PROCEEDINGS OF SCIENCE

Readout via Flex-Prints for the Mu3e Experiment

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The Mu3e experiment at PSI aims to search for the charged lepton flavor violating decay $\mu^+ \to e^+e^-e^+$ with a sensitivity to a branching ratio of 10^{-16}. To achieve this, a high intensity muon beam with a rate of 10^8 - 10^9 muons per second is stopped on a target. The decay electrons are detected with a silicon pixel tracking detector using High Voltage Monolithic Active Pixel Sensors (HV-MAPS) and timing detectors consisting of scintillating fibres and tiles. Instead of a triggered readout, the experiment uses online event filtering. This requires the readout of all hits detected in the pixel sensors. Hence, data from the sensors is transferred using fast serial LVDS links with data rates of 1.25 Gb/s over flex-print cables made of polyimide and aluminium foil. The flex-prints also provide power and control signals. In total, about 1000 sensors have to be powered and read out with one to three fast serial data links each. Studies of the serial data transmitted from the current pixel sensor prototype MuPix7 at 1.25 Gb/s have been performed. Flex-print cables produced in-house have been tested regarding impedance, quality of service, and bandwidth. An outlook on the flex-print design to connect the next generation of MuPix sensors and build first detector modules is given.

Proceedings of the Corfu Summer Institute 2015 "School and Workshops on Elementary Particle Physics and Gravity"
1-27 September 2015
Corfu, Greece

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PoS(CORFU2015)071

1. Motivation for the Mu3e Experiment

The Standard Model of particle physics (SM) describes the interactions of all known fundamental particles successfully. But some questions to the theory are not yet answered. For instance, neutrinos are massless within the SM, but observation of neutrino mixing suggests that the mass differences between the neutrinos are non-zero and that lepton flavor is not conserved. Charged lepton flavor is also violated in decays like $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$. However, these processes are suppressed by more than 50 orders of magnitude [1], putting them well beyond experimental reach. New physics models beyond the SM predict the enhancement of these branching ratios up to measurable levels.

In the late 1980's, a search for the process $\mu^+ \to e^+e^-e^+$ was performed by the SINDRUM experiment without any evidence and a limit on the branching ratio of $BR < 10^{-12}$ was set at a 90 % confidence level [2]. The Mu3e experiment [3, 4] aims to increase the sensitivity for this decay by four orders of magnitude.

This paper gives a short introduction into the experimental concept for the Mu3e experiment. The focus is on the services inside the tracking detector. In order to keep the material budget as low as possible, electrical connections will be realized using flex-prints consisting of thin polyimide films and conducting layers made of aluminium or copper. Studies of prototypes produced in-house are shown and an outlook towards the flex-print design for the vertex detector is given.

2. The Experimental Concept

Mu3e relies on the following experimental concept [5], illustrated in Figure 1: a continuous, high intensity beam of positive muons is stopped on a thin, hollow, double cone shaped target with rates up to 10^9 muons per second. The muons decay at rest. Thus, the momentum of the decay products is limited to $p \leq 53\,\mathrm{MeV/c}$. The trajectories of the decay positrons and electrons, henceforth both referred to as electrons, are bent inside a 1 T solenoidal magnetic field. To reconstruct the momentum and the vertex of the electrons, a barrel shaped tracking detector with four pixel layers is installed around the target. In order to improve the momentum resolution, so called recurl pixel layers are mounted up- and downstream of the central detector.

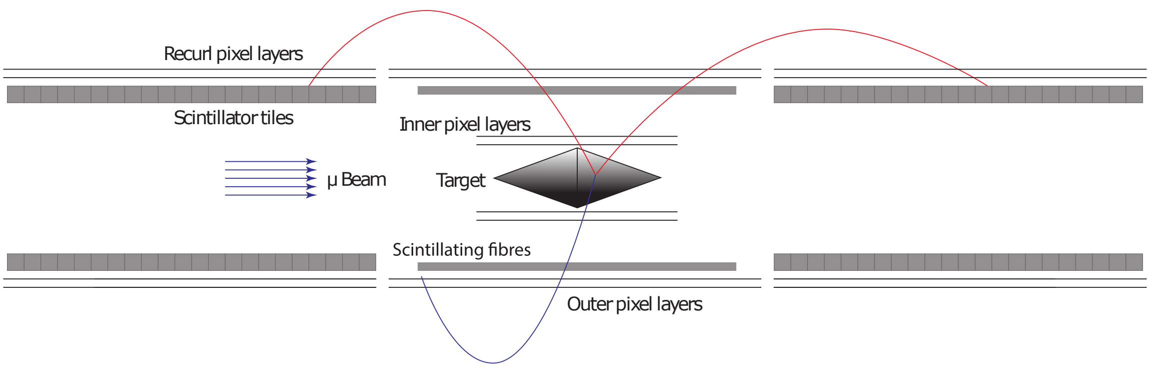

Figure 1: Schematic view of the experimental concept.

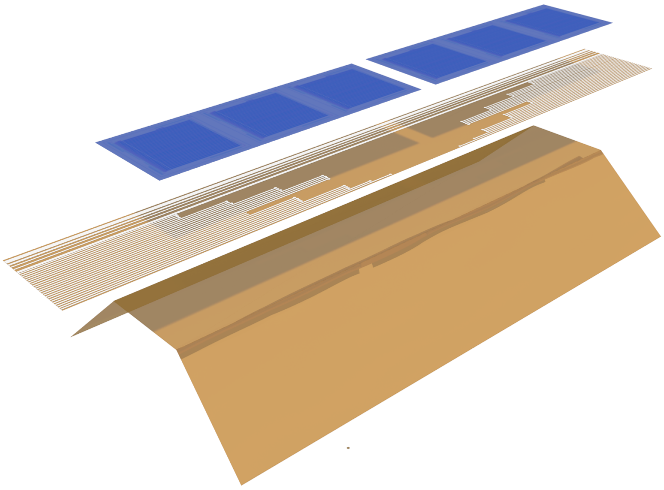

Figure 2: Exploded view of the mechanical assembly of a tracking detector module. The sensors (blue) are located on top of the flex-print. The assembly is mounted on a thin Kapton® support structure.

The main physics background is the radiative standard model decay $\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$. Because the neutrinos carry away momentum, the kinematics of this decay differ from the signal decay. Therefore, an excellent momentum resolution is required to distinguish between signal and background. In order to achieve the design sensitivity a momentum resolution better than 1 MeV/c is required [6]. Due to the high muon decay rate, a good vertex resolution is necessary to separate different muon decays. In order to reduce the accidental background further, a very good time resolution is needed. Scintillating fibres and tiles will be employed for that purpose.

The momentum resolution is dominated by multiple Coulomb scattering due to the low momenta of the electrons. Hence, the material budget of the tracking detector has to be minimal and is limited to 1 ‰ of a radiation length per layer. The tracking detector relies on HV-MAPS (High Voltage Monolithic Active Pixel Sensors) [7]. Several prototypes for Mu3e have been produced and tested successfully [8]. The latest prototype, called MuPix 7 [9], is the first fully monolithic HV-MAPS, incorporating its own clocking, readout state machine and a fast serial readout driver. The fast serial readout is crucial for Mu3e as the experiment runs triggerless and relies on online event filtering instead. Therefore, all hits of the sensors have to be read out. To keep the material budget within the active area as low as possible, thin flex-prints made of materials with low atomic number are used. Their purpose is to supply the high and low voltage, as well as the slow control and the clock signal for the MuPix chip. Being the main supply voltage, the low voltage has to be distributed without significant voltage drop up to a power dissipation of the sensors of 400 mW/cm^2. From the sensors, the serial data is transmitted over the flex-prints towards the frontend board. For the final experiment, of the order of 1000 MuPix sensors have to be powered and read out with up to three data links, each. Sensors, flex-print and a 25 µm thin Kapton® support structure form a detector module as illustrated in Figure 2.

3. Data Transmission Study of the MuPix 7

For a proper operation of the MuPix 7 a stable serial data transmission from the sensor is important. We studied the serial data transmission of the MuPix 7 as this feature was integrated into this prototype for the first time. An eye diagram of the serial data output at 1.25 Gb/s is shown in Figure 3. The serial signal transferred over coaxial cables is sampled using an oscilloscope. We measured an eye width of 525 ps, which corresponds to 65 % of a bit time interval, and an eye height of 132 mV for a total signal amplitude of 172 mV. Both eye parameters indicate a good quality of data transmission. This can be confirmed by a bit error rate (BER) measurement, where we did not observe any bit errors in the data stream running over several hours, setting an upper limit on the bit error rate to BER $< 10^{-13}$ at a 95 % confidence level. The good signal quality led to successful operation of the MuPix 7 at various test beam campaigns at SPS, PSI, DESY and MAMI [9].

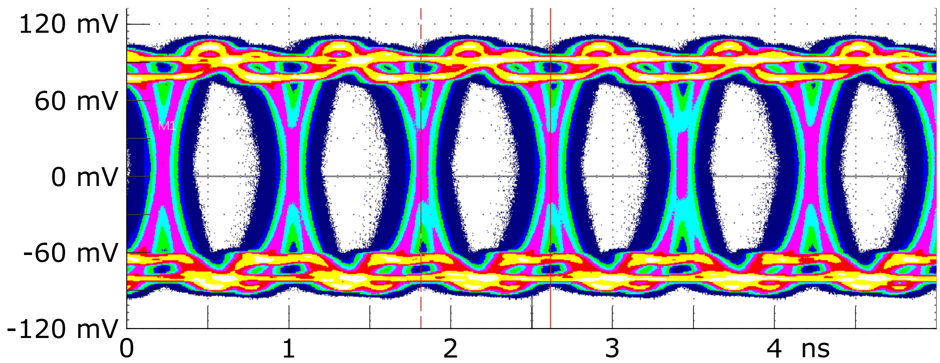

Figure 3: Eye diagram of the fast serial data output of a MuPix 7 prototype at 1.25 Gb/s.

4. Flex-Print Studies

We have produced several aluminium flex-print prototypes in-house. Starting from a laminate of 25 µm Kapton® and 25 µm aluminium foil, signal traces and contact pads are created by laser evaporation. With our current in-house laser setup [10] it is possible to create aluminium structure sizes down to 100 µm. However, for cables longer than 10 cm, a reliable data transmission was only achieved for a trace width of 120 µm and above [11]. Our flex-print prototypes are about 17 mm wide and accommodate 17 differential signal pairs. They are connected using ZIF-connectors (Zero Insertion Force) with 34 contacts and a 0.5 mm pitch. A 10 cm long flex-print prototype is shown in Figure 4.

4.1 Impedance Matching

A reliable fast data transmission is only possible if the impedance along the whole transmission line is well matched. For the Mu3e experiment standard impedances of $Z_0 = 50\,\Omega$ for single ended signals and $Z_{diff} = 100\,\Omega$ for differential signals are used. To achieve the best data quality for

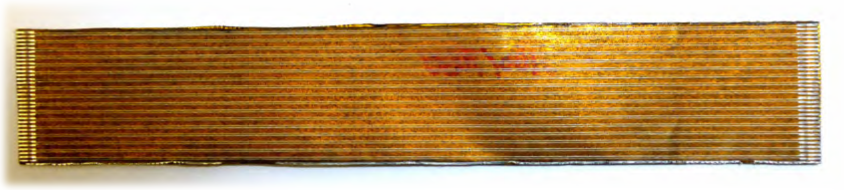

Figure 4: A 10 cm long flex-print prototype produced from an aluminium Kapton® laminate using laser evaporation.

a differential pair, both the single trace and the differential impedance should be matched. To control the impedance, a second aluminium and Kapton® layer is laminated onto the flex-print. The dielectric spacing in our configuration is about 75 µm between the traces and the shielding layer. To match the target impedance within a tolerance of 10 %, the trace width and the separation between the differential lines are chosen to be 120 µm, each. For a 1 m long flex-print prototype the impedance of a differential pair is measured with the time domain reflectometry technique [12] using the Tektronix DSA8300 serial analyzer [13]. The flex-print is connected to the sampling module using SMA coaxial cables and a custom made printed circuit board (PCB). The single line impedance for both traces is measured to be between 52 Ω and 61 Ω (see Figure 5) [14]. This matches our calculations reasonably well.

4.2 Bit Error Rate Tests

We set up a custom bit error rate test on an Altera Stratix V GS FPGA [15] development board to test the quality of data transmission along the flex-print. In this test, up to 17 LVDS transceivers (max. data rate 1.6 Gb/s) and 8 high speed transceivers (max. data rate 14.1 Gb/s) are used. Over all channels 8b10b [16] encoded data streams are serialized and transmitted. The data

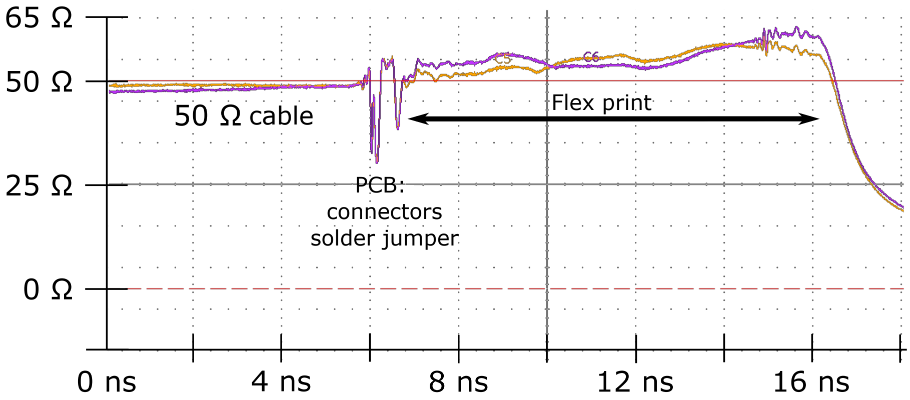

Figure 5: Time domain reflectometry measurement of a 1 m long flex-print transmission line. The analyzer is connected using 50 Ω matched SMA cables to a custom designed PCB. The impact on the impedance by the different components is indicated.

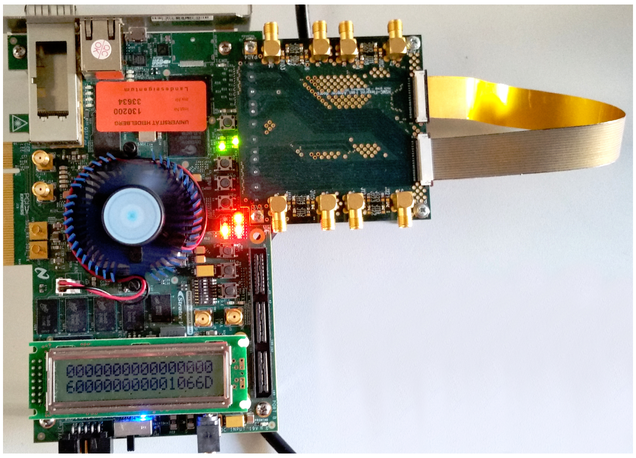

Figure 6: Setup for the bit error rate test using an Altera Stratix V GS development board and a custom designed PCB to connect to the flex-print.

is deserialized in the receivers and checked for bit errors that occurred during transmission. The flex-print is connected to the FPGA development board using custom designed PCBs. The bit error rate test setup is depicted in Figure 6.

Bit error rates for a 20 cm and a 1 m long flex-print prototype are measured at various data rates. Up to 2.5 Gb/s no bit errors over the 20 cm long prototype are observed. At 3.2 Gb/s first bit errors are observed at a bit error rate of 1.6×10^{-16}. The BER can be further reduced by tuning the analogue settings of the transmitter like pre-emphasis. For the 1 m long prototype, first tests show a reliable data transmission at data rates up to 1.6 Gb/s. Results are summarized in Tables 1 and 2.

The quality of data transmission is further checked by analyzing the eye diagram. An exemplary eye diagram of a 1.6 Gb/s LVDS data stream transferred over a 20 cm long flex-print prototype is shown in Figure 7. The logic '0' and '1' states can be distinguished reliably. The eye

Data rate [Gb/s]	Run time [h]	channels	Bit errors observed	Bit error rate
1.0	29	7	0	$\leq 7.1 \times 10^{-15}$ @ 95 % CL
1.6	512	7	0	$\leq 1.8 \times 10^{-16}$ @ 95 % CL
2.5	19	5	0	$\leq 4.3 \times 10^{-15}$ @ 95 % CL
3.2	398	5	36	1.6×10^{-16}

Table 1: Bit error rates measured for a 20 cm long aluminium Kapton® flex-print prototype. When 0 errors are observed, the upper limit at a 95 % confidence level is given. The bit error rate is computed using the run time, the data rate and the number of parallel channels.

Data rate [Gb/s]	Run time [h]	channels	Bit errors observed	Bit error rate
1.0	10	7	0	$\leq 1.1 \times 10^{-14}$ @ 95 % CL
1.6	6	7	0	$\leq 1.2 \times 10^{-14}$ @ 95 % CL

Table 2: Bit error rates measured for a 1 m long aluminium Kapton® flex-print prototype.

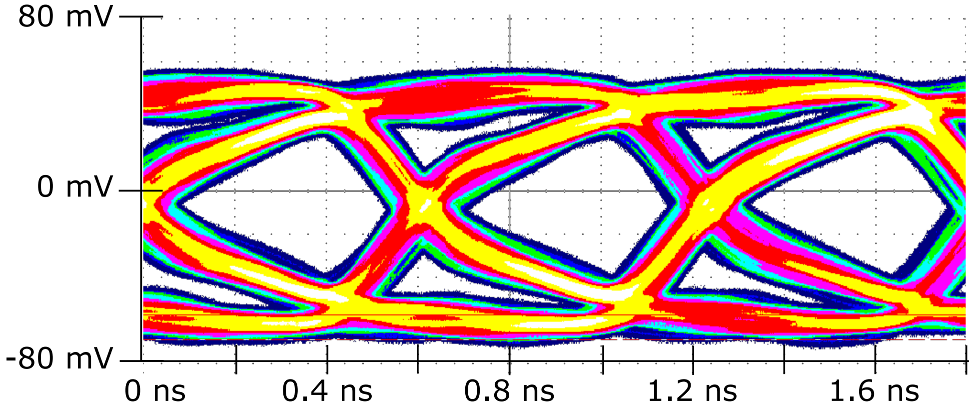

Figure 7: Eye diagram of a 1.6 Gb/s LVDS signal transferred over a 20 cm long flex-print obtained with the Tektronix DSA8300 serial analyzer.

width is about 70 % of a bit unit time interval, the eye height is measured to be about 28 mV of amplitude.

We tested the lifespan of our flex-print prototypes. It was observed that our flex-prints do not survive many connection cycles [14]. After five cycles first channels start to fail. Moreover, we found that prototypes with a thinner layer of aluminium (12 μm) are less robust as traces tend to break more easily.

5. Flex-Prints for Mu3e

Two types of flex print designs are required for the Mu3e experiment. In the inner two layers three MuPix sensors are readout by one flex-print. The flex-print has an area of about $19 \times 68\,\mathrm{mm}^2$ covering the sensors and the end ring of the detector. Two flex prints combined form a ladder which can be readout at both ends, as illustrated in Figure 2. In the outer two layers and in the recurl stations, nine MuPix sensors will be connected using a single flex-print. To meet our design goals, the material budget must not exceed 1 ‰ of radiation length (X_0) per layer. Taking the 50 μm thin silicon sensor into account, a maximum material budget for the flex-print of about 0.5 ‰ X_0 is allowed. As mentioned in Section 4, our current laser process limits the structure sizes to 120 μm, which is too big to implement all signal lines in one metal layer. Smaller structure sizes are required, which means that other production technologies have to be used.

We currently investigate two alternative options. The first option is a two layer aluminium approach produced by LTU, Ukraine [18]. In this technology trace widths down to 65 μm can be used. It would be a viable candidate for the inner layers. The flex-print consists of two 14 μm aluminium and 10 μm polyimide layers, with a dielectric spacing of 45 μm in-between. This results in a material budget of about 0.55 ‰ X_0 for the flex-print, neglecting additional glue between flex-print, sensor and support structure. The drawback of this technology is the current limitation to maximal two layers which poses a challenge regarding power and ground distribution, especially for the outer tracking layers. A preliminary design for this technology to connect three MuPix

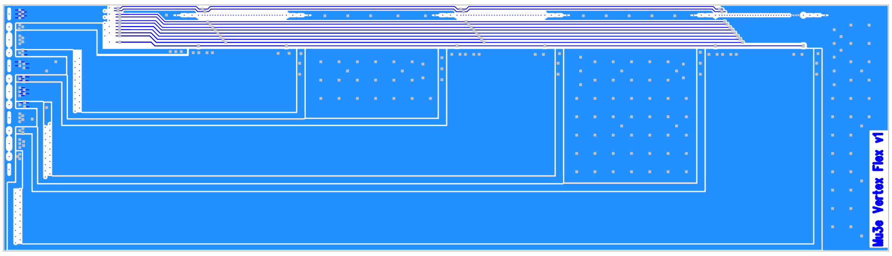

Figure 8: Preliminary design: top layer of the two layer aluminium flex-print.

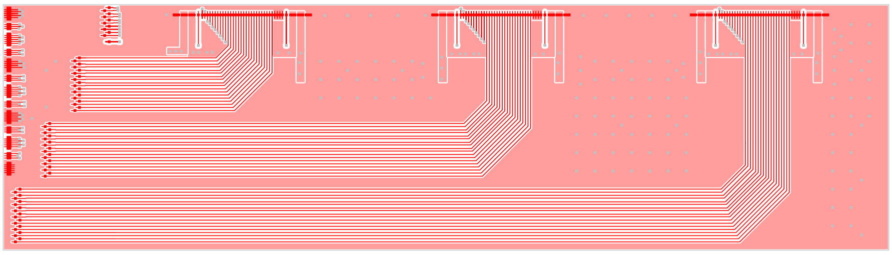

Figure 9: Preliminary design: bottom layer of the two layer aluminium flex-print.

sensors is depicted in Figures 8 and 9. On the top layer the power for the sensors is distributed. The common signals and the high voltage are routed in a bus structure. On the left end of the layer the signals are foreseen to be connected to another flex-print or PCB to connect the module to the frontend readout board. All sensor specific signals like data output are routed on the bottom layer. All signals have their corresponding contact pads on this layer to allow to use the LTU SpTAB technology [18] to connect the flex-print to the MuPix chip.

The second option is a multi-layer laminate approach (see Figure 10). Power and ground will be distributed using two 12 µm aluminium and 25 µm Kapton® laminates which can be produced in-house. Sandwiched in-between is a two layer HiCoFlex® fabricated by HighTec [19] for signal transmission and high voltage supply, illustrated in Figure 11. The aluminium layers are also used to control the impedance of the signal traces. In the HiCoFlex® technology traces can be as thin as 10 µm which allows for a high signal density. The drawback is the usage of copper instead of aluminium, which can be compensated by using thin (2 µm) copper layers with little coverage (5 %). The flex print material budget for this approach adds up to about 0.6 ‰ - 0.7 ‰ X_0.

6. Summary

The Mu3e experiment aims to search for the charged lepton flavor violating decay $\mu^+ \to e^+e^-e^+$ with a target sensitivity for branching ratios of 10^{-16}. The experimental concept relies on an ultra lightweight tracking detector using HV-MAPS. The material budget must be limited to 1 ‰ of a radiation length per layer due to scattering of the low momentum electrons. Flex-prints made of polyimide films and aluminium or thin copper layers will be used to connect the sensors. We studied the production of aluminium and Kapton® foil laminate flex-prints. For a prototype we found that we can match the impedance of $Z_0 = 50\,\Omega$ and $Z_{diff} = 100\,\Omega$ along the transmission line within tolerances. Moreover, we measured bit error rates at the level of 1.6×10^{-16} for data

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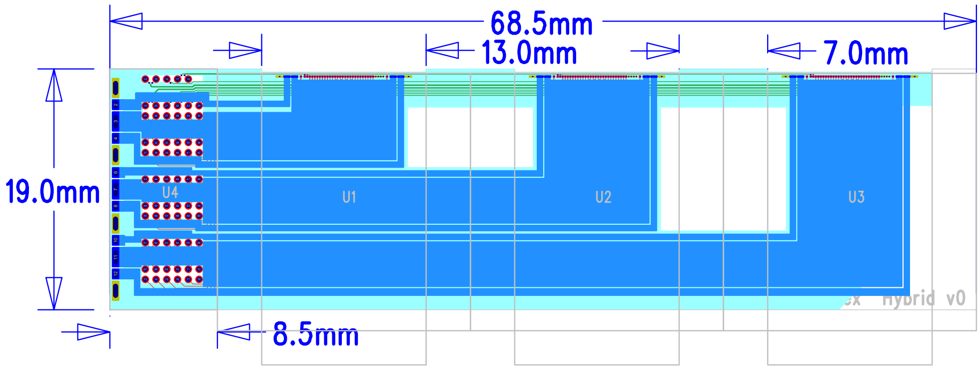

Figure 10: Preliminary design: composite view of the multi-layer laminate approach.

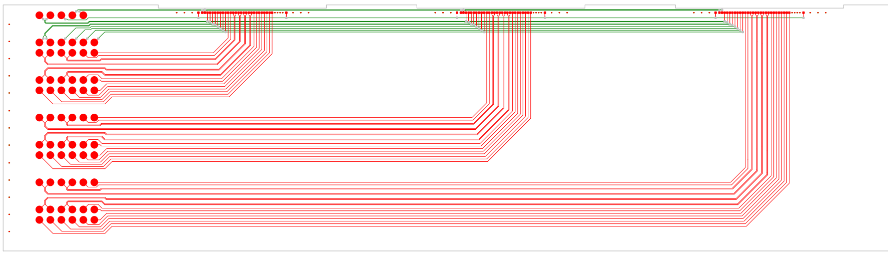

Figure 11: Preliminary design: signal traces (red) and bus connections for common signals (green) using the HiCoFlex® technology with two layers.

rates of 3.2 Gb/s. We presented two options for flex-print designs that are under consideration for first vertex modules for Mu3e: a two-layer aluminium approach and a multi-layer aluminium and copper laminate. Both options yield a satisfying material budget. Further studies of both options are foreseen in order to find the best solution for the first detector modules.

Acknowledgments

S. Dittmeier acknowledges support by the *International Max Planck Research School for Precision Tests of Fundamental Symmetries*.

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