Radiation Damage in Silicon Particle Detectors in High Luminosity Experiments

Agnieszka Obłąkowska-Mucha
AGH UST Kraków
within the framework of
RD50 Collaboration
&
LHCb VELO Group

2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics
June 3rd-11th, Kraków, Poland
1. Introduction.
2. The timeline of LHC and experiments.
3. Radiation induced changes in properties of the silicon tracking detectors.
4. Radiation damage in the LHCb VELO.
5. Development of new structures:
   - 3D Pixels,
   - HVCMOS,
   - LGAD.
6. Measurement technique: TCT.

Simulation of 400 proton-proton collisions in just one 25 ns bunch crossing at the HL-LHC
1. LHC was planned for 10 years of operation ($\mathcal{L} = 300 \, fb^{-1}$), i.e. till the end of Run 3 (2023).

2. It was assumed that tracking detectors will have to be replaced due to radiation damage and ageing (or new physics program).

3. Based on experience from Run I, with new technologies in mind, it’s the right time to design them NOW!

4. Two major shutdowns (LS2 & LS3) – main accelerator and detector upgrades.
5.1. Upgrade of the silicon tracking detector.

Phase 1 Upgrade (24 months):
- CMS - Pixel detector replacement,
- LHCb - VELO strip detector replacement by pixels, new strip UT.
Experiments - Phase 2 Upgrade

5.2. Upgrade of the silicon tracking detector.

Phase 2 Upgrade (30 months):

- LHC: new quadrupoles in the collision region, crab cavities,
- CMS: new tracker, HGCAL,
- ATLAS: replacement of the Inner Detector,
- LHCb major detector upgrade during LS4
1. LHC will produce collisions at a rate of about $5 \cdot 10^9$ s$^{-1}$.

2. The annual dose at HL-LHC will be similar to the total dose until LS3:
   - end of Run III (300 fb$^{-1}$) $\Phi \sim 2 \cdot 10^{15}$ n$_{eq}$ cm$^{-2}$
   - HL-LHC (3000 fb$^{-1}$) $\Phi \sim 2 \cdot 10^{16}$ n$_{eq}$ cm$^{-2}$

4. The main objective for RD50 is development of radiation hard semiconductor detectors for HL-LHC.

5. The radiation hardness above $10^{16}$ n$_{eq}$ cm$^{-2}$ (while maintaining the S/N ratio $> 10$) is required with fast signal collection and affordable cost. Current LHC detector can operate up to fluence $10^{15}$ n$_{eq}$ cm$^{-2}$

6. Defect induced by particle radiation and their influence on detector performance are of major interest to RD50.
**Future Circular Collider**

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    - \(~16\)T magnets \(\rightarrow\) 100TeV pp collider in 97.75km tunnel
  - FCC-ee: as a potential first step
  - FCC-eh: as an option

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision cms energy [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.33</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2 &amp; 2</td>
<td>2 &amp; 2</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>Bunch intensity ([10^{11}])</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2.2 (0.44)</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>Luminosity/IP ([10^{34} \text{cm}^2\text{s}^{-1}])</td>
<td>5</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td># Events/bunch crossing</td>
<td>170</td>
<td>&lt;1020 (204)</td>
<td>~800 (160)</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.3</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>Synchrotron rad. [W/m/\mu\text{p}.]</td>
<td>28.4</td>
<td>4.6</td>
<td>(0.33) 0.17</td>
</tr>
</tbody>
</table>

- **Baseline (phase 1):** 10 yrs of operation \(\Rightarrow\) \(L_{\text{peak}} = 5 \times 10^{34} \text{cm}^2\text{s}^{-1}\) \(\rightarrow\) 2.5 ab\(^{-1}\) per detector
- **Ultimate (phase 2):** 15 yrs of operation \(\Rightarrow\) \(L_{\text{peak}} \leq 30 \times 10^{34} \text{cm}^2\text{s}^{-1}\) \(\rightarrow\) 15 ab\(^{-1}\) per detector

\(\rightarrow\) Total: \(O(20)\)ab\(^{-1}\) per experiment

Z.Drasal, RD50 meeting in Krakow (7th June 2017)
Tracker & Long-term Damage after 30ab\(^{-1}\)

- 1 MeV neq fluence after 30ab\(^{-1}\)

Long-term damage for Tracker after 30ab\(^{-1}\)

<table>
<thead>
<tr>
<th>R [mm]</th>
<th>z [m]</th>
<th>Dose [MGy]</th>
<th>1 MeV equivalent Fluence [cm(^{-2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0</td>
<td>320</td>
<td>5.5 \times 10^{17}</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>88</td>
<td>1.25 \times 10^{17}</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>40</td>
<td>6 \times 10^{16}</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>23</td>
<td>3.3 \times 10^{16}</td>
</tr>
<tr>
<td>270</td>
<td>0</td>
<td>8.8</td>
<td>1.51 \times 10^{16}</td>
</tr>
<tr>
<td>900</td>
<td>0</td>
<td>0.65</td>
<td>3.2 \times 10^{15}</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>410</td>
<td>3.7 \times 10^{17}</td>
</tr>
<tr>
<td>50</td>
<td>16</td>
<td>250</td>
<td>2 \times 10^{17}</td>
</tr>
</tbody>
</table>

Radiation @ FCC:

- @R=25mm: ~6 \times 10^{17} neq cm\(^{-2}\), TID~0.4GGy
- LHC = 1
- HL-LHC → 20x LHC
- FCC → 600x LHC
The source of radiation damage

1. The main source of radiation is from particles produced in soft p-p interactions (neutrons, pions, protons) and secondary interactions with the detector material.

2. Non-Ionizing Energy Loss ($E_k > 15$ eV) of impinging particle may displace a silicon atom from the lattice.

3. Creation of defects depends on the kind of particle and its energy.

4. Displacements of silicon atoms produce vacancies and interstitials.

5. Crystal impurities interact with defects causing the change in electrical properties of detector.

\[ \text{Point defects + cluster defects + impurities = degradation of the detector} \]
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as **macroscopic effects** caused by **microscopic defects**:

- Charged defects \( \Rightarrow \) effective doping concentration \( N_{\text{eff}} \)
- Depletion voltage \( V_{\text{dep}} \)
- Trapping \( (e \text{ and } h) \Rightarrow \) Charge Collection Efficiency \( \text{CCE} \)
- Generation/recombination \( \Rightarrow \) leakage current \( I \)

The microscopic defects accumulate over time and have a damaging impact on the sensor performance.

- Current - Voltage scans \( (IV) \),
- Current - Temperature scans \( (IT) \),
- Charge Collection Efficiency scan \( (\text{CCE}) \),
- Change of effective depletion voltage \( (V_{\text{ED}}) \)
The LHCb VELO

**VErtex LOcator**

- Close proximity of the beam-pipe.
- VELO halves are movable- the movement is steered by a precise system (accuracy of 10 μm),
- When stable beams, the silicon edge is only 8 mm from the proton beam – sensors are in harsh particle fluence.
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.

**Sensors**

- VELO consist of 42 modules (two halves).
- Modules have two (R and Phi) microstrip silicon oxygenated $n^+-on-n$ sensors (two sensons are $n^+-on-p$).
- Sensors are 300 μm thick, strip pitches: 40-100 μm.
- Evaporative CO$_2$ cooling system keeps sensors at -7°C.
1. VELO is currently the most exposed detector in the LHC - fluence up to $1.8 \cdot 10^{14} \text{ 1MeV n}_{\text{eq}}/\text{cm}^2$,
   - LHCb has collected almost 5 fb$^{-1}$ until now,
   - VELO is designed to cope with 10-11 fb$^{-1}$.

2. The radiation field is highly non uniform – the fluence accumulated in inner and outer part of the sensor differs by a factor of ten.
1. The level of leakage current reveals the amount of the radiation damage contained in a detector volume.

2. The increase in leakage current is proportional to the accumulated fluence (time, delivered luminosity): \( \Delta I = \alpha \cdot \phi_{eq} \cdot V \), typically 2 μA per 100 pb\(^{-1}\)

   annealing constant \( \alpha(20^\circ C) = (3.99 \pm 0.03) \cdot 10^{-17} \text{ A/cm} \)

3. The currents of the sensors are measured as a function of time while operating at nominal conditions (depletion voltage, temperature)

   - Bulk currents increases with fluence expected, with occasional drops due to annealing.
1. At the production, initial depletion voltage was 25-70 V.
2. Sensors in 2011-12 were biased at 150 V, currently 150-200 V (250 V for n-on-p).

4. Good agreement with Hamburg model
5. We need to increase the bias voltage to 300 V, first in the most irradiated sensors.
1. LHCb is supposed to collect 8 fb\(^{-1}\) by the end of Run II, what means that the VELO sensors will accumulate maximum of \(7 \cdot 10^{14}\) 1MeV \(n_{eq}/\text{cm}^2\) (most irradiated tips of the sensor).

3. VELO sensors can be operated up to 500V.

4. During LS2 (2018-19) VELO microstrip sensors will be replaced by pixels.
The first radiation concern

The LHCb silicon vertex detector will not be replaced. The main VELO upgrade (pixels) is planned for LS2 (2018).

The new innermost layer of ATLAS Inner Tracker was installed (IBL) inside the Pixel Detector during LS1.

VELO replacement is currently on display at LHCb Pit.
Call RD50 in case of radiation damage problem...

**RD50 - Radiation hard semiconductor devices for very high luminosity colliders.**

2. The main objective is:

   Development of radiation hard semiconductor detectors for the luminosity upgrade of the LHC to $7.5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

3. Challenges:
   - radiation hardness up to $10^{16} \text{ cm}^{-2}$ required,
   - fast signal collection – plan for 10 ns bunch crossing,
   - low mass to reduce multiple scattering close to interaction point,
   - affordable cost.

4. The current activities of RD50 include:
   a) identifying the defects through dedicated measurement techniques (DLTS, TSC, TCT) or monitoring the macroscopic changes in HEP experiments.
   b) work out how to get rid of damage (or avoid it) – **new technologies**, new structures (3D sensors, HV CMOS, LGAD, simulation (FLUKA, GEANT4, TCAD...).
   c) test the solution:
      - neutron exposition in nuclear reactor,
      - proton irradiation at cyclotrons and synchrotrons,
      - new dedicated irradiation center @ CERN.
   d) incorporate the feedback from experiments.
3D Pixels /Strips

1. Currently a well known technology (S.I. Parker et al., NIMA 395(1997)328).

2. 3D pixel sensors are installed in ATLAS IBL, AFP, CMS Totem.

3. They are designed as vertical narrow columnar p and n electrodes penetrating the silicon substrate.

3. Advantages:
   • diameter: 10 μm, distance L: 50 – 100 μm (small drift distance, less trapping),
   • lower depletion voltage: 10-200V (lower power), thinner detectors possible,
   • fast signal formation,
   • radiation hard,
   • active or slim edges technology.

4. Problems:
   • Non uniform spatial response (electrodes are inefficient regions).
   • Higher capacitance, higher noise.
   • Complicated fabrication technology (bump-bonding, time, cost, yield).
3D pixel sensors for LHC

For LHC a few devices were projected and tested for radiation hardness:

- 230 μm thick sensors by CNM and FBK
- FEI4s: 50x250 μm 2E, 67 μm inter-el. distance

Double sided (DDTC) technique:

- n+ and p+ columns are etched from the two sides of the sensor wafer.
- Slim edges (200 μm)

CNM 3D pixels for IBL

3D sensors irradiated (protons, neutrons, pions, electrons) up to IBL fluence $5 \cdot 10^{15} \text{n}_{eq}\text{cm}^{-2}$

Radiation hardness up to $5 \cdot 10^{15} \text{n}_{eq}\text{cm}^{-2}$ established: Efficiency for CNM sensors reached 99%.

G. Pellegrini et. al. NIMA 592(2008), 38
G. Pellegrini et. al. NIMA 699(2013), 27

Promising for HL-LHC!

09.06.2017  A.Obłakowska-Mucha (AGH UST Kraków)  2nd Jagiellonian Symposium
The signal efficiency is about 60-70% at $5 \cdot 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$ and 30% at almost $10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$ with not much increase of $V_{\text{bias}}$.

Signal efficiency was improved with decreasing electrode distance.

**RD 50 project:**

Joint MPW pixel run for ATLAS, CMS, LHCb.

**Motivations:**

1. Manufacture smaller area pixels on thin sensors.
2. Study of radiation hardness.

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Compilation by C. Da Via
High Voltage CMOS

- n-wells are implanted in low resistivity (~10 Ωcm) p-type substrate and play role of electrode implant,
- biased with 60 V but allows only shallow (10 – 20 μm) depletion zone, signal 1-2 kel.
- thin active layer,
- low drift distance, small drift time (fast collection),
- radiation hard (less trapping),
- possible to use capacitive coupling through glue instead of bump-bonding,
- industrial process enables large volume production in relatively short time,
- both pixel and strip detector possible,
- fully monolithic devices don’t require a bump-bonded read-out.

RD50 started to work on HV-CMOS devices in 2014 with a focus on characterizing the radiation damage
High voltage is used to deplete a part of the substrate:

- The main charge collection mechanism is drift,
- Part of the signal originates from the undepleted region and is collected by diffusion,
- Edge-TCT measurements showed drift and diffusion component.

The charge collection profiles of irradiated samples show quick disappearance of drift constituent.
Charge collection properties studied after irradiation to high neutron fluences with Edge-TCT techniques.

AMS 350\textit{nm} production, CHESS-1 sensors
- 2 mm x 2 mm passive sensor (400 pixel)
- Sr90 electrons for CCE, 25 ns shaping, 120 V, TCT

AMS 180\textit{nm} production, HV2FEI4
- 100 \text{	extmu} m x 100 \text{	extmu} m passive pixel,
- IR-laser, 5ns integration

- CCE decreases for fluence up to 2-5\cdot10^{14} \text{n}_{eq}\text{cm}^{-2} due to diffusion decrease.
- For higher fluence the signal is rising due to increase of active volume (acceptor removal).
- Finally CCE degrades due to more intense trapping caused by space charge.
- For fluence 2\cdot10^{16} \text{n}_{eq}\text{cm}^{-2} @ 80V charge collection is 90% of signal before irradiation!

Very promising for high radiation environment!
Charge multiplication in Si detectors

Charge multiplication:
- signal larger than expected from conventional silicon devices observed after irradiation $2 \cdot 5 \cdot 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$,
- irradiation causes negative space charge in detector bulk that increases the electric filed (>15 V/μm), impact the ionisation which manifests through charge multiplication,
- observed in different types of devices (diode, strip, 3D), at very high bias voltages, heavy irradiated,
- could be beneficial for sensors and give extra signal – usable for HL-LHC.

RD50 project: exploit charge multiplication detectors:
- 1 cm x 1 cm, n-in-p FZ strip detectors,
- LGAD sensors (first segmental sensors on thin substrates).

Aims:
- exploit the charge multiplication effect,
- fabricate, test and irradiate sensors,
- simulate and predict (TCAD),
- measure with TCT setup.

Comparison of $I_{\text{rev}}$ and CCE for different sources

3D n-in-p
- Unirradiated
- $2 \times 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$
- $2 \times 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$

Bias Voltage (V)

Signal (keV)
The Low Gain Avalanche Detector (LGAD): a new concept of silicon radiation detector with intrinsic multiplication of the charge.

Advantages:
- higher charge collection efficiency,
- short drift time,
- signal shorter and steeper while retaining a large amplitude due to the multiplication mechanism.

After irradiation (reactor neutrons and 800 MeV protons):
- decrease of charge collection,
- decrease of multiplication (before irradiation it was 3 times higher than standard diode), after irradiation with fluence $2 \cdot 10^{15}$ n$_{eq}$ cm$^{-2}$ the gain was lost.

New technology – Gallium instead of Boron or add Carbon to prevent Boron removal.
**Edge Transient Charge Technique:**

Method of reconstruction of electric field pioneered by Ljubljana group and promoted by RD50.

- photon pulses (below 1Hz) from an infrared laser are directed towards the detector edge, perpendicular to the strips and focused to the region below the readout strip, electron-hole pairs are produced,

- scans across the detector thickness enables relative measurement of the induced current at given depth, extrapolate rise time, drift velocity and charge collection profiles $Q(V_{bias})$,

- mobility of electrons and holes can be extracted from the drift time,

- finally, the electric field can be reconstructed by determination of drift velocity.

Edge-TCT is widely used ideal tool to study substrate properties!
HV-CMOS – different structures:
- irradiated by reactor neutrons and PS protons,
- charge profiles at different depth and vs. bias voltage,
- width of charge collection,
- determination of $N_{\text{eff}}$

AMS CHESS1 chips (20 Ωcm)

Results:
- neutron irradiation up to $2 \times 10^{15} \, n_{eq} \, cm^{-2}$ - increase of depletion region (initial acceptor removal), increase of space charge and charge collection
- these effects are degrading with fluence
**TCT- 3D and LGAD example**

**3D pixels (CNM) –**
irradiated by reactor neutrons with $5 \times 10^{15} n_{eq} cm^{-2}$

**Signal amplification in strip-LGAD**

- Electron injection
- Primary Electrons (faster fall time)
- Secondary Holes (Slower rise time)
- Measured Bottom Red TCT strip LGAD
- Multiplication on-set
- $20 \text{ ns}$

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G. Pellegrini, RD50 Workshop, Dec 2015

Iván Vila, RD50 Workshop, June 2016
1. Silicon detectors currently installed in LHC experiments need to be replaced by 2023 at the latest.

2. Current technologies are not sufficient to withstand fluence at the level of $10^{16} \text{n}_{eq} \text{cm}^{-2}$.

3. The new region of interest for FCC – fluence up to $10^{18} \text{n}_{eq} \text{cm}^{-2}$.

4. RD50 Collaboration has been working on:
   - new technologies and new structures: 3D sensors, LGAD, HV-CMOS description of defects and material characterization,
   - simulation of the structures and radiation effects,
   - methods of measurements and test of irradiated devices.

5. The monitoring of radiation damage in Vertex Locator @ LHCb showed symptoms of degradation at the level as expected.

6. Vertex Locator is performing successfully in Run II obtaining the resolutions similar to Run I.

Thank you for your attention!
Radiation damage effects (1)

Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ...

**macroscopic effects** ... caused by **microscopic defects**

1. Change of depletion voltage:

- Due to charged energy levels in the depleted region.

Defects change the effective doping concentration and has impact on bias voltage used to fully deplete the sensor. Significant progress on identifying defects was performed within RD50 group.

Due to excess of acceptor-like defects and donor removal, initially n-type sensor changes into p-type sensor (at LHC first observed in LHCb VELO).
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ... **macroscopic effects** ... caused by ... **microscopic defects**

2. Increase of leakage current:

![Graph showing the relationship between leakage current and equivalent dose](image)

- Defects are able to capture and emit electrons and holes – source of the reverse-bias current.
- Higher noise and power consumption.
Radiation damage effects (3)

Radiation induced changes in properties and structures of the silicon tracking detectors are observed as...

**Macroscopic effects**... caused by... **Microscopic defects**

3. Decrease of charge collection efficiency:

- Defects act as trapping centers - electrons and holes are re-emitted with some time delay.
- The signal charge is trapped and may be released too late for 25 ns read-out.
- This is the most serious problem for detector irradiated with fluence above $10^{15}$ $n_{eq}$ cm$^{-2}$. 

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CMS Tracker JINST 9 (2014) 12

而对于...
3. The effective depletion voltage ($V_{ED}$) is the voltage where MPV is 80% of maximum.

4. Type inversion occurred at $(10-15) \times 10^{12}$ 1MeV $n_{eq}/cm^2$, inversion started at inner radius.

**Charge Collection Efficiency (CCE)**

1. During data taking a tested sensor is excluded from the track fit.

2. A voltage bias scan is performed on it and the charge deposited in sensor around the track intercept is measured.

**CCE scan is used to measure:**
- Effective Depletion Voltage ($V_{ED}$)
- Cluster Finding Efficiency (CFE)
Development of new generation 3D pixel sensors for HL-LHC:

• radiation hardness up to $2 \cdot 10^{16} \, n_{eq} \, cm^{-2}$.
• reduced pixel size: $50 \times 50 \, \mu m^2$ or $25 \times 100 \, \mu m^2$.
• small inter-electrode distance (less trapping).
• reduced thickness $100 - 150 \, \mu m$ (small leakage current).

First prototype of new generation 3D pixels finished (January 2016).

Three different technologies tested:

SNF (Stanford) / SINTEF (Oslo)  
FBK (Trento)  
CNM (Barcelona)

single sided, active edge  
double sided
Joint 3D MPW pixel run

Joint Multi Project Wafer pixel run for ATLAS, CMS, LHCb.

Test of different configurations for various read out chips and pitch size:

- A: standard Fe-I4
- B: 25x100um2 ("25x500" 1E, with 3DGR - a la GP).
- C: 50x50um2 with the rest connected to GND with 3DGR
- D: 25x100um2 (2E - version 4x100+grid to GND - a la GF)
- E: 50x50um2 with the rest connected to GND without 3DGR
- F: FEI3 device: x 50x50um2 with rest to GND with 3D GR
- G: ROC4sens 50x50um2
- H: PSI46dig
- I: FERMILAB RD ROC 30x100um2
- L: Velopix 55x55um2
- M: Strip 50x50um2
- M Strip 25x100um2
- O Strip 30x100um2f

Also single sided technology:

- 50μm thick detectors with SOI support wafer (350 μm ),
- Possible to thin down the detectors.
- 5μm hole diameter.
- Detector tested, good I-V,
- more complicated technology
RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Co-Spokespersons
Gianluigi Casse and Michael Moll
(Liverpool University, UK & FBK-CMM, Trento, Italy)

Defect / Material Characterization
Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ...
- SIMS, SR, ...
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,..)
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain (avalanche detectors)
- LGAD:Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS
- 3D (R.Bates)
- LGAD (S.Hidalgo)
- Slim Edges (V.Fadeyev)

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

- LHC-like tests
- Links to HEP (LHC upgrade, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibaba)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors

- Test beams
  (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)