PROCEEDINGS OF SCIENCE

Design and Testing of a new Tracking System for the Proton Charge-Radius Measurement with the AMBER Experiment at CERN

M. G. Alexeev,[d,e,*] **C. Alice,**[d,e] **A. Amoroso,**[d,e] **M. Bajzek,**[i] **M. Chiosso,**[d,e]
O. Denisov,[e,g] **C. Dreisbach,**[c] **K. Eichhorn,**[c] **H. Fischer,**[a] **J. M. Friedrich,**[c,f]
C. Garcia Argos,[a] **D. Giordano,**[d,e] **M. Hoffmann,**[k] **A. Jedele,**[i] **O. A. Kiselev,**[i]
P. Klenze,[c] **I. Konorov,**[c] **B. Löher,**[i] **M. J. Losekamm,**[c,f] **D. Panzieri,**[p,e] **S. Paul,**[c,f]
C. Pires,[j] **T. Pöschl,**[g] **J. L. Rodríguez-Sánchez,**[m,n] **L. Rose,**[i,o] **C.J. Schmidt,**[i]
B. Seitz,[b] **S. Sosio,**[d,e] **F. Thomson,**[b] **H. Tornqvist,**[l] **B. M. Veit**[h] **and R. Visinka**[i]
[a] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, 79104 Freiburg, Germany*
[b] *SUPA School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, U. K.*
[c] *School of Natural Sciences, Technical University of Munich, 85748 Garching, Germany*
[d] *Deparment of Physics, University of Torino, 10125 Torino, Italy*
[e] *Torino Section of INFN, 10125 Torino, Italy*
[f] *Excellence Cluster ORIGINS, 85748 Garching, Germany*
[g] *CERN, 1211 Geneva 23, Switzerland*
[h] *Universität Mainz, Institut für Kernphysik, 55099 Mainz, Germany*
[i] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[j] *LIP, 1000-149 Lisbon, Portugal*
[k] *Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany*
[l] *Department of Physics, Chalmers University of Technology, 41296 Göteborg, Sweden*
[m] *CITENI, Campus Industrial de Ferrol, Universidade da Coruña, E-15403 Ferrol, Spain*
[n] *IGFAE, Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, Spain*
[o] *University of York, School of Physics, Engineering and Technology, York, U. K.*
[p] *University of Eastern Piedmont, 15100 Alessandria, Italy*

E-mail: maxim.alekseev@to.infn.it

The concept of the unified tracking station designed for the proton charge-radius measurement planned at the AMBER (NA66) fixed-target experiment at CERN is presented. Composed of scintillating-fiber hodoscopes and silicon-pixel detectors, it aims to provide 30 µrad angular resolution for the measurement of muons at momenta of 100 GeV with a time resolution of 1 ns at a nominal beam rate of 2×10^6 particles per second. Design choices and construction highlights, together with preliminary test results, are presented.

The 32nd International Workshop on Vertex Detectors (VERTEX2023)
16-20 October 2023
Sestri Levante, Genova, Italy

PoS(VERTEX2023)049

---

[*] Speaker

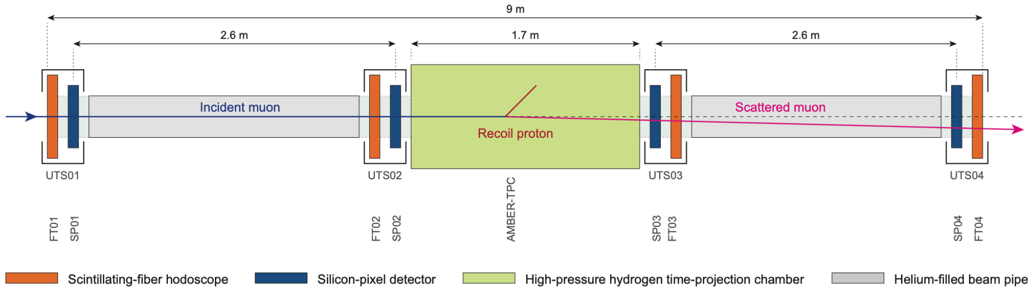


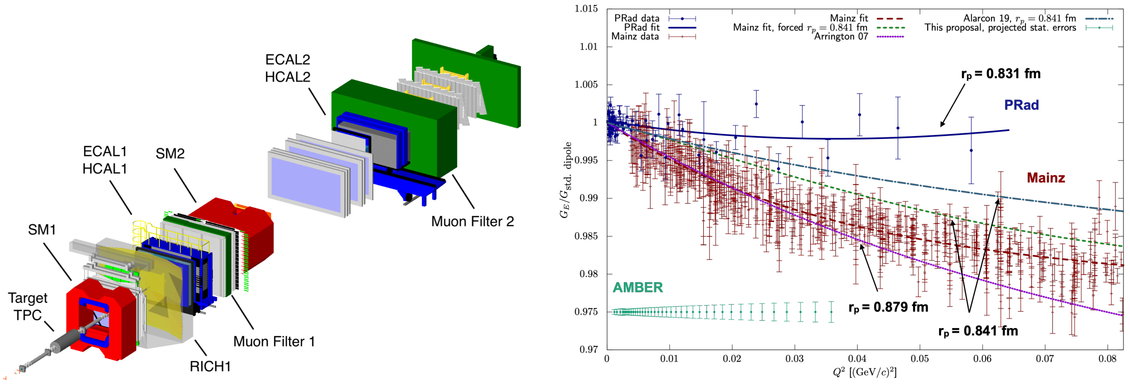
Figure 1: Sketch of the core setup. The active-hydrogen TPC is located in the center with UTS stations equipped with SFH and SPD are located along the 3 m long lever arms. Helium beam pipes are used to further reduce the effect of multiple scattering. [1]

1. Introduction

The Apparatus for Mesons and Baryon Experimental Research (AMBER, NA66) [1] is a high-energy physics project at CERN's M2 beam line at the Super Proton Synchotron (SPS) as successor of the COMPASS experiment [2]. The broad physics program for the upcoming years includes the measurement of the charge-radius of the proton (PRM) using high-energy elastic muon-proton scattering. This novel approach utilizes an active-target high-pressure hydrogen Time Projection Chamber (TPC) to determine the energy of the target recoil proton. In addition, the trajectory of the scattered muon is determined by the high-precision Unified Tracking Station (UTS) surrounding the TPC. This combined measurement approach allows a new view on the systematics compared to the previous measurements using electron scattering. Muon momentum reconstruction as well as muon identification and calorimetry will be provided by the AMBER spectrometer. Here, several detector systems will undergo upgrades in the future and newly designed detectors will be added to cope with the new requirements and match the novel triggerless DAQ system.

2. Requirements on the UTS for the PRM Measurement

AMBER aims to conduct the measurement of the proton charge-radius in 2025. The measurement utilizes a high-energy 100 GeV muon beam to measure the elastic muon-proton scattering cross-section in an active-target TPC filled with hydrogen at pressures up to 20 bar. A total of four UTS, each equipped with three Silicon-Pixel Detector (SPD) planes and two Scintillating-Fiber Hodoscope (SFH) planes are placed up and downstream of the TPC to measure the incoming and outgoing muon trajectory to determine its scattering angle. A sketch of the proposed core setup is shown in Fig. 1. The AMBER spectrometer provides muon momentum measurement as well as muon identification and calorimetry and is used with the described core setup located in the target region, as shown in Fig. 2a. For the SPD, ALPIDE monolithic sensors [3] provide the required spatial resolution. In the fixed-target operation, the time resolution of the sensors results in pile-up hits at the foreseen beam rate of 2×10^6 particles per second. To disentangle those, each SPD is paired within each UTS station with an SFH. First studies evaluated the efficiency of pile-up reduction, as shown in Fig. 3a. Depending on the distance, a hit-time association efficiency better than



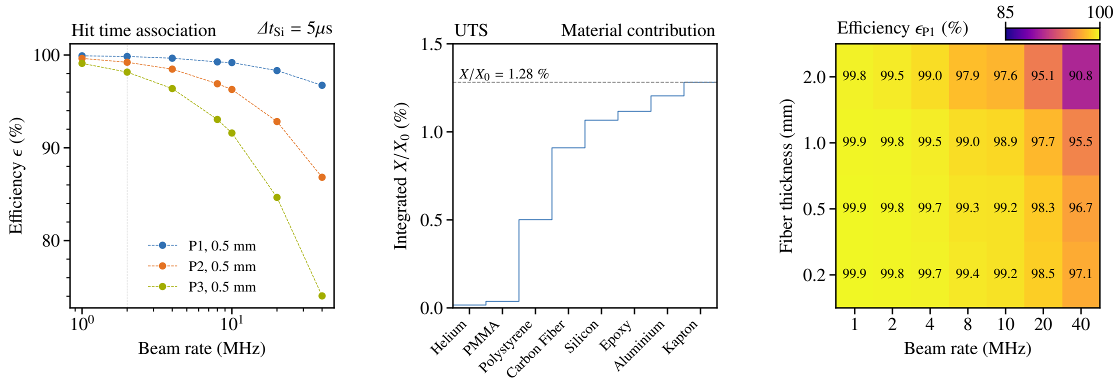
(a) **(b)**

Figure 2: In (a) [4] a sketch of the spectrometer layout for the PRM program is shown, the UTS are located in the target region. The normalized electric from factor is shown in (b) [5] measured by PRad [6] and MAMI [7]. Indicated in green are the expected statistical uncertainties of the proposed measurement.

99.9% at the foreseen beam rate can be archived at a sufficiently small distance between the SPD and SFH. This led to the combined design shown in Fig. 4a. Studies on the leaver arm length led to ~ 3 m distance between the UTS stations to obtain the 30 µrad angular resolution. The required angular resolution is mainly dominated by multiple scattering, therefore, the material budget of the tracking system was optimized to about 1.3% radiation length per UTS with a contribution of about 0.23% per SPD plane and about 0.6% from the SFH, as shown in Fig. 3b. To further reduce the crucial effect of multiple scattering, helium beam pipes are used along the lever arms with directly connected UTS. The total material budget of the core setup is about 4% X/X_0. The proposed method relies on the unique combined determination of the squared four-momentum transfer Q^2 by measuring the energy deposition of the recoil protons in the TPC and the precise measurement of the muon scattering angle. The measurement goal is to extract the electric charge-radius of the proton with a precision of around 1% to contribute to a solution of the so-called *Proton Radius Puzzle*. For this, we aim to access a Q^2-range of $10^{-3} \leq Q^2/(\text{GeV}^2/c^2) \leq 0.04$ as shown in Fig. 2b. This will allow a comparison with previous experiments, i.e., PRad and MAMI. This Q^2-range translates into a muon scattering angle of 316 µrad up to 2 mrad. To achieve the required precision, a muon scattering angle resolution of 30 µrad is the design goal for the UTS. In addition, the vertex position of the scattered muon and especially the recoil proton vertex in the TPC are crucial for the reconstruction in the TPC itself. To cope with the large difference in time resolution between the TPC and tracking system, a novel trigger-less DAQ system is required. First major test in a close-to-final setup configuration is planned during the second half of 2024 at CERN in preparation for the data taking during 2025.

2.1 Scintillating Fiber Hodoscopes

Each SFH (see Fig. 4c) comprises two orthogonally oriented fibers planes, each consisting of two layers of 192 fibers, shifted by 3.5 fiber widths with respect to each other providing an active



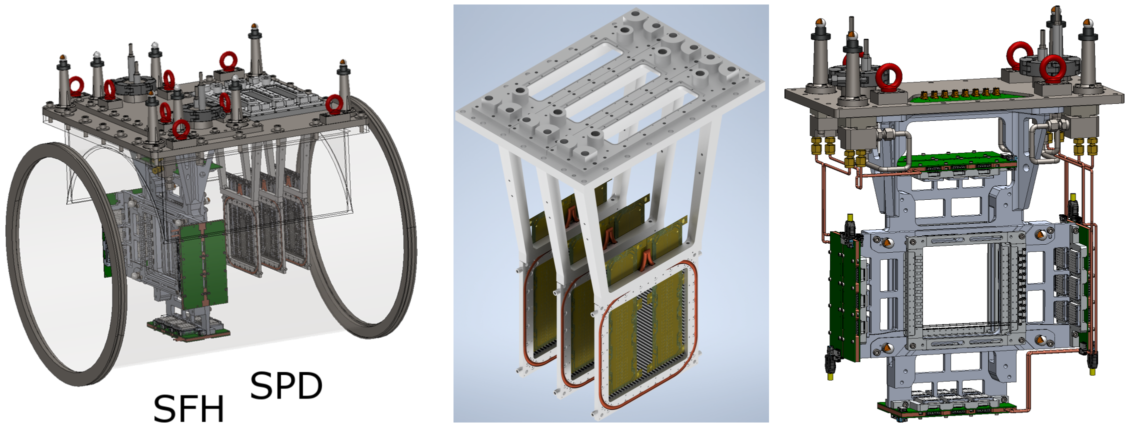
(a) **(b)** **(c)**

Figure 3: In (a) [4] the efficiency for a simplistic reconstruction method to disentangle pile-up events in the SPD within one UTS is shown. The three SPD planes are positioned in steps of 20 cm. The total material budget and contributions for one UTS station is shown in (b) [4]. The efficiency at the first SPD plane for different fiber sizes at different rates is shown in (c) [4].

area of (9×9) cm^2. The fibers in each plane are arranged in bunches of eight to minimize position uncertainties due to mechanical tolerances. Based on simulations of the expected hit-matching efficiency, we found that 500-µm Kuraray SCSF-78 square fibers offer a good compromise between light yield and material budget as shown in Fig. 3c. We use Hamamatsu S13361-3050AE silicon photomultiplier (SiPM) arrays to detect the scintillation light. Each fiber can be read out at both ends; alternatively, mirrors can be installed at one end to increase the light yield for single-sided read-out. The SiPM signals are digitized by CITIROC 1A discriminators [8] and iFTDC [1] time-to-digital converters, providing a time resolution below 1 ns. We constructed a scaled-down prototype to characterize important performance parameters—such as the light yield, position uncertainties of the fibers, and the detection efficiency of the two-layer plane concept. Tests with this prototype were performed with a sampling analog-to-digital converter [9] instead of the CITIROC-based read-out system, allowing us to perform an in-depth study of the above-mentioned parameters. Further optimizations, as well as the development of a prototype read-out system with integrated cooling, are currently ongoing.

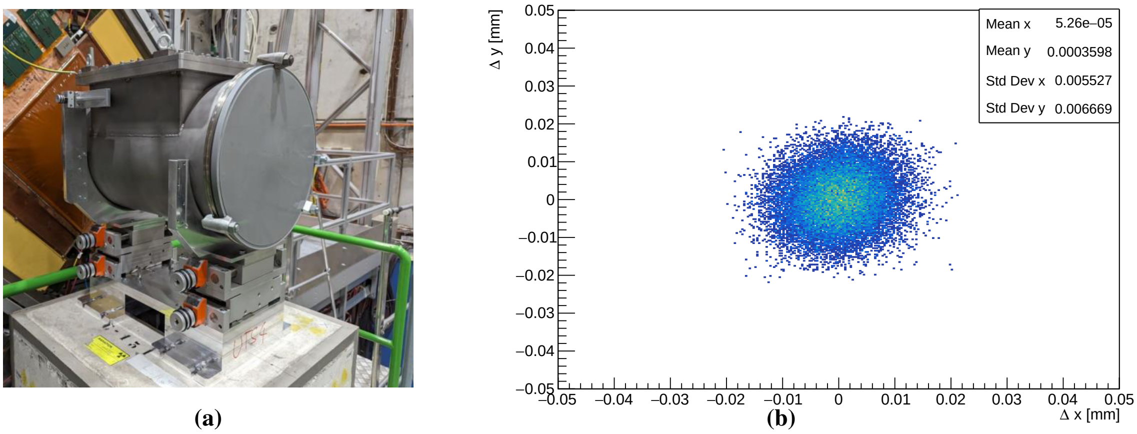
2.2 Silicon Pixel Detectors

Each plane of the SPD is equipped with 18 ALPIDE sensors placed in a 6×3 matrix providing an active area of (9×9) cm^2. The sensors provide a spacial resolution of $\sigma \approx 5$ µm [3] with a 5 µs time resolution and will be mounted on a flexible PCB (FlexPCB) with 10 µm thick aluminum conductors. Those will be glued on a 240 µm thick thermally conducting carbon fibre plate which provides rigidity and heat dissipation at a low material budget. Each carbon plane is mounted on a dedicated aluminum frame with a water cooling that provides the final heat evacuation as shown in Fig. 4b. First sensor mounting tests have been performed using an initial copper-based version of the FlexPCBs. The full production chain is tested at INFN Turin and other participating sites.



(a) **(b)** **(c)**

Figure 4: In (a) a 3D view of the UTS with the moutned SFH and SPD is shown. In (b) a 3D model of the SPD is shown. The 3D model of the SFH is shown in (c).



(a) **(b)**

Figure 5: A prototype UTS body installed in the experimental hall is shown in (a). The spatial resolution measurement with 160 GeV/c muons is shown in (b).

First sensors mounting on the FlexPCBs was performed in Turin and first bonding of the sensors to the FlexPCBs has been achieved at GSI. Preliminary measurements with single sensors read out by the MOSAIC boards [10] have been performed at CERN and COSY (Jülich). Very first position resolutions of one detector extracted from test measurements with 160 GeV/c muons within an ALPIDE-based telescope are shown in Fig. 5b.

3. Read-Out of the SPD Detectors

A Xilinx Kintex-7 K160T FPGA based board called "CMux" is used for the read-out. This FPGA has eight GTX transceivers. Six ALPIDE sensors per FlexPCB are connected to six of those transceivers and two transceivers connect to SFPs. An ethernet interface allows connecting the

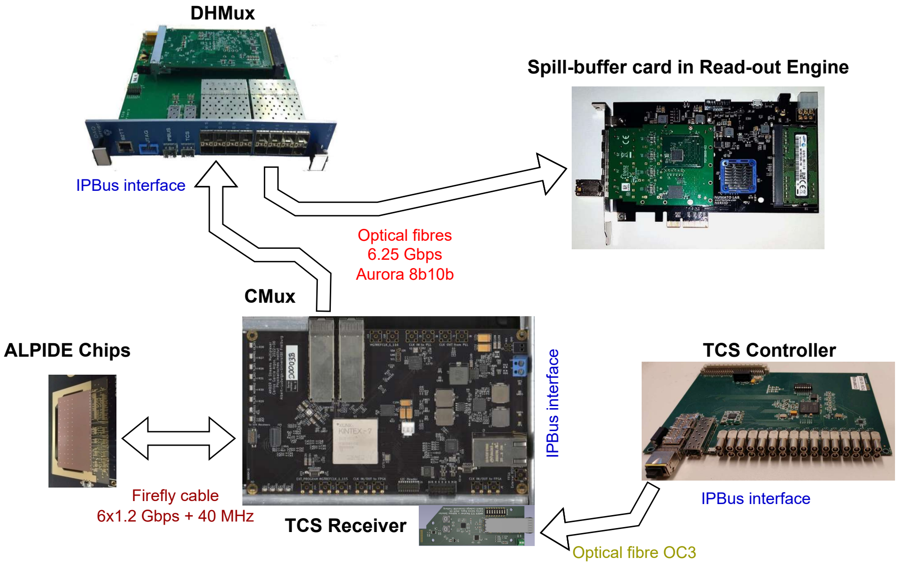


Figure 6: The connectivity of the read-out chain for the SPD sensors

board to the IPBus control network, an on-board Si5344/Si5394 jitter cleaner generates clocks for the transceivers. A 20-pin header gives access to several I/Os of the FPGA. It is currently used to connect a daughter card that provides the TCS receiver [2] function of receiving triggers, slice, spill, run information and other control signals from the TCS controller together with the recovery of the 155.52 MHz clock used to derive the SPS 38.88 MHz clock. Fig. 6 shows a diagram with the main components of the SPD read-out chain. CMux receives the serial data of the sensors and sends back clock and command signals. The data is then filtered and temporarily stored for aggregation on the output optical links, then the raw data is sent to the DHMux [11] using the FriDAQ [11] protocol. The DHMux aggregates multiple links and sends them to the spill-buffer card.

Acknowledgments

J.L.R.-S. is thankful for the support provided by the programme “Proyectos de excelencia” Grant ED431F-2023/43, by the "Ramón y Cajal" programme Grant RYC2021-031989-I and by the Spanish Ministry for Science and Innovation under Grant PID2021-125771NB-C21.

References

[1] B. Adams *et al.* [AMBER], “COMPASS++/AMBER: Proposal for measurements at the M2 beam line of the CERN SPS phase-1: 2022-2024”, CERN, CERN-SPSC-2019-022, SPSC-P-360, `http://cds.cern.ch/record/2676885`.

[2] P. Abbon *et al.* [COMPASS], Nucl. Instrum. Meth. A **577** (2007), 455-518 doi:10.1016/j.nima.2007.03.026 [arXiv:hep-ex/0703049 [hep-ex]].

[3] G. Aglieri Rinella [ALICE], Nucl. Instrum. Meth. A **845** (2017), 583-587 doi:10.1016/j.nima.2016.05.016.

[4] C. Dreisbach, "Preparations for the Proton-Radius Measurement at AMBER and Operation of Silicon-Microstrip Detectors at COMPASS,", Thesis: PhD Munich, Tech. U. (2022), `https://cds.cern.ch/record/2846597`.

[5] J. C. Bernauer, EPJ Web Conf. **234** (2020), 01001 doi:10.1051/epjconf/202023401001.

[6] W. Xiong, A. Gasparian, H. Gao, D. Dutta, M. Khandaker, N. Liyanage, E. Pasyuk, C. Peng, X. Bai and L. Ye, *et al.* Nature **575** (2019) no.7781, 147-150 doi:10.1038/s41586-019-1721-2.

[7] J. C. Bernauer *et al.* [A1], Phys. Rev. Lett. **105** (2010), 242001 doi:10.1103/PhysRevLett.105.242001 [arXiv:1007.5076 [nucl-ex]].

[8] Citiroc 1A is a 32-channel front-end ASIC designed to readout silicon photo-multipliers (SiPM) for scientific instrumentation application, https://www.weeroc.com/products/sipm-read-out/citiroc-1a.

[9] A. B. Mann, I. Konorov, H. Angerer, M. Krämer, S. Huber, B. Grube, J. Friedrich, B. Ketzer, S. Uhl and F. Haas, *et al.* doi:10.1109/NSSMIC.2009.5402077.

[10] G. De Robertis, G. Fanizzi, F. Loddo, V. Manzari and M. Rizzi, EPJ Web Conf. **174** (2018), 07002 doi:10.1051/epjconf/201817407002.

[11] V. Frolov, S. Huber, I. Konorov, A. Kveton, D. Levit, J. Novy, D. Steffen, B. M. Veit, M. Virius and M. Zemko, *et al.* IEEE Trans. Nucl. Sci. **68** (2021) no.8, 1891-1898 doi:10.1109/TNS.2021.3093701.