Cryogenic Operation of Silicon Detectors

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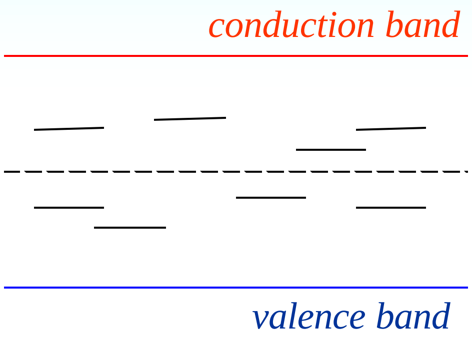
Outline

- The ***"Lazarus effect"***
- Operation at Cryogenic Temperatures
- First Application: the RD39/NA60 Beamscope
- Q&A Issues
- Conclusions

Radiation Damage in Si



- Radiation generates lattice displacements
- Defects appear as energy levels in the forbidden band gap

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

- Trapping and de-trapping of carriers
  - ➔ signal loss

✓ Fraction of defects are filled and therefore charged, so they contribute to the **effective doping concentration** N_{eff}

✓ Under irradiation, space charge becomes more and more negative
  - ➔ dramatic increase of depletion voltage (V_{dep} μ $|N_{eff}|$)
  - ➔ signal loss

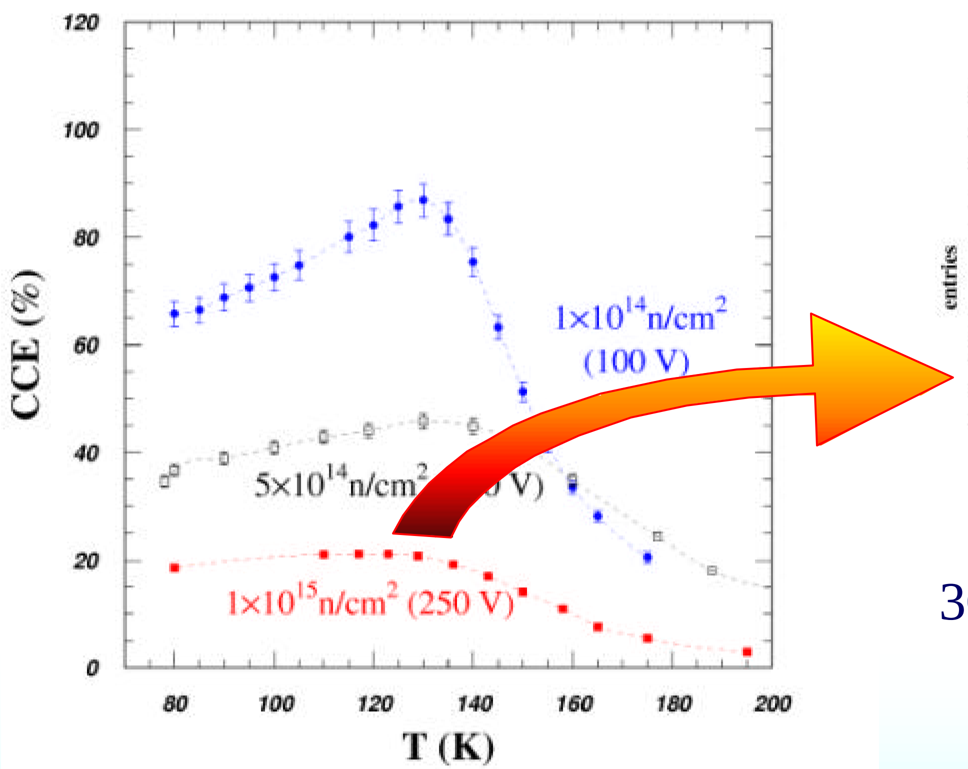
- Annealing: N_{eff} changes also after irradiation
  - ➔ need to keep the detector at -10°C

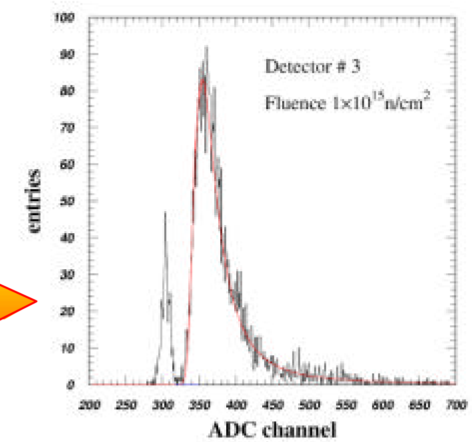
CCE vs Temperature

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

RD39 data
irradiated Si diodes exposed to mips

$$CCE \equiv \frac{Q_{measured}}{Q_{generated}}$$

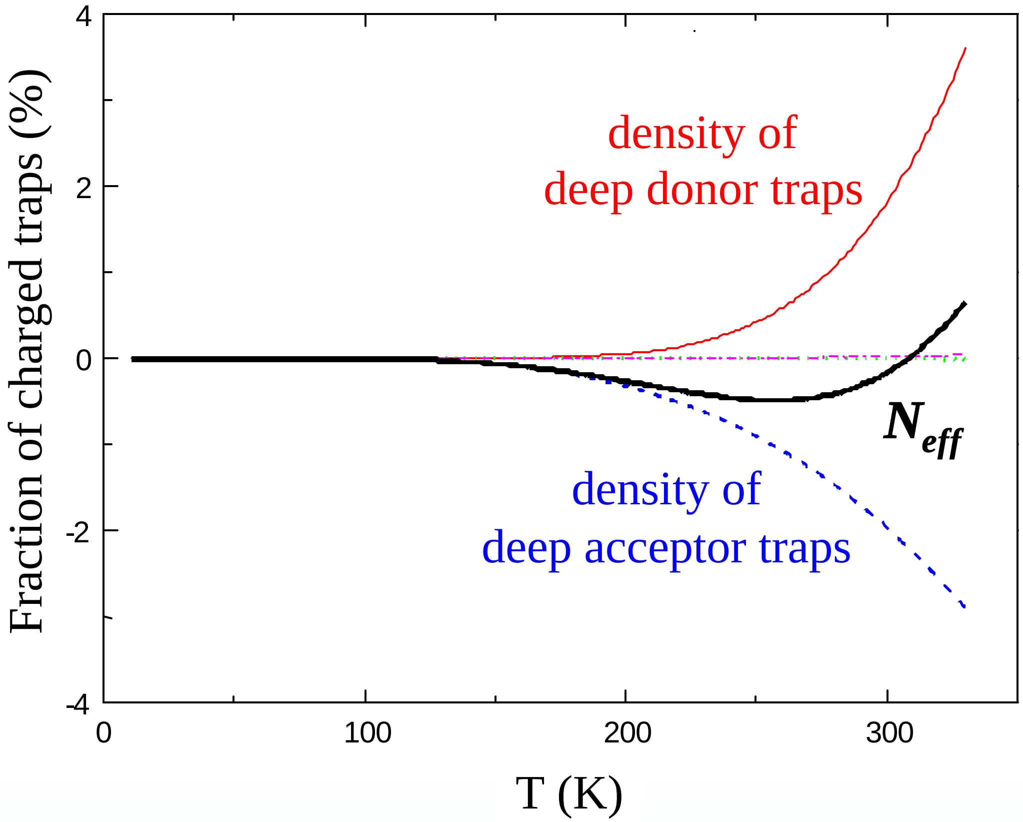




300 μm + 10^{15} n/cm^2
130 K + **250 V**
$\Rightarrow$ **5’000 *e*$^-$**

The Lazarus Effect

- *There is no comprehensive model yet…*



- By cooling, we manipulate the Si bulk properties

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

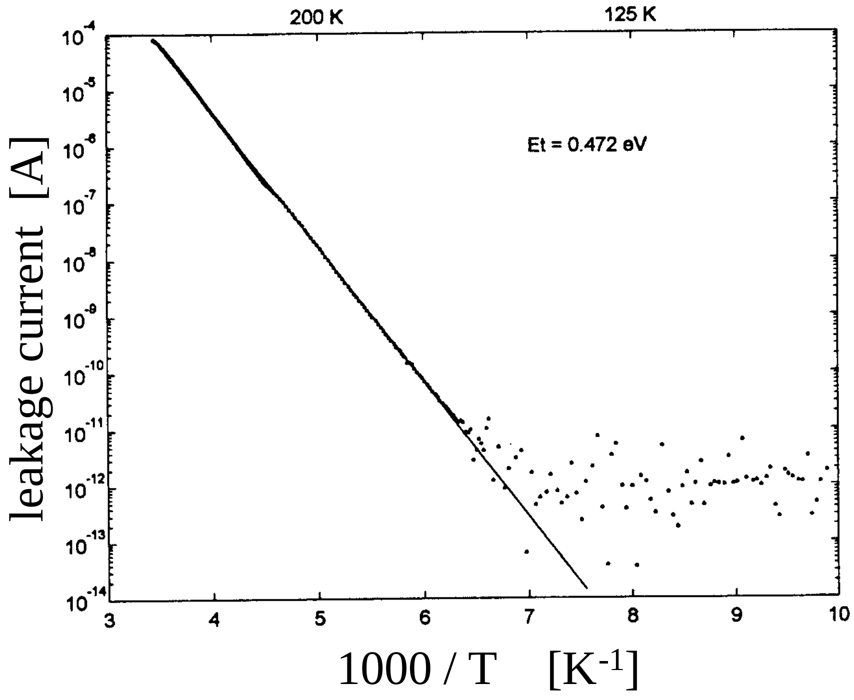
- Cooling ➔ fraction of charged traps decreases

  ➔ $|N_{eff}|$ decreases

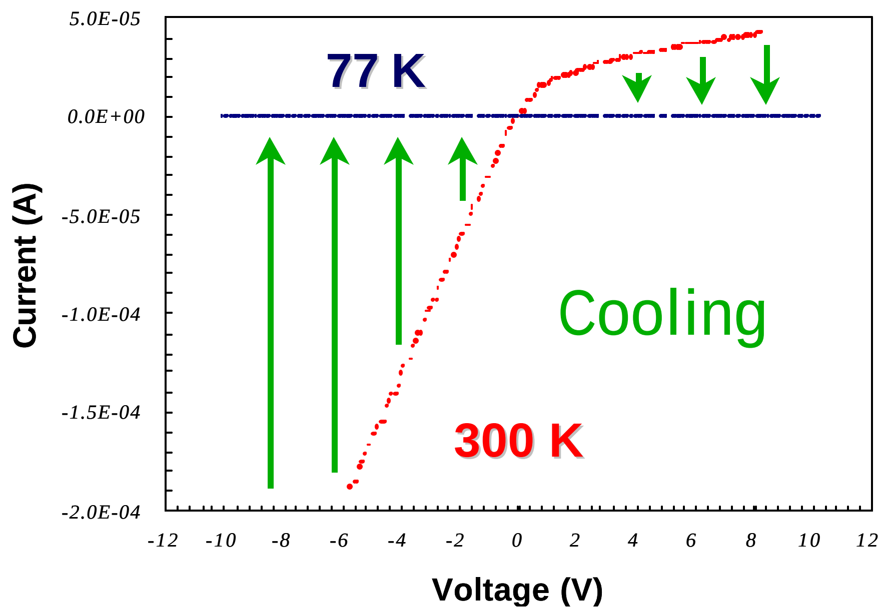
Elena Verbitskaya et al., RD39 Coll. Meeting, March 2001.

Leakage Current vs Temperature

Exponential Decrease of Leakage Current



Irradiated detector



I < 1 nA up to ±500 V !

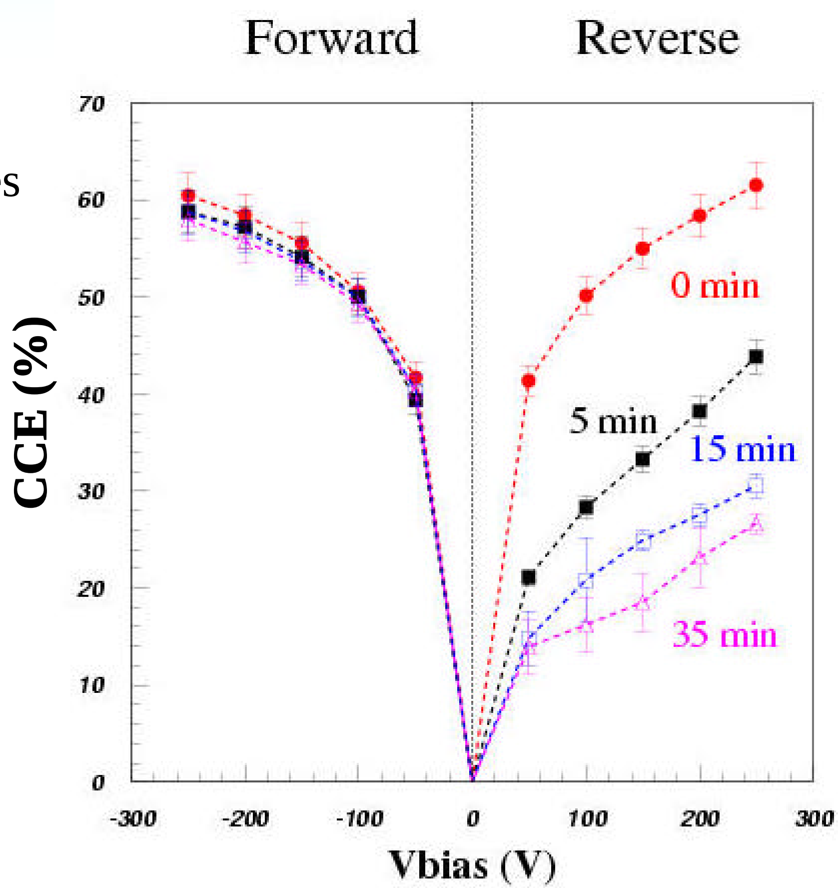
➔ low noise

➔ no power dissipation in the sensor

Forward Bias Operation

RD39 data
irradiated Si diodes
exposed to mips

T = 78 K



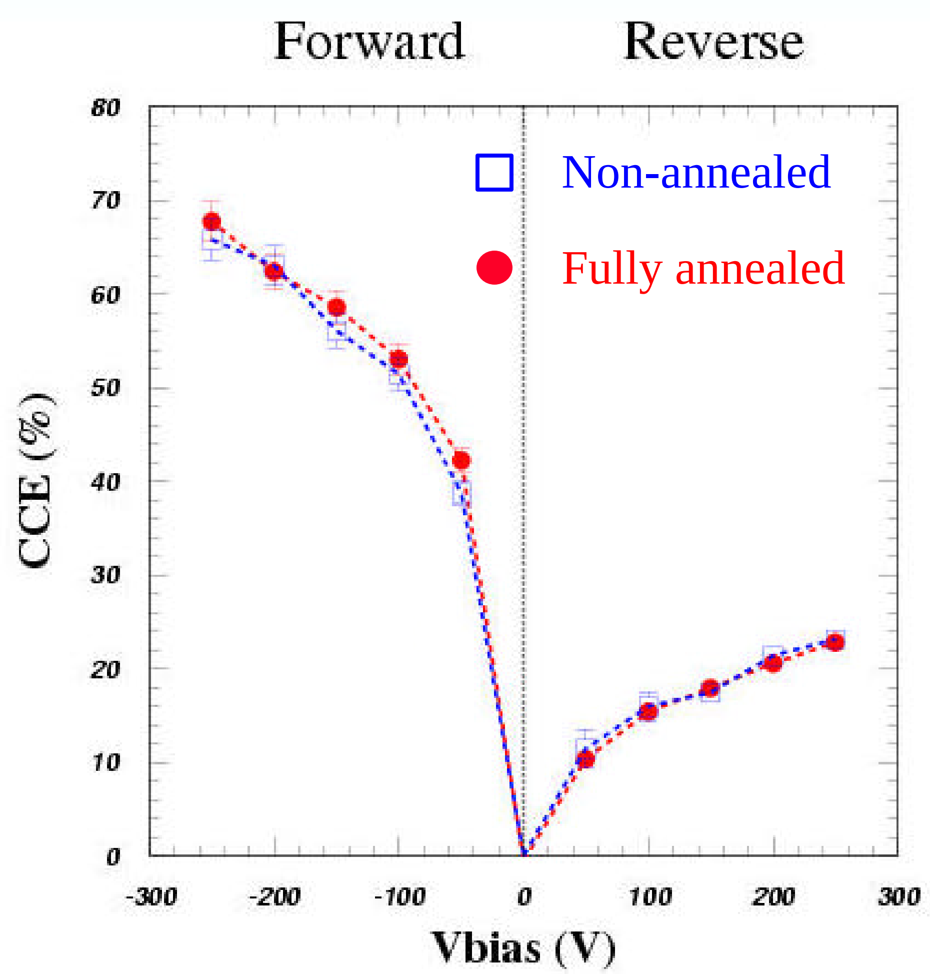
- **Reverse bias:**
CCE decreases with time

- **Forward bias:**
no time evolution !

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

What about Annealing?

RD39 data
10^{15} n/cm^2



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

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

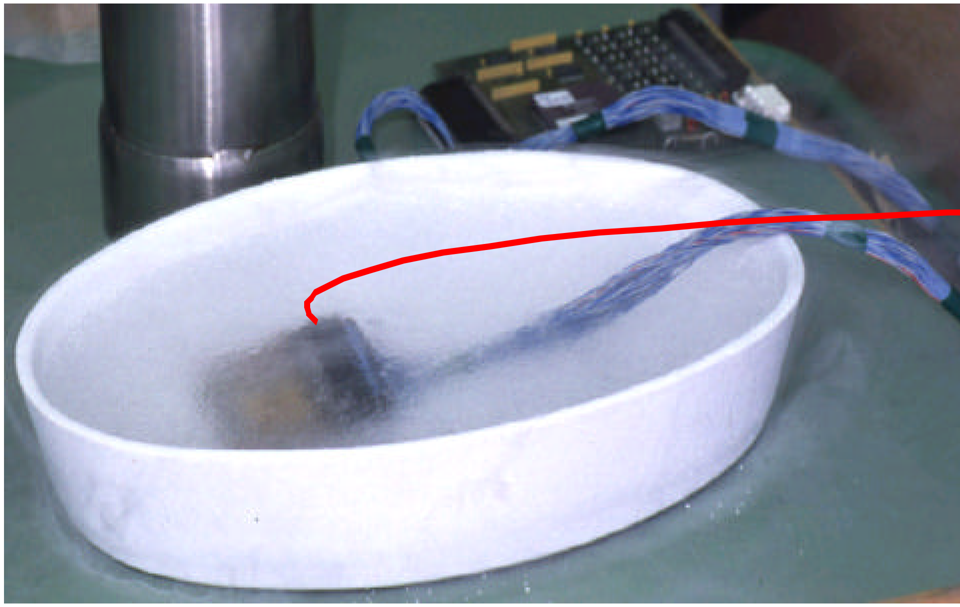
260 K vs 130 K

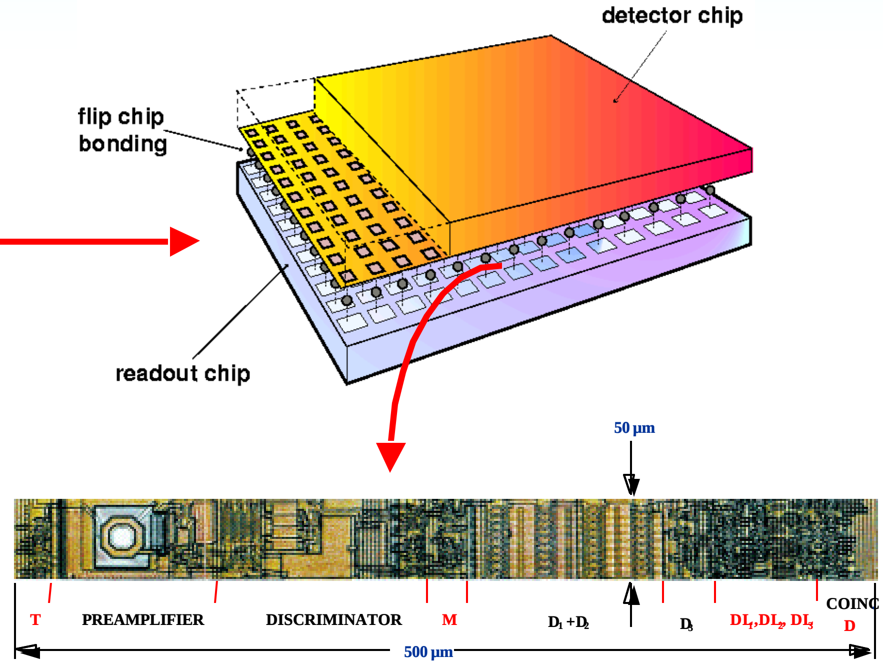
		260 K	130 K
• Leakage current			
➔ detector noise		OK @ >10^{14} n/cm^2	OK @ >10^{15} n/cm^2
➔ power in the sensor		~100µW/mm^2	~1µW/mm^2
• CCE (trapping + depletion)			
reverse bias	3×10^{14} n/cm^2 :	65% @ 500V	100% @ 250V
	2×10^{15} n/cm^2 :	0%	20% @ 250V
forward bias	2.8×10^{14} n/cm^2 :	70% @ 50V (I = 6µA / mm^2)	
	1×10^{15} n/cm^2 :		70% @ 250V (I < 1nA / 5×5mm^2)
• Annealing:		need to keep the detector at -10°C	cooling only during operation

Don’t be Afraid of Operating a Si Detector at Cryogenic Temperatures !

Cold Pixel Lasagna

RD19/WA97 LHC1 Pixel Detector





- CMOS 1μm technology, 2048 cells, 50 × 500 μm^2 , 800 000 transistors
- Designed for RT operation, we managed to operate it at 77 K

  80% of the channels OK

  Average threshold: **7000 e^- @ 300K**, **2500 e^- @ 77K**

(also Alice2Test and APV25, 0.25 μm technology)

- Several thermal cycles: wire-bonding, bump-bonding, etc. OK !
- Simple tests can be done by immersing into liquid nitrogen...

Designing a Cryogenic Tracker

- **More attention to the choice of all materials**
  (for example: thermal expansion of epoxy…)

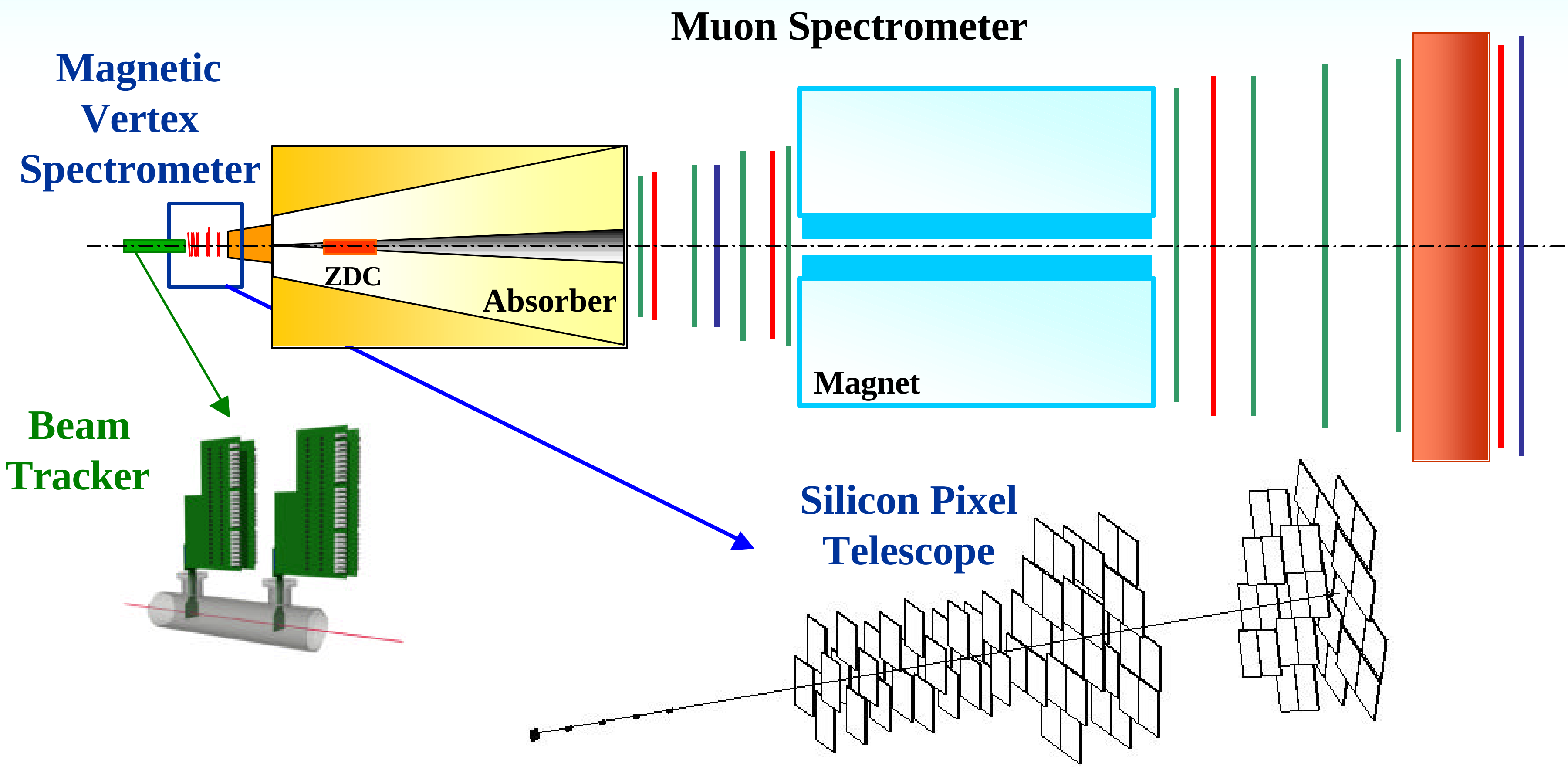
- **Important: cooling must be integrated into mechanics design and should not be an add on**
  (always true…)

- **Nature helps: Si thermal conductivity increases with decreasing temperature**
  use Si as substrate: also matches the thermal expansion of the detector…

- **Two-phase nitrogen is an excellent coolant**

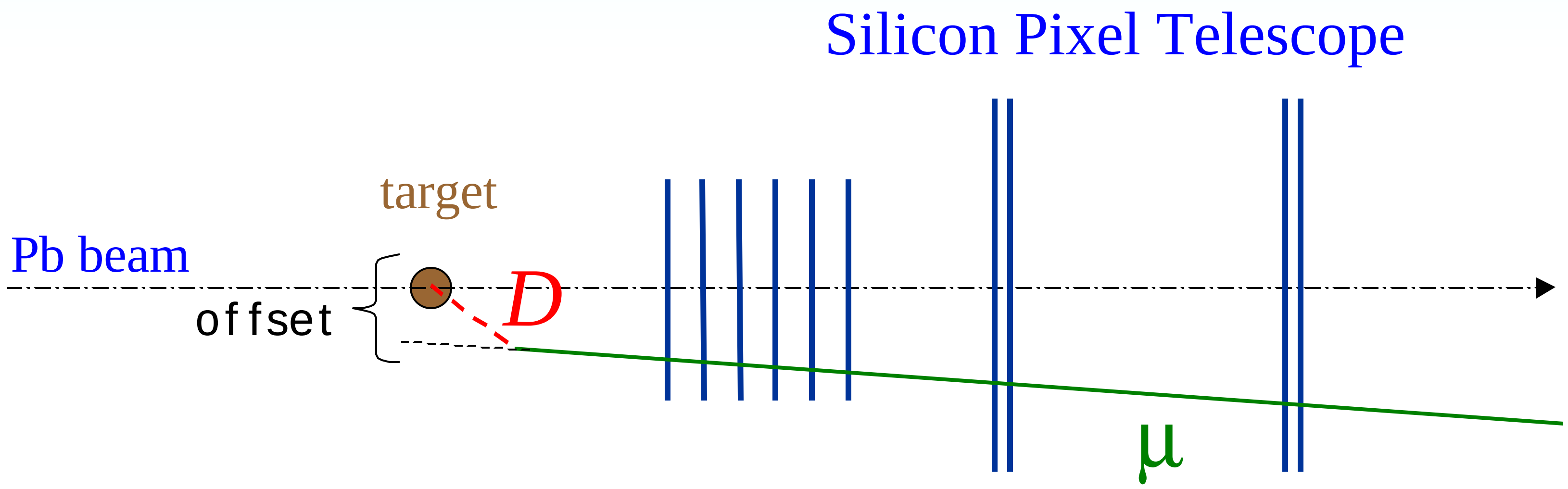
The first application:
Cryogenic Heavy Ion Beam Tracker for the NA60 Experiment

The NA60 Experiment



- 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

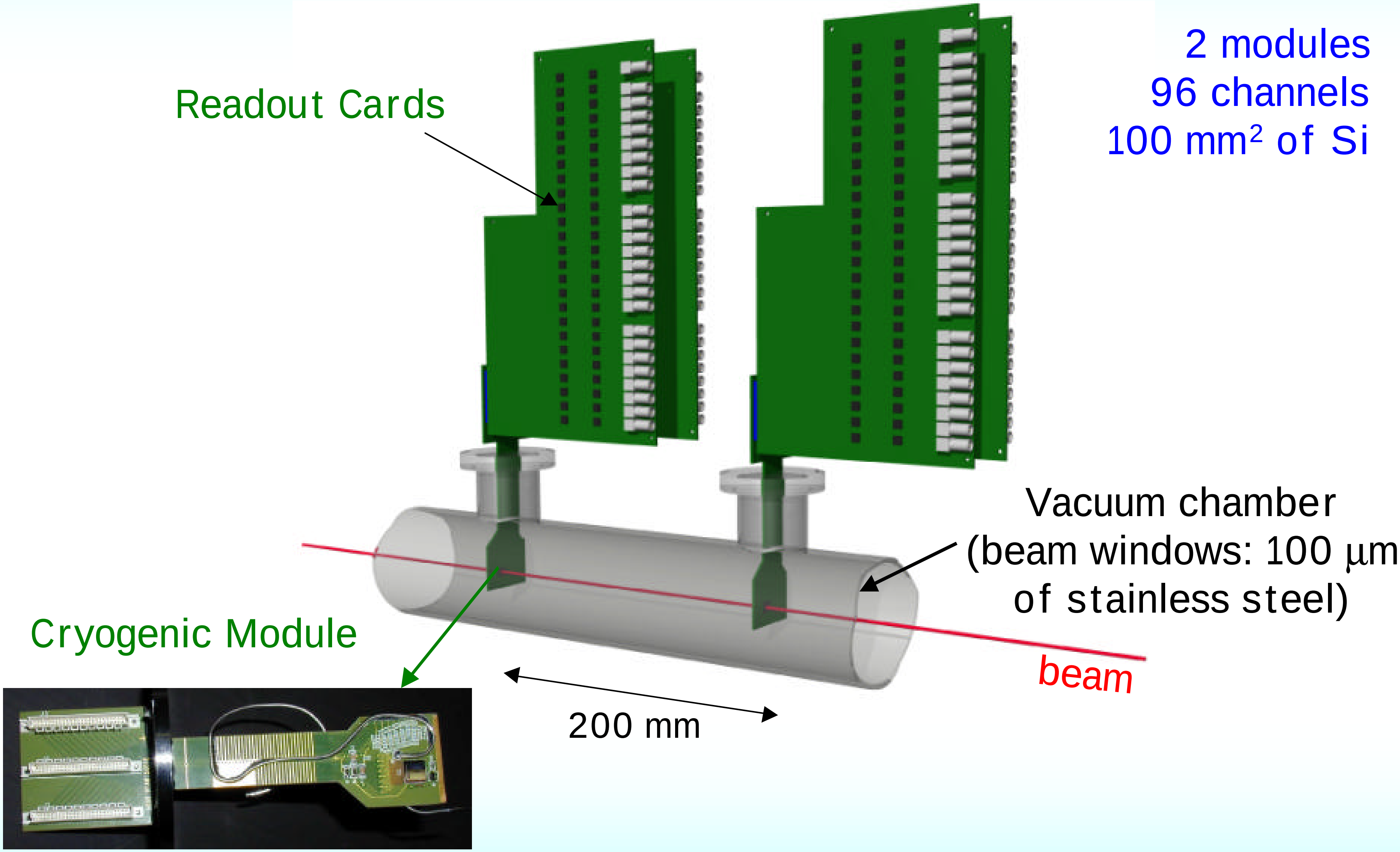


Need to measure the transverse coordinates of the interaction point

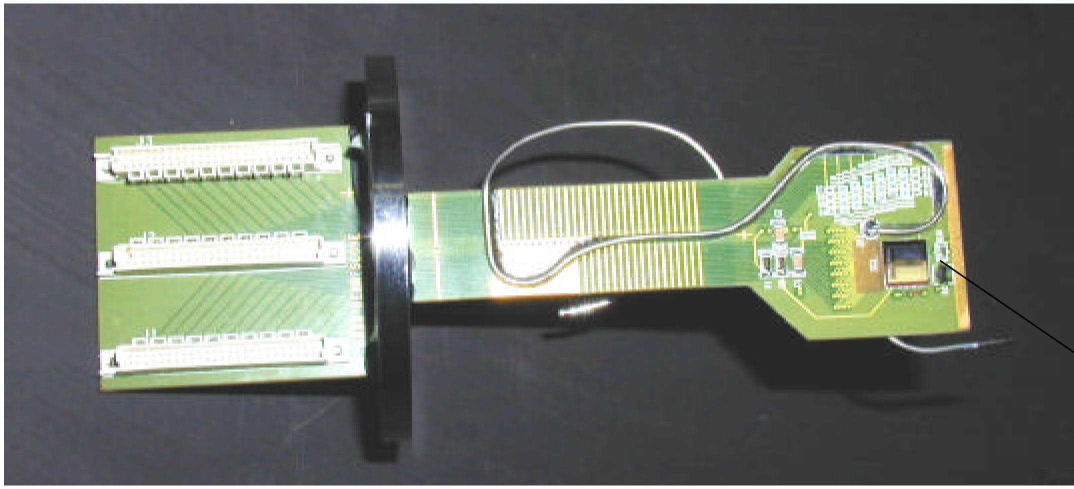
- ✓ Good position resolution: ~20 μm
- ✓ Good timing: two-pulse resolution ~ 5 ns
- ✓ Extreme radiation hardness: ~100 Grad

The Beamscope

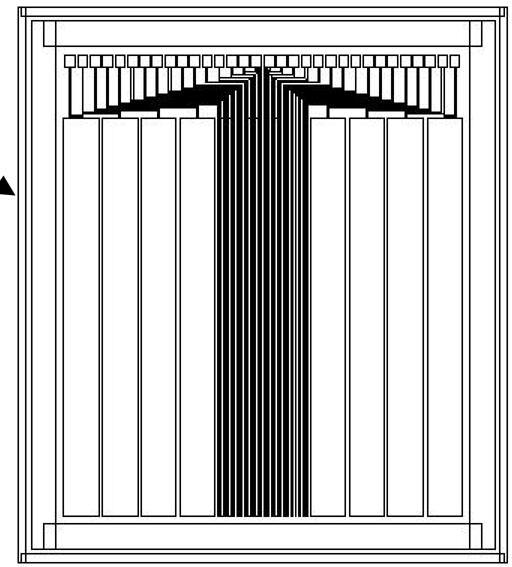
2 modules
96 channels
100 mm^2 of Si



The Cryogenic Module



Double-sided glass-epoxy PCB



- Low mass cooling pipe (Æ = 1mm, 100μm thick)
- Integrated thermo-electrical design
  - ✓ power layers are meshed ➔ reduces **longitudinal** conductivity
  - ✓ patterning of ground layer ➔ improves **transverse** conductivity
- Temperature between 80K and 300K by adjusting LN_2 flow and heater power

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

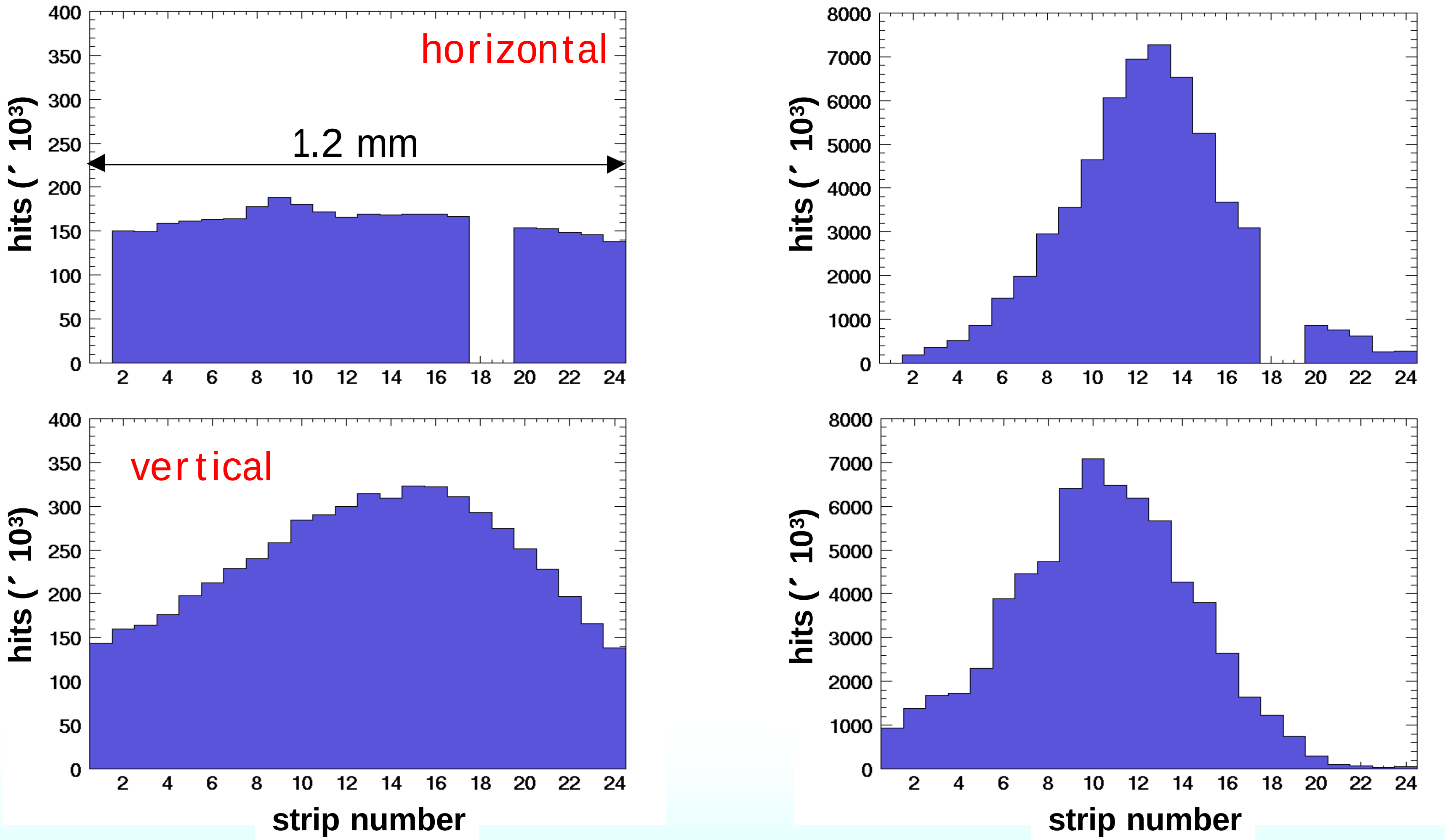
NA60 Beamscope Test, Fall 2000

Exposed ~40 days to the 158 A GeV Pb beam

- *Average beam intensity: 7×10^{7} ions per 4.5 s burst*
- *Total fluence: $5 \pm 2 \times 10^{14}$ ions/cm^{2} (90 ± 40 Grad)*

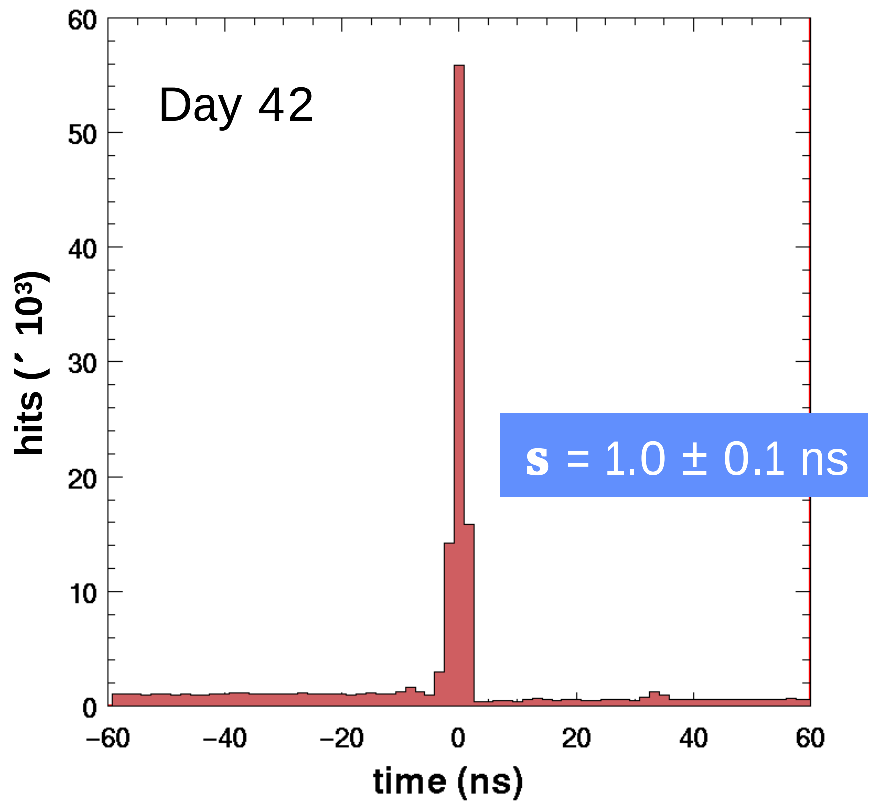
Beam Profile

Day 1 | Day 38 (~85 Grad)

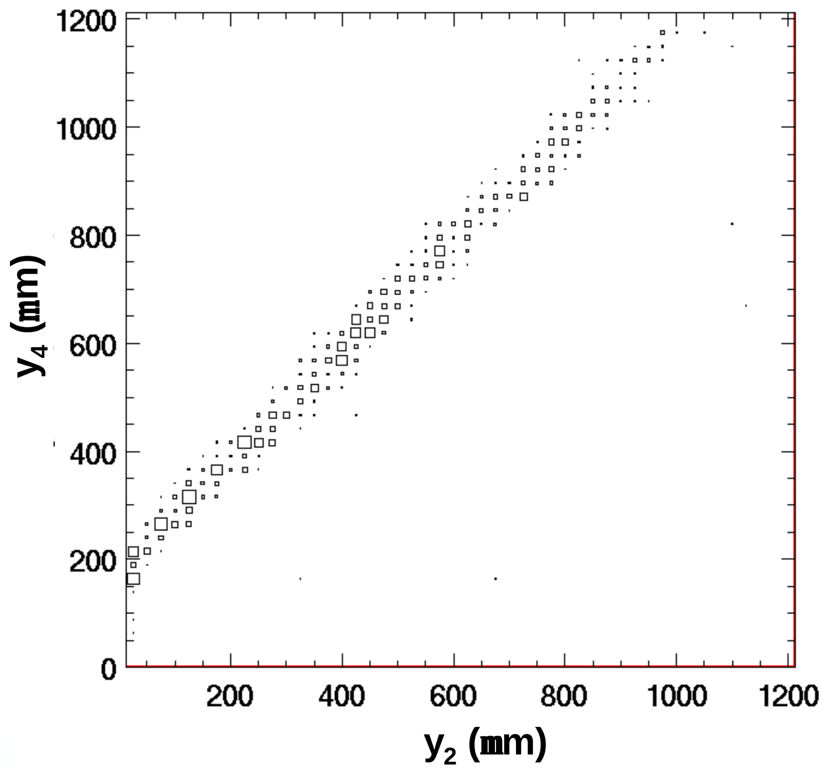


MHTR Timing & Cluster Correlation

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



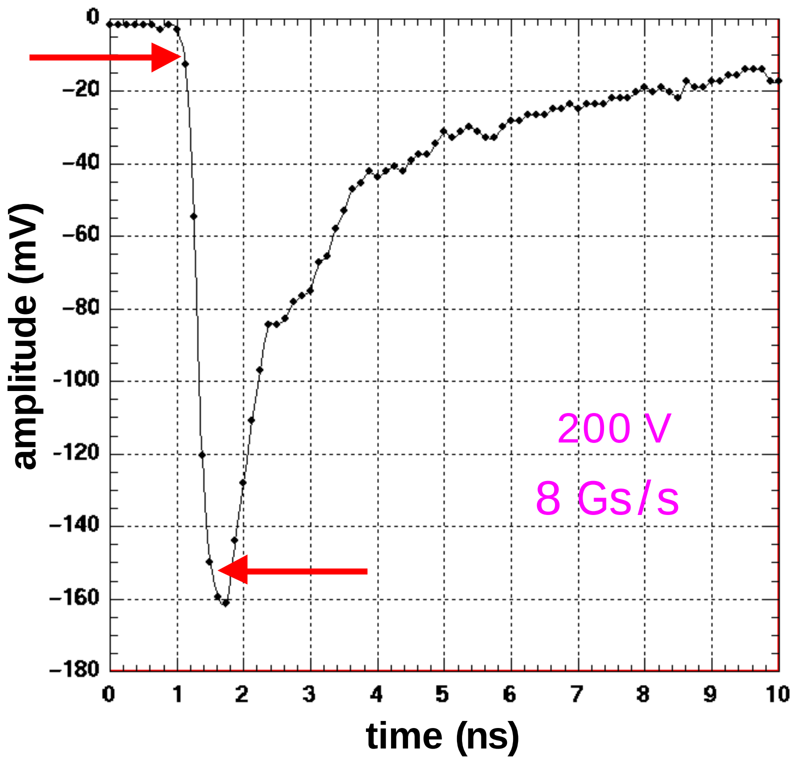
Correlation of clusters in plane 2 and 4 (only hits within 3 σ)



~200 µm misalignment

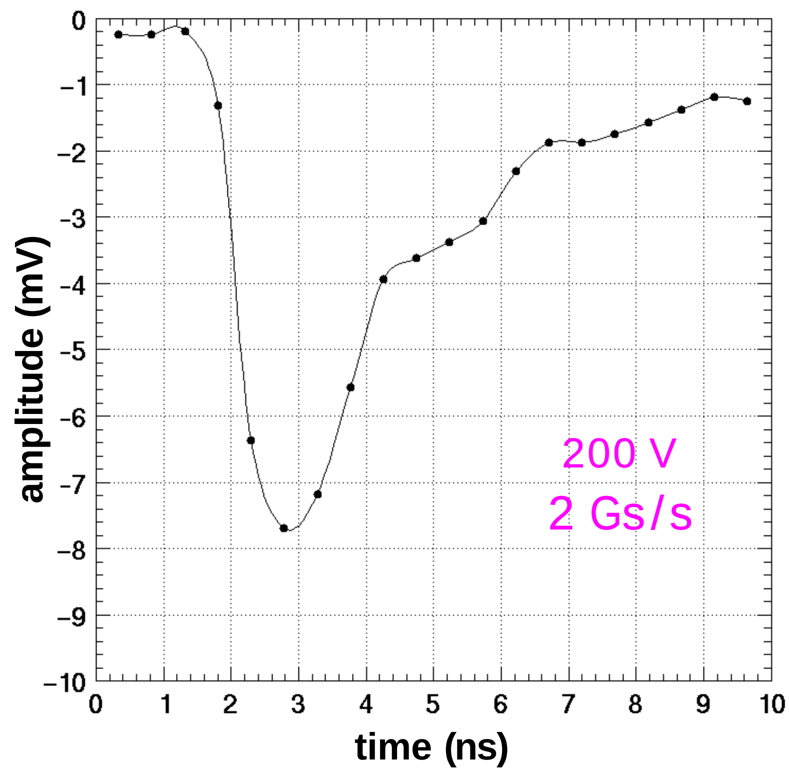
True (unshaped) Pb Ion Signal

Non-irradiated



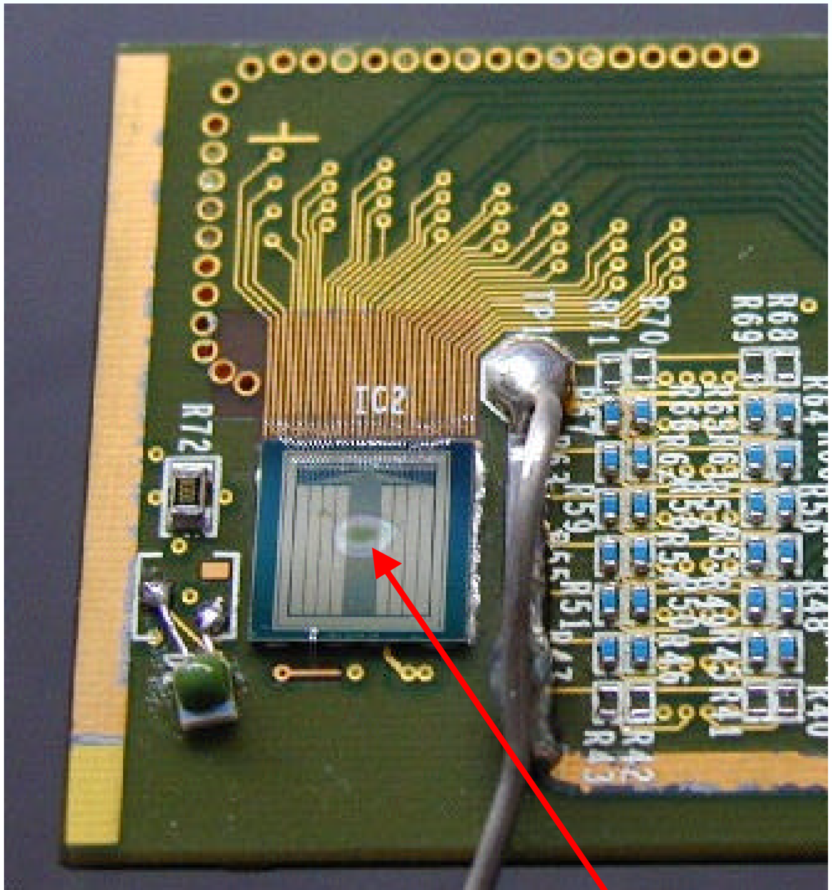
- Very fast rise time (< 500ps)
- Very long tail (~20ns)

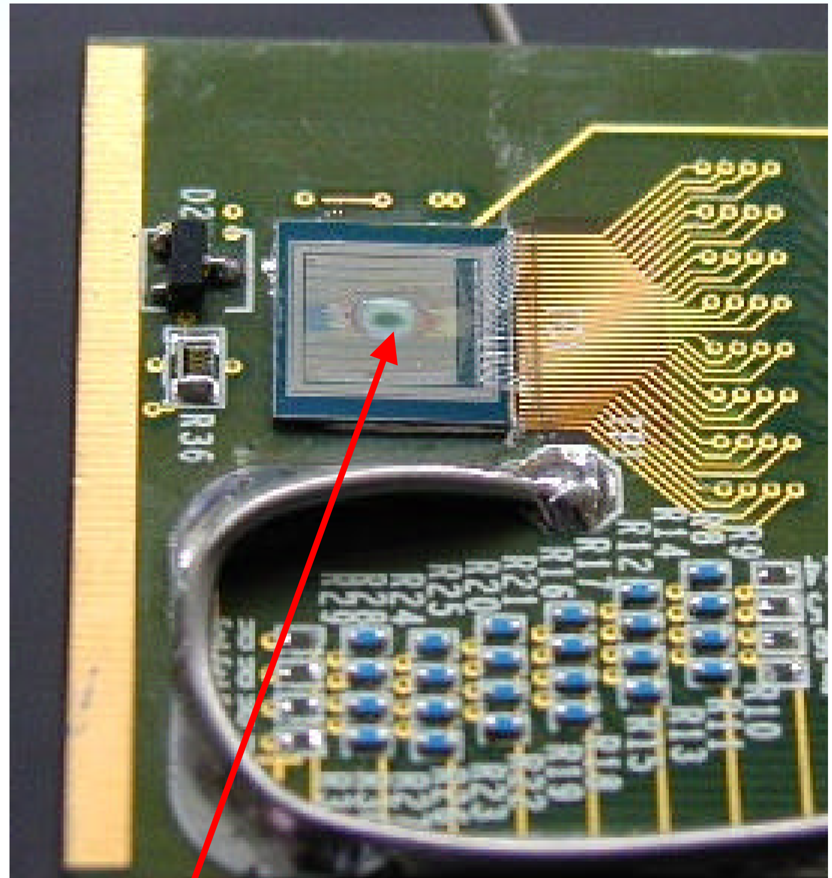
After 20 days (40 ± 20 Grad)



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

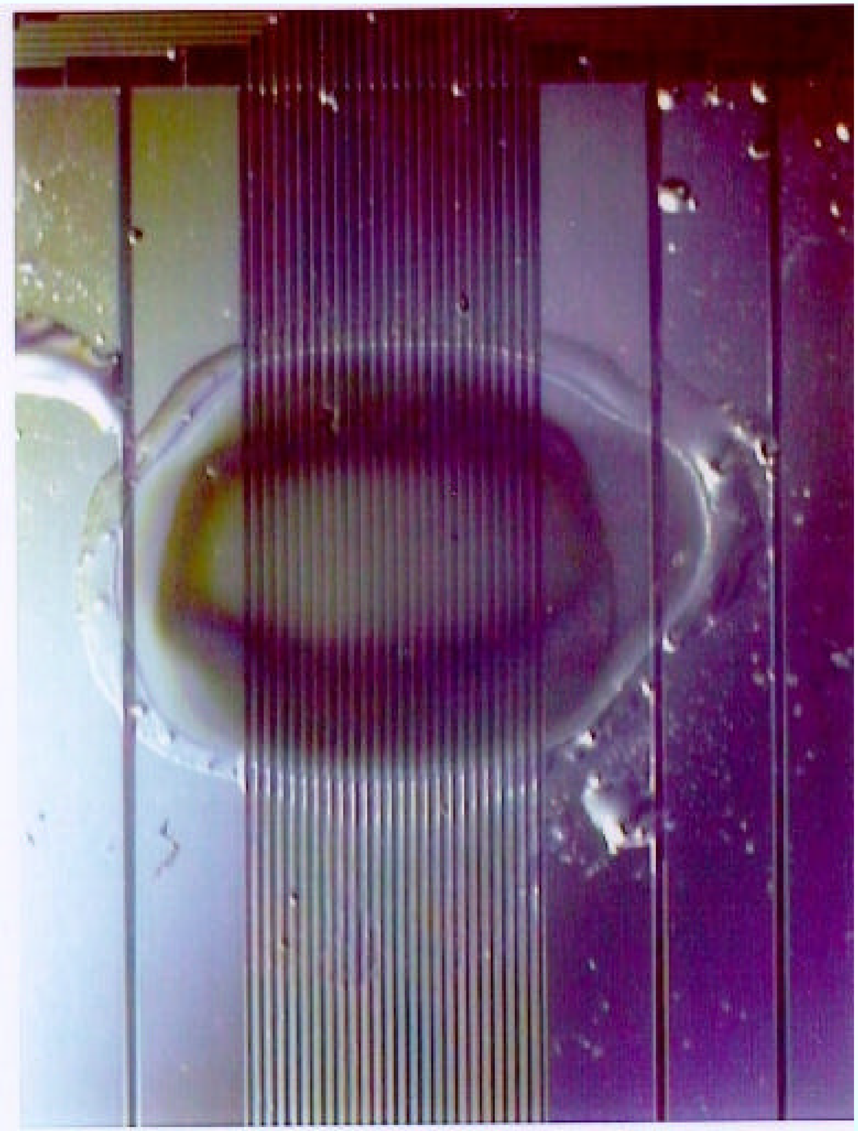
The Beamscope After 90 Grad





Pb beam's signature

The Beamscope After 90 Grad



Q&A Issues

Mechanical properties

✓ some defects may be tolerable at cryogenic temperatures

Electrical properties

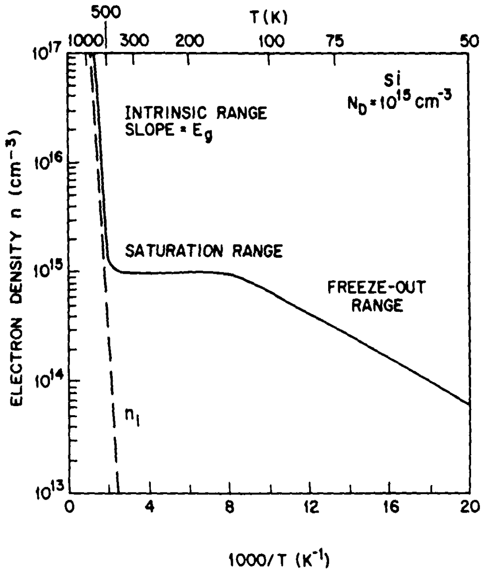
✓ Leakage Current: suppressed at cryogenic T

(note: some nasty surface currents remains…)

✓ Depletion Voltage: lower at cryogenic T

⇨ ***if detector is good @ 300K ➔ better @ 130K***

bad @ 300K ➔ may be good @ 130K



✓ Strip quality: DC coupling can be used

➔ simpler detector processing

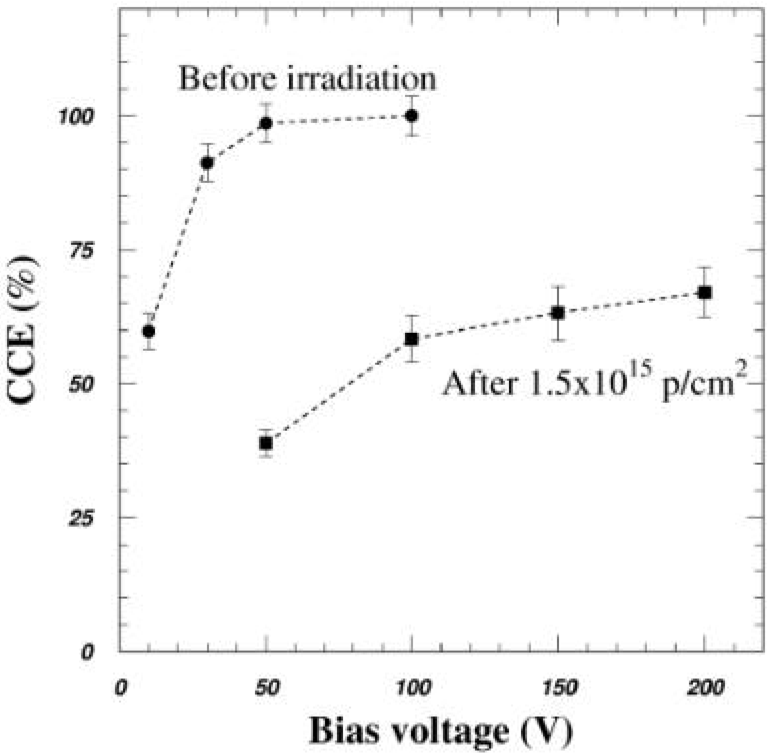
⇨ ***no special testing required for a cold tracker (except for bad detectors)***

⇨ ***higher yield***

Q&A Issues

RD39 data

Si pads irradiated @ 83 K
with 450 GeV protons



➔ no significant differences compared to room temperature !

Irradiation tests

✓ for characterization is OK to irradiate at RT and measure CCE in the cold

✓ no need for annealing studies

Conclusions

- Work to be done to understand the detail of the phenomenon. Nevertheless, data clearly show that Cryogenic Operation is a robust technique to extend the lifetime of Si trackers by more than one order of magnitude
- For heavy ions, where very large signals are obtained, Cryogenic Silicon can work up to several tens of Grad
- Thermal design for operation at 130 K is NOT more difficult than that for -10°C
- QA for a Cryogenic Tracker does not seem to require a more complicated testing procedure
- Future:
  - ✓ Cryogenic Detectors for TOTEM
  - ✓ Vertex Tracker of COMPASS
  - ✓ Beamscope for NA60

    CERN-MIC developed a new CMOS readout chip to work at 130 K to track the proton beam