Vertex 2017 Workshop Summary

T. Bergauer

15 Sept 2017
Past Vertex Conferences

- 2017 Las Caldas, Asturias, **Spain**
- 2016 Isola d'Elba, Italy
- 2015 Santa Fe, New Mexico, USA
- 2014 Mácha Lake, Czech Republic
- 2013 Lake Starnberg, Germany
- 2012 Jeju, Korea
- 2011 Rust, Austria
- 2010 Loch Lomond, Scotland, UK
- 2009 Mooi Veluwe, Putten, The Netherlands
- 2008 Uto Island, Sweden
- 2007 Lake Placid, New York, USA
- 2006 Perugia, Italy
- 2005 Chuzenji Lake, Nikko, Japan
- 2004 Menaggio Como, Italy
- 2003 Low Wood, Lake Windermere, Cambria, UK
- 2002 Kailua-Kona Hawaii, USA
- 2001 Brunnen, Switzerland
- 2000 Sleeping Bear Dunes, Lake Michigan, USA
- 1999 Texel, The Netherlands
- 1998 Santorini, Greece
- 1997 Mangaratiba, Rio de Janeiro, Brazil
- 1996 Chia, Sardignia, Italy
- 1995 Ein Gedi, Dead Sea, Israel
- 1994 Lake Monroe, Indiana, USA
- 1993 Lake Bohinj, Slovenia
- 1992 Basto Island, Finland
Let us know by mail to BRENNER@VXCEM before Friday 15.5.1992 if you are interested. Because of limited space a maximum of 30 persons can attend this workshop.

Everybody is welcome to suggest topics for the meeting and prepare a talk. A big paper screen and colour pens will be available for explanations.

We remind you of the primitive circumstances on the island and kindly ask you to bring your own sleepingbag.
Thanks the local organizing committee as everything was perfectly organized:

Ivan Vila, Marcos Fernandez, Abraham Gallas, Gervasio Gomez, Sebastian Grinstein, Giulio Pellegrini, Marcel Vos
FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

Fachbereich Physik der Technischen Universität München, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof. Dr. H. J. Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm$^{-2}$/100 μm at room temperature. Best values for the energy resolution were 100 keV for the 5.486 MeV alphas of $^{241}$Am at 22°C using 5 x 5 mm$^2$ detector chips
NA11 Detector:

- First proof of principle to use a position sensitive silicon detector in HEP experiment
- Aim: measure lifetime of charm quarks ($c\tau=30 \, \mu m$) ⇒ high resolution required
- 1200 diode strips on 2436mm² active area
- Resolution of 4.5 µm
- 250-500 µm thick bulk material
Computer reconstruction of the production and decay of a $D^-$ into $K^+ \pi^- \pi^-$ as measured in the NA11 experiment in 200 GeV/c $\pi^-\text{Be}$ interactions.

(a) 4 planes of one view.
(b) Enlargement of the vertex region.
The 2017 HEP Prize of the EPS has been awarded to Erik H.M. Heijne, Robert Klanner, and Gerhard Lutz “for their pioneering contributions to the development of silicon microstrip detectors that revolutionised high-precision tracking and vertexing in high energy physics experiments”.

Gerhard Lutz (1939-2017)
SILICON DETECTORS WITH 5 μm SPATIAL RESOLUTION FOR HIGH ENERGY PARTICLES

The detectors [2] are made of high-ohmic n-doped silicon single crystal wafers of 2” diameter and 280 μm thickness (fig. 1). Using the planar process [1], p-doped strip diodes, covered by aluminium contacts, are implanted into one side of the wafer. On the other side a

1983!

Wafer Areas in Chip industries:
• Evolution of the silicon area from $O(1 \text{ m}^2)$ to $O(100 \text{ m}^2)$

• The front of the 1st “wave” has been “Strip” detectors.

• We may see the 2nd “wave” of the “pixel-like” detectors now...
Current and Future

EXPERIMENTS
### ATLAS

- **IBL**
  - splice consolidation button collimators
  - R2E project

- **Ph-I Pixel**
  - experiment beam pipes

### CMS

- **Ph-I Pixel**
  - 150 fb⁻¹
  - experiment upgrade phase 1

- **Ph-II Strips**
  - 300 fb⁻¹

### ALICE

- **ITS+MFT**
  - 98.5 fb⁻¹
  - LHC-b
  - (VELO, TT, IT+OT)

### LHC Roadmap

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4 - 5...</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>2015</td>
<td>2016</td>
<td>2017</td>
<td>2018</td>
</tr>
<tr>
<td>2019</td>
<td>2020</td>
<td>2021</td>
<td>2022</td>
</tr>
<tr>
<td>2023</td>
<td>2024</td>
<td>2025</td>
<td>2026</td>
</tr>
<tr>
<td>2037</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **LS1**
  - 13 TeV
  - injector upgrade
  - cryo Point 4
  - DS collimation
  - P2-P7(11 T dip.)
  - Civil Eng. P1-P5

- **EYETS**
  - experiment upgrade

- **LS2**
  - 14 TeV
  - cryomagnit interaction regions

- **LS3**
  - HL-LHC installation
  - 5 to 7 x
  - nominal luminosity

- **CMS**
  - 3000 fb⁻¹
  - integrated luminosity

### CMS Integrated Luminosity, pp

- Data included from 2010-03-30 11:22 to 2017-09-13 10:33 UTC

- **2010**, 7 TeV, 45.0 fb⁻¹
- **2011**, 7 TeV, 6.1 fb⁻¹
- **2012**, 8 TeV, 23.3 fb⁻¹
- **2015**, 13 TeV, 4.2 fb⁻¹
- **2016**, 13 TeV, 40.8 fb⁻¹
- **2017**, 13 TeV, 24.0 fb⁻¹

### ATLAS ITK

- **Online Luminosity**
  - 13 TeV

### Diagram Notes

- Radiation damage
- 2 x nominal luminosity
- 5 to 7 x nominal luminosity
- 75% nominal luminosity
- 20% nominal luminosity
ATLAS Performance

LHC delivers almost twice of design luminosity:

Martin Kocian

SCT: 60m² Strips (4+2x9)
Pixels: n-in-n, TF
FEI3, IBL: also 3D

Frequent alignment due to rapid temperature changes

Shaun Roe

Pixel Readout Hardware Upgrade:

Martin Kocian

Module Link Occupancy at 100kHz L1

<table>
<thead>
<tr>
<th></th>
<th>μ</th>
<th>B-Layer</th>
<th>Layer-1</th>
<th>Layer-2</th>
<th>Disks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>160Mbps</td>
<td>160Mbps</td>
<td>80Mbps</td>
<td>80Mbps</td>
</tr>
<tr>
<td>30</td>
<td>50%</td>
<td>33%</td>
<td>49%</td>
<td>62%</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>71%</td>
<td>92%</td>
<td>139%</td>
<td>86%</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>101%</td>
<td>125%</td>
<td>188%</td>
<td>115%</td>
<td></td>
</tr>
</tbody>
</table>

SCT Bandwidth: Re-mapping of FE- to S-links

SCT is fine at a L1 trigger rate of 100 kHz and a pile-up of 60.
2015/2016: decrease in signal to noise, loss of hits on tracks traced to saturation effects in the pre-amplifier of the APV25 readout chip
2017 fully recovered after tuning of APV parameters
– Thanks to Erik who actually found the solution!

Channels active in readout: \( \sim 96.5\% \rightarrow \sim \text{stable since 2016} \)
• New pixel detector installed in EYETS 2016/17
• 2 months from installation to data taking!!
• twice number of channels and active area (2m²)
• Innermost layer moved closer to beam pipe (4.4cm → 2.9cm)
• New readout chips: PSI46dig (Layer 2-4+Fpix) and barrel layer 1 (higher rates, PROC600)
• DC-DC conversion powering system
• CO₂ cooling system
• New µTCA DAQ system
• Significantly reduced amount of material

Alignment with cosmics and tracks

Layer 1 resolution limited by
• timing of different chips
• Radiation damage
• SEU in TBM
Inclined pixels

ATLAS Simulation
ITk Inclined

Inclined strips beneficial for $p_T$ concept (Trigger on hardware level)

FTK: Tracking joins the trigger on software level

Extension to $\eta=4$

CMS Simulation
ITk Inclined
Similar approach of ATLAS and CMS

- “classical” hybrid pixel detectors with bump-bonding
  - Planar n-on-p or 3D detectors
  - Prototypes using FEI4 chip, later RD53A
- ATLAS: 10k modules arranged on staves, inclined → up to 14m² detector area
- CMS: ~4.9 m²
- Different pixel layouts being tested → 50 x 50 µm preferred by ATLAS, 25x100 µm preferred by CMS
  - Both need some coating to prevent sparking
- Serial Powering being tested using FEI4
**RD53: HL-LHC readout**

- **RD53**: collaboration of 18 institutes focused on pixel chips for ATLAS/CMS phase2 upgrades.
- **Features**:
  - TSMC 65nm Process
  - Serial powering
  - Aurora Xilinx output protocol
  - SEU protection
  - Radiation hardness: 1 Grad, $2 \times 10^{16}$ $n_{eq}/cm^2$ over 10 years
- **Radiation Hardness studies performed**
  - Edge leakage current, temperature effect, bias effect, annealing effect, low dose rate effect
  - Standard IP block library used, but some modifications (resized cells for better radiation hardness)
- **RD53A chip submitted end of August**
  - Several months of intense face-to-face work of both ATLAS and CMS designers before tape-out
  - Expected to be back by the end of the year

**Features**

- Small pixels: 50x50 $\mu m^2$ (25x100 $\mu m^2$)
- Large chips: ~2 cm x 2 cm (~$10^9$ transistors)
- Hit rates: 3 GHz/cm$^2$
- Trigger: 1MHz, 10us (~100x buffering and readout)

**Dose-rate Effect**

Mohsine MENOUNI
Stereo angle **directly implemented in sensor geometry**

**Wedge-shaped sensors** in petals (similar what CMS Tracker uses now!)

Numbers:
- Petals: 392
- Staves: 384

Modules: 17888

**Active area: 165m²**
(from 65m² as it is now)
Track Trigger:
- Local $p_T$ discrimination will give input to L1 trigger at BC frequency
- Tunable window, different sensor spacings
- Three approaches for back-end

Qualification of Infineon as new supplier for sensors
Initially also L0 trigger capabilities → not considered anymore
→ But Luminosity monitor (40MHz)

11m² of LGADs
\[ \Phi_{\text{eq, max}} = 6 \cdot 10^{15} \text{ cm}^{-2} \]
\[ \text{TID}_{\text{max}} = 4 \text{ MGy} \]

20 (60)ps time resolution

ATLAS

Barrel: LYSO:Ce scintillator with SiPM readout
Endcap: LGADs with custom ASIC with CO₂ cooling a.s.o.

Rachel Yohay

CMS Simulation \( \langle \phi \rangle = 20 \)

Lyso:Ce

ATLAS LgadTiming Integrated ReadOutChip (ALTIROC)
• **ATLAS: AFP**
• **CMS: CT-PPS**

Non-uniform irradiation:

Roman Pots System with movable devices:

Alignment procedure at stable beams:
Tracking Stations

- 3D sensors (50x250 μm² pixel size, 336x80 pixels) with slim edge
- FE-I4 readout chip

**Testbeam result:**
6 μm resolution per plane → 3 μm per station

Timing Stations

**Cherenkov Quartz bars** placed at Cherenkov angle
Readout with Micro-Channel-Plate Photomultiplier (MCP-PMT) at the end of the bars

- time resolution: ~20 ps
- → ~4 mm z-resolution of the primary vertex in the central detector
Tracking Stations

- Upgrade: CNM 3D Sensors+PSI46dig chip
- Installed March this year

Timing Stations

A resolution of ~ 10 ps on the proton arrival time allows to determine the vertex z position with $\sigma_z \approx 2$ mm

plane of UFSD/LGAD (first installation in HEP):
Three independent subdetector systems:
- 2 layers of Silicon Pixels
  - 3.3 + 6.5 M pixels
  - 240 p+n sensors (0.21m²)
- 2 layers of Silicon Drift Detector (260 modules)
- 2 layers of Silicon Strips (1698 modules)
- Surrounded by big TPC

- No increasing leakage current due to radiation, but at some SSD modules due to increasing humidity of the air coming from ventilation
  - 2016: new ventilation machine installed
  - EYETS 2017: new cooling unit to cool down the dry air

The present ITS will be completely replaced in the ALICE upgrade in LS2 (ALPIDE MAPS)
Present muon spectrometer suffering from uncertainties extrapolating tracks through absorber

→ Muon Forward Tracker

920 silicon pixel sensors (0.4 m²) on 280 ladders of 2 to 5 sensors each

ALPIDE pixel sensor (CMOS MAPS, TowerJazz 0.18 µm technology)

• Sensor Thickness 50 µm
• Sensor Size 15 mm x 30 mm. Pixel pitch 29 µm x 27 µm
• Spatial Resolution 5-6 µm
• High-resistivity (> 1kΩ cm) p-type epitaxial layer (25µm) on p-type substrate
• Also being used for ITS upgrade
Giacomo Contin

Need to resolve displaced vertices in high multiplicity environment

TPC – Time Projection Chamber (main tracking detector in STAR)
HFT – Heavy Flavor Tracker
  - SSD – Silicon Strip Detector
  - IST – Intermediate Silicon Tracker
  - PXL – Pixel Detector

Tracking inwards with gradually improved resolution:

SSD  \( r = 22 \)
IST  \( r = 14 \)
PXL  \( r_2 = 8 \)

\( r_1 = 2.8 \)

Success!
Performance exceeded expectations

Weaknesses
- The technology was new for a collider environment
- Short (3-years) physics program

Ultimate-2: third MIMOSA-family sensor version developed at IPHC, Strasbourg
Integration time: 186 \( \mu \text{s} \)
Forward spectrometer:

- Run I → 3 fb\(^{-1}\) collected
- Run II → 6 fb\(^{-1}\) collected
  → 8 fb\(^{-1}\) expected by the end of 2018

Precision of many physics measurements at LHCb will be statistically limited at the end of Run II

**LHCb Upgrade - Run III**
- 5x luminosity → \(L = 2 \times 10^{33} \text{cm}^2 \text{s}^{-1}\)
- 5 fb\(^{-1}\) / year
- Trigger upgrade
- Sub-detectors upgrade

---

15 Sept 2017  
T. Bergauer
Evaporative CO₂ cooling (first in HEP!)

Fluence per fb⁻¹ expected in Run II

Emma Buchanan
Moving from Silicon Strips to Pixels:
• Higher radiation tolerance
• Increased Readout Rate (1 MHz to 40 MHz).
• Closer to Beam
• Microchannel CO₂ cooling
• VeloPix derived from Timepix3:

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel arrangement</td>
<td>256 x 256</td>
</tr>
<tr>
<td>Pixel size</td>
<td>55 x 55 µm²</td>
</tr>
<tr>
<td>Peak hit rate</td>
<td>80 Mhits/s/ASIC</td>
</tr>
<tr>
<td>Readout type</td>
<td>Continuous, trigger-less, TOT</td>
</tr>
<tr>
<td>Resolution</td>
<td>1.5625 ns, 18 bits</td>
</tr>
<tr>
<td>Total Power</td>
<td>&lt;1.5 W</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>400 Mrad, SEU tolerant</td>
</tr>
<tr>
<td>Sensor type</td>
<td>Various, e- and h+ collection</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>5.12 Gbps</td>
</tr>
<tr>
<td>Technology</td>
<td>130 nm CMOS</td>
</tr>
</tbody>
</table>
Upgrade:
- Full software trigger
- Readout and event reconstruction at 40 MHz
- Tracking system replacement

Four Layers of single-sided sensors on vertical double-sided staves:

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Technology</th>
<th># of sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>p-in-n</td>
<td>728</td>
</tr>
<tr>
<td>A</td>
<td>n-in-p</td>
<td>160</td>
</tr>
<tr>
<td>B</td>
<td>n-in-p</td>
<td>48</td>
</tr>
<tr>
<td>C</td>
<td>n-in-p</td>
<td>16</td>
</tr>
<tr>
<td>D</td>
<td>n-in-p</td>
<td>16</td>
</tr>
</tbody>
</table>

Double-metal inefficiencies, solved by thicker SiO$_2$

Front-side biasing with dedicated via in sensor (HPK)

SALT ASIC: TSMC CMOS 130 nm technology 128 channels, wirebonded to sensors. Input pitch 80μm
Belle II at KEK

Jochen Dingfelder, Gagan Mohanty

Challenges for vertex reconstruction:
- Higher backgrounds (lumi. increase, nano-beams) \(\Rightarrow\) higher occupancy
- Boost reduced from \(\beta y = 0.42\) to 0.28

SuperKEKB accelerator
\(E_{cm} = 10.58\) GeV @ \(Y(4s)\)

Peak Lumi \(8 \times 10^{35}\) cm\(^{-2}\)s\(^{-1}\)
Integrated lumi: 50 ab\(^{-1}\)
\(\Rightarrow\) 15 times higher as HL-LHC

15 Sept 2017
T. Bergauer
• DEPFET concept developed by late Gerhard Lutz
  – First use in HEP experiment here
• Pixel is FET transistor
  – amplification in sensor
  – “clearing” of signal necessary

DEPFET Production

3. thin sensor side to desired thickness
4. process DEPFETs on top side
5. structure resist, etch backside up to oxide/implant

21 final production wafers → processing finished
Double-sided silicon microstrip detector (DSSD): p-in-n 6″ wafer

APV25 chip: originally developed for CMS

Ladder Assembly status:
• L3: 100% completed
• L4: 7 out of 12 done (60%)
• L5: Just finished
• L6: 12 out of 20 done (60%)

Shifting now to ladder mount on support structure
Mu3e at PSI

Heiko Augustin

- LFV decay $\mu^+ \rightarrow e^+ e^- e^+$ suppressed in the SM ($\text{BR} < 10^{-54}$)
- current limit $\text{BR} < 10^{-12}$ (SINDRUM)
- aiming for sensitivity of 1 in $10^{16}$ decays
- any observed signal is a sign for new physics

1 T field, continuous $\mu$-Beam:

- irreducible background from internal conversion:
  $\mu^+ \rightarrow e^+ e^- e^- \bar{\nu}_\mu \nu_e$
  $10^9$ decays/s

MuPix8: HV/HR-CMOS
  very advanced,
  128x200 pixels,
  81x80µm, 50µm thick

1.16‰ $X_0$ / layer

He-flow cooling: (4-20m/s)

start data taking in 2020
• Fixed target at SPS to measure BR of K+ decay “in flight”:
  – Installed 2016
  – 75 GeV/c continuous hadron beam

• GTK sensors in direct beam
  – 6x3cm$^2$ size
  – 300x300µm$^2$ pixels
  – Exchanged every 100 days

• ~20 hits per plane

• High Timing precision
  – Time walk correction in chip
  – Time offset (online)
  – Time resolution 130ps
  – Time resolution per track 74ps

• High radiation levels,
• CO$_2$ microchannel cooling
Dark Matter Detector usually 100t of Water/lAr/Xr/Crystals

- Exclusion plot on low-mass scale limited by energy threshold
- Neutral particle scatters off Si atom
- recoils energy produce ionization
- coherent neutrino scattering
- Can be accessed by low-noise CCD
- DAMIC (SNOLAB) & CONNIE (Reactor)

CCD: Pixels 15 x 15 μm
650 μm thick
DETECTOR TECHNOLOGIES
• Move from classical Monolithic CMOS detector to HV-CMOS
• Different processes
  – AMS (MuPix, CCPD, ATLAS)
  – Lfoundry (e.g. Passive LFCMOS)
  – TowerJazz (e.g. ALPIDE)
  – Xfab HV-SOI (up to 7 metal layers) reduces threshold shift
  – Lapis: 0.20um FD-SOI process (SOIPIX → Japanese grant)
• Many groups working on it: Bonn, CERN, Geneva, JSI, UK, US, Japan → mostly ATLAS (where is CMS?)
• Biggest improvement recently: high resistivity material to create thicker depletion zones (20Ωcm (standard) → 2kΩcm)
• Next Steps: radiation hardness – >10^{16} hadrons, stitching

Maps & HV-CMOS technology
Tomasz Hemperek, Hara-san

- Maps: Charge collection in intrinsic depletion zone and by diffusion
- Charge collection drift in E-field → HV-CMOS
- Minimize collection electrode to lower capacitance (noise)

- 700Mrad
- Threshold shift

Xfab HV-SOI

Edge-TCT:
History:
- Medipix2 (1999)
- Timepix 2006 (EUDET/AIDA funded)
- Medipix 3
- Timepix3, Clicpix (2013)
- Velopix, Clicpix2 (2016)
  - 4-side buttable
  - 6.94 cm$^2$ (3.5x more)
  - 200ps time resolution
- 10 years ago: Timepix for TPCs
- Now: Applications everywhere
  - LHC-b VELO, Clicpix

**Timepix with 3-GEM detector**
- Triple GEM gas detector
- Checked-board pattern (TOT and TIME)

**Timepix Applications**
- LCB: Time-resolved neutron imaging
- GEM: Quality inspection in paper industry
- TASC: 16Cr TiC detector in pipe production
- LGEM: Gamma detection in photonics
- LGEM: Recoil detection in heavy ion
- TOT: Neutron imaging with noise
- ELE: Ewing detector for gamma-ray imaging
- SWAX: Space Odyssey
- DSSD: Dedicated Silicon Sensor Detectors

**Ar 150 GeV/c**
[p-on-n 500 µm sensor]
Amplification found “accidentally” as the sensors were getting thinner and higher voltages are being applied.

Now being exploited by highly doped, thin layer of p-implant underneath p-n junction — high electric field accelerates electrons enough to start multiplication

- “Low” Gain since shot noise rises more than signal
- Gain sensitive to doping profile → irradiation reduces gain → time resolution goes worse
  - Irradiation sensitivity mitigated by Gallium dopant (less probabilities for interstitials) and/or carbon
  - LGAD gain prone to annealing effects
- Already 4 suppliers: **CNM**, FBK, HPK, Micron
- Variant of “Inverted-LGAD” with strips on top
Direct Bond Interconnect (DBI) Process

Wafer-to-Wafer bonding
- Sensor diameter must match
- (chips 8-12”, sensor 6-8”)
- Chip and sensor layout must match
- Intrinsically „edge-less“

Die-to-Wafer bonding
- Possible to select good dies (new metallization necessary after probing)

- Application for timing by lowering noise (capacitance)
• Commercial vs. R&D paths
  – e.g. bump-bonding

• Costly, time consuming “commercialization”
  – Demand of technology in HEP is not constant in time
  – Thus companies usually not so interested in us

• Examples:
  – Small detector area → "home made", e.g. DEPFET@HLL (10 working wafers)
  – CMS/ATLAS Trackers ~50k wafers
    Example: 6-8” sensors for CMS Tracker/HGCal Phase-II Upgrade @ Infineon

• Future: Pixels in huge quantities
  – Will only work if commercial processes are used as far as possible, e.g. HV/HR-CMOS
10 years ago: experimental, high pressure, hard to control
- developed for the AMS TRD and for the LHVb Velo
- specific two-phase pumped loop (2-PACL)

Now: established technique for all HEP experiment upgrades
- Thanks to Bart Verlaat, Paolo Petagna et al.

**Past:** CO\textsubscript{2} test facility (CERN) 
Airflow facility (Oxford)

**Present** (Upgrades): Thin silicon substrate with embedded µ-channels

**Future:** same CTE

**“Traditional” approach:** fair enough for STRIPS
**“Integrated” approach:** for the NA62 GTK, the LHCb Velo upgrade and the ALICE ITS upgrade

Microchannels etched in silicon
60 \(\mu\)m \(\times\) 60 \(\mu\)m (40 mm long)
• RD42 collaboration: 32 institutes, 130 people (founded 1994)
• Diamond: no pn-junction, just (segmented) metallization
• Single crystal vs. poly crystalline (grains)
• Application (so far): Beam Conditions Monitors/Beam Loss Monitors

New efforts:
• Radiation tolerance normalized for single and poly-crystal and particle species
• 3D Diamond by laser “drilling of holes” (UK effort) → acts like “single crystal” if grain size > CCD
  – First try 2015 (99 “columns”)
  – Full 3D device 2016 (1188 “columns”, 2µm hole diameter
  – 2017: 3500 cell pixel prototype w/50x50µm

Readout with CMS pixel readout:
• Preliminary efficiency 99.2%
• Collect >90% of charge!
WG1: defect/material characterization
- Thermally Stimulated Current (TSC)
- Deep Level Transient Spectroscopy (DLTS)
- Red/IR front/back TCT
- Edge-TCT
- New: Two-Photon-Absorption-TCT: very powerful technique!

Using these to understand:
- N-Bulk: Donor Removal
- P-bulk: acceptor removal: CiS study, HVCMOS CCE study

Study of irradiated LGAD sensors:
- Onset at low bias voltages
• **RD50 WG2: fast simulators:**
  - KDetSim (Lubljiana), Weightfield2 (Torino), TRACS (IFCA&CERN)

• **Perugia TCAD Irradiation model**
  - Commercial Synopsys Sentaurus
  - >20 publications
  - Parametrization of experimental results of both bulk and surface damage
  - New version up to 2.2E16 n_{eq}/cm^2
  - “Modelling radiation damage effects is a hard task!”

• **Allpix² - Generic Pixel Detector Sim. Framework**
  - Modular easy-to-use
  - Charge generation sim Geant4
  - import electric fields in the TCAD DF-ISE format
FUTURE EXPERIMENTS
FCC-ee, FCC-eh, FCC-hh

- ~16T magnets → 100TeV pp collider in 97.75km tunnel

→ 1MeV $n_{eq}$ fluence $\sim 6 \times 10^{17}$ cm$^{-2}$ & TID $\sim 0.4$GGy

→ data rates (766 TB/s untriggered, 19 TB/s triggered @1MHz)

Forward detectors up to $\eta<6$

Zbynek Drasal
**e^+/e^- Colliders:** Well known initial state, no QCD background, fully reconstructable final states

- **CLIC@CERN:** Up to 50km length@3TeV (100MV/m gradient), beam size 45 x 1 nm
- **ILC@Japan:** Up to 50km length@1TeV, 31.5 MV/m gradient. Two detector concepts (ILD, SiD)

**Detectors:**
- Pixels inside, strips outside
  - ILC: additional TPC with “Silicon external tracker” around it
- Lower radiation w.r.t. LHC
- Bunch train beam allows power pulsing
- Airflow cooling (FEA ongoing)
- Low occupancy
- Very low material budget

**Detector technologies:** HV/HR-CMOS, SOI
  - CliCpix2, C3PD (glued), CLICTD
  - Chronopix, SOI, FPCCD, DEPFET, CMOS
Summary of the

SUMMARY
5 Days with 46 excellent talks, 11 posters, great food and wine

**LHC Detectors performing extremely well**, but getting older and older….
- Automatic procedures being implemented to cope with SEU, de-sync,….
- CMS Pixel replacement happened during winter shutdown 2016/2017
- Upgrade programs everywhere. (LS2: ALICE, LHC-b)
- New situation we are facing now: parallel work of operation of existing detectors and R&D, prototypes (manpower!, funding!)

**Most recent detectors**: NA62 GTK, Forward experiments of ATLAS and CMS

**Upcoming Experiments**: Belle II, Mu3e (FCC very actively investigated)

**New Application of Silicon**: Dark Matter detection

**CO₂ cooling is everywhere**

**Timing, Timing, Timing,**…..

**Much progress on recent developments:**
- LGAD, HV/HR-CMOS, Timepix4/Velopix
- 4-side buttable/stichting sensors to achieve large areas (TSV/Vertical integration)
- “The future is just monolithic” (K. Hara)
Let’s look into a monolithic, precisely timed and amplified future

A three-dimensional integrated circuit, made possible with carbon nanotubes (CNTs). Physics Today 70, 9, 14 (2017)
Thank you for your attention!