Calculation and Measurement of the Interstrip Capacitance on the Readout Board of the GE2/1 GEM Detector

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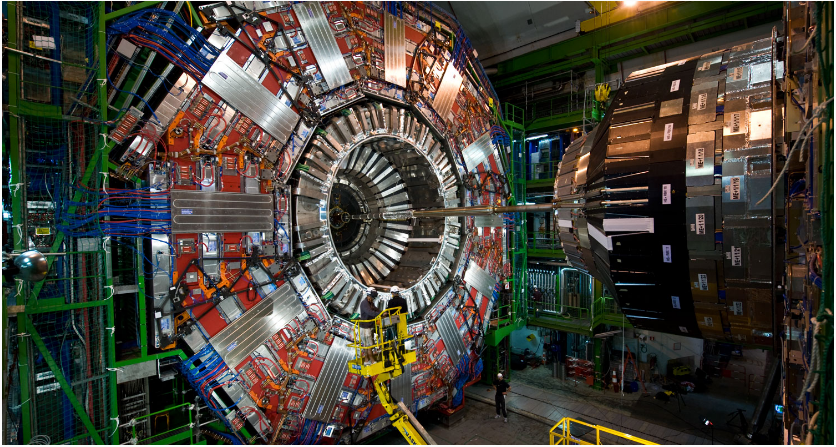
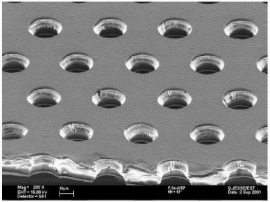
The CMS Experiment



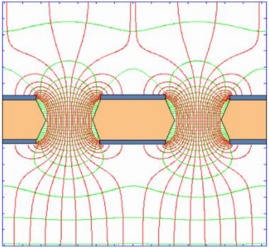
The Compact Muon Solenoid [1].

Gas Electron Multipliers

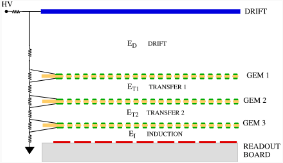
- Gas electron multipliers (GEMs) are a micro-pattern gas detector (MPGD) that consists of three foils inside an active volume filled with gas (in our case its a mix of 70:30 Ar and CO_2)
- The foils are held at different potentials through a high voltage (HV) divider



Electron microscope image of a GEM foil [2].



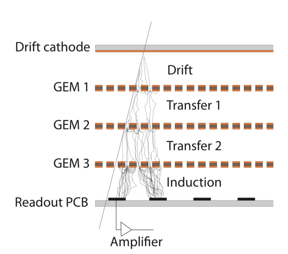
Electric field and potential from the GEM foil [2].



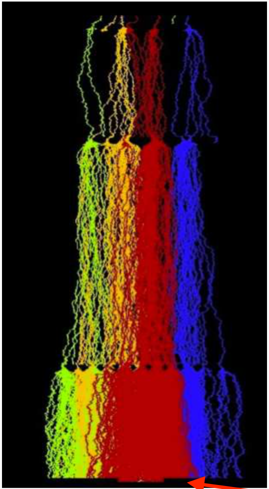
Schematic of the foils in the detector [2].

Gas Electron Multipliers

- As a particle (or photon) enters the detector, it ionizes the gas
- Free electrons accelerated by electric fields cause secondary ionization inside the holes in the foils ($|\mathbf{E}|$ can be as high as 10^7 V/m!) $\Rightarrow$ creates an avalanche
- Charge is collected on the strips on the readout board (ROB) which is then integrated by the readout electronics

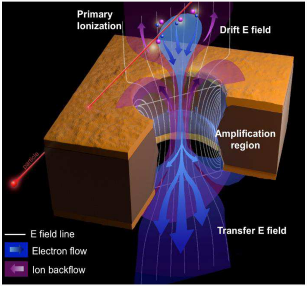


Electron avalanche and gain multiplication between GEM foils [3].



Simulation showing charge multiplication between GEM foils [3].

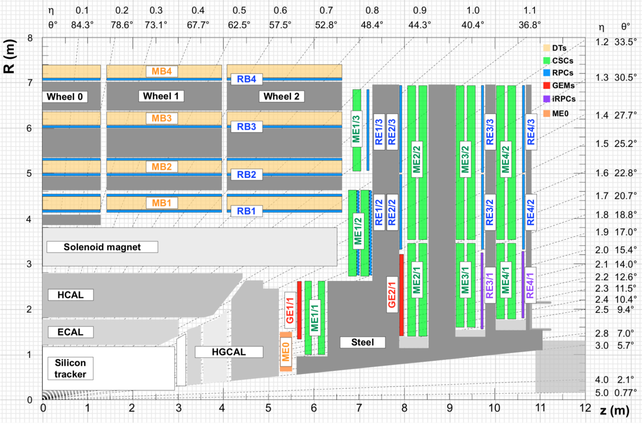
Readout Strips



Ionization process and charge amplification [3].

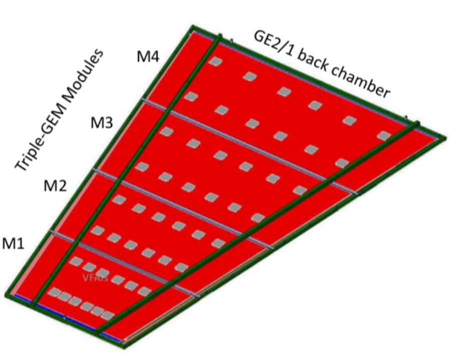
Phase-II Upgrade for CMS

- High Luminosity LHC project (HL-LHC) will increase luminosity $\sim \times 5$
- The Phase-II muon detector upgrade will help increase the redundancy of the muon system
- The new GE2/1 will help lower the Level-1 trigger rate



Muon system for the proposed Phase-II upgrade [4].

The GE2/1 Detector

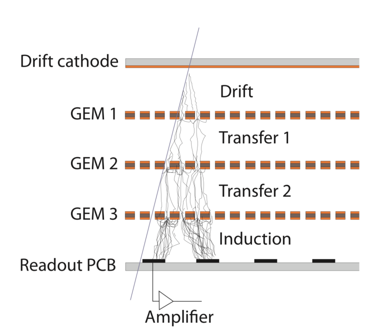


Schematic of the GE2/1 detector [4].

First fully assembled GE2/1 chamber [5].

Interstrip Capacitance of the GE2/1 ROB

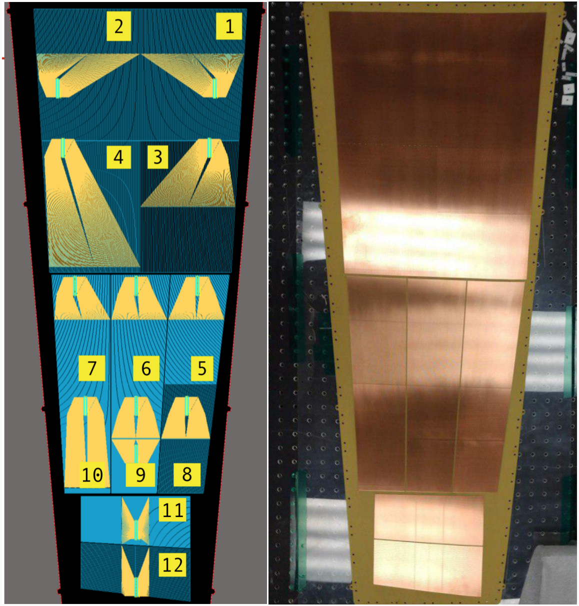
- Interstrip capacitance is an important design parameter
- Lower interstrip capacitance = lower noise ⇒ higher S/N
- Interstrip capacitance influenced by strip length, width, gap width, dielectric substrate, and signal trace dimensions/geometry
- A custom GE2/1 ROB (in the shape of a GE1/1 ROB) was fabricated with twelve different strip geometries and dimensions
- Physical measurements of the interstrip capacitance were made on this board
- Analytical calculations performed



Layout of the GE2/1 ROB

1. M4, Original Design
2. M4, Strip gap = 0.3 mm
3. M4, Strip length halved, neighbors merged (width doubled), (new default)
4. M4, Extra long traces
5. M1, Original Design
6. M1, Strip gap = 0.3 mm
7. M1, Strip gap = 0.4 mm
8. M1, Strip length halved, neighbors merged (width doubled)
9. M1, Strip length halved, original width
10. M1, Extra long traces
11. M1, Minimal traces
12. M1, Minimal traces, strip length halved, width doubled

Figure on left adapted from [6].



Calculation of the Interstrip Capacitance

- Expression for interstrip capacitance/cm obtained from [7] and modified to include the signal traces on the opposite side of the board

$$(C/l) = \left(C_{sa} + C_a\right) l_s^{-1} + \left(C_{st} + C_t\right) l_t^{-1}$$

- Capacitance terms are functions of the complete elliptic integral of the first kind and dielectric constant
- Moduli of the integrals are functions of the strip and trace dimensions/geometry and substrate thickness

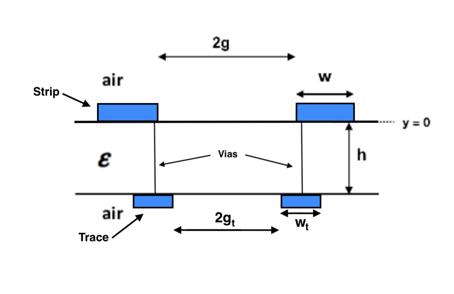
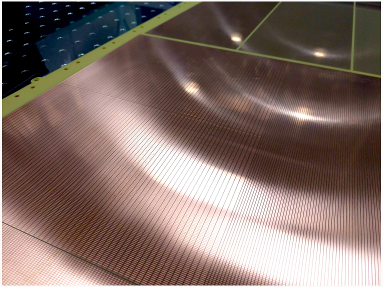


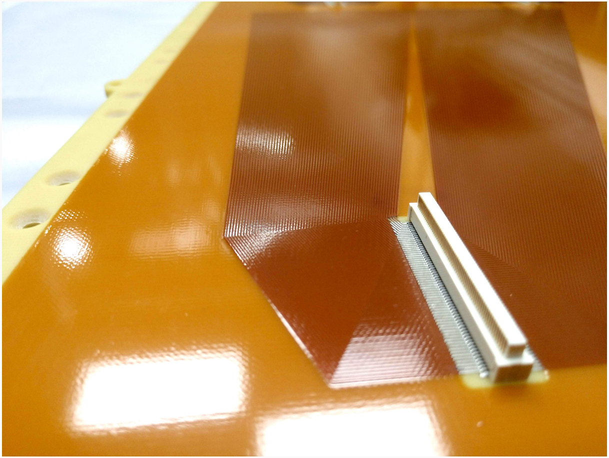
Diagram of the strip/trace/substrate system.



Detailed photo of the strips on the custom GE2/1 ROB.

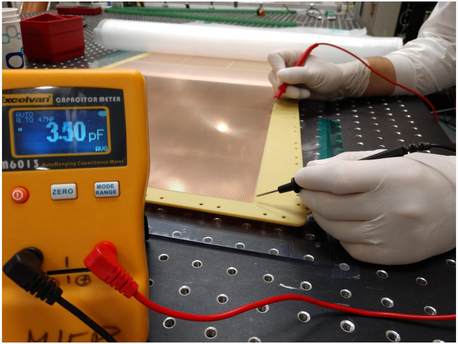
Trace Measurements

- Trace widths, gap widths, and lengths were measured 24 times in each sector; an average and its standard deviation were calculated



Measurement of the Interstrip Capacitance

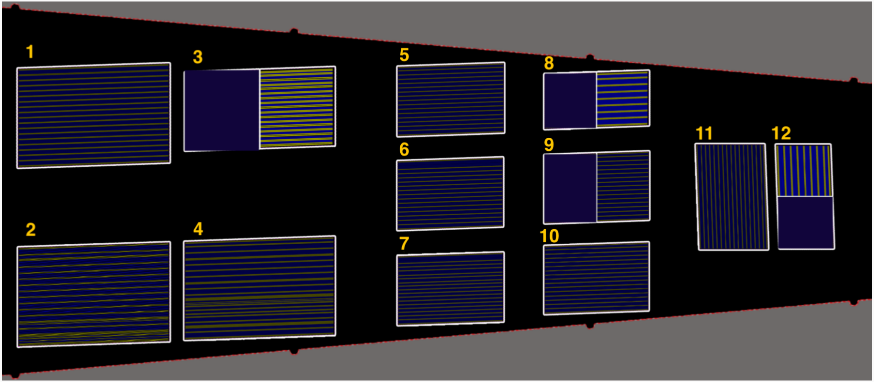
- Probes of the capacitance meter (Excelvan m6013) were placed at opposite ends of two adjacent strips
- The meter was zeroed by a second person while the probes were held ∼1 cm above the strips, then a measurement was taken



- Four measurements taken for 8-19 pairs of strips in each of the 12 sectors on the ROB
- We calculated the weighted mean and its standard error over all trials

Measurement of the Interstrip Capacitance

- In the following discussion, the weighted average of capacitance of all strips measured in each sector is used as the capacitance figure of merit
- Maps of what strips were measured for each sector are shown below [8]; (Yellow lines indicate strip pairs that were measured)



Interstrip Capacitance of the GE2/1 ROB

Table 1: GE2/1 ROB Interstrip Capacitance

Sector	Module	Parameters	Avg. Meas. Cap. (pF)	Calc. Cap. (pF)	(C_m/C_c)
1	M4	Original Design, Gap: 0.2 mm	21.69±0.05	16.7	1.30
2	M4	Gap: 0.3 mm	19.98±0.12	15.3	1.31
3	M4	2xWidth, 0.5xLength	15.32±0.03	10.5	1.46
4	M4	Original Design, Long traces	27.87±0.09	21.1	1.32
5	M1	Original Design, Gap: 0.2 mm	16.27±0.04	12.7	1.28
6	M1	Gap: 0.3 mm	14.65±0.07	11.2	1.31
7	M1	Gap: 0.4 mm	13.17±0.04	10.6	1.24
8	M1	2xWidth, 0.5xLength	11.82±0.06	8.5	1.39
9	M1	0.5xLength	9.32±0.05	5.9	1.58
10	M1	Original Design, Long traces	20.07±0.07	15.3	1.31
11	M1	Original Design, Minimal traces	14.02±0.02	11.8	1.19
12	M1	Minimal traces, 0.5xLength, 2xWidth	10.39±0.07	7.6	1.37

Conclusions

- $\sim$30% discrepancy between calculation and measurement $\Rightarrow$ likely due to the simple model; 128 strips/traces per sector, only two pairs accounted for in calculation
- The predicted "best" strip geometries produce the lowest capacitance measured:
  - Smallest measured interstrip capacitance of M4 module (2xWidth, 0.5xLength): $C = 15.32 \pm 0.03$ pF
  - Smallest measured interstrip capacitance of M1 module (0.5xLength): $C = 9.32 \pm 0.05$ pF
- Traces introduce a non-negligible capacitance to the overall interstrip capacitance $\Rightarrow$ trace length should be minimized
  - Longer traces significantly increase the interstrip capacitance, $\sim$6 pF in M4 and $\sim$4 pF in M1 (relative to default configuration)
  - Minimal traces reduce the interstrip capacitance, $\sim$2 pF in M1 (relative to default configuration)

References

[1] Image obtained from http://www.hephy.at/en/research/cms-experiment-at-lhc/.

[2] "CMS Detector Design," http://cms.web.cern.ch/news/cms-detector-design.

[3] CMS Collaboration, "CMS Technical Design Report for the Muon Endcap GEM Upgrade," Technical Report CERN-LHCC-2015-012, CMS-TDR-013, CERN, 2015.

[4] CMS Collaboration, "The Phase-2 Upgrade of the CMS Muon Detectors Technical Design Report," Technical Report CERN-LHCC-2017-012, CMS-TDR-016, CERN, 2017.

[5] Photo courtesy of M. Bianco.

[6] A. Ovcharova, "GEM Readout Board Design: Overview and Status," Presentation at the GEM Workshop XXII, https://indico.cern.ch/event/722089/contributions/3041863/attachments/1672580/2684057/18-06-21_ana_RO_boards_status.pdf.

[7] S. Gevorgian and H. Berg, "Line Capacitance and Impedance of Coplanar-strip Waveguides on Substrates with Multiple Dielectric Layers," *31st European Microwave Conference, IEEE (2001)*, doi:10.1109/EUMA.2001.339161.

[8] Figure courtesy of J. Collins.

[9] L. M. Milne-Thomson, L. M. (1969). Ch. 17 from *Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables, 9th ed.* Eds. Abramowitz, M. and Stegun, I. A. p. 590. National Bureau of Standards: Washington, D.C.

Adapted from [7]:

$$
\begin{aligned}
(C/l) &= \left(C_{sa} + C_a\right) l_s^{-1} + \left(C_{st} + C_t\right) l_t^{-1} \\
&= \epsilon_0 \left((\epsilon - 1) \frac{K(k')}{2K(k)} + \frac{K(k'_{0s})}{K(k_{0s})} \right) + \epsilon_0 \left((\epsilon - 1) \frac{K(k'_t)}{2K(k_t)} + \frac{K(k'_{0t})}{K(k_{0t})} \right)
\end{aligned}
$$

$$k = \tanh\left(\frac{\pi g}{2h}\right) \coth\left(\frac{\pi(w+g)}{2h}\right), \qquad k' = \sqrt{1-k^2}$$

$$k_{0s} = \frac{g}{w+g}, \qquad k'_{0s} = \sqrt{1-k_0^2}$$

$$k_t = \tanh\left(\frac{\pi g_t}{2h}\right) \coth\left(\frac{\pi(w_t+g_t)}{2h}\right), \quad k'_t = \sqrt{1-k_t^2}$$

$$k_{0t} = \frac{g_t}{w_t+g_t}, \qquad k'_{0t} = \sqrt{1-k_{0t}^2}$$

where $K(k)$ is the complete elliptic integral of the first kind, w is the strip width, $2g$ is the gap width between the strips, w_t is the trace width, $2g_t$ is the gap width between the traces, h is the thickness of the substrate (FR4 with dielectric constant $\epsilon = 4.7$).

Appendix B: Complete Elliptic Integral of the First Kind

- The complete elliptic integral of the first kind is given in [9] as

$$K(k) = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}}$$