Fibre test benches for the characterisation of media for calorimeters with optimal readout

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13 March 2017

The AIDA-2020 Advanced European Infrastructures for Detectors at Accelerators project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

This work is part of AIDA-2020 Work Package 14: Infrastructure for advanced calorimeters.


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Abstract:
For measurements of scintillating fibres, several test benches have been developed and commissioned within WP14 Task14.2.1, such as set-ups for attenuation length measurements, a test bench for investigation of timing properties, and mechanical and data acquisition tools for studying the performance of scintillating fibres using high-energy particles. The different setups are described in this document, providing additional details relevant for Milestone MS56.
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1. INTRODUCTION

An essential part of the activities in WP14 is the development and construction of test infrastructures for calorimeter elements to support the R&D activities in the area of calorimetry for current and future collider detectors. Task 14.2 focuses on calorimeters with optical readout and is subdivided in two subtasks, subtask 14.2.1: “Test benches for characterisation of organic and inorganic scintillator fibers for future calorimetry” and subtask 14.2.2: “Test Benches for the Characterisation of highly granular Calorimeter Elements with Scintillator and SiPM Readout”.

In the frame of sub task 14.2.1, several test setups have been developed for the characterisation and performance study of different types of fibres (heavy crystal fibres and light fibres based on SiO$_2$).

- Attenuation length measurement benches at CERN at UNIMIB
- Uniformity measurement bench at ETHZ
- Pump and probe setup for timing properties investigation at Vilnius
- Test stand for the evaluation of light attenuation variation during irradiation at Brunel
- Co$^{60}$ irradiation bench at CERN
- A setup to study SiO$_2$:Ce fibres as wavelength-shifters by ETHZ
- An absorber made of 0.75W/0.25Cu to evaluate the calorimetric performance of scintillating fibres
- A data acquisition system for high energy beam tests set-up

These different test benches provide an infrastructure for the in depth investigation of optical and radiation hardness properties of all types of scintillating fibres as well as their test in a calorimeter prototype.

In this milestone report we described these different tests set-up, which have been commissioned over the last 2 years.
2. LIGHT ATTENUATION TEST BENCH @CERN

2.1. SETUP DESCRIPTION

In order to quantify the optical quality of the fibers and measure the propagation of the light along them, a setup to measure the light attenuation has been built at CERN. It is based on a double sided readout with two PMTs (see Fig.1). The sample to be measured is hold with two V-shaped mechanical supports. This makes sure to minimize the contact points when measuring the samples with no cladding/wrapping. Direct coupling with no optical coupling media (dry contact) is used as standard measurement since this minimizes the measurement error. The sample is excited with a light source of wavelength chosen to match one of the excitation bands of the scintillating material. In turn the sample is generating isotropic luminescent light. Part of this light is propagating through the sample and reaching its ends, to be readout by the photodectors. As opposed to a transmission/absorption measurement the attenuation measurement involves several modes of propagation of the light and assesses the light guiding properties of the fibers. Figure 1 shows the setup equipped with the LED pulser#2 designed by V. Mechinsky (RINP-BSU). This pulser comes with a 4 to 1 fan-in bundle of optical fibers and a collimator. This allows obtaining a very tiny spot of 2-3 mm to scan the fiber along its axis and to reduce the amount of parasitic light since the beam of light is shaped as a pencil. The output of the LED pulser is hold with a motorized stage and controlled with a computer. The signals of the two PMTs are digitized based on the SYNC OUT signal from the pulser (used as external trigger). The combination of a fast pulser (10-50 ns) with a high repetition (10-50 kHz) rate and a fast motorized stage allows making the measurement of a 20 cm long sample last for less than 30s.

Fig. 1. Setup for the measurement of the attenuation curves of the fiber-shaped samples equipped with a multi-wavelength LED pulser. The light is first coupled to optical fibers to bring the excitation light close to the samples with a collimator.

To adapt for the various samples to be measured, several LED pulsers were built by RINP-BSU. A short history of the different version is presented here after (also see Fig.2Error! Reference source not found.).

UV Pulser #1: prototyping

The first type of UV pulser was based on UV LED with emission maximum 365 nm. The pulser consists of two main blocs: a square-wave generator on the basis of NE555 timer and an electronic key (2N2222 transistor). The pulse duration was of 1500 ns with repetition rate of 13.5 kHz.
UV Pulser #2: Universal concept
This version uses more narrow pulses (50 ns) and a synchronized output (SYNC) to be used as external trigger in the DAQ system. Besides for more versatility, three output optical channels were integrated into the pulse: ~365 nm, ~400 nm and ~470 nm.

UV Pulser #3: Brighter and Faster
This version was dedicated to make the 365 nm LED brighter. A remote emitter is used here to avoid light losses through the optical fiber. An avalanche breakdown of a transistor in self-oscillation mode leads to a significant increase in response with an improved signal-to-noise ratio combined with a further decrease of the pulse duration (10 ns).

UV Pulser #4: 265 nm in addition to 365 nm
To be able to measure some samples with deeper UV excitation bands (e.g. Pr-doped fibers) a new pulser was built based on a UV LED with an emission peaking at 265 nm. To obtain sufficiently high operating voltages, a cascade of avalanche transistors powered with an external HV supply (+650 V) was chosen and for a more stable operation, the electronic key was modified to control the breakdown mode of the transistors. As in Pulser#3 the pulse duration is of 10 ns. This pulser is equipped with two remote probes (265 nm and 365 nm) for more versatility. Because of the increased operational voltage, the 365 nm LED is also brighter as compared to earlier pulsers.

![Image of LED pulsers](image)

Fig. 2. The four versions of LED pulsers produced by INP Minsk.

2.2. EXAMPLE OF MEASUREMENTS
In Figure 3, some examples of recorded data set are shown for a high quality Czochralski grown crystal fiber of YAG:Ce and a sample of poor optical quality for which the good dynamic range of the setup is valuable.

The detection of the luminescent light at both ends of the fibers is very useful to mitigate alignment problems and minimize the influence of scattering centers on the excitation light. By computing the ratio of both signals, these fluctuations in the intensity of the excitation light are cancelled out.

Fig. 3. Example of attenuation curves acquired on high quality fibers (left) and on fibers of poor optical quality (right). From the left plot, we can estimate the spatial resolution of the setup which is very good as can be seen from the sharp peak at d=13.5 cm due to the V-shaped masks. On the right plot, the good dynamic range of the setup is illustrated, ranging from a few tens of photons up to 100'000 photons.

3. OPTICAL ABSORPTION MEASUREMENT SYSTEM @UNIMIB

In this section the system that has been developed at UniMIB to measure the optical absorption of (scintillating) optical fibres will be described; moreover, a measurement example will be presented as well to give a brief idea of the results and information, which can be obtained with the instrumentation.

3.1. SYSTEM DESCRIPTION

The measurement system is composed by a Perkin Elmer Lambda 950 double beam spectrometer equipped with an accessory (see Fig.4), which is able to inject and collect light into, and from, suitably designed optical fibres. The spectrometer is by itself able to cover the entire spectral range from 190 to 3300 nm (from UV to near infrared) with a maximum photometric range of the order of 6 absorbances.

The accessory for fibre measurements is composed by two curved mirrors and two lenses to focus the light beam on the fibre core and match the numerical aperture of the fibres with that of the instrument. According to Perkin Elmer and to our own experience, the accessory has a throughput of the order of 10 % when using 600 µm core fibres.

In order to reliably couple the accessory with the fibres under test, two “launch” fibres have been prepared from a commercial fibre (Polymicro FDP 600, high OH silica, core 600 mm, numerical aperture 0.22). Due to the transparency characteristics of the two launch fibres, the usable range of the spectrophotometer is reduced to about 190-1200 nm. These two fibres have SMA connectors on one end (as an interface with the instrument) and FC connectors on the other (to be connected to the
to-be-measured fibre). The choice of the FC connector to join the launch fibres to the tested one is motivated by the higher reliability and reproducibility of this kind of connectors with respect to others. This however implies that the fibres under test must be terminated with FC connectors. A further extension of the current set-up is presently being designed to make the system more versatile and able to measure reliably fibres without connectors.

![Diagram of fibre test bench](image)

**Fig. 4.** Left panel, picture of the Perkin Elmer accessory for optical absorption measurements on optical fibres. Red arrows, optical path. Top cover removed. Right panel, scheme of the complete spectrophotometer system.

### 3.2. OPTICAL ABSORPTION MEASUREMENTS ON SiO₂:Ce SCINTILLATING OPTICAL FIBRES

As an example of the kind of results that can be obtained with the instrument, Figure 5 presents two measurements performed on scintillating Ce doped silica fibres -- (core diameter 600 µm, F-doped silica cladding 750 µm, Ce concentration 500 ppm) currently being investigated for their possible application in high energy physics detectors – before and after irradiation with ⁶⁰Co γ-rays.
Fig. 5. Optical absorption spectra of SiO$_2$:500 ppm Ce optical fibre before and after irradiation with 1 kGy $^{60}$Co $\gamma$-rays

The spectrum of the not irradiated sample shows weak absorptions above 550 nm and complex structures below 400 nm related to Ce$^{3+}$ and Ce$^{4+}$ absorptions. The region below 400 nm is also distorted by Ce$^{3+}$ luminescence. After irradiation, the picture is modified by the presence of further well evident contributions in the blue-green region of the electromagnetic spectrum; these new, radiation induced absorptions strongly overlap with the emission spectrum of Ce$^{3+}$ (which is centred at about 450 nm). The spectral information of light attenuation allows, then, an evaluation of the radiation induced band impact on the luminescence characteristics of the fibres in terms of absolute absorbed light and of spectral modifications of the transmitted light.

3.3. CONCLUSION

The optical absorption set-up for measuring optical fibres is currently working, and it is being regularly used to characterize scintillating rare earth doped SiO$_2$ fibres. The system is of simple and rather quick use; it also has high sensitivity and reproducibility. The obtained information is very valuable since it contains also the spectral composition of the absorbing species: this is particularly interesting in the evaluation of scintillating fibre radiation hardness. However, in the case of luminescent fibres the obtained spectra can be distorted by luminescence contributions, and attention must be paid in spectra analysis and interpretation. The luminescence issue can be resolved by considering also the use of appropriate filters. Further improvements to make the set-up more versatile in order to measure unprepared fibres (i.e. without FC connectors) are currently in progress.

4. UNIFORMITY TEST BENCH @ETHZ

4.1. DESCRIPTION

A laboratory test bench has been set up and commissioned for the measurement of the signal uniformity of scintillating fibers along their length (Fig. 6). The bench has been commissioned by measuring the light uniformity response of scintillating fibres with and without aluminisation at the end opposite to the photodetector. A $^{90}$Sr source is used for the excitation of the fibres.
Measurements show that, while uniformity is only slightly affected and remains within the 5% of the measurement accuracy, the aluminisation allows to collect 25% more signal.

**5. PUMP AND PROBE TEST BENCH @VILNIUS**

**5.1. DESCRIPTION**

The test bench for pump and probe study (TBPP) is dedicated to monitor dynamics of i) two–photon absorption, ii) population of photo-excited states, and iii) free carrier absorption in scintillation materials. The TBPP is based on Yb:KGW femtosecond laser PHAROS emitting 200 fs pulses at 1030 nm (200 µJ pulse energy, 30 kHz repetition rate). The output of the laser is split into two parts and used to pump two optical parametric amplifiers (OPA) “Orpheus” providing 200 fs pulses continuously tunable between 630–2600 nm (the range can be extended down to 315 nm by frequency doubling). Fixed harmonics of fundamental PHAROS radiation (2nd – 515 nm, 3rd – 343 nm, 4th – 257 nm) can also be used for photoexcitation. The samples under study are probed either by the output of one of the OPA or by a white-light-supercontinuum (spectral range 410–800 nm) generated in a sapphire plate. The delay between pump and probe is varied optomechanically, the time resolution of the system is limited at 200 fs by laser pulse duration (see Fig. 7 and 8).
6. TEST STAND FOR EVALUATION OF LIGHT ATTENUATION VARIATION DURING IRRADIATION @ BRUNEL.

A fibre test stand to enable the determination of real-time degradation of absorbance in optically transparent fibres during irradiation has been designed and is being commissioned at Brunel University London. Real-time measurement of what could be fairly short-lived colour centres is potentially important for an understanding of issues relating to particular scintillating or wave-length fibres that are considered for use in new designs of calorimeters with optical readout.

6.1. DESIGN PARAMETERS

To evaluate changes in optical absorbance and, in principle, fluorescent yield of a WLS fibre, we have designed a test stand that will be used remotely from the light source and spectrometer as the radiation is produced by a $^{60}$Co source which will rapidly damage any electronic systems within the cell. Due to the chicanes in the shielding we need to be located at least 20 m from the radioactive source during an exposure. For these reasons we have designed a system using a fibre-coupled light source and a fibre-coupled UV-visible spectrometer. These instruments are then connected by 20 m lengths of pure-silica core step-index fibres to the test stand itself (see Fig. 9).

![Fig. 9. Fibre test bench. The two optical fibres, connecting the remote spectrometer and light source respectively, come from left and right and light is focussed onto the fibre under test by silica lenses located within the precision manual x-y-z stages. The $^{60}$Co radioactive source, when exposed, is located at the bottom of the steel tube seen in the centre of this photograph. The fibre under test is placed in a holder (not shown) located in the gap between the stages.](image-url)

The key components used in the test bench are listed in the table below:

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Description</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrometer</td>
<td>StellarNet Black Comet spectrometer BLK-C 100</td>
<td>Wavelength range: 190 nm – 850 nm Detector: CCD with 16-bit ADC. Maximum integration time is 65535 ms.</td>
</tr>
<tr>
<td>Light Source</td>
<td>StellarNet SL5</td>
<td>Combined Deuterium &amp; Tungsten Halogen light source.</td>
</tr>
<tr>
<td>Fibres</td>
<td>Two 20 m lengths of Thorlabs UM22-200</td>
<td>0.22 NA, 200 μm diameter silica core, step-index fibre.</td>
</tr>
</tbody>
</table>
6.2. SPECTROMETER PERFORMANCE

The spectrometer has now been fully characterised, the following bullet points summarise the main conclusions:

- Sequentially captured spectra show a very similar mean signal level to within a few counts averaging across the full spectral histogram;
- The dark current signal level is low (~ 200 counts mean for 180 ms integration time) compared to the peak of a measured light source spectra (see Figure 10), a variation of 100 counts in dark signal being a fluctuation of around 0.25% of the peak counts (~42000) in a collected deuterium, halogen light source combined spectrum;
- Data collected at different integration times shows that readout amplifier noise dominates the resulting spectrum until the integration time is increased beyond 2000 ms. Increasing the integration time further results in an approximately linear increase in observed dark current with increasing integration time.

Figure 10 shows the recorded spectra of the deuterium-halogen light source after 20 m of optical fibre. No correction for the wavelength dependence of the fibre absorption or the variation in response with wavelength of the CCD detector in the spectrometer has been applied.

![Figure 10](image)

**Fig. 10.** Recorded spectra with spectrometer connected with one length of 20 m fibre directly to the deuterium/halogen light source. The spectra are uncorrected for any variation in CCD response with wavelength and the integration time was 180 ms. The “combined” curve is taken with both light sources on simultaneously.

6.3. OPTICAL SYSTEM CHARACTERISATION

Figures 11 and 12 show the predicted sensitivity of the optical system to misalignment of the fibre under test. Optical modelling was done in ZEMAX OpticStudio in non-sequential mode and the fibre...
under test was assumed to be a 100 mm long, 2 mm diameter quartz rod with no cladding and planar faces. Such a reference fibre has recently been ordered from UQG Optics Ltd, Cambridge.

![Graph showing incoherent irradiance in the optical fibre](image)

**Fig. 11.** The incoherent irradiance in the optical fibre taking light back to the spectrometer following the collection lens. The light has traversed a perfectly aligned quartz rod of 2 mm diameter. The core diameter of the collection fibre was 200 µm

![Graphs showing lateral and angular misalignment](image)

**Fig. 12.** Predicted effects, using ZEMAX OpticStudio software, of lateral and angular misalignment of a 100 mm long, 2 mm diameter quartz rod in the fibre test bench. Both curves illustrate the decrease in optical power coupled from the rod into the fibre returning from the test bench to the spectrometer. The data are normalised to the value of the coupled power for perfect alignment.

### 7. CO$^{60}$ IRRADIATION BENCH @ CERN

In order to study the radiation hardness of the samples, a secured Co$^{60}$ source of high activity (2.5 GBq) is available at the CERN group laboratory (see Fig.13). Samples can be exposed to the gamma rays at a rate of ~1 Gy/day.
Fig. 13. Pictures of the Co60 radioactive source used for studies on radiation hardness.

Access to Co60 source allowing higher dose rate (500Gy/h) near CERN is also available for Aida project as well as the PS proton irradiation facility, IRRAD, at CERN. These irradiation facilities will allow evaluating the radiation behaviour of the investigated materials at the radiation level required in future high energy experiments.

8. A SETUP TO STUDY SiO$_2$:Ce FIBRE AS WAVELENGTH-SHIFTERS @ ETHZ

A test setup has been developed in order to study SiO$_2$:Ce fibres as wavelength-shifters in a sampling calorimeter single-channel prototype that uses CeF$_3$ as a scintillator (Fig.14). The readout system developed and commissioned in 2015 has been used for that purpose at the CERN SPS accelerator. The test has allowed to observe that SiO$_2$:Ce fibres exhibit, as visible in Fig.15, the following properties:

- the WLS emission time constant typical of Cerium (folded in twice in this setup)
- a fast Cherenkov component (rise time few ns, dominated by PMT response time).

The observed response could exploited in timing measurements, and for this purpose, dedicated tests have been performed.
The Cherenkov component of SiO$_2$:Ce fibres has been studied in a dedicated test. The direct Cherenkov light from SiO$_2$:Ce fibres has been detected by blinding one bundle towards the Cerium Fluoride scintillation light (Fig.16-left). For this test, Hamamatsu SiPM have been used, read out by a preamplifier board developed by ETH for this purpose. The timing resolution constant term achievable for electrons impacting on the fibres is below 100 ps (Fig. 16-right). The calorimeter remains as an infrastructure for tests of various fibres.
A matrix of 5 x 3 channels (Fig.17) has been prepared for beam tests in June 2016 at CERN. Test beam data have been taken and are currently being analyzed. The aim is to extract the ultimate energy and angular resolution. Construction parameters are:

- Dimensions: 12 x (6mm CeF$_3$ + 5 mm W) x 25X0, transverse dimension 17 mm
- High granularity: R$_M$ = 17 mm
- WLS fibers for readout: Kuraray 3HF-SC, 1 mm diameter
- 3 mm-wide, depolished chamfers to favour scintillation light escape towards the WLS fibers, thus dimensioned to accommodate fibers
- 4 fibers signals onto one photodetector, read out independently for one single channel (in green in Fig.17)
- APD readout, as for the CMS ECAL barrel

**Fig. 16. Left** SiO$_2$:Ce bundle screened by black paper from receiving the calorimeter scintillation light  
**Right:** Timing resolution for the W-CeF$_3$ calorimeter read by SiO$_2$:Ce WLS fibers, as a function of signal amplitude

9. **AN ABSORBER MADE OF 0.75W/0.25CU TO EVALUATE THE CALORIMETRIC PERFORMANCE OF SCINTILLATING FIBRES**

In order to evaluate the energy resolution of a fibre based calorimeter in high energy particle beams, a dedicated prototype has been built in a configuration where the fibres are pointing to the beam, commonly referred to as SPACAL.
9.1. DESCRIPTION

The setup is composed of an absorber made of 40 plates of 0.75W/0.25Cu with grooves of 1.1x1.1mm² (see Fig.18). The plates are stacked together and fixed by two stainless steel plates at the top and bottom of the module. The absorber contains a total of 1200 holes and has an overall dimension of 60x60x200mm³. The dimension has been defined in order to achieve full energy containment of electromagnetic showers with energy up to ~200 GeV for scintillating and/or Cerenkov fibres of density between 2.7 and 7.3 g/cm³.

The light produced by a group of 11x11 fibres is readout simultaneously with a photodetector (PMT or SiPM) optically coupled to the end of fibres through an optical light guide in order to increase the light collection and reduce the channel counts (See Fig.19). The module consists thus of a 3x3 channel array, where each channel is about the width of one Moliere radius and contains 80-90% of the shower. If needed the read-out granularity can be increased by developing a new system of light guides and by increasing the number of photodetectors.

The fibers can be easily inserted and removed from the module without the need to disassemble the tungsten-copper plates and thus testing of different type of fibers in relative short time is possible.

*Fig. 18. Left:* Plate of 0.75W/0.25Cu with groove to insert the fibres. *Right:* completed absorber made of X plates

*Fig. 19. Light guide at the end of the fibres*
9.2. COMMISIONING OF THE SETUP

The prototype made of the Tungsten-Copper absorber has been demonstrated to be valid with 121 fibers of YAG fibres crystals in the central channel and 1500 plastic fibers to fill the remaining fraction of the absorber. The 9 channels have been read-out with individual PMTs and signals produced by electron showers between 50 and 200 GeV have been measured. The energy distributions are reported in Fig.20. This first beam test allowed commissioning the module layout and its read-out by measuring the response of both plastic and crystal fibers whose signal was digitized with a CAEN V1742 digitizer.

![Energy reconstruction in YAG fibres](image)

**Fig. 20. Energy reconstruction in YAG fibres**

10. A DATA ACQUISITION SYSTEM FOR HIGH ENERGY BEAM TESTS

A data acquisition for high-energy beam test setups has been developed, commissioned and maintained under the responsibility of one postdoctoral researcher (F. Micheli, ETHZ), who has been hired through Aida for this purpose. It has been used for the tests performed in 2015 in the H4 beam line at the CERN SPS accelerator.

The DAQ system allowed to read-out and reconstruct the information provided by the wire chambers and hodoscopes positioned along the beam line and thus to associate the particle impact point to each event. The software is also configurable to read-out the information from a multi-channel ADC and from a CAENV1742 5Gs/s digitizer with 32 channels capable to provide detailed sampling of pulse shapes and excellent time resolution. The DAQ system is synchronized with the beam signal provided by the synrotron facility (e.g. PS or SPS) and requires a trigger which can be provided by standard scintillators.

The software also includes tools for data quality monitoring (DQM) which produce a quick analysis of the data to monitor the beam intensity, position, etc. and a user interface GUI to control both the DAQ and DQM.

All softwares have been released on github and can be downloaded and reproduced on multiple machines with small changes in configuration files:

- [https://github.com/cmsromadaq/H4DAQ](https://github.com/cmsromadaq/H4DAQ)
- [https://github.com/cmsromadaq/H4DQM](https://github.com/cmsromadaq/H4DQM)
https://github.com/cmsromadaq/H4GUI

The main beam test studies which have been performed with this DAQ system included:

- Timing resolution measurements of Lead Tungstate scintillators
- W/CeF$_3$ sampling calorimeter with Ce doped quartz fibers as WLS
- W/LYSO Shashlik calorimeter with capillaries
- SPACAL calorimeter with heavy scintillating fibers

![Experimental setup for precision timing studies located in the H2 beam test facility at CERN SPS connected to the DAQ system mentioned above for data read-out.](image)

**Fig. 21.**

11. **CONCLUSION**

In the last two years several complementary test stands have been produced and commissioned in different institutes to characterize the optical, the radiation hardness and the performance under high energy particles beam. These different infrastructures are now available to test any type of fibers.

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13. ACKNOWLEDGEMENTS

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme AIDA 2020 under Grant Agreement no. 654168 and under the Marie Skłodowska-Curie grant agreement No 644260