Gbit/s data transmission on carbon fibres

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ABSTRACT: Data transmission at the upgraded Large Hadron Collider experiments, foreseen for mid 2020s, will be in the multi Gbit/s range per connection for the innermost detector layers. This paper reports on first tests on the possible use of carbon cables for electrical data transmission close to the interaction point. Carbon cables have the potential advantage of being light, having a low activation and easy integration into the detector components close to the interaction point. In these tests commercially available carbon fibres were used, in which the filaments had a very thin nickel coating. For these cables data rates beyond 1 Gbit/s over more than 1 m with an error rate of less than $10^{-12}$ could be reached. The characteristics of the cables have been measured in terms of S-parameters and could be converted to a SPICE model. Some outlook on potential further improvements is presented.

KEYWORDS: Special cables; Electronic detector readout concepts (solid-state); Detector design and construction technologies and materials

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1 Introduction

Experiments at the upgraded Large Hadron Collider (LHC) [1], planned for mid 2020s, will deliver unprecedented high data rates. By colliding protons with highest energy and intensity the LHC will allow the experiments to explore in depth building blocks of matter in distances smaller than $10^{-19}$ m. The upgraded LHC will explore and possibly reach beyond the limits of the Standard Model of particle physics. Whereas, on the one hand, data will be collected in a much harsher environment of high particle flux than before, on the other hand the extremely high precision of the measurement with current experiments has to be retained, if not improved. These goals impose challenges for both the LHC accelerator and its detectors.

In this paper the potentials of carbon cables for high-speed electrical data transmission will be discussed. To define the environment: the new pixel detector, part of the ATLAS detector [2] at the LHC, will consist of electronically autonomous entities, called modules, which comprise the silicon sensors and custom made front-end (FE) electronic chips to read out the signal and provide a first processing. These modules are glued on staves, ultralight mechanical carbon structures, which serve to both hold these modules in place and remove the heat generated by electronics and sensors. Data collected in the FE electronics is transmitted electrically along the staves and beyond where it is converted into optical signals and sent over some 80 m via optical fibres to computing farms. Similarly, control signals have to be electrically transmitted to the modules. The services to provide electrical connections for supply and read-out to the modules are shown in figure 1.

The detectors have to withstand an accumulated radiation dose of up to 7.7 MGy after some 10 years of operations. It is currently planned that data of each module will be read out with a single electrical link of up to 5 Gbit/s before conversion to an optical link [3]. The electrical path has a
length of some 5 m between modules and opto-converters. The signal must be DC-balanced and the bit error rate (BER) should be less than $10^{-12}$.

Current electrical links, which have to cope with much lower radiation doses and data rates of only 160 Mbit/s, use copper bands embedded in kapton foils. Copper cables are suitable for high data rates, but, having a small radiation length, introduce unwanted material and have a thermal expansion coefficient (CTE) different from the mechanical support. Searching for alternative materials suitable for high frequency electrical transmission would therefore be desirable and has created an active R&D field.

In this paper, the potential of carbon fibres (CF) to transport high data rates is investigated. Carbon materials have several potential advantages compared to copper and other metallic materials used for cables:

- Carbon is some factor 3.5 lighter than copper, important to achieve an optimal tracking precision,
- Carbon has little activation,
- Fibres made from carbon have the same CTE as the stave itself, thereby avoiding any additional stress on the stave, even offering the possibility to integrate them into the structure.

The key question is, if a high-speed data transmission is achievable. In this paper first results on the performance of carbon cables for up to 1.25 Gbit/s will be discussed.

Figure 1. Sketch of read-out and service connections for each half stave of the current ATLAS pixel detector. Per read-out chip there are several data lines needed to transmit data to and from the detector. The innermost part of the cabling is foreseen to be electrically connected to the electrical-to-optical converters. The zoomed-in picture shows a service panel carrying cables and cooling pipes for a quarter of one detector half.
The organisation of the paper follows the design flow as shown in figure 2. It will start by describing the fabrication of carbon cables (section 2), verifying their reproducibility (section 3) and then present an FPGA based real-time test of Gbit/s transmission (section 4). Finally, a simulation of the cable in time- and frequency-domain will be discussed (section 5) which aims for determining cable parameters for modeling.

2 Cable fabrication

At the start of this project, several potential geometries of carbon cables were briefly studied, i.e. coaxial and twisted pair carbon cables. Based on these first results as well as to account for fabrication simplicity and performance, a twisted-pair cable configuration was preferred.

Poly-Acryl-Nitril type fibres were preferred over pitch based fibres to arrive at more reliable cables. Pitch based fibres have lower resistivity and higher tensile strength, but are extremely brittle and difficult to bend. In a first step, without optimizing for thickness, HTS40\(^1\) fibres were used consisting of 12,000 filaments of 7 µm thickness each. Each of these filaments was coated with 250 nm of nickel. For isolation, the carbon cables were inserted into a 0.3 mm thick thermoplastic PVC sleeve. During fabrication, the carbon fibres were crimped to a nylon cable (see figure 3a), with which the fibres were pulled through the sleeve (see figure 3b). It has to be ensured that the fibres are not bent too strongly to avoid broken filaments. In a final step the sleeve is shrunk to a third of its original diameter using a hot air gun. The total diameter of the resulting twisted cable is about 2 mm.

To check if the cable is not broken and functioning, its DC-resistance is measured. In average the DC-resistance was determined to be \(R = (1.55 \pm 0.08) \Omega\) per meter carbon cable. Once correct operation is shown, the cable is cut to the desired length and both ends are crimped (see figure 3c) and soldered to a SMA connector (see figure 3d). Two of these cables are used to realize a twisted-pair cable, in which one of the lines is connected to ground of the SMA connector and the other is used for the signal transmission.

\(^1\)The A23 MC 12K 1420tex MC fibre from Toho Tenax® Europe GmbH [4] was used.
Some 20 cables have been produced with various lengths up to 3 m.

The principle functionality of the carbon cables was confirmed with some initial tests at modest transmission rates. The cable was successfully inserted into a setup to read-out an actual front end module at 160 Mbit/s as used in the recently installed IBL\textsuperscript{2} pixel detector [5–7]. Bit-Error-Rate (BER) tests over several weeks were performed using a commercial 200 MHz BER-tester.

The fabrication procedure leads to high efficiency and reproducibility, as will be shown in the next section.

3 Fabrication reproducibility

Since the cables are not manufactured in an automated process, the reproducibility of their fabrication was verified. To this end, four identical CF-cables of 1.0 m length were produced and characterized. All of the cables passed the first tests for fractures or short circuits and were checked using the 200 MHz BER-tester. No errors were observed in the some 17 Tbit sent for either of these cables.

Furthermore the S-parameters of the cables were measured and compared using a Rohde & Schwarz\textsuperscript{®} ZND 2-port network analyzer [8] in the single wire configuration. S-parameters offer an easy to measure characteristics of electronic devices with a certain number of ports (here two ports corresponding to the input and output port of the cable that has been instrumented). All S-parameters were found to be consistent between the four cables. The amplitudes of the $S_{21}$ parameters are shown together with the mean value in figure 4.

To quantify the reproducibility of the cable manufacturing process all $S_{21}^n$ parameters (where $n=1$ to 4 is the cable number) are compared to $S_{21,\text{mean}}$ and the maximal difference $S_{21,\text{maxErr}}$ is determined using

$$S_{21,\text{maxErr}} = 20 \cdot \log_{10} (\max (|S_{21}^n| - S_{21,\text{mean}})), \quad n = 1 \cdots 4. \quad (3.1)$$

\textsuperscript{2}IBL: Insertable B-Layer.
Figure 4. S-parameter $S_{21}$ for the four cables to test reproducibility of production process. Here $n=1$ to 4 is the cable number.

Figure 5. Maximal difference of the measured S-parameter $S_{21}$ compared to mean value.

This difference in dB can be seen in figure 5. $S_{21,\text{maxErr}}$ starts with a very small difference between the cables of approximately $-55\,\text{dB}$ for frequencies in the kHz-range. Parameters of the manufactured cables are in good agreement up to $800\,\text{MHz}$ with increasing difference for higher frequencies up to $2\,\text{GHz}$, but stay below $-20\,\text{dB}$. Assuming homogeneous carbon cables the deviations should be due to differences during soldering and crimping of the connectors. In the following these differences will be neglected.

4 Performance measurements

Several measurements on cables were performed to study the signal quality and its dependence on the cable length. The pulse shape will be presented and the S-parameters for different cable lengths. Finally, the BER at different transmission rates and for different cable lengths were tested.
4.1 Pulse shape and signal transmission delay

The pulse shape, attenuation, and propagation delay are measured using a pulse generator and an oscilloscope. Since the pulse generator features two outputs (inverted and non-inverted) two transmission paths (carbon cable + copper cable and copper cable only) can be compared simultaneously. A 1 m carbon cable was measured with a signal being sent with an original amplitude of 2.5 V. Figure 6 shows a pulse delay of approximately 5 ns and a reduced pulse amplitude of 1.9 V (corresponding to an attenuation of −2.4 dB). Starting at 115 ns a weak reflection can be observed indicating a mismatch of the characteristic impedance of the carbon cable and the input impedance of the oscilloscope (i.e. 50 Ω).

4.2 S-parameter

The four S-parameters (i.e. $S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$) are shown for a 1 m CF-cable in figure 7. It can be seen that the two transmission parameters (i.e. $S_{12}$, $S_{21}$) are nearly identical and feature a maximum attenuation of approximately −17 dB at 2 GHz. Furthermore, the transmission parameter $S_{21}$ for 1 m carbon cable is strongly frequency dependent. All S-parameters exhibit a periodic ripple pattern, resulting from standing waves caused by reflections due to the mismatch of the characteristic impedance of the carbon cable and the 50 Ω impedance of the network analyser. These reflecting components and the associated matching issues will be subject of future investigations.

The S-parameter measurements also allow one to determine the group delay $\tau_{gd}$ via

$$\tau_{gd} = -d\phi/d\omega \quad \text{with} \quad \phi = \arctan(\Re(S_{21})/\Im(S_{21}))$$

and yield $v_g \approx 0.2 \text{ m/ns}$. This result is consistent with the time domain measurement shown in figure 6. It corresponds to a so called velocity factor ($VF = v_g/c$) of 0.6 (here, $VF$ is assumed to be frequency independent).

The measurements of the S-parameters were extended to cables of various lengths. A comparison for $20 \cdot \log_{10}(|S_{21}|)$ is shown in figure 8 for cables of 0.5 m, 1 m, 2 m and 3 m.
Two important effects can be observed:

- The maximum attenuation at 1.2 GHz increases with the cable length from 7 dB (0.5 m cable length) to ≈ 25 dB (for 3 m cable length).
- As expected, the period of the oscillation of $S_{21}$, which results from the standing wave on the transmission line, depends on the length of the cable.

### 4.3 BER-tests

As a final step the cable was verified using a BER-tester implemented in an FPGA development board [9]. Figure 9 shows the development board with the carbon fibre cable attached using
differential signal transmission having two of the cables connected to the board. The BER-tester software comes as VHDL-core alongside the FPGA integrated development environment [10]. The current FPGA-board setup is restricted to certain frequencies commonly used by serial interface protocols.

The CF-cables of different lengths have been tested at different transmission rates. Results and associated BER-values are shown in table 1. During the FPGA-based BER-tests RX-equalization (parameter $RxEq$) and a variable transmit voltage swing (parameter $TxEmp$) supported by the transceivers were used.

| Cable        | Tx Rate      | BER   | TxEmp | RxEq |
|--------------|--------------|-------|-------|------|
| 0.5 m, 1.0 m, 2.0 m, 3.0 m | 0.625 Gbit/s | $1 \times 10^{-13}$ | 0 dB  | 0 dB |
| 0.5 m, 1.0 m, 2.0 m | 0.781 Gbit/s  | $1 \times 10^{-13}$ | 0 dB  | 0 dB |
| 3.0 m        | 0.781 Gbit/s | $3 \times 10^{-13}$ | 0 dB  | 2.6 dB|
| 0.5 m, 1.0 m  | 1.25 Gbit/s  | $1 \times 10^{-13}$ | 0 dB  | 0 dB |
| 2.0 m        | 1.25 Gbit/s  | $4 \times 10^{-13}$ | 7.6 dB | 2.6 dB|
| 3.0 m        | 1.25 Gbit/s  | $4.6 \times 10^{-12}$ | 7.6 dB | 2.6 dB|

Table 1 shows that 1.25 Gbit/s can be transmitted over a carbon cable of up to 2 m length with an error rate of less than the required $10^{-12}$ mentioned in the introduction.

The bit error rate in this paper is given by:

$$BER = \frac{1}{\text{transmitted bits}}.$$  \hspace{1cm} (4.2)

To state the BER at a confidence level of 95\%, this value has to be multiplied by a factor three.
5 Simulation

This section describes setting up a simulation environment for the CF-cables. SPICE simulations [11] allow studying the time-domain behaviour of the transmission line. Here, the two aspects pulse shape and pulse delay are of major interest to compare simulation and measurement results.

The S-parameters are converted to a broadband SPICE model using a commercial tool [12] and freely available software (s2spice [13]) to assess the detailed characteristics of the transmission line (i.e. the lumped elements $R'$, $L'$, $C'$, and $G'$ of the classical transmission line model [14]) and additional external components (i.e. load and inner impedance) during simulation. This step is essential during possible impedance matching, optimization of the cable architecture as well as to find optimal cable and material properties. The simulation setup includes a pulse generator featuring a 50 $\Omega$ inner impedance and a 50 $\Omega$ load. Both tools (i.e. [12] and [13]) used for broadband model generation show comparable results. During the next step the consistency of the measured values and the results predicted based on the simulation of the transmission line model is shown to prove the validity of the approach. As SPICE simulation tool, the freely available LTSpice [15] has been chosen. As a first test signal a pulse train with adjustable pulse length (i.e. different data rates) is used as input signal during a time-domain simulation. This input signal can be replaced by a pseudo random sequence in future simulations to generate eye-diagrams to assess the quality of the transmission line. The results of the pulse train simulation are shown in figure 10 for an input signal with a data rate of 1 GHz and an arbitrary peak voltage of 1 V. Subfigure 10a shows the start of the transmission while 10b shows the stable state of transmission with the expected offset value of 0.5 V. Again, the pulse delay of approximately 5 ns/m shown in subfigure 10a is consistent with the measurements and the group delay determined in section 4.2. It can be seen in subfigure 10b that in the stable state the output signal’s amplitude is reduced to approximately one third of the input amplitude (i.e. 10 dB attenuation). Additionally, a filter effect can be observed (i.e. the cable causes a smooth shape of the output signal).

![Figure 10](image-url)

**Figure 10.** SPICE based broadband simulation of a 1 m carbon-cable. Input signal $v(1)$ (black) output signal $v(3)$ (blue). Subfigure 10a shows the beginning of the transmission, while subfigure 10b shows the steady state.

6 Conclusions and outlook

In this paper, first studies on high data rate transmission on carbon cables, made of 12000 nickel coated filaments, were presented. Twisted-pair cables have been manufactured and were used...
for signal transmission of either unbalanced or balanced signals. Although rather delicate, the fabrication process leads to a reproducible performance.

The first attempts showed encouraging results. Without detailed optimization of the termination and choice of the fibre it already can be observed that 1.25 Gbit/s can be transmitted over a length of about a meter with an error rate of less than $10^{-12}$. These results were obtained with a differential transmission on two of the twisted pair cables. Although, as expected, the transmission becomes less reliable with higher data rate and length, even for a cable of 3 m the BER is less than $10^{-11}$ if signal pre-emphasis and equalization implemented in the FPGA transmitters and receivers is used.

Whereas this paper reports on first studies to establish a proof of principle, further improvements and more systematic studies are planned. Given the good agreement of data and simulation, the model based on a frequency dependent lumped element description of carbon fibre and connector can be used for further optimization. This model should also include any mismatching issues. Based on this model it will be possible to specify clear guidelines for the transmission line (i.e. fibre and sleeve material, number of filaments, thickness, connectors) as well as for the manufacturing process.

Several measurements should be performed to systematically improve the performance and identify the potentials. E.g. different types of filaments with and without coating and varying thickness will be systematically studied and characterized. One of the aims is also to reduce the thickness, respectively radiation length of the cables and to optimize the connection. Because of the large difference between the characteristic impedance of twisted-pair (balanced) realization of the carbon fibre cables and classical coaxial 50 $\Omega$ equipment (unbalanced) used in the presented test-setup and also in the final application, some broadband transformation from unbalanced to balanced and vice versa have to be investigated. These investigations should be based on the rather good description of the transmission line with a SPICE model.

Finally, although, the development focused on the application in an LHC pixel detector, the advantages of carbon cables could also be used for other kinds of detectors or even outside high energy physics.

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