# Cryogenic Silicon Detectors

Luca Casagrande, CERN

# The CERN-RD39 Collaboration

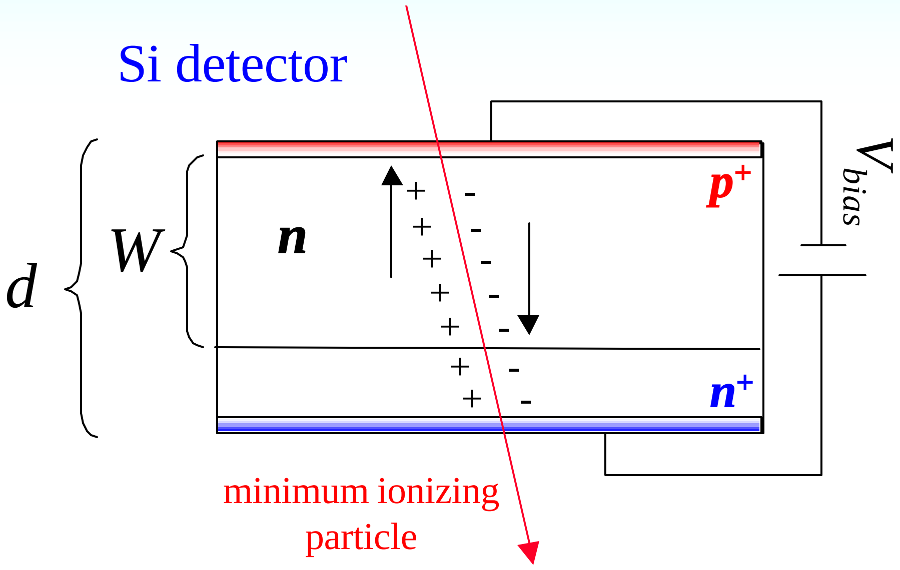
M. C. Abreu[1], V. Bartsch[2], W. H. Bell[3], P. Berglund[4], W. de Boer[2], J. Bol[5], K. Borer[6],
S. Buontempo[7], L. Casagrande[14], S. Chapuy[8], V. Cindro[9], P. Collins[14], N. D'Ambrosio[7],
C. Da Viá[10], S. Devine[3], B. Dezillie[11], A. Dierlamm[2], Z. Dimcovski[8], V. Eremin[12],
A. Esposito[13], V. Granata[10,14], E. Grigoriev[2], S. Grohmann[5,14], F. Hauler[2], E. Heijne[14],
O. Hempel[5], R. Herzog[5], S. Janos[6], L. Jungermann[2], I. Konorov[13], Z. Li[11], C. Lourenço[14],
I. Mandic[9], M. Mikuz[9], T. O. Niinikoski[14], V. O'Shea[3], S. Pagano[7], S. Paul[13], K. Pretzl[6],
P. Rato Mendes[1], G. Ruggiero[3,14], K. Smith[3], B. Perea Sorano[14], P. Sonderegger[14], P. Sousa[1],
E. Verbitskaya[12], S. Watts[10], E. Wobst[5], M. Zavrtanik[9]

[1] LIP, Faro, Portugal
[2] IEKP, Karlsruhe University,Germany
[3] Glasgow University, UK
[4] Helsinki University of Technology, Espoo, Finland
[5] ILK, University of Dresden, Germany
[6] LHEP, University of Bern, Switzerland
[7] INFN and University of Naples, Italy
[8] University of Geneva, Department of Radiology, Switzerland
[9] JSI and University of Ljubljana, Slovenia
[10] University of Brunel, UK
[11] Brookhaven National Laboratory, USA
[12] IOFFE, St. Petersburg, Russia
[13] Munich Technical University, Germany
[14] CERN, Geneva, Switzerland

# Outline

- (Radiation Damage in Silicon)
- Silicon at Cryogenic Temperatures:
  - ✓ Known Properties
  - ✓ The ***Lazarus Effect***
- Experimental Results on Diodes
- Position Resolution of a “Resurrected” Detector
- Irradiation in the Cold
- First Application of a Cryogenic Silicon Tracker in a High-Energy Physics Experiment

# Working Principle of a Si detector



- Charged particle generates charge by **ionization**

- External field ➔ detect signal **induced** on the electrodes by the charge carriers that drift in the **depleted region *W***

$$W \propto \sqrt{V_{bias}}$$

$$Q_{induced} = q\,\frac{\Delta x}{d}$$

- For a **non-irradiated** detector (the non-depleted region is metal-like):

$$CCE \equiv \frac{Q_{measured}}{Q_{generated}} \propto \frac{W}{d}$$

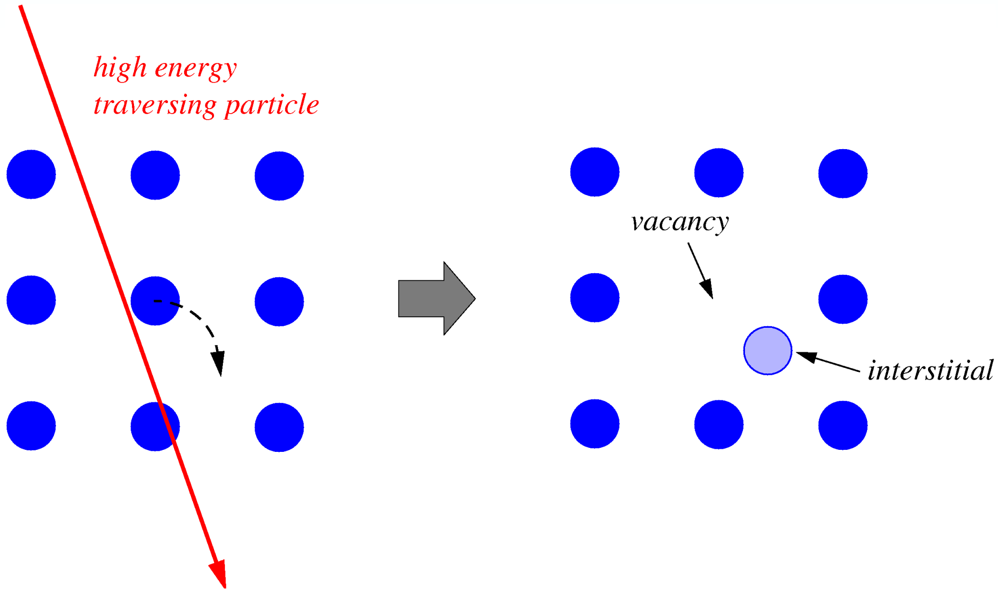
- *CCE* = 100% ➔ need to apply $V_{bias}$ such that ***W* = *d***

$$V_{bias} = V_{dep} = \frac{q}{2e_0 e_S} N_D\, d^2$$

$V_{dep}$ : depletion voltage

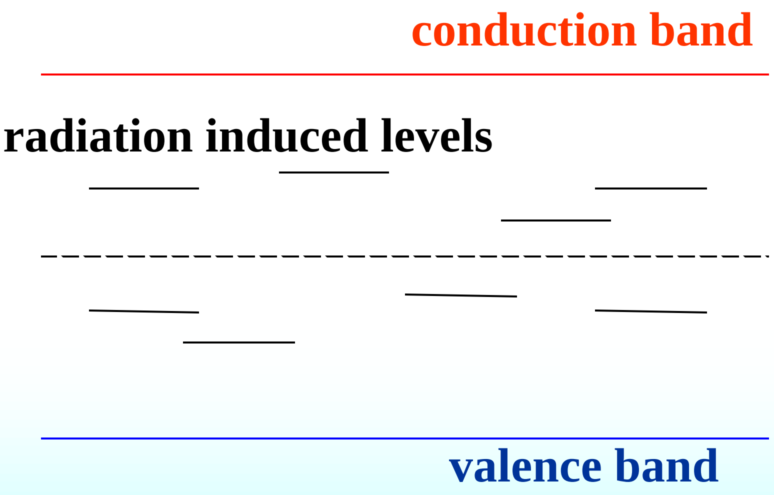
$N_D$ : density of impurities (donors, ~$10^{12}$ cm$^{-3}$)

# Radiation Damage in Si



- **Non-ionizing** energy loss ➔ displacement of lattice atoms, creation of a **Frenkel pair** (vacancy + interstitial)

- **Vacancies** and **interstitials** move around and combine with lattice impurities ➔ stable defects, which appear as deep energy levels in the forbidden band gap of silicon



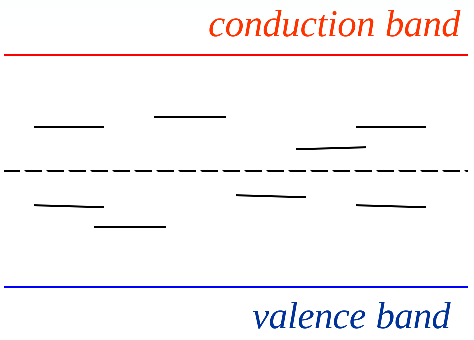
**conduction band**

**radiation induced levels**

**valence band**

# Radiation Damage in Si

## Macroscopic observables:



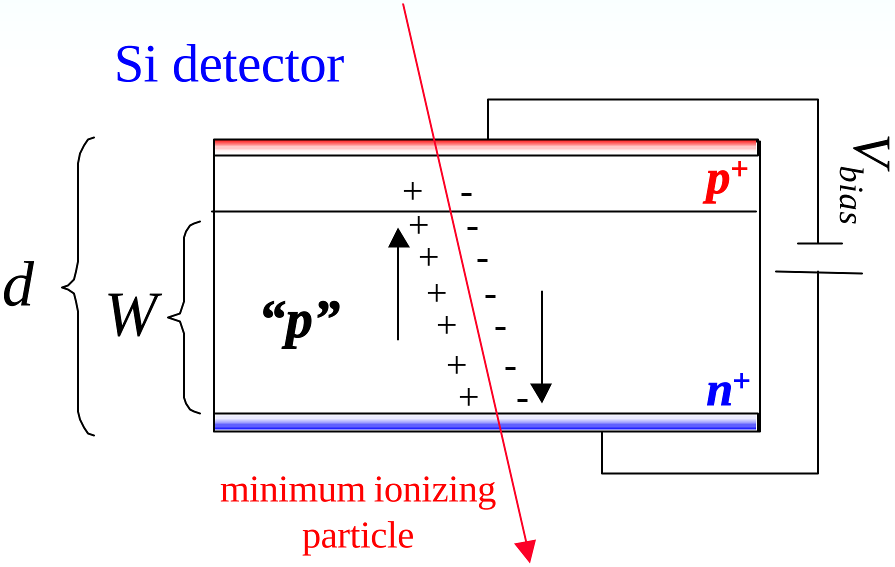
- Leakage current increases linearly with dose
  ➔ increase of detector noise
  ➔ power dissipation in the sensor

- Trapping and de-trapping of carriers
  ➔ signal loss

- At equilibrium, a certain fraction of defects are filled and therefore charged, so they contribute to the **effective doping concentration** ($N_D \rightarrow N_{eff}$)
- Experimental observation: under irradiation, space charge become more and more negative
  ➔ dramatic increase of depletion voltage ($V_{dep}\ \mu\ N_{eff}\ d^{2}$)

- Annealing: $N_{eff}$ changes also after irradiation
  ➔ need to keep the detector at -10°C

# CCE for Irradiated Detectors



- Under bias, space charge is negative, ➔ bulk behaves like a ***p*-type** material.
- The junction develops from ***n*** $^+$

- Heavily irradiated detector

➔ the non-depleted region behaves like an insulator

$$\rightarrow \quad Q_{induced} \propto W/d$$

$$\Rightarrow \quad CCE \propto \left(\frac{W}{d}\right)^2$$

*W/d* = 70% ➔ CCE = 50% !!!

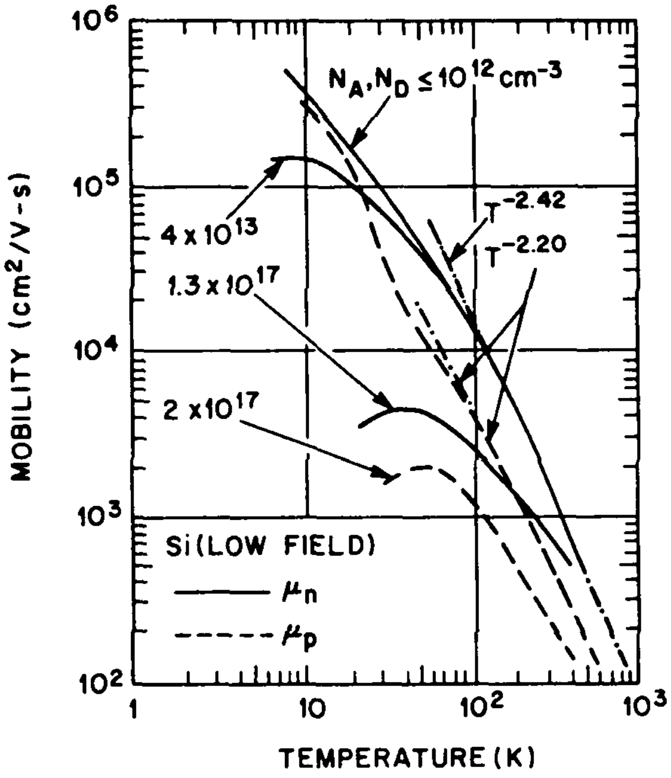
- Experimental observation: there is trapping

➔ even for a fully depleted detector CCE < 100%

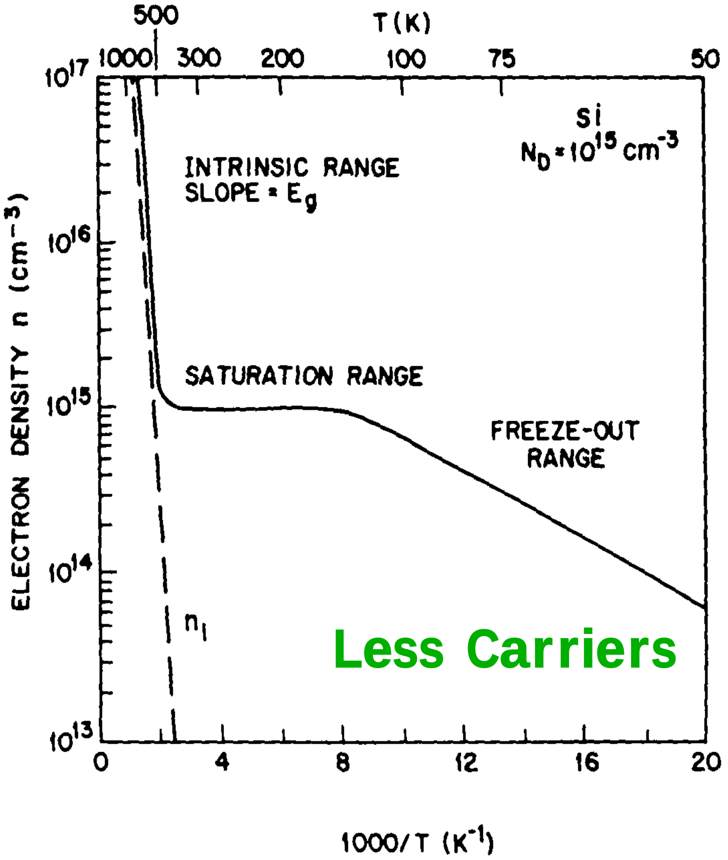
# Known Properties of Si at Cryogenic Temperatures

# Silicon at Cryogenic Temperatures

**Higher Mobility**



→ *fast signals*



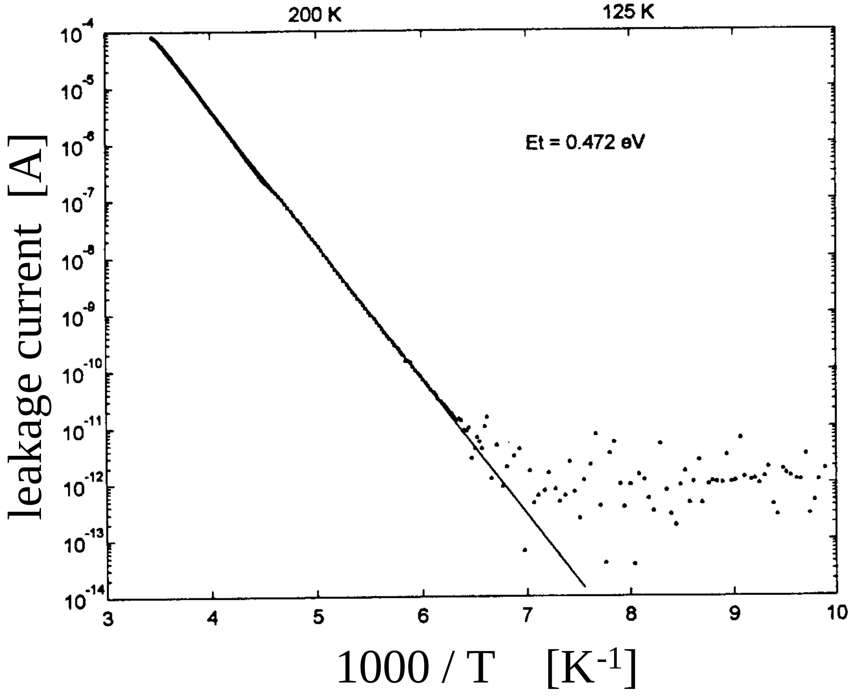
**Less Carriers**

→ *higher bulk resistivity*

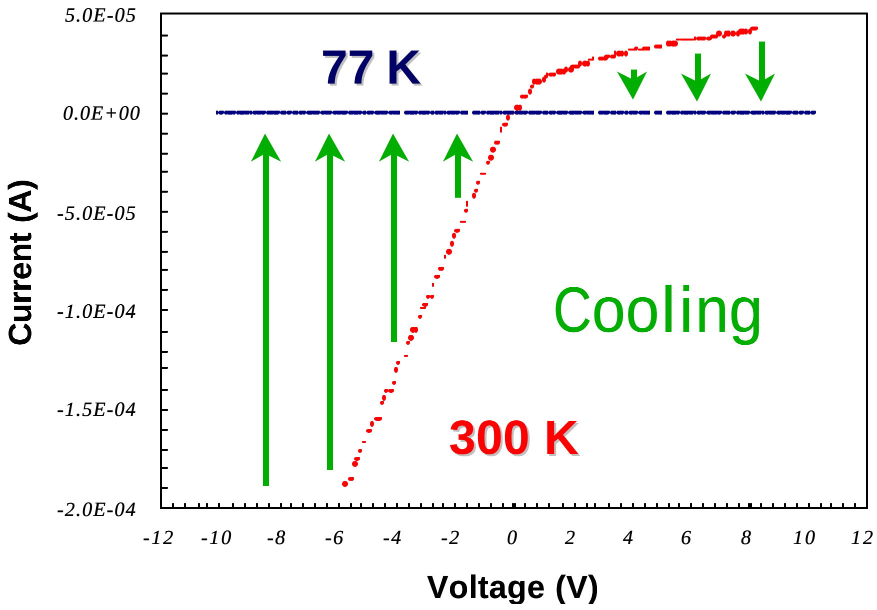
→ *lower depletion voltage*

# Leakage Current vs Temperature

Exponential Decrease of Leakage Current



Irradiated detector



I < 1 nA up to ±500 V !

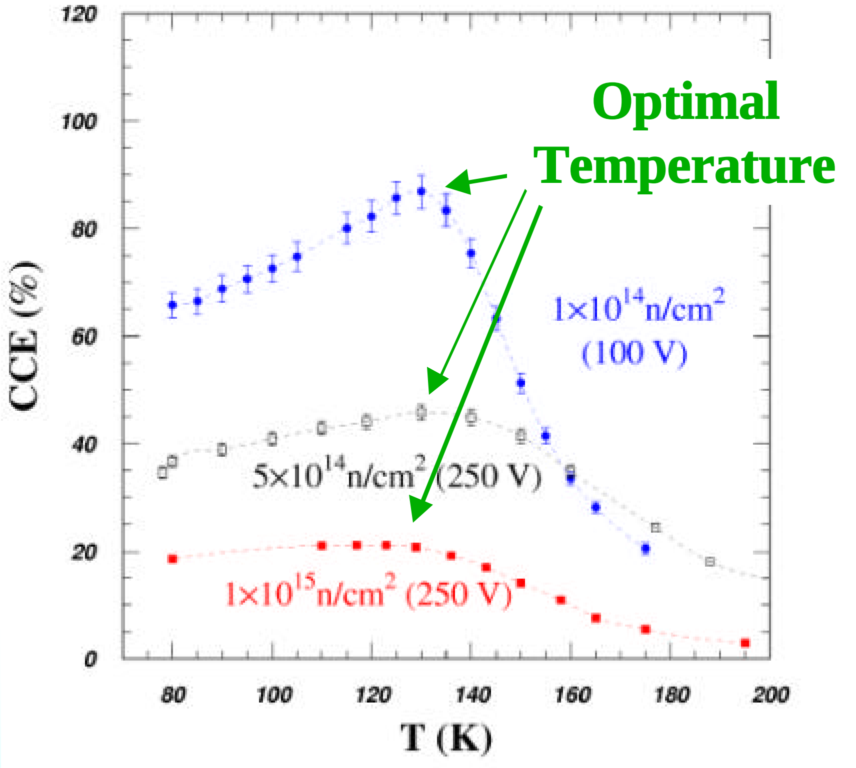
➔ *low noise*

➔ *no power dissipation in the sensor*

# Is there anything else ?

# CCE vs Temperature

- Experimental observation: heavily irradiated Si detector no longer operational at room temperature “resuscitate” when cooled down to cryogenic temperatures



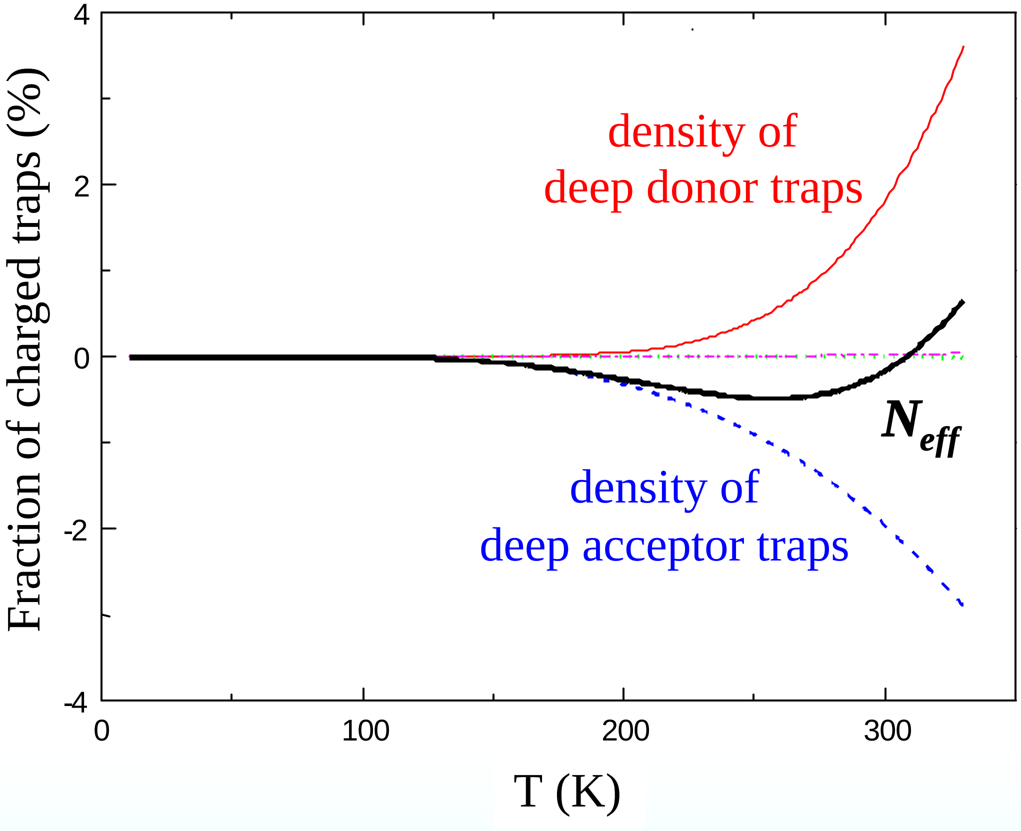
**Optimal Temperature**

# Is there anything else?

**_The Lazarus Effect_**

# The Lazarus Effect

Elena Verbitskaya et al., presented at RD39 Coll. Meeting, CERN, March 1-2 2001.



- By cooling, we manipulate the Si bulk properties

- Most relevant:
  - ✓ charge carrier density
  - ✓ de-trapping probability

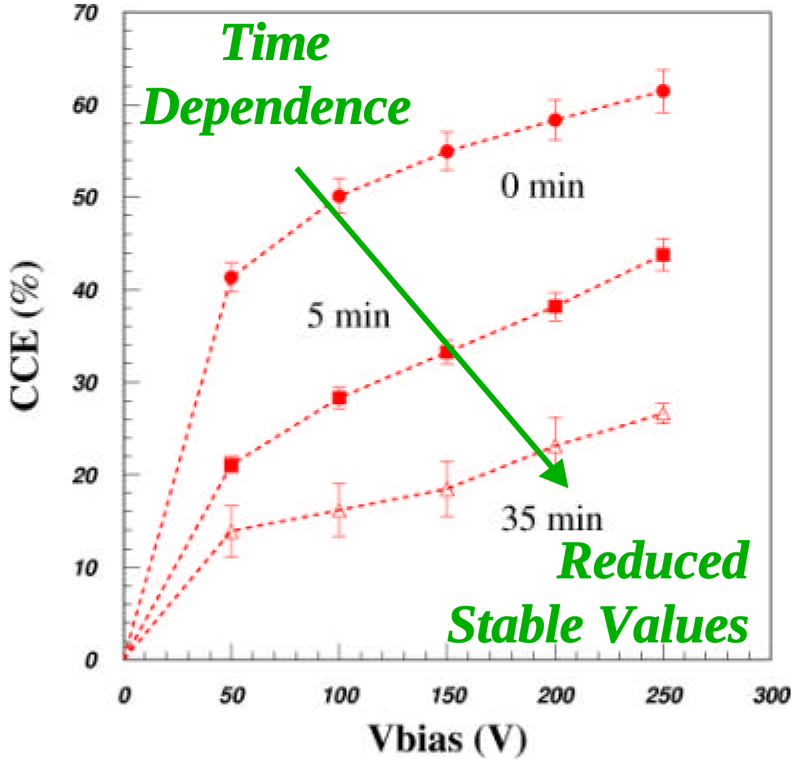
- Cooling ➔ fraction of charged traps decreases

  ➔ $|N_{eff}|$ decreases

# Results on Diodes

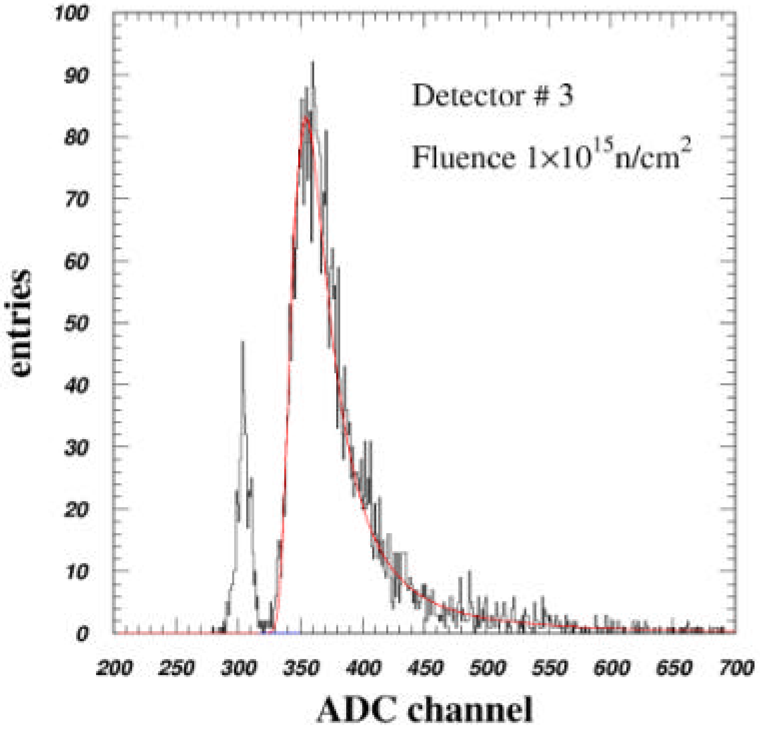
# Conventional Operation

T = 80 K



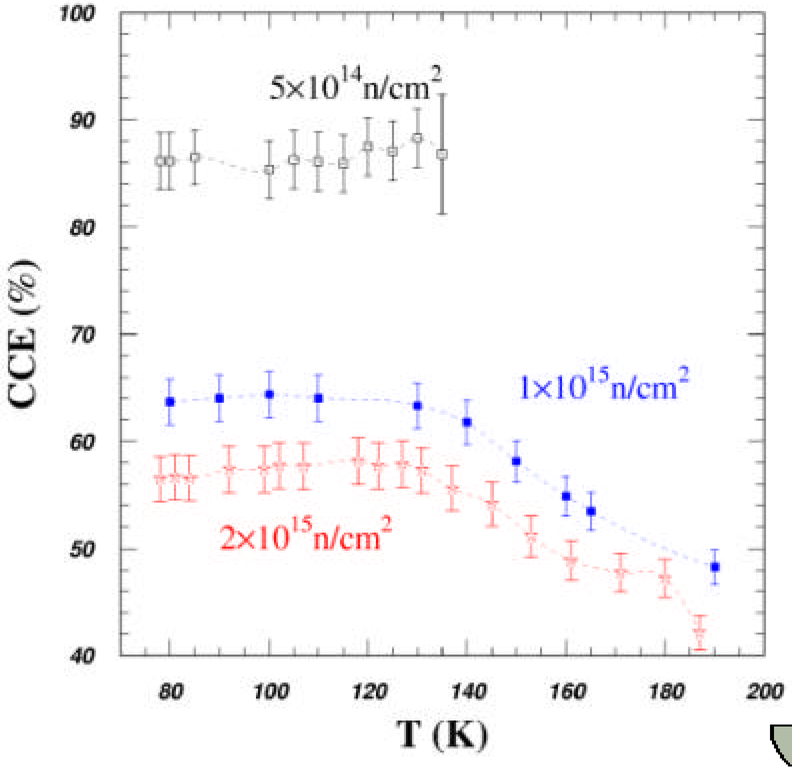
*Time Dependence*

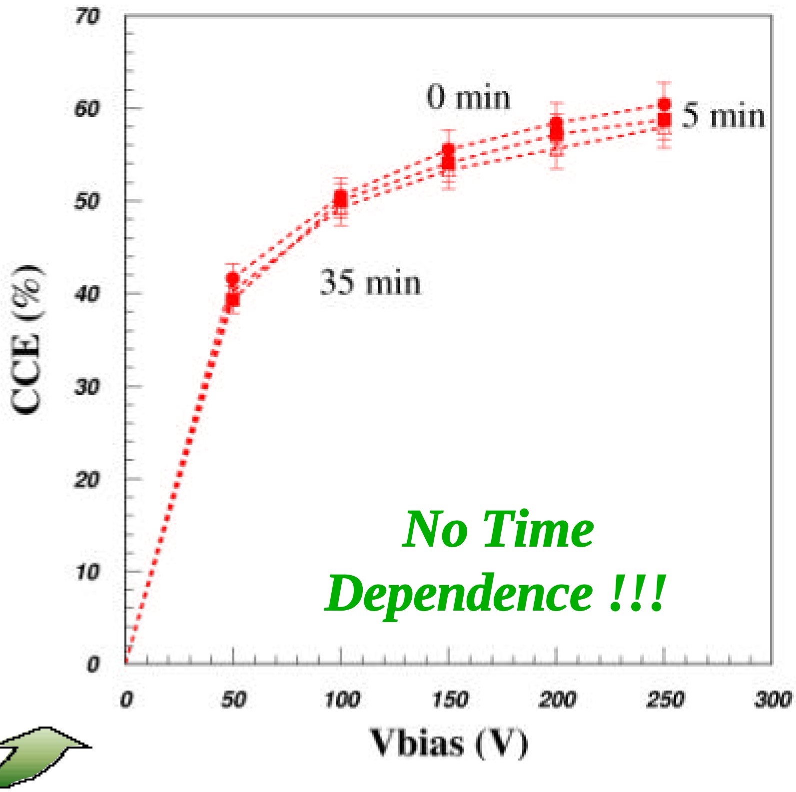
*Reduced Stable Values*



300 μm + $10^{15}$ n/cm$^2$ @ **130 K** @ **250 V** Þ 5'000 $e^-$

# Forward Bias Operation

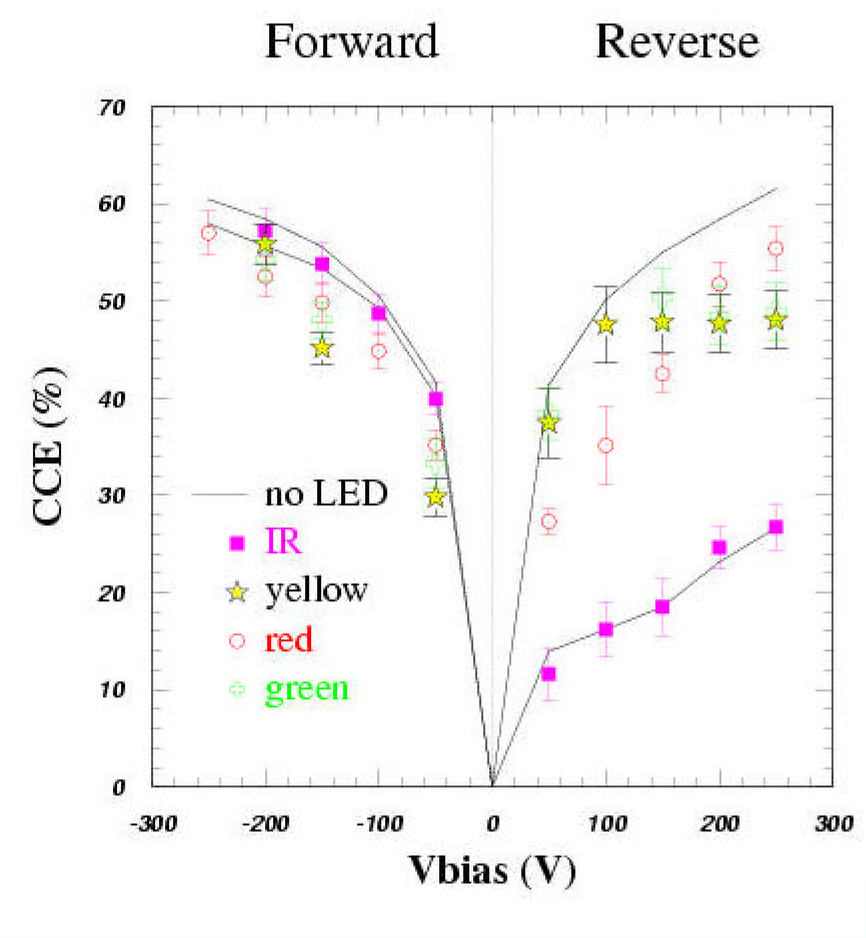




***No Time Dependence !!!***

300 µm + $10^{15}$ n/cm$^2$ @ **130 K** @ **250 V** Þ 15’000 $e^-$

# Operation in Presence of Light

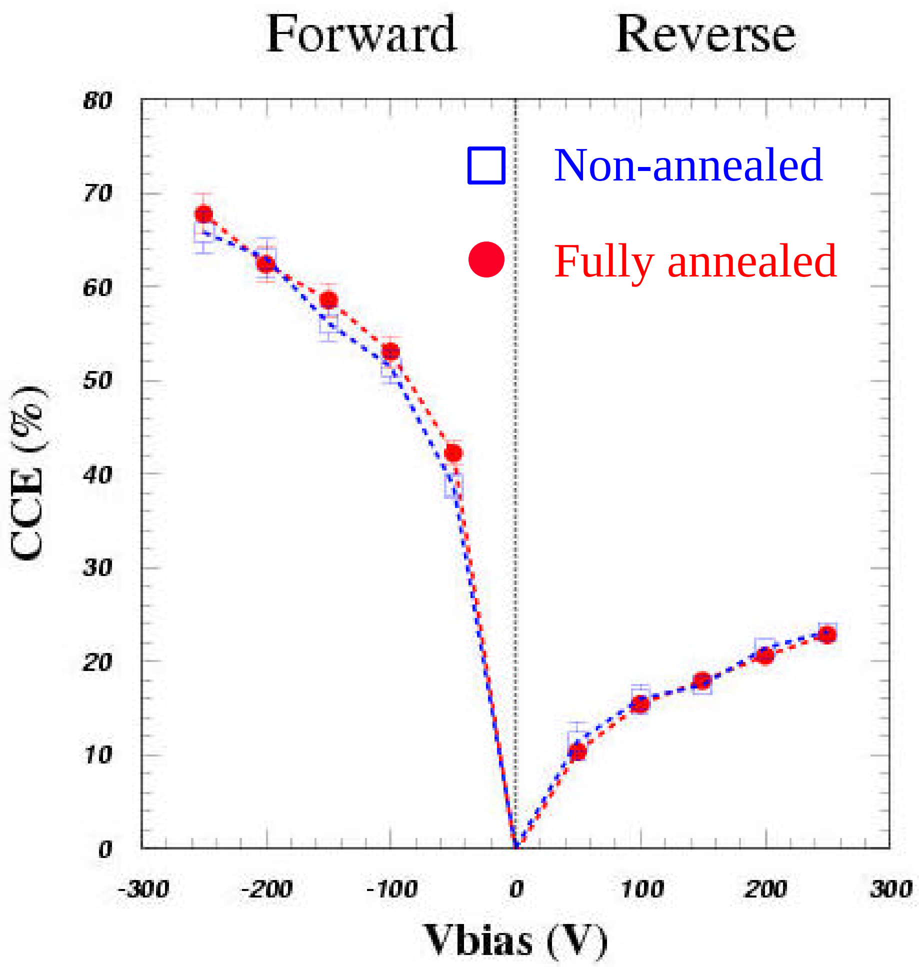


- Short wavelength light absorbed in few µm ➔ only positive charge flows through the bulk, compensating negative space charge:

  ➔ |*Neff*| becomes smaller

**G. Lutz**, NIM A 377 (**1996**) p. 242:
“Partial charging of defects can be influenced by increasing the carrier density of one type against the other by e.g. providing a surface generated current (e.g. illumination of one side of the detector). Reducing the full depletion voltage of a detector by this method may work only in **unpractical conditions** (as e.g. **very low temperature** or high current)…”

# What about Annealing?



The CCE at cryogenic temperatures does not depend on the annealing status of the detector

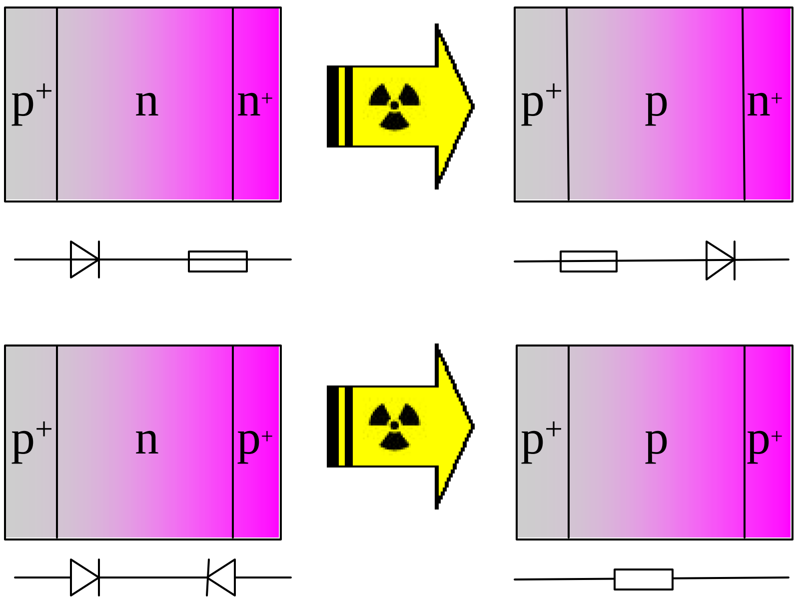
➔ ***need to cool only during operation !!!***

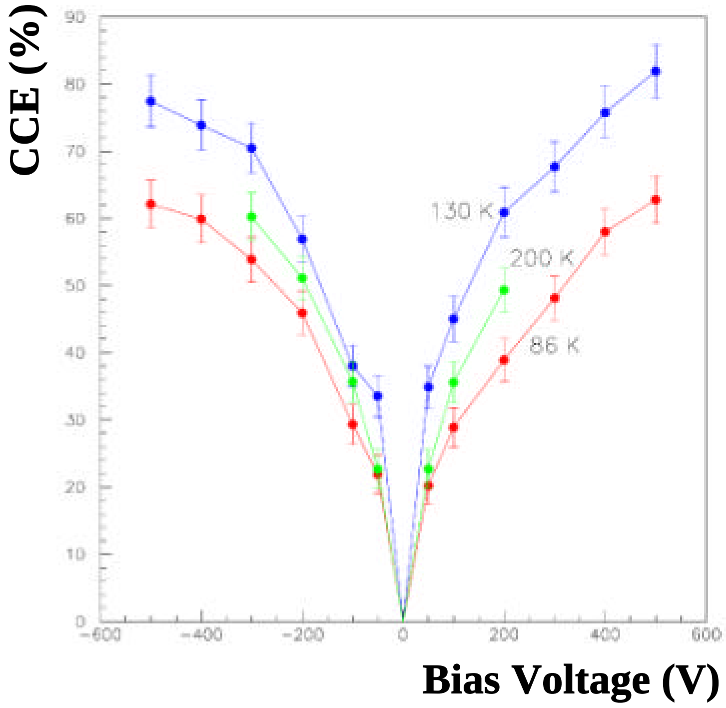
# Cryogenic silicon is a (kind of) new material ...

# …what can we do with it ?

# “Double P” Detector

**Before Irradiation** **After Irradiation**

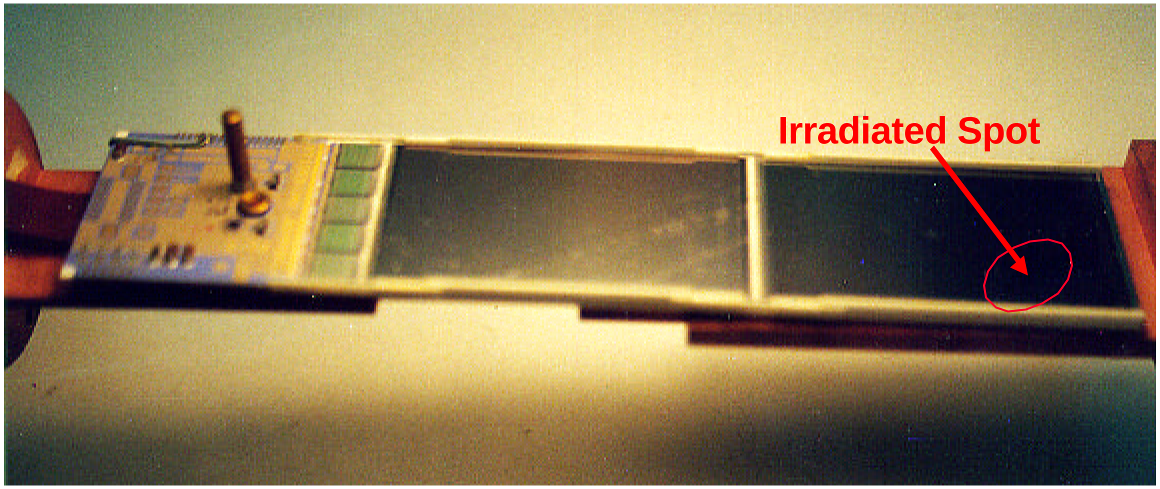


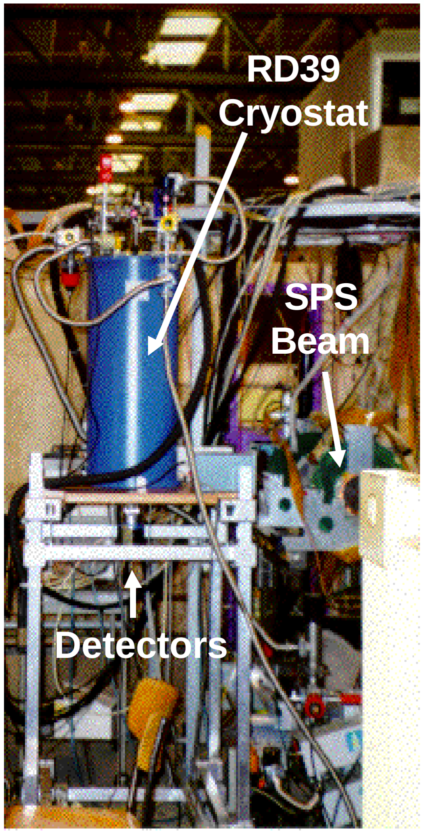


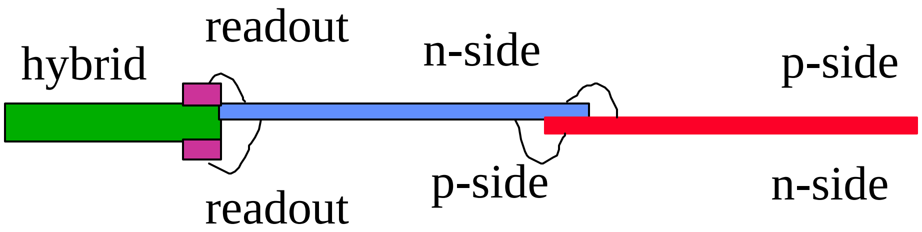
400 µm + $10^{15}$ n/cm$^2$ @ 130 K @ 500 V Þ **27’000 *e*$^-$**

# The charge is back, but what about position resolution ?

# The DELPHI Microstrip Detector





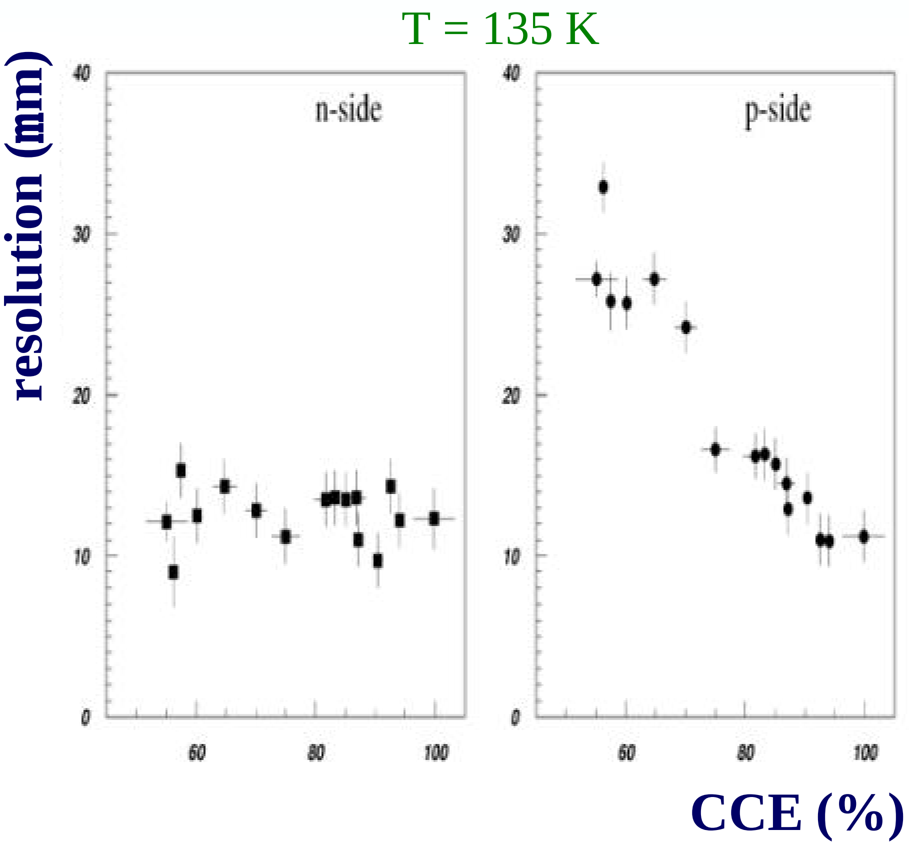


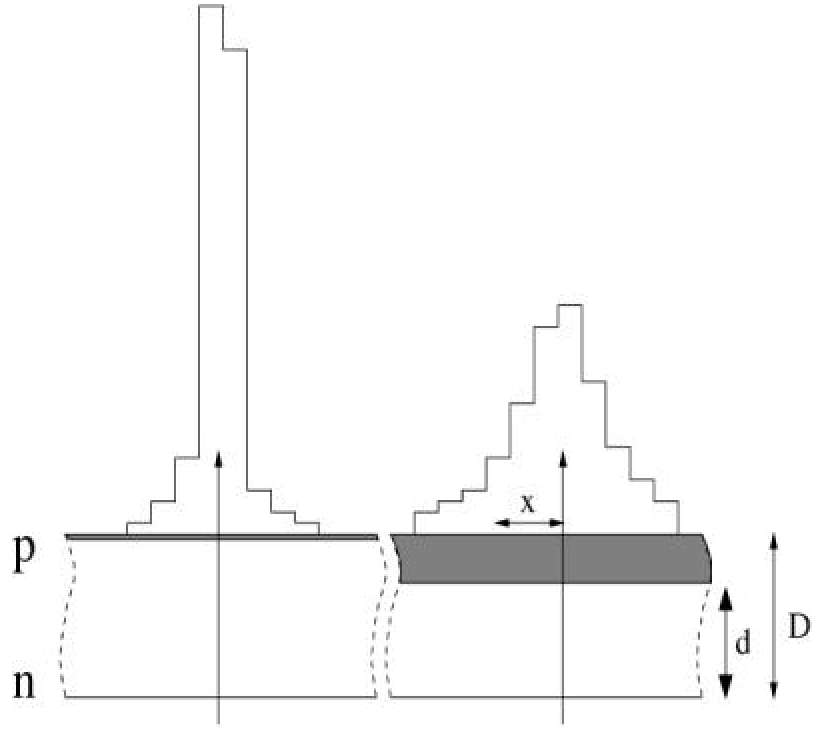
- *3.2 × 11.5 $cm^2$ double sided detector*
- *1 module = 1280 channels*
- *strip pitch: p-side 25 μm, n-side 42 μm*
- *AC coupling*
- *readout: MX6, 3 μm CMOS, 1 μs peaking time*

*irradiated with*
*$3.5 \times 10^{14}$ 24 GeV protons / $cm^2$*

K. Borer et al, NIM A **440** (2000) 17

# Position Resolution

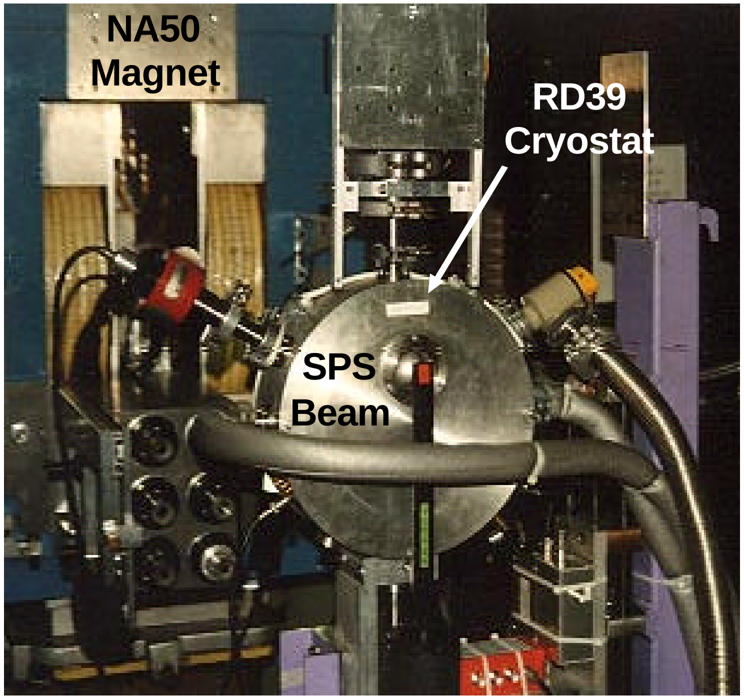




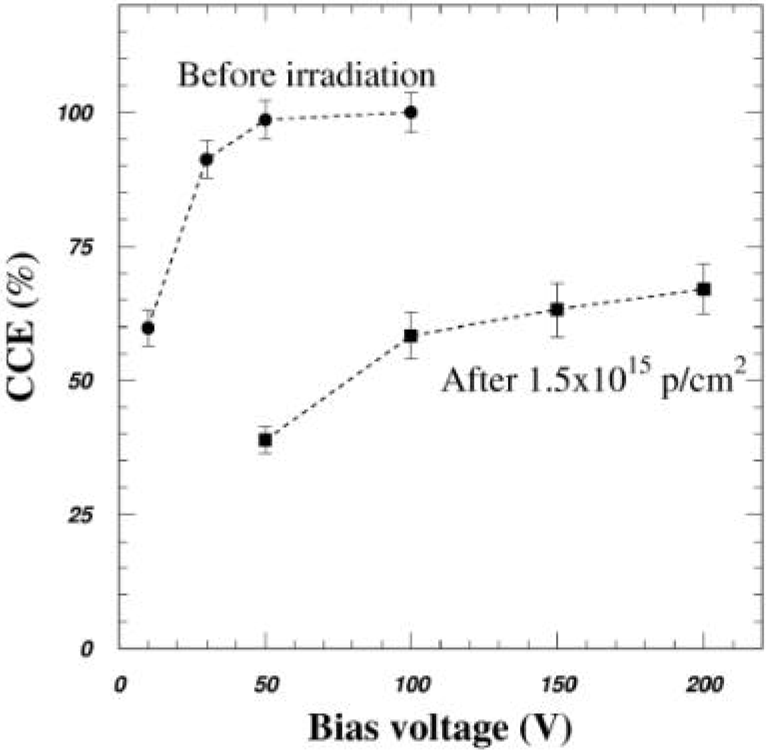
***Cryogenic cooling of a segmented detector results also in recovering the position resolution !***

# What happens when irradiating in the cold ?

# Si Detector Irradiated at 83 K



Irradiation with (400 GeV) protons



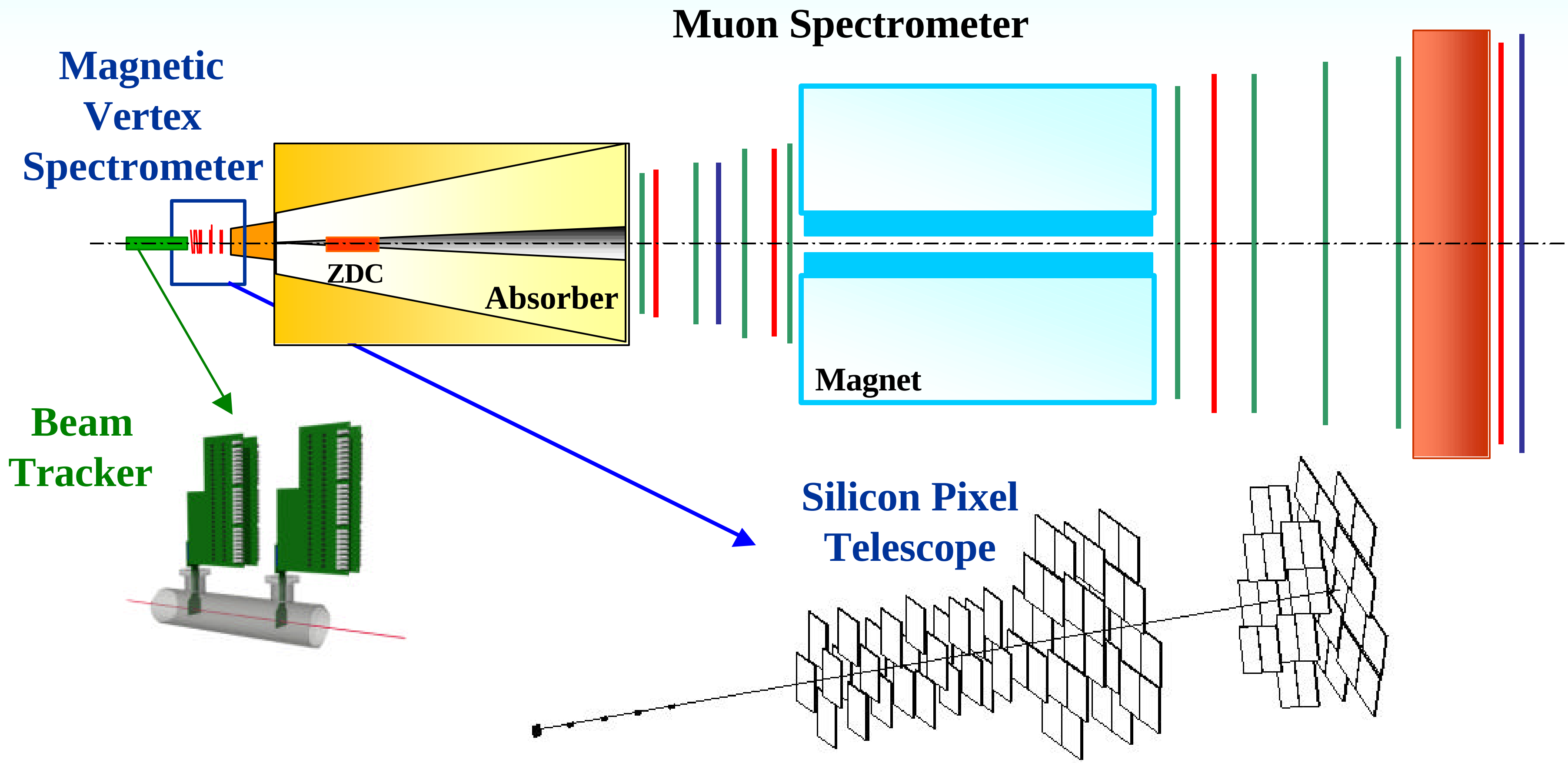
***No significant differences compared to room temperature !***

# 260 K vs 130 K

| | | 260 K | 130 K |
|---|---|---|---|
| • Leakage current | | | |
| → detector noise | | OK @ $10^{14}$ n/cm$^2$ | OK @ $2\times10^{15}$ n/cm$^2$ |
| → power in the sensor | | ~100µW/mm$^2$ | (~1µW/mm$^2$) |
| • CCE (trapping + depletion) | | | |
| reverse bias | $3\times10^{14}$ n/cm$^2$ : | 65% @ 500V | 100% @ 250V |
| | $2\times10^{15}$ n/cm$^2$ : | ? | 20% @ 250V |
| forward bias | $2.8\times10^{14}$ n/cm$^2$ : | 70% @ 50V<br>(I = 6µA / mm$^2$) | |
| | $1\times10^{15}$ n/cm$^2$ : | | 70% @ 250V<br>(I < 1nA / 5×5mm$^2$) |
| • Annealing: | | need to keep the detector at -10°C | cooling only during operation |

# The first application:
# Cryogenic Heavy Ion Beam Tracker for the NA60 Experiment

# The NA60 Experiment



**Muon Spectrometer**

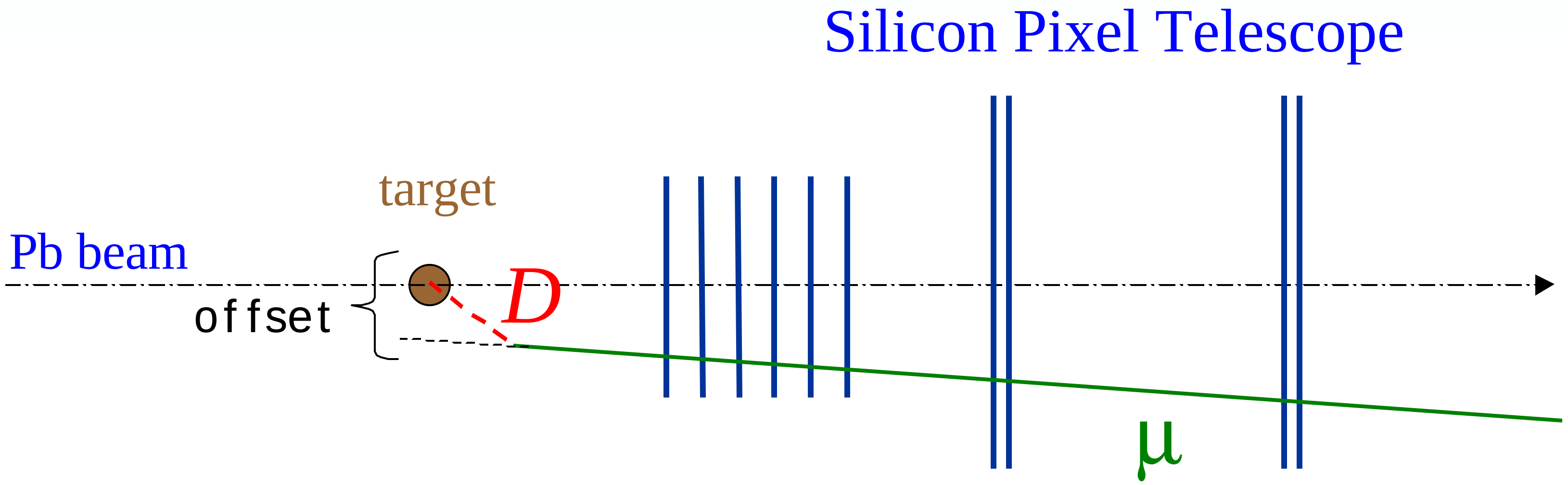
**Magnetic Vertex Spectrometer**

**Beam Tracker**

**Silicon Pixel Telescope**

- Study $\mu^+\mu^-$ production in heavy ion collisions
- Signals related to phase transition from hadronic matter to Quark-Gluon Plasma
- First measurement of charm production in heavy ion collision

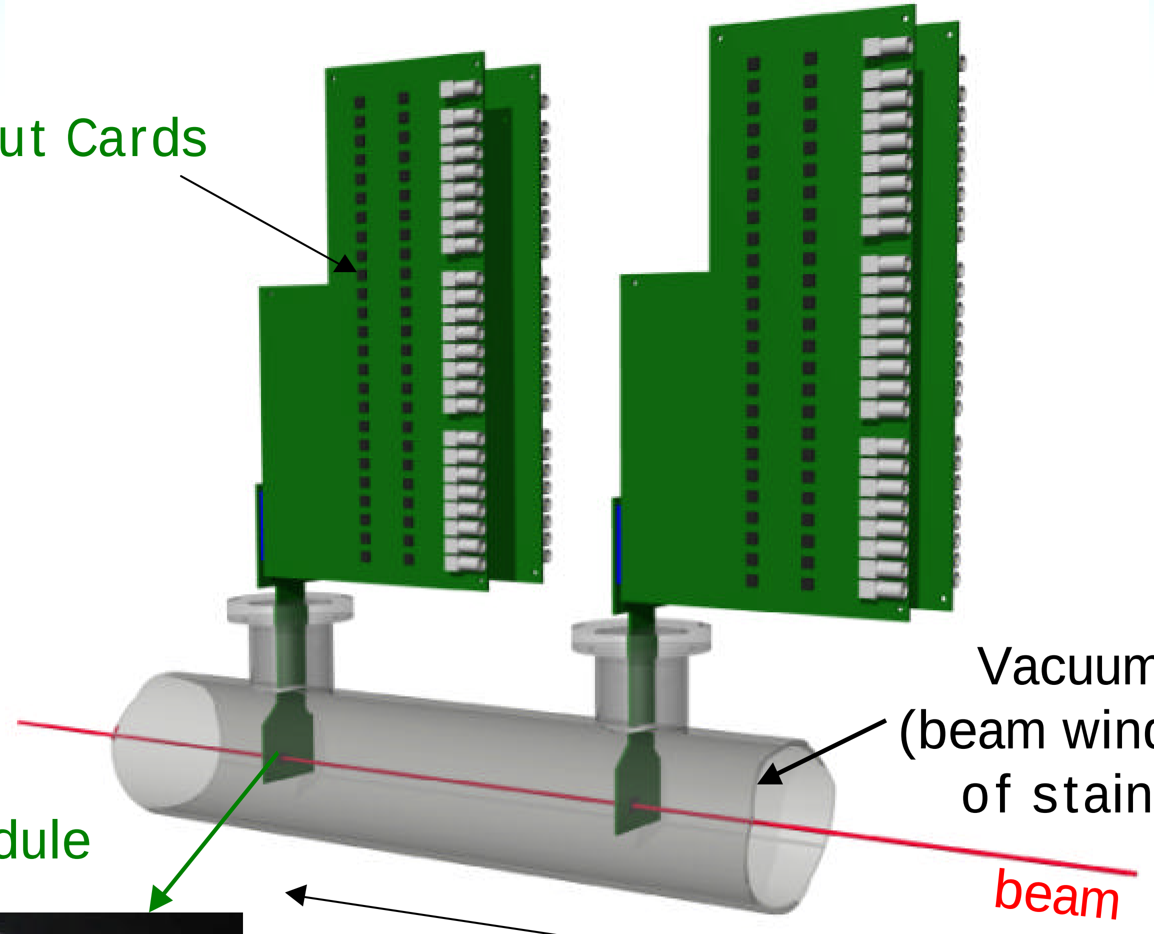
# Charm Measurement in NA60



Need to measure the transverse coordinates of the interaction point

| | | |
|---|---|---|
| ✓ | Good position resolution: | ~20 μm |
| ✓ | Good timing: two-pulse resolution | < 5 ns |
| ✓ | Extreme radiation hardness: | ~100 Grad |

# The Beamscope



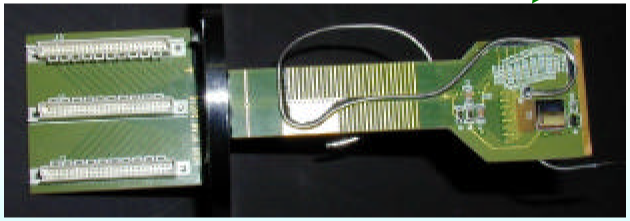
Readout Cards

Vacuum chamber (beam windows: 100 µm of stainless steel)

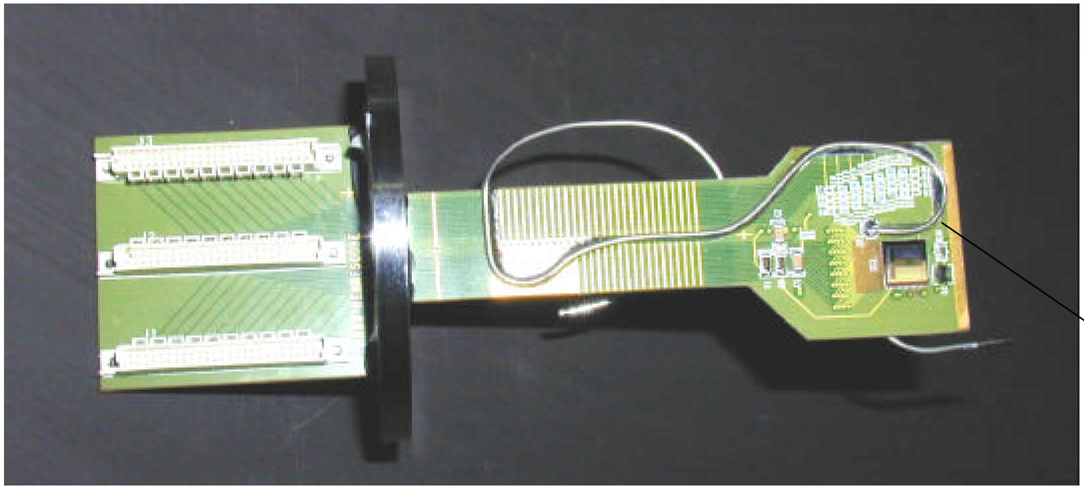
Cryogenic Module

beam

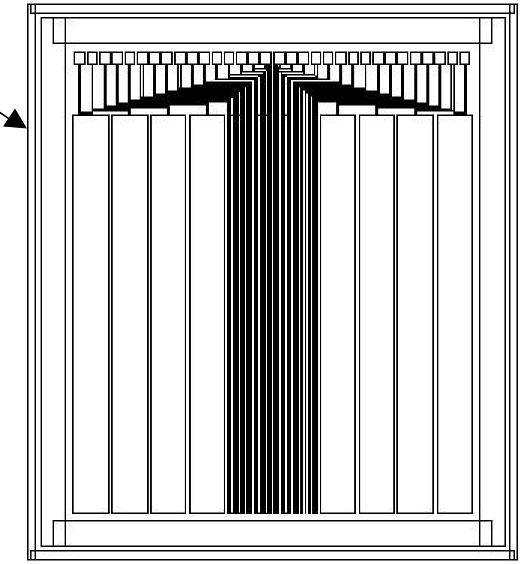
200 mm



# The Cryogenic Module



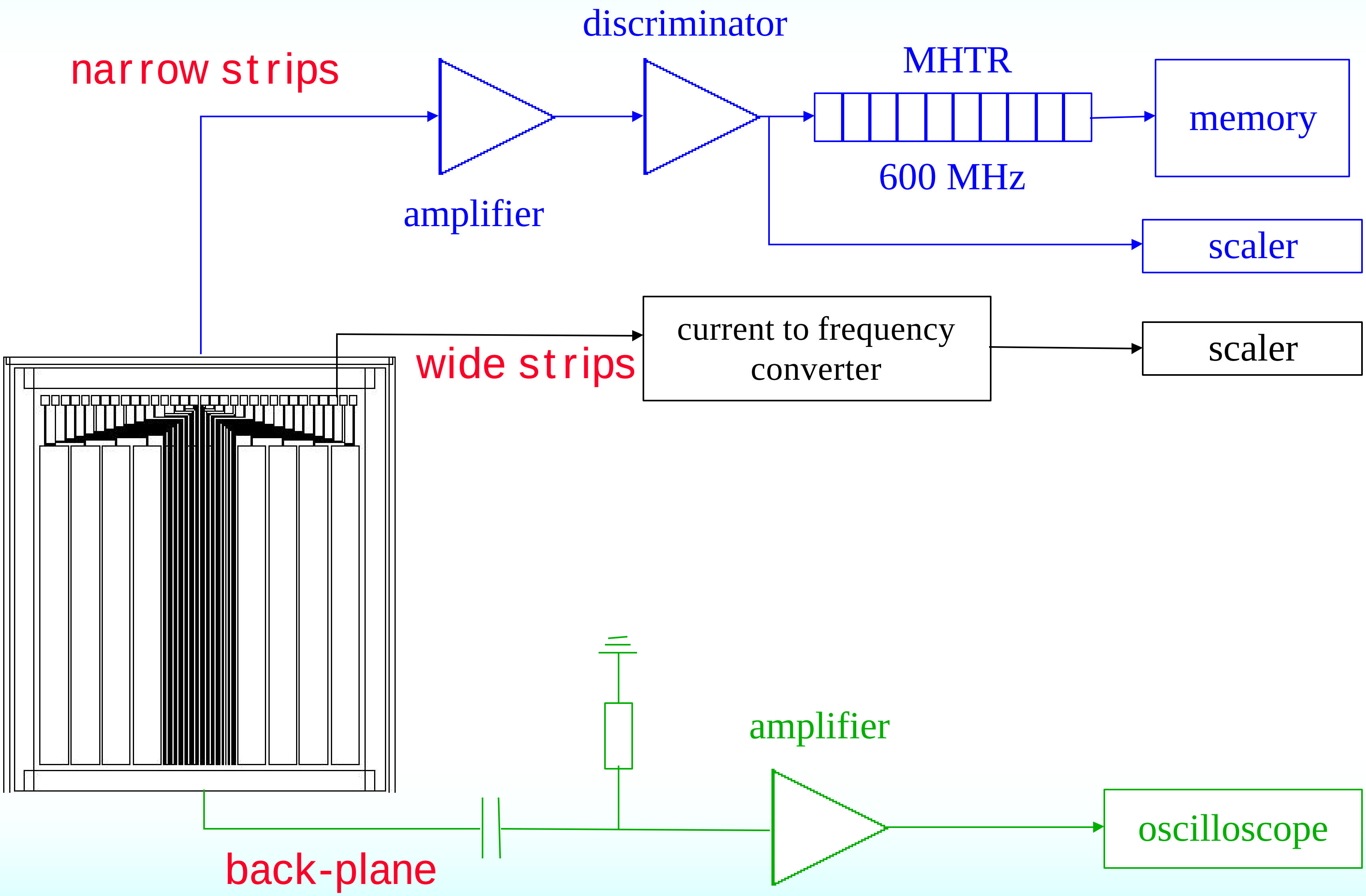
Double-sided glass-epoxy PCB



- Low mass cooling pipe (**Æ =** 1mm, 100µm thick)
- Integrated thermo-electrical design improves performance
- Temperature can be adjusted between 80K and 300K by adjusting the LN$_2$ flow and the power dissipated through a heater placed on the PCB

- *24 narrow strips (50 mm pitch)*
- *2´4 wide strips (500 mm pitch)*

# The Beamscope Readout



# Test Beam Conditions

November 1999: detector concept

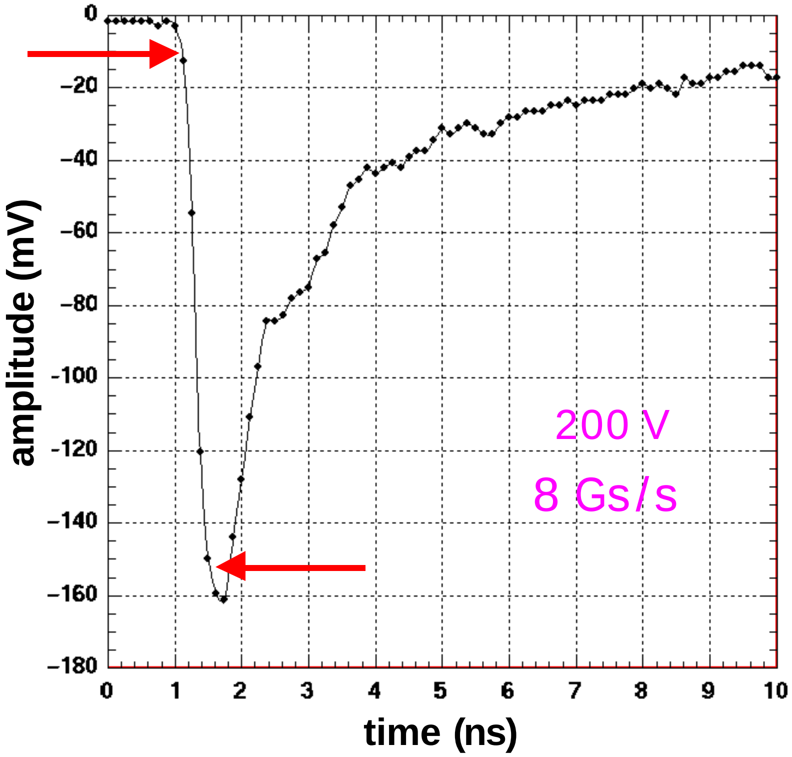
- *Exposed for 3 days to 40 A GeV Pb beam*
- *Average beam intensity: $5 \times 10^{6}$ ions per 4.5 s burst*
- *Total dose: ~ 1 Grad*

October - November 2000: radiation tolerance

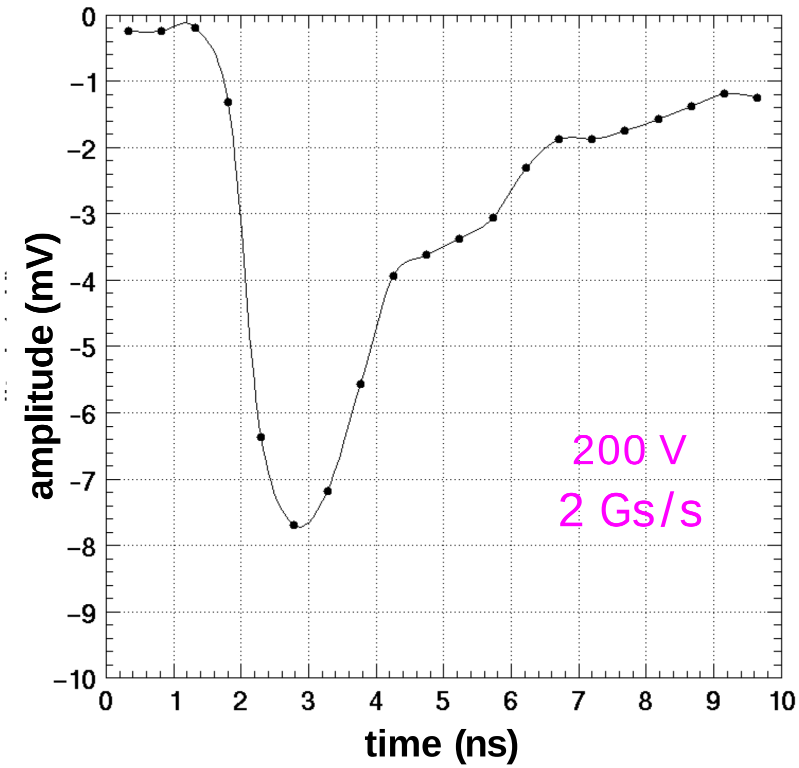
- *Parasitic to NA50*
- *Exposed 4 days to 40 A GeV and 38 days to the 158 A GeV Pb beam*
- *Average beam intensity: $7 \times 10^{7}$ ions per 4.5 s burst*
- *Total fluence: $5 \pm 2 \times 10^{14}$ ions/cm$^2$ (90 ± 40 Grad)*
- *Electronics suffered much from radiation in the beam area...*

# True (unshaped) Pb Ion Signal

Non-irradiated



After 20 days (40 ± 20 Grad)

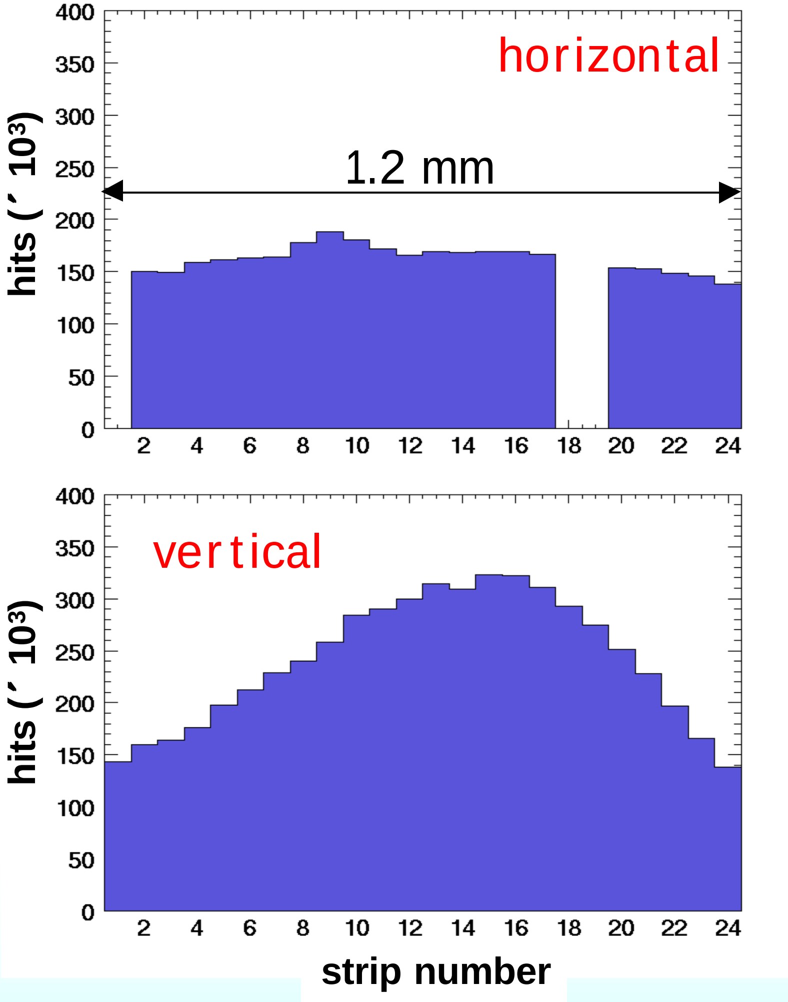


- Very fast rise time (< 500ps)
- Very long tail (~20ns)

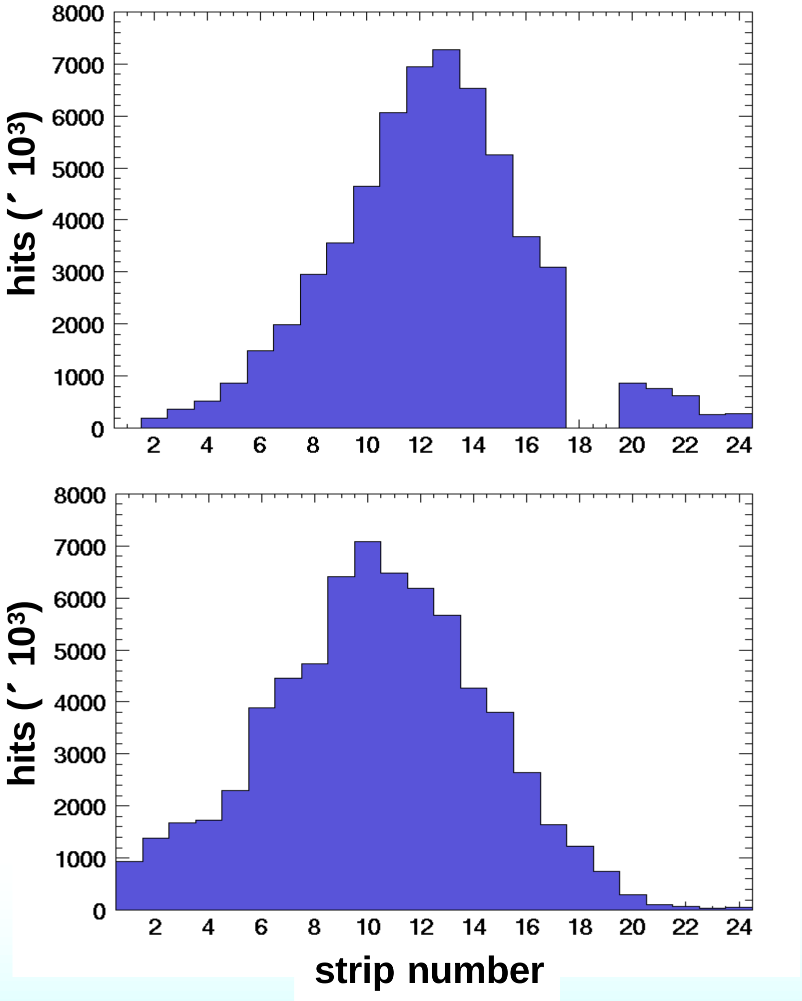
- Signal is broader
- Amplitude ~20 times lower…
  but we see it !

# Beam Profile

## Day 1

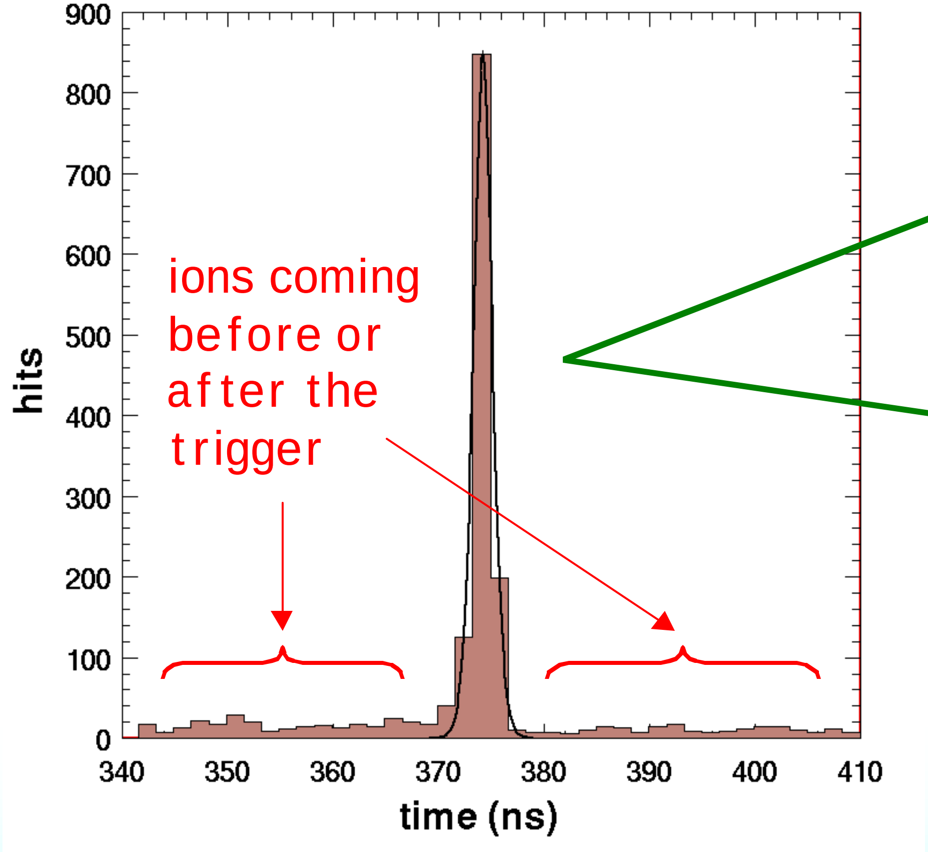


## Day 38 (~85 Grad)

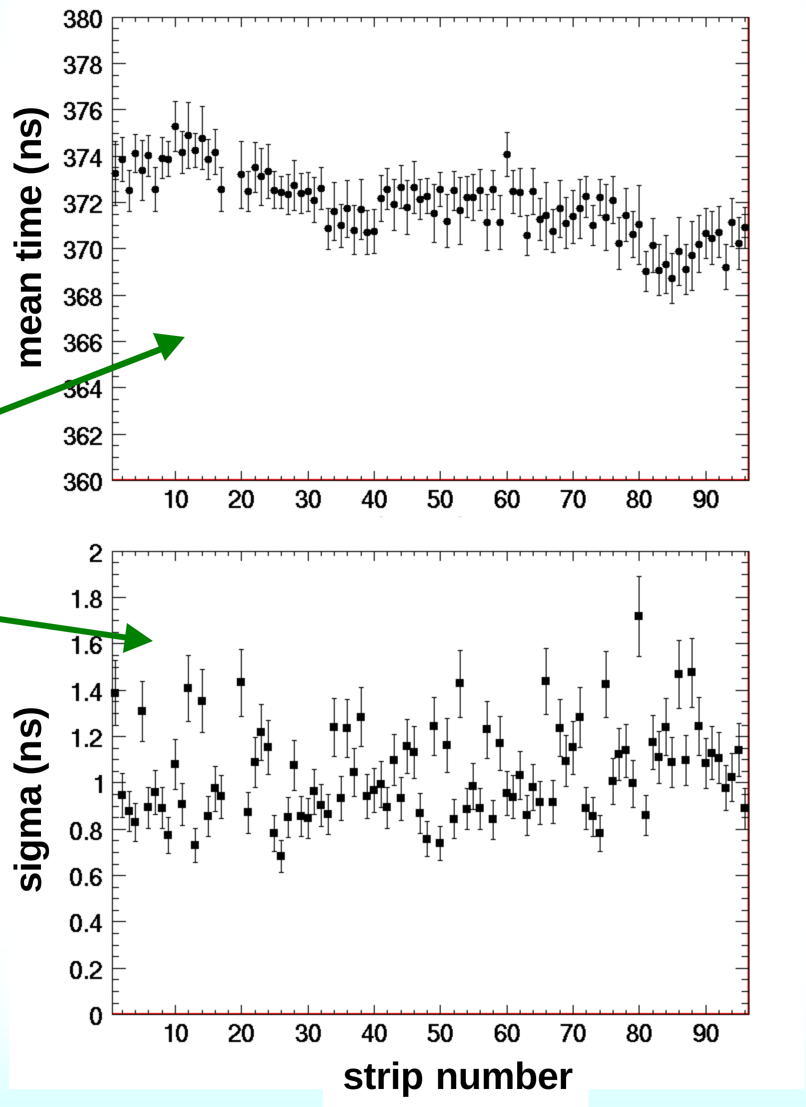


# MHTR Timing

Time of arrival wrt the trigger of the hits in one strip integrated over several spills

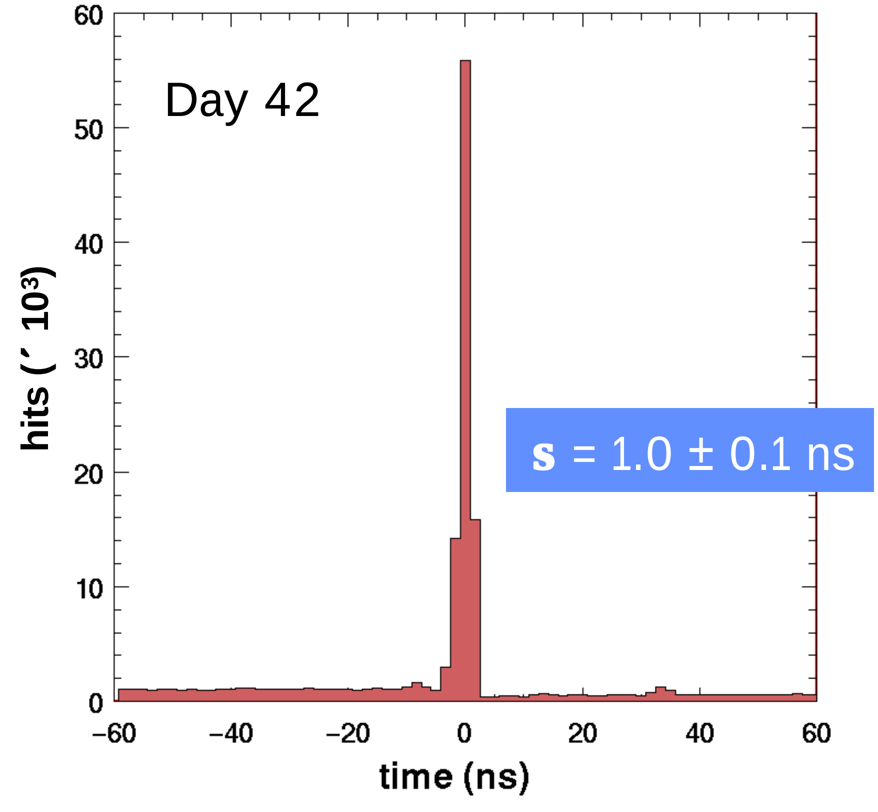


ions coming before or after the trigger

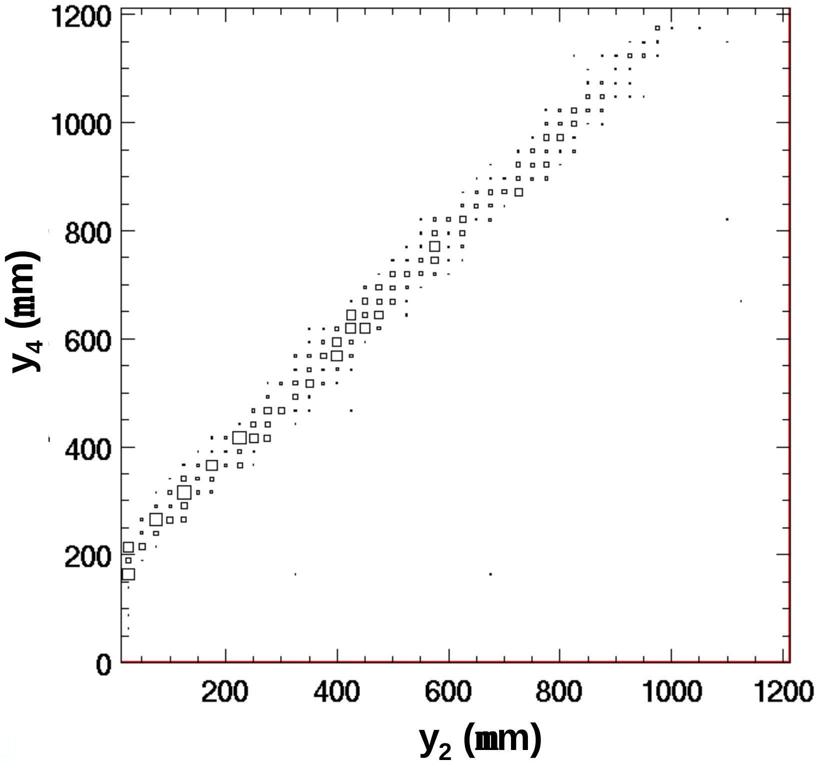


# MHTR Timing & Cluster Correlation

Time of arrival wrt the trigger of the hits in all strip integrated over several spills, normalizing to the same mean time.

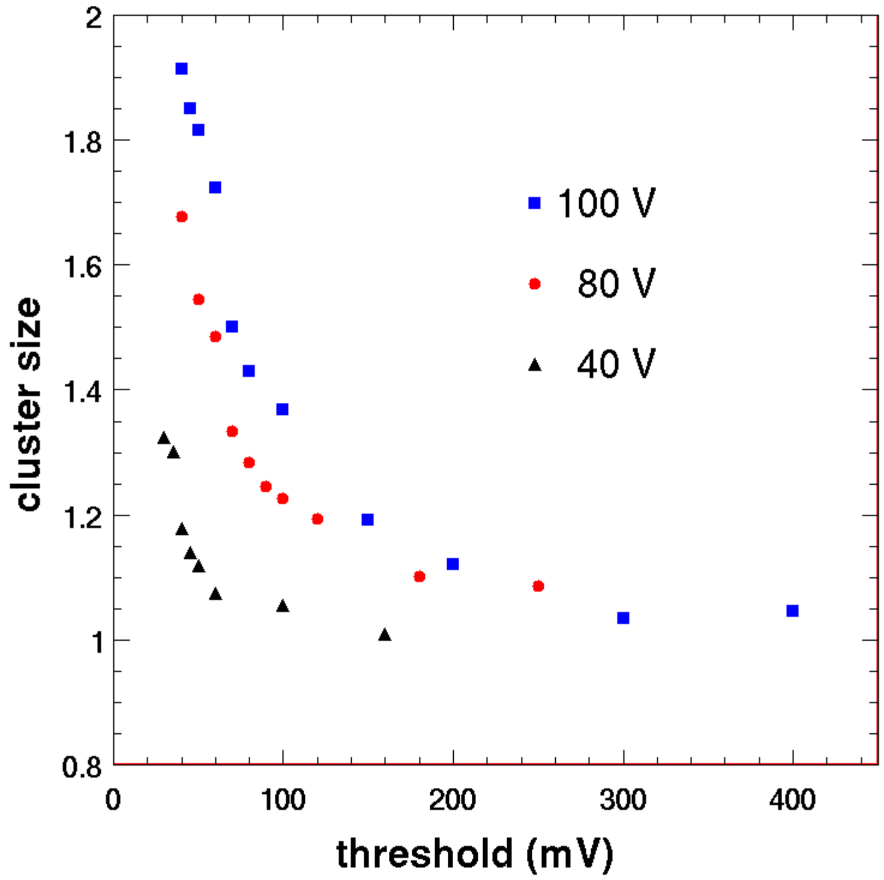


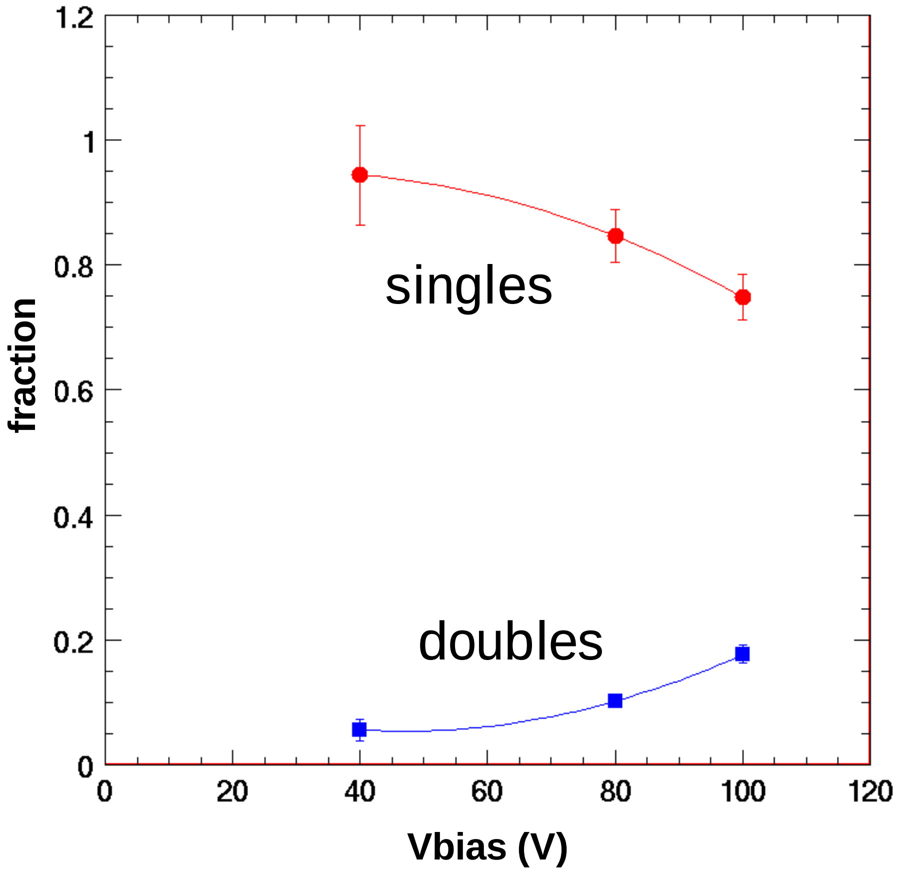
Correlation of clusters in plane 2 and 4 (only hits within 3 σ)



~200 μm misalignment

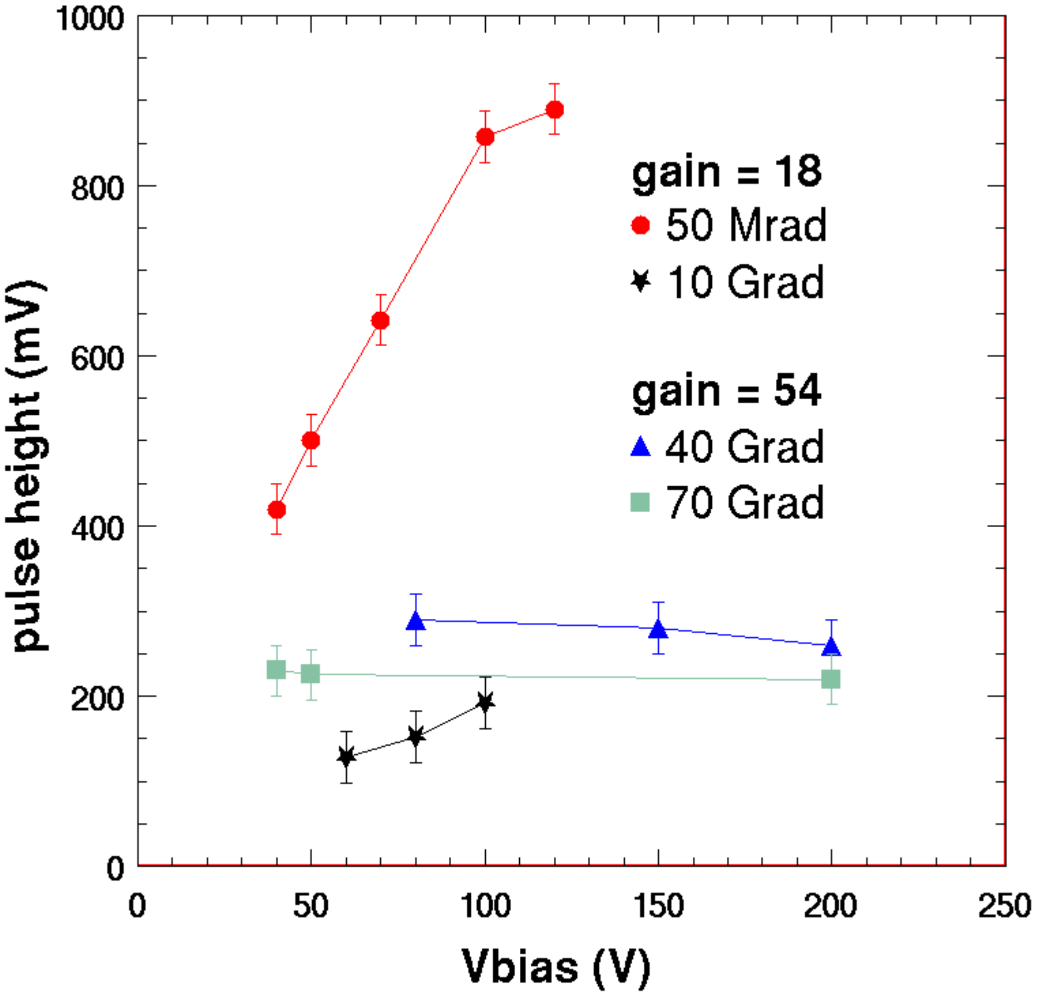
# Cluster Size





- Contrary to what is expected in segmented Si detectors, cluster size increases with Vbias.
- Different charge generation process of Pb vs MIPs ?

# Pulse Height Evolution



- After 40 Grad no dependence of the pulse height on the bias voltage.
- To be checked: possible bias of signal shaping

# Conclusions

- Work to be done to understand the detail of the phenomenon. Nevertheless, data clearly show that:
  - ✓ CCE dramatic improves at T ~ 130 K
  - ✓ If charge is back, the position resolution is also recovered

➔ **Cryogenic Operation is a robust technique to extend the lifetime of Si trackers by more than order of magnitude**

- For heavy ions, where very large signals are obtained, Cryogenic Silicon can work up to several tens of Grad

☛ Cooling must be integrated in the mechanical design
☛ Thermal design is easier at 80 K than at 250 K
☛ 2-phase nitrogen is an excellent coolant

- Future:
  - ✓ Cryogenic Detectors for TOTEM
  - ✓ Beamscope for NA60 (also for protons)
  - ✓ Vertex Tracker of COMPASS