Timing resolution studies of the optical part of the AFP Time-of-flight detector

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Abstract: We present results of the timing performance studies of the optical part and front-end electronics of the time-of-flight subdetector prototype for the ATLAS Forward Proton (AFP) detector obtained during the test campaigns at the CERN-SPS test-beam facility (120 GeV π+ particles) in July 2016 and October 2016. The time-of-flight (ToF) detector in conjunction with a 3D silicon pixel tracker will tag and measure protons originating in central exclusive interactions $p + p \rightarrow p + X + p$, where the two outgoing protons are scattered in the very forward directions. The ToF is required to reduce so-called pileup backgrounds that arise from multiple proton interactions in the same bunch crossing at high luminosity. The background can fake the signal of interest, and the extra rejection from the ToF allows the proton tagger to operate at the high luminosity required for the measurement of the processes. The prototype detector uses fused silica bars emitting Cherenkov radiation as a relativistic particle passes through them. The emitted Cherenkov photons are detected by a multi-anode micro-channel plate photomultiplier tube (MCP-PMT) and processed by fast electronics.

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1. **Introduction**

Precise timing is necessary for many applications, ranging from Positron Electron Tomography (PET) scans to particle physics. For high energy physics, it is typically combined with a momentum measurement to determine the mass of the particle, which in turn defines the particle’s identity. Timing detectors can be used as well as a part of the proton tagging detectors to decrease the background to central exclusive production (CEP) events $p + p + X + p$, where $X$ stands for the centrally produced system, which could consist of a pair of jets or particles, a pair of intermediate vector bosons ($W'W'$), or even a Higgs boson $H$. At a high luminosity, the environment of the Large Hadron Collider (LHC) places stringent demands on the timing detectors: high resolution (~10–20 ps, equivalent to the 2.1–4.2 mm interaction vertex resolution), radiation hardness, long lifetime (the integrated charge of at least 10 C/cm$^2$/yr), and multi-proton detection capabilities. To access low masses of the centrally produced system $X$, it is crucial to measure as close to the proton beam as possible, therefore an edgeless design is required. ToF detectors based on Cherenkov emission in fused silica radiators are treated as an interesting choice.

The AFP detector is designed to tag protons outgoing from ATLAS interaction point (IP) in the very forward direction. For this purpose, it consists of two near stations (at 206 m from IP), one per side, fitted with a 3D silicon pixel tracker; and two far stations (at 217 m from IP, one per side) with the silicon tracker together with a ToF detector. The two ToF detectors provide a time difference between the times of flight of the two protons in the CEP events. As the speed of the protons differs from the speed of light by a negligible amount, it is possible...
to determine where the protons originated from (the longitudinal primary vertex position) based on the time difference, which provides high background rejection when combined with other means of the vertex reconstruction.

The ToF design for the AFP project is based on benchmark studies [4]. The ToF geometry is outlined in Fig. 1. It consists of a 4 × 4 matrix of L-shaped bars made of fused silica. Each bar serves both as a Cherenkov radiator and a light guide towards a fast MCP-PMT device. The rows of four bars alongside the beam axis are called trains and labeled with a number, Fig. 1(a). The columns are labeled with letters A, B, C, and D along the direction of the incoming particle. In this way, the bars in the Train 1 are labeled 1A, 1B, 1C, and 1D and so on for the other trains. We produced two extra sets of bars (constituting full trains) with different geometries for the positions of the Train 1 and the Train 2. We labeled them the Train 5 and 6 to distinguish the original trains from the new ones (still having at most four trains in a ToF installation).

The selected shape originates from the space limitation given by the available space inside the housing that AFP uses (the Roman pot). The benchmark study [4] introduced several key concepts adopted in the final design and construction of our ToF prototype and also shown simulation results for the developed geometry. Particularly a taper cut was proposed to speed-up total-reflection pathways. Also, the radiators are tilted at an angle of 48° with respect to the beam, which corresponds to the Cherenkov angle for the fused silica. Because of this, the direct photons from all bars within a train arrive at the same time. The bars are produced from 2 pieces and glued by the Epotek 305 UV transparent glue [5]. All the surfaces of the bars are polished and only the area of the 45° cut on the outside of the right angle joint of the radiator and light guide parts is aluminized, since it is the only part where the total reflection condition is not met for a substantial fraction of photons. Construction details are discussed in the previous study [6] together with the first timing results.

The edge plane of the ToF detector is an important characteristic which is formed by individual edges of all bars, Fig. 1(a). It is the place where the detector has the best resolution as discussed throughout the paper. The AFP detector acceptance area is 16.3 × 20.0 mm² given by the tracker dimensions [7] and the tracker tilt as illustrated in Fig. 1(b).

![Fig. 1. (a) Geometry of ToF, (b) ToF with tracker modules (not in scale).](image)

2. Experimental setup

The ToF prototype was tested during several test campaigns at the CERN-SPS test-beam facility (120 GeV π+ particles) in the last three years. Here we present results from the campaign in July 2016 and October 2016 which were dedicated to timing studies.
The ToF subdetector is depicted in Fig. 2. The matrix of 4 × 4 bars is fixed to the PMT by a duralumin holder, Fig. 2(a). The bars are held by the duralumin plates within machined grooves. The plates are partially separating the light guide part of the bars of different trains. The grooves are designed to provide firm placement of the bars while keeping the minimal touching surface between the bar and the holder. The PMT is a new Planacon XPM85112 MCP-PMT [8] with 16 pixels (channels) in the 4 × 4 matrix, Fig. 2(b). Each bar is designed for a dedicated pixel. The layout of pixels occupancy is sketched in Fig. 2(c). The trains 1 and 2 were alternatively replaced by the trains 5 and 6, respectively, during the studies. Table 1 summarizes dimensions of the bars. See Fig. 1(a) for the meaning of the light guide and the radiator and [6] for the geometry and the construction details.

### Table 1. Dimensions of the ToF bars.

| Train | Light guide length [mm] | Length of the radiator [mm] | Radiator height [mm] | Taper* [mm] |
|-------|-------------------------|-----------------------------|----------------------|-------------|
|       | Bar A | Bar B | Bar C | Bar D | Bar A | Bar B | Bar C | Bar D | Bar A | Bar B | Bar C | Bar D | |
| 1     | 63.4  | 57.8  | 52.2  | 46.5  | 3     | 2     |       |       |       |       |       |       |       |
| 2     | 59.2  | 53.5  | 47.9  | 42.3  | 5     |       |       |       |       |       |       |       |       |
| 3     | 52.9  | 47.3  | 41.7  | 36.0  | 5     |       |       |       |       |       |       |       |       |
| 4     | 46.6  | 41.0  | 35.4  | 29.8  | 5     |       |       |       |       |       |       |       |       |
| 5     | 62.4  | 56.8  | 51.2  | 45.5  | 2     |       |       |       |       |       |       |       |       |
| 6     | 58.2  | 52.5  | 46.9  | 41.3  | 4     |       |       |       |       |       |       |       |       |

The cross-section dimension of all light guides is 5 × 6 mm², the thickness of all radiators is 6 mm [6].

*The taper value is the difference between the nominal and tapered light guide width at the narrowest place. For more details on the taper optimization, see the design study [4].

The photograph of the measurement setup is shown in Fig. 3. The beam passed through two tracker modules, the ToF subdetector under study, an auxiliary ToF module, other two tracker modules, and two SiPM detectors used as a trigger. The auxiliary PMT detector was added for complementary studies and it is not discussed in the paper.
Each SiPM trigger detector consisted of a 30 mm long fused silica bar of $3 \times 3$ mm$^2$ cross-section coupled to a silicon photomultiplier (SiPM) manufactured by ST Microelectronics (NRC09.1 with $3.5 \times 3.5$ mm$^2$ and 58 μm cell size). The SiPM detectors are also based on Cherenkov radiation. The trigger detectors were placed on a two-axis movable stage (remotely controlled) to select dedicated areas of the ToF detector for timing studies. We mostly used the first SiPM detector (closer to the ToF part) as a trigger. The latter one was used for the measurement of their mutual resolution and in turn the resolution of the first one. We added another SiPM detector (not in the figure) to measure the timing resolution of the first and the second SiPM detectors at the beginning of the timing performance studies. The third SiPM detector comprised of SensL SiPM sensor (MicroFC-SMA-30050 with $3 \times 3$ mm$^2$ and 50 μm cell size) coupled to 10 mm long fused silica bar of $3 \times 3$ mm$^2$ cross-section. In the following, we use the term trigger for the first SiPM detector.

The Planacon XPM85112 MCP-PMT operated at the high voltage of 2100 V, corresponding to the gain $5 \cdot 10^4$ for an optimal separation of the useful signal from the pedestal (see distribution of signal amplitudes in Fig. 4(b) – the noise pedestal is represented by narrow peaks reaching down to $-100$ mV, while the useful signal amplitudes fall below $-150$ mV). The signal output of the MCP-PMT was amplified by two-stage preamplifiers. The first stage consisted of a current-to-voltage (A-V) converter with a 1 kΩ resistor and a voltage amplifier with the amplification of 10 (the gain of 20 dB). The second stage was a voltage amplifier (V-V) with the same amplification of 10. For raw signal studies, the amplified signal was then directly analyzed with the Agilent Infinium DSA91204A oscilloscope (12 GHz, 40 GS/s, 4 channels) together with the LeCroy WavePro 7200A (2 GHz, 10 GS/s, 4 channels) in a slave mode. For timing studies, the raw signal was preprocessed with a constant fraction discriminator (CFD) with the constant fraction tuned for the MCP-PMT signal shape (42%). Apart from the constant fraction, there is also a fixed threshold in the CFD, above which, the signal is rejected. The threshold level was set to $-150$ mV for the pedestal rejection. In both cases, the signal was triggered with the SiPM detector signal amplified by a 32 dB amplifier and processed with another CFD module (here the threshold was set to $-400$ mV). The trigger detector was moved vertically to select a specific train for measurements.

### 3. Measurements and results

During all measurements, we positioned the trigger to have its coincidence with a dedicatedToF area in the beam. We used the tracker module to align and mark the positions of the trigger to have the coincidence with any of the trains (the vertical position of the trigger) both at the edge of the ToF and at the distance of 5 mm from the edge (the horizontal position). There was a special scan of the timing resolution in the range of distances from the edge. The
measurements on the (ToF) edge were done having the edge of the SiPM trigger (with the 3 × 3 mm² cross-section) aligned to the ToF edge. Thus, the measurements on the edge were in fact aggregate measurements in the range of distances from 0 mm to 3 mm from the edge and similarly the measurements at 5 mm from the edge were aggregate measurements in the range of distances from 5 mm to 8 mm from the edge.

In the following, we refer to the measurements at each train having in mind the chain of bars in the given train and corresponding pixels of the PMT. In several places the results are presented for a single bar, where all bars, but the one under study, were removed from the ToF detector. This provides a useful insight about a crosstalk and an uncorrelated time resolution.

**Raw signal measurements**

Measurements of the raw signal were important for setting up the operating high voltage of the PMT and the threshold of the CFD modules. As we mentioned in the previous section, we found the optimal operating high voltage of 2100 V. The thresholds of the CFD modules were set to −150 mV. Moreover, a crosstalk between the PMT pixels was studied in the raw signal domain.

A typical signal output from the bar 6B is plotted in Fig. 4(a) in the overlapped mode to see how the signal fluctuates within run. Figure 4(b) shows several histograms of the signal amplitudes of the bars in the Train 6 to compare the signal level at the edge of the trains and at the distance of 5 mm from the edge. There is a significant decrease of the signal amplitude of the bar 6A (and the A bars in general) by 29% at the distance of 5 mm from the edge compared to the situation at the edge due to a missing contribution of the Cherenkov cone otherwise reflected from the edge side. This missing part of the cone is accepted by subsequent bars. We measured the decrease by 19% for the bar 6B, 6% for the bar 6C, and 2% for the bar 6D. The analogous decrease in case of the Train 2 was 46% (!) for the bar 2A, 24% for the bar 2B, 14% for the bar 2C, and no change in case of the bar 2D. The situation is analogous for the other trains. This effect was partly studied in the design study [4] and it is discussed in the Discussion section below.

Concerning the effect of the taper, we found the signal coming from the bars with the taper to be higher by at least 33% with respect to the bars without the taper (on average, the mean values −450 mV or −400 mV compared to −300 mV). This was also observed in the previous measurement campaigns [6,9]. As a result, the efficiency of the detection is higher for the bars with the taper. The detector efficiency was not the subject of the presented measurements as the measurements in combination with the tracker provide more information [10]. The preliminary result, based on the presented raw measurements, is that the efficiency with respect to the trigger of single bars in the Trains 2, 3, and 4 (without the taper) is at least 72% for given HV and threshold settings and it is higher by 5-10% in the Train 5 (with the
taper). Furthermore, the efficiency is higher when all bars are installed, where the efficiency of all but A bars is above 85%.

We were also interested in the leakage of the signal from a single bar into adjacent pixels of the PMT. Selected results of the crosstalk studies for the bars 6A and 6B are plotted in the Fig. 5(a). Here, each cell represents a pixel of the PMT and the layout corresponds to the one in Fig. 2(c). The pixel occupied by a bar is red. The crosstalk was treated as a relative level of signal coincidences between the pixel occupied by a bar and a given adjacent pixel - in other words, how often an adjacent pixel and the pixel occupied by the bar produced a signal above the specific amplitude level in the same event. This quantity is labeled $c_i$ in the plots in Fig. 5 and three values are displayed for three thresholds of the amplitudes: $-100$ mV (the pedestal limit), $-150$ mV (the CFD thresholds), and $-200$ mV. The $m$ quantity is the mean amplitude of the signal detected in a pixel. Note that we found the pixel 21 to be noisy (the mean pedestal amplitude $m$ was higher by the factor of 1.4).

The threshold $-100$ mV is approximately the limit of the pedestal region, see Fig. 4(b), thus the $c_i(-100$ mV) indicates the total signal coincidences regardless the amplitude threshold except the pedestal. The level of coincidences is less than 5% at this threshold across all measured pixels (except the noisy pixel 21). The amplitude level $-150$ mV is the CFD threshold value. Thus, the coincidence above this level refers to the signals used in the timing processing. The level of coincidences is less than 2% at this threshold across all measured pixels. We added the amplitude threshold $-200$ mV for the test of eventual change of the CFD threshold setup. We got 0.5% of coincidences in this case.

Of course, the crosstalk to an empty pixel is enhanced if two adjacent bars are occupied by bars producing a signal. Figure 6(a) plots coincidence results on selected pixels in the scenario with the bars 6A (the pixel 31) and 6C (the pixel 33) involved. In this case we studied the signal coincidence of the empty pixel 32 when the both bars triggered a signal in the same event. The level of coincidences grew up to 7% at the threshold of $-150$ mV. Figure 6(b) compares histograms of the signal amplitudes in the pixel 32 in three cases: (1) with no bar anywhere (the pedestal), (2) with one bar on the pixel 31, and (3) with the situation using the two bars on the pixels 31 and 33. The last case indicates the crosstalk level between pixels in the train. As we can see, the mean amplitude of the signal grew up by $-43$ mV from the value of $-56$ mV (the pedestal) to $-99$ mV. As the mean amplitude of the signal from the bar 6B is $-523$ mV, see Fig. 4(b), the crosstalk contribution from the adjacent bars (pixels) is approximately 8%. This is already a relevant factor influencing the timing performance of trains because the correlation between bars in a train has a negative impact on the train’s timing resolution.
Fig. 6. (a) Leakage of the signal to adjacent pixels from the pair of bars 6A and 6C (the axes give the MCP-PMT pixel number, as shown in Fig. 2(c)), (b) histogram of the signal amplitudes in the empty pixel 32 in different bars configuration.

Timing measurements

The measurements of the timing resolution of the bars and the whole trains were performed with respect to the first SiPM detector acting as the trigger. Its cross-section dimension of $3 \times 3$ mm$^2$ defined the spatial resolution in the characterization of the ToF timing performance. We preprocessed the output signal by the CFD module. The timestamp of the leading edge was treated as the arrival time of a signal pulse. The arrival time of a signal pulse from a PMT pixel was determined relative to the arrival time of the trigger (the time difference). In the following, we express the timing resolution by the sigma parameter $\sigma_{\text{fit}}$ of the Gaussian fit of the timestamps distributions, see the example in Fig. 7(a), and by the full width at half maximum (FWHM) of the measured data sample.

First, the timing resolution of the trigger was investigated. To do so, we added the third SiPM detector to the setup right after the second SiPM detector. We measured the mutual timing resolution of all SiPM detectors using each detector one after another as a trigger. The resolution of the first SiPM detector was resolved to $\sigma_{\text{fit}} = 10$ ps (FWHM 25 ps). The stability of its timing performance was then repeatedly verified with respect to the second SiPM detector. The third SiPM was then dismounted from the setup.

We mainly focused on the timing resolution of all trains at the edge and 5 mm from the edge and of selected single bars at the edge. Note the train resolution is the time resolution obtained from the distribution of the average times $t_{\text{pulse}} = \frac{1}{N} \sum_{i=1}^{N} t_i$, where $t_i$ is the time with respect to the trigger measured by i-th bar in the train in a given event. Figure 7 plots examples of the timing resolution of the bars 2B at the edge. Note that the sigma
parameter in the statistics box is the sigma of the distribution fit which is not corrected to the contribution of the trigger. Table 2 summarizes the timing resolution of dedicated bars at their edge. The bars 2A and 2B without the taper have a slightly worse resolution by 2 ps compared to the rest of the bars in with the taper. Measurement uncertainty was estimated from 5 independent measurements of the same bar to be ± 2 ps in terms of standard deviation σ (± 5 ps in FWHM), which corresponds to ± 1 ps uncertainty of the train time resolution σ (± 2 ps in FWHM).

Table 2. Timing resolution of selected single bars at their edges (uncertainty ± 2 ps in \( \sigma_{\text{fit}} \), ± 5 ps in FWHM).

| Bar | \( \sigma_{\text{fit}} \) [ps] | FWHM [ps] | Bar | \( \sigma_{\text{fit}} \) [ps] | FWHM [ps] |
|-----|-------------------------------|----------|-----|-------------------------------|----------|
| 1B  | 22                            | 54       | 5B  | 22                            | 53       |
| 2A  | 24                            | 58       | 6A  | 20                            | 50       |
| 2B  | 24                            | 58       | 6B  | 21                            | 52       |
| 5A  | 23                            | 60       |     |                               |          |

Measurements of the timing resolution of the whole trains were the main scope of the presented test campaigns. We measured the resolutions at the ToF edge and at the distance of 5 mm from the edge. The example of the timing resolution of the Train 6 is shown in Fig. 8. Results of the timing studies for all trains are summarized in Table 3.

Table 3. Timing resolution of trains (uncertainty ± 1 ps in \( \sigma_{\text{fit}} \), ± 2 ps in FWHM).

| Train | edge of the ToF \( \sigma_{\text{fit}} \) [ps] | FWHM [ps] | 5 mm from the edge \( \sigma_{\text{fit}} \) [ps] | FWHM [ps] |
|-------|---------------------------------------------|----------|---------------------------------------------|----------|
| 1     | 14                                          | 34       | 15                                          | 38       |
| 2     | 15                                          | 34       | 17                                          | 41       |
| 3     | 15                                          | 34       | 17                                          | 42       |
| 4     | 15                                          | 35       | 17                                          | 43       |
| 5     | 14                                          | 36       | 17                                          | 36       |
| 6     | 14                                          | 35       | 15                                          | 37       |

The Train 2 was also the subject of the scan over the range of distances from 0 to 20 mm from the edge. As in all the previous cases, the distance value is the lower bound of the 3 mm interval given by the 3 × 3 mm² trigger. Therefore, the 0 mm corresponds to aggregate measurements in the range of distances from 0 mm to 3 mm from the edge and similarly e.g.
20 mm from the edge were aggregate measurements in the range of distances from 20 mm to 23 mm from the edge.

The timing resolution of the Train 2 as a function of the distance from the edge is plotted in Fig. 9(a). The timing resolution is approximately linearly dependent on the distance from the edge (however, there is a deviation from the linear fit in case of the FWHM). σ and FWHM values are in a good agreement as shown in Fig. 9(b) (for a Gaussian distribution FWHM \( \equiv 2.35\sigma \)), which justifies the use of the σ for the timing resolution, even though the time distribution, as shown in Fig. 8, slightly differs from a Gaussian distribution.

**4. Discussion**

The raw signal studies confirmed a variable strength of the signal across the bars in a train. We expected a lower signal level at the A bars compared to the rest of the bars in the train due to the leakage of the optical signal near the train edge. According to the simulations, the part of the Cherenkov cone leading to the edge of the bar is totally reflected towards the sensor. We call this part of the Cherenkov cone a negative wing, as in the previous studies [4]. However, photons of the negative wing also leak to the successive bars near the back end of the bar as visualized in Fig. 10(a) using the Geant4 toolkit [9,11].

![Fig. 9](image1.jpg)

**Fig. 9.** (a) Timing resolution of the Train 2 as a function of the distance from the edge; (b) correlation of σ and FWHM measures of the timing resolution.

![Fig. 10](image2.jpg)

**Fig. 10.** Optical leakage between bars near the train edge, (a) visualization in Geant4, (b) contribution of the own and the parasitic fractions to the total hit count in the sensor.

This effect strongly depends on the distance of the beam particle from the edge as seen in Fig. 10(b) for the case of the pair of the bars 1A and 1B (the models). In the plot, the green curve plots the total amount of photons generated by a proton traversing the bars at the given distance from the edge, reaching the detector pixel for the bar 1B normalized to the case at the edge. It is the sum of the contribution of the photons generated in the bar 1B itself (the blue
curve) and of the contribution of the parasitic photons generated in the bar 1A (the red curve). As there is no bar in front of the A bars, those bars suffer from the missing parasitic fraction resulting in a lower signal level and in turn a worse timing resolution and efficiency.

We can see that the total number of detected photons (the green curve) decreases with the distance from the edge. This results in the worsening of the bar resolution with the increased distance of the beam from the bar edge. At the distances above 10 mm the effect diminishes because all photons from the negative wing leave the ToF and they do not contribute to the signal output from the train. This has a negative impact on the timing resolution of the bars and of the trains themselves as seen in Fig. 9. Moreover, a lower signal level also means a lower detection efficiency of a single bar.

The measurements of the bars with the taper are in agreement with the expectation from the simulation results presented in the design study [4]. However, the uncertainty of the simulation is large due to the lack of a more precise PMT response model. The simulation predicted an increase of the number of detected photons by 20-50% depending on the collection time of the PMT, while the presented measurements show at least 33% increase.

The obtained timing resolution comprises of time smearing in bars and MCP-PMT, and a jitter of the CFD module ($\sigma = 5$ ps). In addition, there is a systematic shortening of an optical path of the fastest photons as the distance of a hit from the edge increases. The shorter optical path is partially compensated by a longer time of flight of a beam particle before reaching the bar. Since we are triggering on the $3 \times 3$ mm$^2$ SiPM detector, the obtained time distributions are smeared mixture distributions for the range of hit positions. We calculated the combined contribution $\sigma$ to be less than 3 ps.

There is still an additional contribution of a TDC used to read out the ToF system, which is not included in the presented results. The currently used HPTDC [12] based unit adds 14 ps [10] in quadrature to a single bar time resolution (specific channel combinations might lead to a larger contribution), but there is a planned upgrade to a picoTDC based unit (which is under development), where the jitter should be below 3 ps.

Concerning the timing resolution of the whole trains, the electronic crosstalk would play a significant role (since the optical signal from all bars in a train arrives at the MCP-PMT at the same time, optical crosstalk is not causing deterioration). As seen in Fig. 6, its level was approximately 7% based on the contribution from both adjacent pixels (in frame of the train alone). Although it increases the signal amplitude of the channel (the bar plus the pixel), it has no positive effect on the timing resolution of the channel comparing results of the timing studies of single bars to the ones of the whole trains, see the sigma values of the bar 6B in Fig. 7(a) and Fig. 8. Conversely, this crosstalk deteriorates the resolution of the whole train.

Theoretically, the timing resolution of the train is better than the one of single bars by the factor of $1/\sqrt{N}$, where $N$ is the number of bars in the train, providing the output signals from the bars are mutually independent (uncorrelated) and the time resolutions of bars are similar. For instance, it is visible in Fig. 8, that the bars of the Train 6 have the timing resolution approximately 22 ps on average (after the subtraction of the trigger contribution). This theoretically leads to the timing resolution of 11 ps of the whole train. Due to the crosstalk, the measured resolution is 14 ps instead. We obtained similar results in our previous measurements with a different PMT [6] where we estimated the level of crosstalk to be 10%.

5. Conclusion

Despite the negative contributions of the crosstalk, we measured the time resolution of the ToF optical part and front-end electronics to be below 20 ps. The ToF was installed to the LHC tunnel together with the AFP detector in March 2017 and it is being tuned now to achieve a requested operational performance.

There are still several issues to be solved. The production of the bars is based on the bonding of the bar arms together with a suitable glue [6]. The glue itself attenuates the signal...
approximately by 20% in the deep UV region. In the near future, the development of a single-piece bar production is of the highest priority.

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