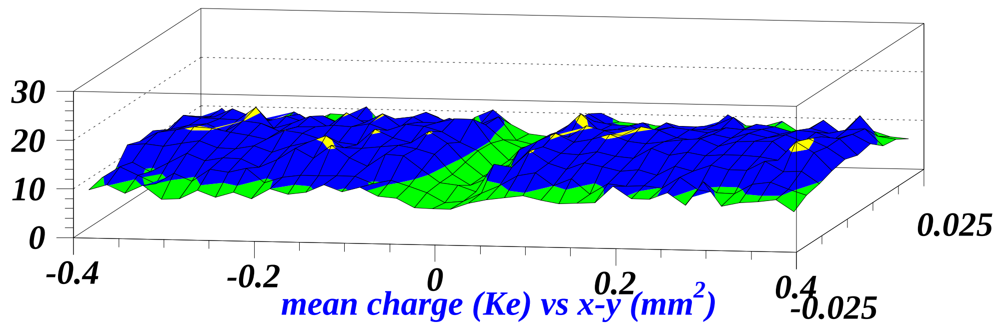
mean charge (Ke) vs x (mm)

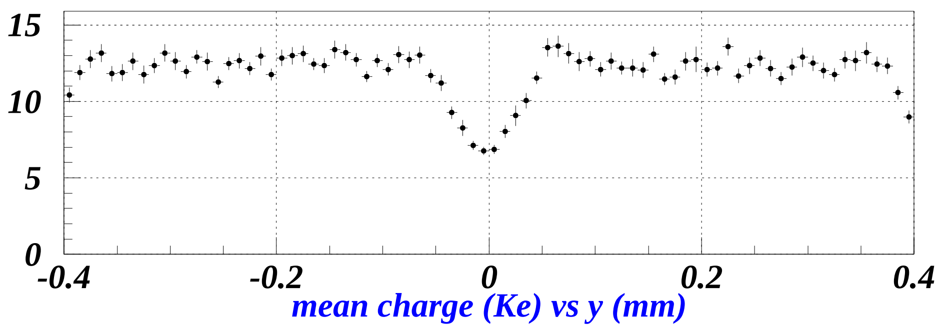
Moderated losses near the pixel edges probably due to p-stop

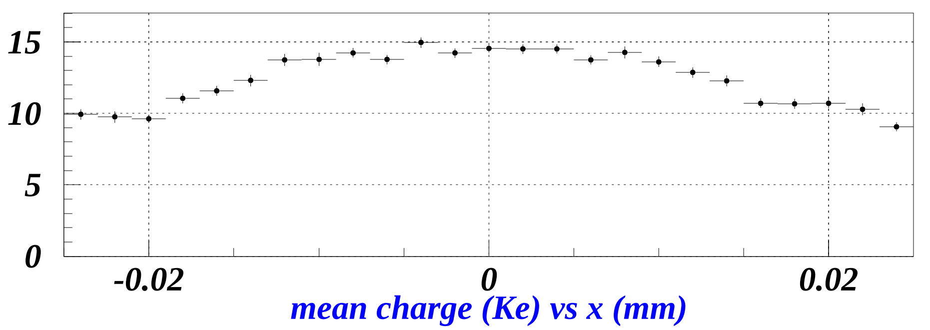
unfortunately not radiation hard

Charge Collection

Irradiated Tile 2 Design

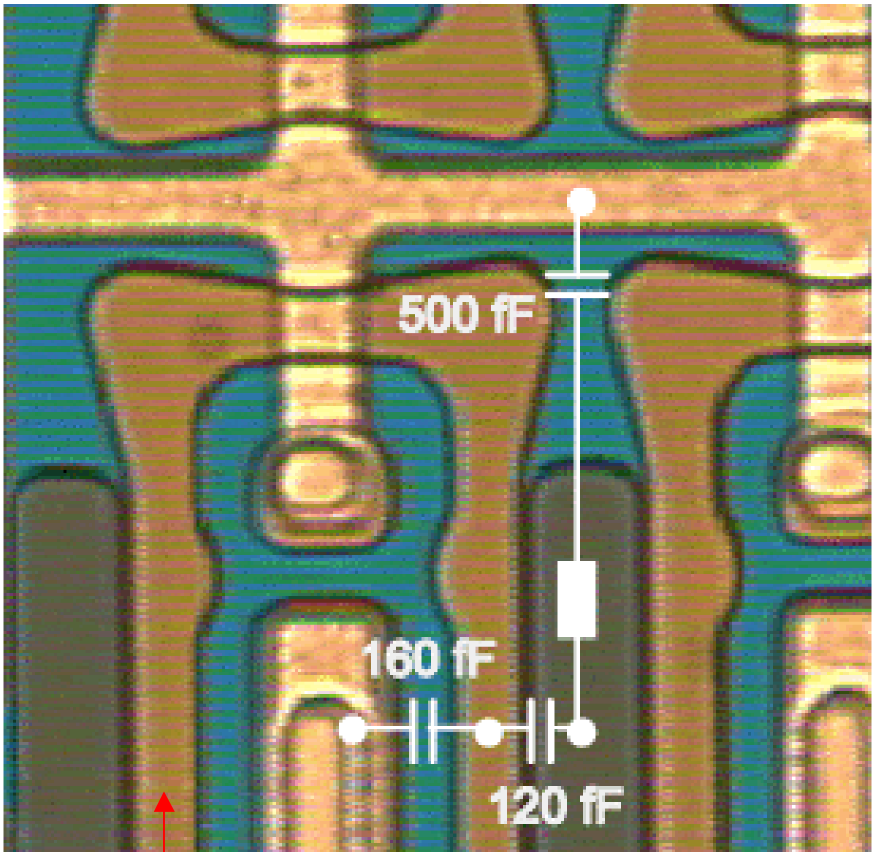






Charge Collection

A possible explanation:



The ring did'nt float as it should

• *Charge is collected on the ring*

Charge Collection

The Tile 1 design has better charge collection properties

However it does not survive the high radiation damage foreseen

The Tile 2 design meets the radiation hardness requirement of LHC

The Tile 2 design has to be improved to eliminate the charge loss due to the floating atoll and to the bias grid

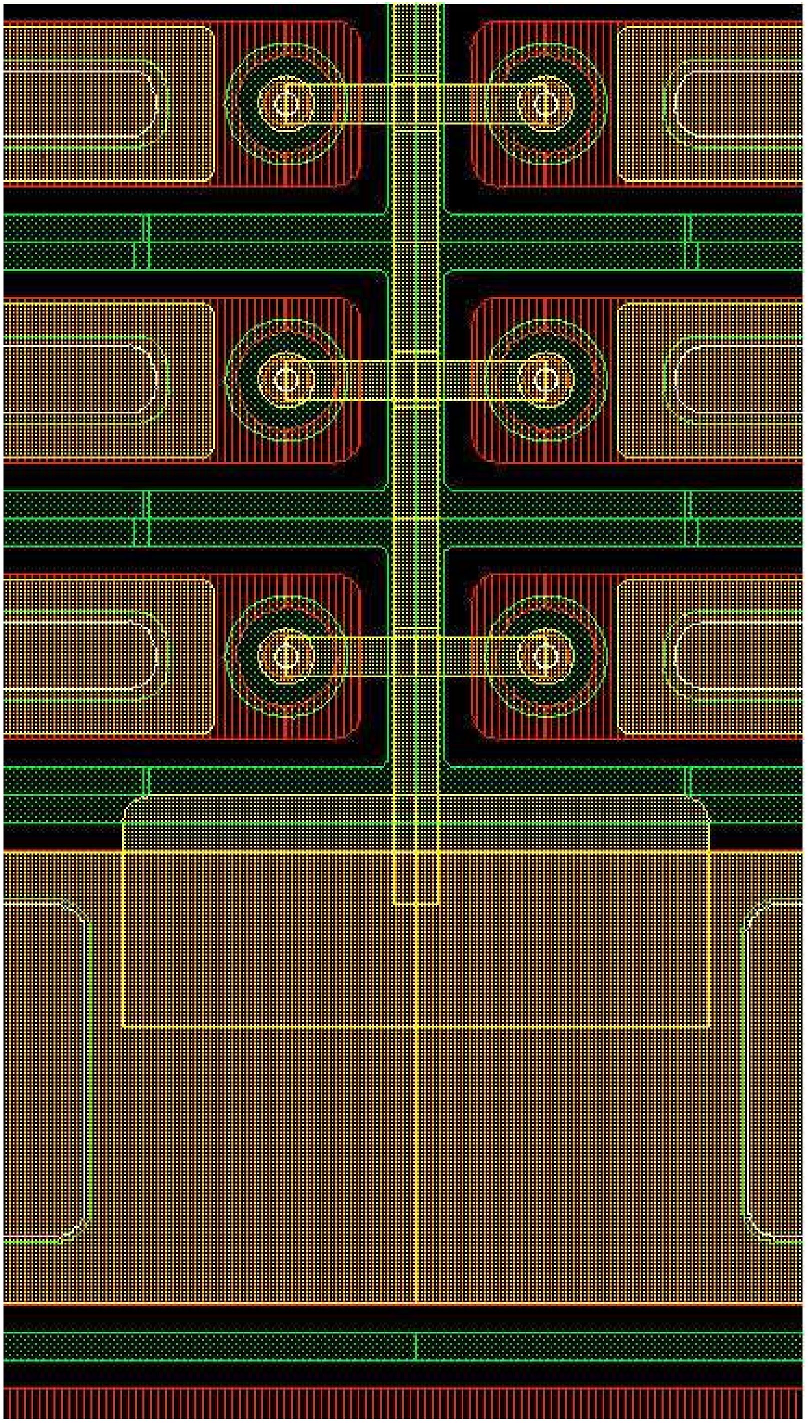
A new design (1.b) submitted in august 1998 with p-spray insulation featuring

- *modified bias grid*
- *floating atoll removed*

plus one more design without bias grid

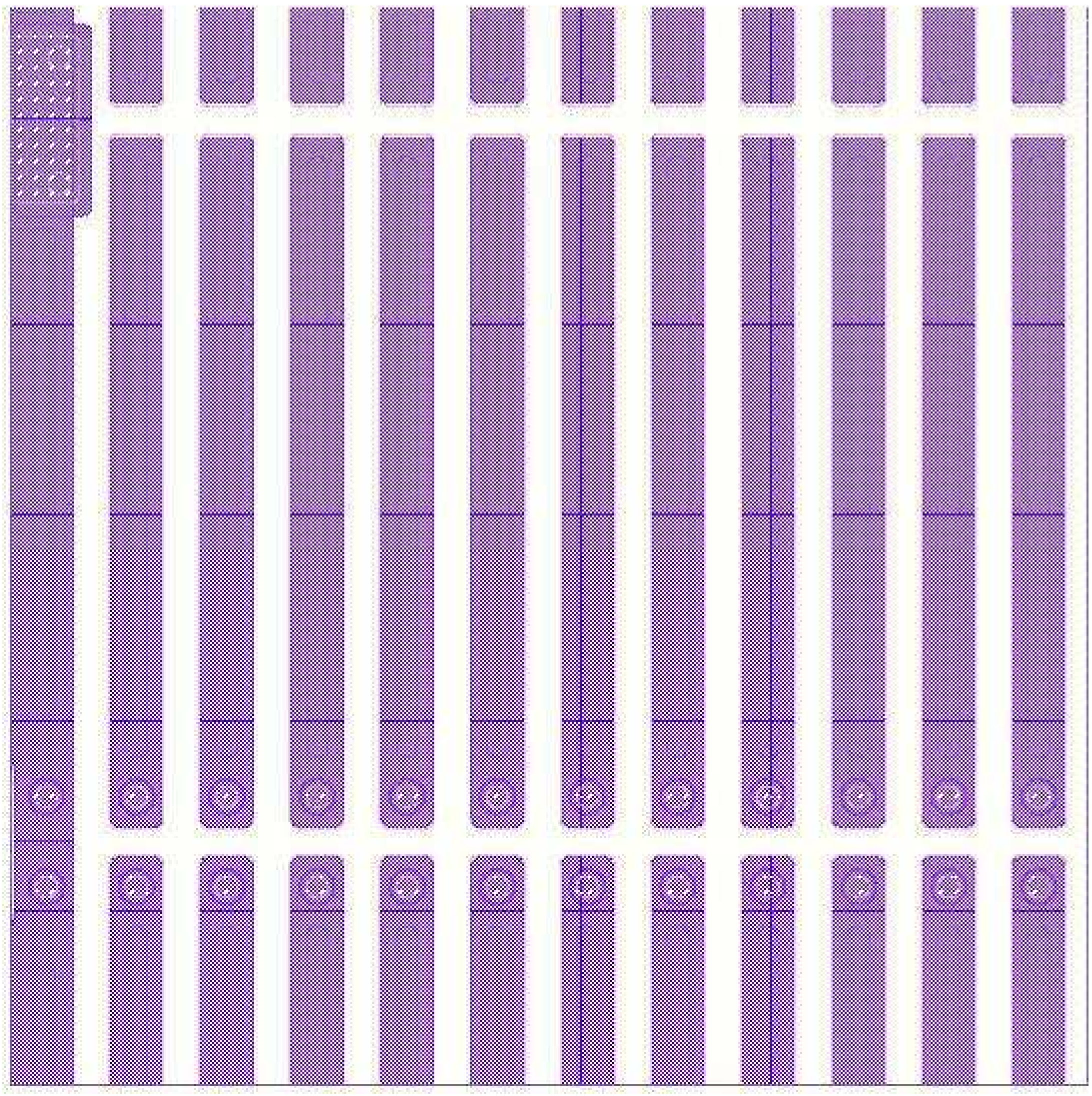
Design 1b

P-spray insulation with bias grid



Design 1b

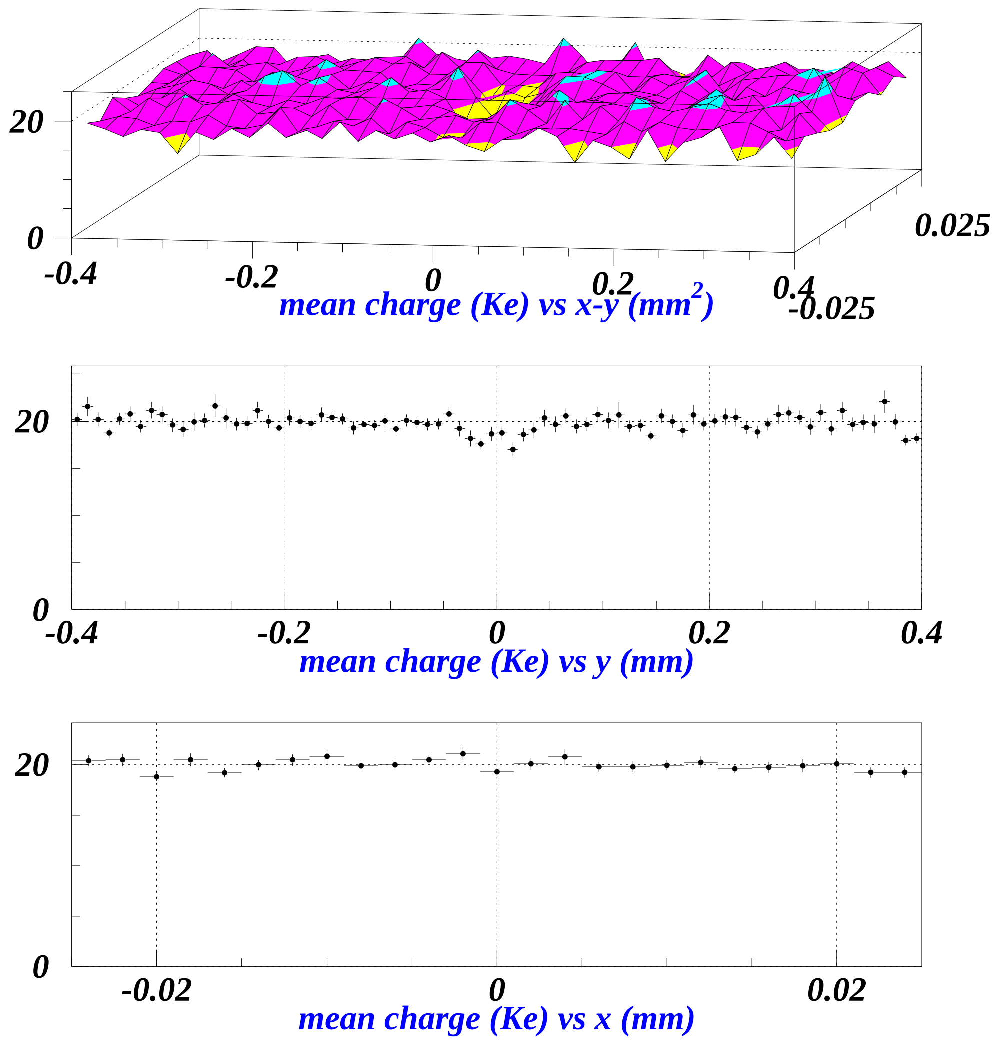
p-spray insulation without bias grid



Charge Collection

Design 1.b:

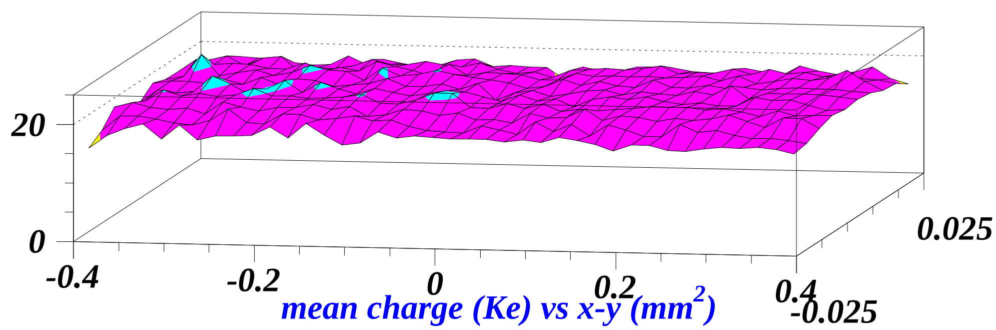
- p-spray insulation
- no floating atoll
- modified bias grid

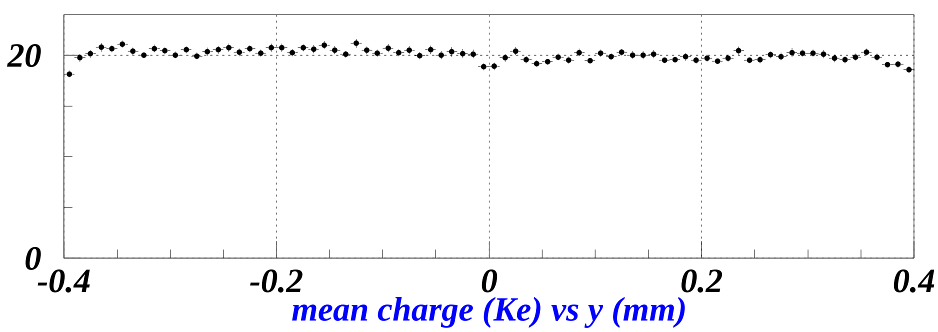


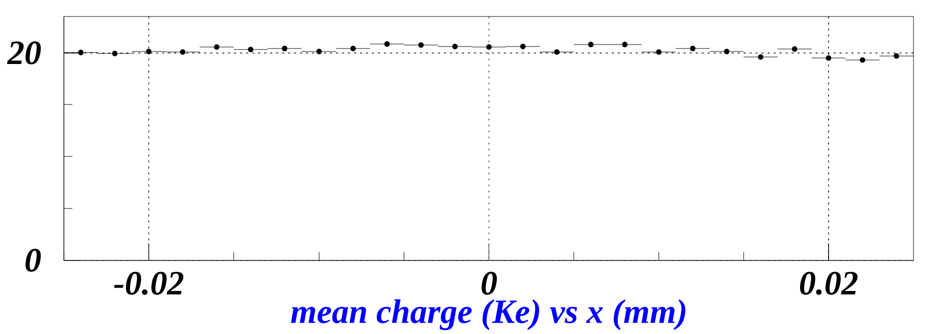
Charge Collection

Design 1.b:

- *p-spray insulation*
- *no floating atoll*
- *no bias grid*







Charge Collection

- *The new design without the floating atoll do not show charge collection problems*
- *Although the design with no bias grid is better, the preferred solution in ATLAS is the design with a bias grid (testability)*
- *The p-spray insulation works well after irradiation. Measurements of the new design after irradiation are in progress*
- *Taking into account the depth of the depleted region after irradiation, comparing the charge collected before and after irradiation, an upper limit to charge trapping of ~ 20 % can be assessed*

Efficiency of the New Design

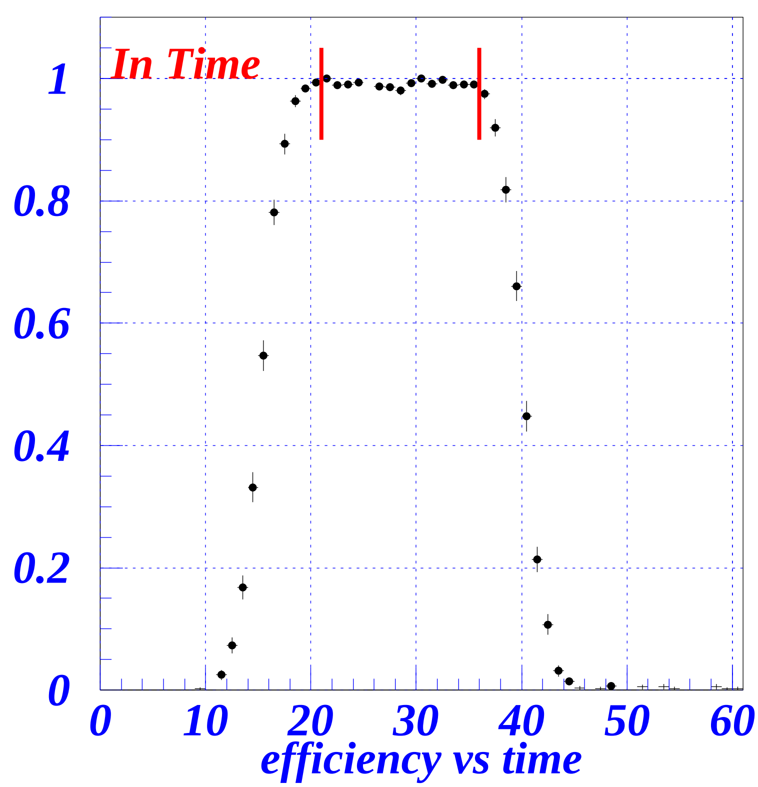
Efficiency vs Time

Efficiency 'In Time'

Detector Tile 2 new design (with bias grid)

not Irradiated - Thr. 3 Ke

efficiency	**99.1**	**Losses**	**0.9**
1 hit	81.8	0 hits	0.4
2 hits	15.6	not matched	0.1
>2 hits	1.7	not in time	0.4



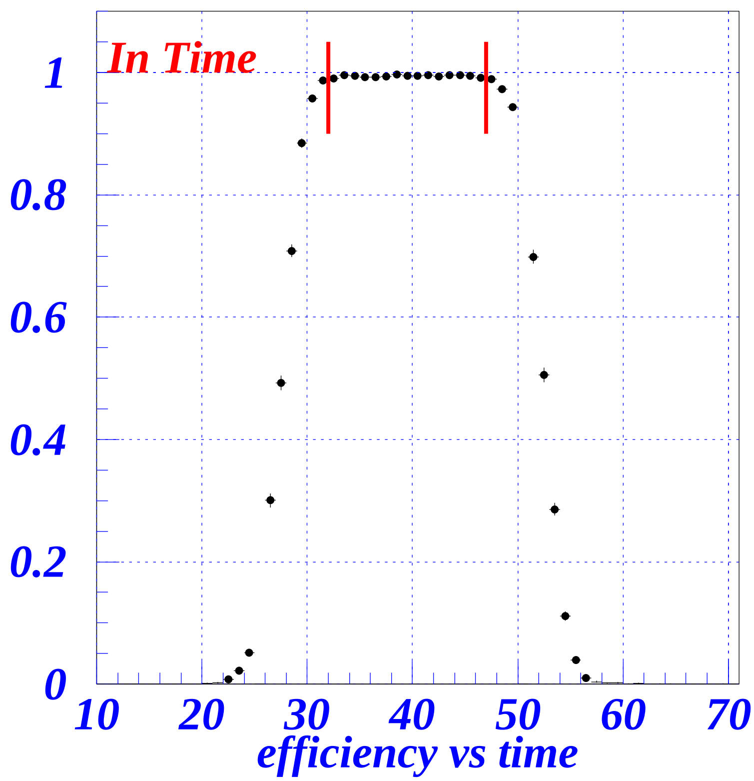
Efficiency vs Time

Efficiency 'In Time'

Detector Tile 2 new design (no bias grid)

not Irradiated - Thr. 3 Ke

efficiency	**99.5**	**Losses**	**0.5**
1 hit	84.4	0 hits	0.4
2 hits	15.0	not matched	0.0
>2 hits	0.1	not in time	0.1



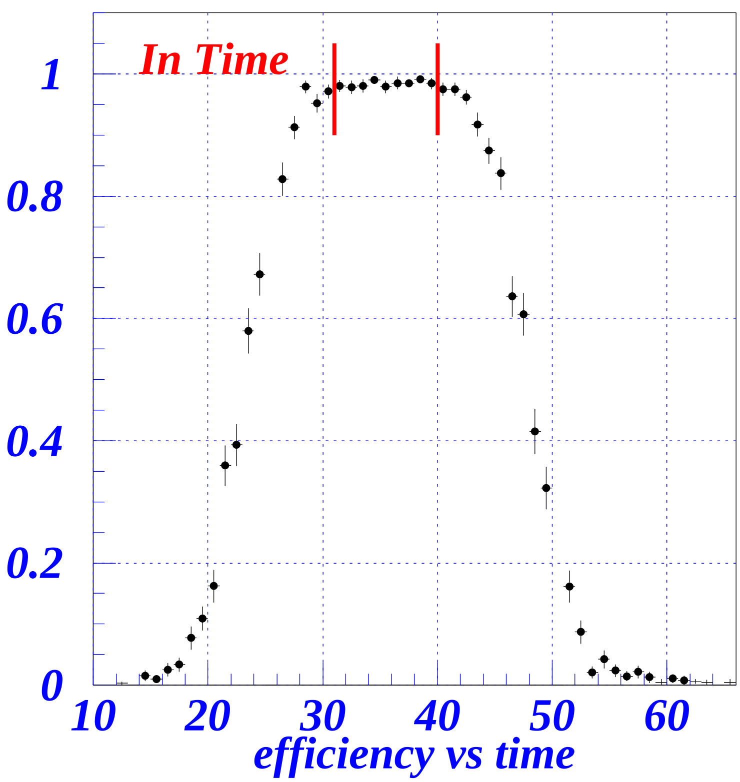
Efficiency vs Time

Efficiency 'In Time'

Detector Tile 2 - Irradiated V_{bias} = 600 V

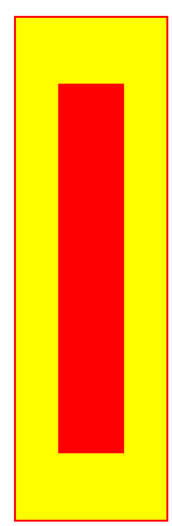
Fluence 10^{15} n/cm^2 - Thr. 3 Ke

efficiency	**98.4**	**Losses**	**1.6**
1 hit	94.2	0 hits	0.4
2 hits	3.1	not matched	0.0
>2 hits	1.1	not in time	1.2



|xloc| < 0.01

|yloc| < 0.15



Efficiency Summary

Threshold: 3 Ke

	Old Design 280 µm		New Design 200 µm		Old Design 10^{15} n/cm^2	
	T2	T1	T2 bg	T2 nbg	T2	T2 x,y cut
1 hit	82.0	72.0	81.8	84.4	86.3	94.2
2 hits	14.6	25.2	15.6	15.0	7.6	3.1
≥3 hits	2.2	2.4	1.7	0.1	1.4	1.1
Efficiency	98.8	99.6	99.1	99.5	95.3	98.4
Losses	1.2	0.4	0.9	0.5	4.7	1.6
0 Hits	0.4	0.1	0.4	0.4	2.2	0.4
Not matched	0.2	0.2	0.1	0.0	0.1	0.0
Not in time	0.6	0.1	0.4	0.1	2.4	1.2

- ***The new design has an efficiency in excess of 99. %.***
- ***Work in progress to study the efficiency of the new design after irradiation***

Efficiency versus Azimuthal Angle

Efficiency vs. azimthal angle

The efficiencies measurements presented so far are for tracks perpendicular to the sensor

- the fraction of double hit cluster is given by diffusion and threshold
- the efficiency depend on the hits pule heights

With inclined tracks, the fraction of multiple hits clusters increase

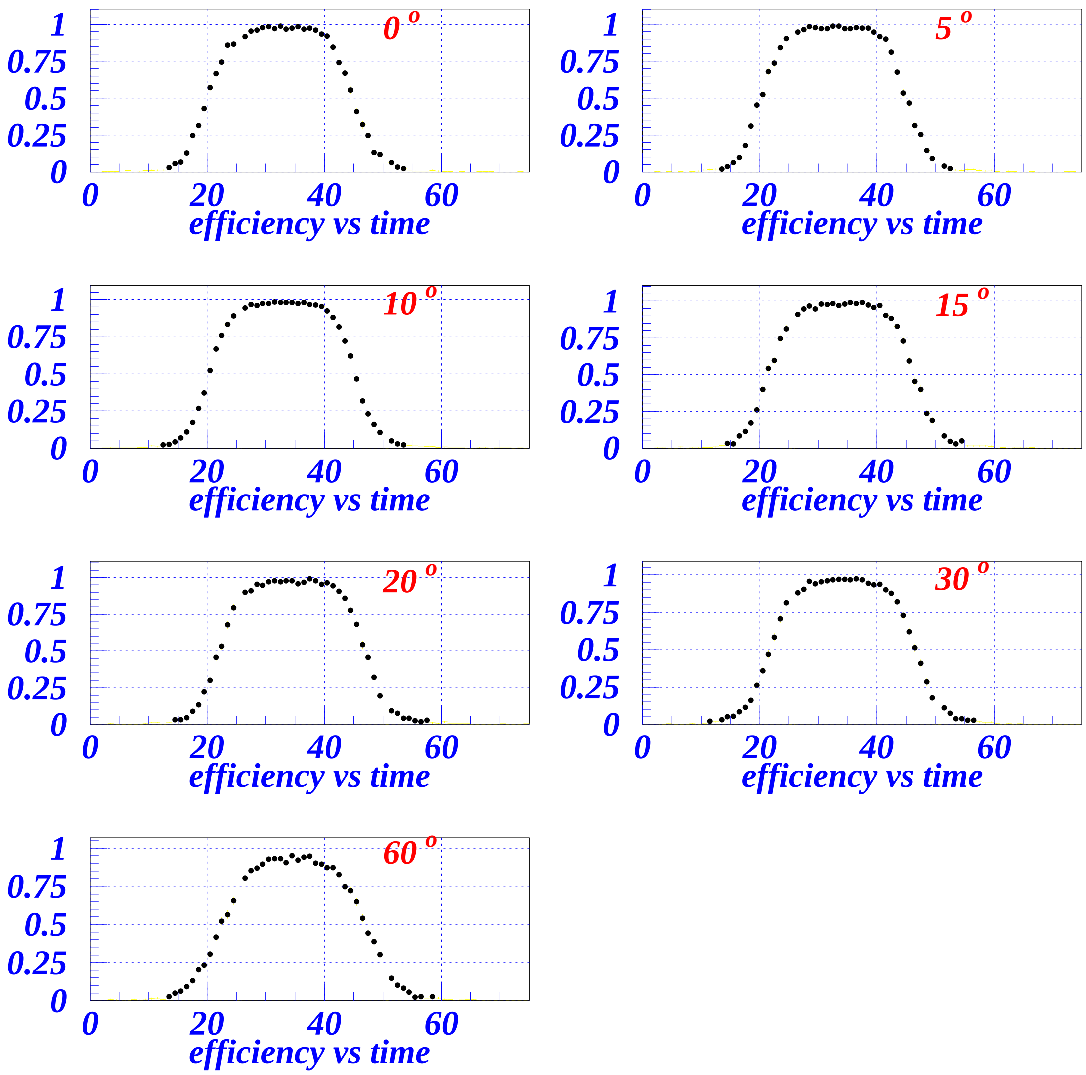
We have studied the dependence of the efficiency on the track angle

- Tile 2 sensor not irradiated
- Tile 2 sensor irradiated 5×10^{14} n_{eq}/cm^2
- Tile 2 sensor irradiated 1×10^{15} n_{eq}/cm^2
- New Tile 2 sensor(200 μm) not irradiated

Efficiency vs. azimthal angle

Timing curves the for Tile 2 sensors

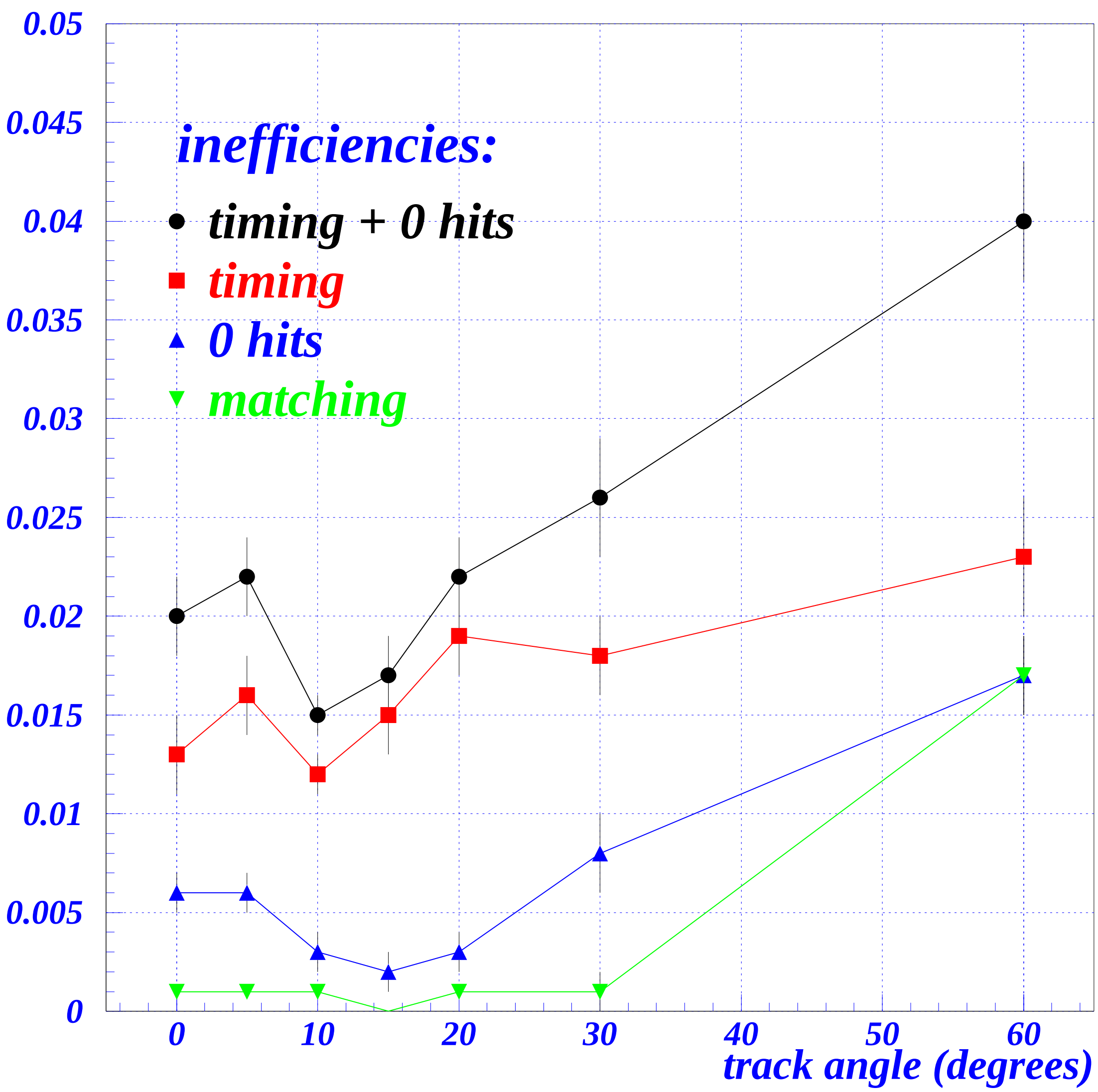
Fluence = 0



Efficiency vs. azimthal angle

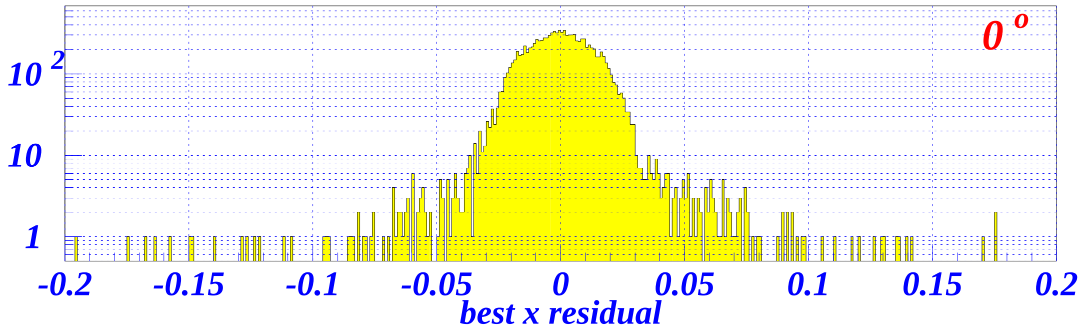
Inefficiencies for the Tile 2 sensors

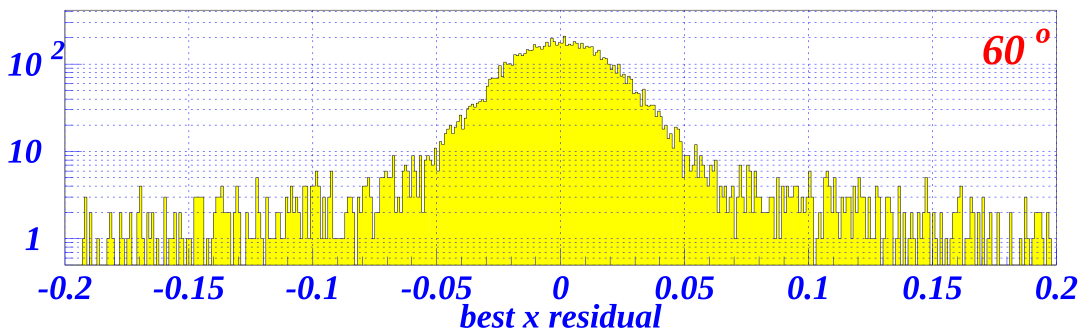
Fluence: 0

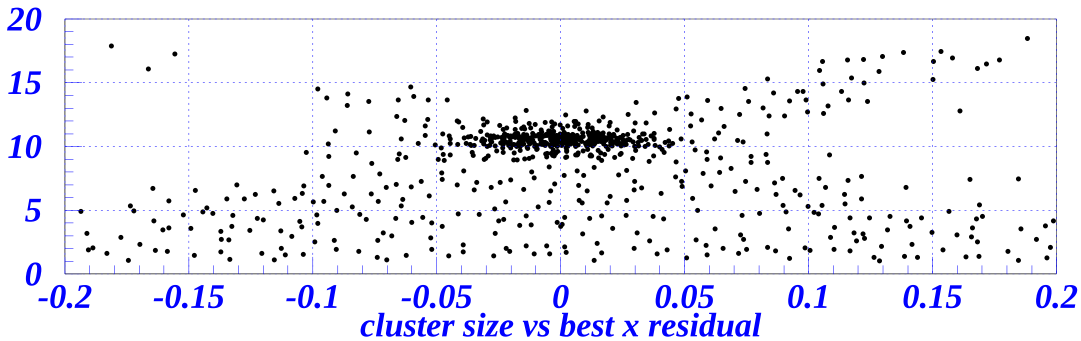


Efficiency vs. azimthal angle

Understanding Matching Losses for the Tile 2 sensors

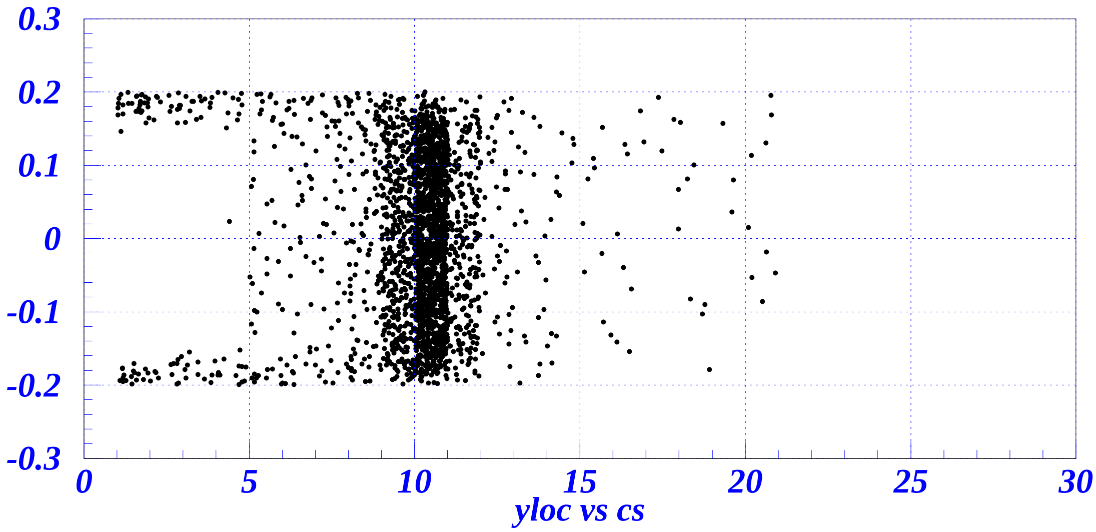


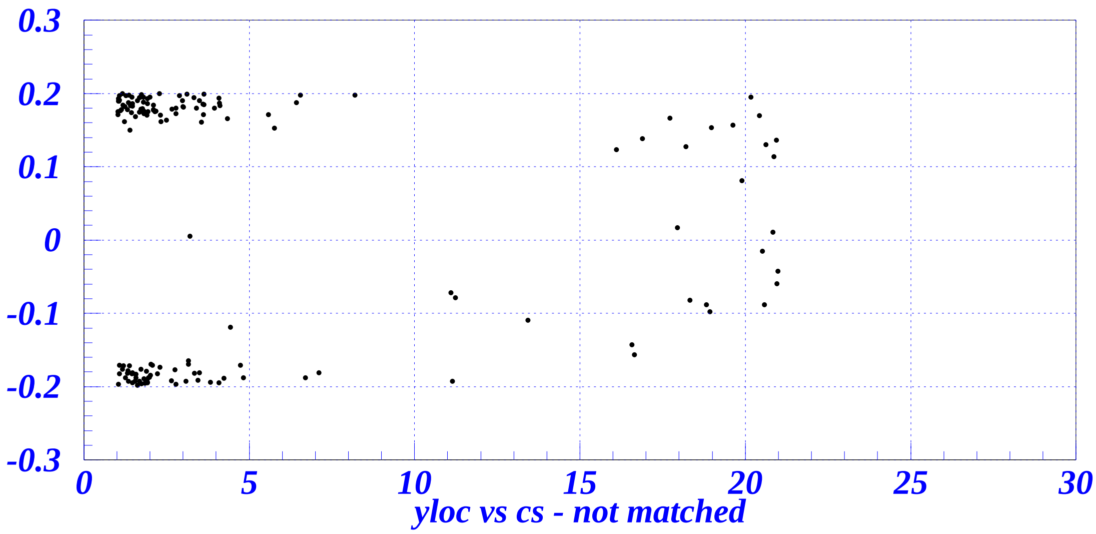




Efficiency vs. azimthal angle

Understanding Matching Losses for the Tile 2 sensors at 60^0

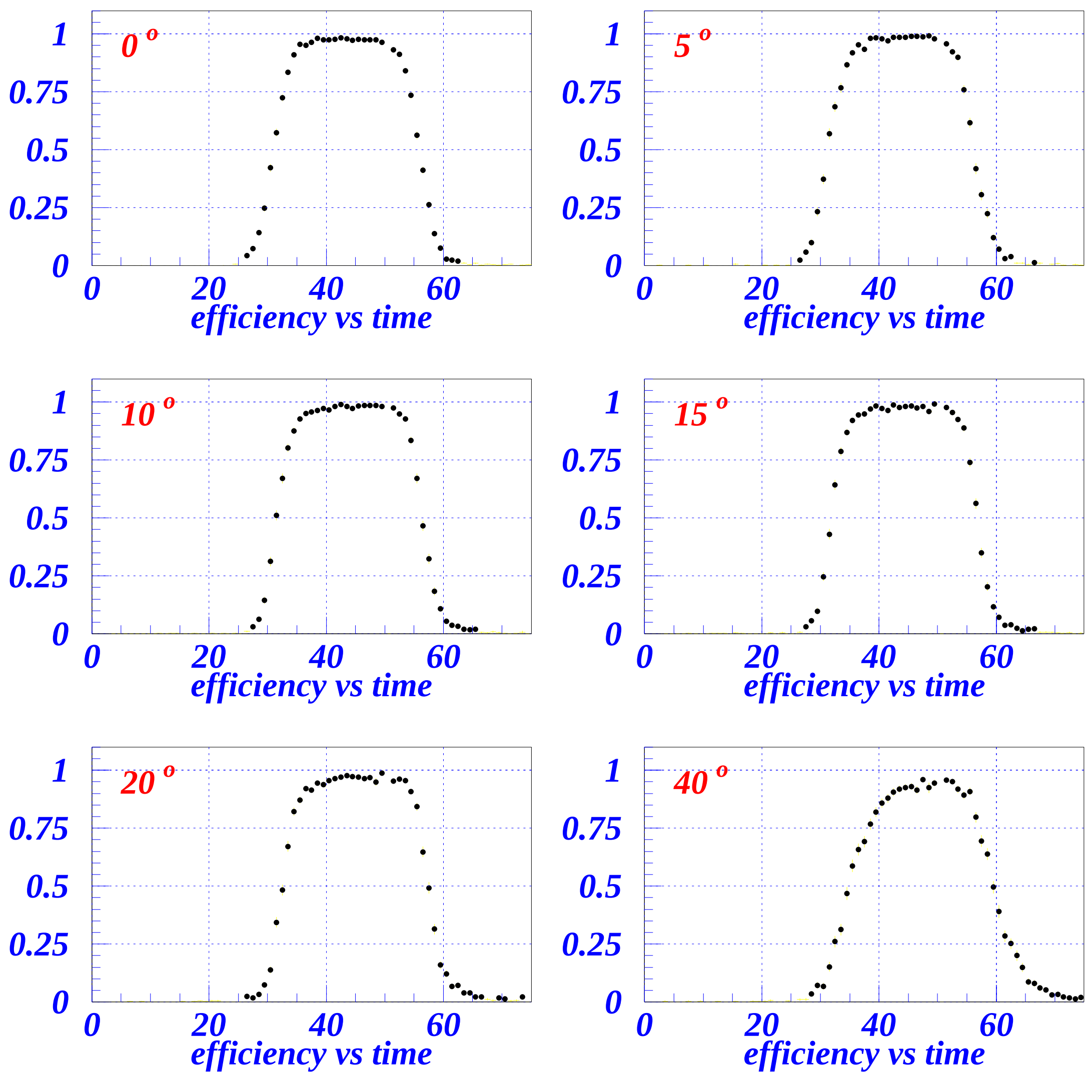




Efficiency vs. azimthal angle

Timing curves for the Tile 2 sensors

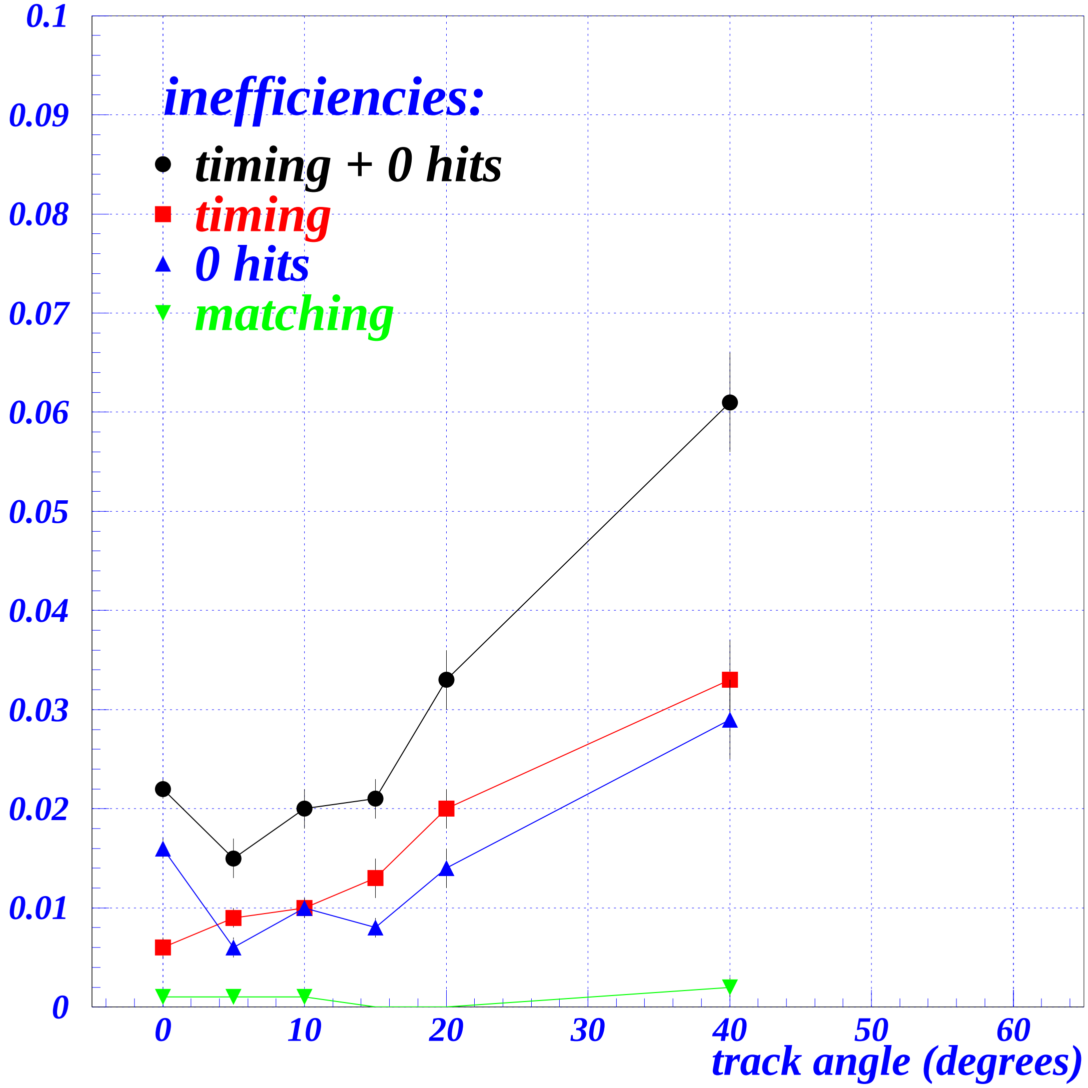
Fluence: 0.5 x 10^{15} n_{eq}/cm^2



Efficiency vs. azimthal angle

Inefficiencies for the Tile 2 sensors

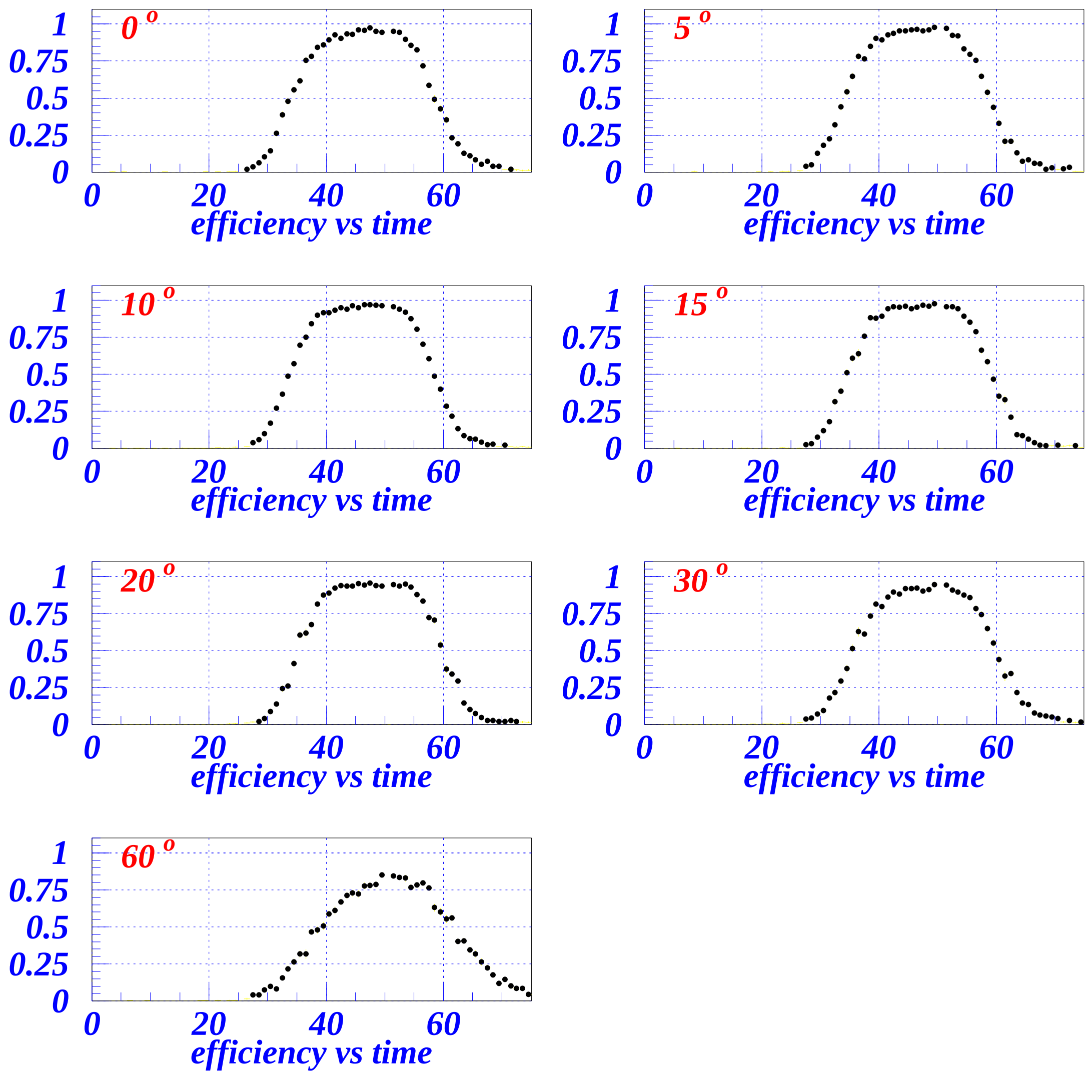
Fluence: 0.5 x 10^{15} n_{eq}/cm^2



Efficiency vs. azimthal angle

Timing curves for the Tile 2 sensors

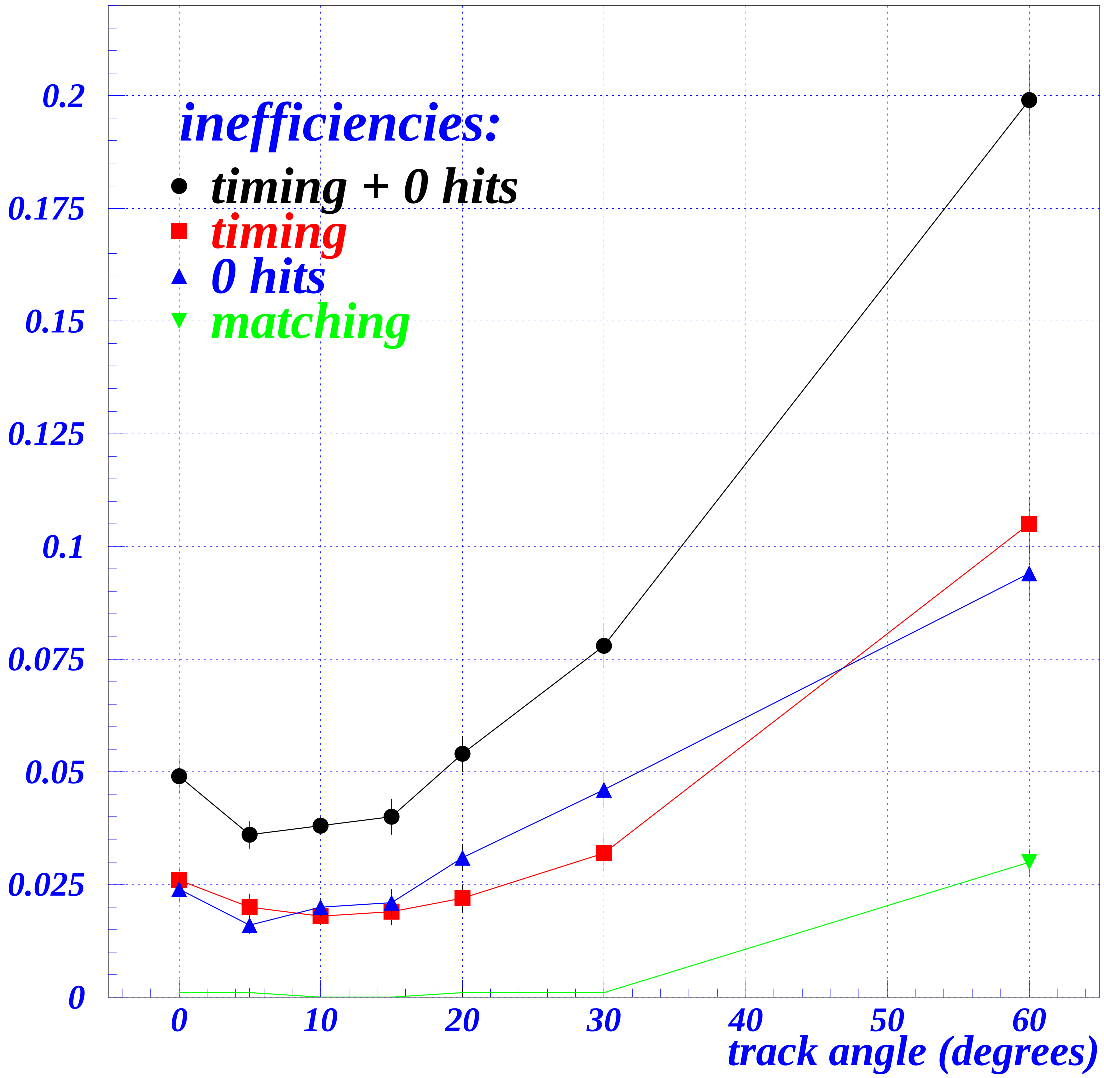
Fluence: $1 \times 10^{15}\ n_{eq}/cm^2$



Efficiency vs. azimthal angle

Inefficiencies for the Tile 2 sensors

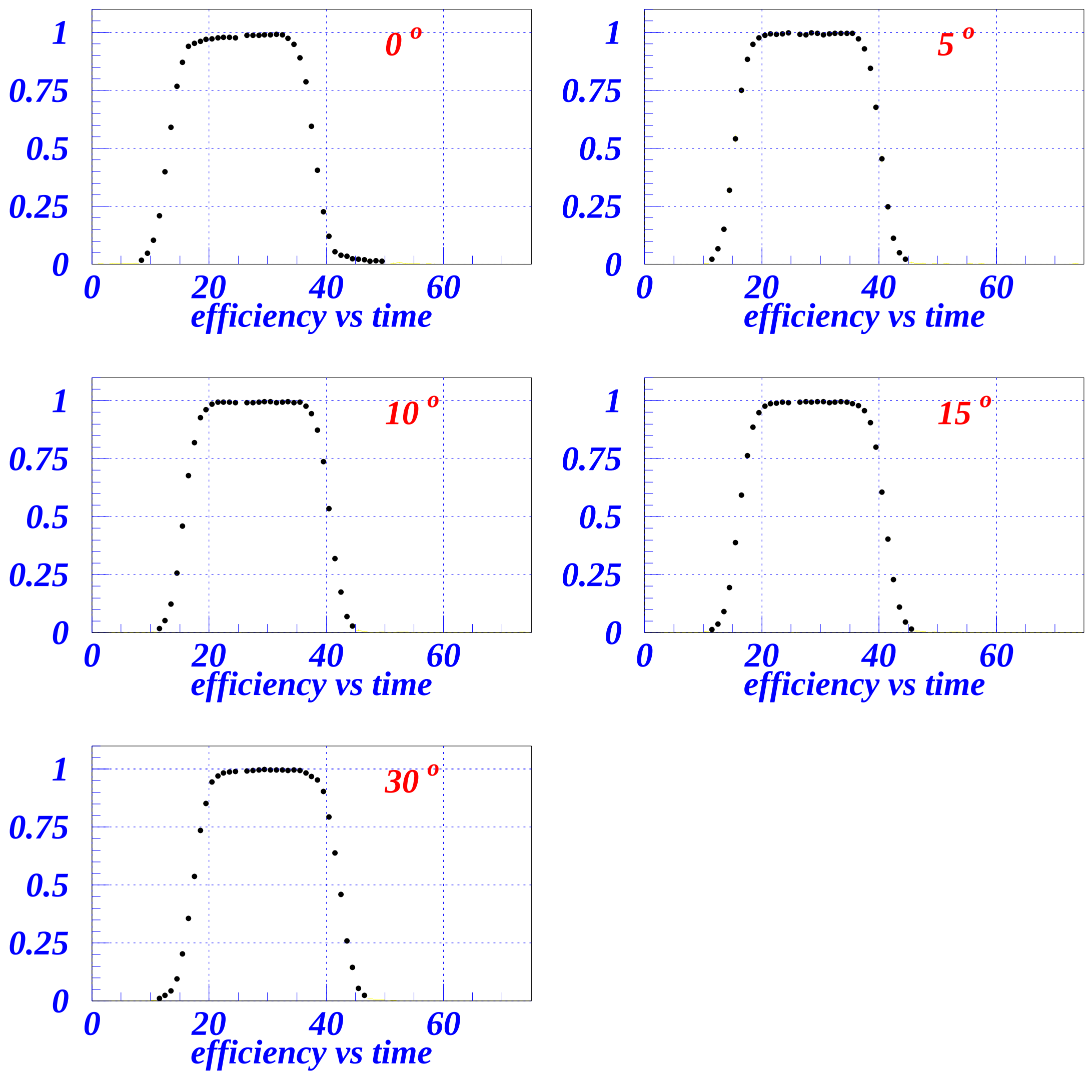
Fluence: 1 x 10^{15} n_{eq}/cm^2



Efficiency vs. azimthal angle

Timing curves for the new Tile 2 sensors

Fluence: 0



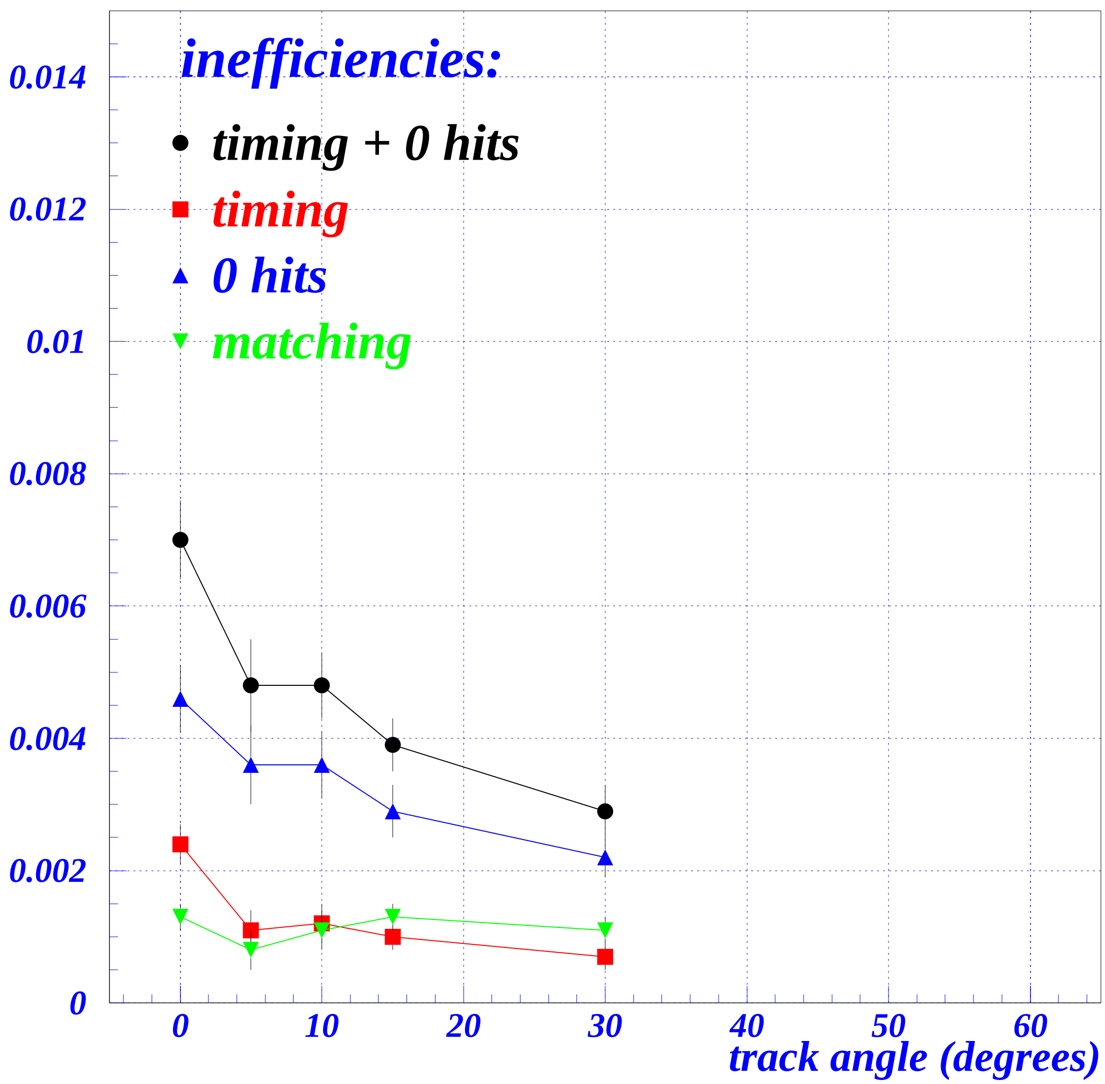
Pixel Week - September 1999

F. Ragusa - Milano

Efficiency vs. azimthal angle

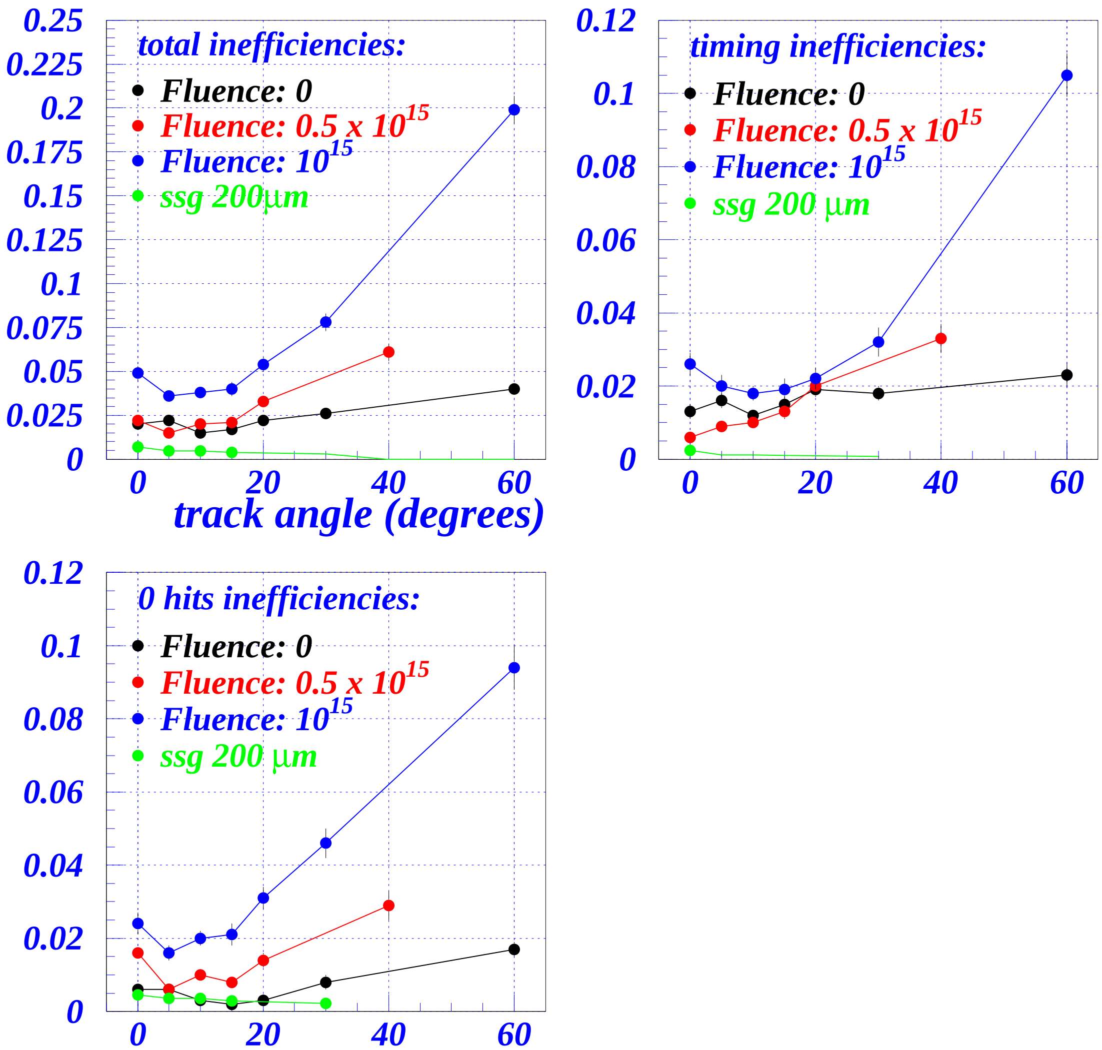
Inefficiencies for the new Tile 2 sensors

Fluence: 0



Efficiency vs. azimthal angle

Inefficiencies Summary



Efficiency vs. azimthal angle

Conclusions on efficiency studies

- *Inclined tracs improve the efficiency of the Tile 2 sensors*

  more charge sharing

  less sensitivity to inefficient regions

- *Maximum efficiency observed at ~ 10^0*
- *Worst case losses (let's say at 30^0)*

T2 - fluence = 0	***2.8%***
T2 - fluence = 0.5 x 10^{15}	***4.7%***
T2 - fluence = 1.0 x 1015	***8.0%***
New T2 - fluence 2	***0.3%***

- *New Tile 2 sensors have impressive performances*

Resolution

Resolution

Resolution Studies

- residuals of 1 pixel clusters
- residuals of 2 pixel clusters

  digital algorithm

  analog algorithm

Analog algorithm

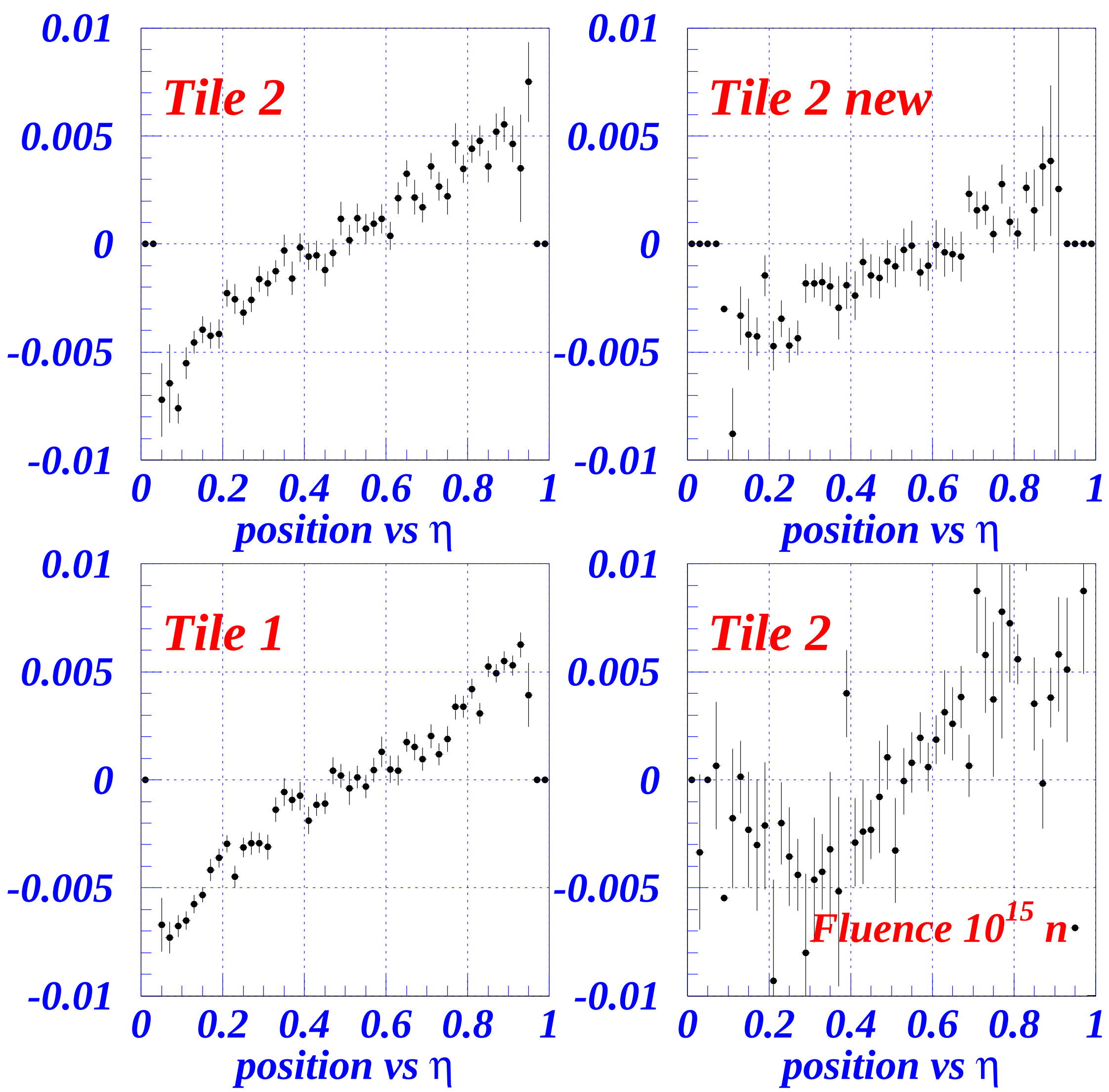
- define η as

$$\eta = \frac{PH_L}{PH_L + PH_R}$$

- study η as function of the position
- correct the digital position using η

Resolution

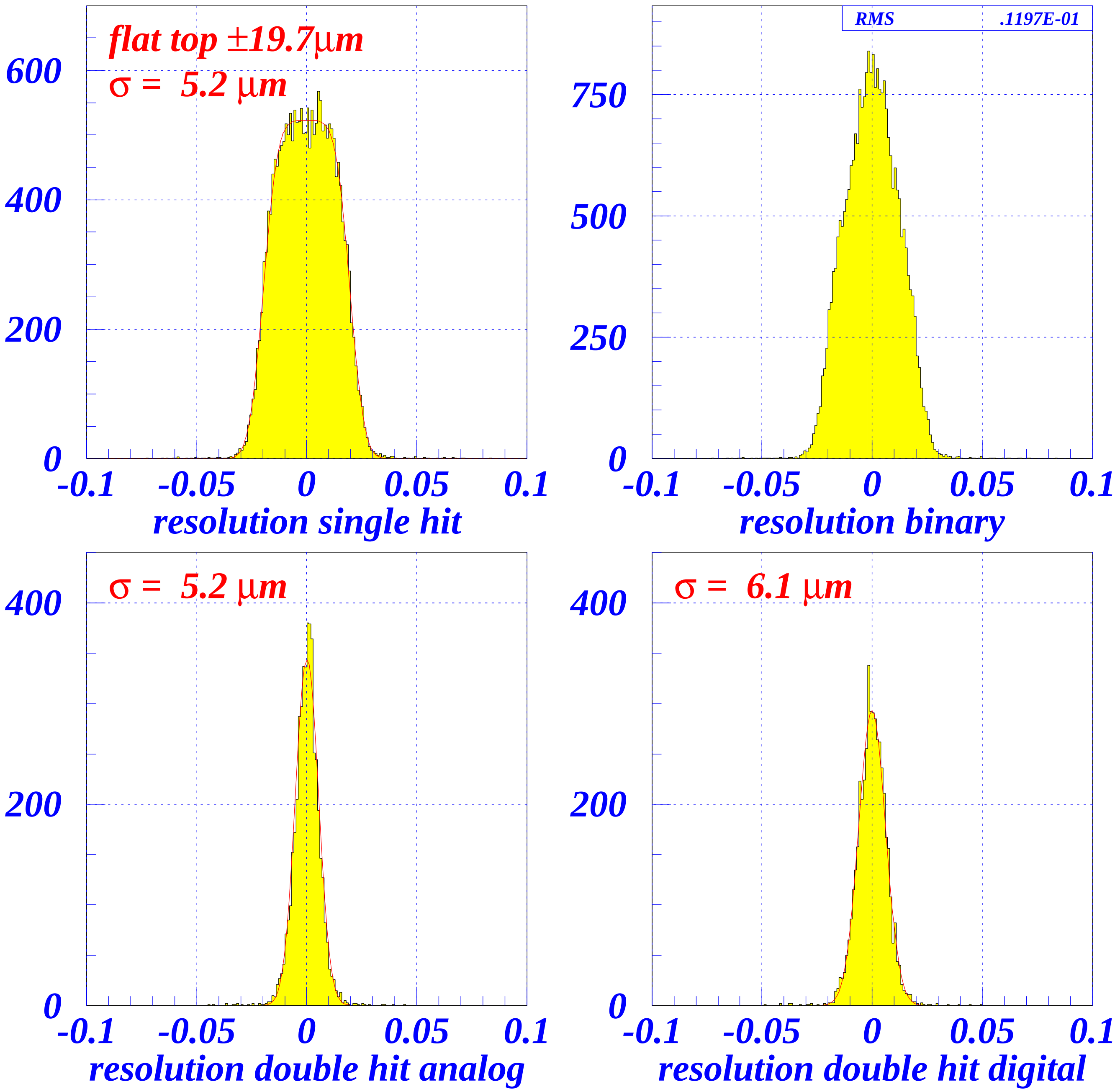
Charge Sharing - η



- ➨ charge sharing confined to $\pm$5. μm between adjacent pixels
- ➨ 2 pixels clusters fractions ~ 15.% at 0^0 before irradiation
~ 7.% after 10^{15} n_{eq}/cm^2

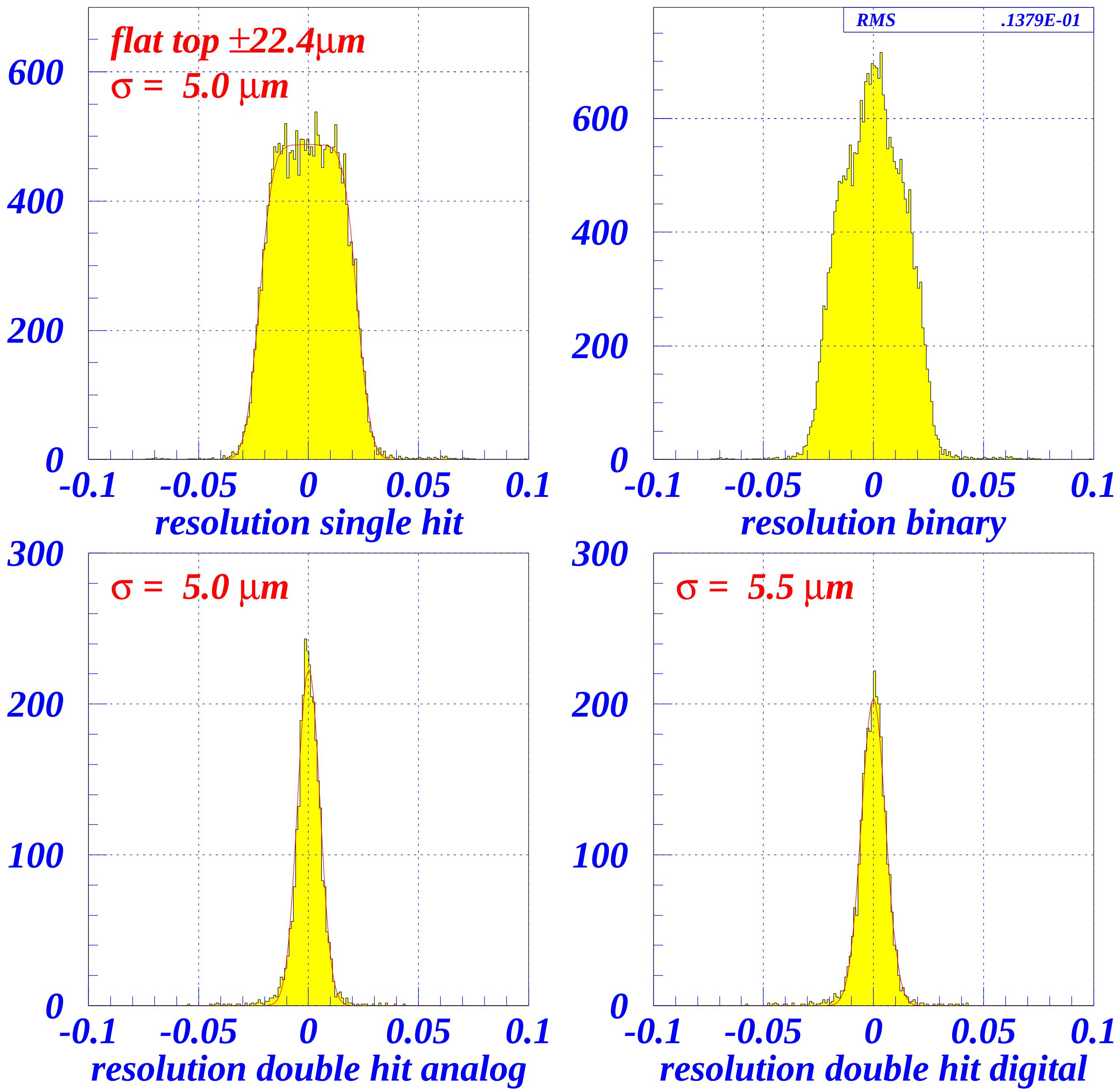
Resolution

Tile 1 Design



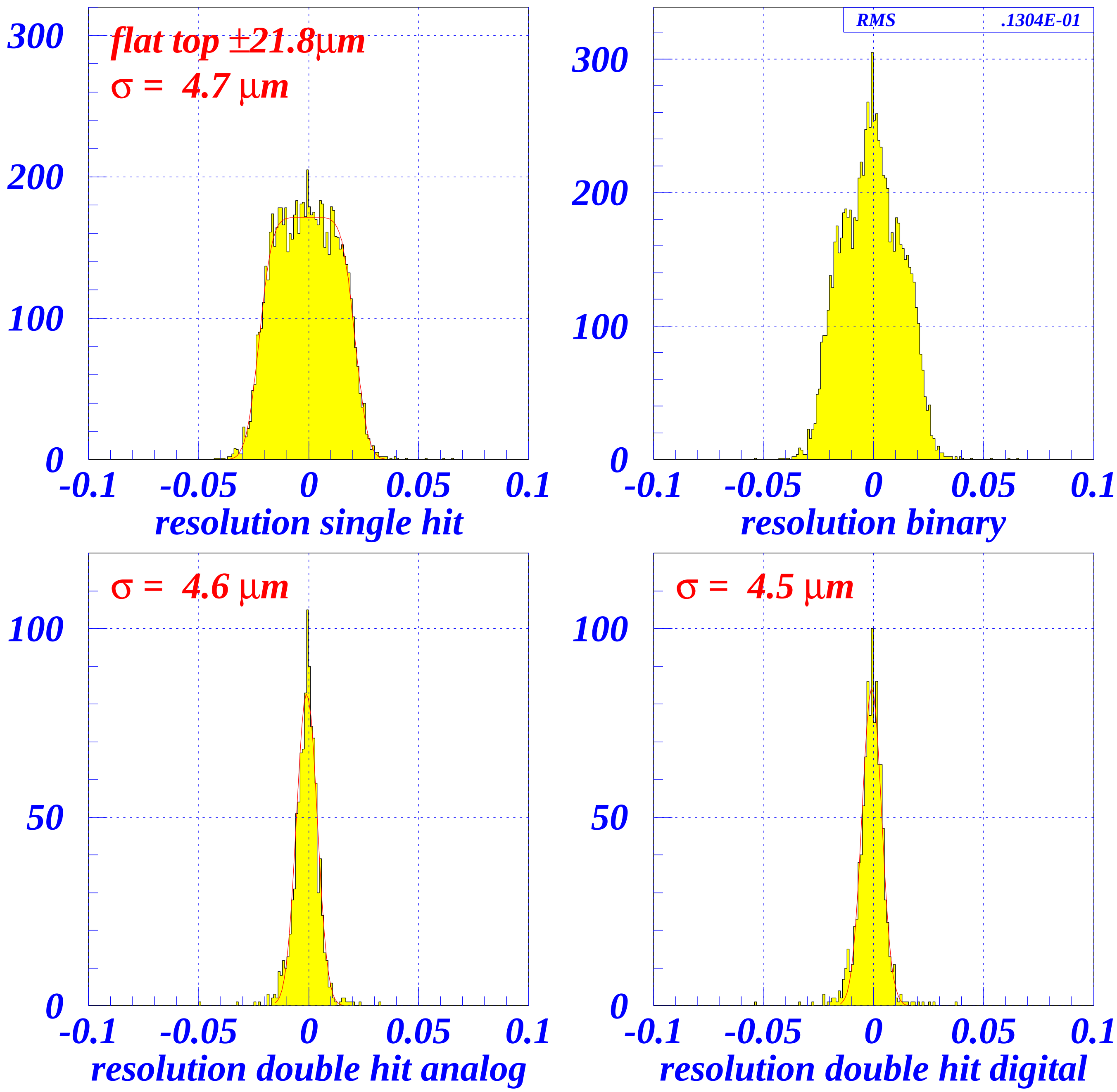
Resolution

Tile 2 Design



Resolution

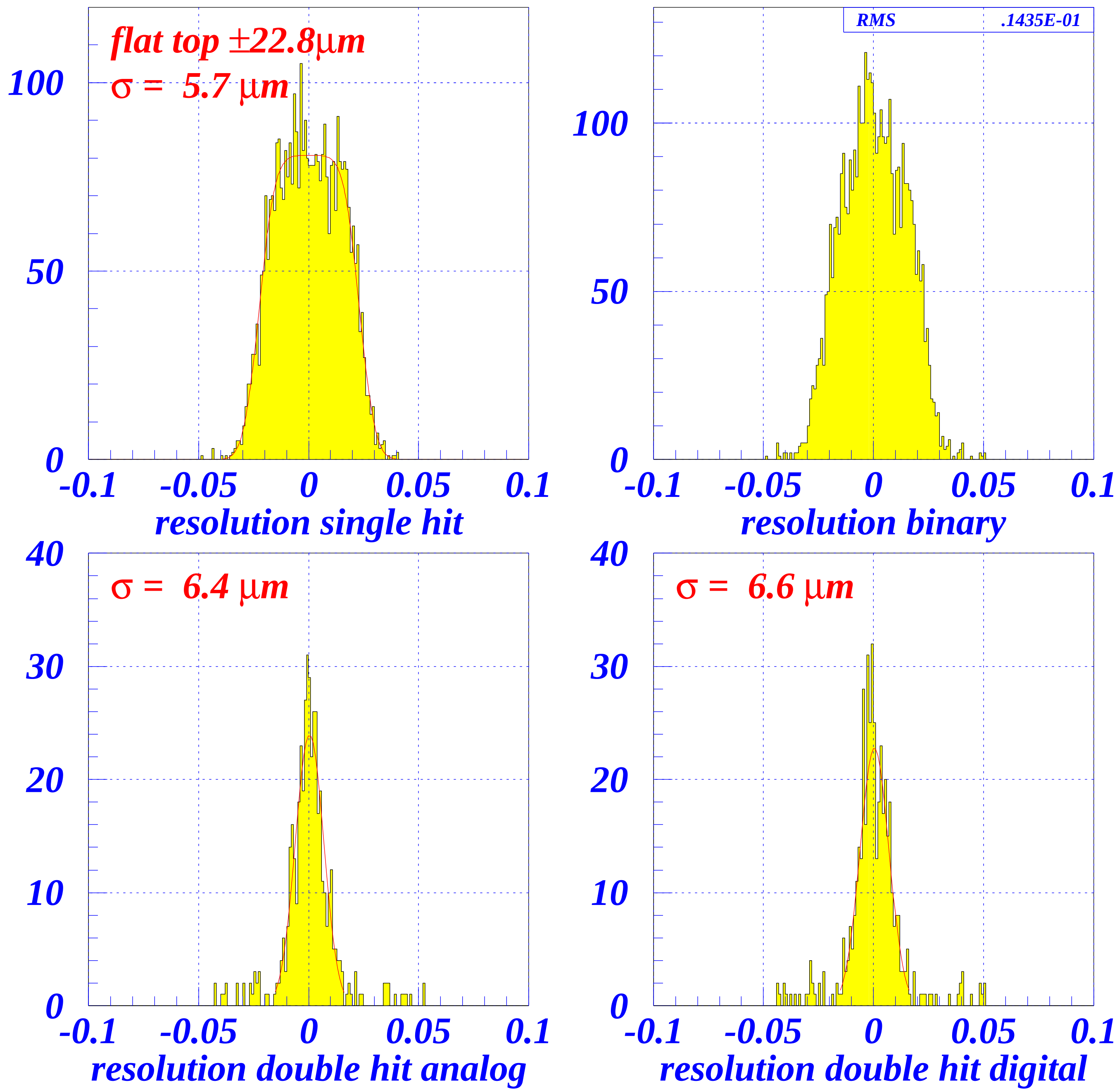
Design 1.b



Resolution

Irradiated Tile 2 Design

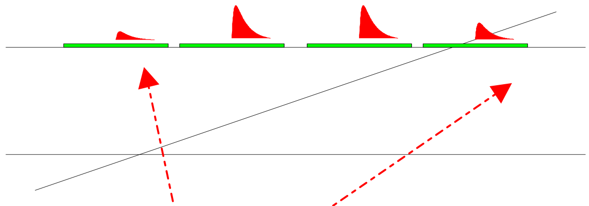
- Dose 10^{15} n /cm^2



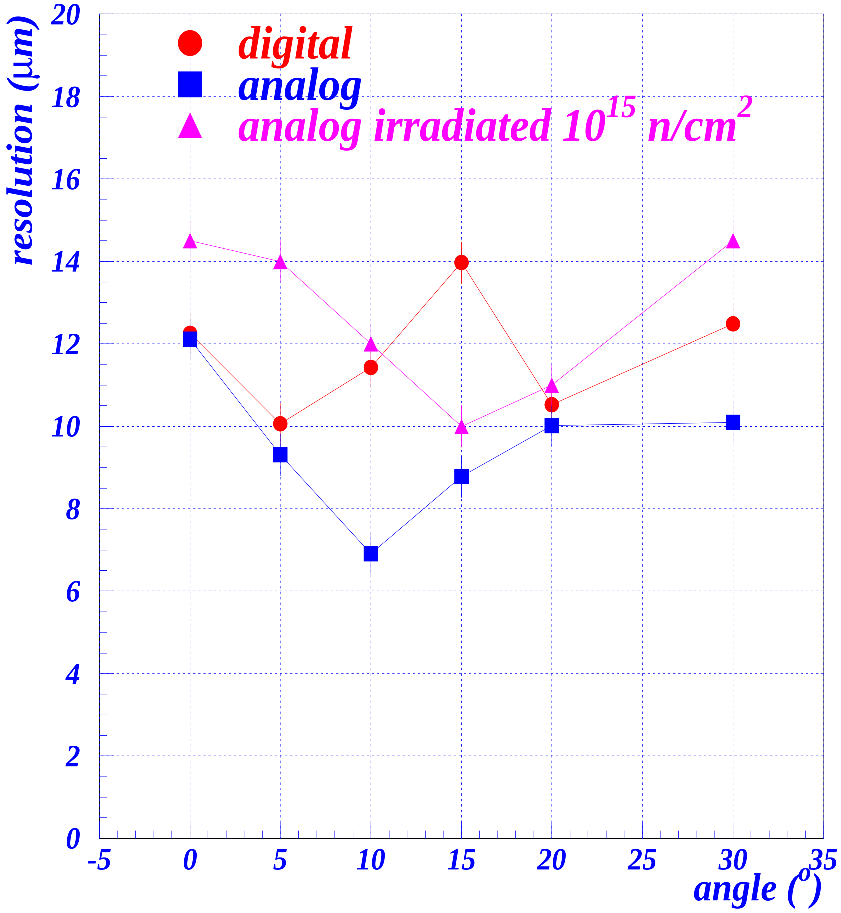
Resolution vs angle

Resolution determined by

- 1 pixel to multi-pixel cluster fraction
- algorithm



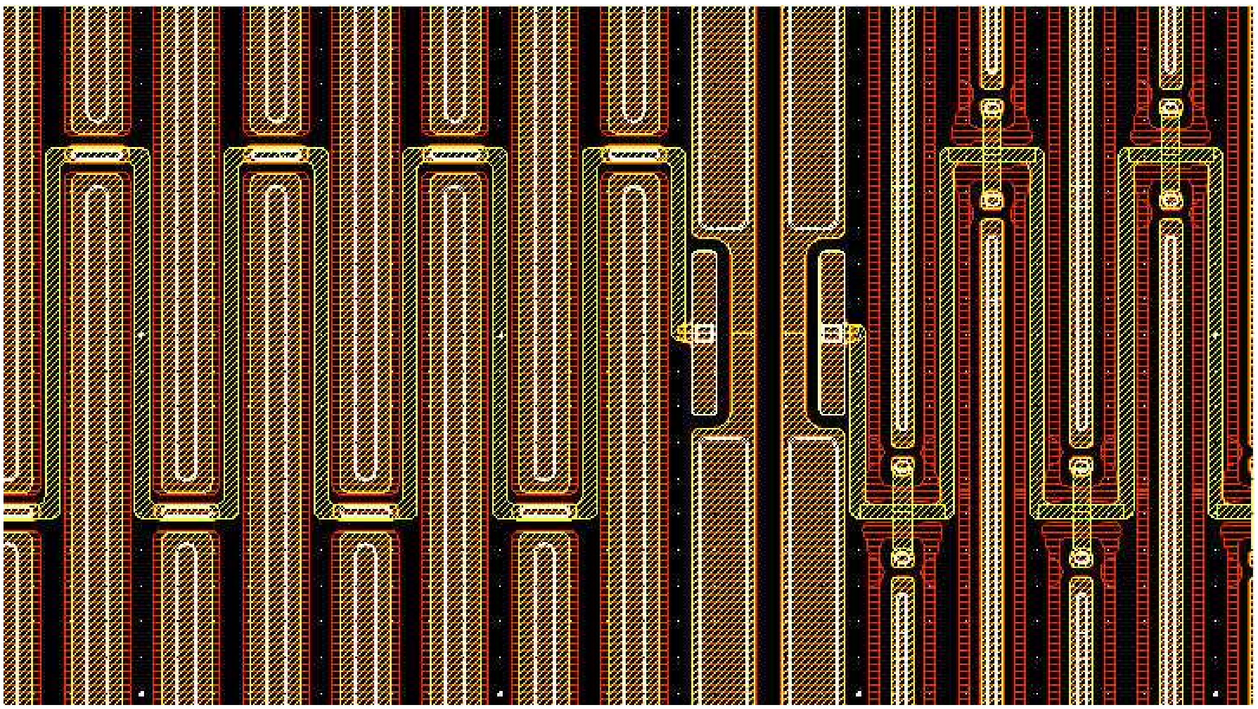
Charge interpolation on the external pixels in the cluster allows for excellent space precision



Resolution: Bricked Design

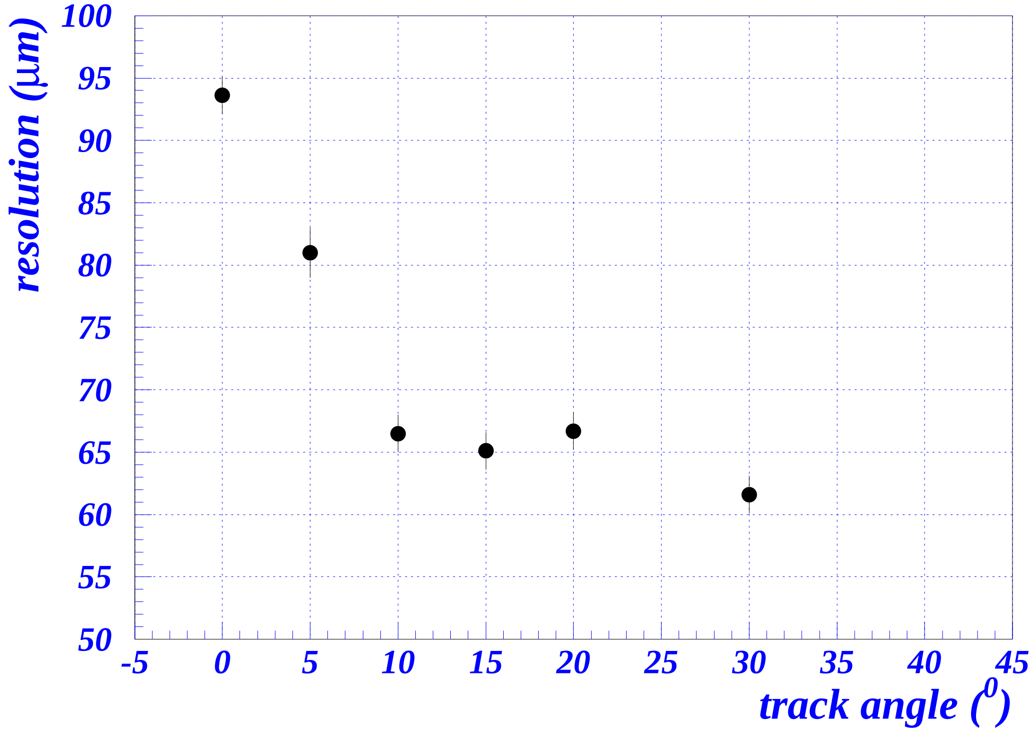
The Bricked Design Layout

- *The pixels are staggered by 200 μm in the long direction*



Resolution: Bricked Design

Resolution as function of the angle



Resolution

Summary:

- *The charge sharing is confined to a region $\pm 5\ \mu m$ between 2 adjacent pixels for 280 μm thick detector; the region shrinks to $\pm 4\ \mu m$ for a 200 μm detector*

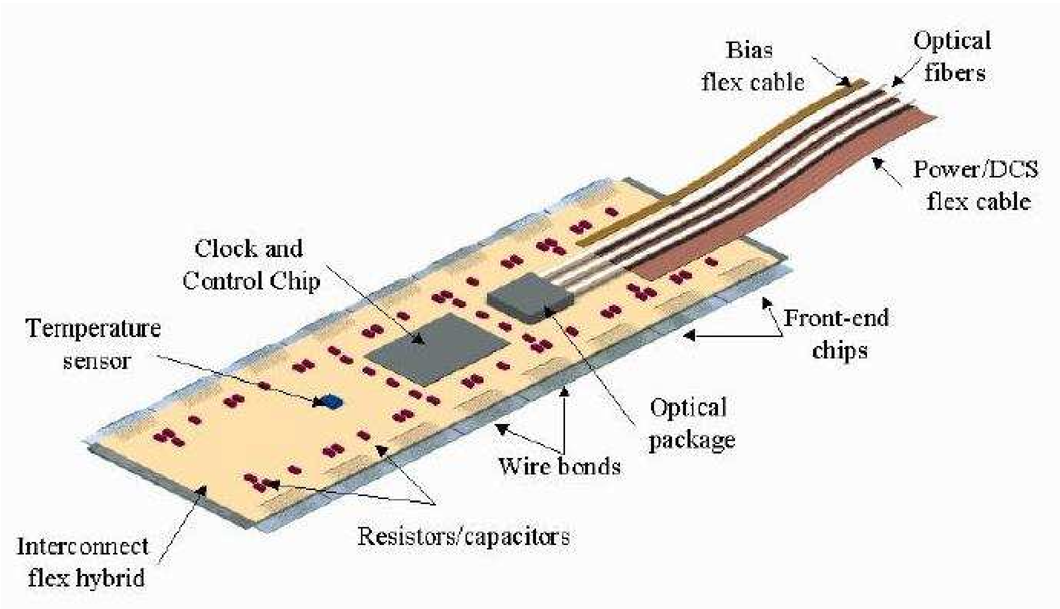
- *The fraction of 2 pixels clusters is ~ 15% for the Tile 2 design at 0^0 before irradiation with a threshold of 3 Ke*

- *The fraction of 2 pixels clusters is only ~7.5 % after a dose of 10^{15} n/cm^2*

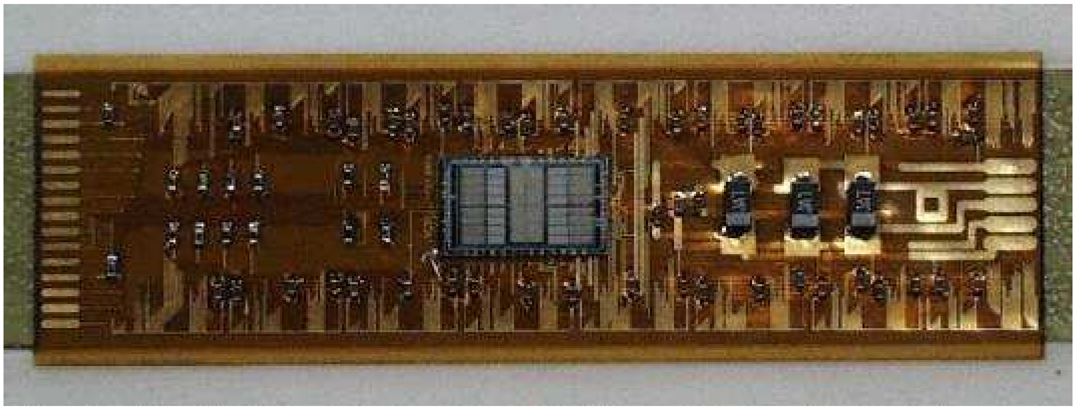
Modules

Modules

The module concept

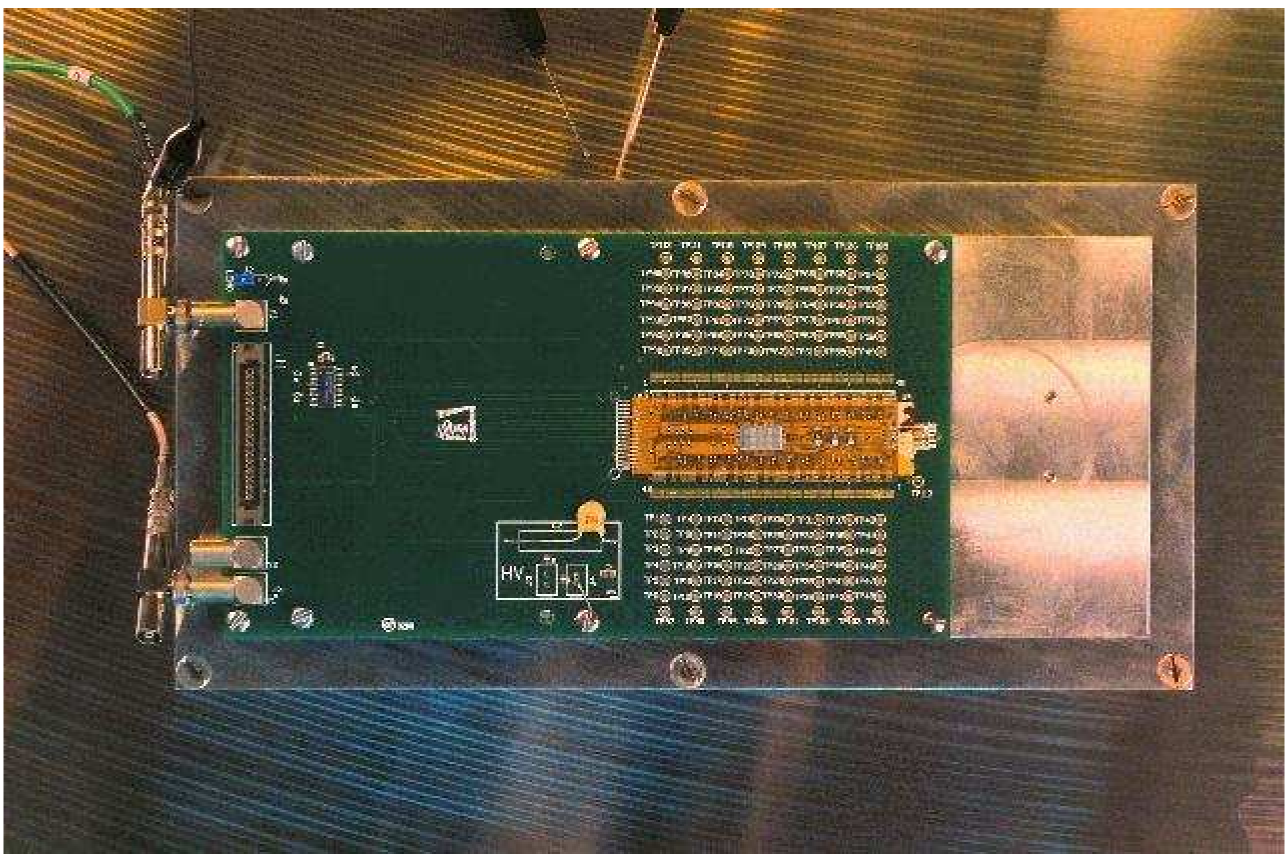


A Flex Hybrid Module



Modules

- First prototypes tested with a test beam in May 1999
- Mounted on dedicated board
- Features:
  - SnPb bump (solders) on a Tile 1 detector 200 μm thick
  - 16 F.E. chips
  - read-out using MCC

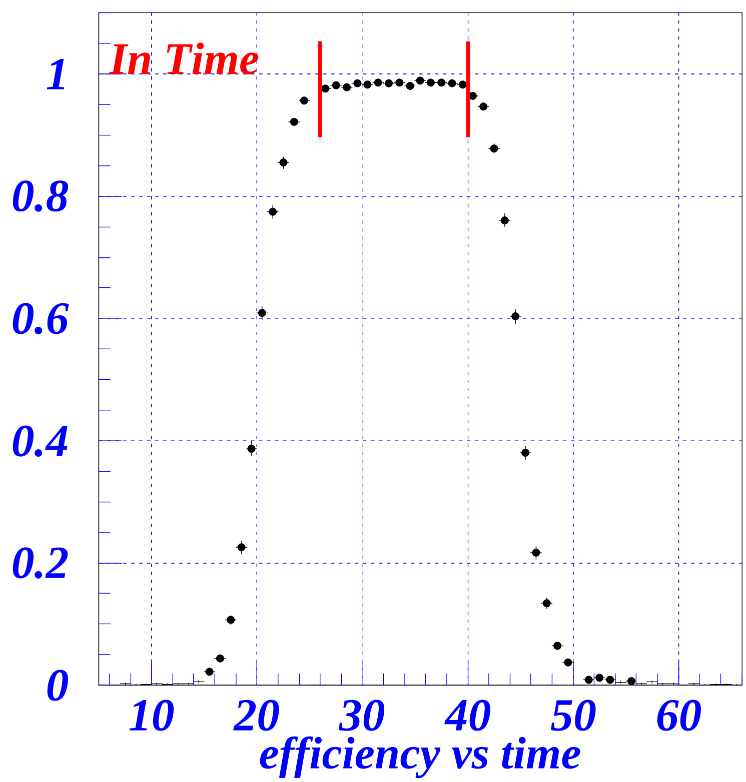


Modules: Efficiency vs Time

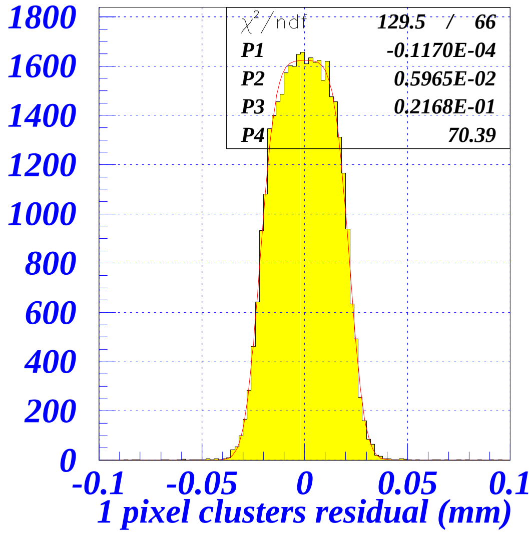
Efficiency 'In Time'

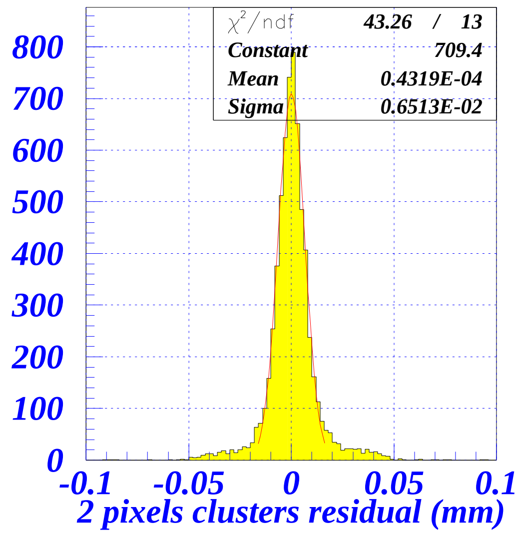
Tile 1 module - not Irradiated - Thr. 4 Ke

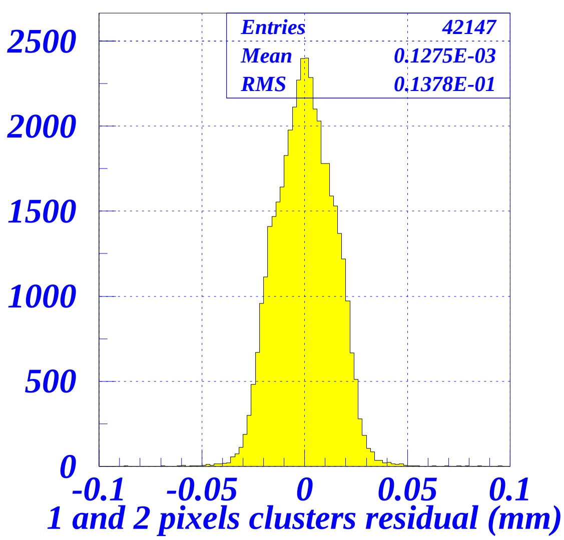
efficiency	98.4	Losses	1.6
1 hit	81.2	0 hits	0.7
2 hits	15.1	not matched	0.2
>2 hits	2.1	not in time	0.7



Modules: Resolution





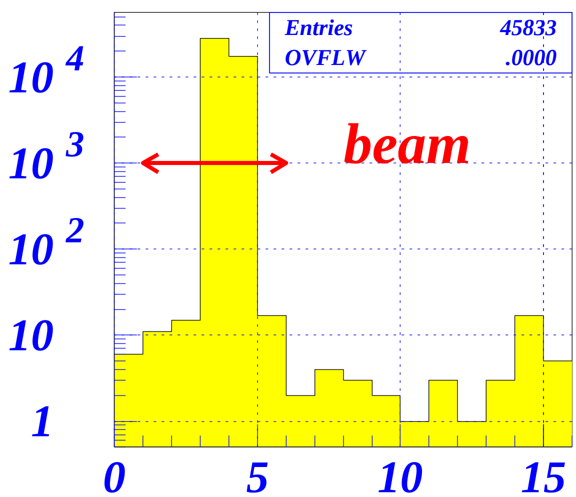


Occupancy

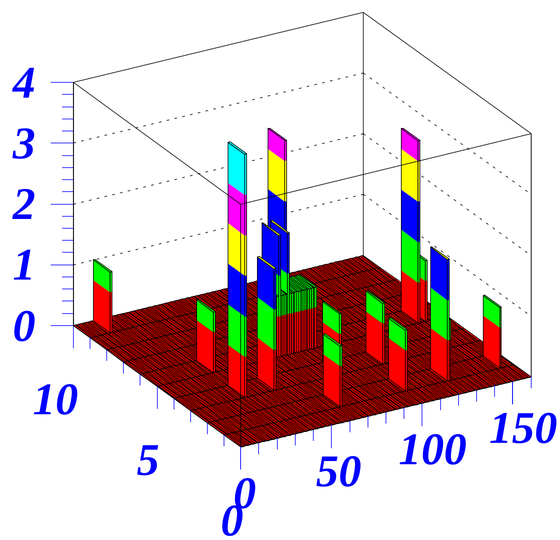
Occupancy

Tile 2 (p-spray) design

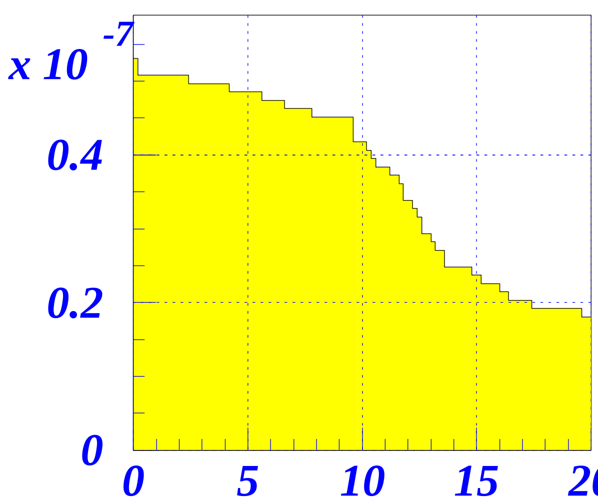
- **Fluence 0**
- **occupancy = 0.5×10^{-7}**



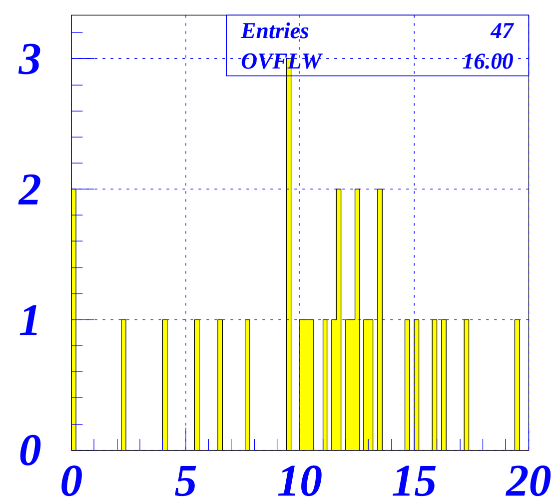
lvl1 of all hits



noisy pixels



occupancy vs threshold (Ke)

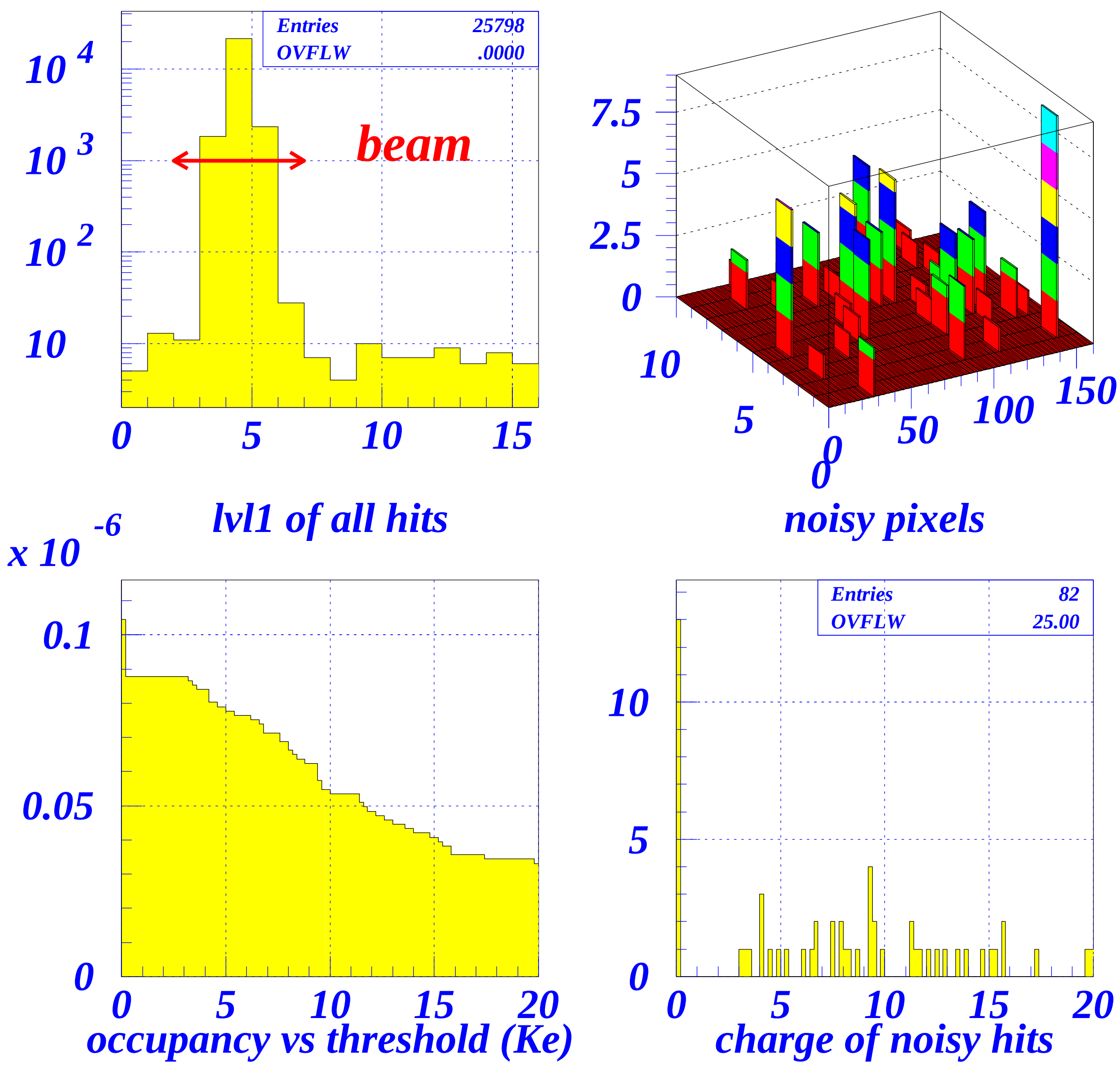


charge of noisy hits

Occupancy

Tile 2 (p-spray) design

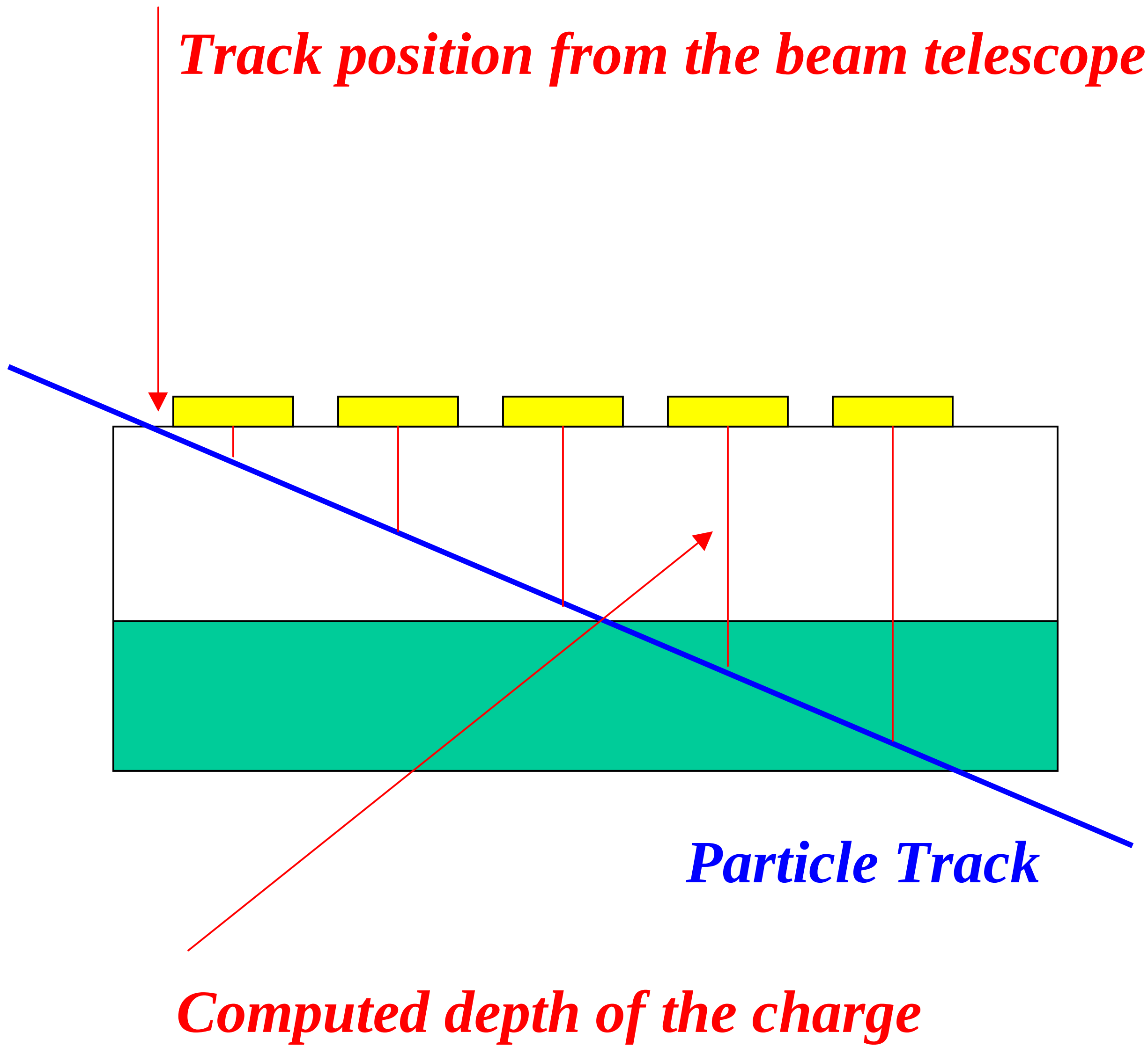
- Fluence 1×10^{15} n/cm^2
- occupancy = 0.9×10^{-7}



Depletion Depth

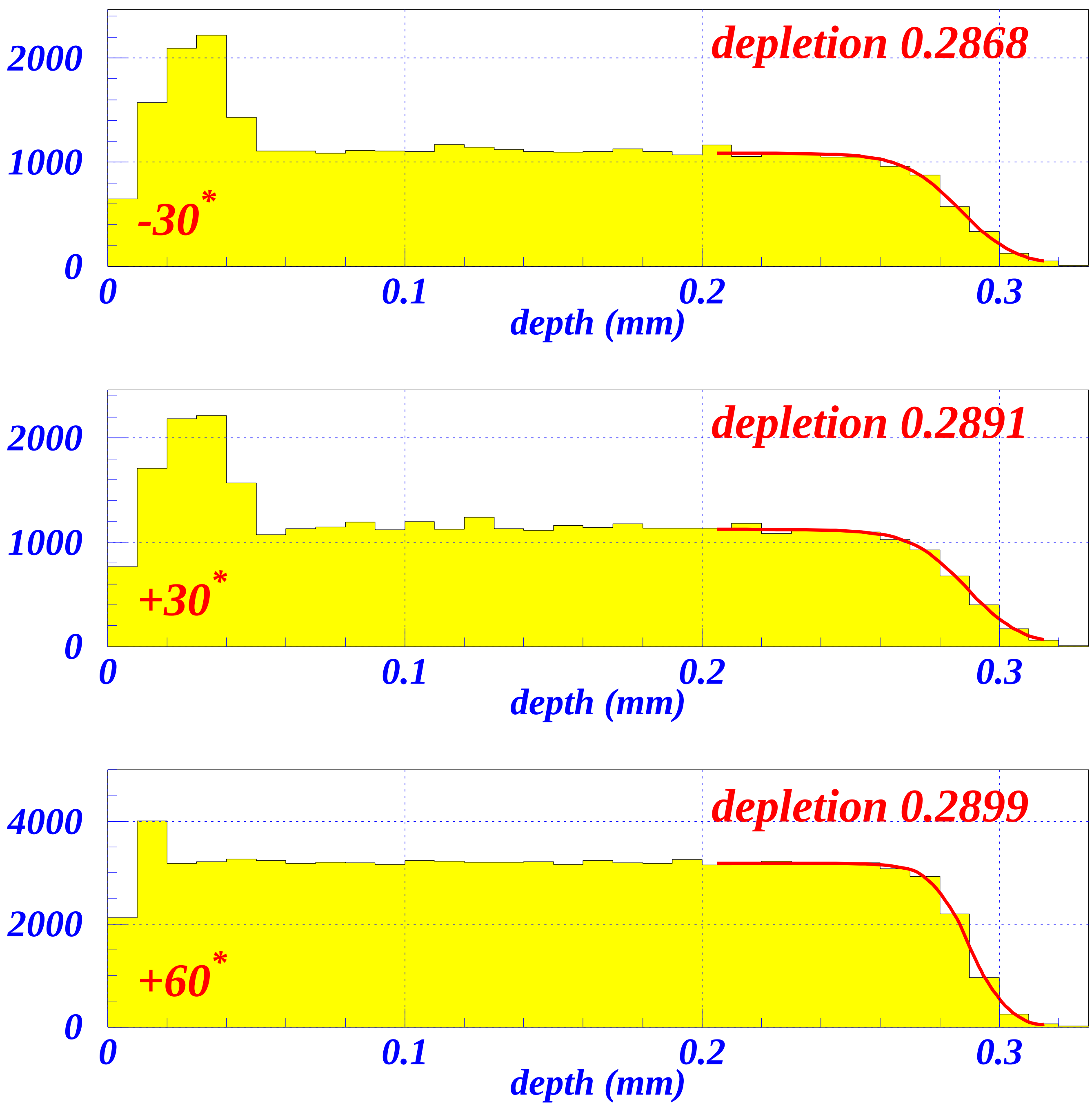
Depletion Depth

Measurement of the Depleted Thickness



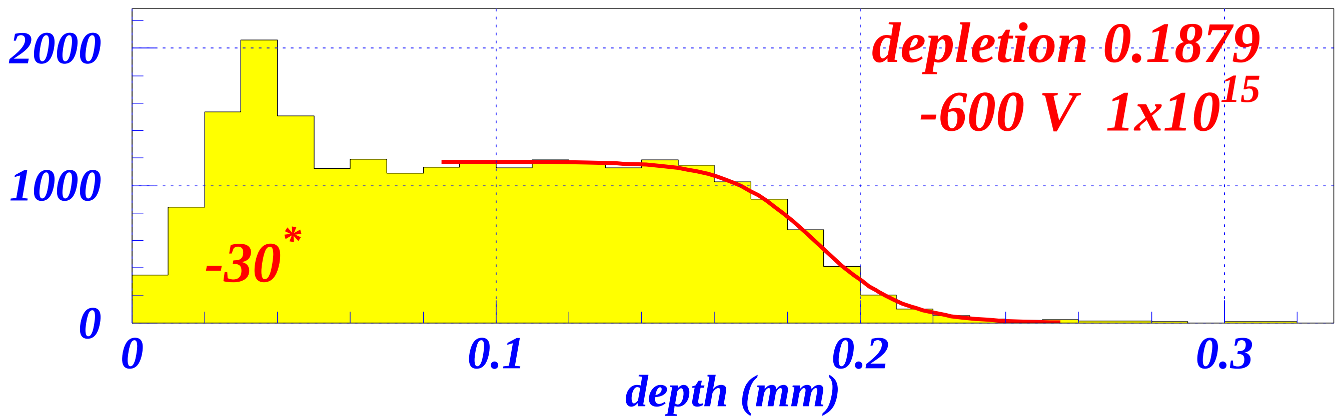
Depletion Depth

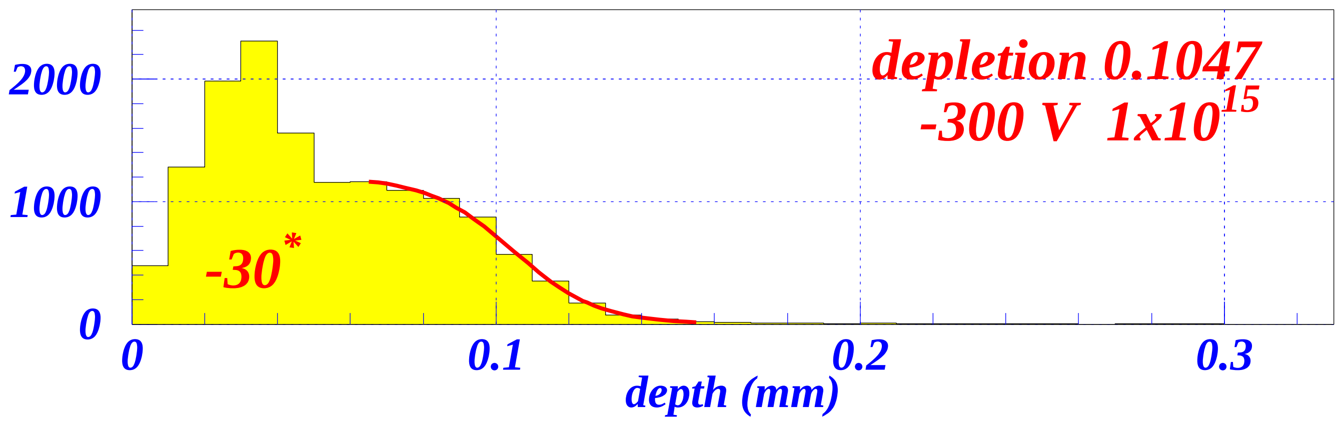
Checks with detectors not irradiated

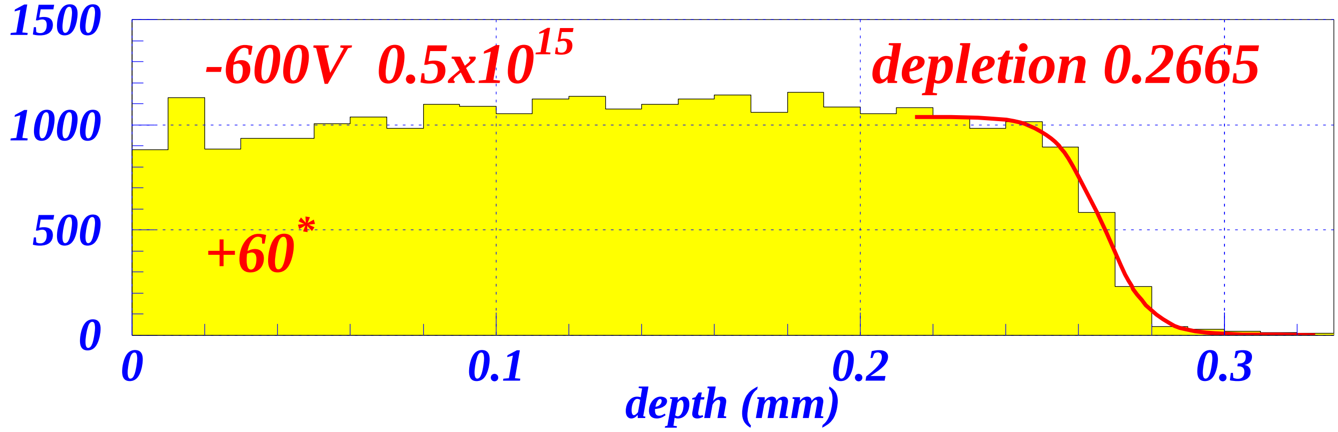


Depletion Depth

Irradiated Detectors





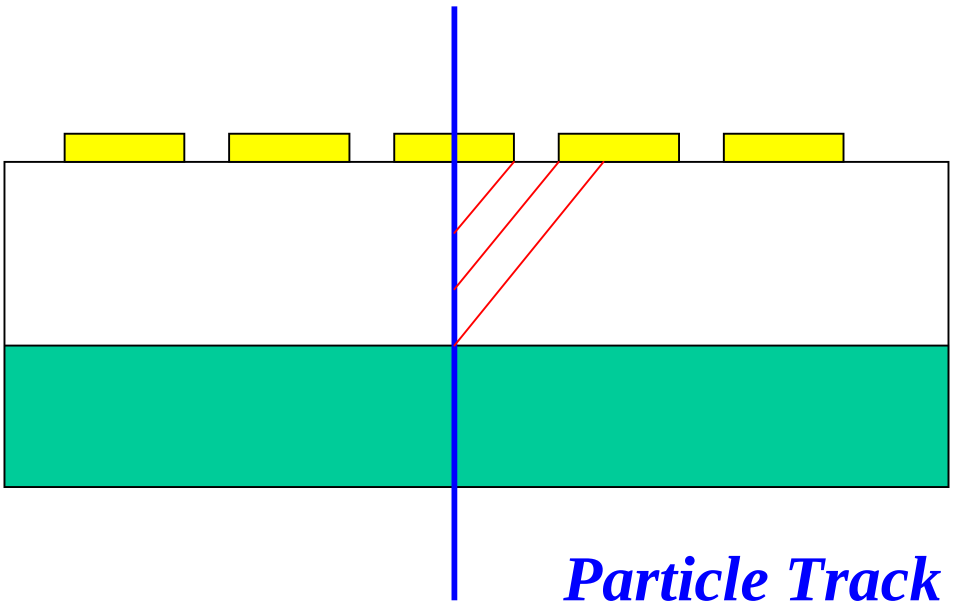


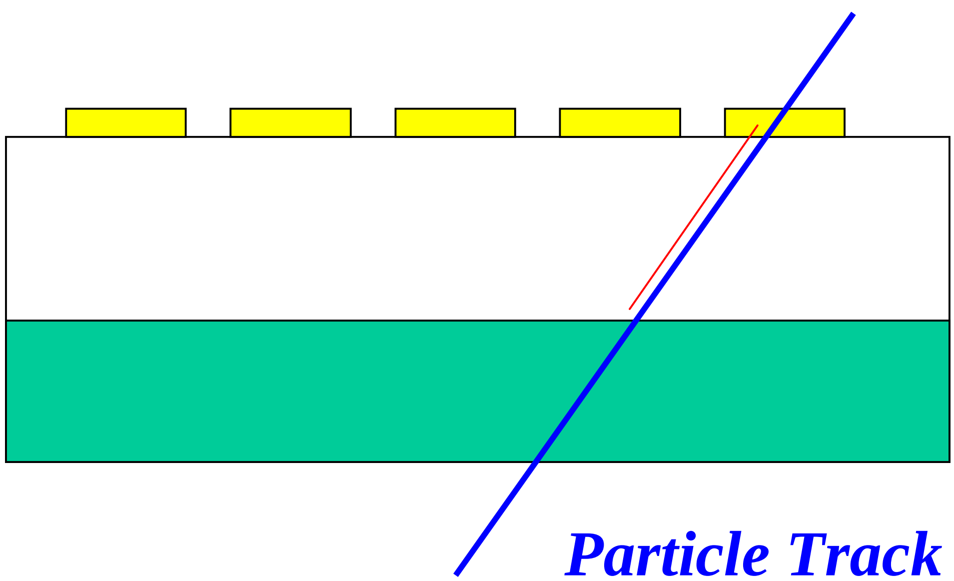
Lorentz Angle

Lorentz Angle Measurement

Method:

- *measure the mean cluster length as function of the track incidence angle*





Lorentz Angle Measurement

For every angle data taken with

- Field on
- Field off

For a given angle/field the mean cluster size is measured

Data with field off should give $\theta=0$

- result used as systematic error

Mean cluster size vs angle

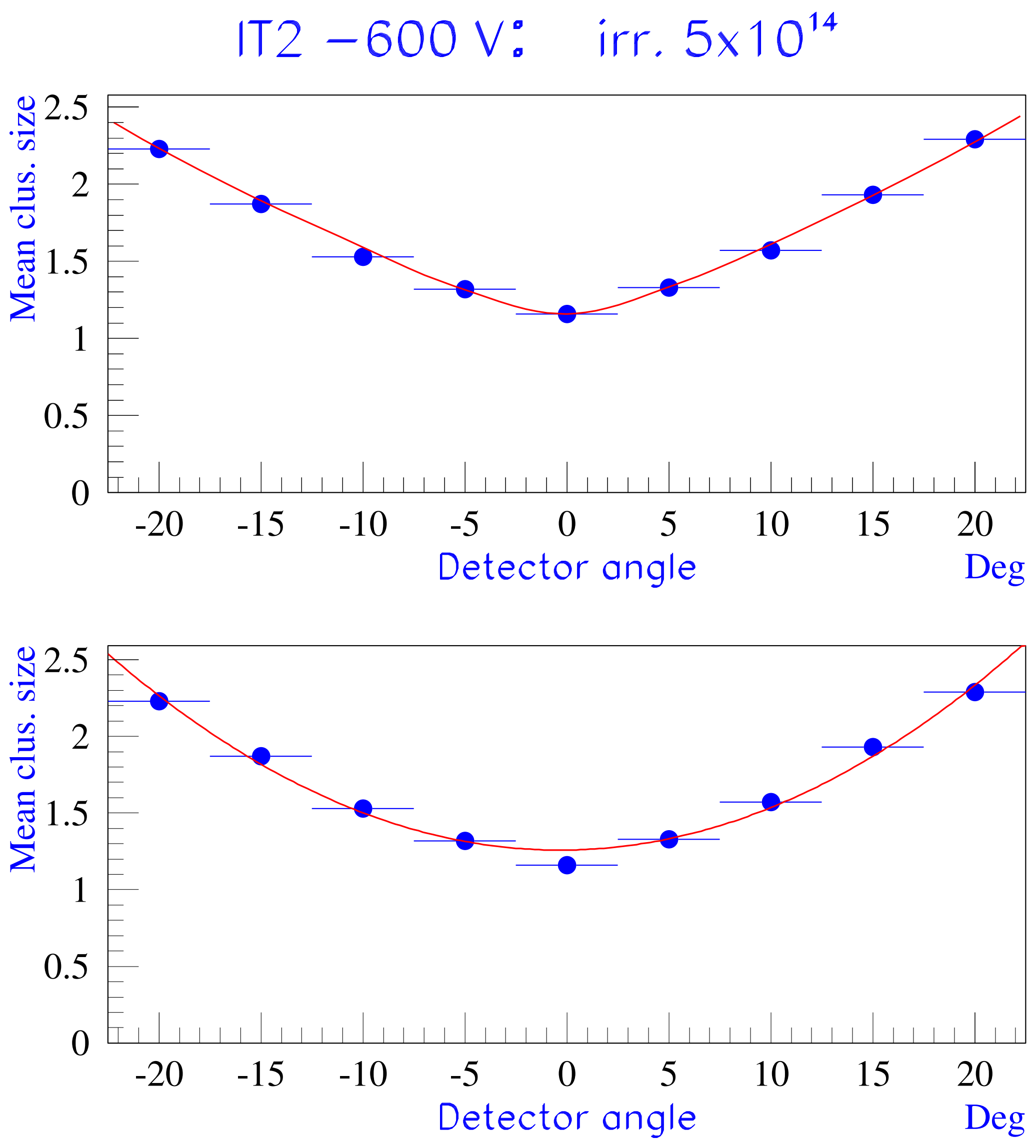
- fit with
  - model of charge collection (diffusion)
  - parabola

Lorentz Angle Measurement

Detector Tile 2 - Dose 5 10^{14} n/cm^2

B = 0

$\theta_L = 0.2^0 \pm 0.4^0$



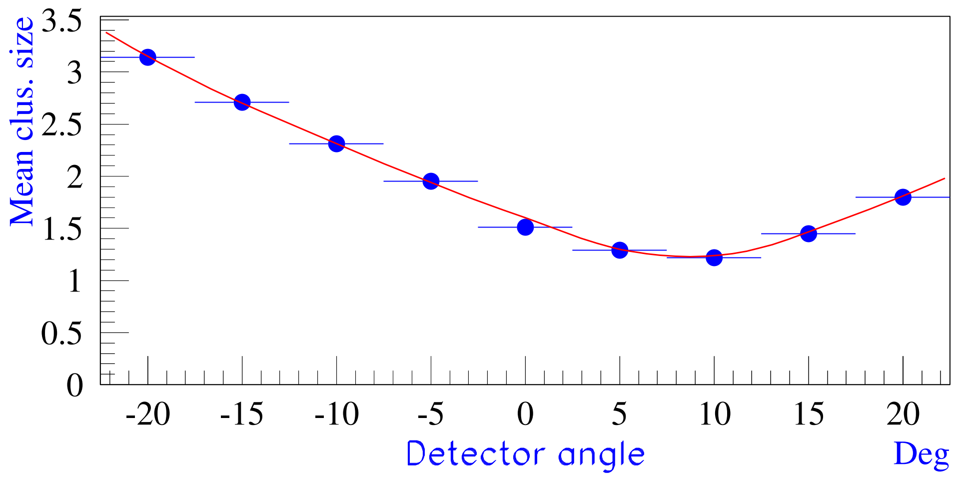
Lorentz Angle Measurement

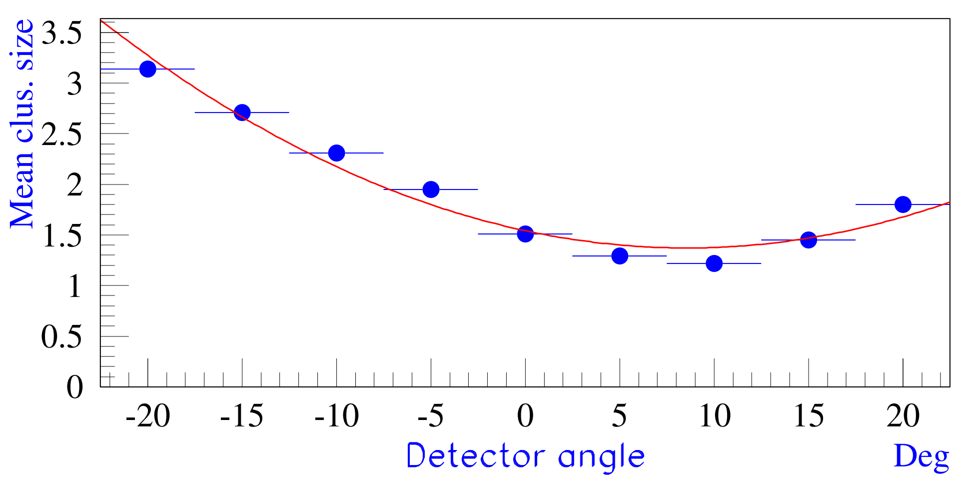
Detector Tile 2 - not irradiated

$B = 1.4\ T$

$\theta_L = 9.1^0 \pm 0.1^0 \pm 0.6^0$

ST2 non irradiated



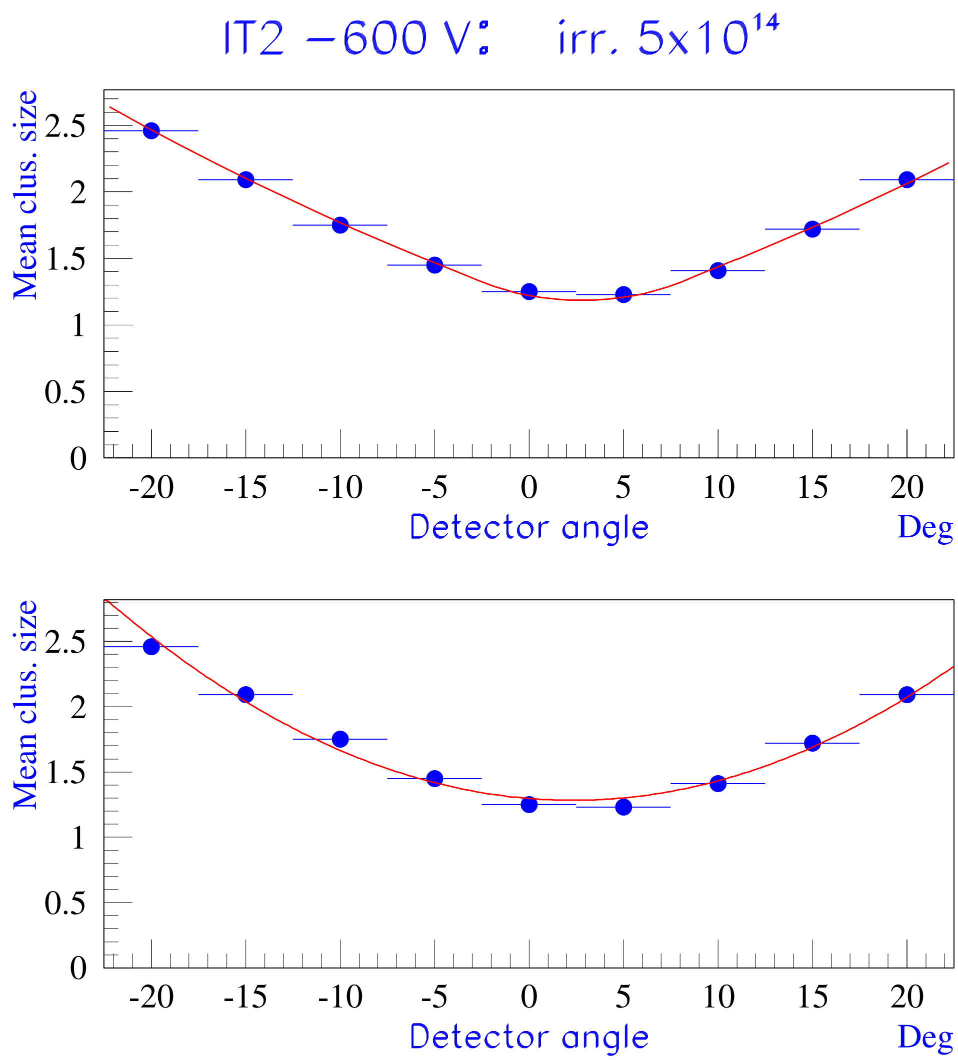


Lorentz Angle Measurement

Detector Tile 2 - Dose 5 10^{14} n/cm^2

B = 1.4 T

$\theta_L = 3.0^0 \pm 0.5^0 \pm 0.2^0$

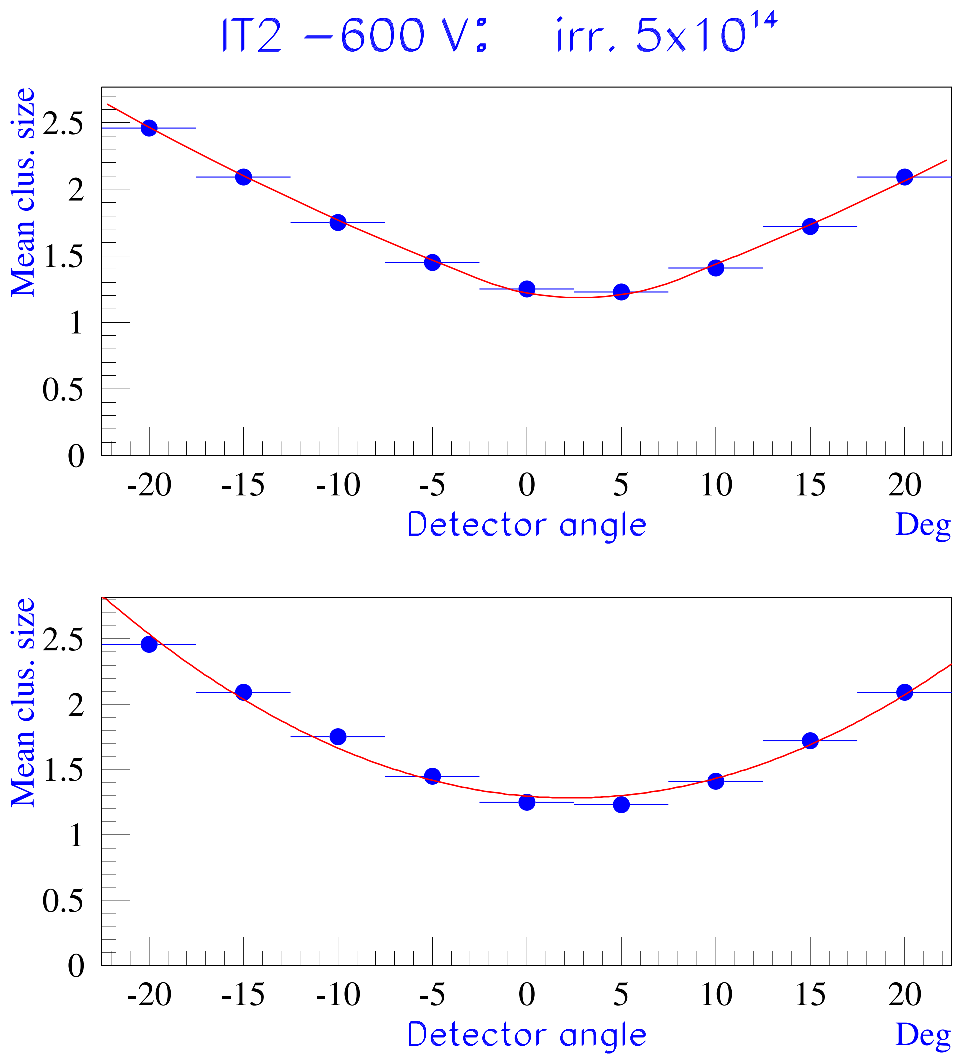


Lorentz Angle Measurement

Detector Tile 2 - Dose 10^{15} n/cm^2

$B = 1.4\ T$

$\theta_L = 3.25^0 \pm 1.2^0 \pm 0.5^0$

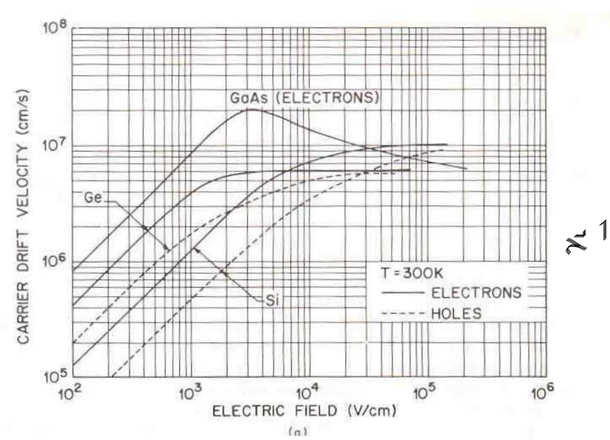


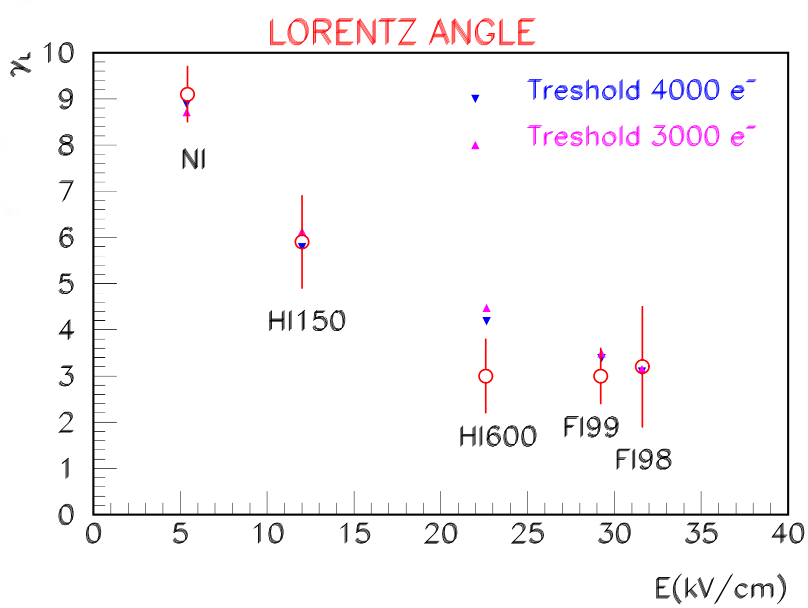
Lorentz Angle Measurement

Summary

- Lorentz angle at B = 1.4 Tesla
- depletion depth

			depletion (μm)
not irradiated	@ -150 V	9.1 ± 0.1 ± 0.6	290 ± 10
dose 5 10^{14} n_{eq}/cm^2	@ -150 V	5.9 ± 1.0 ± 0.3	125 ± 22
dose 5 10^{14} n_{eq}/cm^2	@ -600 V	3.0 ± 0.5 ± 0.2	265 ± 11
dose 1 10^{15} n_{eq}/cm^2	@ -600 V	3.2 ± 1.2 ± 0.5	190 ± 14





Conclusions

- The F.E. electronics (not yet radiation hard) works very well
- The ToT has been an essential tool to study and optimize the sensor designs
- The p-spray insulation technique survives a dose of 10^{15} n/cm^2

  190 mm depletion depth at 600 V
- The modified design has good charge collection performances. A problem arising from the floating atoll has been corrected
- Efficiencies in excess of 99% are measured for Tile 2 detectors before irradiation
- We are confident to reach the same level of efficiency after irradiation
- Modules studied with a test beam work well
- Lorentz angle measured after 10^{15} n/cm^2

$$\theta_L = 3.2^0 \pm 1.3^0 \text{ at } 1.4\ T$$