Performance Evaluation of the Detector and Ultra-Light Micro-cable Assembly for Tracking Application in CBM experiment

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1. Introduction to CBM experiment and STS detector architecture.


3. Sensor and cable models and parameters.

4. The transfer characteristics of the cables and sensors with different load.

5. Studies of the output current pulse shape.


7. Conclusions
The CBM experiment at GSI

**STS (Silicon Tracking System) detector**

- Tracking and momentum determination of the charged particles at the interaction rate of 10 MHz
- 8 tracking stations in distances from 30 cm to 100 cm from the target within a 1T magnetic dipole field

**STS metrics:**
- >1 790 000 channels
- >14 000 ASICs
- 1752 FEBs
- 600 ROBs
- 78 DPB s

**Aim:** Creation of the highest baryon densities in nucleus-nucleus collisions, exploration of the properties of the super-dense nuclear matter.
The CBM experiment at GSI: STS (Silicon Tracking System) detector

quarter of a detector station

readout electronics (STS-XTER2 chips) at the perimeter of the detector stations on FEB boards (8 chips/board) + data concentrators (GBTx-based ROB boards)

multi-line micro-cables -> sensors read out double-sided, micro-strip sensors, 1024 CH/side, 7.5° stereo angle, 58 µm strip pitch

The STS/MUCH-XTER2:
- developed at AGH University Cracow
- 10 mm × 6.75 mm
- 128 readout channels
- two test channels
- Each channel:
  - Charge Sensitive Amplifier (CSA),
  - Polarity Selection Circuit (PSC),
  - fast and a slow pulse shaping amplifiers (shapers),
  - timing discriminator
  - 5-bit continuous-time, flash analog-to-digital converter (ADC)
Motivation

- The noise performance of the entire detector module depends on:
  - the read-out IC architecture and characteristics,
  - power supply system performance,
  - the sensor's and cable's parameters
    - Sensors' and cables' capacitance
    - Series resistance of long sensors and cables.

- Continuously evolving development of the STS detector components required new studies of achievable noise performance in the STS detector system.

\[
\frac{<dv_{\text{CSAout}}^2>}{df} = \frac{a}{(2\pi f C_{fb})^2} + (b + \frac{A_F}{f})(\frac{C_{tot} + C_{fb}}{C_{fb}})^2
\]

\[
a = 2qI_{\text{leak}} + \frac{4kT}{R_{\text{bias}}} + \frac{4kT}{R_f} \quad \text{current noise,}
\]

\[k \quad \text{Boltzmann constant, } T \quad \text{temperature}
\]

\[b \quad \text{thermal noise of the CSA input transistor}
\]

\[\frac{A_F}{f} \quad \text{flicker noise of the CSA input transistor}
\]
Sensor and cable models

Cross section and parasitic capacitances of double-sided detector

- array of strip-shaped, reverse-biased diodes on a common bulk;
- 1024 strips with 58 µm pitch;
- 7.5º stereo angle on each side;
- thickness - 300 µm;
- lengths - 2, 4, 6 and 12 cm;
- AC coupled (the coupling capacitor formed with the metal strip deposited over a diffusion strip and an isolation layer);

Cross section and parasitic capacitances of ultra-light micro-cable assembly

- multi-line micro-cables;
- 128 thin aluminum trace lines;
- 116 µm pitch, 15 µm thickness, 35 µm width;
- two polyimide signal layers;
- signals’ transfer between the sensors and front-end (FE) electronics and for the sensors biasing;
- insulating meshed spacer made from polyimide foil between the layers of cables in a bundle -> reduction of the cross-talk and inter-layer capacitance;
- shielding of the stack with four micro-cable layers (cutting-down the interference coupling).
## Sensor and cable models

### Electrical model of double-sided sensor

<table>
<thead>
<tr>
<th>Sensor parameter</th>
<th>Value</th>
<th>Cable parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strip to strip $C_{p-p}$ (p+)</td>
<td>0.36 pF/cm</td>
<td>trace material &amp; dimensions</td>
<td>Al 35 µm × 14 µm</td>
</tr>
<tr>
<td>strip to strip $C_{p-p}$ (n+)</td>
<td>0.37 pF/cm</td>
<td>capacitance to same-layer neighbor</td>
<td>0.119 pF/cm</td>
</tr>
<tr>
<td>strip to metal strip $C_{p-m}$</td>
<td>10 pF/cm</td>
<td>to a neighbor on adjacent layer $C_{1:2}$</td>
<td>0.139 pF/cm</td>
</tr>
<tr>
<td>strip to bulk $C_{b}$</td>
<td>0.18 pF/cm</td>
<td>to ground plane $C_{1:G}$</td>
<td>0.38 pF/cm</td>
</tr>
<tr>
<td>metal (Al) strip $R_{s,m}$</td>
<td>10.5 Ω/cm</td>
<td>trace series resistance $R_s$ (signal)</td>
<td>0.29 pF/cm</td>
</tr>
<tr>
<td>strip $R_{s,p}$ (p+)</td>
<td>66 kΩ/cm</td>
<td>trace series resistance $R_s$ (bias)</td>
<td>0.635 Ω/cm</td>
</tr>
<tr>
<td>strip $R_{s,n}$ (n+)</td>
<td>44 kΩ/cm</td>
<td></td>
<td>0.618 Ω/cm</td>
</tr>
<tr>
<td>Bias resistance $R_{bias}$ (p-side)</td>
<td>500 kΩ/strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias resistance $R_{bias}$ (n-side)</td>
<td>500 kΩ/strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>285 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total strip capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-side</td>
<td>1.02 pF/cm</td>
<td></td>
<td>0.382 pF/cm</td>
</tr>
<tr>
<td>n-side</td>
<td>1.02 pF/cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Electrical model of ultra-light micro-cable signal traces and sensor biasing traces

<table>
<thead>
<tr>
<th>Sensor parameter</th>
<th>Value</th>
<th>Cable parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strip to strip $C_{p-p}$ (p+)</td>
<td>0.43 pF/cm</td>
<td>trace material &amp; dimensions</td>
<td>0.119 pF/cm</td>
</tr>
<tr>
<td>strip to strip $C_{p-p}$ (n+)</td>
<td>0.57 pF/cm</td>
<td>capacitance to same-layer neighbor</td>
<td>0.139 pF/cm</td>
</tr>
<tr>
<td>strip to metal strip $C_{p-m}$</td>
<td>18 pF/cm</td>
<td>to a neighbor on adjacent layer $C_{1:2}$</td>
<td>0.38 pF/cm</td>
</tr>
<tr>
<td>strip to bulk $C_{b}$</td>
<td>0.21 pF/cm</td>
<td>to ground plane $C_{1:G}$</td>
<td>0.29 pF/cm</td>
</tr>
<tr>
<td>metal (Al) strip $R_{s,m}$</td>
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<td></td>
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<td>500 kΩ/strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>285 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total strip capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-side</td>
<td>1.74 pF/cm</td>
<td></td>
<td>0.382 pF/cm</td>
</tr>
<tr>
<td>n-side</td>
<td>1.52 pF/cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Total cable capacitance

- 0.382 pF/cm
Transfer function

- cable length from 14.8 cm through 49 cm
- ideal load (Zin=0Ω)

- Bandwidth↓ with the increasing length of the cable;
- Bandwidth: 0.59 GHz (L=49 cm) to 6.6 GHz (L=14.8 cm).

- sensor’s length - 6 cm
- different sides (p or n)
- two vendors
- different parasitic components depending on the side (p or n) and on the manufacturer

bias resistor value (3x higher value for n-side)

FAB1 - differences are negligible (<3%).

strip-to-strip capacitance differences between p and n side (31% )
Sensors comparison

Two sets of cable-sensor lengths, two different manufacturers and for two sides of the sensor, loaded with an ideal amplifier with zero input impedance.

Sensors of different lengths from 2 to 12 cm from the two manufacturers.

Charge leakage to the neighbouring channel.
Output current pulse shape simulations

Simulations for three various types of load impedances:
- simple 200 Ω resistor
- simplified CSA model
- fully-featured analog front-end channel implemented in the STS/MUCH-XYTER2 ASIC.

- Charge generated by the ideal current pulse (1 ns rise/fall times, 10 ns width) at the furthest part of the sensor
- The impact of the growing sensor's and cable's lengths on the output pulse shape (amplitude ↓, pulse duration ↑)

<table>
<thead>
<tr>
<th>Detector / Cable length case</th>
<th>Charge transfer efficiency (source to middle channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% for ideal load (Z_{in}=0 Ω)</td>
</tr>
<tr>
<td></td>
<td>p-side</td>
</tr>
<tr>
<td>D: 2 cm C: 25 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FAB1</td>
</tr>
<tr>
<td></td>
<td>86.0 %</td>
</tr>
<tr>
<td></td>
<td>83.7 %</td>
</tr>
<tr>
<td>D: 6 cm C: 35 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FAB1</td>
</tr>
<tr>
<td></td>
<td>87.4 %</td>
</tr>
<tr>
<td></td>
<td>84.0 %</td>
</tr>
<tr>
<td>D: 12 cm C: 41 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FAB1</td>
</tr>
<tr>
<td></td>
<td>88.3 %</td>
</tr>
<tr>
<td></td>
<td>85.7%</td>
</tr>
</tbody>
</table>

The total integrated charge does not change significantly!
Noise simulations’ results

- The sets of the sensor from two considered manufacturers,
- Sensors: length from 20 mm up to 120 mm
- Cables: length from 148 mm to 490 mm
- measured channel of the STS/MUCH-XYTER2 loaded with full analog charge processing chain,
  - the neighboring channels were loaded with 200 Ω resistors

lower noise levels -> FAB2 sensors,
ENC values for freshly fabricated sensors: 425 - 797 e- rms,
- this result will be significantly affected by the increased leakage current due to the aggregated TID (780 – 1016 e- rms),
- the end-tapped long sensor appears to perform better compared to the center-tapped one.

Summary of the ENC values obtained for selected cases

<table>
<thead>
<tr>
<th>Sensor length: D</th>
<th>ENC (e- rms) @ I_d=2mA, t_p=150 ns, R_f=9.22 MΩ</th>
<th>(% charge transferred to the FE channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h_leak=0, no ESD circuit</td>
<td>h_leak=0, with ESD circuit</td>
</tr>
<tr>
<td></td>
<td>h_leak=8nA/cm, with ESD circuit</td>
<td>h_leak=400 nA/sensor, with ESD circuit</td>
</tr>
<tr>
<td>D: 6 cm C: 14.8 cm FAB1/FAB2</td>
<td>e^+ 466.5 / 399.4 (85.4% / 88.9%)</td>
<td>479.1 / 411.5 (85.4% / 88.9%)</td>
</tr>
<tr>
<td>D: 2 cm C: 25 cm FAB1/FAB2</td>
<td>e^+ 545.2 / 485.4 (85.7% / 89.5%)</td>
<td>559.2 / 498.3 (85.7% / 89.4%)</td>
</tr>
<tr>
<td>D: 6 cm C: 35 cm FAB1/FAB2</td>
<td>e^+ 548.7 / 476.3 (84.5% / 89.3%)</td>
<td>562.7 / 489 (84.5% / 89.3%)</td>
</tr>
<tr>
<td>D: 2 cm C: 47 cm FAB1/FAB2</td>
<td>e^+ 530 / 481.6 (84.0% / 87.5%)</td>
<td>543.9 / 495.1 (84.0% / 87.5%)</td>
</tr>
<tr>
<td>D: 4 cm C: 49 cm FAB1/FAB2</td>
<td>e^+ 606.1 / 563 (84.5% / 88.2%)</td>
<td>621.9 / 577.9 (84.5% / 88.2%)</td>
</tr>
<tr>
<td>D: 12 cm C: 41 cm Center tap FAB1/FAB2</td>
<td>e^+ 640.8 / 559.5 (83.5% / 87.6%)</td>
<td>657.4 / 611.5 (83.5% / 87.6%)</td>
</tr>
<tr>
<td>D: 12 cm C: 35.5 cm End tap FAB1/FAB2</td>
<td>e^+ 600.7 / 591.5 (84% / 87%)</td>
<td>615.7 / 606.4 (84% / 87%)</td>
</tr>
</tbody>
</table>

noiseless power supplies, interferences that may occur in the assembled system not considered in simulations
Conclusions: CiS behave better although the parasitic capacitance is larger! This is due to the biasing resistor thermal noise -> larger biasing resistance results in lower overall noise.

Sensor: Hamamatsu, 12cm, n-side (electrons), without cable. Lekagae current $I_{\text{leak}} = 8\text{nA/cm}$.

The noise introduced by $R_{\text{bias}}$ (n-side) related to the overall noise is $\sim 17\%$ (based on simulated list of noise contributors).
Conclusions

1. The overall noise level of the entire system depends on the processing chain performance and sensor's / cable's length in conjunction with load impedance characteristics.

2. The comparison of the charge transfer effectiveness and noise performance of the sensors with different lengths provided by two different manufacturers will be an important issue in the CBM experiment construction.

3. The ENC value versus biasing resistance considerations will be helpful in sensors' selection for the target application.

4. Obtained noise levels show that the architecture and design variables settled in recently fabricated prototype samples can be considered as the ones desired for mass production.
References