Vertiefungsmodul

AFP 420 m/220 m
A Cherenkov Fiber Detector for ATLAS

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In the framework of the ATLAS project, proton tagging detectors at 420 m and 220 m from the interaction point are planned to be installed. The task is the examination of protons from central exclusive productions. These protons create a new particle and survive after the collision. By tagging the surviving protons, the mass of the created particle can be calculated by the missing mass method. The hope is to discover the Higgs boson by this very clean method. The prototype needs good time resolution in order to detect the two protons from one central exclusive production that are scattered in opposite directions. Therefore the principle of Cherenkov detectors is used. In this paper a prototype for a Cherenkov fiber detector is introduced.

1 Detecting the Higgs Boson at the LHC

The LHC is a proton-proton collider with 7 TeV beam energy. At high energies like these the protons would usually break up during the interaction. In order to reconstruct the Higgs particle all final state particles and their parameters have to be measured. However, in central exclusive processes the protons lose a small fraction of their momentum but stay intact. All of the protons' lost momentum goes into the production of the central system. Those forwardly scattered protons can be detected with forward detectors at 420 m and 220 m from the ATLAS interaction point (IP).

1.1 Central Exclusive Production (CEP)

In the central exclusive production

$$pp \to p + X + p \tag{1}$$

two protons interact, create a new particle X by transferring a small fraction of their momentum into the central system and do not disintegrate. Fig.1 shows the Feynman diagram for this interaction. Gluons from each proton fuse to produce the central system by hard scatter. A second color-screening gluon, which is needed for color conservation, is exchanged between both protons, which allows the protons to stay intact. The term "exclusive" means that the central system only consists of the products from the hard scatter. The longitudinal momentum the protons lose during the interaction is ξ (the incoming proton trajectory demands the longitudinal direction). ξ can in principle be measured. Then the mass M of the central system can be calculated by the missing mass method:

$$M^2 = \left(p_1 + p_2 - p_1' - p_2'\right)^2 \approx \xi_1\, \xi_2\, s \tag{2}$$

where s is the center of mass energy, p_i the momentum of the incoming proton, p_i' the momentum of the outgoing proton and ξ_i its longitudinal momentum loss. The momentum transfer of each proton is given by:

$$q_i = \left(p_i' - p_i\right)^2 \; = 2\left(m_p^2 - EE' + |\mathbf{p}||\mathbf{p}'|(1 - \cos\theta)\right), \tag{3}$$

where m_p is the proton mass and θ the angle to which the proton is scattered.

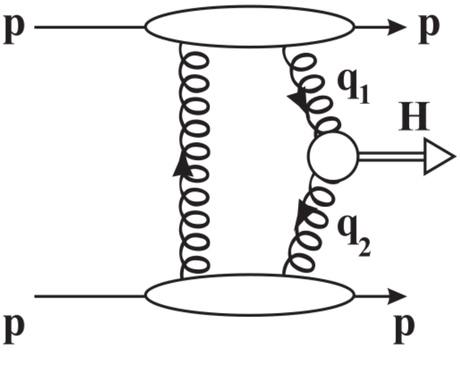

Figure 1: Feynman diagram for central exclusive production: $pp \to p + X + p$ [1].

Since the protons remain intact at CEP, there is no underlying event that is caused by proton disintegration. For a hadron collider this is a very clean environment. If the protons and their momentum loss are detected it is possible to achieve very good resolution on the mass of the central system. If the central system is resonant, the mass can be determined very precisely regardless of the decay products of the central system. At the ATLAS experiment the produced particle X is expected to be the Higgs boson. [8]

1.2 AFP 420 m/220 m – A Magnetic Spectrometer

The detectors are to be installed at the high dispersion region, where they can act as magnetic spectrometers. Magnets between the IP and the 420 m/220 m region cause those protons, that lost a small fraction of their momentum during the CEP interaction, to be deflected out of the beam envelope. Fig. 2 shows the location of the detectors relative to the ATLAS detector and fig. 3 shows the beam line top view in the range of the ATLAS detector and 500 m away from its IP.

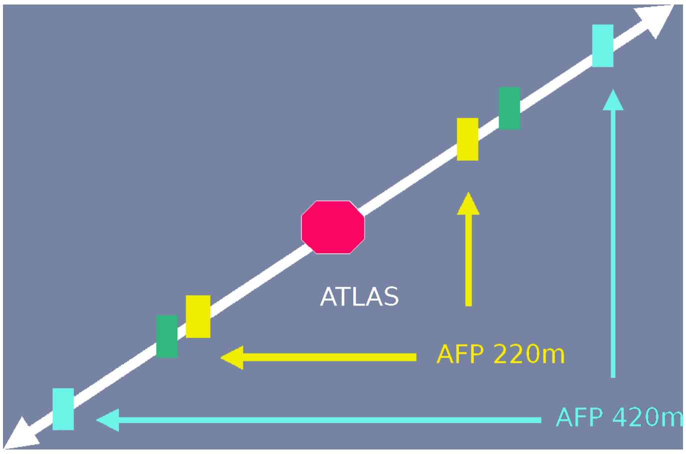

Figure 2: The ATLAS detector (red) and the location of the detectors respectively at 420 m (turqoise) and 220 m (yellow) from the ATLAS IP [6].

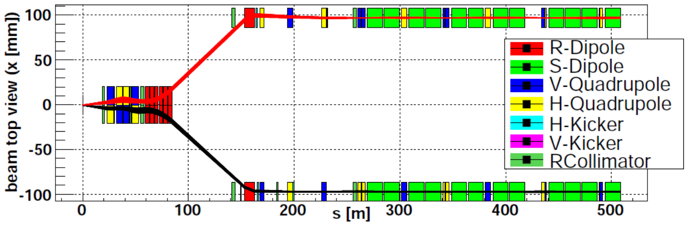

Figure 3: In the beam line top view, starting at the IP, the splitting of the beam (due to the magnetic field) is visible. The detectors will be placed at the high dispersion regions at 420 m and 220 m from the IP [1].

In order to use the missing mass method (eq. (2)), the displacement and the scattering angle of the protons are needed. Therefore, the detector has to be divided into several bins in order to get spatial resolution in horizontal direction. Fig. 4 shows such a geometry. The proton beam is shot into the plane. Spatial resolution in x-direction is possible. [1][3]

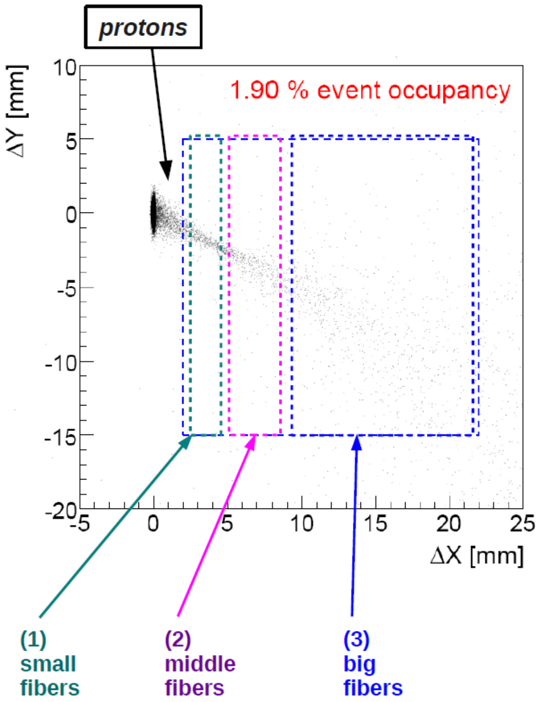

Figure 4: The proton beam is shot into the plane. By binning the detector in horizontal direction, spatial resolution in that direction is possible. Most protons hit the detector on the left side, only a few will disperse into the outer region. Therefore the binning becomes rougher towards the outer (right) side [5].

1.3 Prototypes

The detector prototype for AFP 420 m/220 m is a Cherenkov fiber detector. A fiber consists of three different parts: the core (here: quartz), the cladding (also quartz) and the coating which is made of some kind of plastic. Some fibers do not need coating, for quartz however, it is necessary lest they break. This fiber geometry is illustrated in fig. 5.

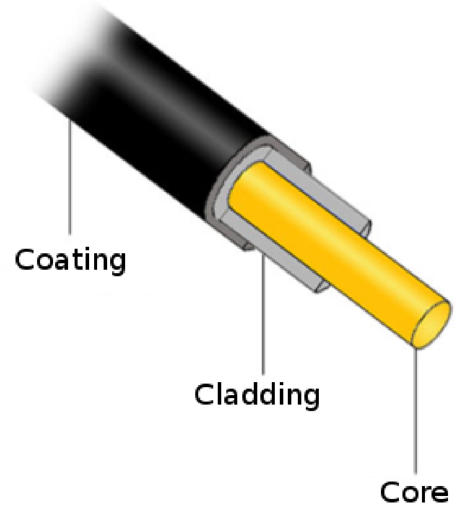

Figure 5: The geometry of a typical fiber. Coating is the outer part, the inner part is the core, the material between core and coating is called cladding, which is needed for reflexion [2].

If a proton hits a fiber, due to the Cherenkov effect, a light cone is emitted. The light inside the fiber is reflected back and forth along the way to the end of the fiber (fig. 6). The numerical aperture NA is given by

$$NA = \sqrt{n_1^2 - n_2^2} \tag{4}$$

where n_1 is the refractive index of the core material and n_2 the refractive index of the cladding material. NA indicates how much light can be contained within a fiber [9].
The light is reflected at the crossing of the core and cladding material. The Cherenkov angle of the produced light cone is given by

$$\cos(\varphi_C) = \frac{1}{n\beta}, \tag{5}$$

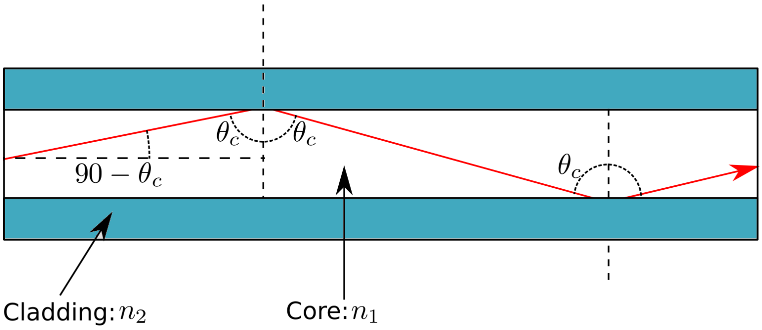

Figure 6: The light propagation within a fiber is shown. Due to the cladding the light is reflected at the interface of core and cladding [7].

where n is the refractive index of the material through which the charged particle propagates and β its velocity in units of c. β can be calculated from the particle's momentum, which is

$$p = m\gamma\beta c. \tag{6}$$

With

$$\gamma = \sqrt{\frac{1}{1-\beta^2}} \tag{7}$$

we obtain

$$\beta = 1/\sqrt{\left(\frac{mc}{p}\right)^2 + 1}. \tag{8}$$

With the value of the refractive index for quartz, $n_{\text{quartz}} = 1.4585$, we obtain

$$\varphi_C = \arccos\left\{\frac{\sqrt{\left(\frac{938\text{ MeV}}{p}\right)^2 + 1}}{1.4585}\right\} \tag{9}$$

for the opening angle.
For the LHC proton momentum of 7 TeV the opening angle is $\varphi_C = 46.71°$.
If the detector's fibers are aligned along this angle, a fraction of the produced light can directly pass through the fibers. The light can be detected by photo detectors without taking a longer path by being reflected throughout the whole distance within the fibers.

1.4 Prototype Layout

For each pixel (in terms of photon readout) a certain number of fibers is bundled and glued together at one end (see fig. 7).

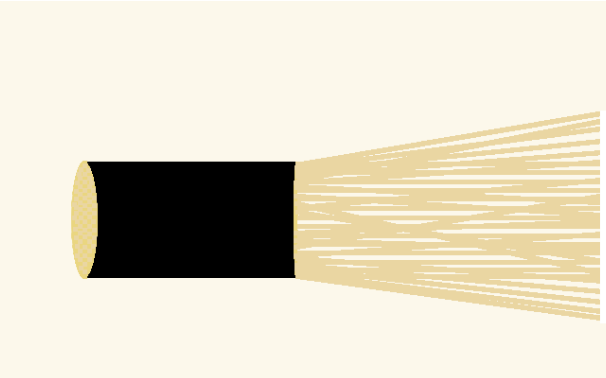

Figure 7: A fiber bundle contains a certain number of fibers of the same length. They are glued into a small tube ($l \approx 1$ cm). Depending on the desired prototype the loose end can be brought into a layer structure by glueing or pressing.

In order to get a binning like mentioned before, the fibers are glued or pressed to get a flat layer structure. Depending on the desired prototype, a certain amount of fiber layers can be glued for each bin or fiber bundles are pressed together for each bin. Due to a similar refractive index of glue and cladding the light might leave the fibers. For this reason only the more promising (pressed) prototype was built and tested for now. The glued prototype will be built and tested in the future.

1.4.1 Boxed Fibers

A detector with two bins was built. Each fiber bundle has a diameter of 3.5 mm and an angle of 45 °relative to the beam.

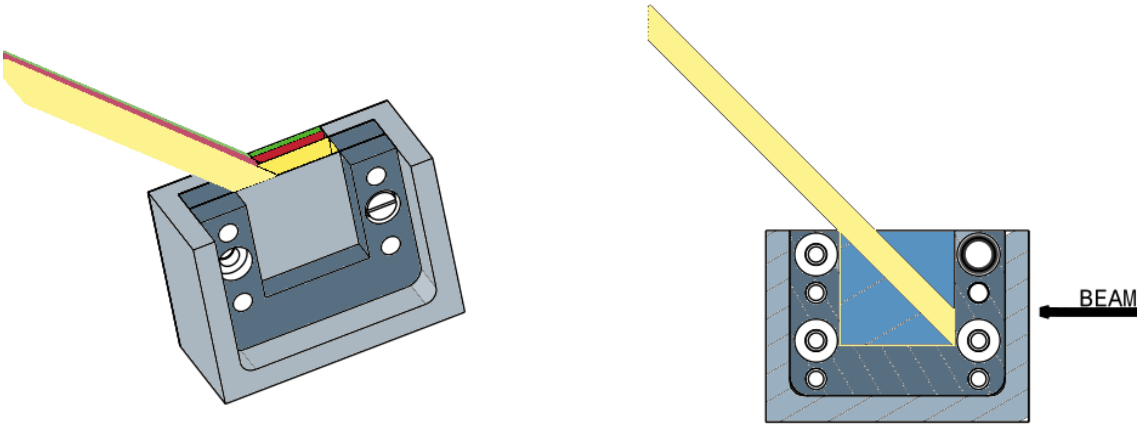

Figure 8: The boxed fiber prototype is shown from two perspectives, left: top view, right: cross section from the side. On the left hand side the different binnings of fibers are visible in different colors: green as the smallest binning (here: 0.5 mm wide), red: 1.5 mm and yellow: 3 mm. The side view picture on the right shows a side cross section. Two triangle shaped pieces keep the fiber bundles in position. The beam hits the fibers under an angle of 45° and propagates the bundle throughout a distance of 1 cm. All fiber bundles are 15 cm long, the width depends on the bin size.

Fig. 8 shows the principle setup of a boxed prototype. The arrow is the direction of the proton beam. This prototype was tested recently.

1.5 Test Beam Results

The test experiment was conducted in February 2010 at the Jülich research center. For a first test only one bundle of fibers was tested, in order to find out how the quartz fibers behave under proton beam radiation. Quartz fibers with a 400 µm core and 300 µm cladding and coating were used. The coating material is Tefzel® buffer and the fibers numerical aperture $NA = 0.37$. The proton beam momentum was 2.95 GeV.

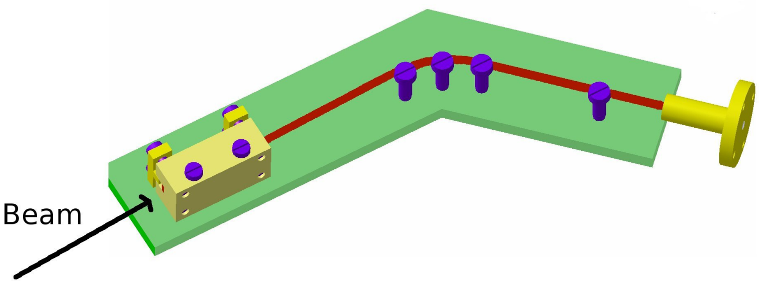

Figure 9: This fiber bundle is bent under 45°. Proton beam and fiber bundle are parallel to each other. The fibers are hit on the left end. On the right end an MCP PMT can be connected. Due to the curvature the MCP PMT is protected from being hit by the proton beam.

A sketch of the tested bundle is illustrated in fig. 9. The bundle is bent since it was tested with the beam parallel to the fibers. By bending the fibers the MCP PMT was protected from sitting in the direct beam line. The bundle was also tested under 45° relative to the beam.
The setup for all detectors, that took part at the test, is shown in fig. 10.

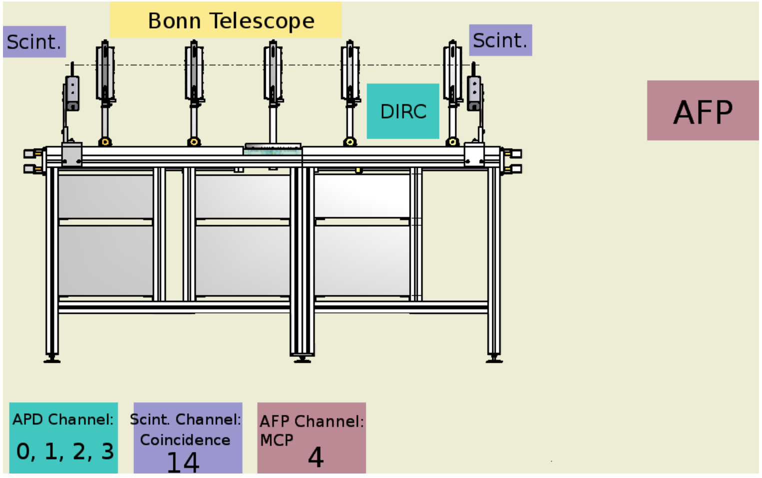

Figure 10: Setup at the Jülich test experiment in February. The beam line went from left to right. Two scintillator crosses (purple) served as triggers. In between both scintillators, two detectors from other experiments were placed. The fiber bundle was placed behind the second scintillator.

Two scintillator crosses (property of the university of Bonn) were used as triggers. In between the scintillators the Bonn Telescope and DIRC box (property of the JLU Gießen) were placed. The fiber bundle was placed behind the second scintillator cross. The APDs that were used from the PANDA group have a time resolution of about 130 ps, the MCP PMT used for the fibers has a time resolution of about 90 ps.
The results show that more photons were detected when the fibers were tilted 45° relative to the

beam (fig. 11). The width and rectangular shape is due to the DAQ clock frequency.

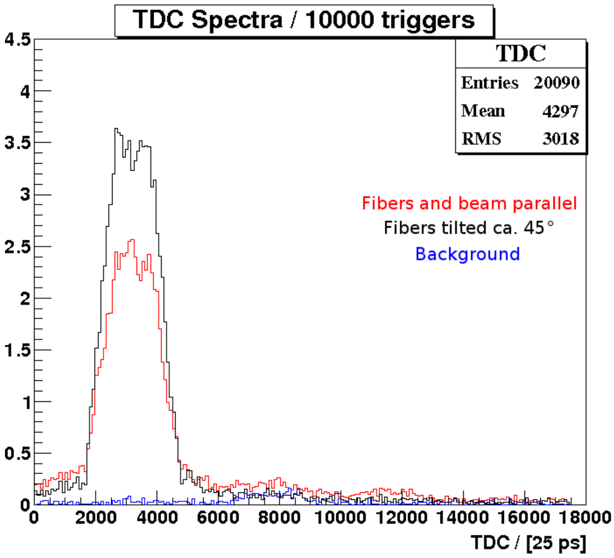

Figure 11: Fiber bundle parallel and under 45 ° to the beam

The coincidence between the scintillator trigger and the fiber bundle shows an insufficient time resolution of σ = 800 ps, which is probably due to the scintillators (fig. 12). This is affirmed by the time resolution between the APDs from the DIRC box and the fiber bundle. A σ of 380 ps is still unsatisfactory but it shows that the signal gets better with a different detector (fig. 13).

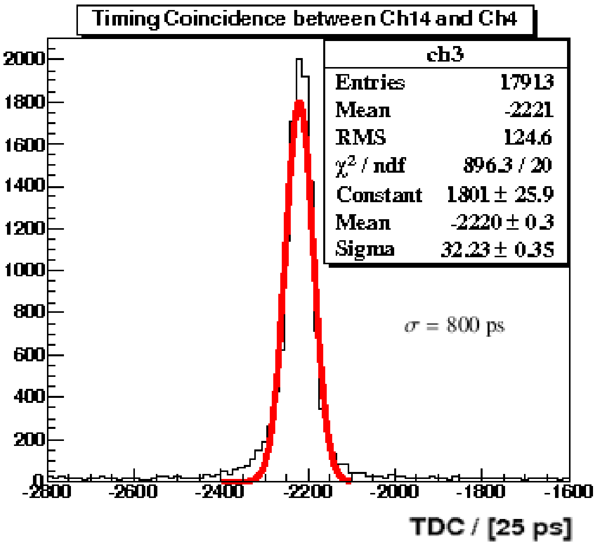

Figure 12: Coincidence between scintillators and fiber bundle

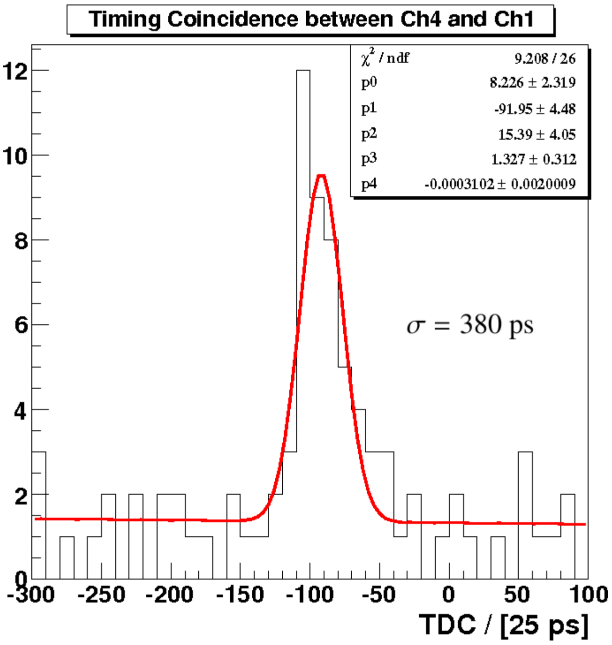

Figure 13: Coincidence between APDs and fiber bundle

Finally, a timing coincidence between two APDs shows that the time resolution was not as good as expected: σ = 400 ps (fig. 14). Earlier measurements showed that the APDs performance can do much better, but still another, even faster, timing detector is needed.

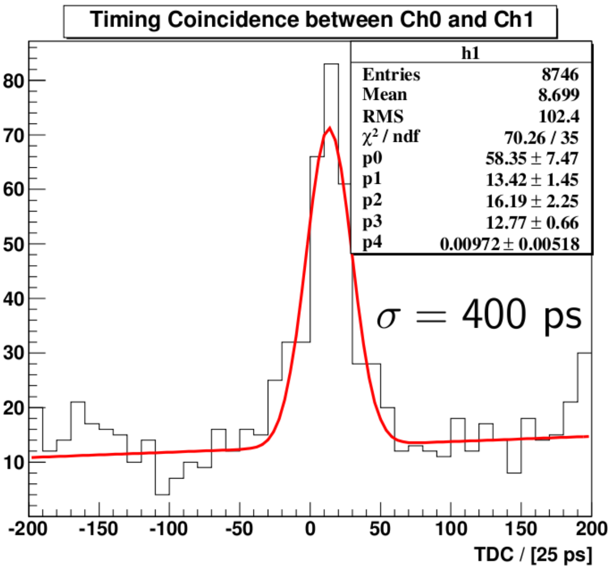

Figure 14: Coincidence with two APDs

2 Conclusion and Outlook

The test experiment in Jülich at the beginning of February 2010 showed that a detector made of quartz fibers works in principle. Due to the lack of a fast timing detector, the time resolution of the quartz detector could not be determined. For this reason a dedicated timing detector made of plastic glass connected to a MCP PMT was built. Preliminary results from the test experiment in Jülich in April 2010 show that the signal and timing improved considerably.

For the next test experiment, a prototype of the boxed type with desired dimensions for the ATLAS experiment is under construction. Also, a glued prototype is planned to be tested soon. The two prototypes will be compared. Information whether there is cross talk between the fibers must be obtained as well.

References

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