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Scanners for the quality control of scintillating plastic fibres

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Abstract

The use of scintillating plastic fibres in the SciFi tracker requires rigorous quality control. The fibre diameter and in particular local variations in form of bumps and necks have an impact on the regularity of the winding pattern and hence the spatial resolution. Defects in the fibre cladding lead to light losses and inter-fibre cross talk. Machines have been developed which allow scanning at high throughput of the fibre diameter and the integrity of the cladding. We describe the design principles and implementations of these machines and illustrate their performance. While these machines allow to identify and quantify performance issues of the prototype fibres, they will also play a major role during the series production of the SciFi tracker. If needed, the capacity of the machines allows scanning of the full production volume.

Contents

1 Introduction

The upgrade of the LHCb detector [1], which will take place during the Long Shutdown 2 (LS2) from end 2018 to the end of 2019, will extend significantly the physics reach of the experiment by allowing it to run at higher instantaneous luminosity with increased trigger efficiency for a wide range of decay channels.

The Scintillating Fiber (SciFi) Tracker [2] is based on 2.5 m long multi-layered fibre mats of 250 μm diameter scintillating fibres. The fibre mats are assembled into 12 planes covering 350 m^2 active area. The total fibre length exceeds 10'000 km. For the readout cooled SiPM arrays with 128 channels and 250 μm channel width will be used.

2 Scintillating Fibres

The scintillating plastic fibre Kuraray SCSF-78MJ is the baseline choice for the tracker because their peak emission wavelength at 450 nm (blue) matches well the spectral sensitivity of the used SiPMs. The multi-clad fibres have a scintillating fibre core with a refractive index of 1.59 surrounded by two claddings with refractive indices of 1.49 and 1.42, respectively.

Scintillating plastic fibres are produced by a continuous pulling technique, starting from a heated macroscopic preform which has the same diameter proportions of core and cladding as the final fibre. The diameter of the final fibre is controlled by the interplay of drawing speed and temperature.

The constancy of the diameter is ensured by an appropriate control loop which regulates e.g. the drawing speed as a function of the deviation of the actual diameter from the set value. The corresponding diameter variations are usually small (% of diameter) and happen on a typical length scale of meters.

Plastic fibres, particularly those with small diameter like the ones used in the SciFi tracker, exhibit also diameter variations on a much smaller length scale, namely cm or even mm. The origins of those are being discussed with the fibre producers, however as they are related to the production technology, they fall under non-disclosure agreements. Therefore they cannot be discussed in a public note. The amplitude of these short defects can exceed ±10% of the diameter and therefore compromise the light transport, the mechanical stability and last but not least impact on the winding pattern during the production of fibre mats.

2.1 Scintillating Fibre Quality Assurance

Quality Assurance (QA) is an important tool to identify performance issues during the R&D phase and to ensure full compliance during the series production phase.

In addition to the fibre scanner described in this note, the fibres undergo several other tests, for which dedicated test benches were developed:

- Measurement of the attenuation length

- Measurement of the scintillation yield following energy deposition by ionising radiation
- Irradiation tests.

These test benches are described in separate documents.

Diameter variations

As mentioned above, the control of the diameter is a challenge for the fibre producers, particularly for small diameter fibres. The producers measure the fibre diameter on-line during the drawing process, typically by means of optical micrometers. The results were found to be not always reliable. This may also be due to the fact that the fibre runs at a relatively high speed which is determined by the drawing process. This makes fine sampling, e.g. in sub-mm steps, difficult and requires a very high sampling frequency.

The verification of the fibre diameter (nominal 250 μm) and its uniformity is therefore an essential part of the fibre quality assurance. The scintillating fibres arrive on spools from the producer. These fibres are rewound while continuously measuring the diameter (see figs. 2,3) on dedicated rewinding stands. Some of the developed set-ups provide the possibility to verify the quality of the fibre cladding

3 Principle of the scanners

We describe the requirements, principles and performance of the scanning machines which have been developed for the measurement of the diameter variations and the integrity of the cladding at high speed. The technical implementation details are described in the appendices.

Most of the development work has been carried out at RWTH Aachen and University of Dortmund. While the Dortmund machine was conceived for general studies, the Aachen machine served for QA during the production of the PERDAix [3] project (500 km of fibres). In 2014, a slightly upgraded machine was jointly built by CERN and Aachen, largely following the design of the first Aachen machine. Currently, the construction of a further machine at Kurchatov institute is in progress, which is again based on the Aachen design.

3.1 Requirements of the fibre scanners

In the context of the LHCb SciFi project more than 10’000 km of scintillating plastic fibres of 0.25 mm diameter are processed to fibre mats. The production is foreseen to last about 18 months.

The main requirements of a fibre scanner are:

- Measurement of fibre diameter with micrometer resolution in steps of less than 0.1 mm.

- Verification of the integrity of the cladding structure
- High throughput to cope with typical rates for series production, i.e. typically tens of km per day.
- Tension and bending of the fibre must be maintained well below the limits beyond which damage may occur.
- The data needs to be stored for later processing and reference.

3.2 Principle of operation

The principle of operation, common to all devices used in the SciFi project, is schematically shown in Fig. 1. The units shown as dashed boxes are implemented on some but not all of the devices described in sec. 4.

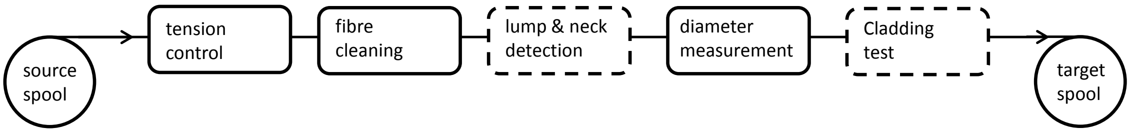

Figure 1: Flow diagram of a fibre scanner.

The fibre scanners consists of a take-off reel (also called source spool) and the take-up reel (target spool). Both reels are motor driven. The motor speed of the take-up reel is set to a constant value, the speed of the take-off reel is regulated by a dancer roll tension control unit in order to ensure a constant tension during the rewinding process[1]. Typically the tension is set to 50 cN. Starting from the take-off reel the fibre passes through the dancer roll tension control unit followed by a cleaning device which ensures that the fibre is clean of dust and dirt when it enters a combination of a lump/neck (LN) detector and a 2D-laser micrometer which find bumps in the fibre and measure the fibre diameter. The LN detector is a binary device based on a fast laser micrometer with programmable thresholds relative to the diameter average. It outputs a logical signal which can be used to control the scanner, e.g. reduce the fibre speed such that a higher measurement density in the 2D-laser micrometer can be achieved. The possibility to vary the fibre speed during the scan process is a major advantage compared to on-line measurements during the drawing process. Subsequently the fibre runs through a cladding quality monitor in order to record segments with damaged cladding. Directly before the take-up reel, a small guiding pulley is mounted on a motor driven slide to ensure a flat distribution of the fibre over the spool width. All reels have a diameter of at least 5 cm. The minimum allowed bending diameter is 100-200 times the fibre diameter, i.e. 25 - 50 mm for a 0.25 mm fibre. The reels have dry running ball bearings and are free of burrs and sharp edges which could damage the fibres.

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[1] The fibre transport control and the cladding test are implemented different in the Dortmund Scanner, see chapter 3.

4 Implementations

In the following we briefly describe the various configurations implemented at RWTH Aachen, Univ. Dortmund, CERN and Kurchatov Institute. A summary table can be found at the end of the section.

4.1 Fibre scanner at RWTH Aachen

Fig. 2 shows the configuration of the fibre scanner at RWTH, after the upgrade with a lump/neck detector which was realised in 2014. Details of the used components are given in Annex 1. The controls and software are described in Annex 2.

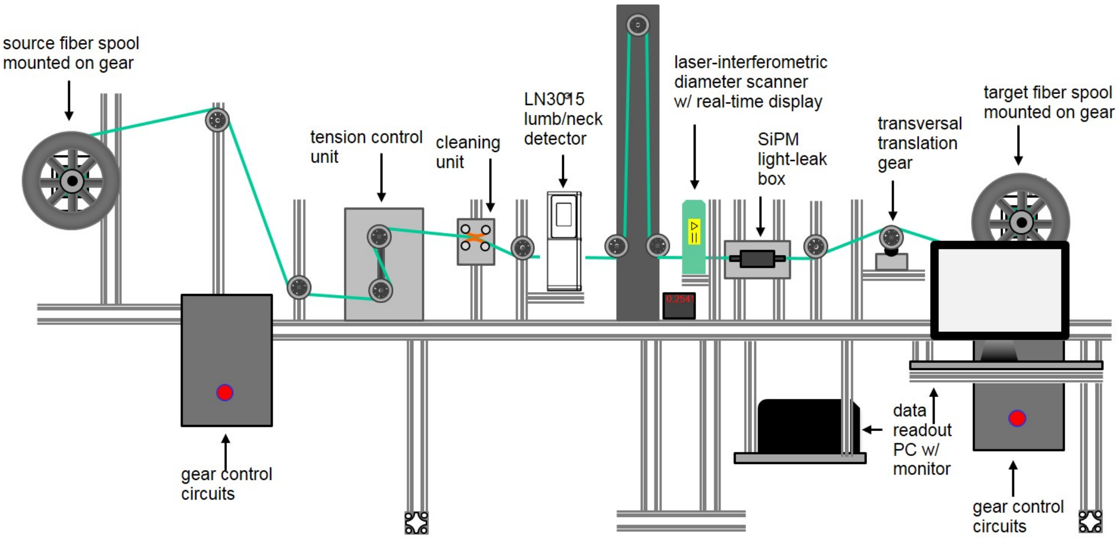

Figure 2: Principle of the RWTH Rewinding Stand

4.2 Fibre scanner at University of Dortmund

Fig. 4 shows the configuration of the fibre scanner at the University of Dortmund. The main components where developed for the prototype scanner from 2009 to 2014. Currently the scanner is set up as series production machine. The movement (and position) of the fibre is controlled by a dedicated spool in the middle of the set-up near the laser micrometer and the light guidance test. The tension is defined by two loose spools. Their position is controlled by light barriers which are read out by the controllers of the take-off reel and take-up reel.

To test the light guidance the fibre is excited by an UV-LED. The lateral light is detected with two SiPMs. The distance between these is chosen long enough to enable the measurement of an effective attenuation length (see chapter 5). The diameter of the fibre is controlled by a laser micrometer only. The measuring interval depends on the fibre

Figure 3: Photo of the RWTH Rewinding Stand

speed which is kept constant. Details of the used components are given in Annex 1. The controls and software are described in Annex 2.

4.3 Fibre scanner at CERN

CERN took the responsibility for the procurement and quality control of the main part of the fibre volume foreseen for the LHCb SciFi project. Jointly by CERN and RWTH Aachen, a fibre scanner was built during summer 2014, which is largely based on the existing RWTH scanner. The main differences are (1) the fast analog readout of the BLM [2] Accuscan AS 5010, which allows to access diameter data at a rate of 2400 Hz per axis and (2) a cladding test based on UV excitation of the fibre.

Fig. 5 shows the fibre scanner at CERN. Its total width is about 6 m.

4.4 Fibre scanner at Kurchatov Institute

The scanner at Kurchatov Institute is currently under construction. It is also based on the RWTH concept and layout and will implement the same fast analog readout as CERN. Details of the fibre tensioner and cladding test differ from the RWTH and CERN scanner. Fig. 6 shows the mechanical frame of the scanner at Kurchatov institute, currently under construction.

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[2] Beta Laser Mike Europe, NDC Technologies, Dortmund (Germany)

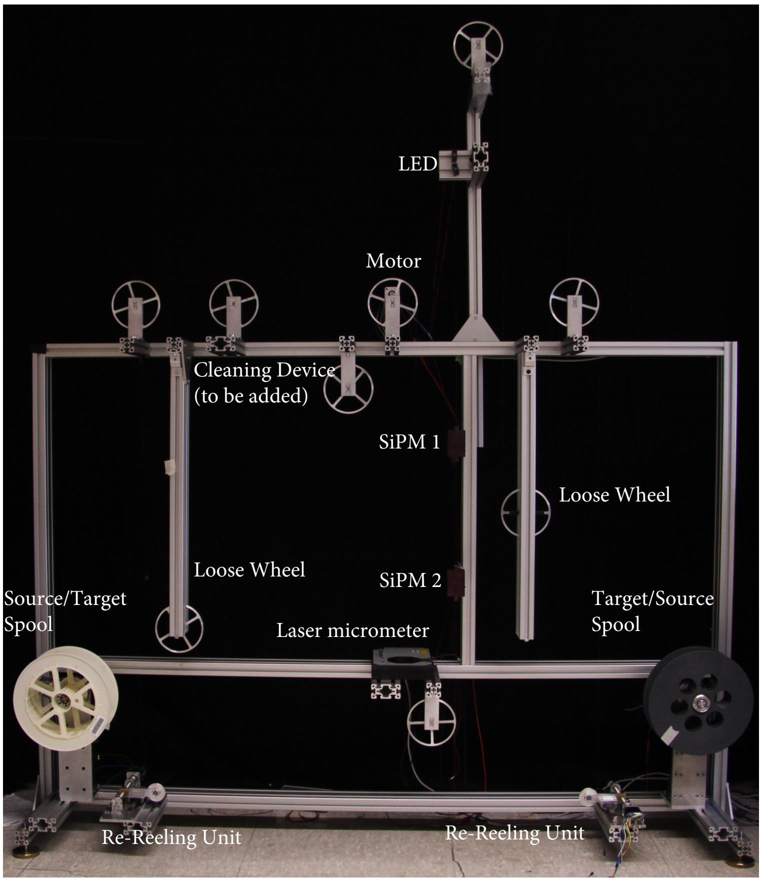

Figure 4: The TU Dortmund scanner (preliminary picture).

Figure 5: Panoramic photo of the fibre scanner at CERN

Figure 6: Mechanical frame of the scanner at Kurchatov institute currently under construction

Table 1: Summary of the features and installed instruments at the various sites. BLM = Beta Laser Mike.

site	RWTH Aachen	Univ. Dortmund	CERN	Kurchatov
tension control	dancer with torsion spring	linear gravity dancer	gravity loaded dancer	dancer with torsion spring
LN detector	BLM LN3015	none	BLM LN3015	BLM LN3015
diameter measurement	Zumbach ODAC 15XY	BLM Accuscan AS 5010, digital readout	BLM Accuscan AS 5010, fast analog readout	BLM Accuscan AS 5010, fast analog readout
cladding test	ambient light excitation	light guidance test with UV light excitation	UV light excitation	UV light excitation
fibre speed	max. 1.2 m/s	typical 0.34 m/s	max. 1.2 m/s	max. 1.2 m/s
measurement interval	30 Hz, typ. 3 mm	100 Hz, typ. 3.4 mm	2400 Hz, min. 0.04 mm	2400 Hz, min. 0.04 mm
comments				

5 Measurements

The plots in Fig. 7 show diameter profiles taken with the CERN scanner. The scanner runs at high speed (1.2 m/s). Following a variation in the fibre diameter by more than 20μm, detected by the LN 3015 detector, the scan speed is reduced to about 15 cm/s and the fibre scanned by the BLM AccuScan at a frequency of 2400 Hz. This high frequency per axis translates to an interval between data points of about 50μm. It allows to resolve long O(cm) and short O(mm) structures with high precision and to determine their maximum and minimum amplitudes. The plots were produced with a root based offline analysis program which finds the bumps and necks automatically.

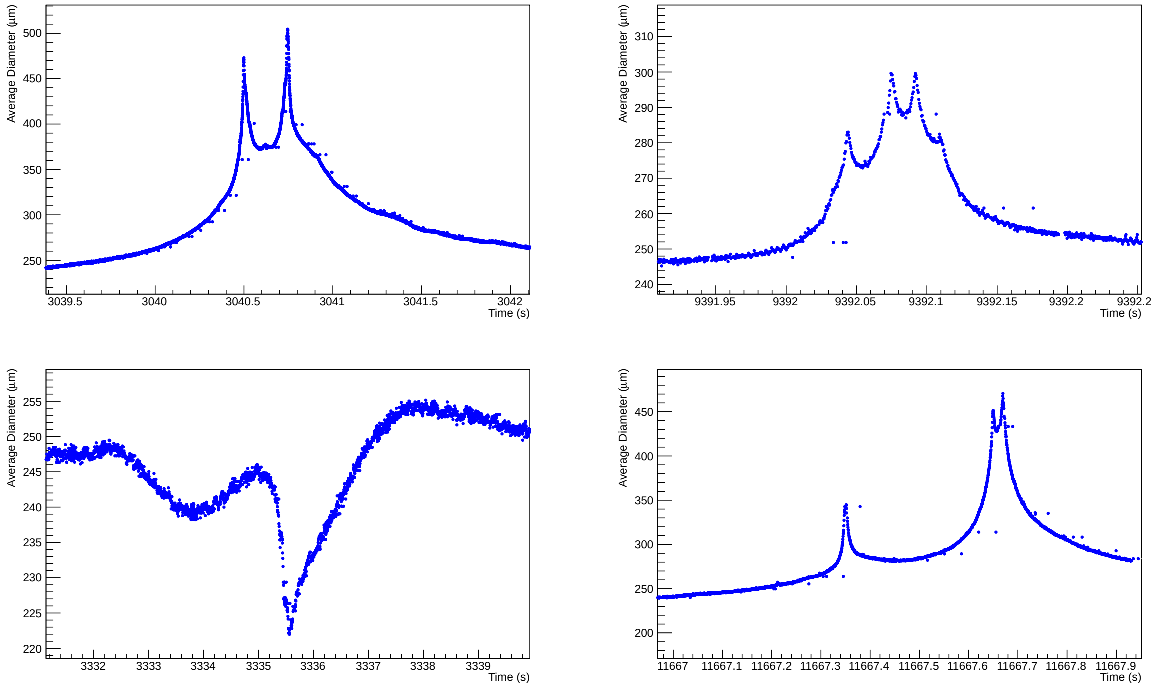

Figure 7: Fibre diameter versus scan time in seconds (1s = 15 cm). Top left: Double bump with 500 μm peak height. Top right: Multi-bump defect with 300 μm peak height. Bottom left: 220 μm neck defect. Bottom right: Defects with 350 and 450 μm peak height.

6 Conclusions

Within the LHCb SciFi project, several high performance scan set-ups are available or are under construction which allow to assess the geometrical quality and the integrity of the cladding of the scintillating fibre. The combination of high sampling frequency (up to 2400 Hz) and automatically modulated fibre speed is a powerful approach to guarantee at the same time high throughput and precise diameter profile measurements. The machine at CERN, tuned for production mode, is able to scan a 12.5 km fibre spool in about 3.5 hours and can therefore cope with the whole fibre volume foreseen for the SciFi project. The offline analysis of the diameter data provides lists of defects for every spool, which can be read by the STC fibre winding machines. The winding machine can then pre-warn the operator of an irregular fibre section which may need to be removed.

Recently, Kuraray has upgraded their on-line fibre diameter measurement by a laser micrometer Keyence [3] LS-9000, which features a sampling frequency of 16 kHz per axis. A first comparison between Kuraray's and CERN's measurement of the very same fibre spool showed a high level of agreement, both for the bump height and the positions. Consistent measurements provide the basis for further fibre quality improvements, in particular a further reduction of bump heights and rates.

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[3] www.keyence.eu

Appendices

A Components

A.1 Tension Control Unit RWTH Aachen

The tension control unit with which the tension of the fibre is kept constant during the rewinding process, operates like a rotating dancer roll tension control and consists of a two-armed lever that is pivot-mounted in the center and has a pulley at each end respectively (see figs. 8, 9).

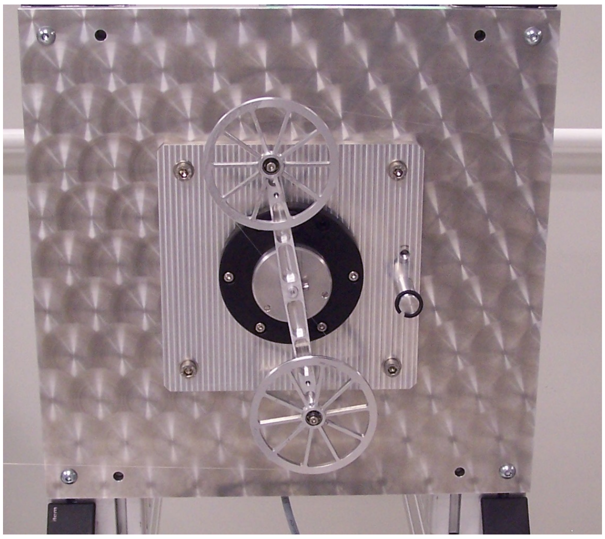


Figure 8: Photo of Tension Control Unit

The fibre runs in a "‘S"’-shaped manner around the two pulleys. The lever is kept in a vertical position by compensating the tension of the fibre with a spiral spring at the pivot. This spring also governs the setting of the winding tension. In case there is a variation in the tension the lever will loose its vertical orientation and the angular change is measured and gives rise to a signal that controls the speed of the two motors of the take-off reel and the take-up reel (see fig. 9). By this the tension is kept constant to 50 cN pull strength.

The scanner at CERN makes use of a very similar tensioner, however the spiral spring has been replaced by a weight which provides constant tension, independent of the angular rotation.

A.2 Tension Control Unit TU Dortmund

The tension of the fibre is defined by the weight of the loose spools. Each loose spool is used to control the turning speed (and direction) of the take-off(up) reel. Light barriers are used to check whether the loose spool is pulled up or goes down and the speed of the take-off(up) reel is adjusted appropriately. There is no defined direction of the fibre.

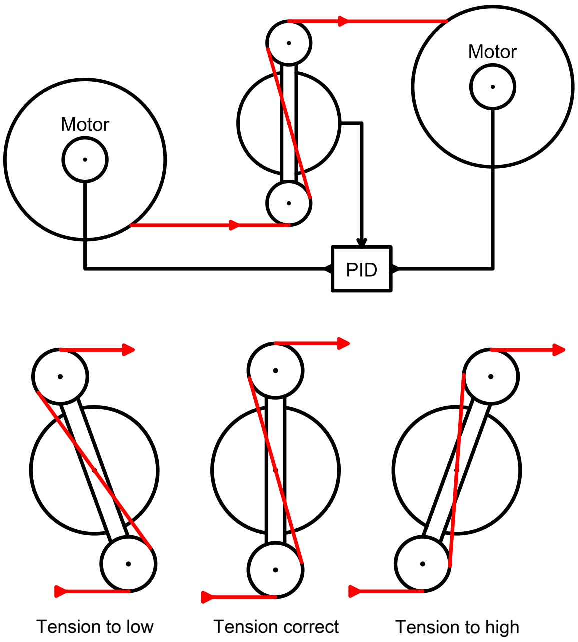


Figure 9: Principle of Tension Control

A.3 Cleaning Device

The fibre passes by two small tapes made from antistatic fleece, that are pressed against the fibre from above and from the bottom. Both tapes are steadily moistened with isopropanol by drip feed. In this way it is ensured that the fibre is clean of dust and dirt (see fig. 10).

A.4 Lumb/Neck Detector

The Beta LaserMike LN3015 uses three optical axes spaced at 60 °-intervals to deliver a higher degree of coverage around the fibre circumference to detect lumbs or necks in the fibre diameter. If the fibre diameter exceeds or falls below the programmable thresholds of the LN detector a signal is sent to the control unit which changes the speed of the winding motors which switches from fast mode (> 1 m/s) to slow mode (≈ 0.1 m/s) so that the profile of the defects can be measured with higher precision with the 2D-laser micrometer.

A.5 Zumbach 2D Laser Micrometer

The 2D Laser Micrometer (Zumbach ODAC 15XY, see fig. 12b) measures the fibre diameter and is readout by a computer and the measured value is saved to a file on hard disk together with the actual length of the spooled fibre. The measurement principle is shown in figure 12a). Two orthogonal laser beams are directed from the side onto the

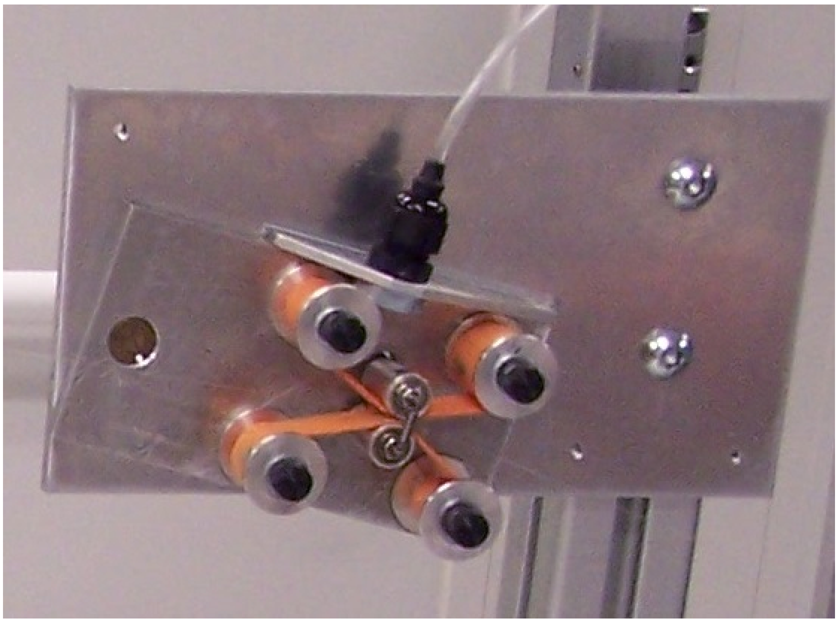


Figure 10: Photo Cleaning Device

object, the shadows of the object are detected by a receiver with a frequency of around 30 Hz, analyzed and the width of the object is calculated.

A.6 Beta Laser Mike AccuScan 5010

CERN and University of Dortmund use a two-axes analog laser micrometer of type BLM AccuScan 5010. The device is highly precise (better than 0.1 μm) intrinsically fast (2400 scans/s) however the throughput is limited by the serial communication protocols (RS232, USB, Ethernet). While the device at Dortmund is read via the RS232 interface achieving about 100 Hz, CERN implemented a fast analog readout scheme which runs at 2400 Hz for both axes.

A.7 Cladding Quality Tester RWTH Aachen

After the 2D-laser microscope the cladding is tested for damage. Therefore the fibre passes through a dark box in which 3 silicon photomultipliers are mounted (see fig. 13). The fibre is excited outside the box by daylight and if the fibre cladding is damaged the SiPMs will detect the changes in the light condition while the fibre is running through the small dark volume.

A.8 Light guidance test TU Dortmund

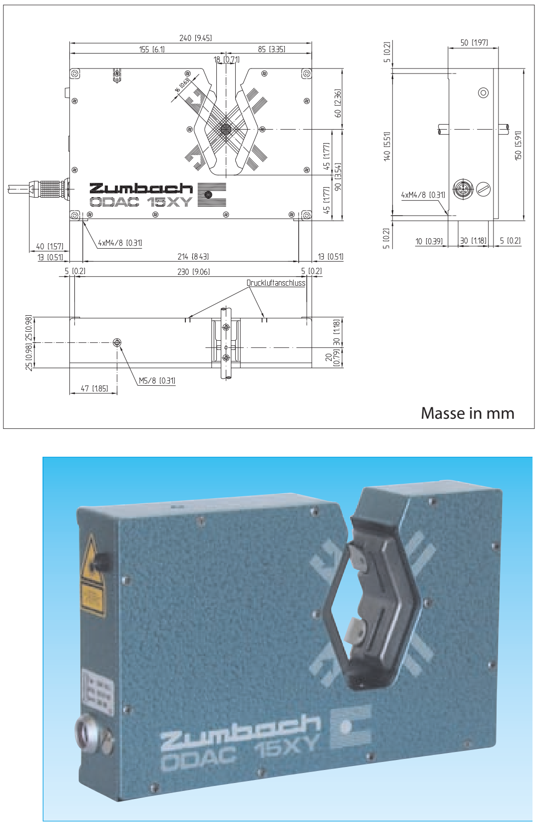
Also an undamaged fibre leaks some light along the length. It's amount is dependent of the light which is guided through the fibre. To test the light guidance the fibre is excited

Figure 11: Photo Lumb Neck Detector LN3015

at one position with an UV-LED. At two positions downstream the light leaving the fibre is detected with SiPMs (Hamamatsu SiPM-Module C11208) (see Fig. 4 on page 6). The ratio of the signals can be used to calculate an effective attenuation length (see chapter 5).

A.9 Re-Reeling Unit RWTH Aachen

Robust new take-up reels (winding diameter 314 mm, width 40 mm) have been produced from polycarbonate in the institute's workshop. A ball bearing mounting on the axle provides low friction easy running when driven by a motor. A flange with two pins that insert into respective holes in the reel is driven by a motor and provides the winding moment. Brushes are in contact with the fibres during the winding on the take-up reel to avoid electrostatic charging. Just in front of the reel a pulley is mounted on a slide which is motor driven and moves the pulley in axial direction by roughly 250 μm per revolution of the reel (see fig. 14). The distance is limited by two end switches which respectively reverse the direction of motion within the range of the winding width of the reel. The progressive feed is not as important as is the steady and smooth rotation of the reel without swaying.



a) b)

Figure 12: a) Laser Micrometer Principle, b) Photo 2d Laser Micrometer ODAC 15XY Zumbach

A.10 Re-reeling unit TU Dortmund

In front of the target spool a carriage with a mounted wheel is placed. This moves 250 μm sideward by signal after every full rotation of the spool and distributed the fibre homogeneous on the hole spool width. The same unit is placed right after the source spool to enable spooling in the opposite direction.

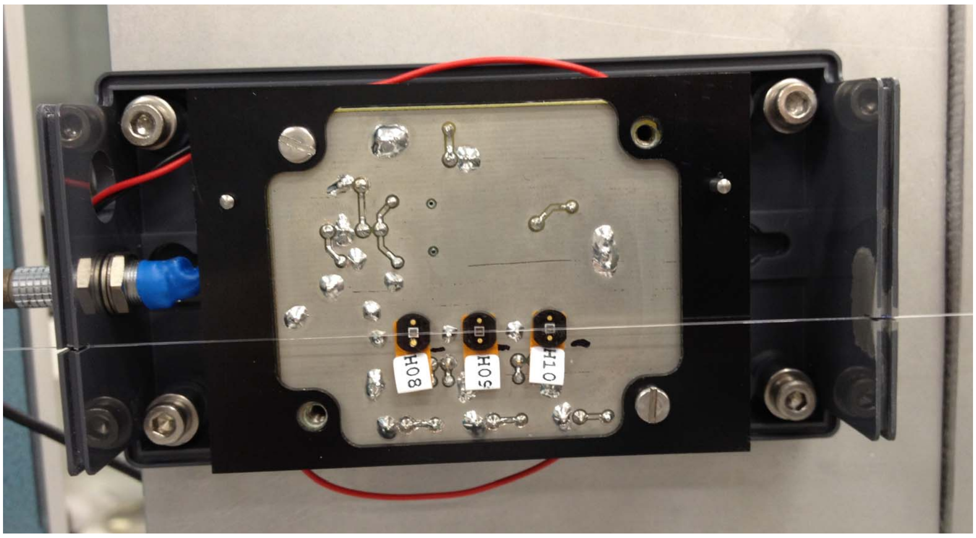


Figure 13: Photo Cladding Tester Unit (Cover Removed)

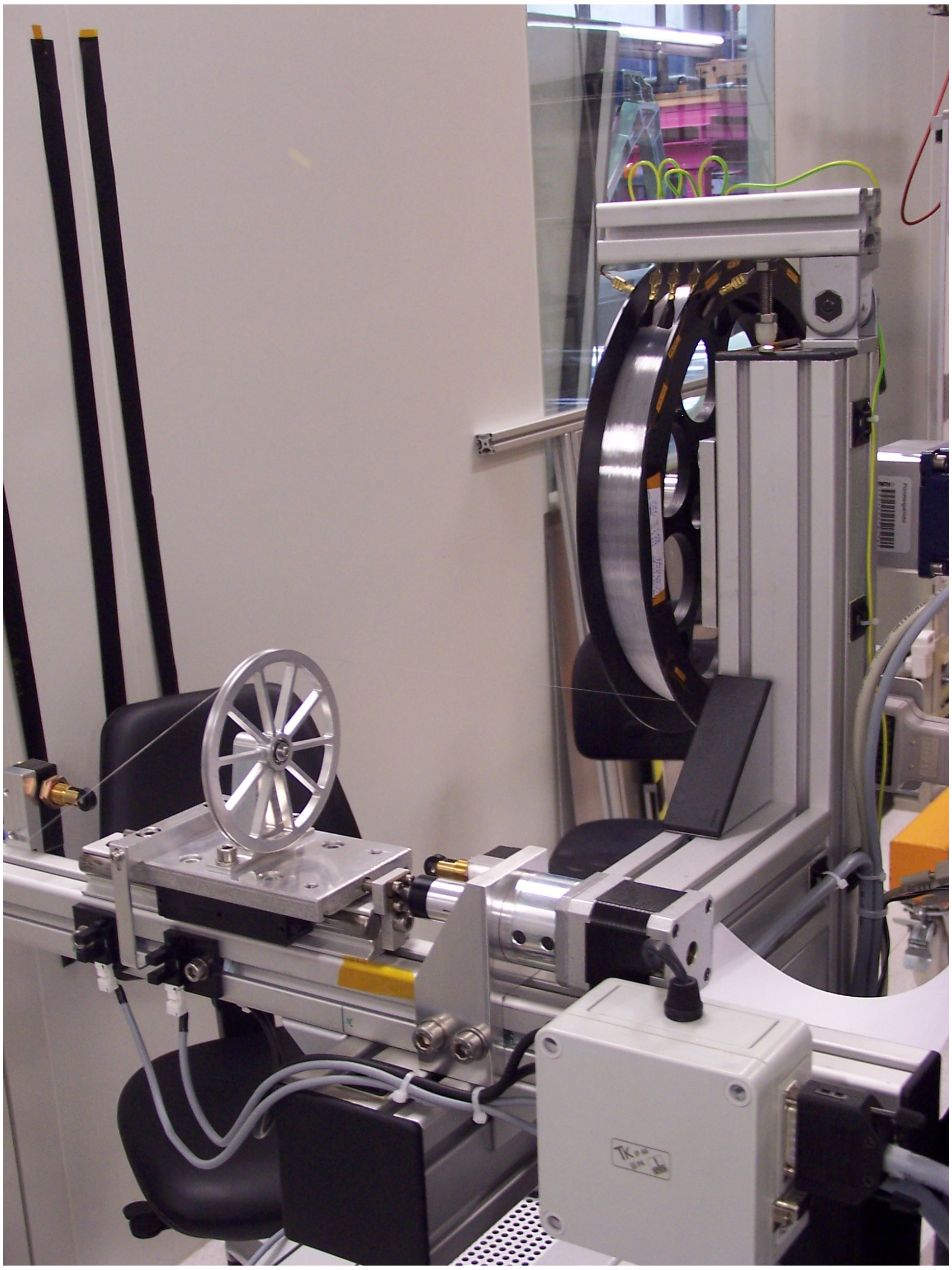


Figure 14: Photo Re-Reeling Unit

B Controls and monitoring

B.1 Controls hardware and software of the RWTH scanner

The schematic below shows the main elements of the controls hardware and software of the scanner developed at RWTH Aachen. The scanners at CERN and Kurchatov institute use copies of these elements.

B.2 Monitoring software of the RWTH scanner

The monitoring software takes care of the readout and writing of the data, makes a simple online analysis and manages additional comments for the individual winding measurements. Existing measurements can be read in again for further studies. The software has a multi-threaded structure with different threads responsible for reading the different sensors, managing the events internally, visualizing and writing them to a file.

The software package consists of multiple libraries which handle the readout, processing, plotting and provide additional helper tools and the so called windingmanager program. The Qt framework is used for the GUI and build system and ROOT for data analysis and the qcustomplot library for visualization. The readout utilizes the comedilib to talk with the PCI I/O card and a helper library to communicate with the serial port.

The processing library takes care of handling readout and provides a framework to process the events you receive. The `Event` data structure holds information about the individual measurements. It provides a measurement type enum, a timestamp in milliseconds and provides a vector to store the sensor data. Each measurement is represented by such an event. The qcplot and rootplot libraries provide visualization tools and the global library some general helper classes.

For each individual sensor a separate thread inheriting from `VirtualReaderThread` is responsible for reading the data. These threads have to provide knowledge how to initialize the sensor and communicate with it to read the data, fill an event and hand them over to an external event buffer. There are the `ComediReaderThread`, `SpeedoMeterReaderThread`, `DigitalWireMasterReaderThread` and `LumpDetectorThread`. A dedicated so called `ReadoutThread` takes care of starting and stopping these individual threads. The so called `ProcessingThread` manages this `ReadoutThread`, owns an `EventQueue` as a buffer which is filled by the individual threads and knows about the so called `EventDestinations` and hands the events from the buffer to these destinations to be processed. An `EventDestination` takes care of handling the events content for example for visualization, analysis or writing to file. When all registered `EventDestinations` have processed the event it is removed from the buffer. The buffer is continuously filled by the readout threads and processed by the individual `EventDestinations`. The enqueuing and dequeueing from the buffer are running independently to not disturb the readout by the processing of the events and is handled by the `EventQueue` class.

The events are written to a pure text file but a converter for conversion of those text files to root files is included in the software. The text file contains at the beginning some header information like start time of the measurement and the settings of the software. This is followed by the list of events. Each line represents one event. This first item in this line is a number representing the sensor type followed by the timestamp and the vector of the `Event` data. When the readout is stopped the comments and information of the measurements are written to the end of the file.

For the different types of sensors algorithms try to detect errors in the measurements continuously. If there are errors detected in the fiber position and type of error is logged.

B.3 Monitoring software of the CERN scanner

The Aachen software was extended to take into account the hardware modifications described in section 4.3. In order to read and acquire the analog outputs from the Accuscan AS 5100 and from the SiPM for the cladding test and also count the number of ticks/turns of the target spool, a fast USB Input Output Card (NI-USB 6009)[4] was installed and a single new thread, `NIUSB6009Thread.cpp`, was implemented.

In a 12.5 km spool, the vast majority of its length has no diameter defects. Therefore, to save disk space and reduce the output file size, the events are written at two different rates: 1) if a bump or a neck is detected by the LN3015, the entire available information is recorded at a rate of 2400 Hz; 2) In defect free zones, only every tenth data point is saved, i.e. the rate is reduced to 240 Hz.

Another modification concerns the output file type. The size of the raw text file mentioned above reaches about a Gb for a spool of 12.5 km length and any machine upgrade would increase even more its size. The events are now written directly into a root file with $\sim$ 200 Mb.

B.4 Control of the TU Dortmund scanner

A block diagram of the control (hardware and software) is shown in Fig. 16.

The driving spool, the laser micrometer and the light guidance test are controlled by a LabView program[5]. Variables are the positioning motor speed, distance of rewinding, gate time and threshold of the SiPM. The data are matched with the help of timestamps. With this information and the step counter of the motor the fibre position for each datapoint is calculated. All data is stored on hard disk for later analyses like the bump-protocol. Additionally there is an online monitoring for the laser micrometer and the SiPMs.

The take-off reel and take-up reel and the fibre guidance carriage are controlled by dedicated software on the controllers of their stepping motors. They operate completely autonomic.

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[4] The NI-USB 6009 has 8 analog inputs at 12 or 14 bits with maximum sampling rate of 48 KS/s. Besides, it has a 32-bit counter with 5 MHz maximum input frequency.

[5] National Instruments, LabVIEW, http://www.ni.com/labview/

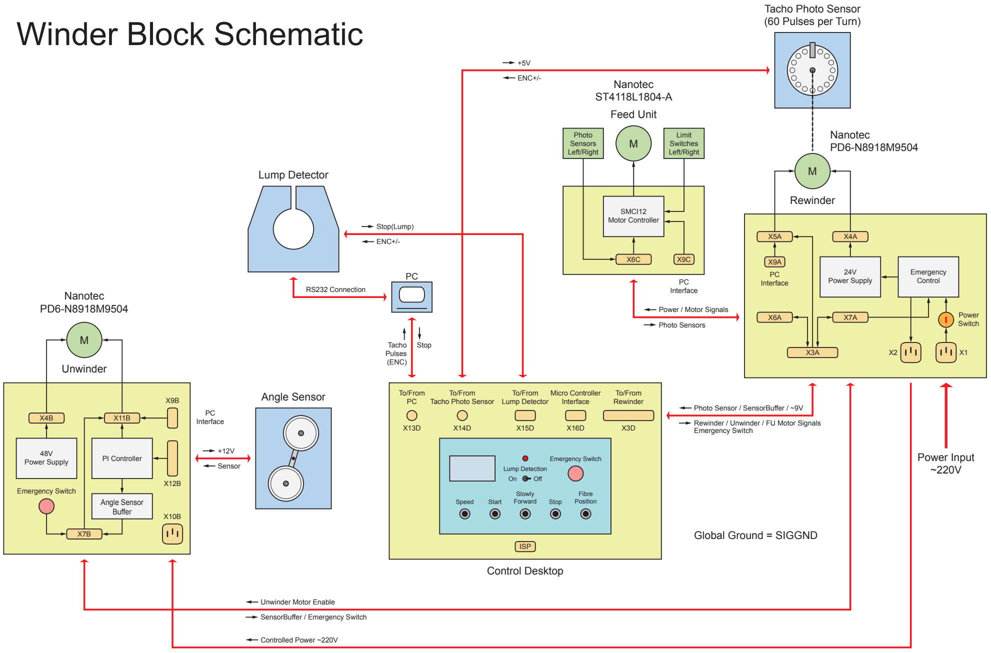

Figure 15: Schematic diagram of winder control electronic

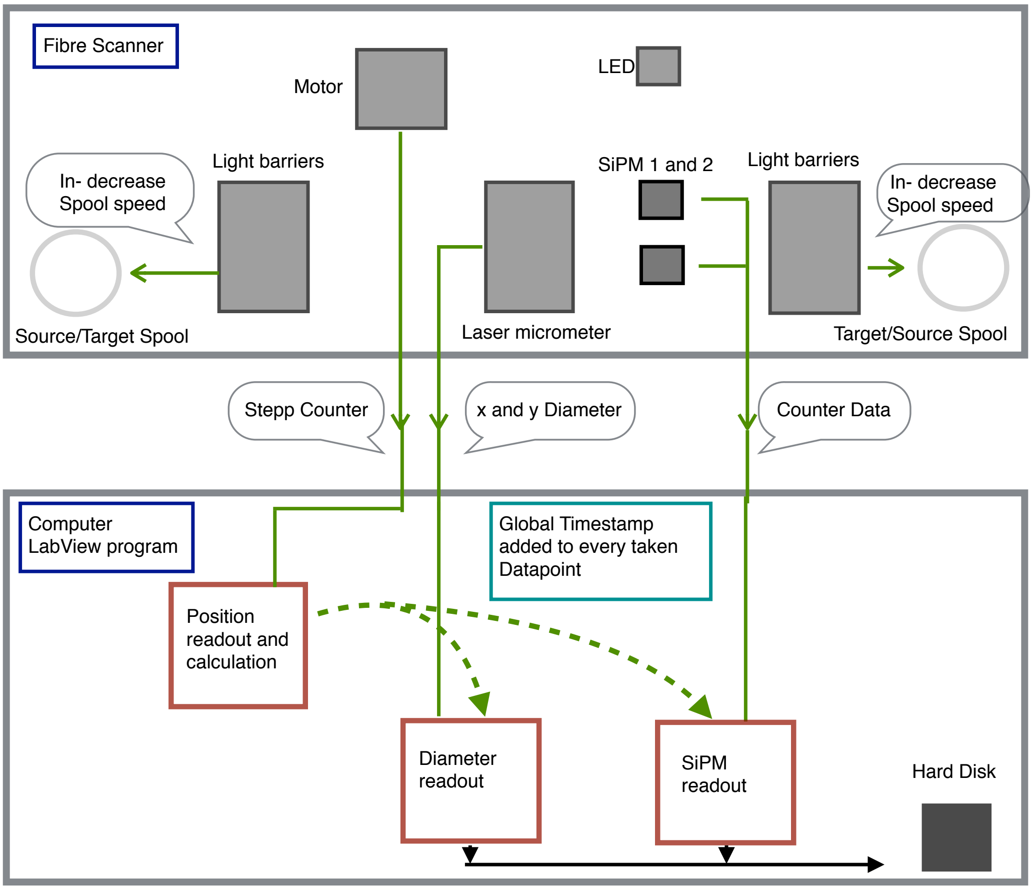

Figure 16: Schematic diagram of the control of the TU Dortmund scanner

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