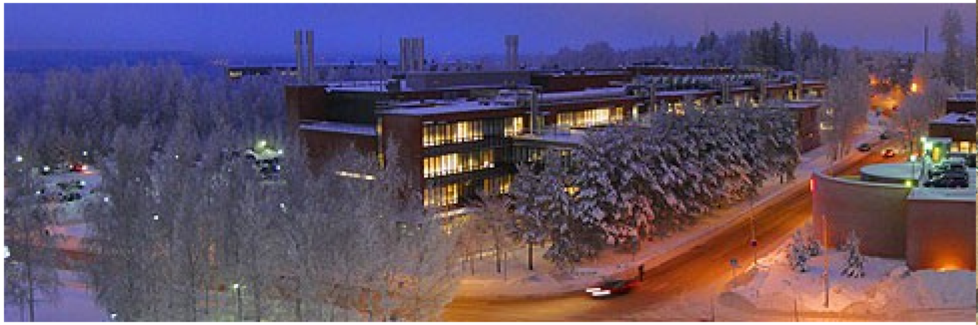
Compact
Muon
Solenoid
experiment at
CERN's LHC

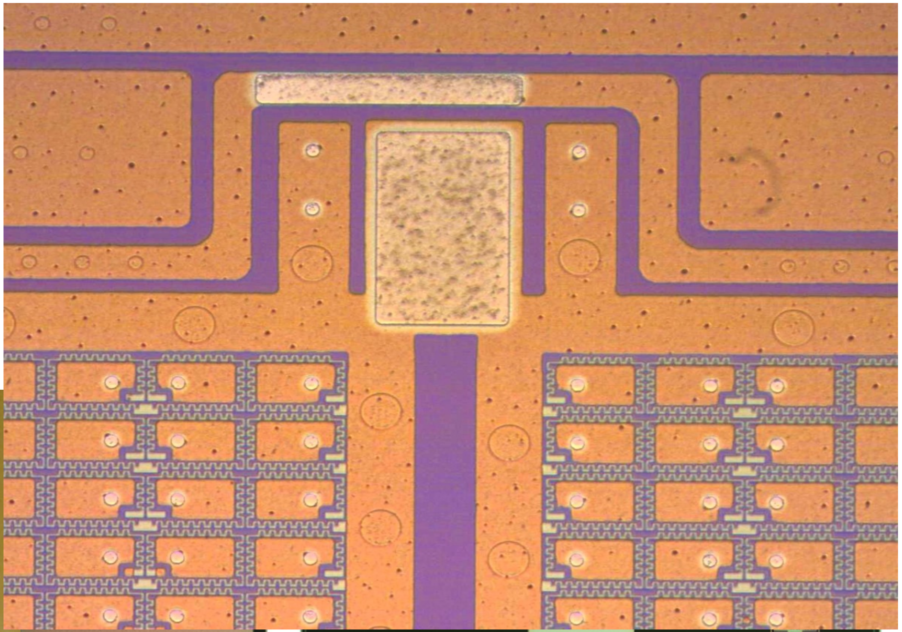
Development of radiation hard silicon radiation detectors for upgraded LHC experiments

Detector research – Helsinki Institute of Physics



Silicon detector R&D at HIP

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



Jaakko Härkönen
Helsinki Institute of Physics
Project Leader
CMS Upgrade Project
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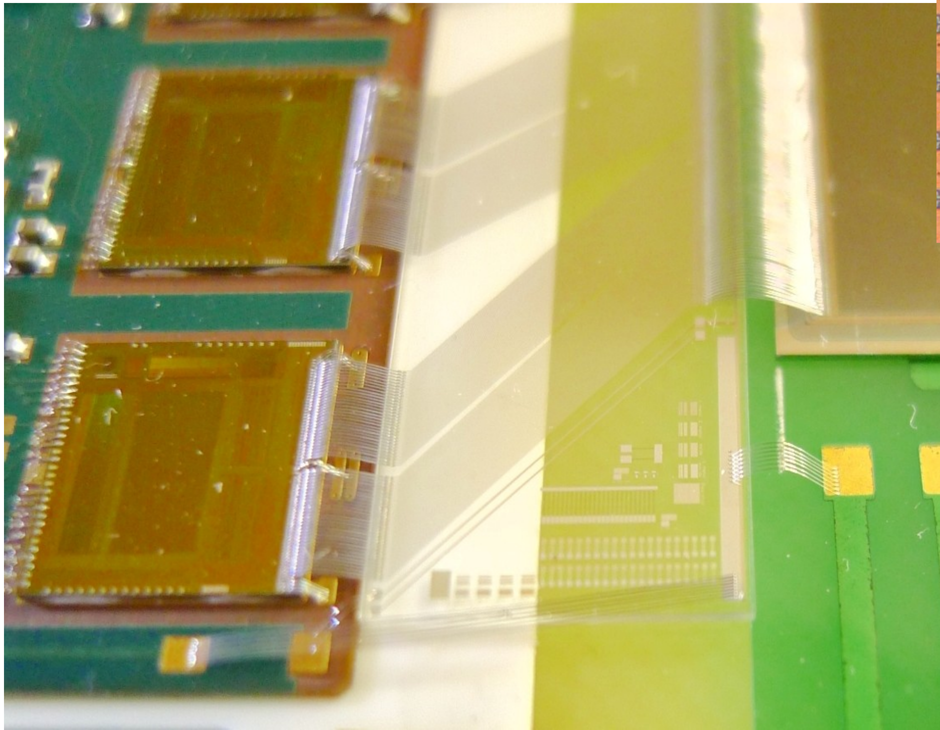
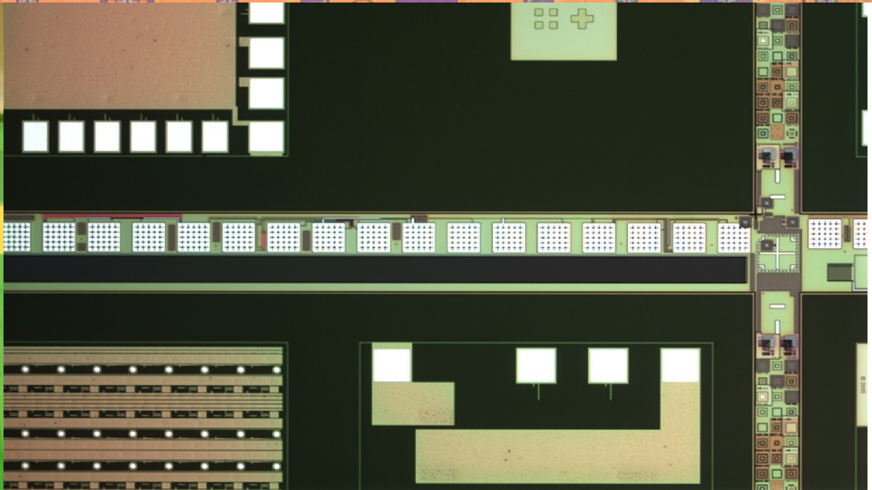




Outline

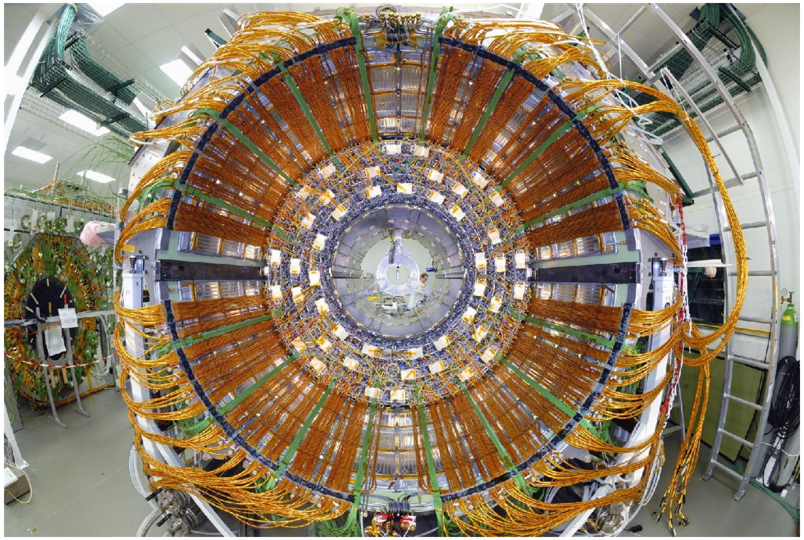
Who are we ?

Our activities – CMS experiment upgrade and detector R&D

- Detector processing at Micronova
- Networking with CERN RD39 and RD50 Collaborations
- Detector characterization

Future trends in radiation detection

- Particle and nuclear physics
- Photon science
- Medical and industrial imaging
- Space applications



The CMS Tracker implements 25000 silicon strip sensors covering an area of 210m^2. Connected to 75000 APV chips, one has to control 9600000 electronic readout channels, needing about 26 million microbonds.

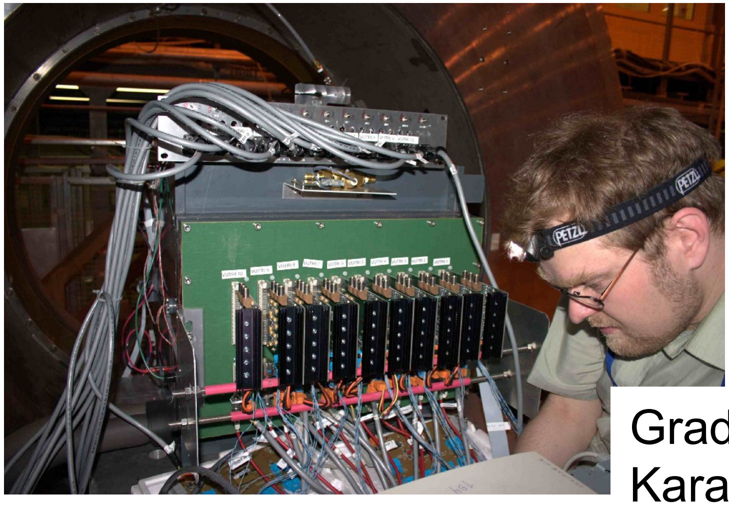
HIP CMS Upgrade Project

Dr. Jaakko Härkönen

Dr.Esa Tuovinen

Dr. Panja Luukka

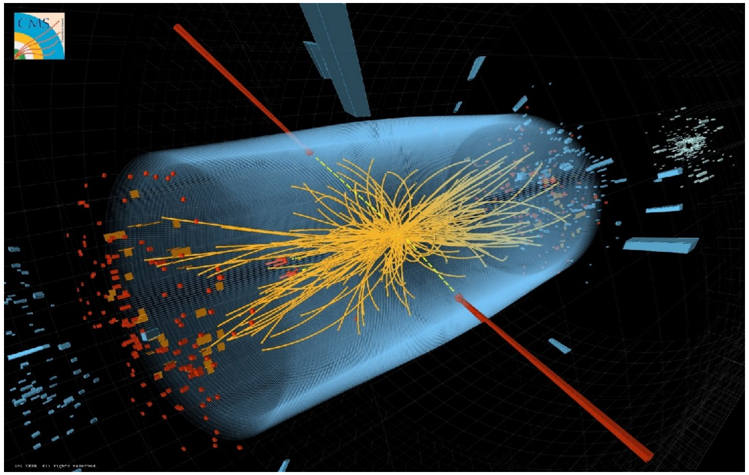
Grad.stud Timo

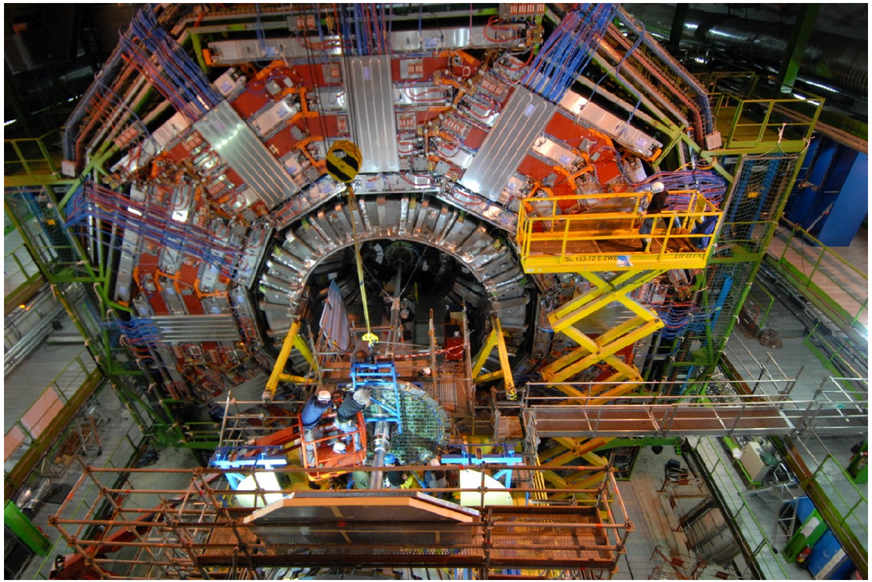


Grad.stud Aneliya Karadzhinova

CMS experiment upgrade and detector R&D

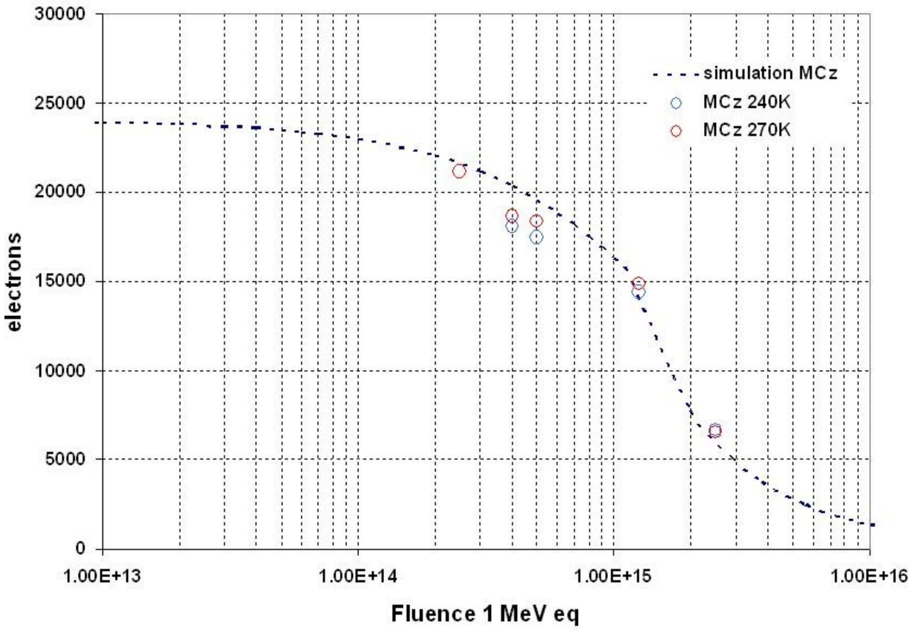
- Compact Muon Solenoid is “flagship” project of Finnish HEP community
- CMS will be upgraded in two steps
  - Phase I: Innermost Si pixel detector will be completely replaced in 2015-2016.
  - Phase II: Entire Si detector (pixels + strips) ~ 2020.
- Upgrade projects are mainly *in-kind* from collaborating institutes
  - Institutes are usually looking for industrial return for home countries.
- Motivation for upgrades is search for more rare particle decay events
  - Radiation hardness of Si devices is major challenge





Radiation hardness challenge

- Constant Luminosity increase is foreseen after the 1st phase of the LHC
- Extensive R&D is required becau



1. **Leakage current (I_{leak}) increases 10 X**

   - Increased heat dissipation
   - Increased shot noise

2. **Full depletion voltage (V_{fd}) will be >1000**

3. **Trapping will limit the Charge Collection efficiency (CCE).**

   - CCE at 1×10^{15}cm^{-2} ≈ 50% (strip layers of HL-LHC Tracker)
   - CCE at 1×10^{16}cm^{-2} ≈ 10-20% (pixel layers of HL-LHC Tracker)

Traditionally used detector material -Float Zone silicon (FZ

- Very high resistivity of Si is required to fully deplete typically 300µm thick bulk

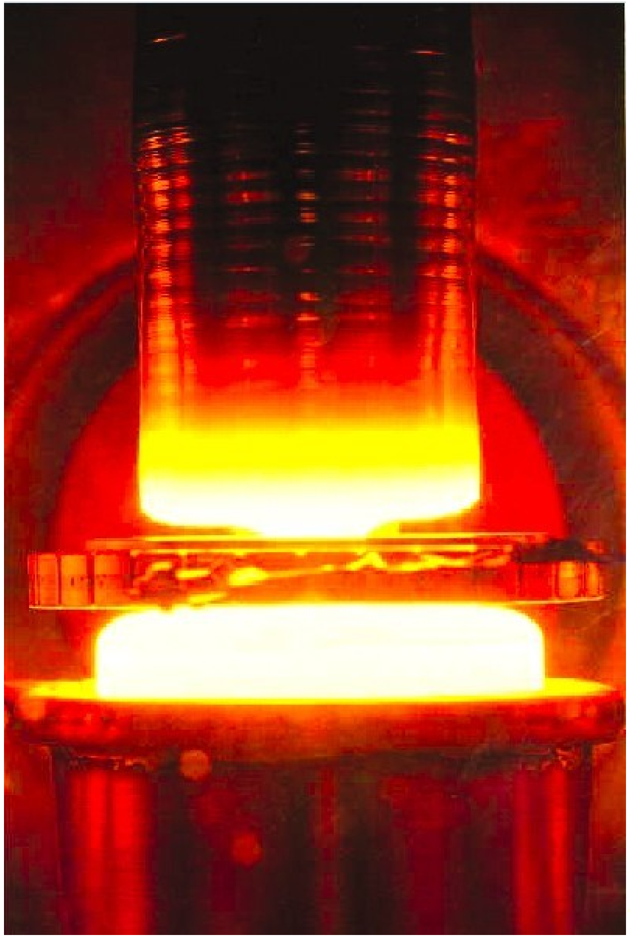
- Float Zone silicon is very pure silicon obtained by vertical zone melting.

- The process starts with a polysilicon rod inside a chamber either in a vacuum or an inert gas

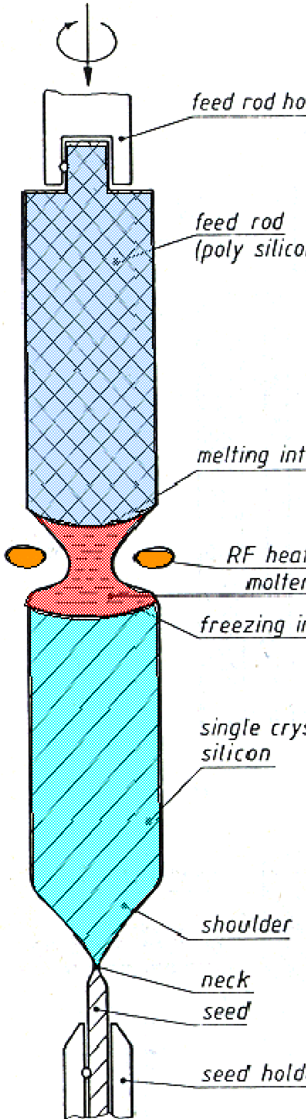
- An RF heating coil melts about a 2 cm zone in the rod

- The RF coil moves through the rod, moving the molten silicon region with it. This melting purifies the silicon rod

- Oxygen can be diffused into the silicon – called Diffusion Oxygenated Float Zone (DOFZ) (done at the wafer level)



Float-zone pulling



Simple solution -Magnetic Czohralski silicon (MCz-Si)

High resistivity magnetic Czochralski silicon (MCz-Si):

- Contains intrinsically high level of oxygen (typically 10^{17}-10^{18} cm^{-3}).
- Oxygen content can be adjusted by crystal pulling speed within the range from few ppma above the O solid solubility in Si

- Formation of thermal donors in p-type MCZ-Si can be compensated by intentionally introducing thermal donors (TD

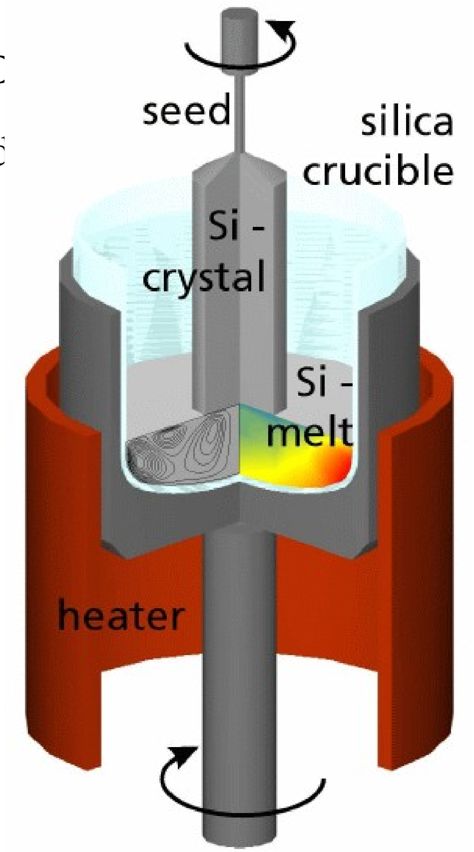
- Depletion voltage of detectors can be tailored
  a) oxygen concentration in the bulk.
  b) thermal history of wafers
  (Thermal Donor killing).

- Possibility for internal gettering.

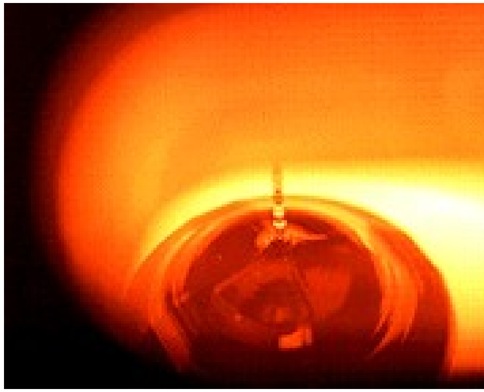
-Higher mechanical strength.

-Less prone to slip defect formation.

-Cost effectiveness compared to e.g. Float Zone silicon (FZ).

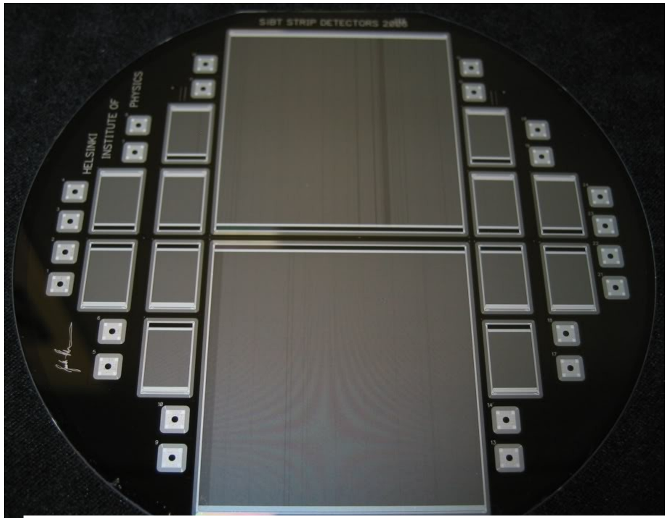


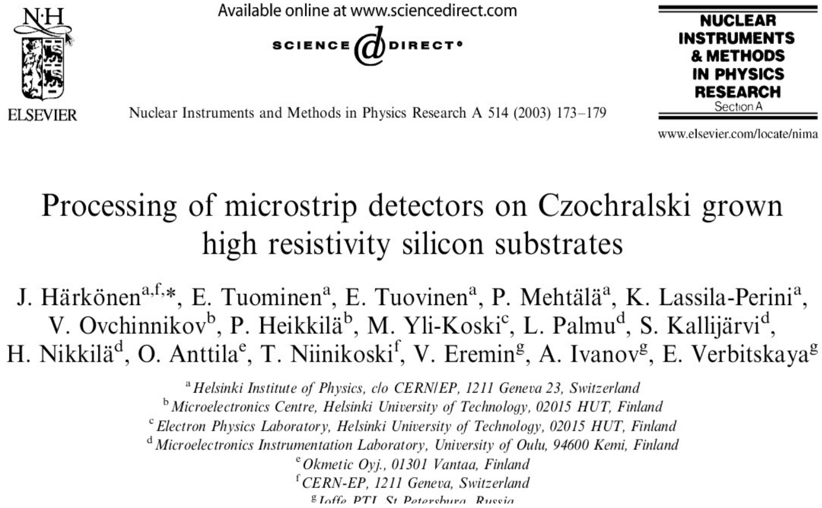
Si-crystal is pulled from a Si-melt while rotating. Magnetic field is used for damping the oscillations in the melt.



Radiation hard MCz-Si particle detectors

Original paper in 2003 was collaboration of HIP-Ioffe PTI-Brookhaven National Lab-Okmetic

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Nuclear Instruments and Methods in Physics Research A 514 (2003) 173–179

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A

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Processing of microstrip detectors on Czochralski grown high resistivity silicon substrates

J. Härkönen[a,f,*], E. Tuominen[a], E. Tuovinen[a], P. Mehtälä[a], K. Lassila-Perini[a], V. Ovchinnikov[b], P. Heikkilä[b], M. Yli-Koski[c], L. Palmu[d], S. Kallijärvi[d], H. Nikkilä[d], O. Anttila[e], T. Niinikoski[f], V. Eremin[g], A. Ivanov[g], E. Verbitskaya[g]

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[g] *Ioffe PTI, St Petersburg, Russia*

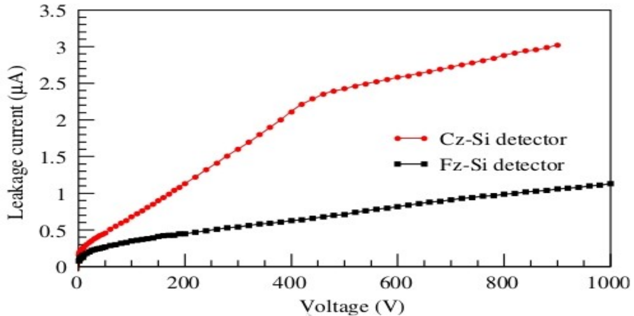


Fig. 4. Current–voltage characteristics measured from 32.5 cm^2 Cz-Si and Fz-Si detectors.

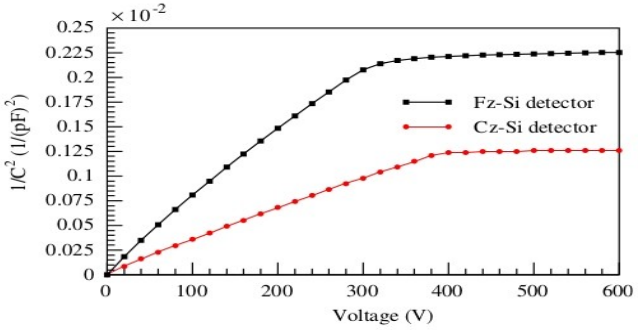
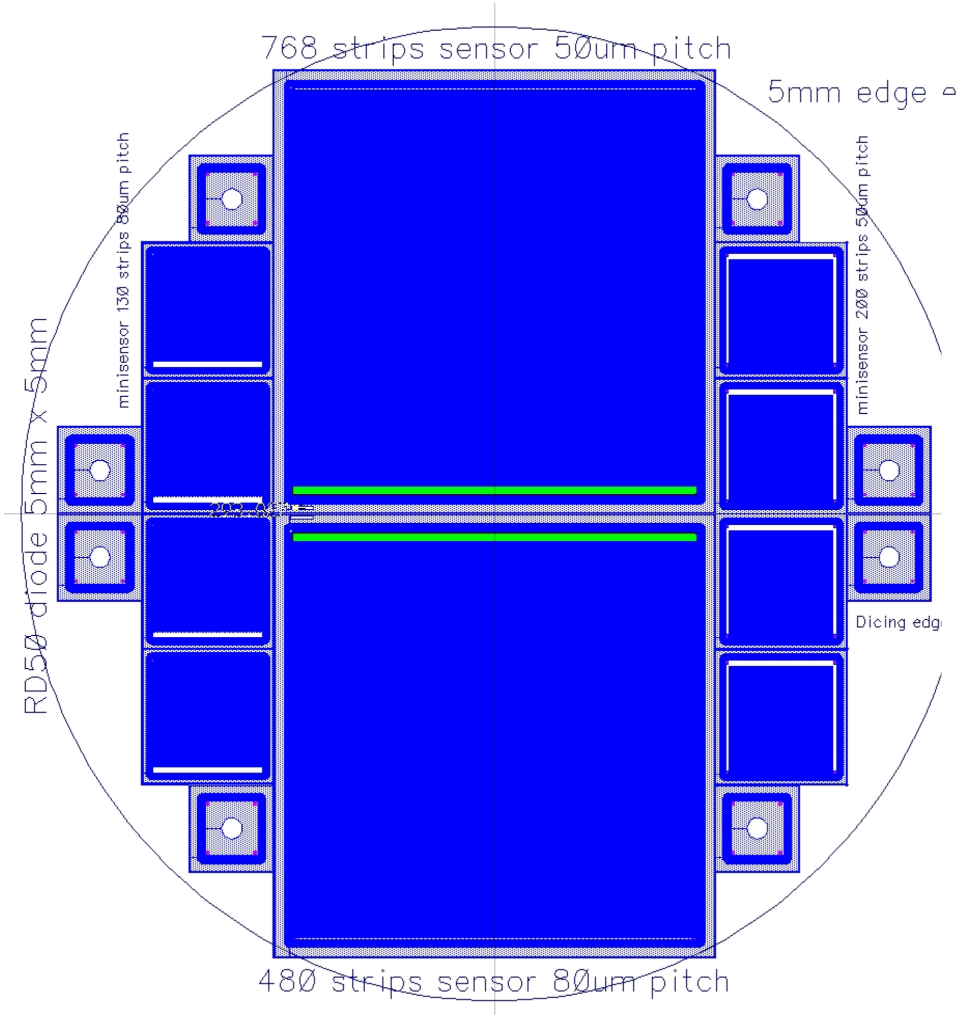


Fig. 5. Capacitance $1/C^2$ plots from Cz-Si and Fz-Si samples.

Czochralski (MCZ) method. The

Helsinki sensor -Benchmark device



4" inch wafer

design details of the AC-coupled strip detector.

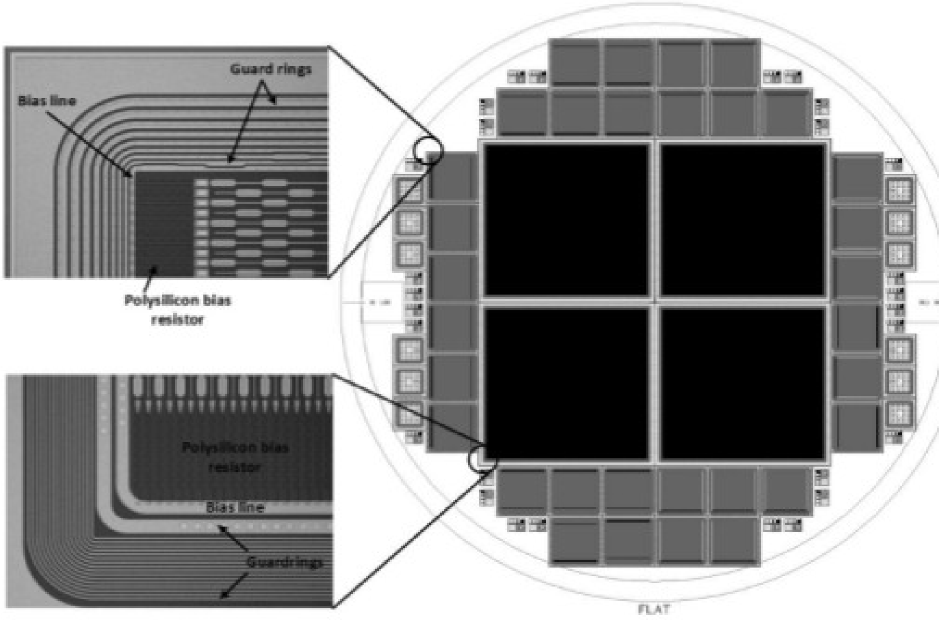
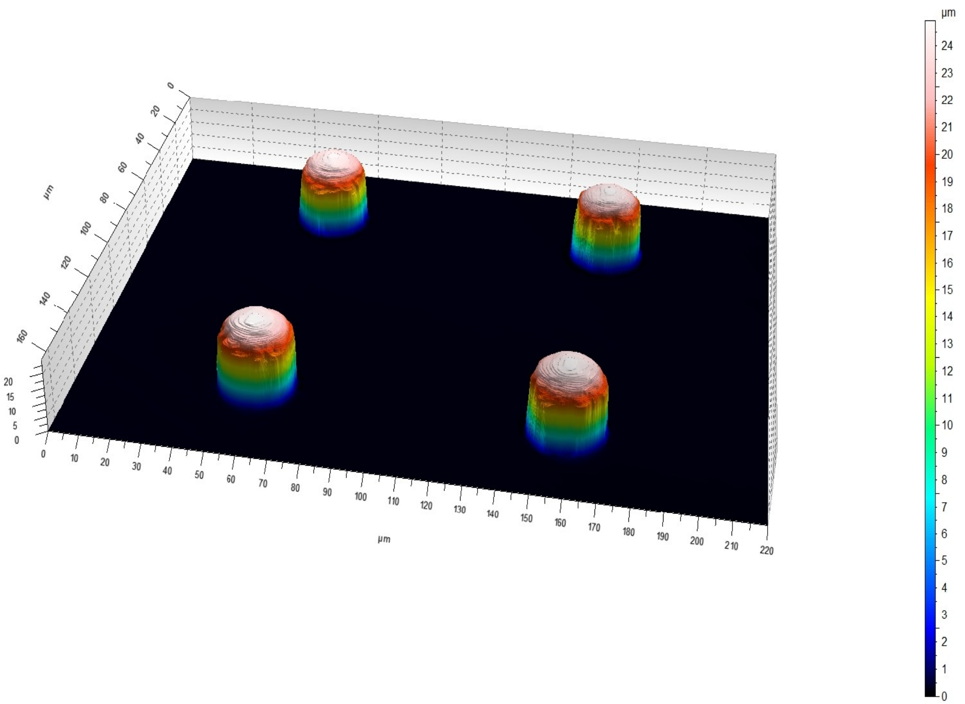
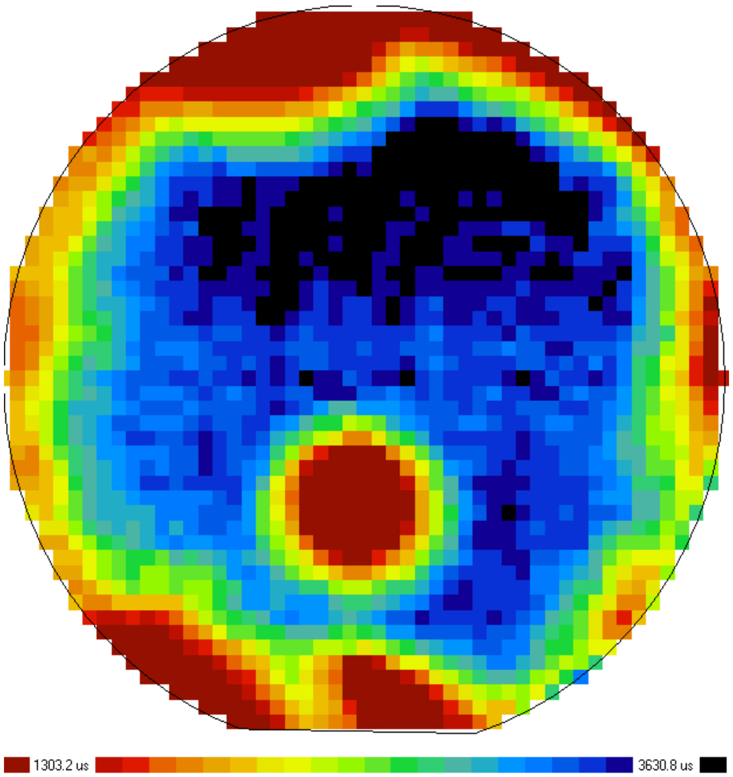


Figure. 2. The layout of the six inch wafer. The two insets on the left show corners of AC-coupled strip detectors. Strip electrodes are connected t common bias ring through snake-shape polysilicon resistors. In the mini-s sensors, the active areas are embraced by 6 guard rings with stepup pitc While in the full-size strip sensors, 16 isometric narrow guard rings and one w guard ring are implemented.

6" inch wafer

Characterization of radiation detectors -Processing / clean room / wafer

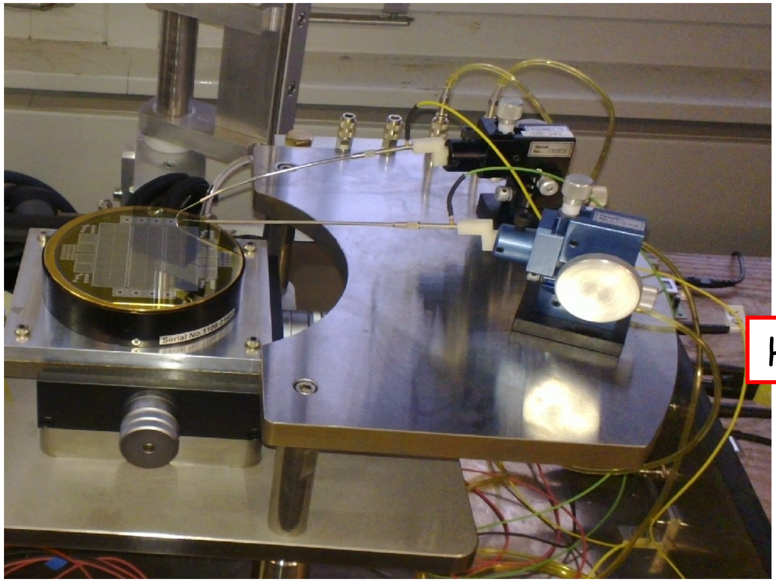




Scanning White Light Interferometry
- Practical tool for step height / coverage mappings
- Applications e.g. solder bump dimension mapping for pixel detectors / read-out ASICs, various MEMS applications....

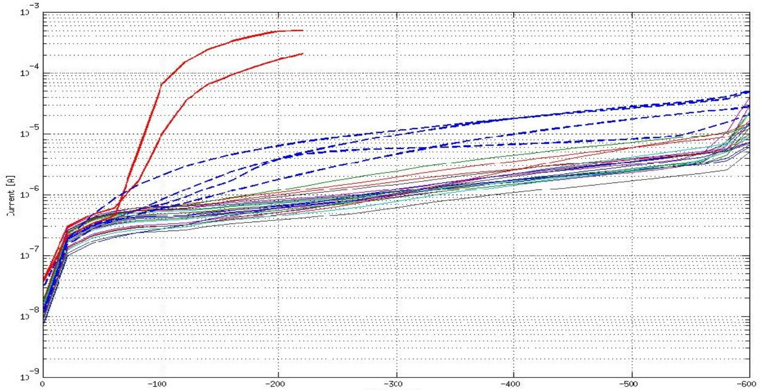
Lifetime scanner
- Provides many measurements such as PCD, SPV, LBIC, QV etc
- Essential tool for contamination control and thin film / interface characterization

Characterization of radiation detectors -Device level

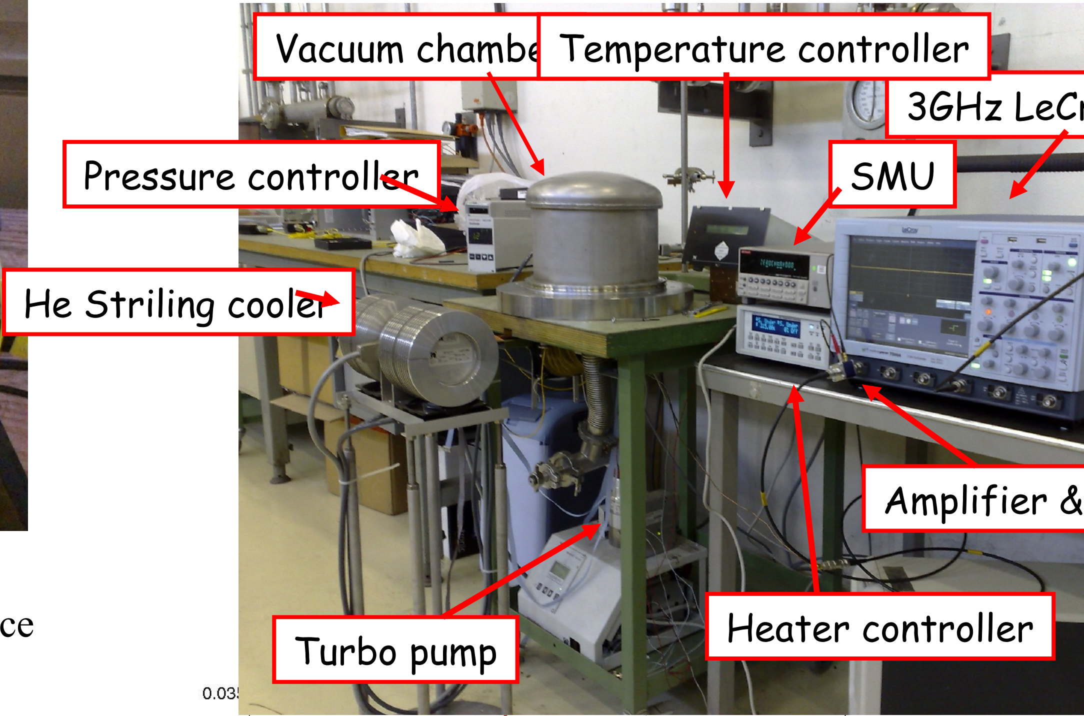


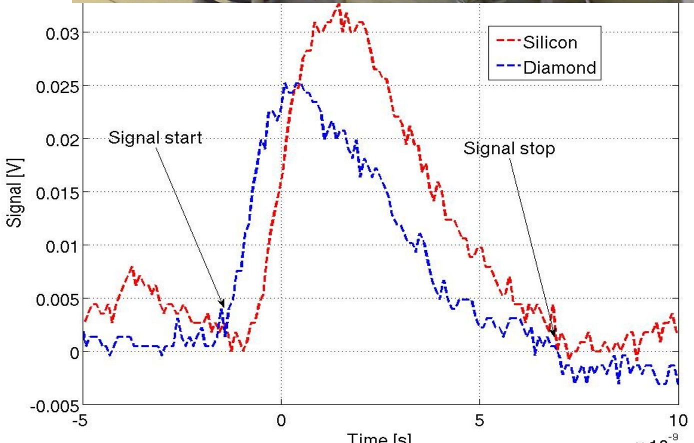
Capacitance-Voltage/Current-Voltage probing

- Essential tool for QA of any semiconductor device
- In detector applications, the measurements typically must be made at low T and in darkness

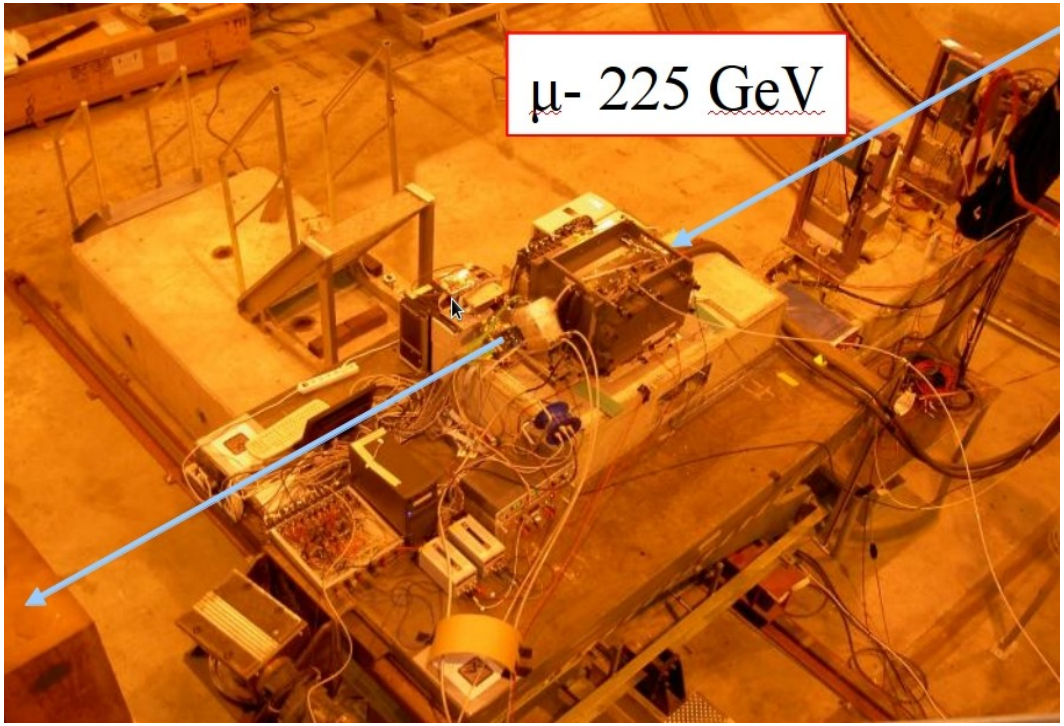


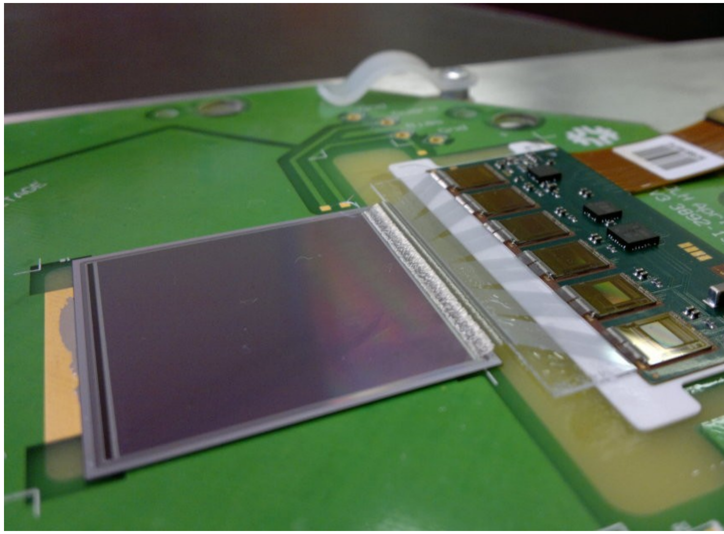
Transient Current Technique TCT





Characterization of radiation detectors -System level

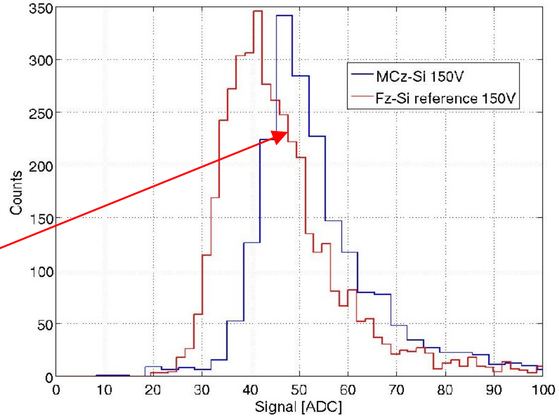




Full size Si detector (768 channels)
- Processed at Micronova by HIP CMS
- Bonded into CMS APV25 ASICs operating with 40 MHz

Silicon Beam Telescope SiBT
- Operated by HIP CMS group
- Data taking at CERN SPS or FNAL Tevatron accelerators

Comparison of signal [ADC, arbitrary units]
HIP/Micronova made MCz-Si detector (BLUE)
Commercial Hamamatsu Fz-Si detector (RED)



R&D Collaborations and networking

CERN RD39 Collaboration: Cryogenic Tracking Detectors

- Established in 1990's. Strongly pursued by TKK Low Temeperature Lab.

-57 members from 14 institutes

- Device Physics for radiation-hard silicon detectors

- Basic Research of heavily irradiated silicon at sub LHe temperatures.

- Cryogenic TCT

- Development of Charge Injected Detector (CID)

- Currently developing Beam Loss Monitor (BLM) detectors together with CERN LHC Instrumentation group.

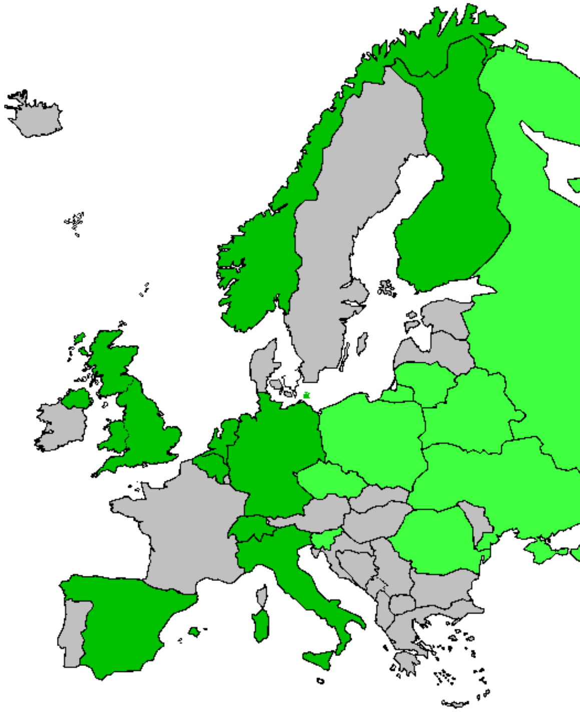
- New BLMs are mandatory in upgraded LHC maschine. >2000 detectors are needed.

- BLMs will be placed into cold mass of super conductive magnets (<1.8K) and they must simultaneosly be very radiation hard.

R&D Collaborations and networking

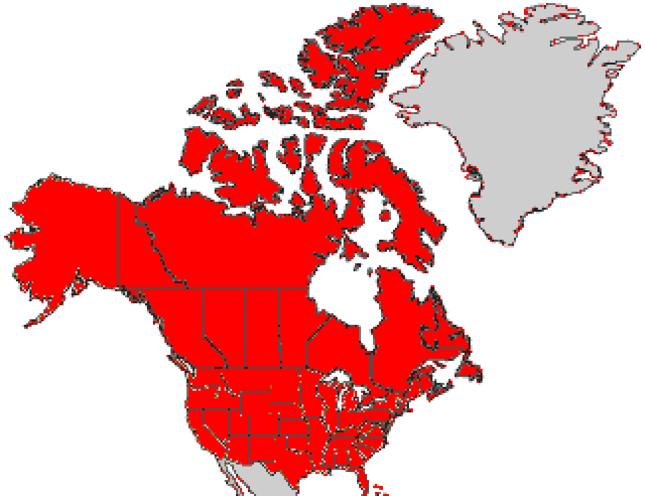
RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

261 Members from 50 Institutes



41 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki) , Laappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool)



8 North-American institutes

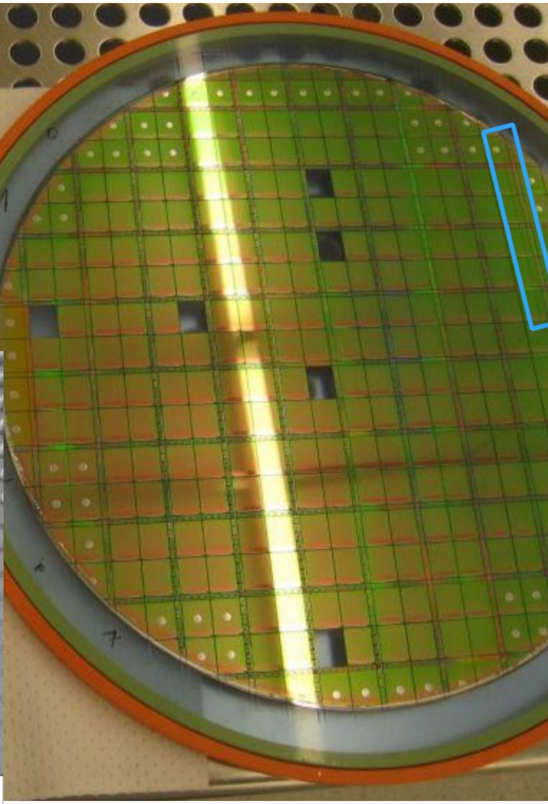
Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Pu
Rochester, Santa Cruz, Syracuse)

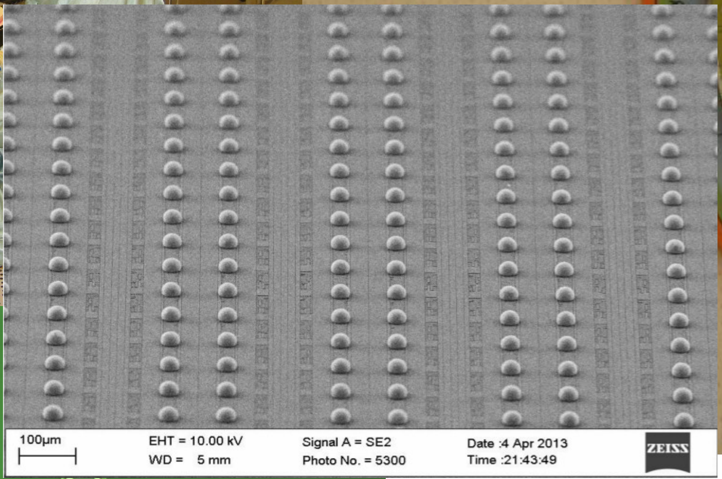
1 Middle East institute

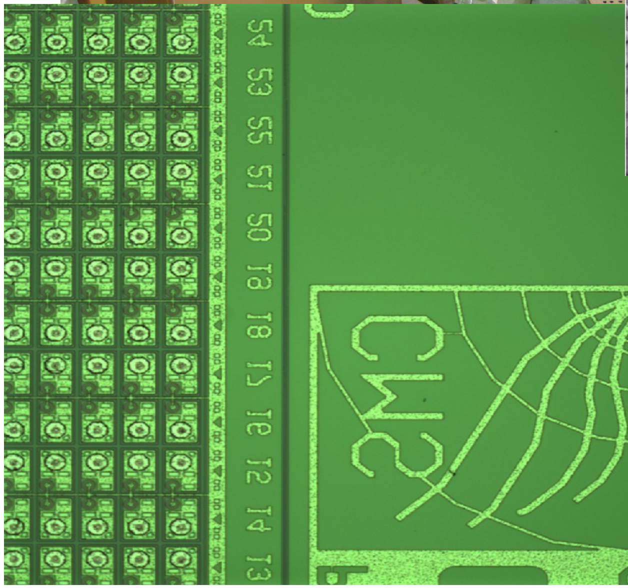
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50

On-going activities of HIP CMS group -Phase I pixel upgrade







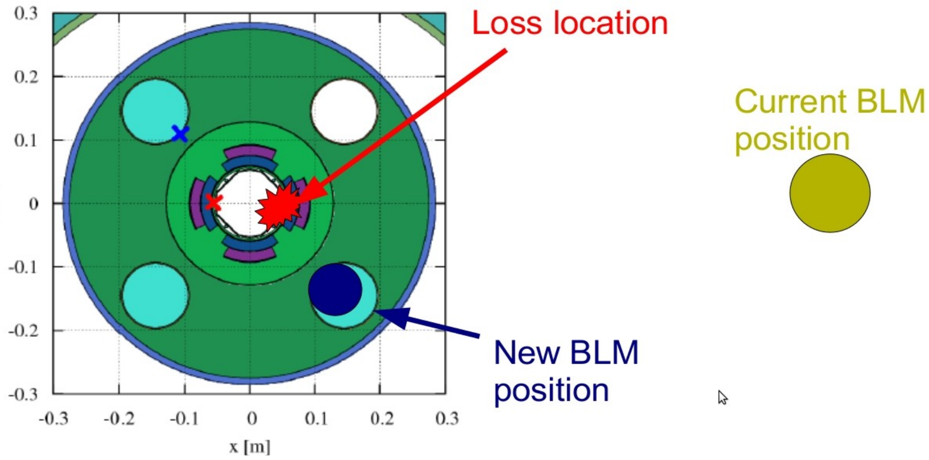
-Finland has committed to deliver in-kind 50% on pixel modules of CMS Layer3.

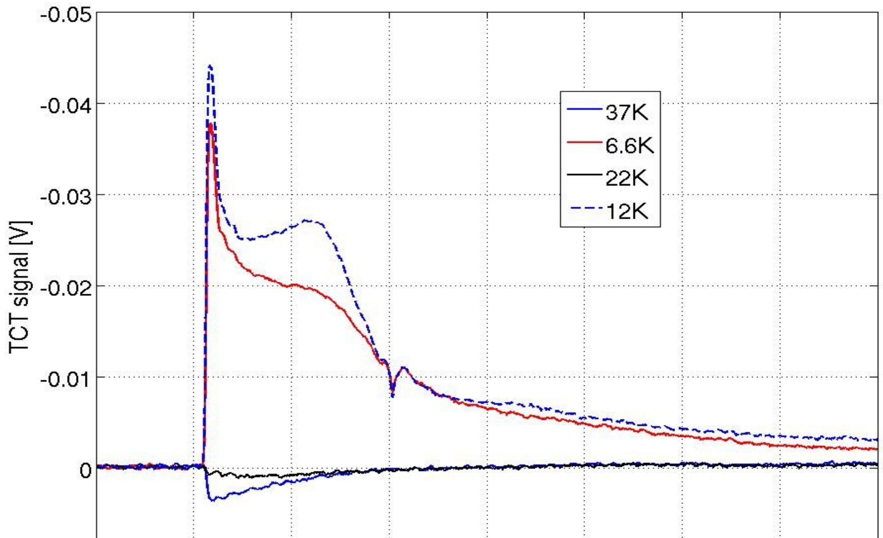
-4000 read-out ASICs will be Flip-Chip bonded in Micronova resulting in >16M channels

- Simultaneously, we have launched internal R&D for next generation pixel sensors utilizing potential of ALD technology.

Future projects under consideration -Particle physics

Beam Loss Monitoring (BLM) for LHC





There are currently about 4000 BLMs in LHC

BLM is needed in order to give warning signal of a beam loss that might result in magnet quenching.

In current BLM devices, it is possible that signal of a dangerous beam loss is hidden behind of background induced by normal beam debris.

BLM has to be placed inside of cold mass, close to interaction point

Challenge: Si detector should operate at LHe temperature <2K and should simultaneously be radiation hard up to 1 MGy.

At LHe temperature there is no annealing of radiation defects + shallow donor/acceptor impurities are not ionized

Magnetic Czochralski Silicon MCz-Si

Original paper 2003 was collaboration
of HIP-Ioffe-BNL-Okmetic

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
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Processing of microstrip detectors on Czochralski grown high resistivity silicon substrates

J. Härkönen[a,f,*], E. Tuominen[a], E. Tuovinen[a], P. Mehtälä[a], K. Lassila-Perini[a], V. Ovchinnikov[b], P. Heikkilä[b], M. Yli-Koski[c], L. Palmu[d], S. Kallijärvi[d], H. Nikkilä[d], O. Anttila[e], T. Niinikoski[f], V. Eremin[g], A. Ivanov[g], E. Verbitskaya[g]

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[b] *Microelectronics Centre, Helsinki University of Technology, 02015 HUT, Finland*
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[d] *Microelectronics Instrumentation Laboratory, University of Oulu, 94600 Kemi, Finland*
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Abstract

chralski (MCZ) method. The

178 J. Härkönen et al. / Nuclear Instruments and Methods in Physics Research A 514 (2003) 173–179

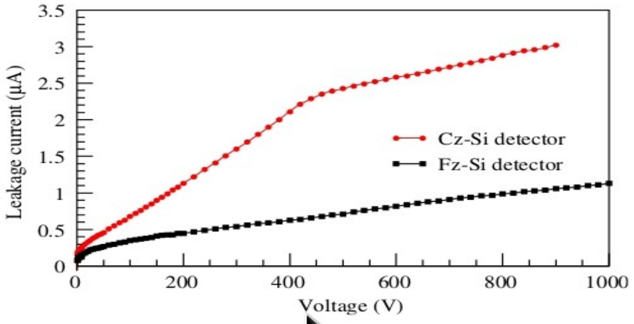


Fig. 4. Current–voltage characteristics measured from 32.5 cm^2 Cz-Si and Fz-Si detectors.

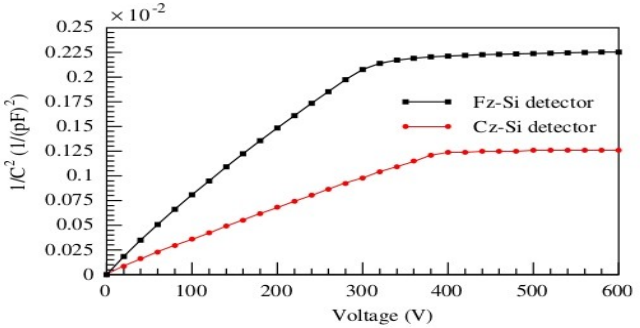
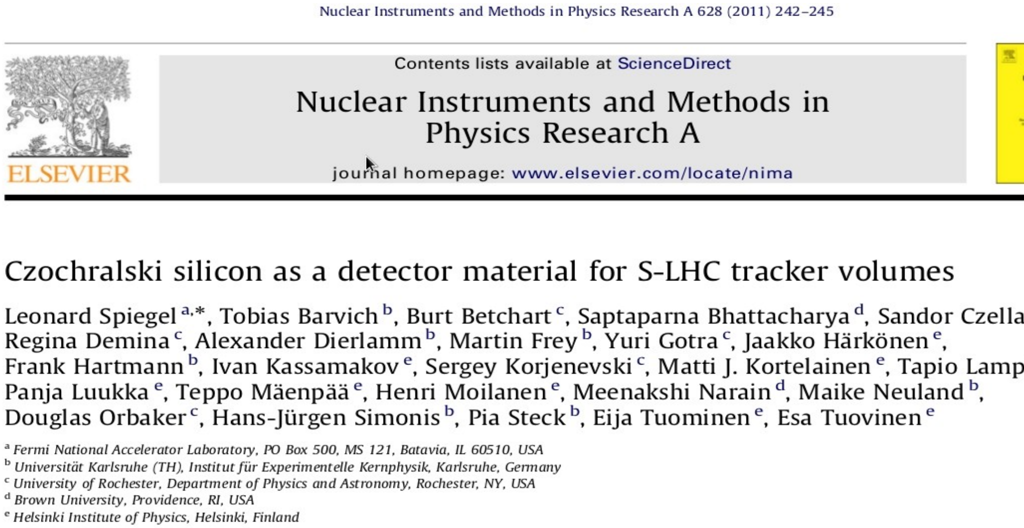


Fig. 5. Capacitance $1/C^2$ plots from Cz-Si and Fz-Si samples.

Results of n-type MCz-Si



Nuclear Instruments and Methods in Physics Research A 628 (2011) 242–245

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

journal homepage: www.elsevier.com/locate/nima

Czochralski silicon as a detector material for S-LHC tracker volumes

Leonard Spiegel [a,*], Tobias Barvich [b], Burt Betchart [c], Saptaparna Bhattacharya [d], Sandor Czella
Regina Demina [c], Alexander Dierlamm [b], Martin Frey [b], Yuri Gotra [c], Jaakko Härkönen [e],
Frank Hartmann [b], Ivan Kassamakov [e], Sergey Korjenevski [c], Matti J. Kortelainen [e], Tapio Lamp
Panja Luukka [e], Teppo Mäenpää [e], Henri Moilanen [e], Meenakshi Narain [d], Maike Neuland [b],
Douglas Orbaker [c], Hans-Jürgen Simonis [b], Pia Steck [b], Eija Tuominen [e], Esa Tuovinen [e]

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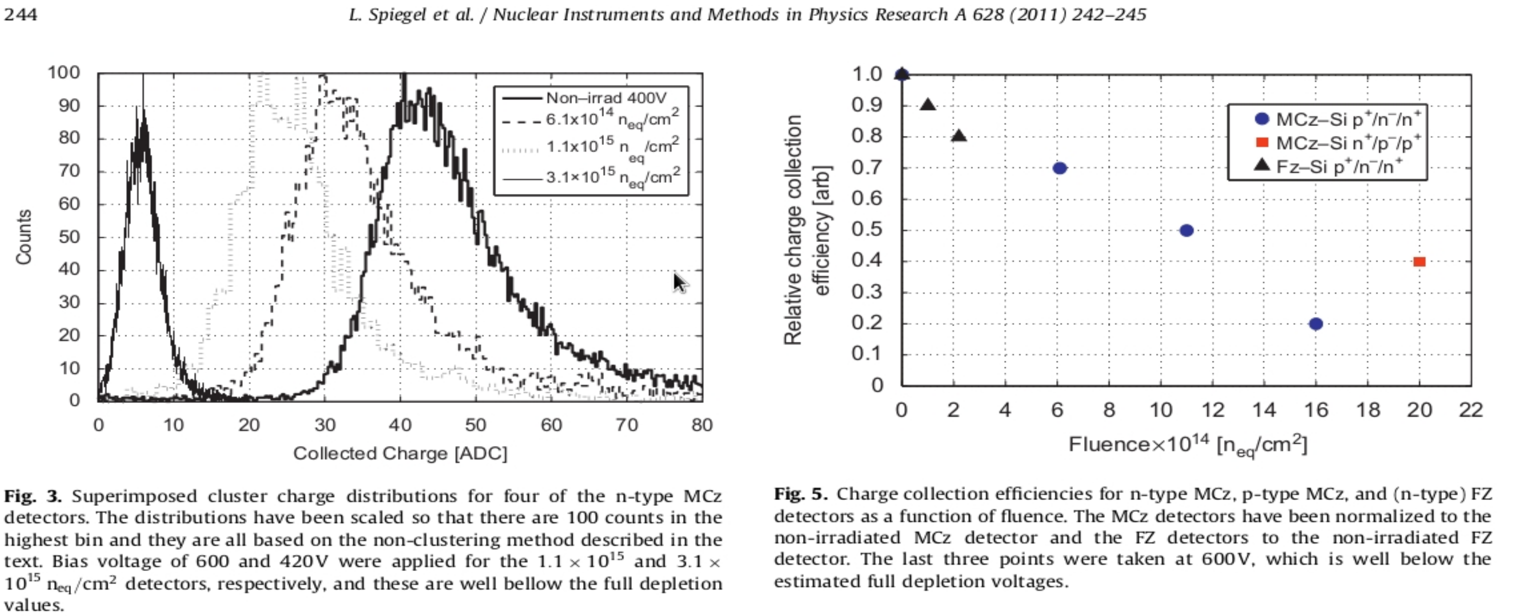
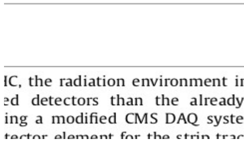


244 L. Spiegel et al. / Nuclear Instruments and Methods in Physics Research A 628 (2011) 242–245

Fig. 3. Superimposed cluster charge distributions for four of the n-type MCz detectors. The distributions have been scaled so that there are 100 counts in the highest bin and they are all based on the non-clustering method described in the text. Bias voltage of 600 and 420 V were applied for the 1.1×10^{15} and 3.1×10^{15} n_{eq}/cm^2 detectors, respectively, and these are well bellow the full depletion values.

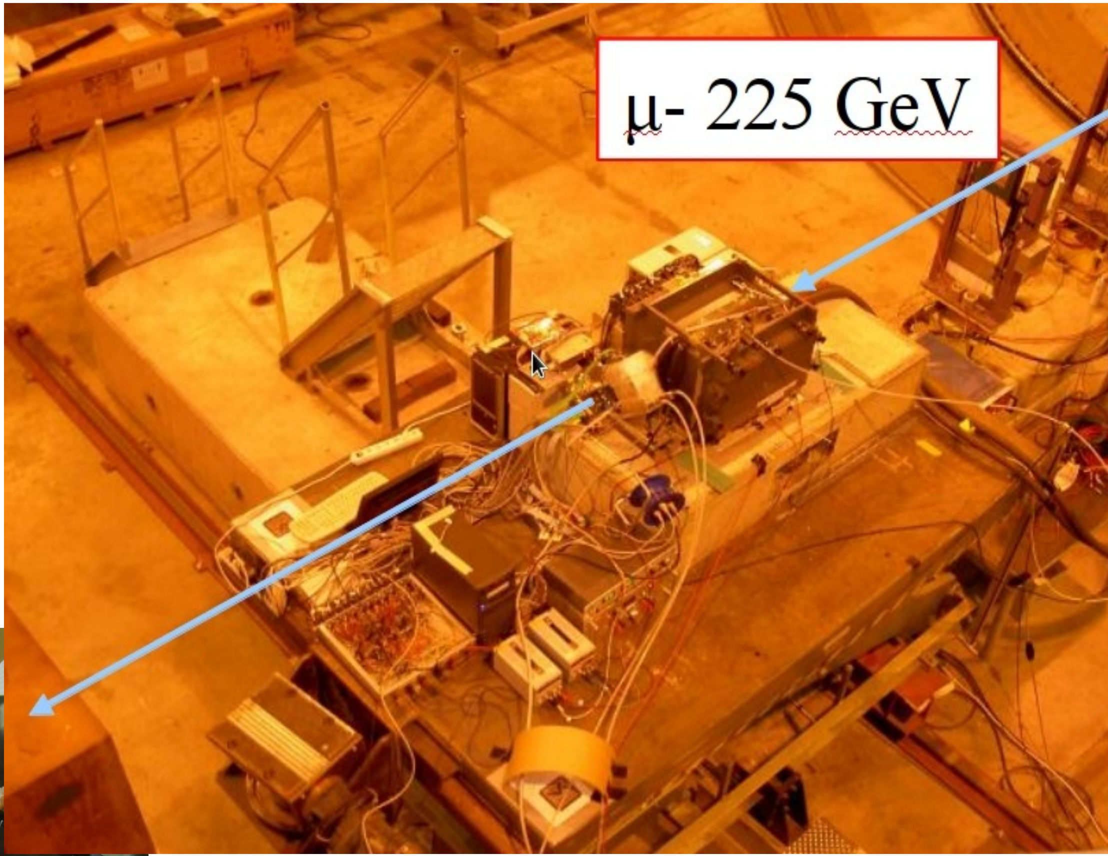
Fig. 5. Charge collection efficiencies for n-type MCz, p-type MCz, and (n-type) FZ detectors as a function of fluence. The MCz detectors have been normalized to the non-irradiated MCz detector and the FZ detectors to the non-irradiated FZ detector. The last three points were taken at 600 V, which is well below the estimated full depletion voltages.



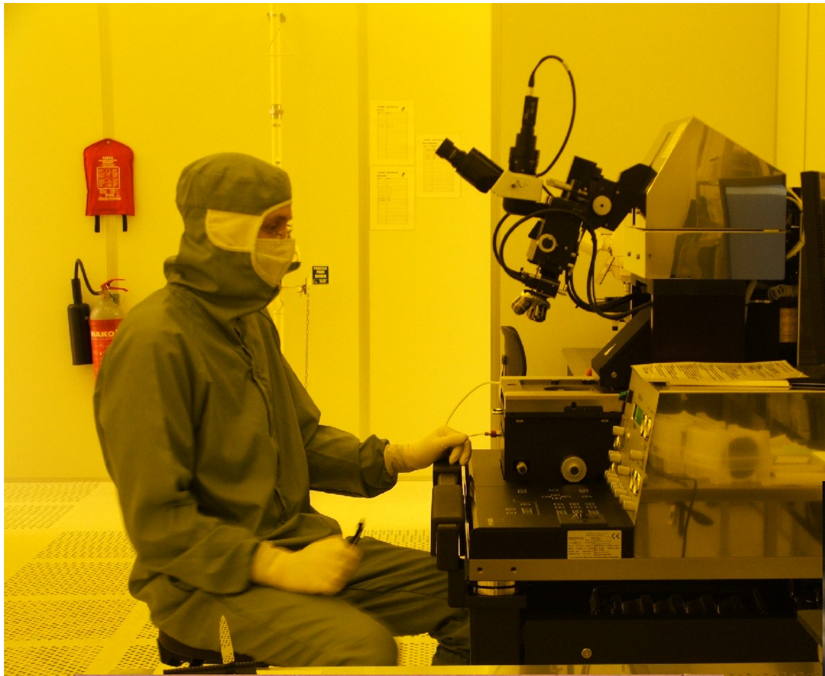
IC, the radiation environment i
ed detectors than the already
ing a modified CMS DAQ syste

Silicon Beam Telescope (SiBT)

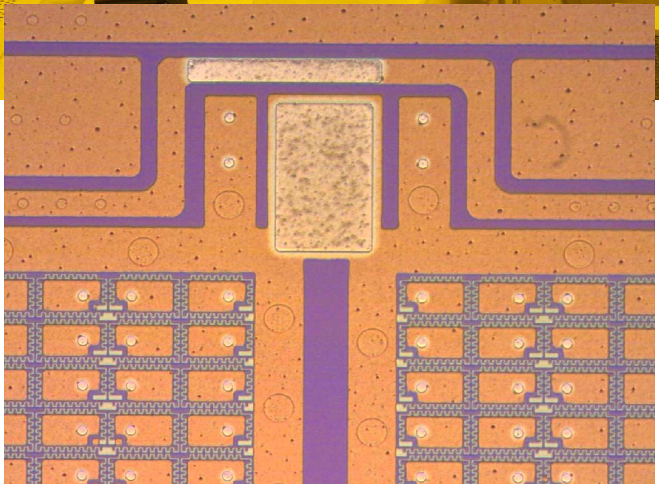
- on-going activity since 1990's
-major uprgrade was made by 7
Panja Luukka in 2006 > Read-out
To CMS APV and data-analysis
> CMSSW

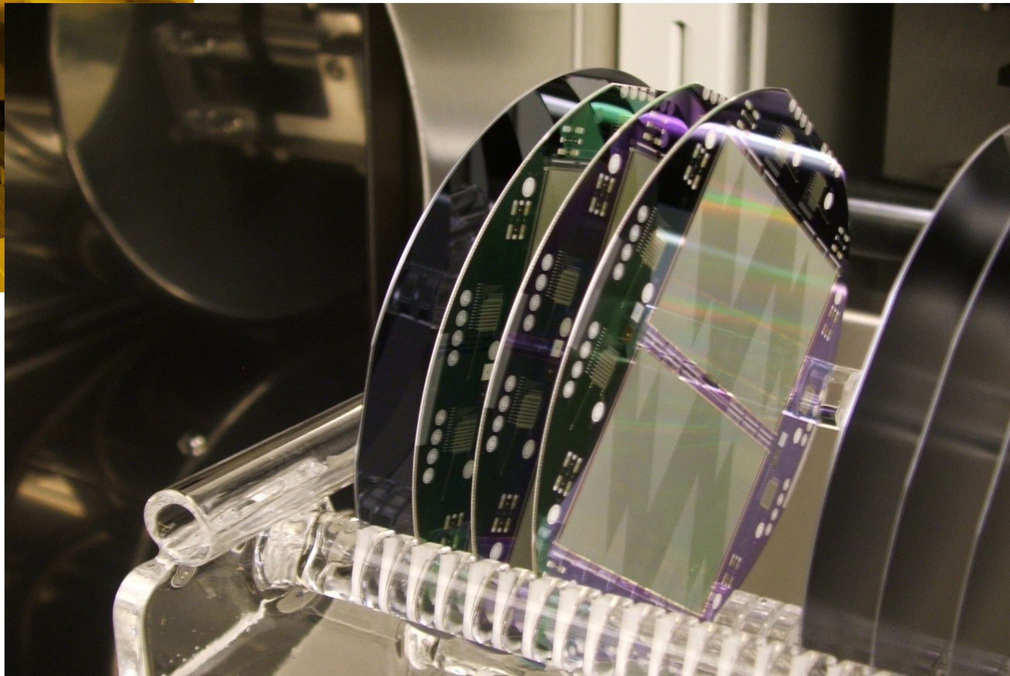


HIP activity with ALD



-Since 2006 we have applied ALD thin films on MCz-Si detectors
- test beam results from 2008 ind
>50% CCE of 2×10^{15} irradiated p-MCz-Si detectors





Helsinki SiBT results – 1×10^{15} irradiation

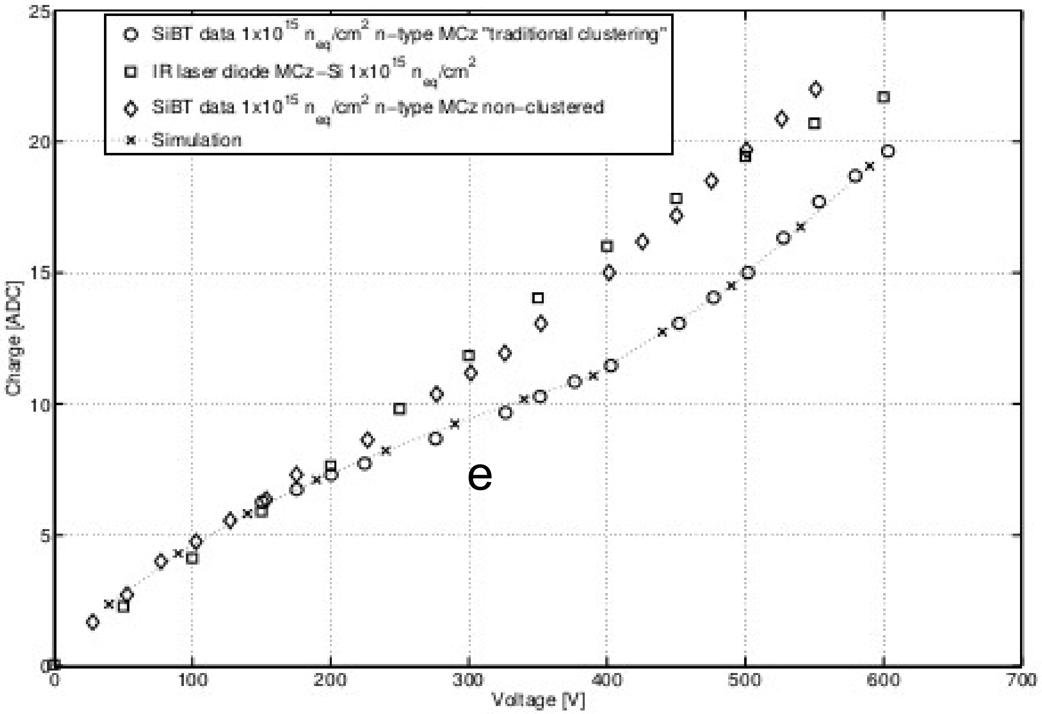


Figure 6: Charge collection in irradiated MCz-Si detectors, experimental data and simulation results. The experimental data and simulations correspond when assuming double peak electric field distribution.

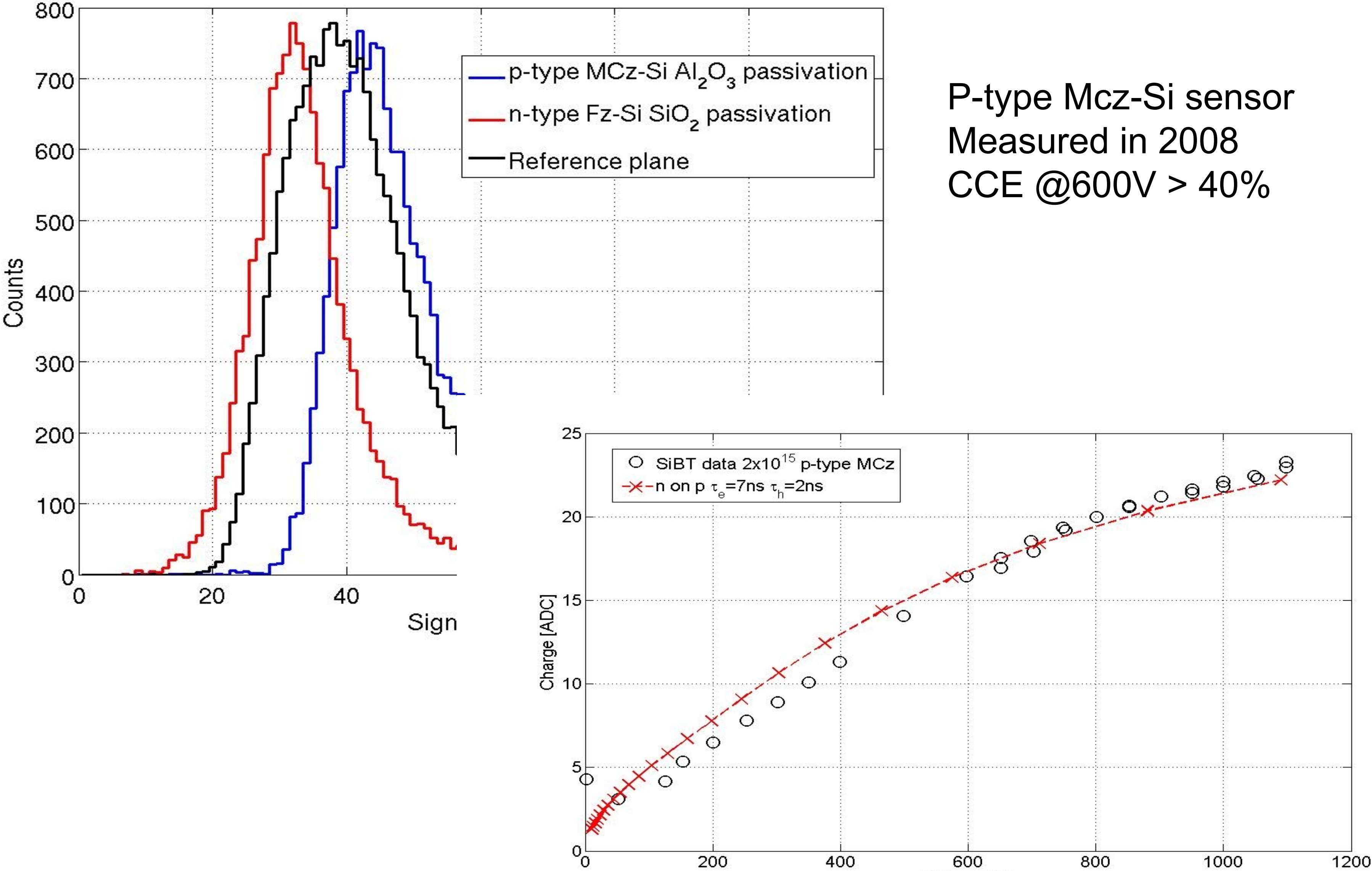
At 600V bias, n-type MCz-Si shows absolute CCE >50%

Picture from:

Magnetic Czochralski silicon stri
detectors for Super-LHC experim
Esa Tuovinen∗,a , Jaakko Härkö
Panja Luukka , Teppo Mäenpää
Moilanen , Ivan Kassamakov , Ei
Tuominen

Helsinki SiBT results – 2×10^{15} irradiation

P-type Mcz-Si sensor
Measured in 2008
CCE @600V > 40%



Summary

Charge Collection Efficiency (CCE) is a complex product of

- E(x)
- trapping

One cannot influence trapping (unless going to cryogenic)

One can influence on E(x) by choosing O rich material = MCz-Si.

Hamamatsu provided "deep diffusion" is not an option.

300µm thick, MCz-Si has proved to be radiation hard up to 1×10^{15} irradiation

N-type (p on n bulk) MCz-Si seems to be the only reasonable and economically feasible solution as sensor material of future HL CMS.

Summary

- HIP CMS Upgrade group has been active user of Micronova facility for >10 years.
- We have processed hundreds of detectors creating ~70 journal papers + good number of PhD/M.Sc degrees for Aalto/TKK.
- We are pretty well internationally networked. Our papers (excluding CMS physics papers and collaboration papers) are co-authored with people from about 20 institutes/companies.
- Micronova is one of the few academic places in Europe having expertise starting from semiconductor material characterization ending to interconnection technology (and everything between).
- Any detector system consists of: sensor, read-out electronics, DAQ software and interconnections adapting these together.
- To make R&D/science in detectors, good processing itself is not enough. Sensor must be adapted into surrounding world before any scientific report is made.
- Flow of a typical detector R&D: Need/Idea > Design/Simulation > Processing > Characterization > Irradiation/Test in realistic conditions > Analysis/Reverse calculation/Simulation = long way to go...
- Radiation detection is growing field of industry globally. Scientific applications are just small fraction. On top of that: industrial, medical imaging, dosimetry, radio protection etc

Operating the CMS Detector
is a 24/7 task