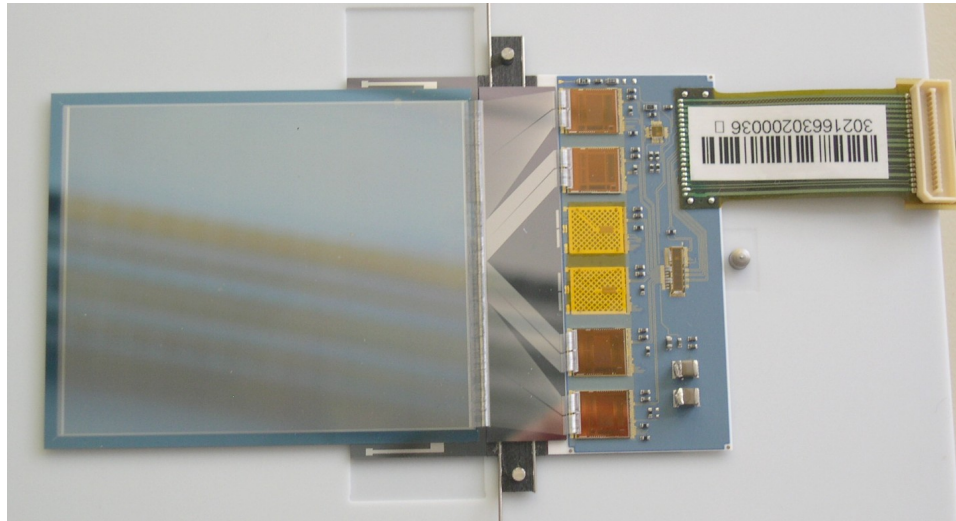


Development of ultra radiation hard silicon detectors for LHC Upgrade



<http://www.hip.fi/research/cms/tracker/php/home.php>

Outline

- Radiation hardness challenge at S-LHC
- Development of radhard Si detectors for CERN S-LHC
 - Magnetic Czochralski silicon (MCz-Si) as detector material
- Trapping and Charge Collection Efficiency (CCE)
- Low temperature operation and Charge Injected Detector (CID)
- Characterization of irradiated detectors
 - Principle of TCT measurement
 - CCE measurements
 - Measurement of full size segmented detectors with read out and DAQ
- Summary

Esa Tuovinen loading MCz-Si wafers into oxidation furnace at the Microelectronics Center of Helsinki University of Technology, Finland.



R&D Challenge of GSI/FAIR experiments

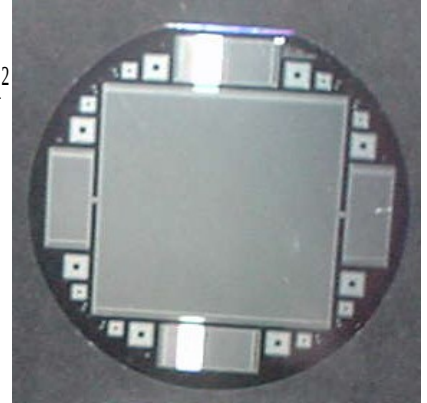
- 1 MeV neutron equivalent fluence (n_{eq}) up to $1 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ is expected.

- Extensive R&D is required because

1. Leakage current (I_{leak}) increases $\sim \Phi$
 - Increased heat dissipation $\sim I_{leak}$
 - Increased shot noise $\sim \sqrt{I_{leak}}$

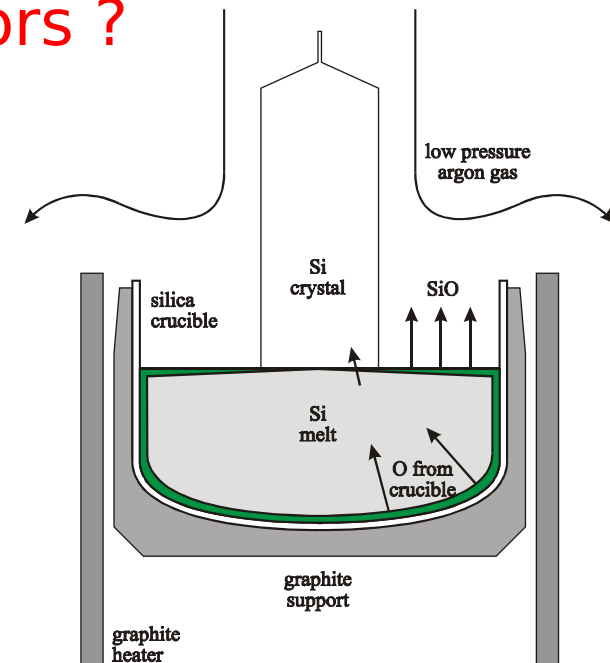
2. Full depletion voltage (V_{fd}) will be $>1000\text{V}$. $\sim N_{eff}(\Phi)$ and $\sim d^2$
$$V_{fd} = \frac{qN_{eff}(\Phi)d^2}{2\epsilon\epsilon_0}$$

3. Trapping will limit the Charge Collection efficiency (CCE).
 - CCE at $1 \times 10^{15} \text{ cm}^{-2} \approx 50\%$ (strip layers of S-LHC Tracker)
 - CCE at $1 \times 10^{16} \text{ cm}^{-2} \approx 10\text{-}20\%$ (pixel layers of S-LHC Tracker)



Why Cz-Si for particle detectors ?

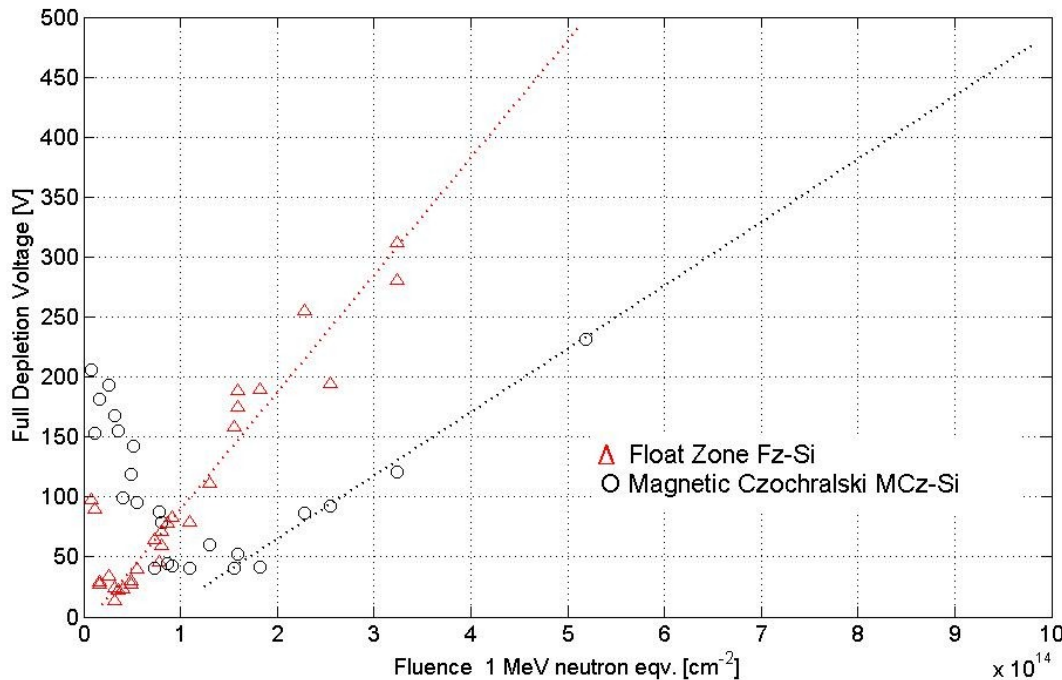
- Cz-Si available in larger diameters
- Lower wafer cost
- Better compatibility with advanced CMOS processes
- Oxygen brings significant improvement in thermal slip resistance
- Oxygen gives **significant radiation hardness** advantage.



Detectors have traditionally made on Fz-Si. Why not before Cz-Si ?

- No demand for high resistivity Cz-Si -> No availability
- Price for custom specified ingot 25,000 € - 40,000 € (too much for university lab)
- Now RF-IC industry shows interest on high resistivity Cz-Si (=lower substrate losses of RF-signal)

Radiation hardness of MCz-Si



- High O content MCz-Si is significantly more radiation hard in terms of V_{fd} than Fz-Si
- No difference observed in I_{leak} or τ_{eff}
- No difference in neutron irradiation

Proton irradiation results obtained from Jyväskylä RADEF Facility irradiation campaigns 2002-2004
E. Tuominen et al., IEEE TNS 50 (1) (2003) 1942-1946.
J.Härkönen et al., NIMA 518 (2004) 346-348.

Trapping effect on CCE in Super-LHC

$$CCE = CCE_{GF} \times CCE_t = \frac{w}{d} \cdot e^{-t_{dr}/\tau_t}$$

w = width of electric field E(x)
d = thickness of Si
t_{dr} = drift time
 12ns e⁻
 24ns h⁺
τ_t = trapping time

Trapping term (points to τ_t)
Depletion term (points to $\frac{w}{d}$)

Overall CCE is product of

1. CCE_t trapping factor

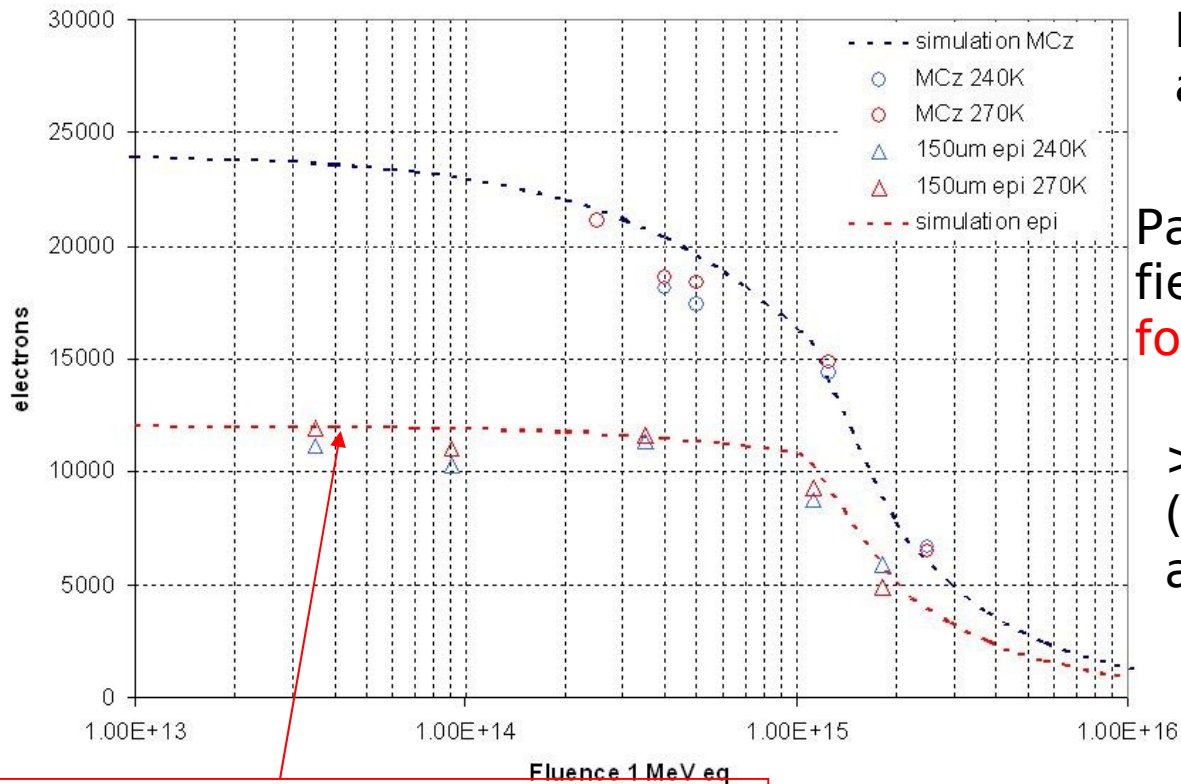
2. CCE_{GF} geometrical factor

$$w = \sqrt{\frac{2\epsilon\epsilon_0 V}{eN_{eff}}} \quad \text{and} \quad \frac{w}{d} = \sqrt{\frac{V}{V_{fd}}}$$

For fluence less than **10¹⁵** n/cm², the trapping term CCE_t is significant

For fluence **10¹⁶** n/cm², the trapping term CCE_t is a limiting factor of detector operation !

Charge Collection Efficiency



Measurement with IR laser and 500V bias

Pad detectors >> no weighting field effect >> **test beam for strip detectors needed**

>1×10¹⁵ cm⁻² fluence MCz (300μm) and epi (150μm) are under depleted both

Two time lower collected charge in thin detector
Thin Si = similar with diamond

$$CCE = CCE_{Geometrical} \times CCE_{trapping} = \frac{w(V_{bias}, x)}{d} \times e^{-t_{dr}/\tau_{trapping}}$$

Why to go low temperatures ?

1. Leakage current scales down exponentially $\rightarrow$ less shot noise $\sqrt{I_{\text{leak}}} \rightarrow$ Read-out threshold lower for given S/N $\rightarrow$ thinner detector = lower mass.
2. Material engineering helps only V_{fd} for charged hadrons. No help for I_{leak} or trapping, which eventually limits the detector operation.
3. Only way to reduce trapping effects is either:
 - Thin detectors $\rightarrow$ Small signal, difficult production, high cost.
 - Complex geometries (3D) $\rightarrow$ Not feasible manufacturing, high cost.
 - Cooling $\rightarrow$ Difficult engineering.
4. Cooling is needed anyway. Not only because of radiation damages, but mainly because power dissipation on high speed read-out electronics. Do the participating institutes possess sufficient mechanical engineering expertise or is the subject disregarded ?

How the trapping is influenced by temperature ?

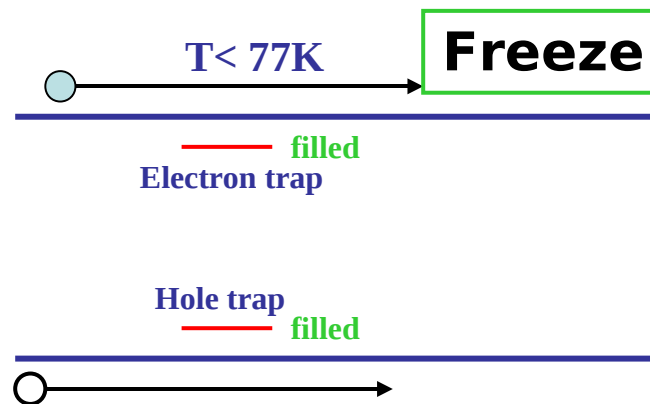
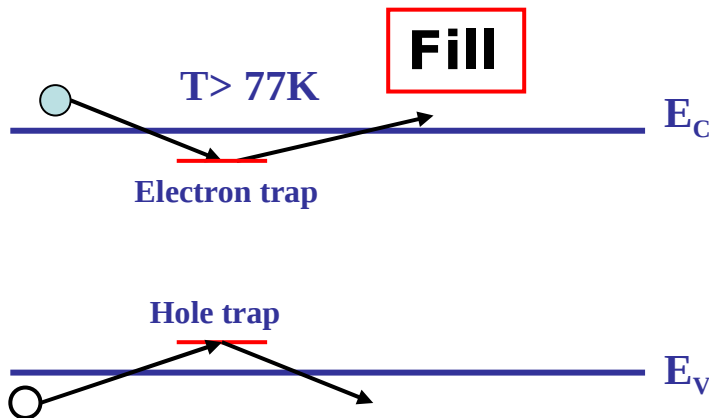
Trapping is balanced by the detrapping.
At the “low” temperature, the traps remain filled considerably long time ($\gg$ shaping time of Read-out electronics)

$$\tau_t = \frac{1}{\sigma v_{th} N_t}$$

$$\tau_d = \frac{1}{\sigma v_{th} N_C e^{-E_t/kT}}$$

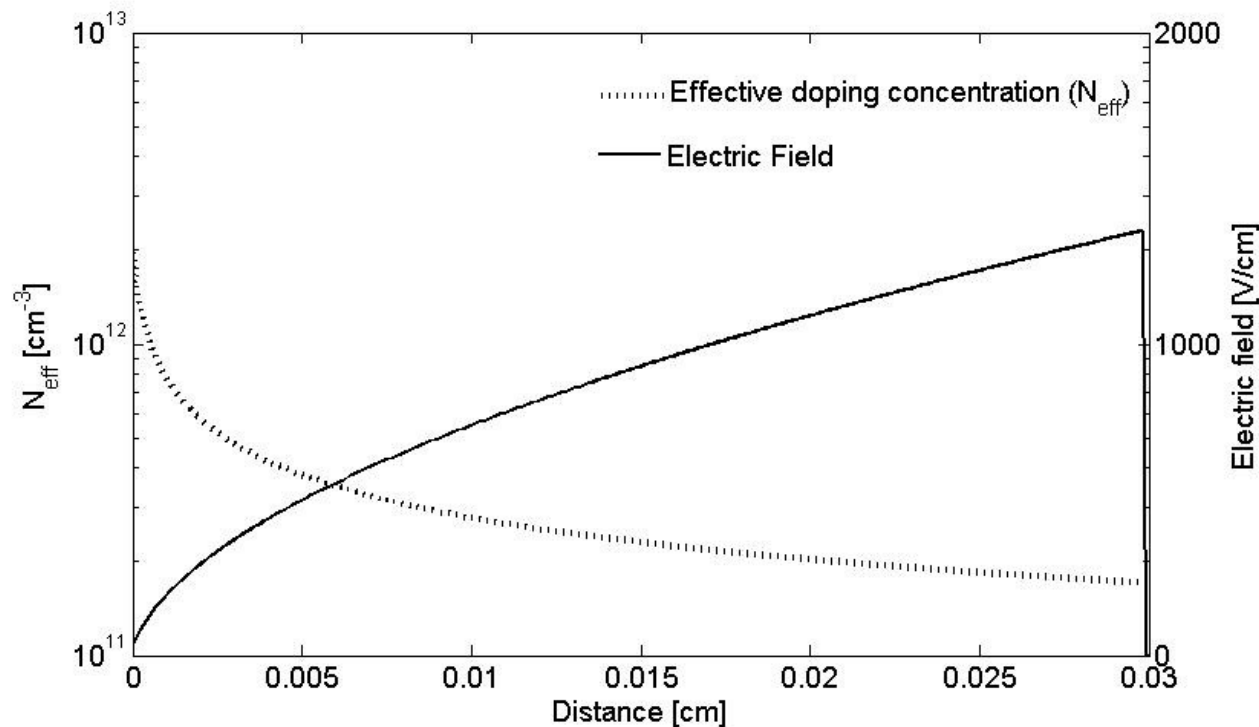
For A-center (O-V at $E_c - 0.18$ eV with $\sigma \approx 10^{-15} \text{ cm}^2$)

T(K)	300	150	100	77	60	55	50	48	47	46
τ_d	3.7 ns	3.9 μ s	4 ms	2 s	1.22 hrs	1.2 days	53 days	302 days	2.1 years	5.47 years



Charge Injected Detector (CID) –Operational Principle

The electric field is controlled by charge injection, i.e. charge is trapped but not detrapped at “low” temperature

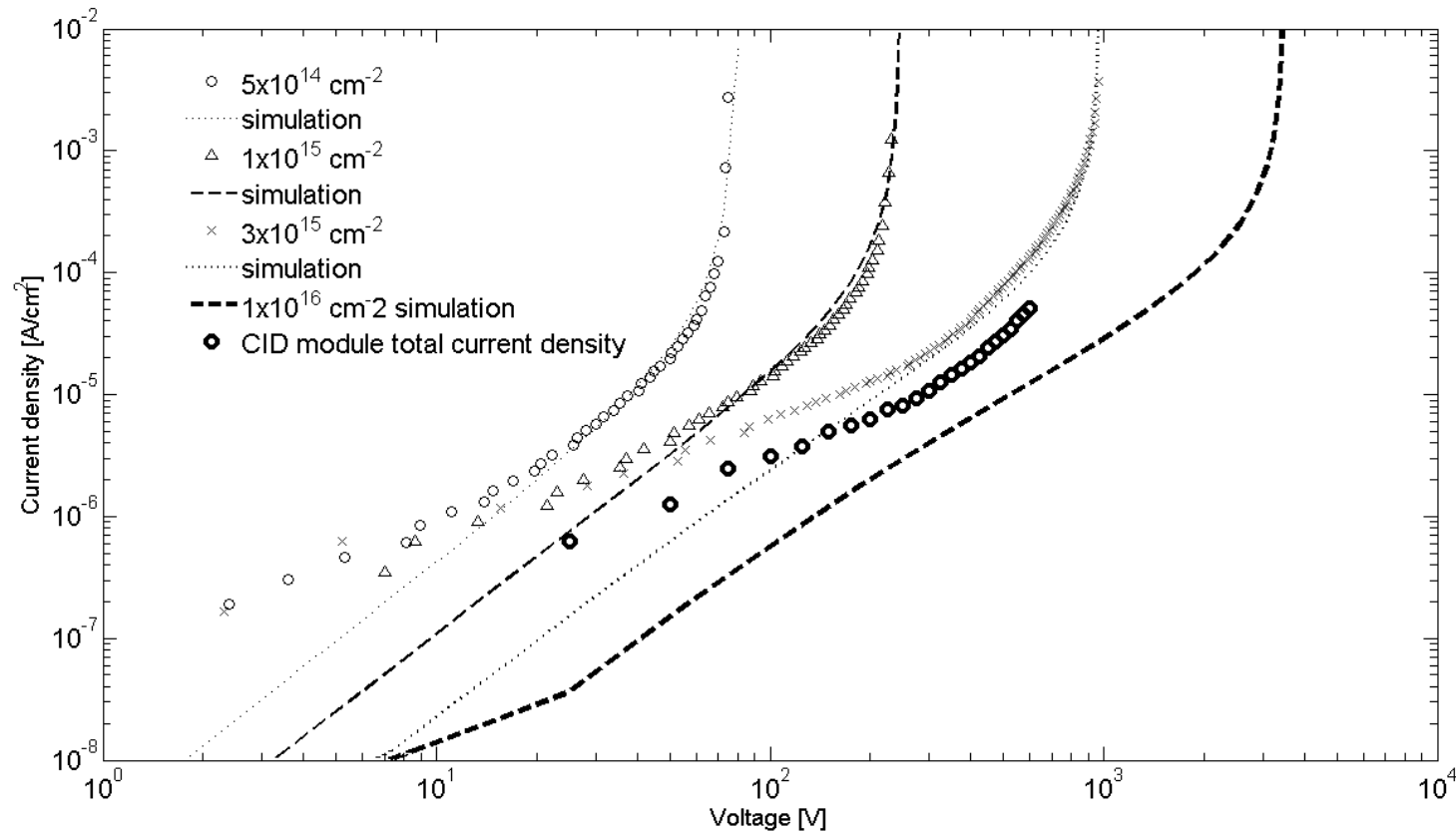


Electric field is extended through entire bulk regardless of irradiation fluence.

Electric field is proportional to square of distance
 $E(x) \sim \sqrt{x}$

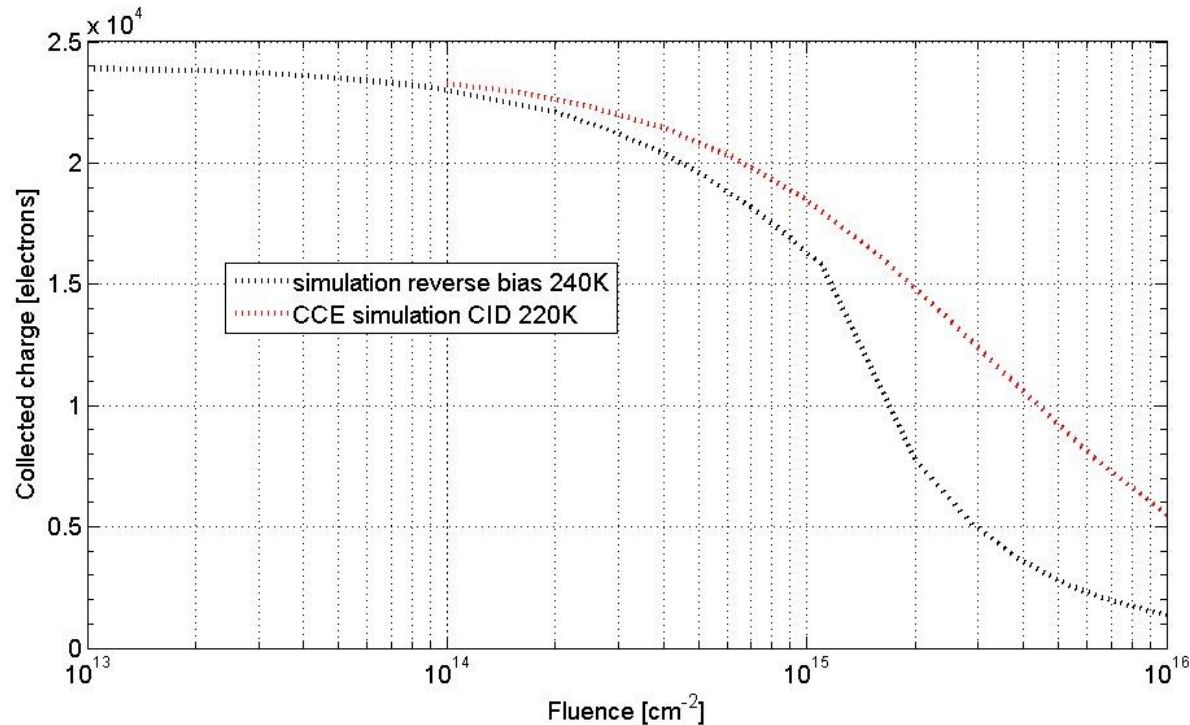
Detector is “fully depleted” at any bias or irradiation fluence

Interesting feature of CID -Current goes down
with given V_{bias} as fluence increases



Expected CCE of CID at -50°C

strips $\longleftrightarrow$ pixels



- Simulation takes into account linear trapping
- $\beta = 0.01 \text{ cm}^{-1}$
- ∇ $\sqrt{x}$ E-field distribution is assumed

$$W_{pin} \propto \left(1 - \frac{x}{d}\right)$$

$$W_{CID} \propto \sqrt{x}$$

$$CCE = CCE_{Geometrical} \times CCE_{trapping} = \frac{w}{d} \times e^{-t_{dr}/\tau_{trapping}}$$

$$1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$$

$$\tau_{trap} = 10\text{ns}$$

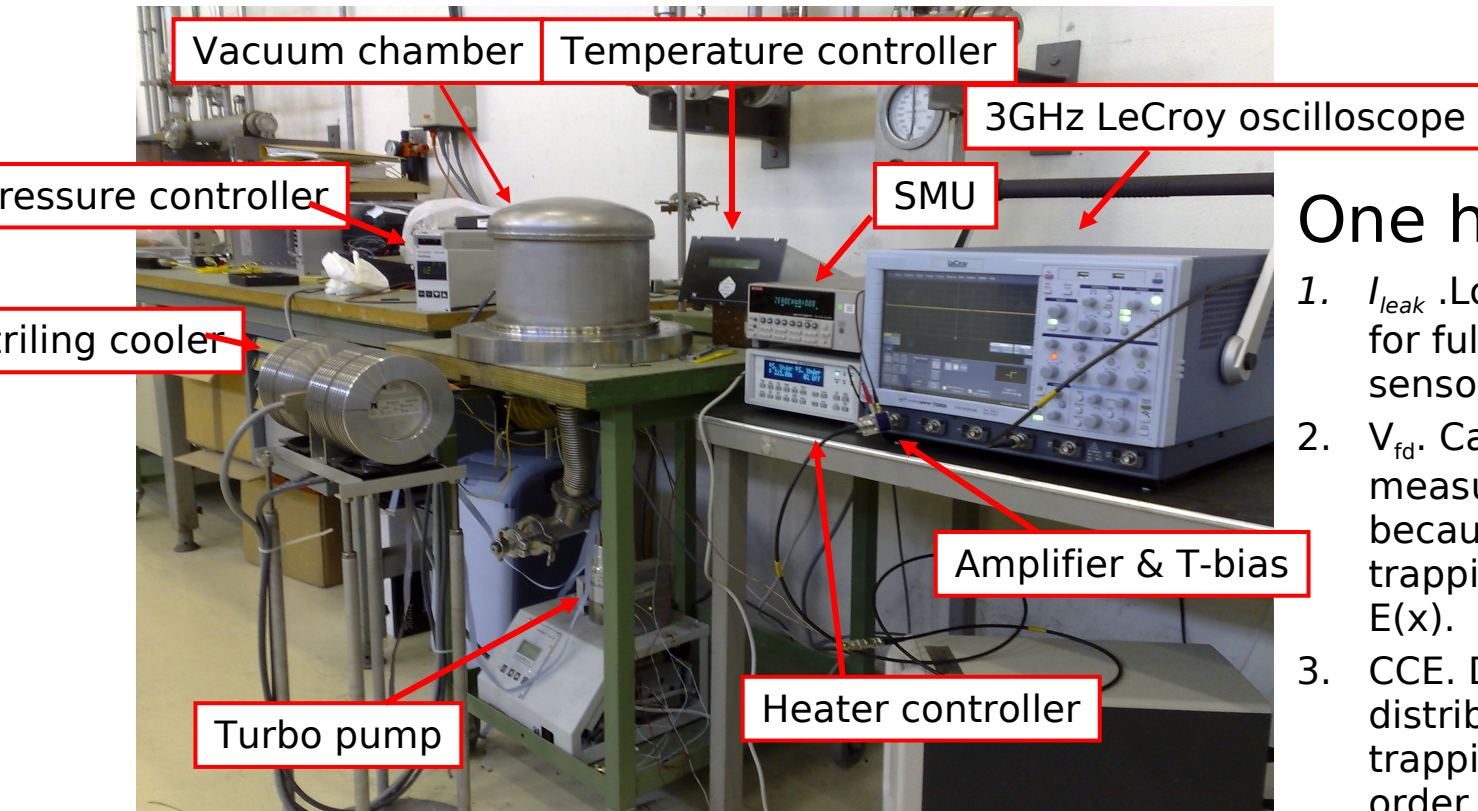
$$1 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$$

$$\tau_{trap} = 1\text{ns}$$

$$1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$$

$$\tau_{trap} = 0.1\text{ns}$$

Characterization of irradiated detectors



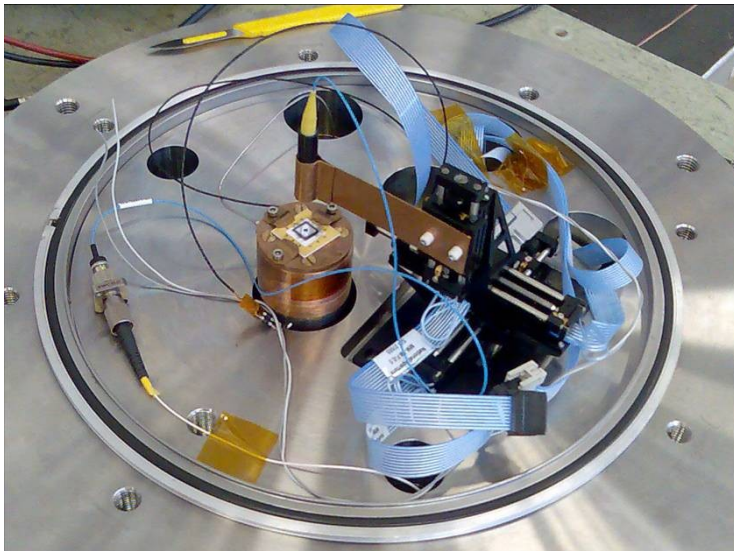
One has to resolve:

1. I_{leak} . Low temperature needed for full size heavily irradiated sensors.
2. V_{fd} . Capacitance-Voltage measurements work poorly because geometrical effects, trapping and inhomogeneous $E(x)$.
3. CCE. Data about electric field distribution and effective trapping times are needed in order to establish reliable radiation hardness scenario

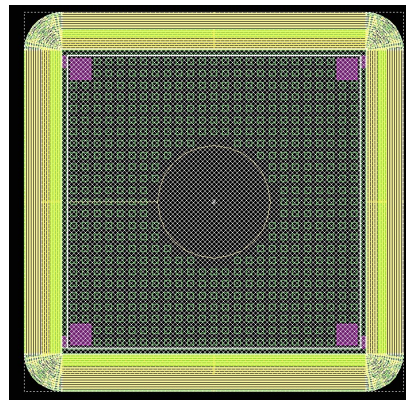
Cryogenic Transient Current Technique (C-TCT)
-Tool to study trapping effects and Charge Collection Efficiency

Transient Current Technique (TCT)

Transient Current Technique is research tool to study E-field in irradiated silicon. Originally developed by Vladimir Eremin (Ioffe PTI) and Zheng Li (Brookhaven National Laboratory)

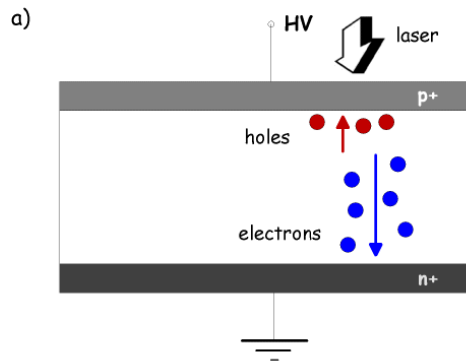


- Detector can be illuminated by red (670nm) or infrared (1060nm) laser light.
- IR light simulates MIPs. Red light is absorbed within few μm .
- If the detector is illuminated by red laser, only one type of carrier drift through the Si bulk and produce TCT signal

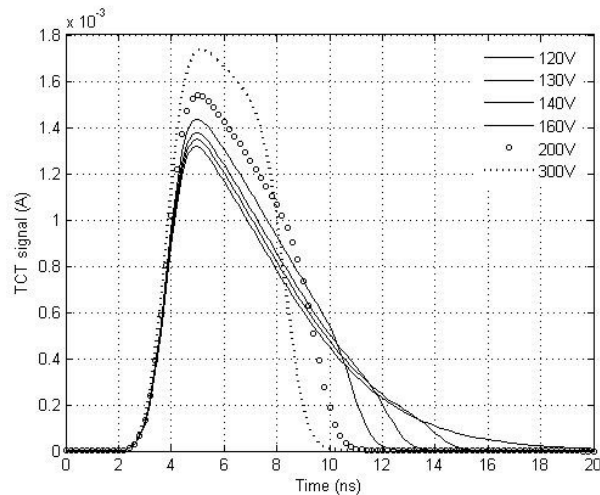


The sample is diode with opening in Al metallization and contact openings in the corners.
Size is typically $5 \times 5 \text{ mm}^2$
Back side at HV, front side grounded

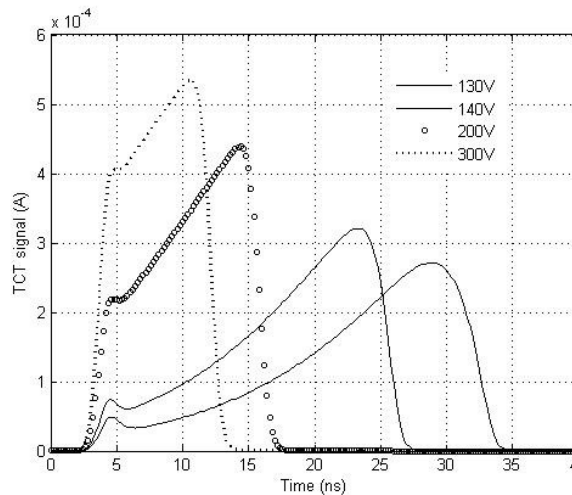
Principle of TCT measurement



- Hole current is collected to the p⁺ implant faster than the RC time constant of measurement circuit
- Electrons drift through the entire bulk (typically 300 μm)
- The recorded transient is electron current
- If the bulk is n-type the highest electric field (i.e. collecting junction) is at front side of the detector
- This results in **decreasing** current transient
- If the bulk is type inverted (n → p), the junction is on the back side and the transient in **increasing**.



non type inverted signal



type inverted signal

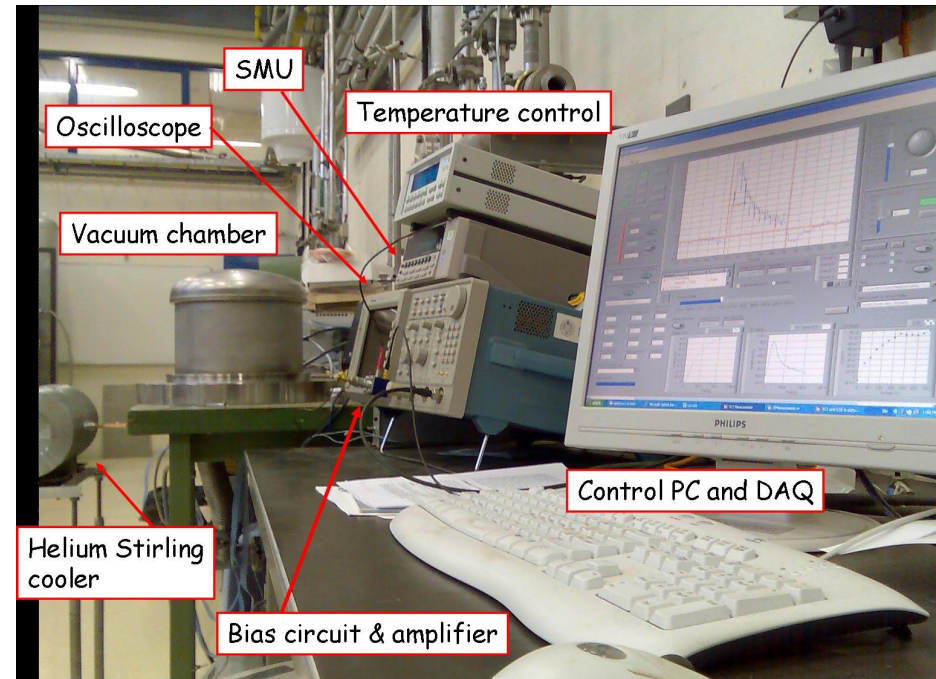
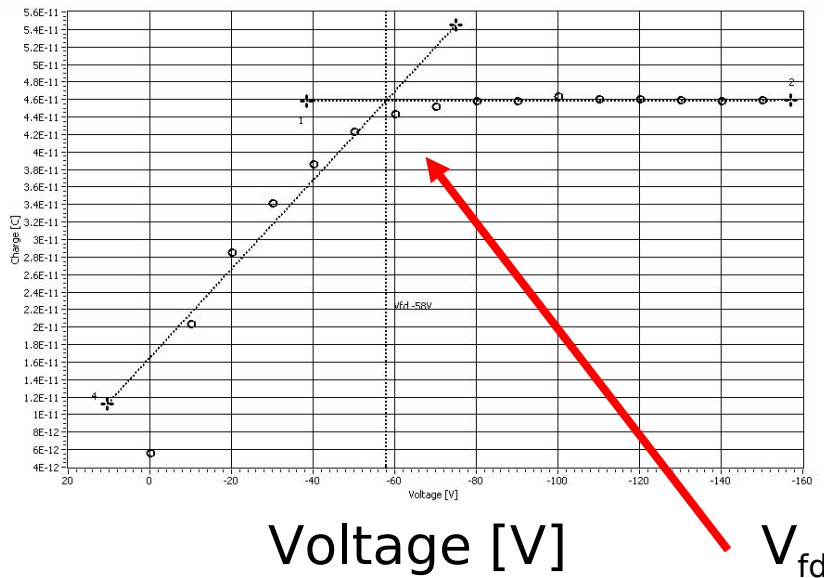
$$i(t) \propto \frac{Q_0}{d} \mu E(x) e^{-\frac{t_{drift}}{\tau_{trap}}}$$

Cryogenic Transient Current Technique (C-TCT)

With C-TCT it is possible to measure and extract

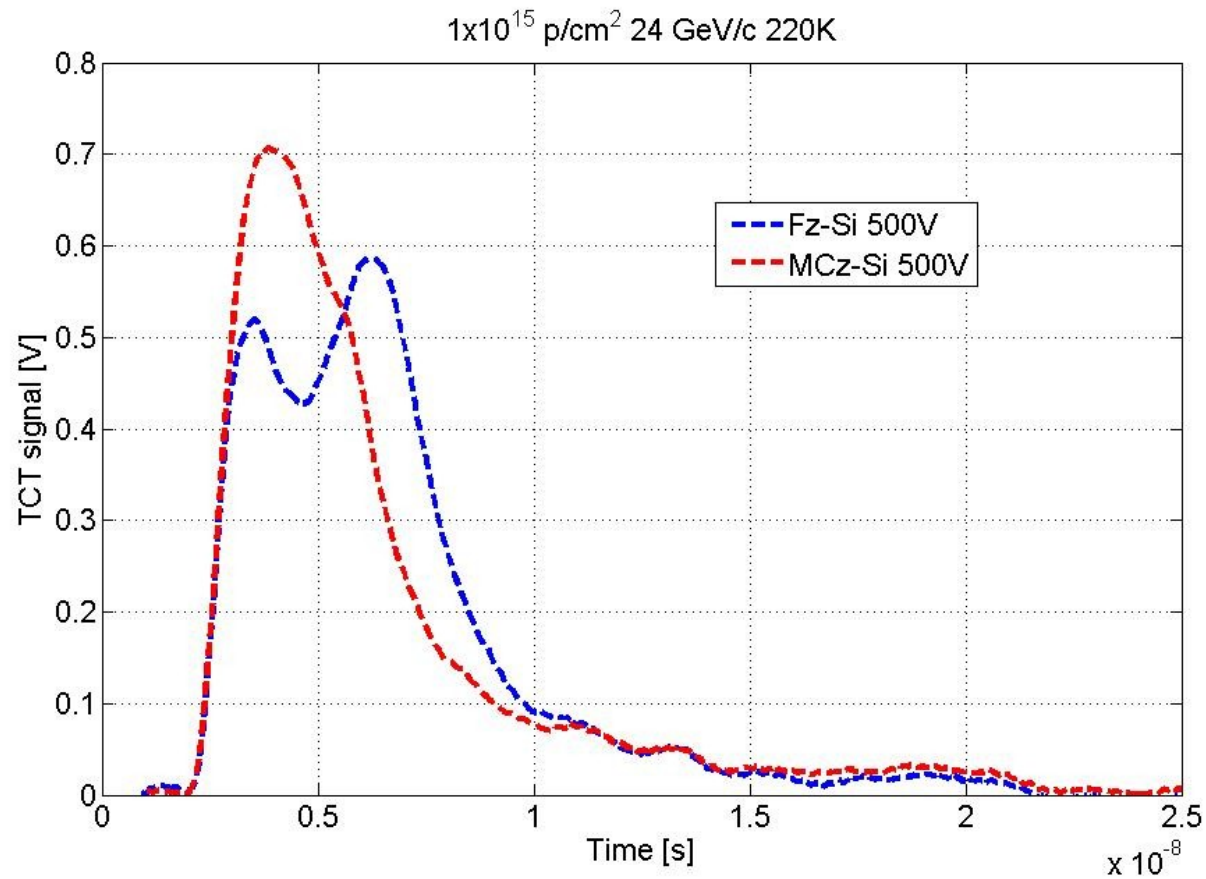
- Full depletion voltage V_{fd}
- Charge Collection Efficiency (CCE)
- Type of the space charge (n or p)
- Trapping time constant $\tau_{e,h}$
- Electric field distribution $E(x)$

Collected Charge [C]

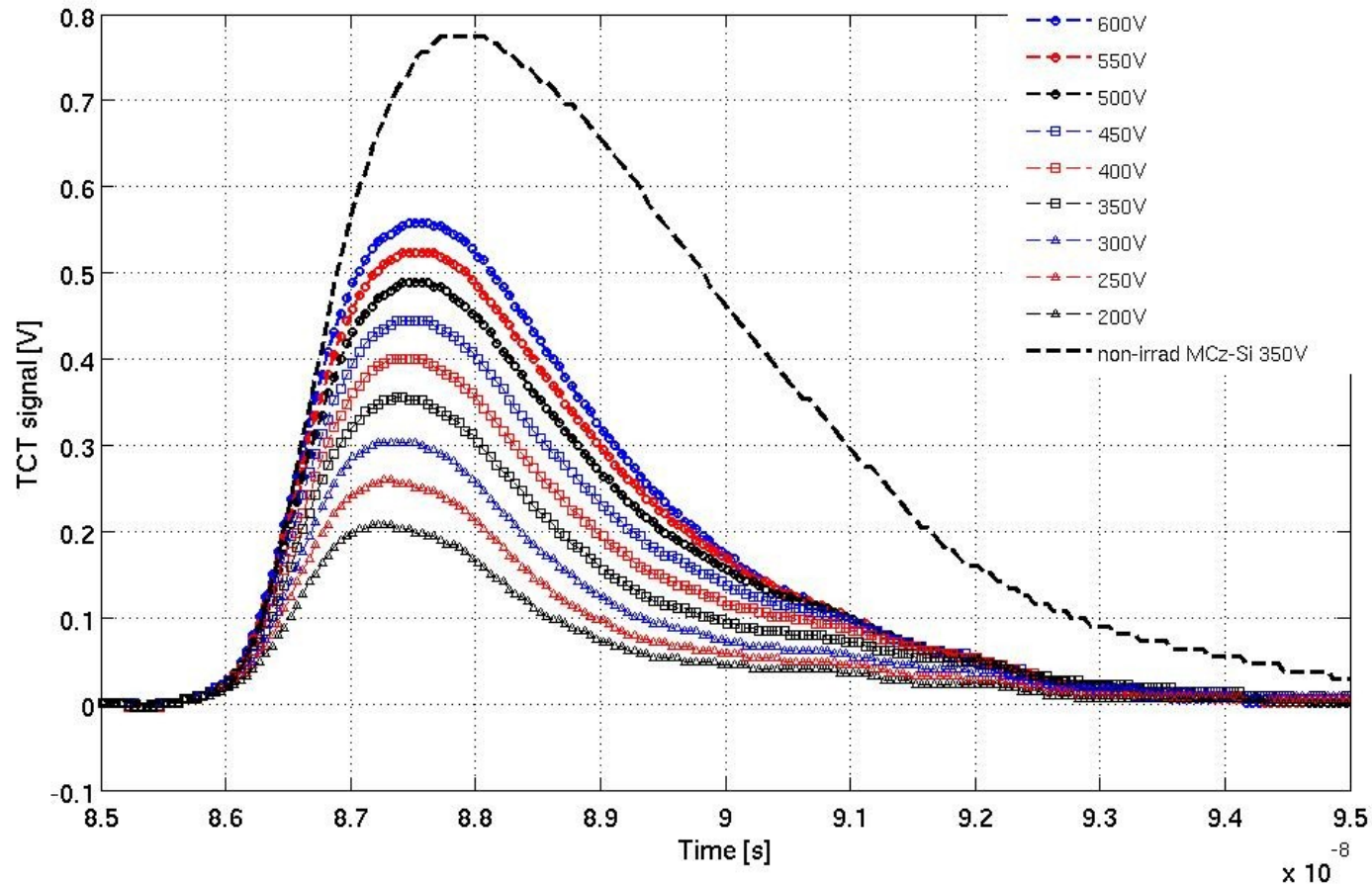


$$N_{eff} = \frac{2\epsilon_0 \epsilon_{Si} V_{fd}}{qd}$$

Comparison of irradiated MCz-Si and Fz-Si

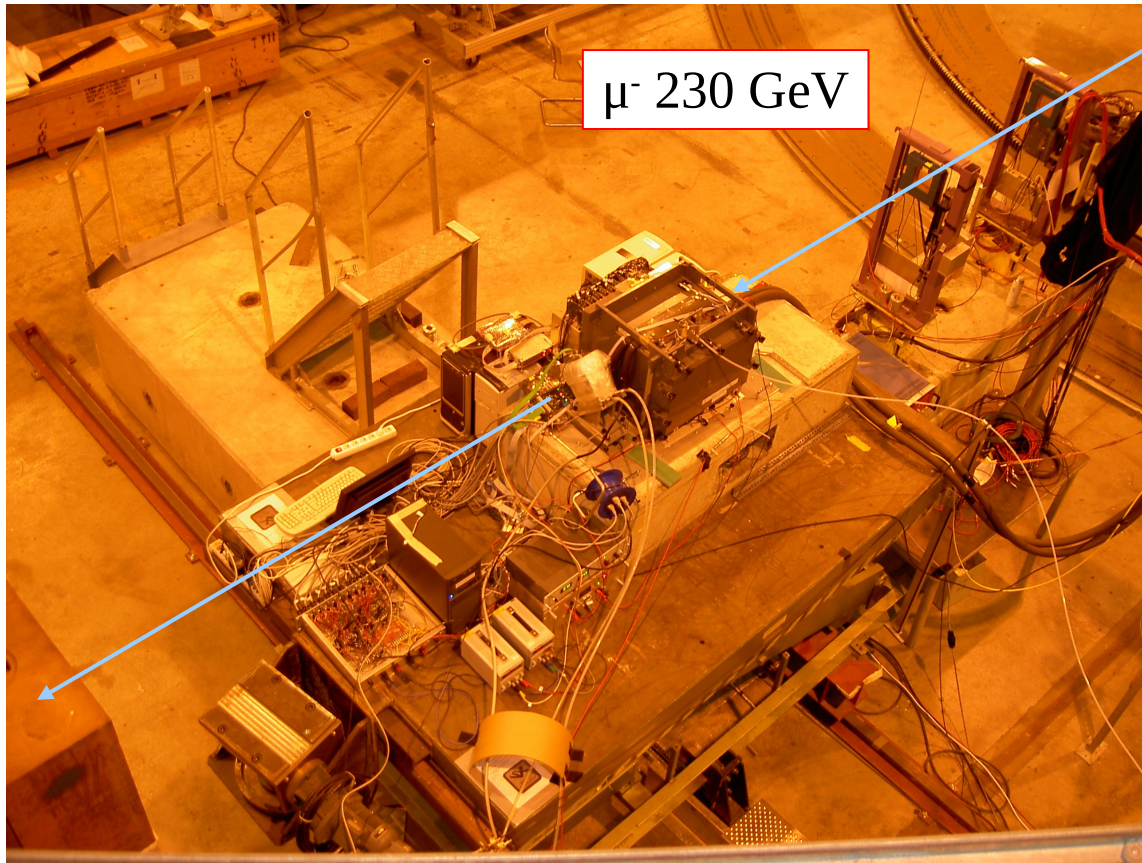


Infra Red CCE measurement with TCT



1×10^{15} irradiated
MCz-Si diode

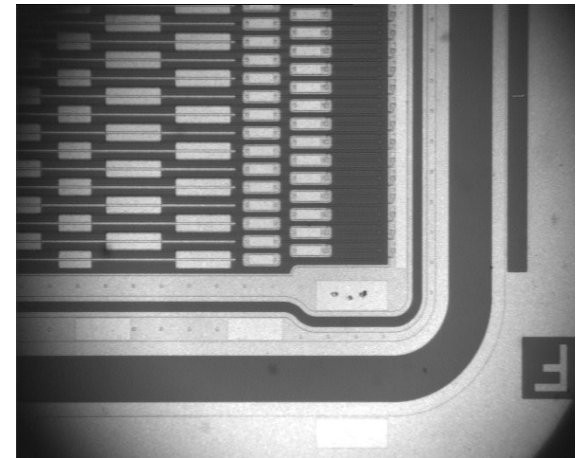
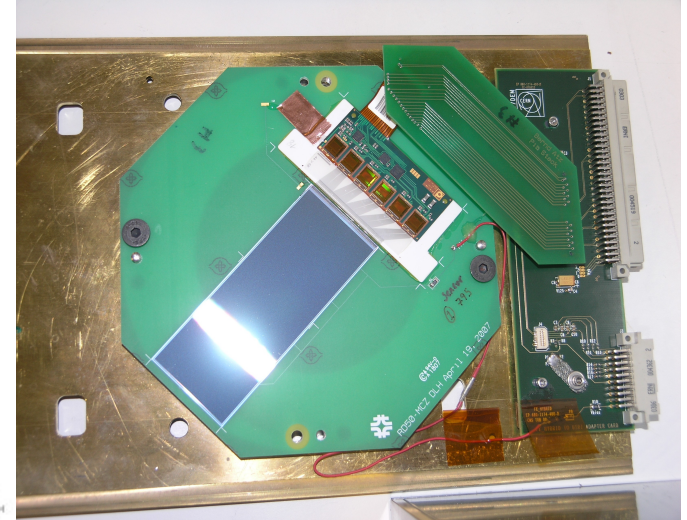
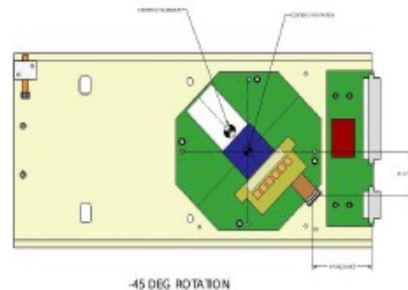
Detector Characterization -Silicon Beam Telescope (SiBT)



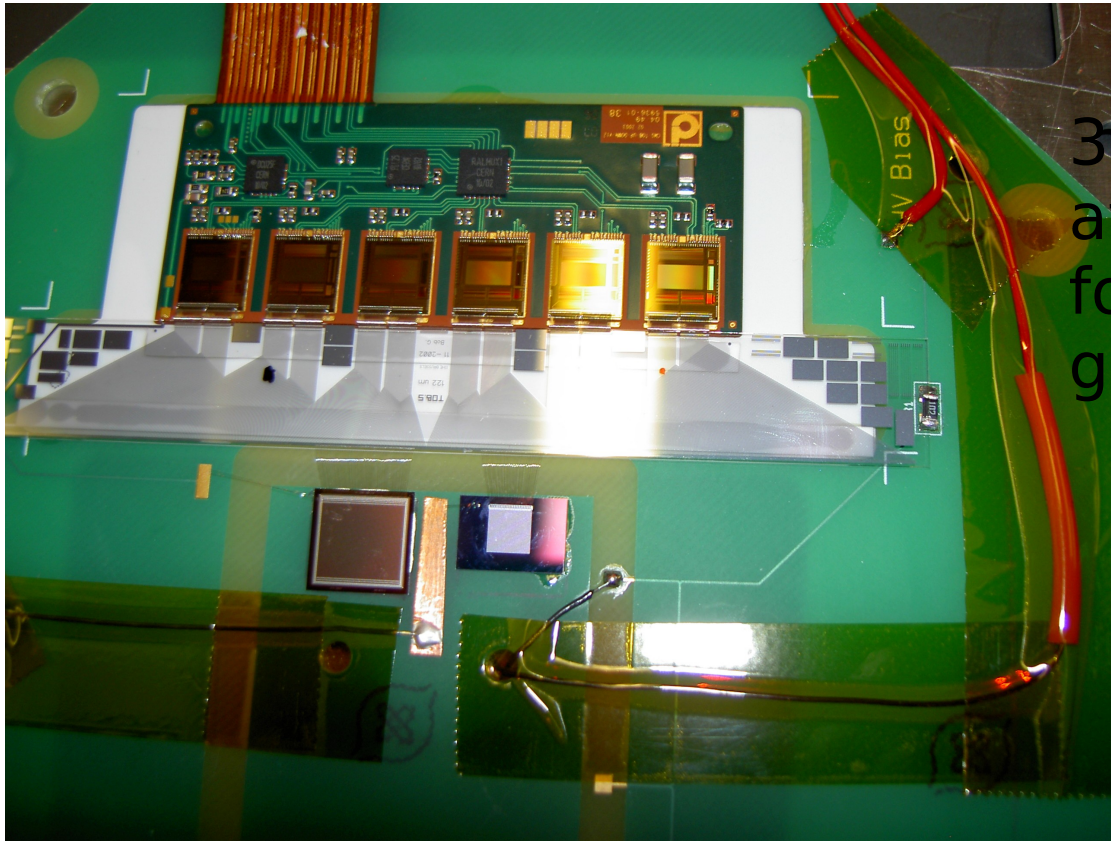
- Operated by HIP at CERN H2 area
- 230 GeV muon beam from SPS accelerator
- CMS based read-out electronics (APV25) and DAQ
- 8 detector planes providing reference tracks for DUT
- Measurement down to -50°C
- 20 000 events in about 15min

SiBT reference detector modules

- Reference detectors of the telescope are **Hamamatsu sensors originally designed for Fermilab D0 run IIb**
 - 60 micron pitch
 - intermediate strips
 - size 4 cm x 9 cm
 - 639 channels
- Readout electronics: **CMS AF**
 - Fully analog architecture
 - Shaping time 25ns
 - Can handle both signal polarities
 - (CID detectors, p and n-type detectors)

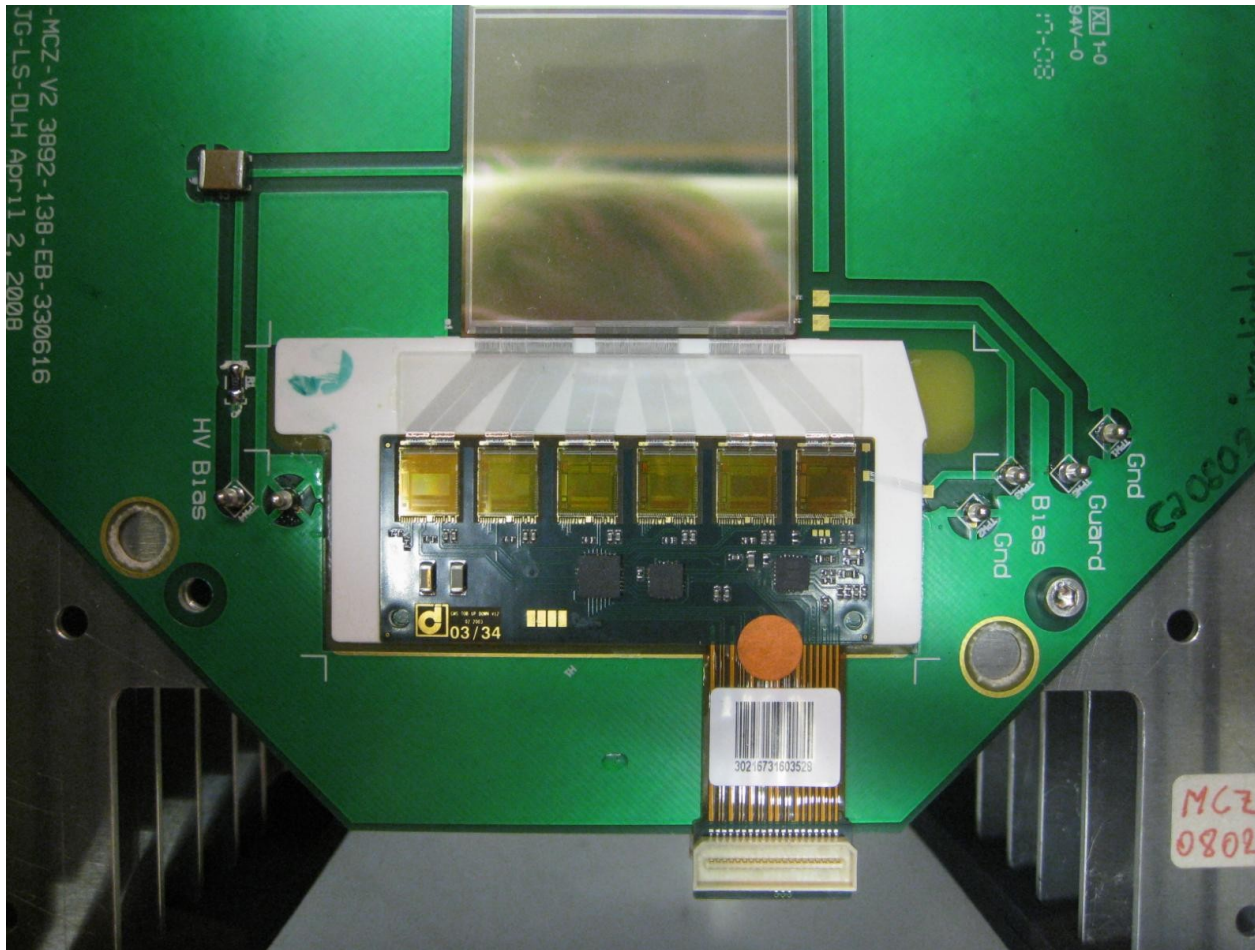


3D detectors at SiBT with APV read-out



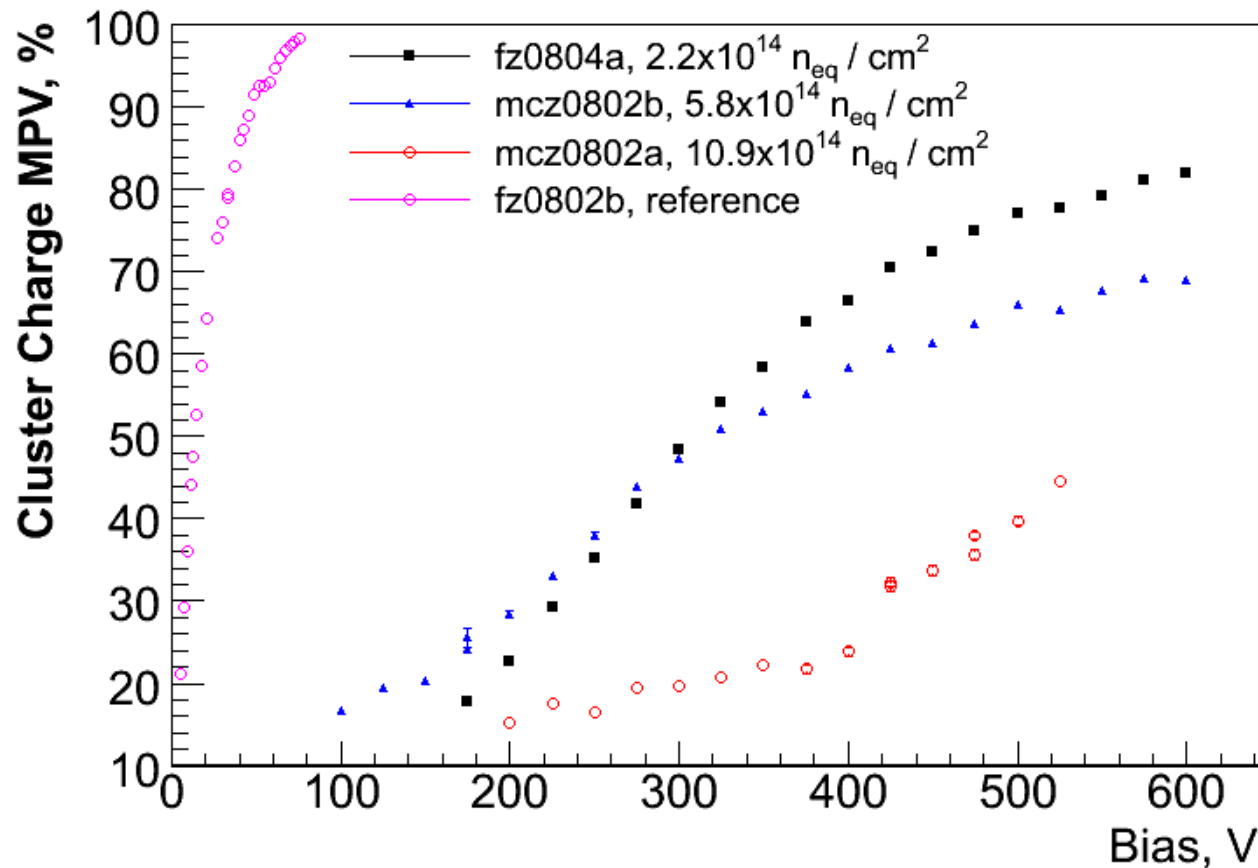
3D detectors fabricated at CNM and FBK-IRST for Atlas and LHCb pixel groups.

$1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ irradiated MCz-Si detector with APV read-out



- 768 channels AC-coupled strip detector
- Detector and pitch adapter fabricated by HIP @ Micronova
- 26 MeV proton irradiation @ University Karlsruhe

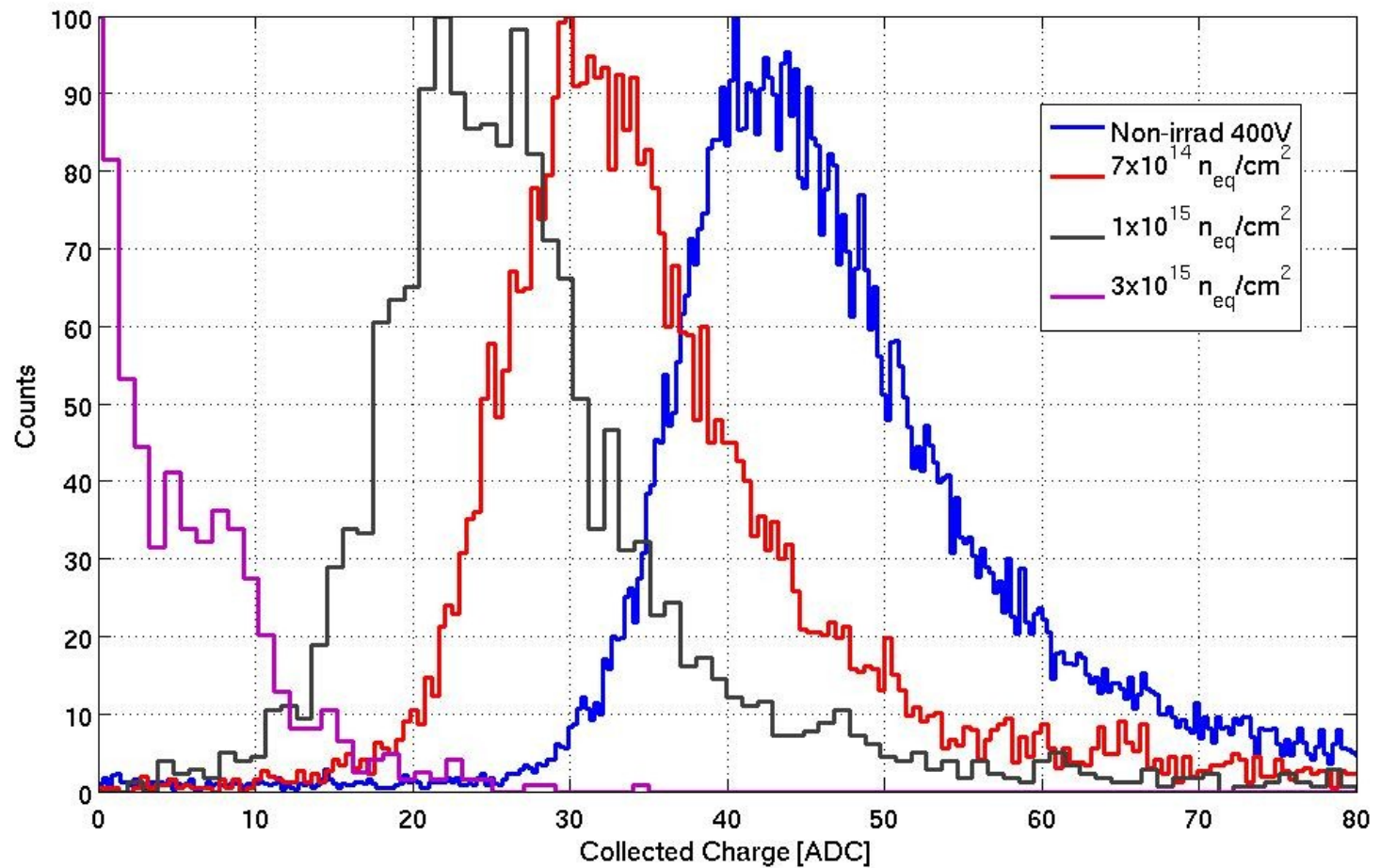
Summary results obtained by SiBT



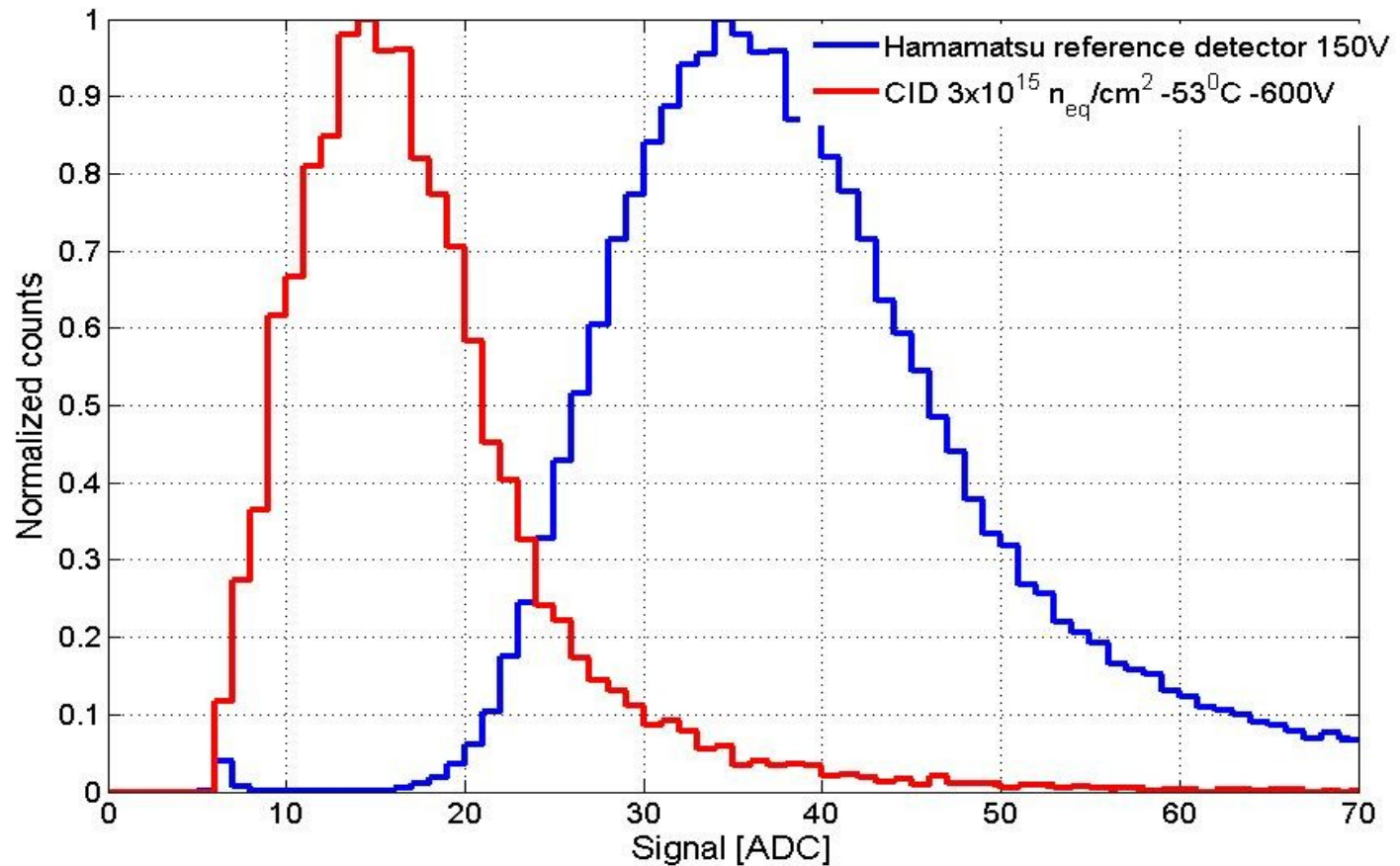
MCz-Si:

- >50% CCE at $1 \times 10^{15} n_{eq} / cm^2$
- S/N > 10 at -20°C

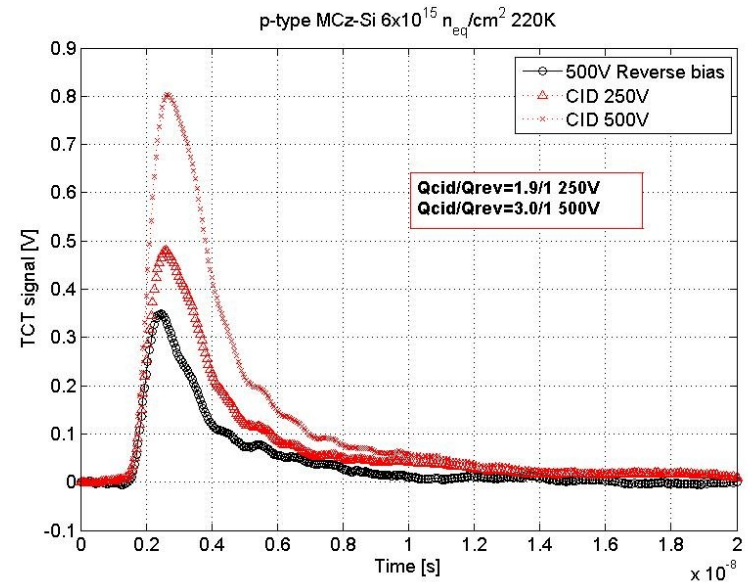
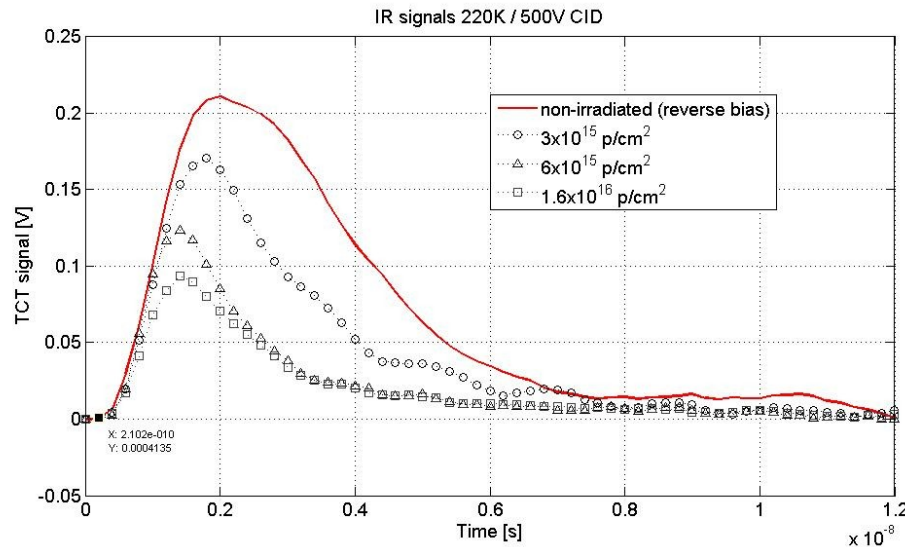
Same data -in different format



CID detector $3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$



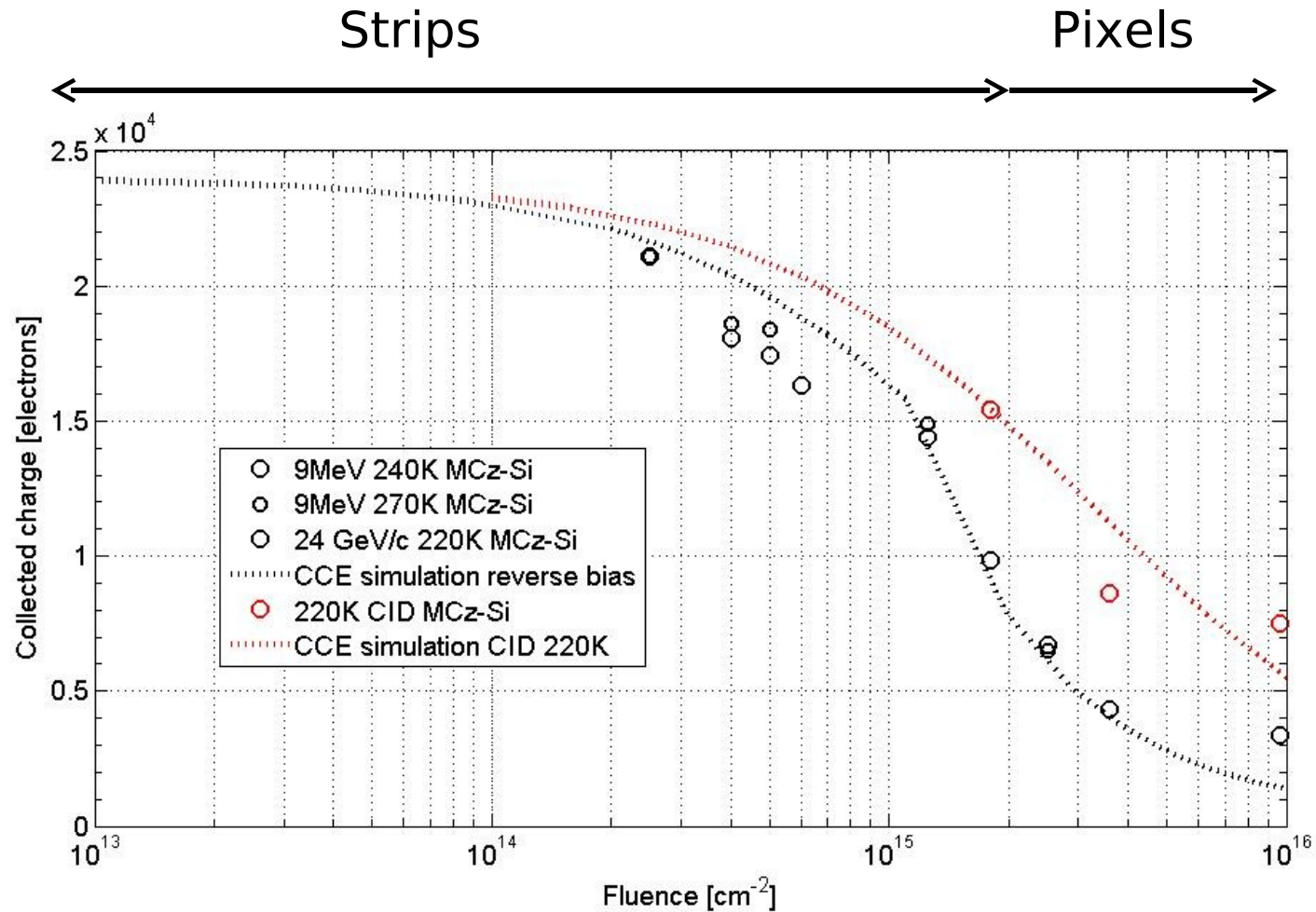
Performance of CID detector -TCT



- Relative CCE $\sim 30\%$ / $1 \times 10^{16} n_{eq}/cm^2$
- $-50^\circ C$ / 500V (practical upper limit of V_{bias})

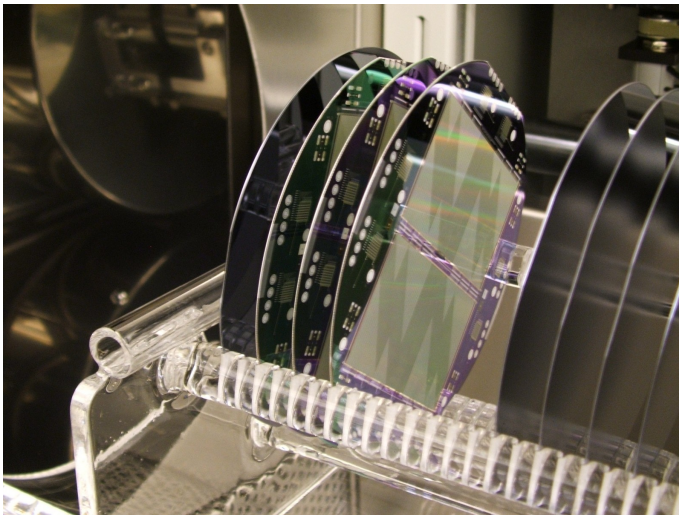
- $2 \times$ higher CCE at 250V compared with standard operation at 500V
- CID concept works with $n^+/p-/p^+$ and $p^+/n-/n^+$ structures both

Charge Collection Efficiency (Reverse bias and CID)



Is Charge Injected Detector (CID) concept feasible ?

- At S-LHC/FAIR efficient cooling is needed anyway.
- Currently engineers at CERN are studying CO₂ cooling.
- CO₂ is attractive option because industry is moving towards CO₂
- -50°C is relatively easily achieved by CO₂
- That's operational temperature of CID detector
- 2x higher CCE can be achieved at -50°C



Summary

- Standard detector operation possible by 300 μ m MCz-Si up to $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ fluence, i.e. strip layers in Super-LHC trackers.
- The CCE is limited by trapping and elevated V_{fd} .
- CID detectors provide two times higher CCE than detectors operated under normal conditions.
- CID operation possible up to $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ fluence.
- Collected charge equals $\approx 7000e^-$ and 30%.
- Read-out electronics, DAQ, irradiated MCz-Si sensors bonded to the CMS RO already demonstrated.
- Operation of CID detector at $-50^\circ\text{C}/3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ demonstrated.
- Pad detector characterization does not include possible weighting field effects >> systematic test beam experiments with segmented detectors and appropriate RO electronics are needed.
- R&D infrastructure (TCT, SiBT) largely exists.