Radiation hard silicon detectors for GSI/FAIR experiments

J. Härkönen[1], E. Tuovinen[1], S. Czellar[1], I. Kassamakov[1], P. Luukka[1],
E. Tuominen[1]

[1] *Helsinki Institute of Physics, CMS Tracker Project.*

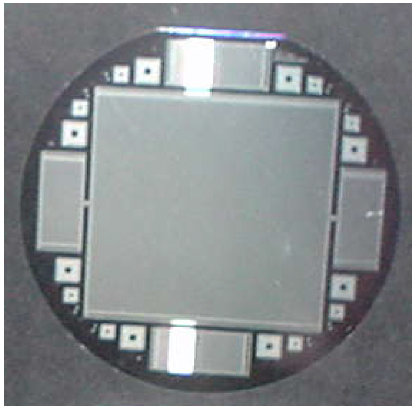
http://www.hip.fi/research/cms/tracker/php/home.php

Outline

- Radiation hardness challenge at GSI/FAIR
- 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 Technoly, Finland.

R&D Challenge of GSI/FAIR experiments



- 1 MeV neutron equivalent fluence (n_{eq}) up to $1\times10^{15}\ n_{eq}/cm^2$. 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 >1000V. $\sim N_{eff}(\Phi)$ and $\sim d^2$

$$V_{fd} = \frac{qN_{eff}(\Phi)d^2}{2\varepsilon\varepsilon_0}$$

3. Trapping will limit the Charge Collection efficiency (CCE).
   - CCE at $1\times10^{15}\ cm^{-2} \approx 50\%$ (strip layers of S-LHC Tracker)
   - CCE at $1\times10^{16}\ cm^{-2} \approx 10\text{-}20\%$ (pixel layers of S-LHC Tracker)

Requirements of GSI/FAIR experiments

Silicon Tracking System:

track reconstruction, momentum measurement:
Hybrid pixel detectors

- high space point resolution, ~ 20 μm locally;

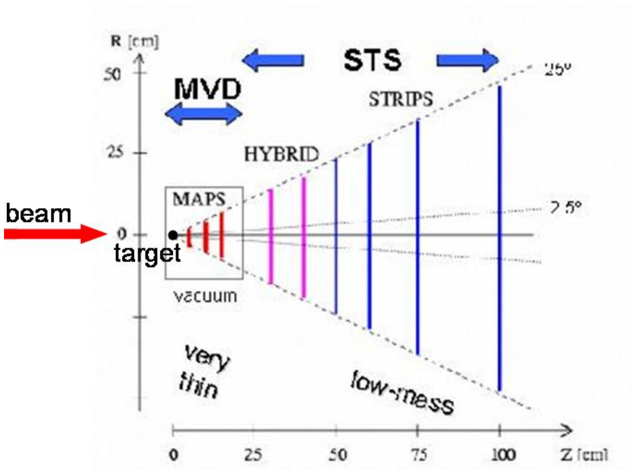
Micro-strip detectors

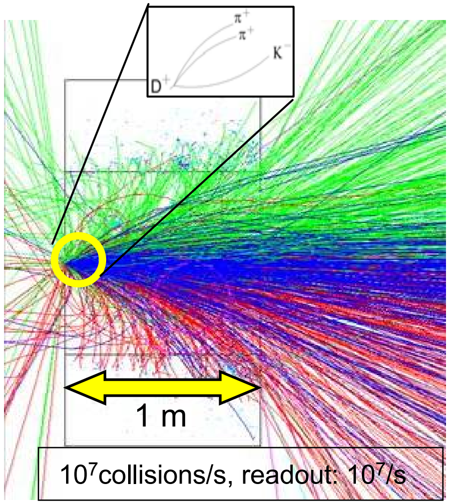
- fast readout (10^7/s);
- thin detector stations, to achieve momentum resolution of ~1%.

Micro Vertex Detector:

distinguish decay vertices from the primary vertex:
Monolithic Active Pixel Sensors

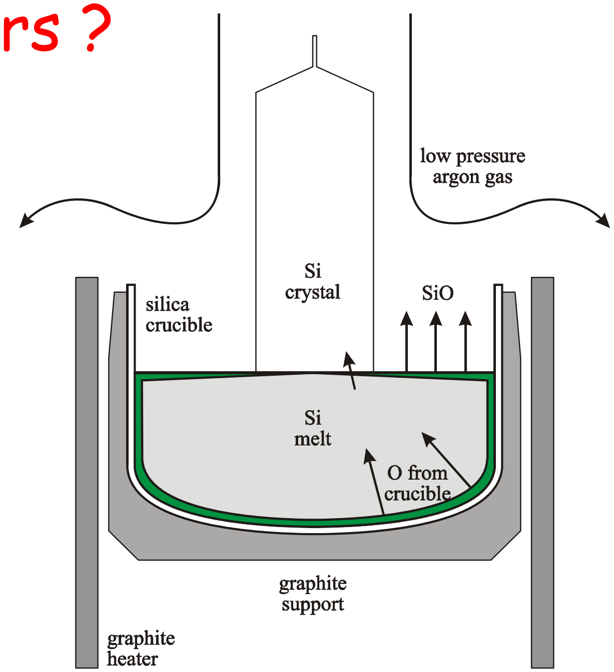
- very high space point resolution, ~ 3 μm locally
- very thin detector stations, to achieve vertex resolution <50 μm





Source: Johann Heuser, CBM meeting at GSI, Darmstadt, 20.04.2007

Why Cz-Si for particle detectors ?

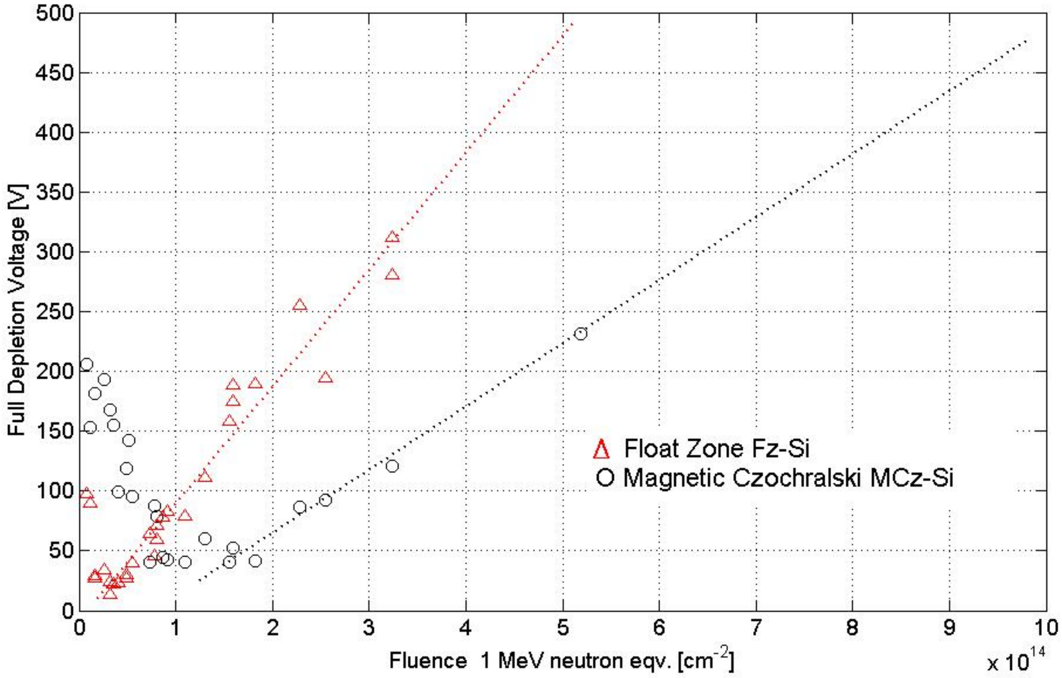


- Cz-Si available in larger diameters
- Lower wafer cost
- Better compatibility with advanced CMOS processes
- Oxygen brings significant improvement in thermal slip resistance
- Oxygen gives **significant radiation hardness** advantage.

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

Trapping term

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

Depletion term

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

Overall CCE is product of

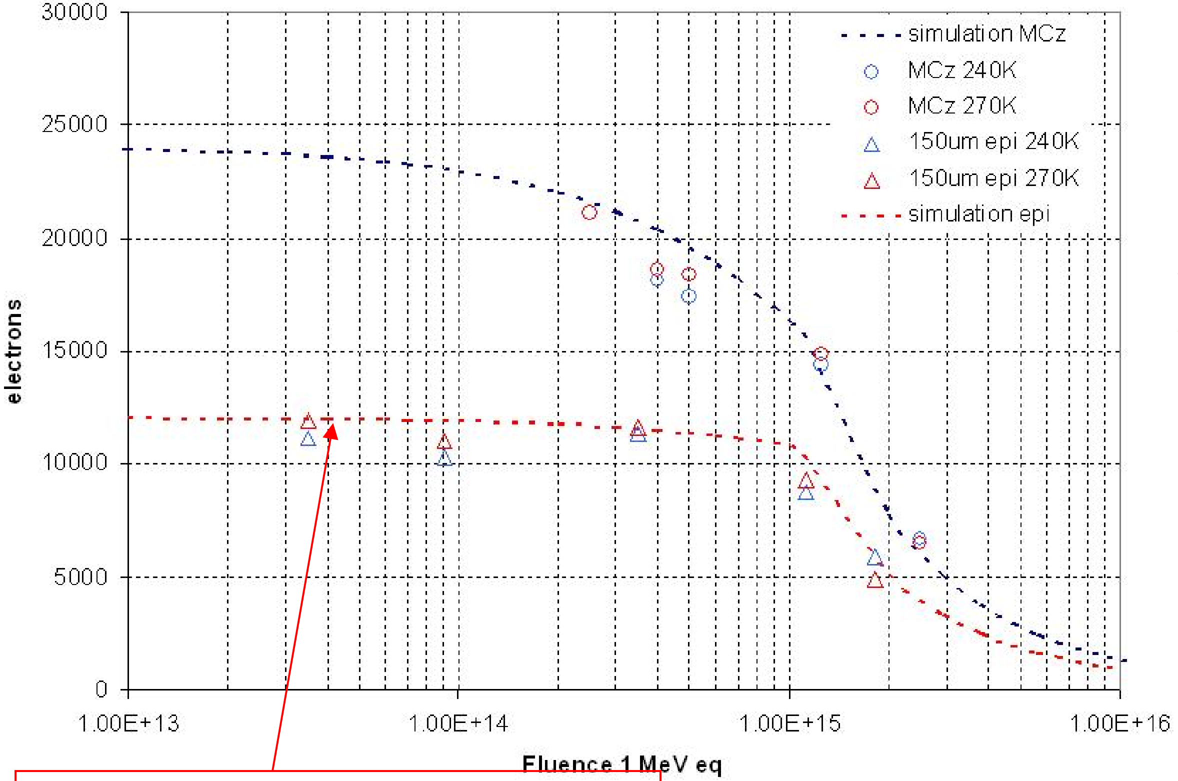
1. CCE_t trapping factor
2. CCE_{GF} geometrical factor

$$w = \sqrt{\frac{2\varepsilon\varepsilon_0 V}{eN_{eff}}} \text{ and } \frac{w}{d} = \sqrt{\frac{V}{V_{fd}}}$$

For fluence less than 10^{15} n/cm², the trapping term CCE_t is significant

For fluence 10^{16} n/cm², the trapping term CCE_t is a limiting factor of detector operation !

Charge Collection Efficiency



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

Measurement with IR laser and 500V bias

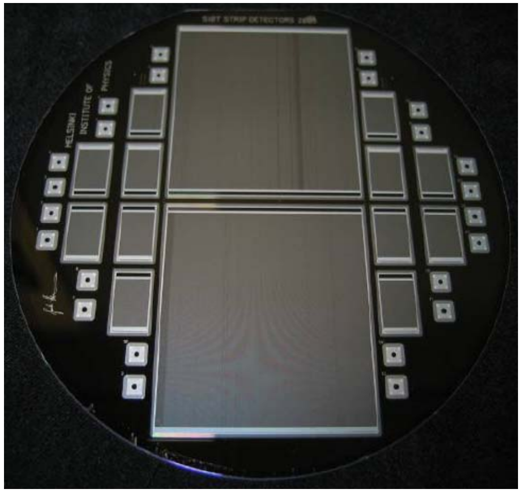
Pad detectors >> no weighting field effect >> test beam for strip detectors needed

>1×10^{15} cm^{-2} fluence MCz (300µm) and epi (150µm) are under depleted both

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

Requirement for low mass –Thin sensor vs. 2 sided

Drawnbacks of 2-sided sensor technology



1. Difficult biasing in heavy radiation environment. The DSD sensor needs to be read-out and biased on both sides. Thus, the read out circuits have to be in floating ground potential, which would be in case of heavy radiation environment, hundreds of volts.
2. High production costs due to the double sided fabrication process and increased mask levels that are necessary in order to process complicated double sided guard ring structure.
3. Complicated module assembly.

Can two one-sided thin detectors (e.g. 150μm thick do the same job as one double sided sensor ?

Why to go low temperatures ?

1. Leakage current scales down exponentially → less shot noise $\sqrt{I_{leak}}$ → Read-out treshold lower for given S/N → 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 → Small signal,difficult production,high cost.
    - Complex geometries (3D) →Not feasible manufacturing,high cost.
    - Cooling → 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 posses sufficient mechanical engineering expertise or is the subject disregarded ?

How the trapping is influenced by temperature ?

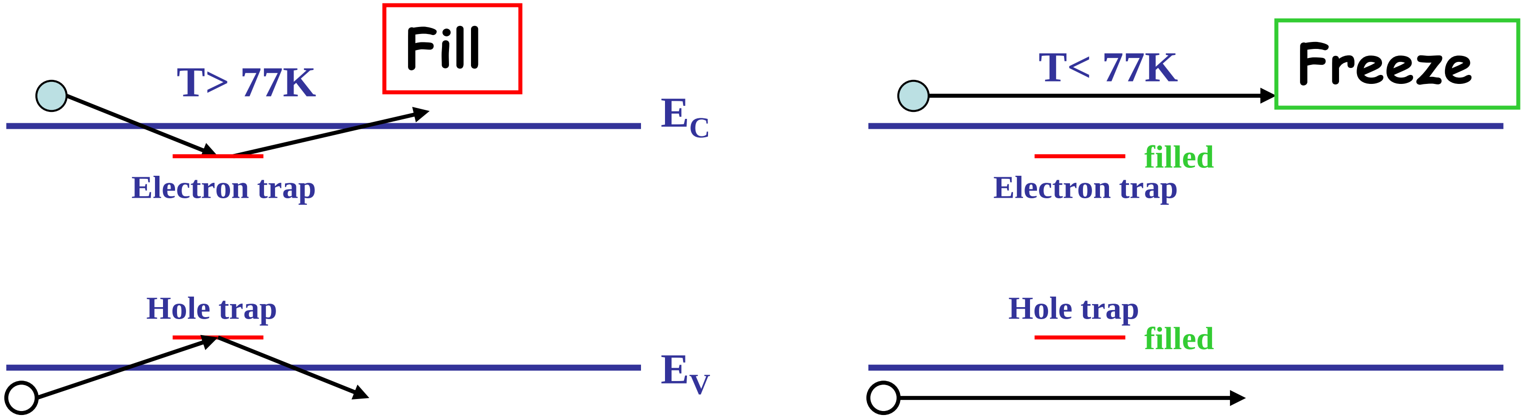
Trapping is balanced by the detrapping.
At the "low" temperature, the traps remain filled considerably long time (>>shaping time of Read-out electronics)

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

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

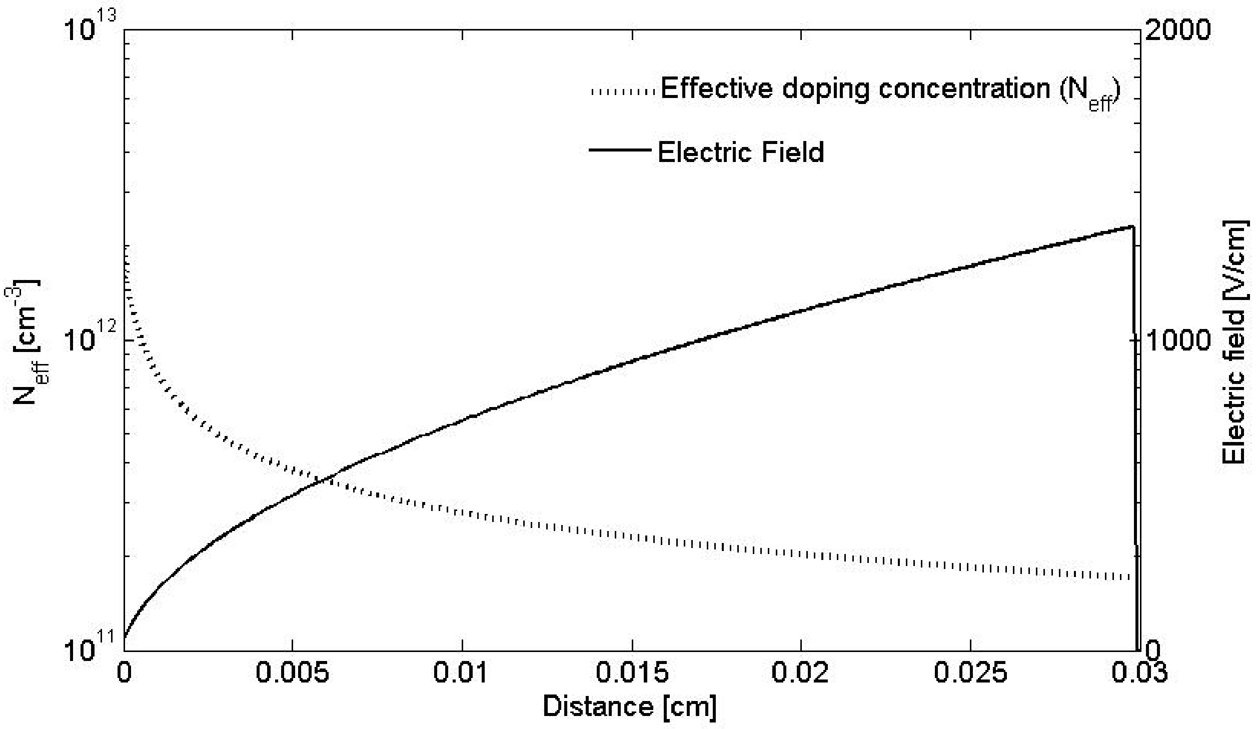
For A-center (O-V at E_c-0.18 eV with $\sigma \approx 10^{-15}$ cm^2)

T(K)	300	150	100	77	60	55	50	48	47	46
τ_d	3.7 ns	3.9 µs	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



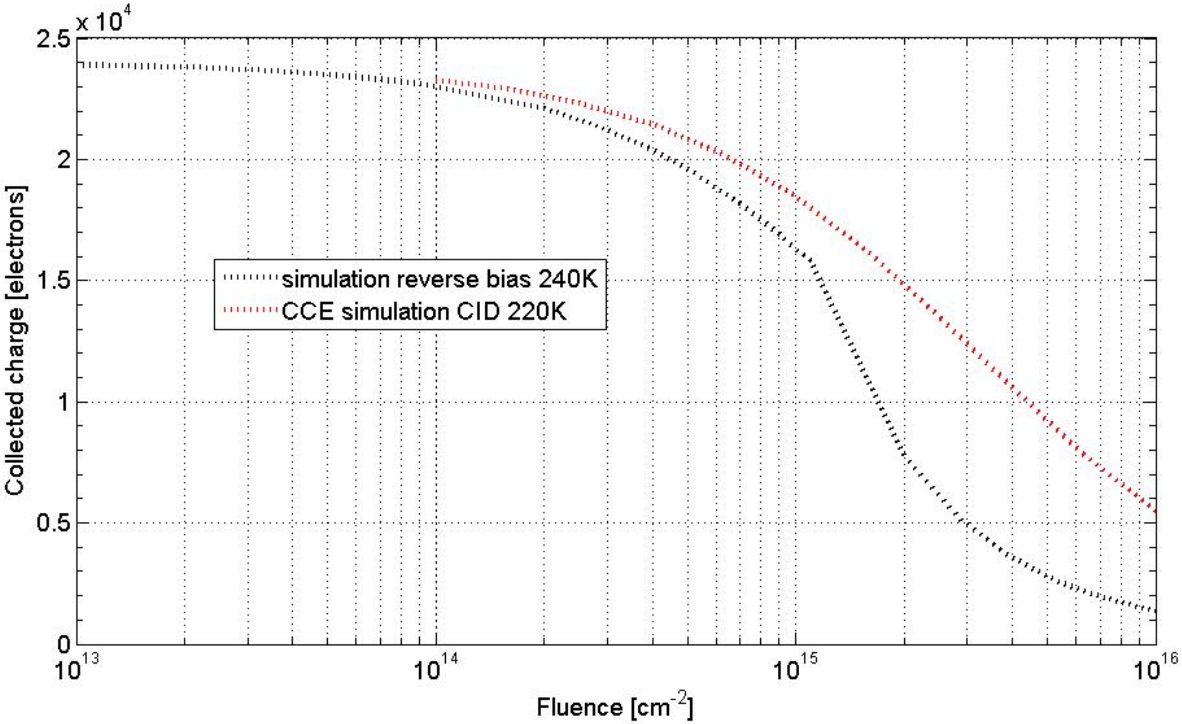
Electric field is extended through entire bulk regardless of irradiation fluence.

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

Detector is "fully depleted" at any bias or irradiation fluence

Expected CCE of CID at -50°C

strips ↔ pixels



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

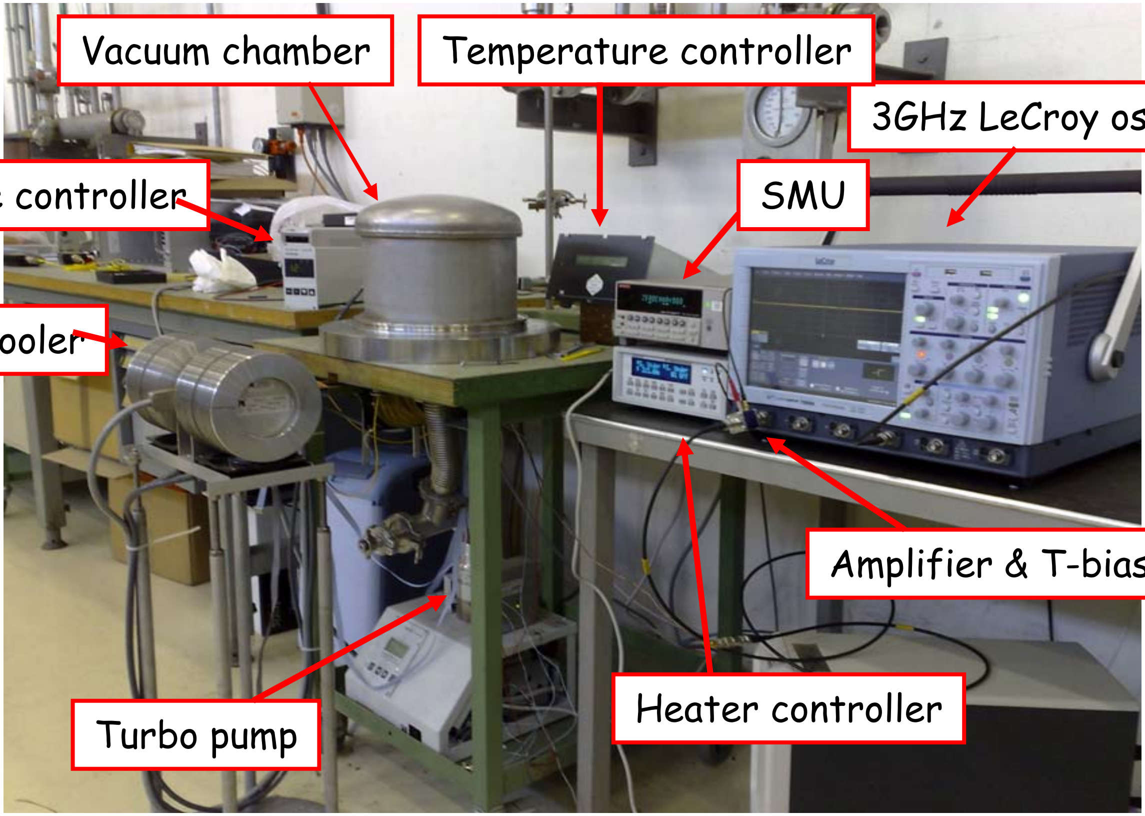
$$w_{pin} \propto \left(1 - \frac{x}{d}\right)$$

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

1×10^{14} n$_{eq}$/cm^2	τ_{trap}=10ns
1×10^{15} n$_{eq}$/cm^2	τ_{trap}=1ns
1×10^{16} n$_{eq}$/cm^2	τ_{trap}=0.1ns

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

Characterization of irradiated detectors



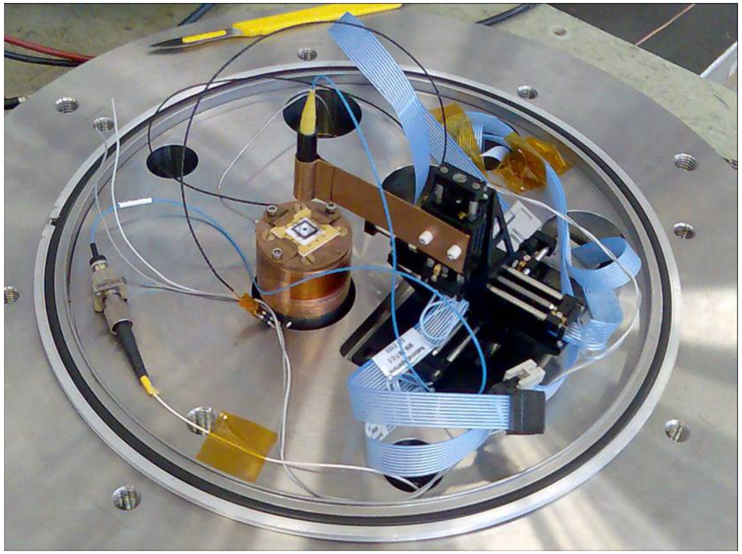
One has to resolve:

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 inhomogenous E(x)
3. CCE. Data about electric field distribution and effectice trapping times are needed in order to establish reliable radiation hardness scenario

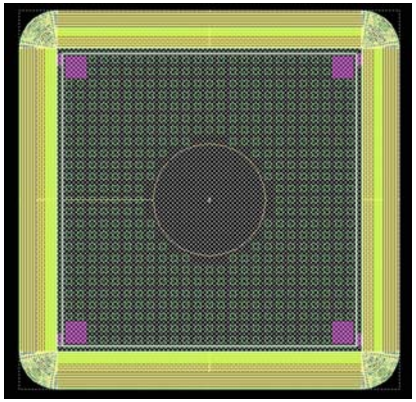
Cryogenic Transient Current Technique (C-TCT)
-Tool to study trapping effects and Charge Collection Efficiency

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)

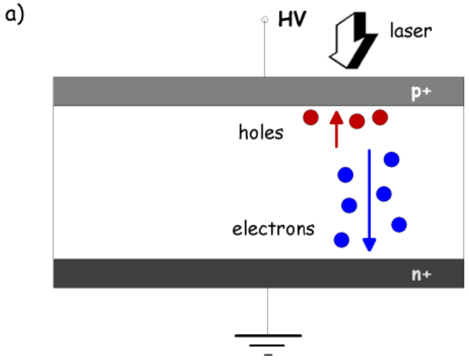


- Detector can be illuminated by red (670nm) or infrared (1060nm) laser light.
- IR light simulates MIPs. Red light is absorbed within few µm.
- If the detector is illuminated by red laser, only one type of carrier drift through the Si bulk and produce TCT signal

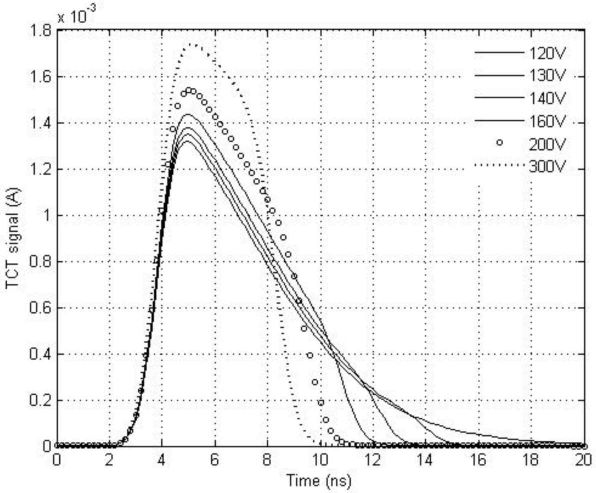


The sample is diode with opening in Al metallization and contact openings in the corners.
Size is typically 5 x 5 mm^2
Back side at HV, front side grounded

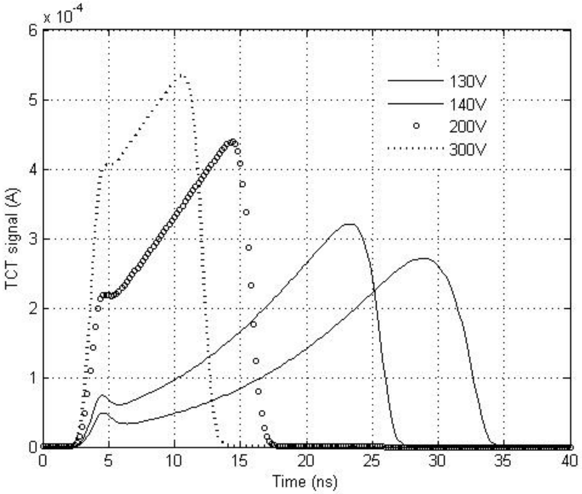
Principle of TCT measurement



- Hole current is collected to the p^+ implant faster than the RC time constant of measurement circuit
- Electrons drift through the entire bulk (typically 300µm)
- 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



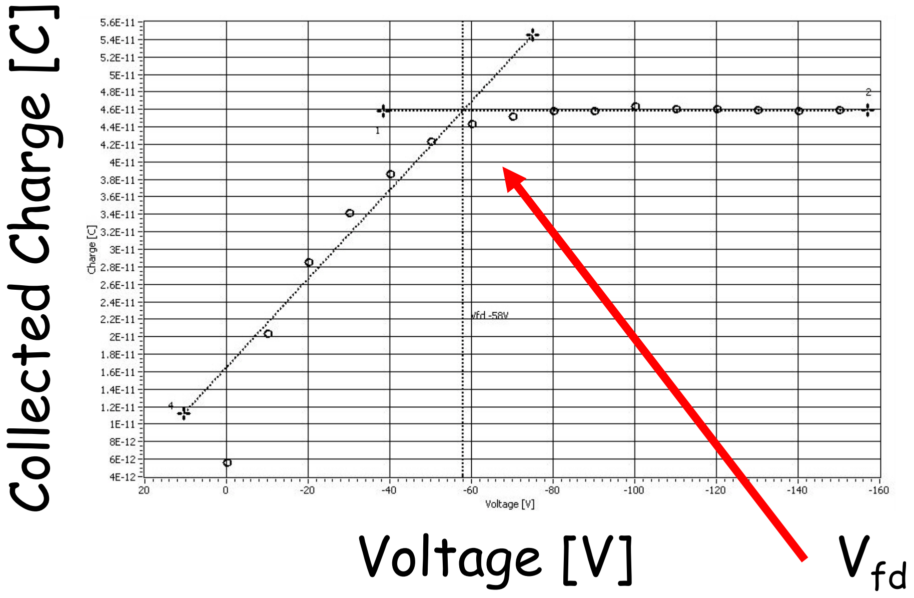
type inverted signal

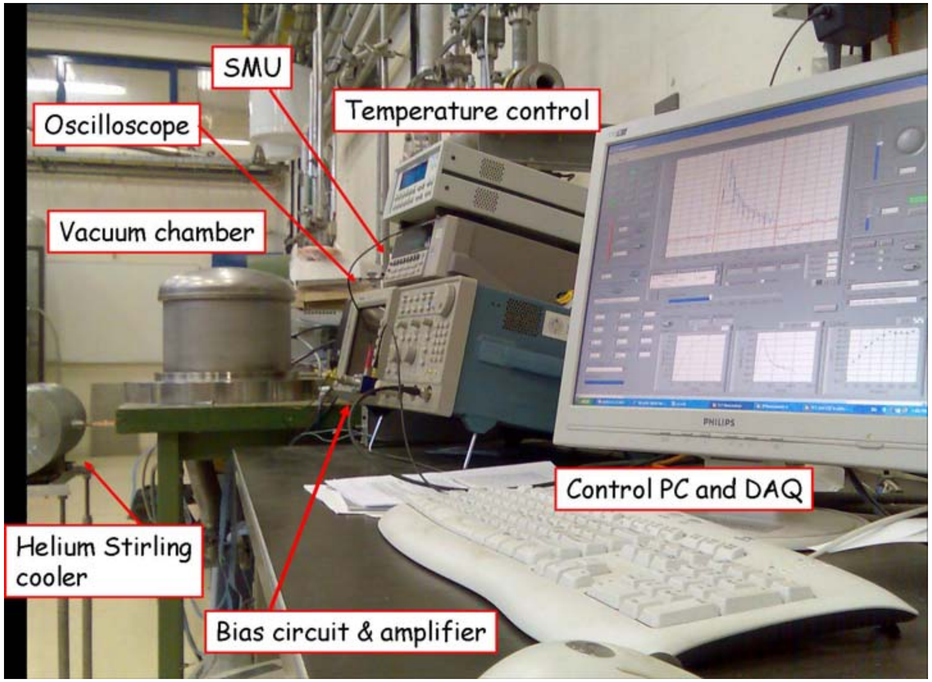
$$i(t) \propto \frac{Q_0}{d} \mu E(x) e^{-\frac{t_{drift}}{\tau_{trap}}}$$

Cryogenic Transient Current Technique (C-TCT)

With C-TCT it is possible to measure and extract

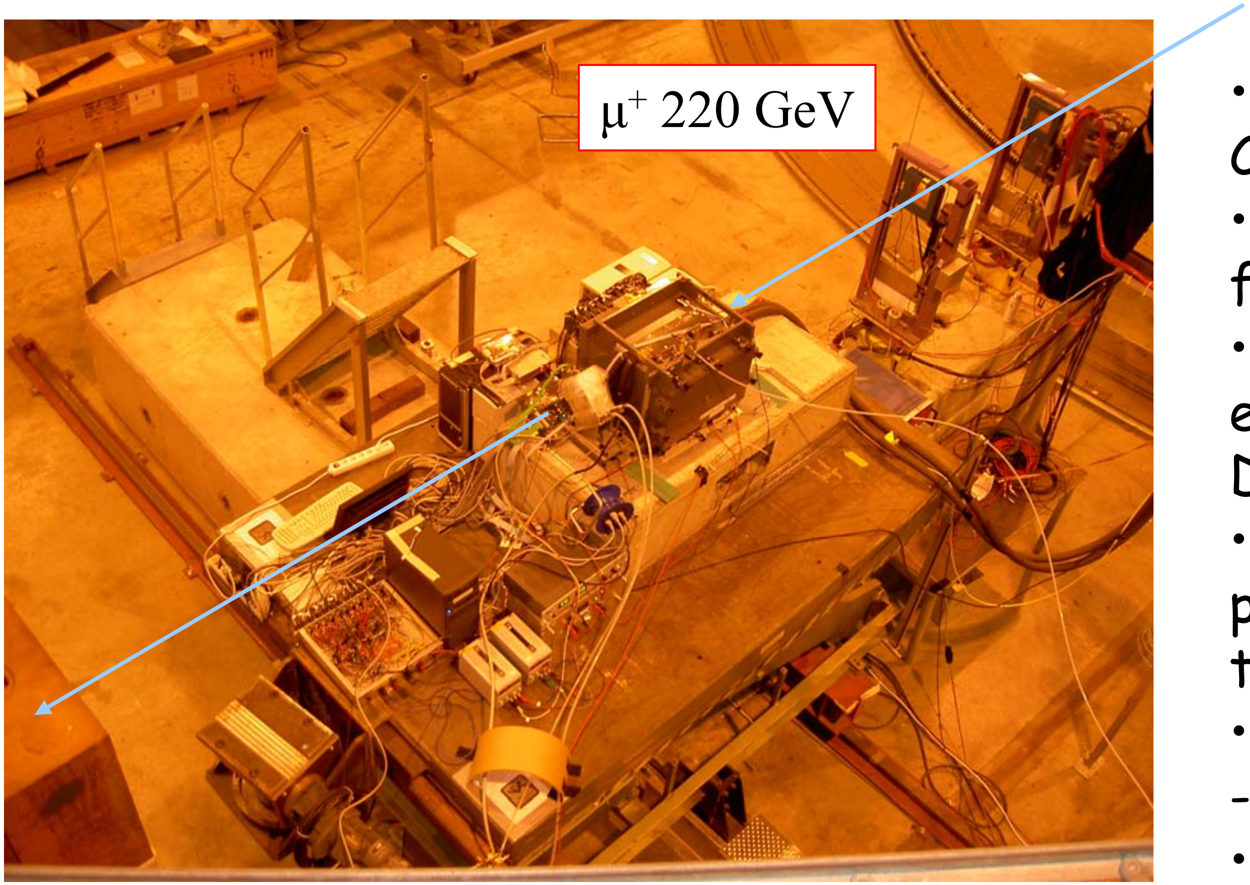
- -Full depletion voltage V_{fd}
- -Charge Collection Efficiency (CCE)
- -Type of the space charge (n or p)
- -Trapping time constant $\tau_{e,h}$
- -Electric field distibution $E(x)$





$$N_{eff} = \frac{2\varepsilon_0\varepsilon_{Si}V_{fd}}{qd^2}$$

Detector Characterization -Silicon Beam Telescope (SiBT)

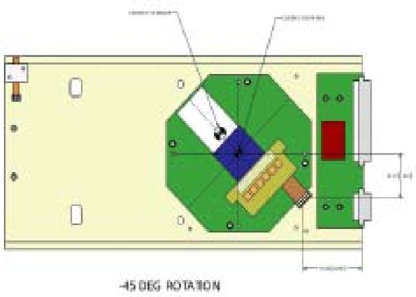


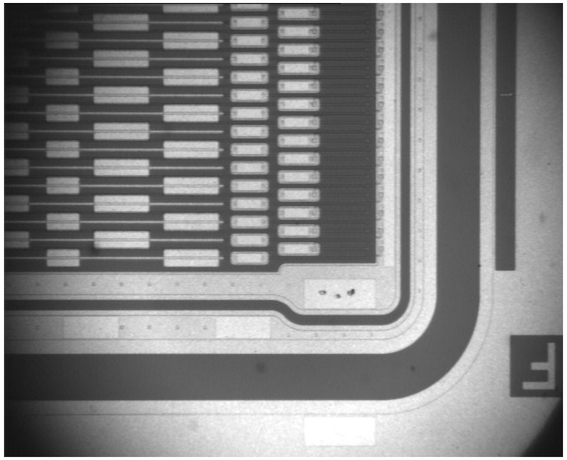
- Operated by HIP at CERN H2 area
- 220 GeV muon beam from SPS accelerator
- CMS based read-out electronics (APV25) and DAQ
- 8 detector planes providing reference tracks for DUT
- Measurement down to -50°C
- 20 000 events in about 15min

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 APV
  - Fully analog architecture
  - Shaping time 25ns
  - Can handle both signal polarities

    →(CID detectors, p and n-type detectors)

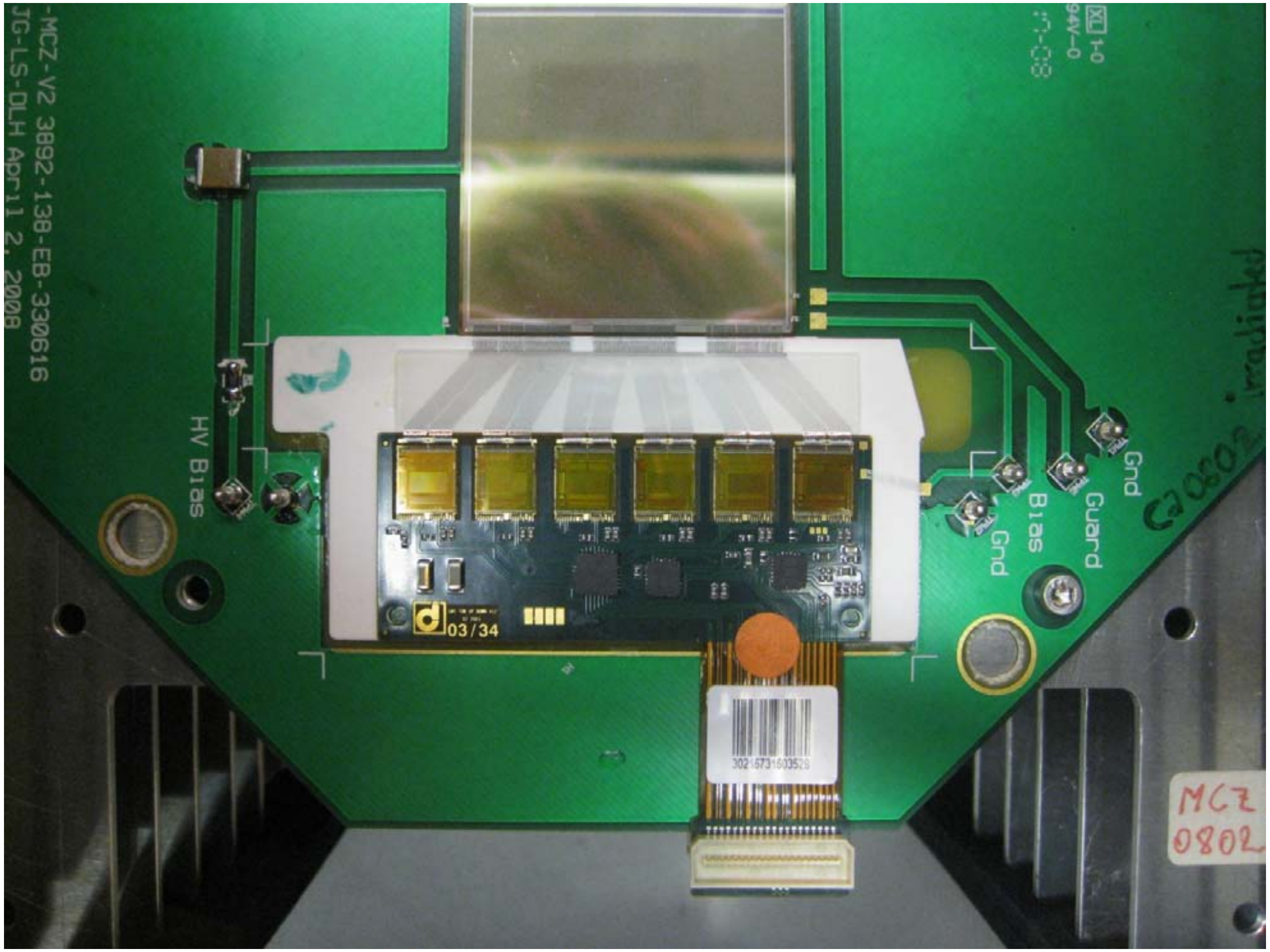




3D detectors at SiBT with APV read-out

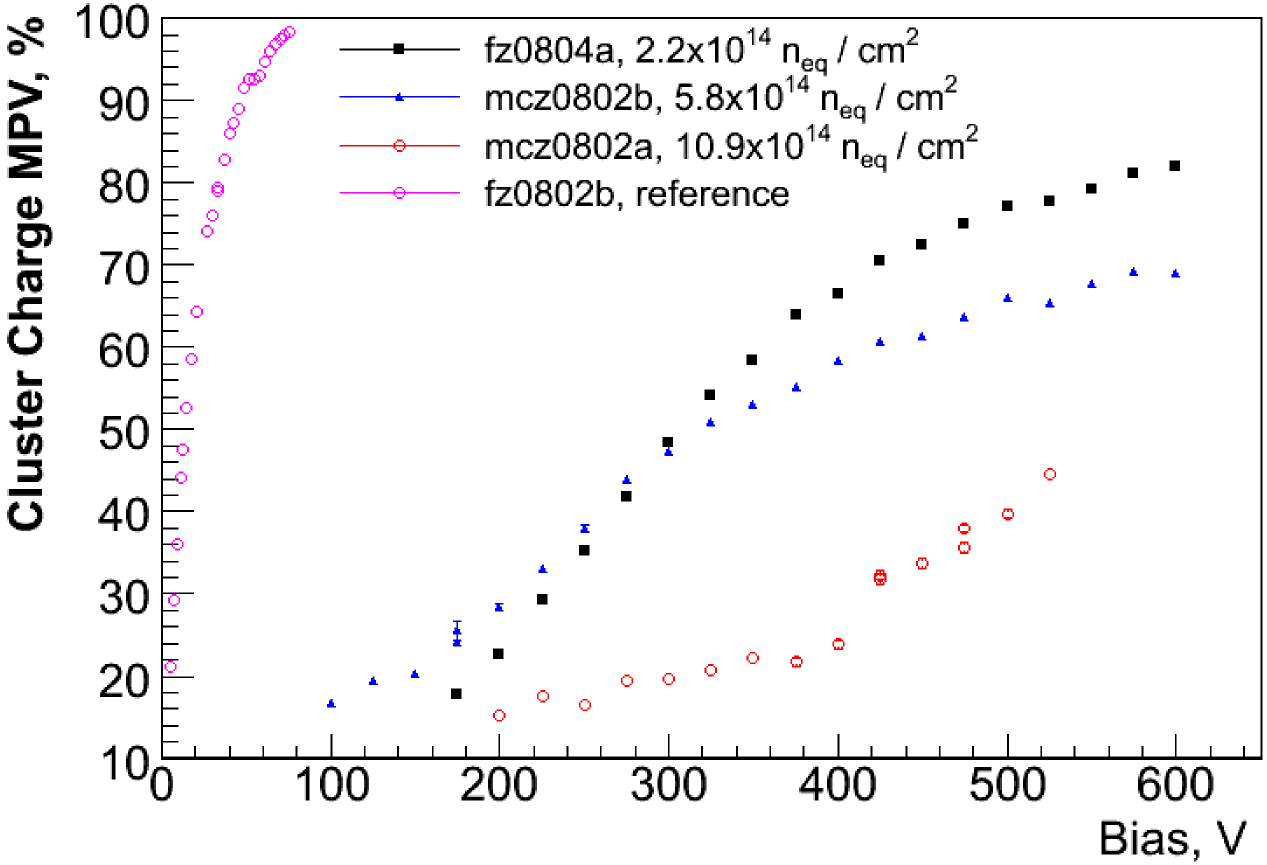
3D detectors fabricated at CNM and FBK-IRST for Atlas and LHCb pixel groups.

1×10^{15} n_{eq}/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

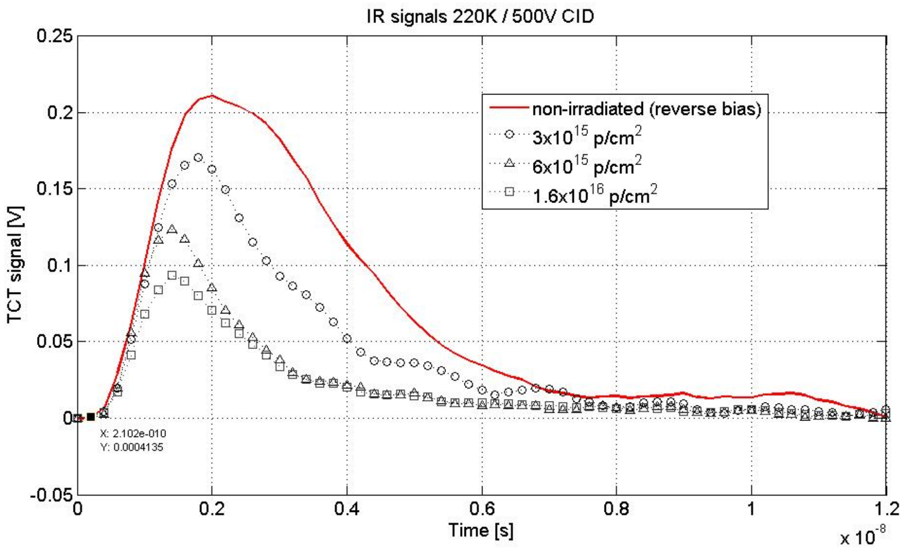
Summary results obtained by SiBT

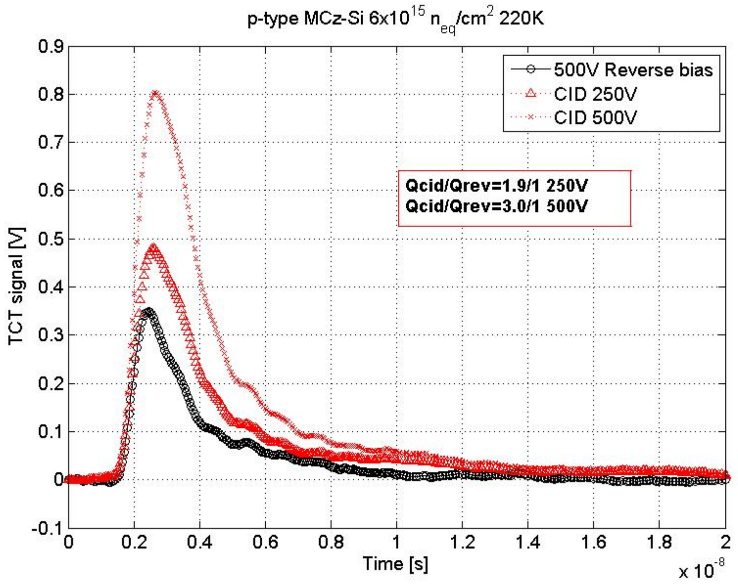


MCz-Si:

- 150% CCE at $1\times10^{15}n_{eq}/cm^2$
- S/N > 10 at -20°C

Summary of results obtained by TCT -performance of CID detector

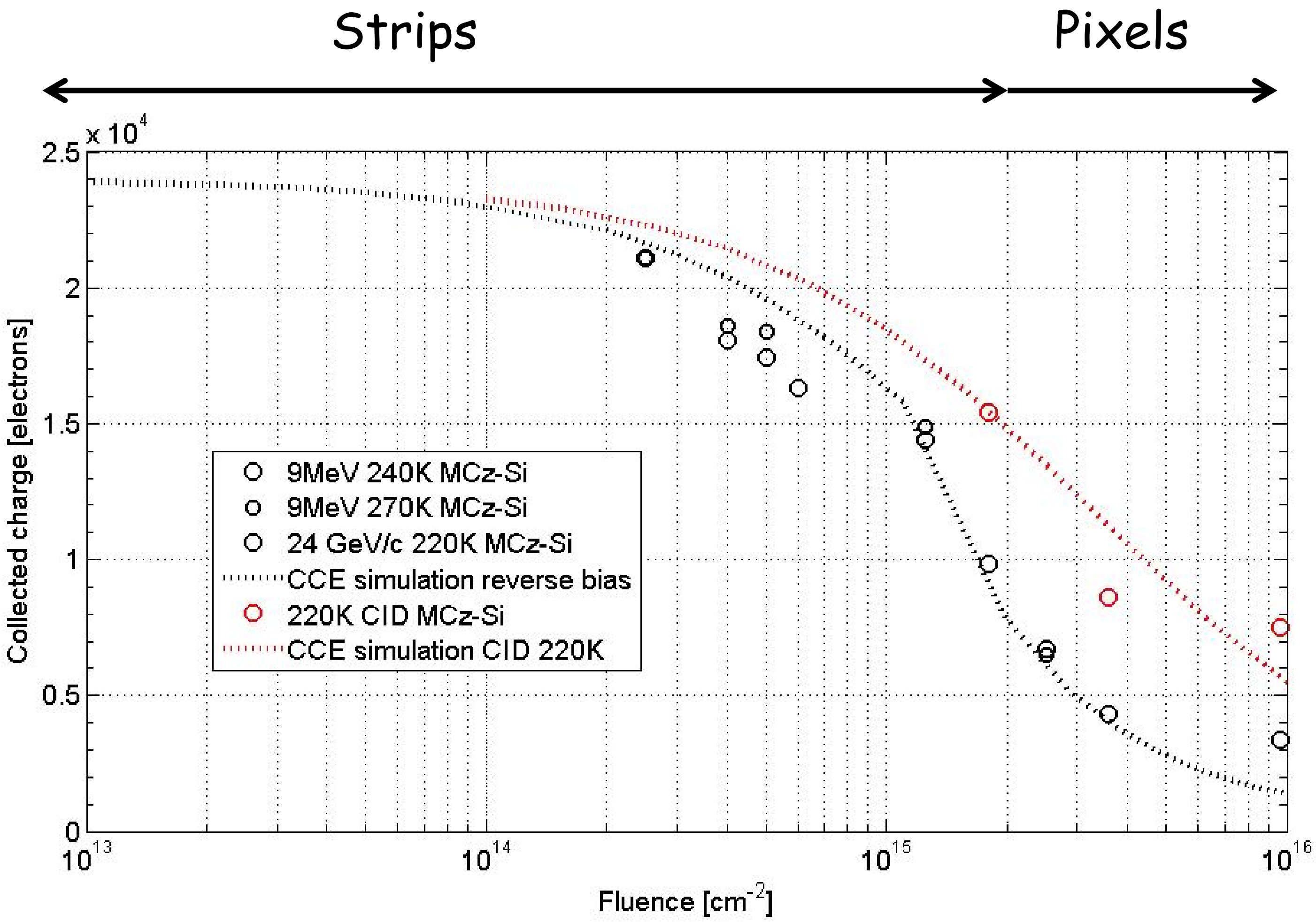




- Relative CCE ~30% / $1\times10^{16}n_{eq}/cm^2$
- -50°C / 500V (practical upper limit of V_{bias})

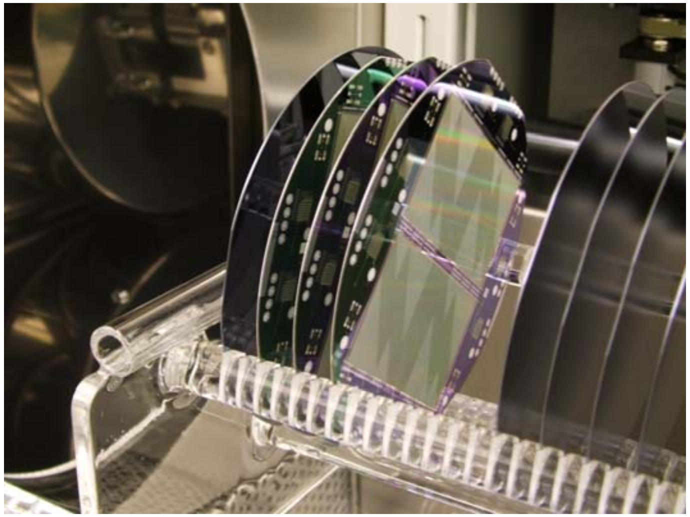
- 2×higher CCE at 250V compared with standard operation at 500V
- CID concept works with $n^+/p^-/p^+$ and $p^+/n^-/n^+$ structures both

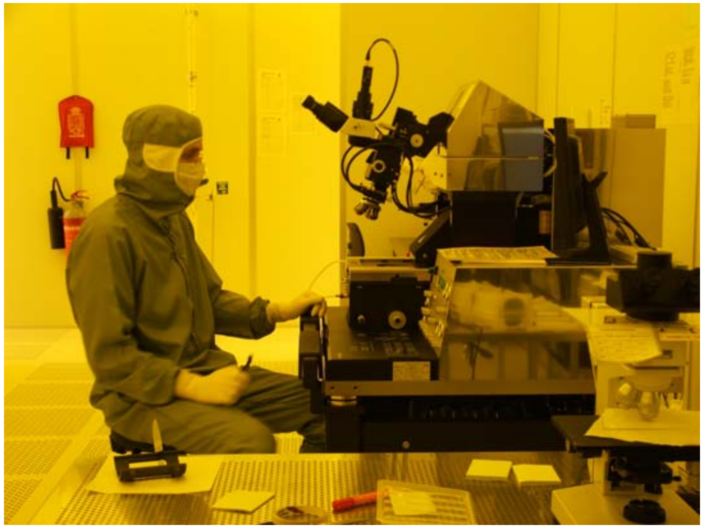
Charge Collection Efficiency (Reverse bias and CID)



Is Charge Injected Detector (CID) concept feasible ?

- At S-LHC/FAIR efficient cooling is needed anyway.
- Currently engineers at CERN are studying CO_2 cooling.
- CO_2 is attractive option because industry is moving towards CO_2
- -50^{0}C is relatively easily achieved by CO_2
- That's operational temperature of CID detector
- 2x higher CCE can be achieved at -50^{0}C





Summary -Technical

- Standard detector operation possible by 300μm MCz-Si up to 1×10^{15} n_{eq}/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 1×10^{16} n_{eq}/cm^2 fluence.
- Collected charge equals $\approx$7000e^- and 30%.
- Read-out electronics, DAQ, irradiated MCz-Si sensors bonded to the CMS RO already demonstrated.
- Operation of CID detector at -50^{0}C/3$\times10^{15}$ n_{eq}/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.

Summary -General

- GSI/FAIR experiments need radiation hard silicon sensors (pixels, strips, MAPS) several tens of m^2's.
- Main requirements are radiation hardness and low mass, i.e. thin or 2-sided (or both).
- The volume of GSI/FAIR is somewhere in between "large scale" and "niche" → Probably only middle sized companies/institutes are motivated vendors.
- R&D and testing are required before "cashflow" to Finnish industry.
- There is also potential for interconnection technology, e.g. Pitch Adapters, Flip-Chip bonding, fine granularity tab bonding etc.

- Expertise/infrastructure accumulated from CERN experiments participation is largely applicable to GSI/FAIR.