Development of the BCM' abort and luminosity system at the HL-LHC based on poly-crystalline CVD diamond pixel-pad detectors

14th Trento Workshop on Advanced Silicon Radiator Detectors, 25. 02. 2019

Bojan Hiti (Jožef Stefan Institute, Ljubljana, Slovenia) for ATLAS BCM'
ATLAS BCM and BCM'

• Current ATLAS abort system: Beam Condition Monitor (BCM)
  • 2 stations 6.25 ns from IP
  • Dumps the LHC beam if ATLAS endangered (scattered beam – out of time measurements ± 12.5 ns)
  • Also used for luminosity measurement

• 10 x 10 mm$^2$ single pad pCVD diamond sensor → occupancy at high pile-up is problematic (1.5 MIPs / pp collision)
• After HL-LHC upgrade (2024—2026) luminosity will increase by factor 5
BCM' upgrade for HL-LHC

- pCVD diamond sensor, segmented into 8 pads → flexible acceptance
- Custom analogue front end BCM' ASIC (designed by OSU)
  - 65 nm TSMC process, 4 readout channels
  - Separate front end functionality for Abort (high signals) and Luminosity (low noise)
  - Current amplifier; < 1 ns rise time, fast (~10 ns) baseline restoration
  - Desired sub-ns time resolution for beam diagnostics
  - Large pitch bump bonding or wire bonding
- First prototypes available in September 2018
- Presenting first results from beam tests at CERN SPS and PSI in October 2018

![Diagram of BCM' ASIC and diamond sensor](image)
CERN H6 test beam

- CERN SPS H6 test beam: 120 GeV hadrons
- KarTel (Mimosa) beam telescope
  - Tracking resolution ≈ 3 μm
- DRS 4 analog readout
  - 3 GS/s acquisition rate, 700 MHz bandwidth
- DUT:
  - + 1000 V bias voltage
  - DUTs pumped with Sr90 before measurements
  - Output oscillated if more than one channel per chip active → Recorded two channels per run

- Dataset:
  - All channels measured (separate runs)
  - several 10k tracks per channel
Signals and pick-up

- Large pick-up from the setup/environment
- Same shape in all channels → Mitigation by subtracting two waveforms
- \((ch1 - ch2)\) or \((ch2 - ch1)\) depending on track position
- Pick-up reduced by factor 2

![Graph showing noise before and after subtraction](image)
Signal measurement

- Average waveform of 1000 acquisitions
- Select an integration window around the peak \([t_{\text{min}}, t_{\text{max}}]\)
- Signal = Integral around the peak

\[
S = \frac{1}{t_{\text{max}} - t_{\text{min}}} \int_{t_{\text{min}}}^{t_{\text{max}}} Ud\text{t}
\]

- Long integration window \([-6 \text{ ns}, 6 \text{ ns}]\) to mitigate for noise
- Hit criterium: signal threshold = 4\(\sigma\) above noise

![Noise spectrum](image)

Noise level varies by factor 2, depending on the channel
Efficiency measurement Chip 2 channel 1 (1000 V)

Tracks through sample
- avg. eff. 99.0 % at thr 4σ
- ≈ 25 tracks per bin

Signal Spectrum
- > 99 % hits above threshold
- Measured in the fiducial region at + 1000 V
- MPV = 7.5 mV, mean 9.8 mV
- Noise RMS = 0.5 mV
- S/N ratio (mean) ≈ 20

Noise Spectrum
- thr. = 1.9 mV
- MPV = 7.5 mV, mean 9.8 mV
- Noise RMS = 0.5 mV
- S/N ratio (mean) ≈ 20
Chip 2 channel 3

- High resolution run on a small pad
- Efficiency > 99 % in fiducial region at thr. $4\sigma$
- Signal size varies with position (pCVD diamond)
- Should average out over large pad
PSI test beam

- High Intensity Proton Accelerator (HIPA) at PSI, beam line PiM1, 260 MeV/c pions
- PSI beam telescope (150 x 100 μm pixels) + multiple scattering → lower resolution
- DRS 4 readout, modifications to reduce ringing
- Measurements at positive and negative bias voltage: ± 200 V, ± 300 V (sample 1), ± 500 V, ± 1000 V (sample 2)

Thanks to ETH for measurements and analysis!
Waveforms at PSI

- Much lower noise than at CERN – no pickup

- $\sim 1.4 \text{ ns}$ Average rise time (20% – 80%),

- DRS 4 analog bandwidth (700 MHz) may be the limiting factor in the rise time measurement

- Baseline restoration after 10 ns

- Analysis: Integration time $[-1.5 \text{ ns}, 3 \text{ ns}]$
Signal Rise Time

- Rise time (20 % – 80 %) ≈ 1 ns
- Improves with bias voltage – very few outliers at 1000 V
Charge measurement + 200 V

- Charge measurement in fiducial region
- 10% difference for different sign of $V_{\text{bias}}$ at low voltages (0.4 V/μm)
- Distribution fitted with convoluted Landau + gaussian
- Noise distribution independent of bias voltage, offset is a feature of DRS 4
Signal spectra at 1000 V

- At 1000 V signal spectrum is the same for both polarities
- Small pedestal – due to low tracking resolution
**Signal summary**

### Diamond 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+200 V</td>
<td>14.07</td>
<td>1.15</td>
<td>12.23</td>
</tr>
<tr>
<td>2</td>
<td>+200 V</td>
<td>36.52</td>
<td>2.73</td>
<td>13.37</td>
</tr>
<tr>
<td>1*</td>
<td>+200 V</td>
<td>13.73</td>
<td>1.03</td>
<td>13.33</td>
</tr>
<tr>
<td>2*</td>
<td>+200 V</td>
<td>13.66</td>
<td>1.15</td>
<td>11.88</td>
</tr>
<tr>
<td>1</td>
<td>−200 V</td>
<td>12.04</td>
<td>1.28</td>
<td>9.40</td>
</tr>
<tr>
<td>2</td>
<td>−200 V</td>
<td>30.12</td>
<td>2.70</td>
<td>11.16</td>
</tr>
<tr>
<td>1*</td>
<td>−200 V</td>
<td>12.23</td>
<td>1.18</td>
<td>10.36</td>
</tr>
<tr>
<td>2*</td>
<td>−200 V</td>
<td>10.18</td>
<td>1.10</td>
<td>9.25</td>
</tr>
<tr>
<td>1</td>
<td>+300 V</td>
<td>21.93</td>
<td>1.21</td>
<td>18.12</td>
</tr>
<tr>
<td>2</td>
<td>+300 V</td>
<td>56.87</td>
<td>2.67</td>
<td>21.30</td>
</tr>
<tr>
<td>1</td>
<td>−300 V</td>
<td>16.53</td>
<td>1.26</td>
<td>13.12</td>
</tr>
<tr>
<td>2</td>
<td>−300 V</td>
<td>44.62</td>
<td>3.01</td>
<td>14.82</td>
</tr>
</tbody>
</table>

### Diamond 2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+500 V</td>
<td>35.16</td>
<td>1.02</td>
<td>34.47</td>
</tr>
<tr>
<td>2</td>
<td>+500 V</td>
<td>38.43</td>
<td>1.15</td>
<td>33.42</td>
</tr>
<tr>
<td>1</td>
<td>+1000 V</td>
<td>45.62</td>
<td>1.15</td>
<td>39.67</td>
</tr>
<tr>
<td>2</td>
<td>+1000 V</td>
<td>47.16</td>
<td>1.06</td>
<td>44.49</td>
</tr>
<tr>
<td>1</td>
<td>−500 V</td>
<td>33.10</td>
<td>1.18</td>
<td>28.05</td>
</tr>
<tr>
<td>2*</td>
<td>−500 V</td>
<td>24.32</td>
<td>1.21</td>
<td>20.10</td>
</tr>
<tr>
<td>1</td>
<td>−1000 V</td>
<td>44.96</td>
<td>1.12</td>
<td>40.14</td>
</tr>
<tr>
<td>2</td>
<td>−1000 V</td>
<td>45.75</td>
<td>1.12</td>
<td>40.85</td>
</tr>
</tbody>
</table>

**S/N ratio = mean signal / noise RMS**

At highest bias voltages **S/N ≈ 40 (mean)**

Timing resolution: $t_{\text{rise}} / (S/N) = 1.4 \text{ ns} / 40 = 35 \text{ ps}$ → very promising
Efficiency vs. threshold

- Efficiency improves from 300 V (0.7 V/μm) → 1000 V (2 V/μm)
- Inefficiency in part due to low tracking resolution
Interchannel coupling

• Couplings to the neighbour pad observed – cross talk on the sensor suspected
• Similar behaviour observed at SPS
• Small signals every time a particle hits the neighbour pad
Toward the BCM\textsuperscript{1} module

- Module = Sensor + analogue front end + digitization + data transmission

- Use "existing" components:
  - PicoTDC: time-to-digital converter (TDC) developed by CERN
  - Compatible with lpGBT
  - 65 nm TSMC process
  - 12 ps inherent time resolution
  - 32 channels, selectable between measurement of
    - Time of arrival
    - Time over threshold
    - BCM\textsuperscript{1} requires 16 channels
Summary and outlook

- Successfully demonstrated functionality of the first BCM' front end prototype
- > 99 % efficiency measured in the test beam
- S/N (mean) = 40 before irradiation
- Good timing performance
  - Rise time 1.4 ns
  - Baseline restoration 10 ns
  - < 100 ps timing resolution is already achievable
- Further analogue front end submissions planned
- Module production using common components: PicoTDC, lpGBT
BACKUP
• Observed cross talk on the sample
• Separate readout chips, so cross-talk most likely from the sensor
• Noise level larger with larger pads → 2x higher threshold, efficiency slightly lower