Scintillator Fiber Trackers for the ZDC and off-momentum detectors

C. Ayerbe Gayoso (PI)[1], F. Hauenstein[2], W.B. Li[3,4], R. Montgomery[5], and N. Santiesteban[6]

[1]William & Mary, Williamsburg, Virginia 23185, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[3]Stony Brook University, Stony Brook, New York 11794, USA
[4]Center for Frontiers in Nuclear Science, Stony Brook University, Stony Brook, NY 11794, USA
[5]University of Glasgow, Glasgow, G12 8QQ, Scotland
[6]University of New Hampshire, Durham, New Hampshire 0382, USA

14 July 2023

Abstract

During the past years, several EIC working groups had presented potential physics studies and the detectors needs to achieve the physics goals. In particular, in the Meson Structure Group was raised the necessity of a charged particles veto tracker in front of the Zero Degree Calorimenter. The idea of a scintillator fiber detector was presented, and it was suggested for its possible use as off-momentum detector in the far-forward region. We are proposing the construction of a prototype to be tested under beam conditions in order to validate the simulations for the final design. The technology was proven to have 300 μm special resolution with a timing resolution 300 ps, at a projected cost of \$500/cm^2.

1 Introduction

The Electron-Ion collider (EIC) is the new project in Nuclear Physics dedicated to explore different aspects of Quantum Chromodynamics (QCD) at levels not reached before. The EIC has been approved under Critical Decision 0 (CD-0) to be constructed in Brookhaven, NY. Several working groups (WGs) were formed to present the physics and detector case for the EIC project, which produced a Yellow Report. After the publication of the Yellow report, three consortiums were launched with the intention to present a more detailed project (physics and detector) case. The project has been recently approved under CD-1 for the ECCE consortium.

The use of several technologies, the need, and the design of several detectors were discussed in several WGs during the Yellow report and the consortium phases. In particular, the meson structure WG research for the EIC has shown the need of a tracker, in combination with the ZDC, to be used as a veto detector for π^- for an efficient measurement of the $\Lambda \to n + \pi^0$ channel [6]. Besides this main purpose, adding a tracker could improve the reconstruction of charged particles in the ZDC for other different channels. Furthermore, a concern was raised during ECCE discussion of what kind of detectors could be used as off-momentum detectors in the far forward region.

The use of scintillator fibers (SciFi) as detectors had been widely used since end of the 80's. They combine the efficiency and speed of a scintillator detector with the flexibility and hermiticity of fiber technology. Several experiments have made use of this technology, from nuclear physics, to medical imaging or Archaeology [5, 9–12], showing great performance with high spatial and timing resolution [1, 4, 7] with an affordable material and R&D cost. In particular, detectors based on scintillating fibers are used as fast tracking/position devices, and in combination with a magnetic field, capable to measure the particle momentum.

The use of scintillating fiber detectors as a tracking device for both cases, ZDC front tracker and off momentum detectors, was presented as a possible option in several EIC forums.

2 Scintillator fiber trackers

SciFi trackers combine the fast response of scintillator detectors with the flexibility and granularity that fibers can provide. A high efficiency fiber is made of a core of polystyrene-based scintillator surrounded by a cladding of PMMA, and some fibers by another cladding of fluorinated PMMA. A SciFi tracker can handle high rates and is highly tolerant to radiation[8][1], but in the other hand, the photon yield is quite low due to the small photon capture fraction, about 5% for the double cladding fibers[2]. Detection efficiency is increased adding extra fiber layers per detection channel.

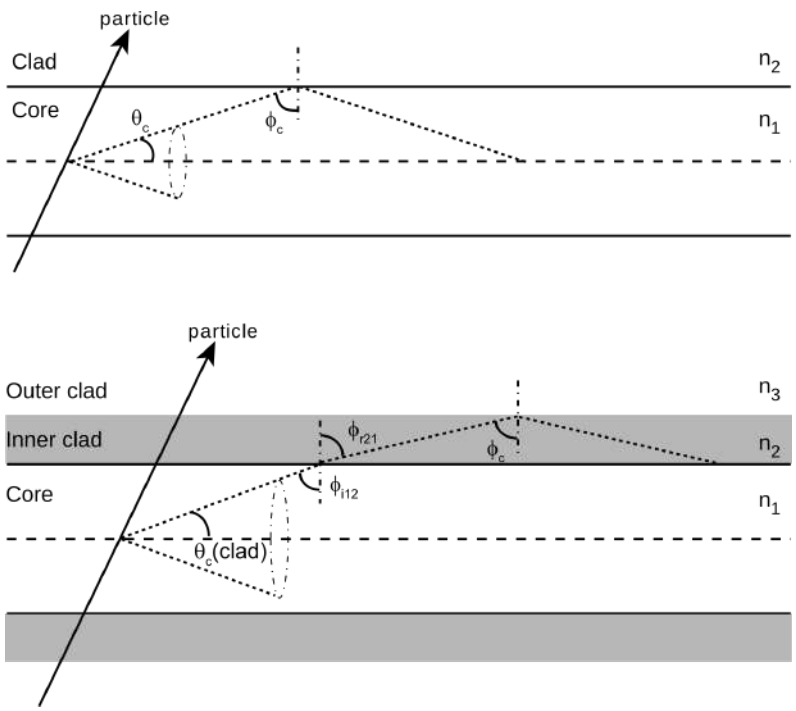

Figure 1: Single (Top) and multiclad light capture scheme. The potential light captured by the interface air-clad is not considered due to possible imperfections and larger path length.

SciFi arrangements allows flexible configurations depending on the needs. In SciFi planes two of the most mechanically stable configurations are shown in Fig.2. A circular configuration is also possible, as was done for HERMES[2] (Fig.3), showing the versatility of the SciFi.

[1]Naturally, this affirmation depends on the dose, and particles to detect, but in general, the organic fibers have good tolerance to radiation damage.

[2]one side output of the fiber

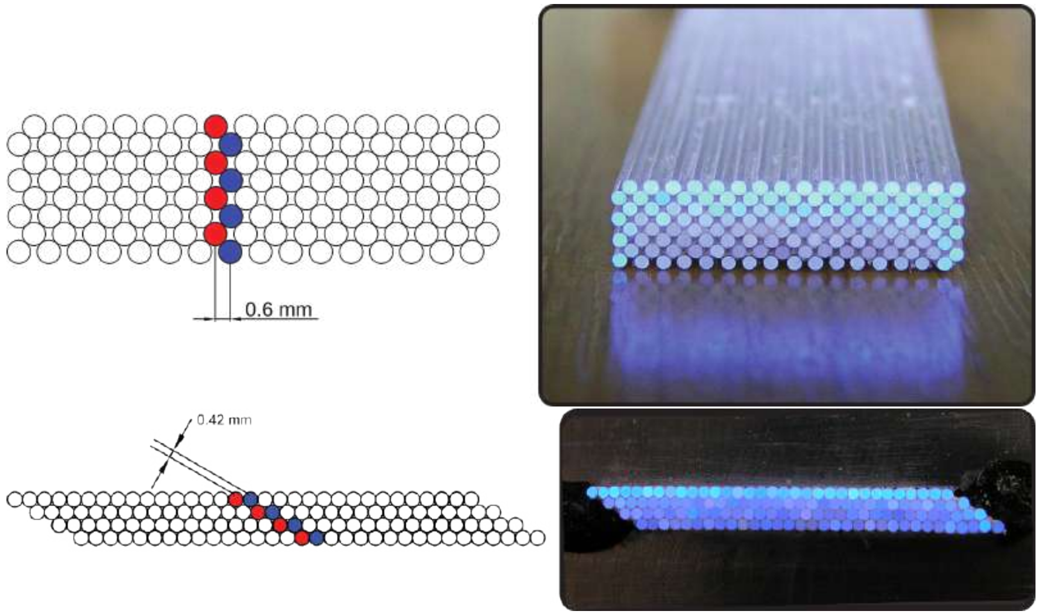

Figure 2: Top, scheme (left) and picture (right) of a 4 layer SciFi layout in a 0° arrangement, showing two read-out channels in red and blue. Bottom, a four layers SciFi 60° arrangement scheme (left) and picture (right) showing, similarly to the 0° case, two read-out channels. [3]

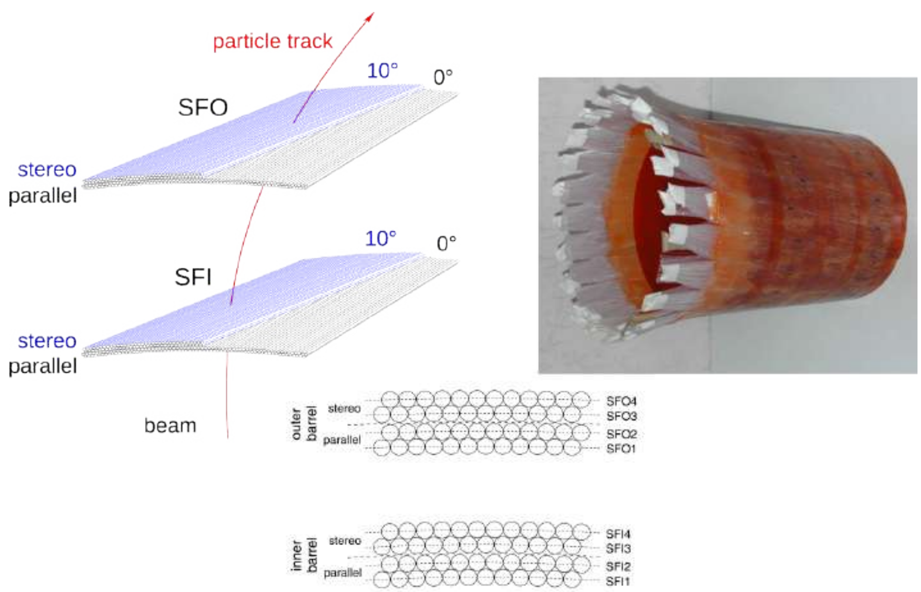

Figure 3: The HERMES recoil proton detector consisting in two planes, each of them also conformed by two layers, one parallel to the beamline and one rotated 10° [2].

3 Proposed ZDC SciFi trackers

A charged particle tracker before the ZDC should cover the acceptance of the ZDC in order to properly veto the charged particles for the $\Lambda \rightarrow n + \pi^0$ decay[3]. The ZDC cross-section has been proposed to

[3]For practical purposes, we will focus on this channel, regardless of the potential utility for other channels

be of $60 \times 60\,\text{cm}^2$. In order to identify or reconstruct a charged particle track, four modules in X-Y arrangement (two Xs, two Ys), or two in X-Y and two X-Y rotated 45° would be necessary. Ideally a third station would improve the determination of the trajectory, but for the channel under discussion, the reconstruction of the track is not critical since its purpose is to be a veto detector.

The simple tracker would be a $3-4$, 1 mm fibers/channel zero degree layout of 60 cm length + 10-15 cm extra length, in order to manipulate the signals from the active area to the photosensor, with a total width of ~60 cm. The fibers will be readout from one side, whereas the other side could be coated with a reflective paint in order to increase the light yield.

For a configuration with a station rotated 45°, it is necessary to have better acceptance studies, since the simple rotation of such a station will produce a non-overlapping area deficit of 17% with respect, if placed closer, to the ZDC face. Increasing the area of the station, to fully cover the ZDC front face, would be an impractical and less-efficient cost solution.

3.1 SciFi proposed description

In order to fix the number of channels to be read-out, it is necessary to determine certain parameters of the construction of the SciFi bundle. Fig. 3.1 shows the parameters to consider in the fiber arrangement. The pitch, p, is the distance center-to-center between two columns. The overlap between two columns is $o = \varnothing - p$. The theoretical spatial resolution, for events exclusively one column (no overlap region), is determined by $\sigma = (\varnothing - 2o)/\sqrt{12}$. For events in the overlap region, the resolution is $\sigma = o/\sqrt{12}$.

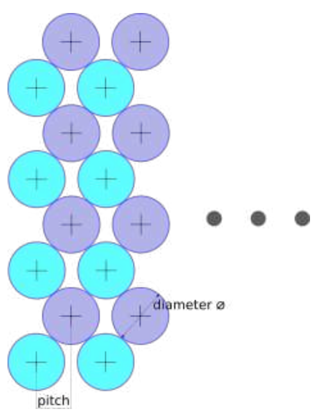

Figure 4: Scheme of two 4 fiber read-out columns.

The resolution, as a function of the pitch (overlap), is a combination of those two relations. The overlap range goes from $p = \varnothing/2$ with complete overlap between columns up to $p = \varnothing$ with not overlap. Fig. 5 shows both resolutions as a function of the pitch with $\varnothing = 1$. From the plot it is evident that between a pitch of 0.6 and 0.7 mm the resolution for both events are quite similar, serving as starting point for the configuration of the tracker.

The width of the SciFi bundle as a function of the diameter, pitch and number of channels is determined by

$$L = \varnothing + p \times (ch - 1) \tag{1}$$

This relationship allow us to relate the dimensions of our detector with the necessary number of channels to use.

The scintillating fibers to consider are the Kuraray SCSF78M of 1 mm diameter. The characteristics of this fiber are summarized in the table. The diameter of 1 mm is preferred to the 0.5 mm for being easy to handle and assemble.

	Color	Peak [nm]	Decay Time [ns]	Att.Leng. [ns]
SCSF-78M	blue	450	2.8	>4.0

Table 1: Kuraray SCSF-78 Multiclad scintillating fiber characteristics

As was mentioned, the SciFi layout is more stable mechanically, with certain overlap between columns. A pitch of 60-70% of the diameter is a compromise between stability and spatial resolution. In the ZDC case, the width of single plane is of 600 mm. Making use of the equation 1 we can get a first estimation of the number of channels needed (table 2. The number estimated is based in the exact size of the ZDC. In practice, two more conditions should be considered in order to design a more cost-efficient detector. A more detailed study of the acceptance of wrt to the face of the ZDC upstream, which could reduce the size of the trackers, and a number of channels multiple of the read-out channels of the opto-devices.

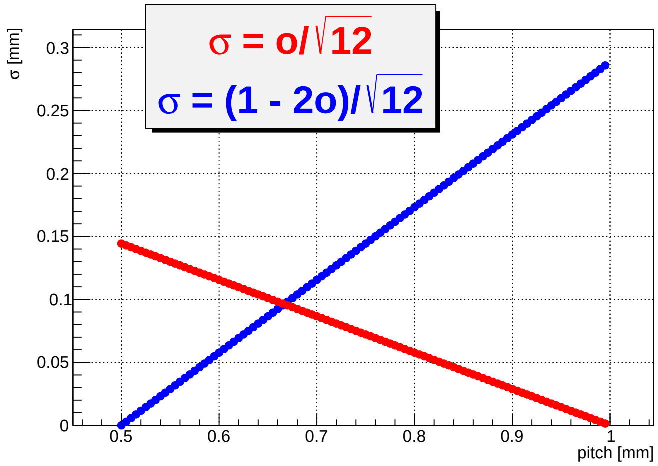

Figure 5: The theoretical spatial resolution as a function of the pitch between columns. A compromise of the spatial resolution between the two kind of events, is with a pitch between 0.6 and 0.7 mm

Pitch [mm]	Channels	Adjusted channels	Adjusted width [mm]
0.6	999.33	1000	600.4
0.7	856.71	857	600.2

Table 2: Estimated number of channels based on two different pitches. The number of channels is the exact number based on the eq. 1, adjusted channels are the round number up of the channels calculated and Adjusted width is the new width of the tracker based in the adjusted number of channesls.

3.2 Read-out devices

Several devices are suitable for the SciFi tracker, multianode photomultipliers, avalanche photodiodes, silicon photomultipliers. The characteristics of the ZDC tracker, requires a fast device to act a veto detector. Given that the ZDC is part of the called far-forward region, the presence of magnetic fields allows the use of photomultipliers. Also, the density of channels requires the use of multichannel photomultipliers (mPMTs).

The market offers linear or square read-out configuration of the mPMTs, and some of them very compact arrangement (e.g. Hamamatsu H7260 consists in 32 pixels comprise in 32 pads of 0.8 mm). But those mPMT would need a wave length shifter or similar optical fiber to collect the light from 3-4 1,/mm fibers to ≈ 1,/mm pixel. The new H12700/H14220 series from Hamamatsu offers a larger pixel size with a very compact case. The square configuration allows an easily mapping of the channels in non-consecutive way, which allows a significant reduction of the crosstalk [2]. Figure 6 shows a picture and description of the H12700/H14220.

4 Proposed R&D

4.1 Overall plan

The plan to study the capacity of the SciFi tracker is to build two planes of 64 channels each and test them under cosmic, radiative sources and real beam. In parallel, we want to develop a realistic simulation with GEANT4 which allows to understand the prototype in order to move forward with a design of a larger tracker.

The prototype will be a smaller version of a longer tracker, as was described previously, so each one of the planes should have the same length as the corresponding width of 64 channels. According to Eq.1

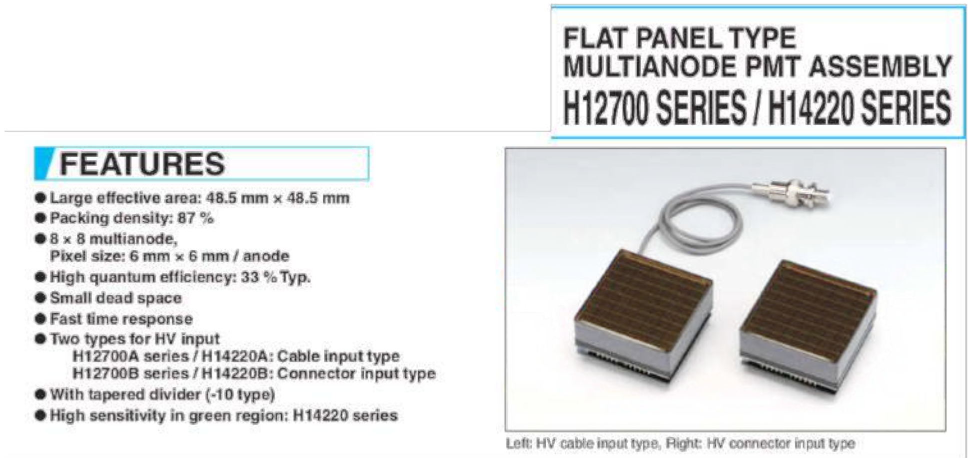

Figure 6: Data sheet of the H12700/H14220 mPMT

and a pitch of 0.6 mm, the length and width should be of 318 mm[4]. Fig. 8 and Fig. 9 show a conceptual design. The mold/jig for gluing of the fibers in the desired pattern will be manufactured in the Stony Brook Machine shop. Once the fibers are stacked in layers, the will be glued together with optics cement. The fiber polishing will also take place in Stony Brook CFNS.

In order to increase the light yield, the side of the fibers without instrumentation will be evaporated with aluminum. The evaporation will be completed by the evaporator at CFNS Stony Brook University (as in kind contribution), see Fig. 7.

Figure 7: Evaporator setup at CFNS, Stony Brook University.

The R&D plan will include the tools to assembly the fiber bundle, the interface fiber-mPMT, and mechanic infrastructure of the fiber bundle. Two sets of readout boards from the GlueX DIRC project will be loaned to support this R&D proposal.

The commission and characterization of the proposed detector prototype will utilize the well know beam test configuration in Jefferson Lab Hall D behind the pair spectrometer magnets. This arrangement also allows the proposer to use the existing DAQ system which consists of an ASIC and SSP crate. The length of the beam test is assumed to be at least three weeks.

[4]In comparison, the bundles built for the Mainz hodoscope, had a width of 19.5 mm

4.2 Deliverables FY 2024

4.2.1 Q1

This quarter mainly focus to obtain required material for the test prototypes and start development of assembly stands and read-out.

- Buy fibers and support material
- Purchase of mPMT H12700
- Development of fiber assembly and mPMT interface
- Production of mold/jig for gluing at machine shop
- Development of GEANT4 simulation of test prototype

4.2.2 Q2

This quarter focusses on the production of test detector at Stony Brook.

- Fiber evaporation with aluminium at CFNS
- Fiber glueing and polishing
- Transport of detector to Jefferson Lab
- Assembly of detector and PMTs
- Completion of simulation work

4.2.3 Q3

This quarter mainly focus on tests of the detector.

- Test of detector in dark box with cosmics and raadiative sources
- Assembly of detector at HallD test stand
- Take data with beam (if available)

4.2.4 Q4

- Beam tests at Jefferson Lab Hall D
- Analysis of data to determine proporties of detector
- Compare of test results with simulations

5 Prototype Budget

The budget sheet is presented in Table 3. The budget does not include the HV and DAQ necessary to proper make use of the trackers. These will be requested to be a loan of the labs where the tests will be done. The read-out/power board and DAQ system will be loaned from the GlueX DIRC project in Hall D.

5.1 Impact of Reduced Funding Scenarios

If the project is funded at 80%, we will reduce the number of personal during the beam test, which will result in installation delay. If the project is funded at 60%, we will reduce the detector prototype with segmentation to one dimension (only segmented vertically).

Item	Quantity	Cost/unit [$]	Total [$]
Hamamatsu mPMT H12700/H14220	3	5000	15,000
Scintillating Fibers Kuraray SCSF78M	$1 \times 300\,\mathrm{m}$	NA	2,000
Read-out/power board	2		
Optic fiber/WLS	2		500
Frame support material (3D printing and Metal)	NA	NA	4,000
SBU Machineshop Cost	60 hours	50/hour	3,000
Expendables (epoxy and coating paint)	NA	NA	1,000
Aluminum Evaporation	NA	NA	
Pulsed LED System			3,000
Transportation costs of detector			1,000
Travel budget			10,000
Total budget	NA	NA	39,500

Table 3: Two SciFi prototypes budget. These costs are projected are based from recent R&D experience, scaled to the accumulated inflation. Note that the read-out/power board and DAQ system will be loaned from the GlueX DIRC project in Hall D. Travel budget assumes two members (in additional to P.I.) will station at JLab for two weeks during the installation and beam test (airfare + lodging).

6 Experience from the proponents. Diversity, Equity, and Inclusion.

C. Ayerbe brings over a decade of extensive postdoctoral experience specializing in various types of detectors. His expertise spans the entire lifecycle of SciFi technology, from the initial design stages to mechanical and electronic development, all the way through to commissioning. He proficiently utilizes CAD software to design assembly tools and multiple detector components, ensuring efficient and precise construction.

F. Hauenstein, a dedicated member of JLab at Hall B, possesses a wealth of knowledge in DAQ analysis, simulations, and spectrometer operations. With a track record of successfully proposing multiple experiments, he has taken charge of their commissioning processes. Additionally, he has demonstrated exceptional mentorship skills by supervising several graduate students on diverse projects at JLab.

W. Li is a postdoctoral associate at Stony Brook University. He has experience in mirror evaporation and detector R&D. Experience with GlueX Hall D DIRC DAQ system.

R. Montgomery holds the position of Research Fellow (tenure track) at the University of Glasgow and has significantly contributed to the JLab and EIC (Electron-Ion Collider) initiatives. Her impressive portfolio boasts numerous successful projects, often assuming the role of spokesperson. She possesses extensive expertise in DAQ systems, mPMTs, and SciFi utilization. Furthermore, she is an authority in simulation and digitization of complex systems. Notably, her research group has actively participated in the development of the HERMES recoil and Lynkeos company[5].

N. Santiesteban serves as an Assistant Professor at the University of New Hampshire, showcasing exceptional skills in managing complex experiments at JLab. She is a recognized specialist in polarized cryo-targets and excels in the development of experiment simulations and data analysis.

The proponents of this proposal recognize the importance of a diverse, inclusive environment that offers equitable opportunities for everyone. All participating institutes operate extensive DEI programs to further the goal of a diversified academic workplace. The proposed research will advance diversity, equity, and inclusion initiatives of the proposing institutions. Several of the lead-proponents of the proposed R&D are female early-career scientists. They are role models with a track record of attracting and engaging female students in nuclear physics and instrumentation, thereby increasing female representation and narrowing the gender-gap in instrumentation-related experiences in a differentiating development stage.

[5] `https://www.lynkeos.co.uk/`

7 Final remarks and conclusions

This proposal present a modest request to start the R&D of a detector system to be used as ancillary system for the ZDC (it was not included as part of the EIC main detectors), and potentially a detector to be use as off-momentum detectors in the far-forward region. This concept involves a fast detector ($\approx$ 510 ps, high granularity ($\approx 300\mu$m with a relatively low cost ($\approx$ 100$ per channel [6]), simple construction and low maintenance. The prototype designed will establish a path work through simulations validated with the cosmic and in beam tests to a formal proposal of a full detector.

8 Appendix.

8.1 Blueprints examples from Mainz experience

[6] not included DAQ system

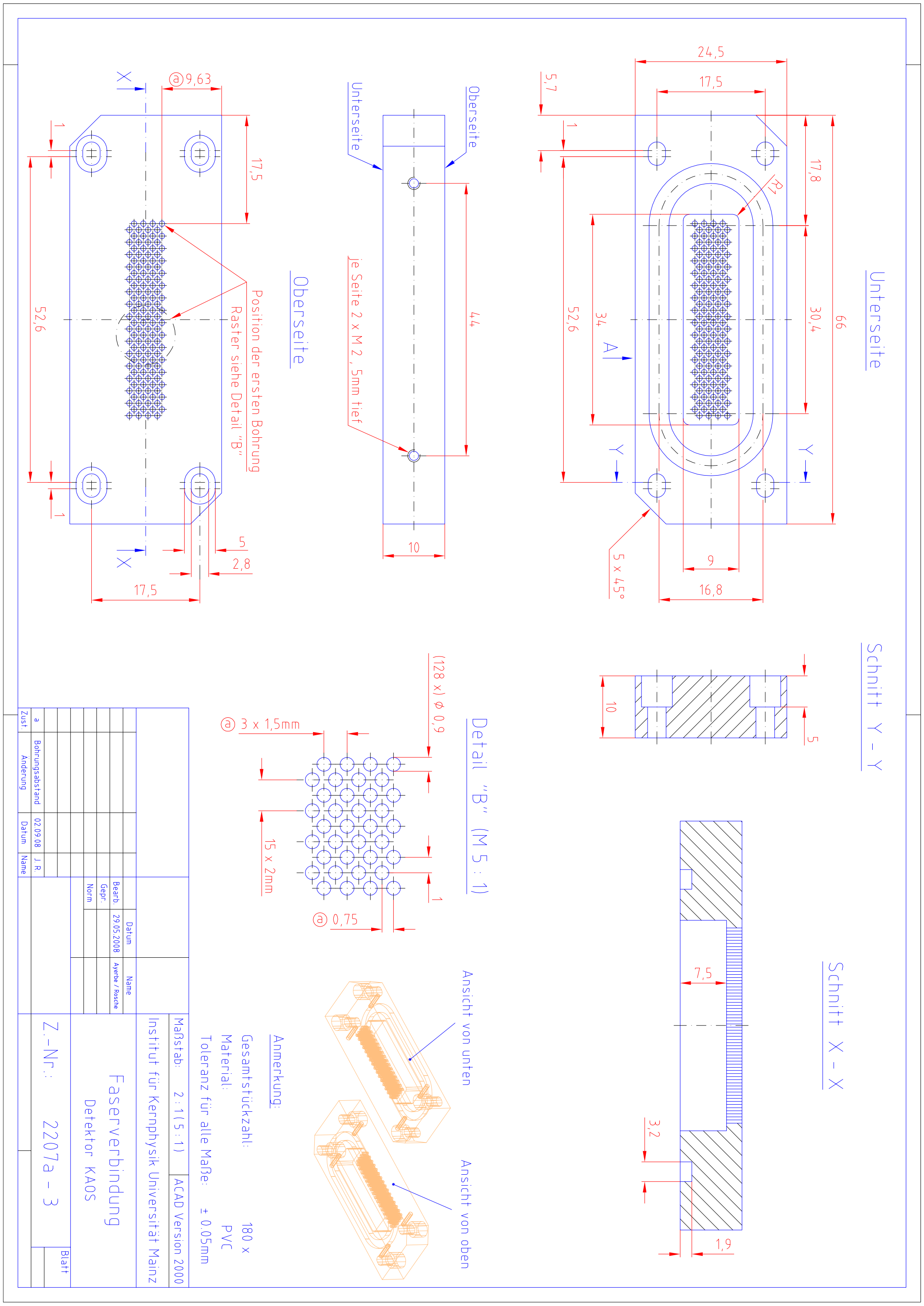

Figure 8: Technical CAD drawing of the 32 linear interface SciFi bundle-PMT

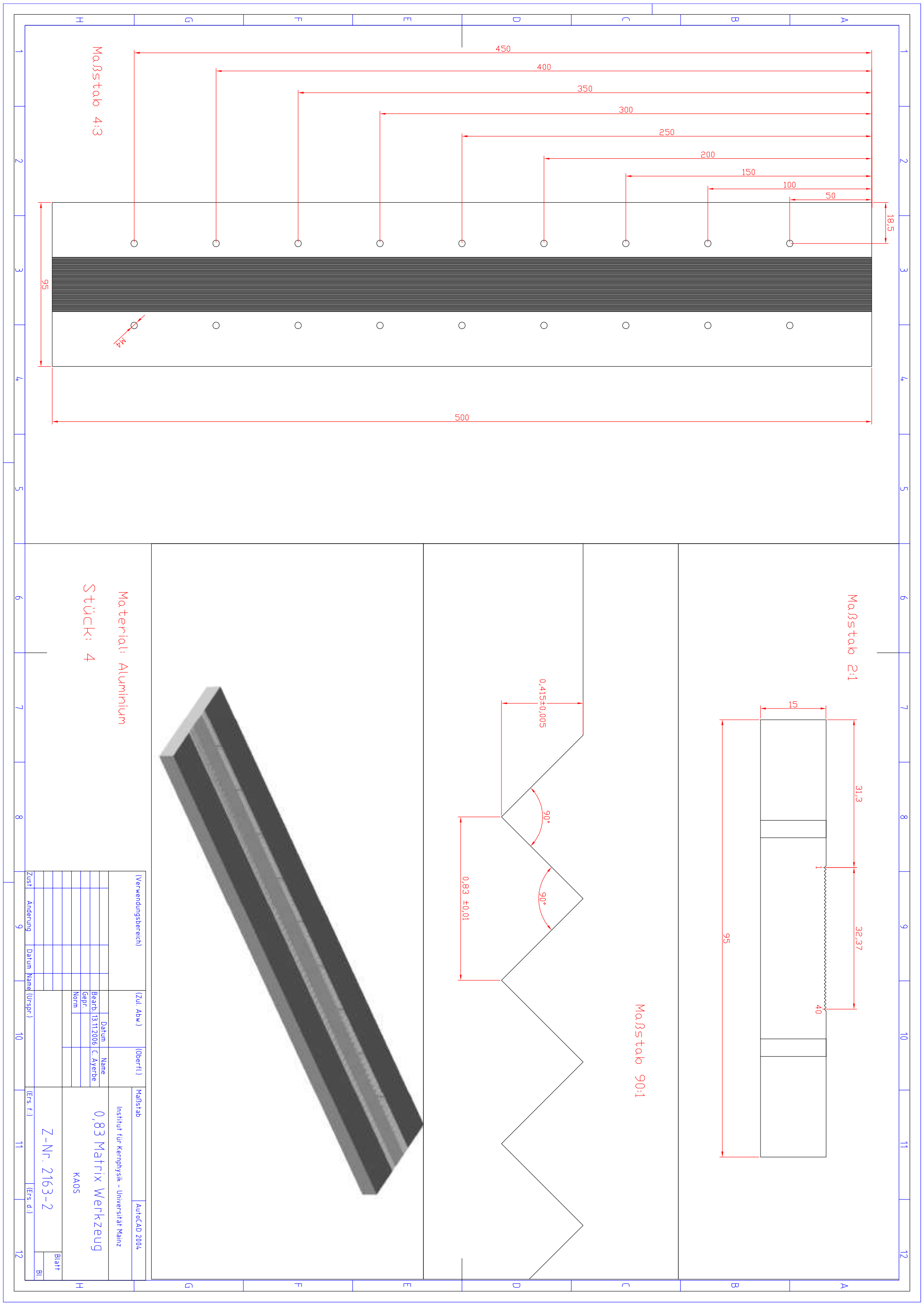

Figure 9: Technical CAD drawing of the assembly jig for the assembly of 32 channels bundle.

8.2 Picture examples of the Mainz experience

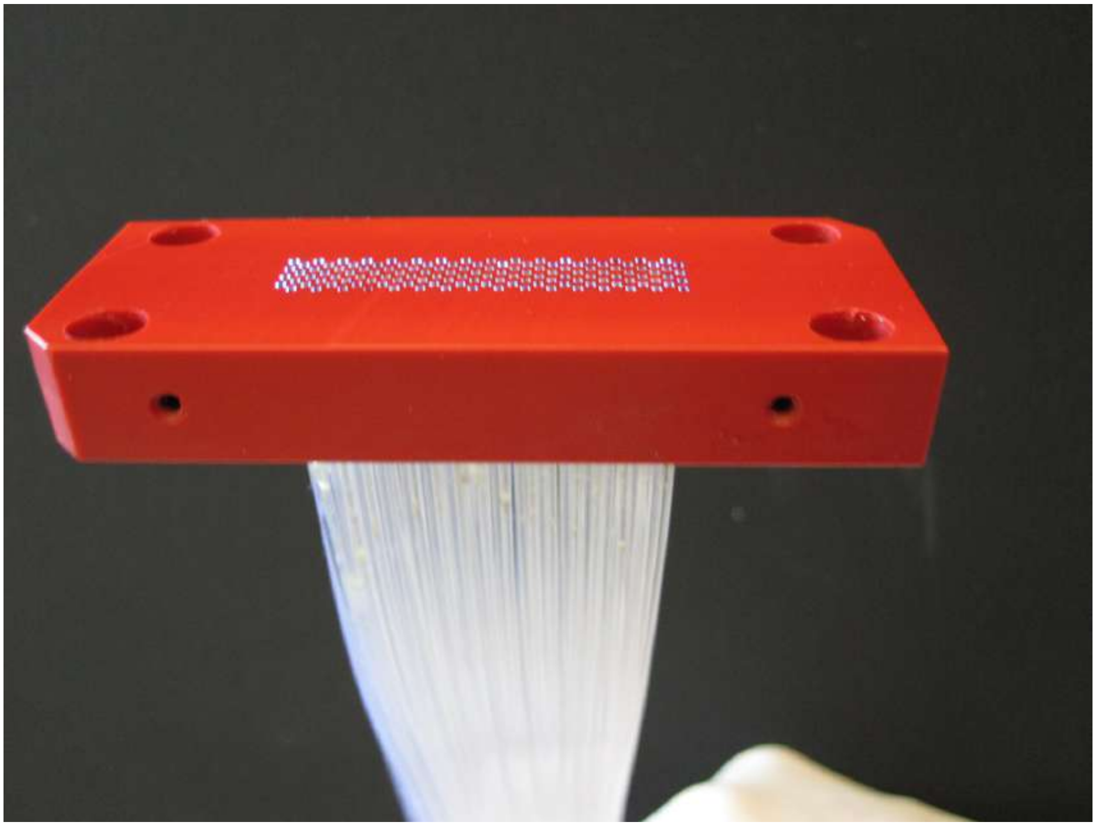

Figure 10: Detail of polished bundle side to the mPMT.

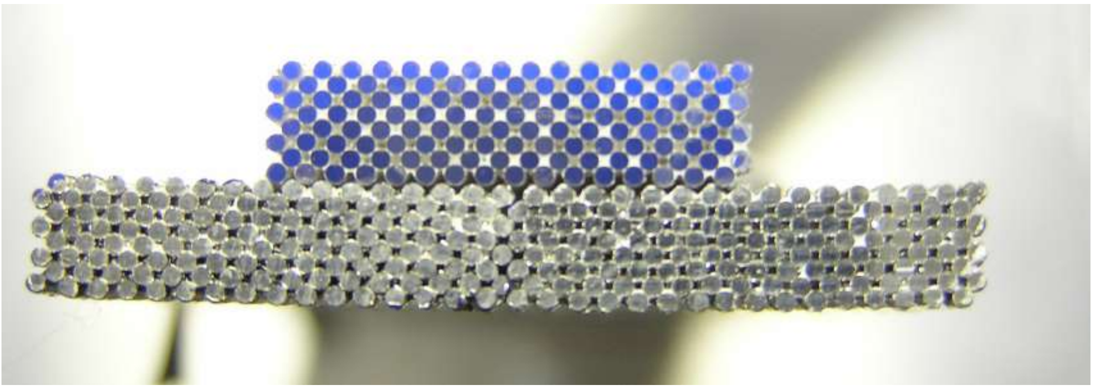

Figure 11: Detail of two 32 linear bundles coated with vaporized aluminum (bottom compared with one bundle not coated (top)

References

[1] P. Achenbach et al. In-beam tests of scintillating fibre detectors at MAMI and at GSI. *Nucl. Instrum. Meth. A*, 593:353–360, 2008.

[2] A Airapetian, E C Aschenauer, et al. The hermes recoil detector. *Journal of Instrumentation*, 8(05):P05012, may 2013.

[3] Carlos Antonio Ayerbe Gayoso. *The scintillating fiber focal plane detector for the use of Kaos as a double arm spectrometer.* PhD thesis, Mainz U., Inst. Kernphys., 2012.

[4] A. Bravar et al. The Mu3e scintillating fiber timing detector. *Nucl. Instrum. Meth. A*, 958:162564, 2020.

[5] M. Ferro-Luzzi, A. Gorin, M. Kobayashi, V. Korolev, A. Kuznetsov, T. Maki, I. Manuilov, K.-I. Kuroda, A. Penzo, A. Riazantsev, A. Sidorov, F. Takeutchi, K. Okada, and Y. Yoshimura. Scintillation fiber hodoscope for topological triggering. *AIP Conference Proceedings*, 450(1):278–285, 1998.

[6] Y. Furletova. First look on Lambdas in FF region. General Meson Working Group Meeting. May 11, 2020.

[7] A. Gorin et al. Scintillating fiber hodoscopes for DIRAC and COMPASS experiments. *Czech. J. Phys.*, 49S2:173–182, 1999.

[8] Yu.N. Kharzheev. Radiation Hardness of Scintillation Detectors Based on Organic Plastic Scintillators and Optical Fibers. *Phys. Part. Nucl.*, 50(1):42–76, 2019.

[9] Thomas Kirn. SciFi – A large scintillating fibre tracker for LHCb. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 845:481–485, 2017. Proceedings of the Vienna Conference on Instrumentation 2016.

[10] M. Menichelli, S. Ansoldi, M. Bari, M. Basset, R. Battiston, S. Blasko, F. Coren, E. Fiori, G. Giannini, D. Iugovaz, A. Papi, S. Reia, and G. Scian. A scintillating fibres tracker detector for archaeological applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 572(1):262–265, 2007. Frontier Detectors for Frontier Physics.

[11] M.J. Murray. The HERMES recoil detector. In *IEEE Nuclear Science Symposium Conference Record, 2005*, volume 2, pages 823–826, 2005.

[12] Vincent Turgeon, Gustavo Kertzscher, Liam Carroll, Robert Hopewell, Gassan Massarweh, and Shirin A. Enger. Characterization of scintillating fibers for use as positron detector in positron emission tomography. *Physica Medica*, 65:114–120, 2019.