Institute for Hadronic Structure and Fundamental Symmetries
School of Natural Sciences
Technical University of Munich

Development of FPGA frontend electronics of the scintillating fiber hodoscope of AMBER at CERN

Tim Maehrholz

Bachelor's Thesis

Supervisor:
Prof. Dr.
Chair of

Second Examiner:
PD Dr.

January 2025

Abstract

Here will be my abstract for thesis Thesis template from the ZNN, updated for Biblatex and Biber.

Zusammenfassung

German Abstract

Contents

CHAPTER 1

Introduction

"Nature will reveal its secrets, but only if we ask the right questions."[Werner Heisenberg]
Progress in particle physics has always been driven by the desire to understand the fundamental building blocks of our universe.

Our current best theory for the innnerworkings of our world, the standart model of particle physics shows us, that the matter we see around us is mostly made up of down and up qurks and electrons. Combinations of these quarks, held together by the strong nuclear force form the proton and neutron,the nuclei of the atoms that make up the matter of the everyday world. Eventhough the Proton was discovered over a hundred years ago by Ernest Rutherford[Pea89], it is still not fully understood.

Since the proton, unlike the electron is a composite particle, it follows that it has an internal structure. The semantic meaning of size in the realm of particele physics is not as straight forward as in the macroscopic world.An answer to the question, what is the size of the proton can be given by looking at the charge distribution of the proton, which defines the charge radius of the proton.

The proton radius measurment at AMBER at CERN aims to reselove a discrepency between the charge radius of the proton as measured by the Lamb shift in muonic and ordinary hydrogen and the electron-proton scattering experiments, the so called proton radius puzzel.

To achieve this, the PRM experiment will measure the cross section of elastic scattering of muons on protons. The scintillating fiber hodoscope is a key component of the PRM experiment, as it provides crucial time measuments of the incoming and scattered mouns, needed for the measurment of the proton radius[BAd19].

This thesis will focus on the development of the FPGA driven frontend electronics of the scintillating fiber hodoscope for the proton radius measurment at AMBER at CERN, especially on the development of the FPGA firmware required for the control of the CITIROC ASIC, a part of the readout and trigger electronic.

CHAPTER 2

Theoretical concepts and AMBER overview

2.1. Measurment of the charge radius of the proton (PRM)

The proton is a baryon, a composite particle made up of one down quark and two up quarks. From this follows that the proton is not a point particle,but has an internal sturucture.
The internal structure can be discribed by the structure functions of the proton, the electric and magnetic form factors G_E and G_M [BAd19].

2.1.1. Previous measurements of the proton radius

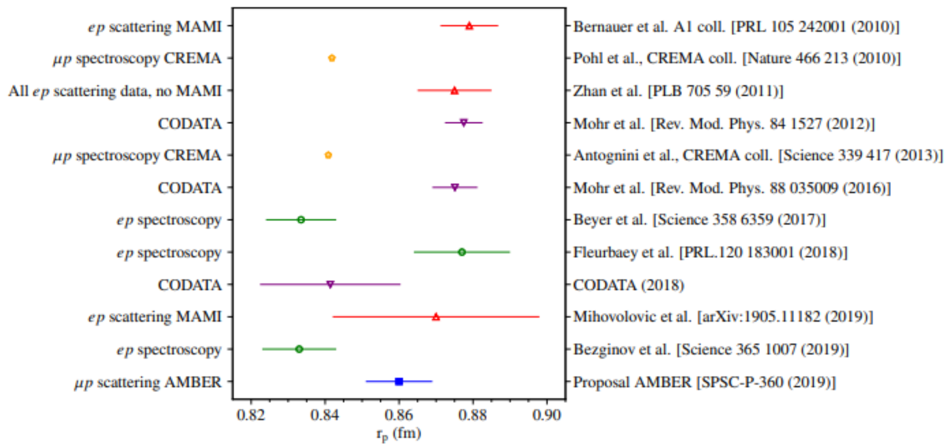

Figure 2.1.: Previous measurements of the proton radius from electron proton scattering experiments and the Lamb shift in muonic and ordinary hydrogen, the measurements differ from each other by five standard deviations [BAd19]

The charge radius of the proton has been massured several times before with different methods. The two premier methods are electron proton scattering experiments and the Lamb shift in muonic and ordinary hydrogen. The results of these measurements differ by five standard deviations as shown in figure 2.1, this has given rise to the so called proton radius puzzle [BAd19].

2.1.2. Elastic scattering of muons on protons

The AMBER PRM experiment at CERN aims to reslove the proton radius puzzle, by measuring the elastic scattering of muons on protons. The first order cross section,taking into account only interactions where one virtual photon was exchanged, for the elastic scattering of muons on a proton target is [Ada19] INSERT: maybe here more explantation

$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 p_\mu^2}\left[\left(G_E^2 + \tau G_M^2\right)\frac{4E_\mu^2 m_p^2 - Q^2(s - m_\mu^2)}{1+\tau} - G_M^2 \frac{2m_\mu^2 Q^2 - Q^4}{2}\right] \tag{2.1}$$

with $Q^2 = -q^2$ the squared transferred four-momentum, $\tau = Q^2/4m_p^2$, $s = (p_\mu + p_p)^2$, G_E the electric form factor of the proton, G_M the magnetic form factor of the proton and α the fine structure constant.

INSERT: maybe here more explantation
Through determining the form factor G_E for small Q^2 , the charge radius of the Proton can be claculated with the following equation [Ada19]

$$r_p^2 = -6\frac{dG_E}{dQ^2}\bigg|_{Q^2=0} \tag{2.2}$$

2.2. General setup for PRM at AMBER

2.2.1. Detectors for PRM

To determine the magentic and electric form factors of the proton and thus the charge radius of the Proton, the experimental cross section of the elastic scattering of muons on protons has to be measured.
The general setup of the PRM experiment, with focus on the new detectors needed for the proton radius measurment, is shown in figure 2.2.

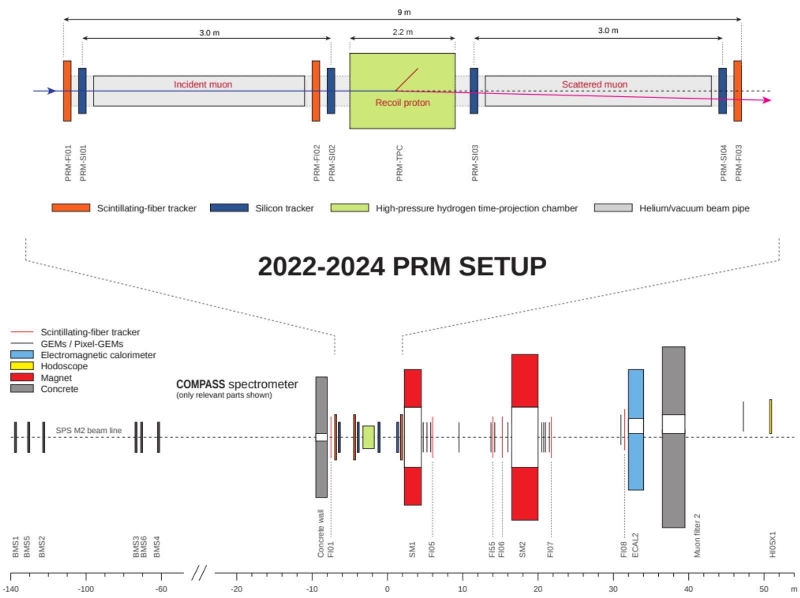

Figure 2.2.: General setup of the Amber experiment with new detectors for PRM,INSERT:BETTER DISCRIPTION [BAd19]

INSERT: MAYBE FLUX;ENERGY Maybe include detetor specs
The incoming muon beam is scattered on a pressurized hydrogen gas target, located in the Time Projection Chamber (TPC), which also acts as the detector for the recoil path of the proton. INSERT: should i included precicion values and other characteristics of the detectors The reconstruction of the path of the muon is achieved through the usage of two detector types, combined into one unified tracking station (UTS) as shown in (pic-

ture/shematic 2.3).
Each UTS consists of three layers pixilized silicon detectors (ALPIDEs),for precises positional measurments (spacial resolution of about 8 µm [KAR]) of the incoming and scattered muons, but lacking the time resolution(5 µs[Fri22]) required for the PRM experiment. For this reason each UTS includes a scintillating fiber hodoscope (SFH),the detector of intrest for this thesis, which provides the time precision(300 ps[Fri22]) of the measurment. Four of these unified tracking stations,two before and two after the active target, are placed in the beamline as shown in 2.2. The measurment of the momentum of the scattered moun is done by existing COMPASS detectors located after the, for the PRM newly included, detectors[BAd19].

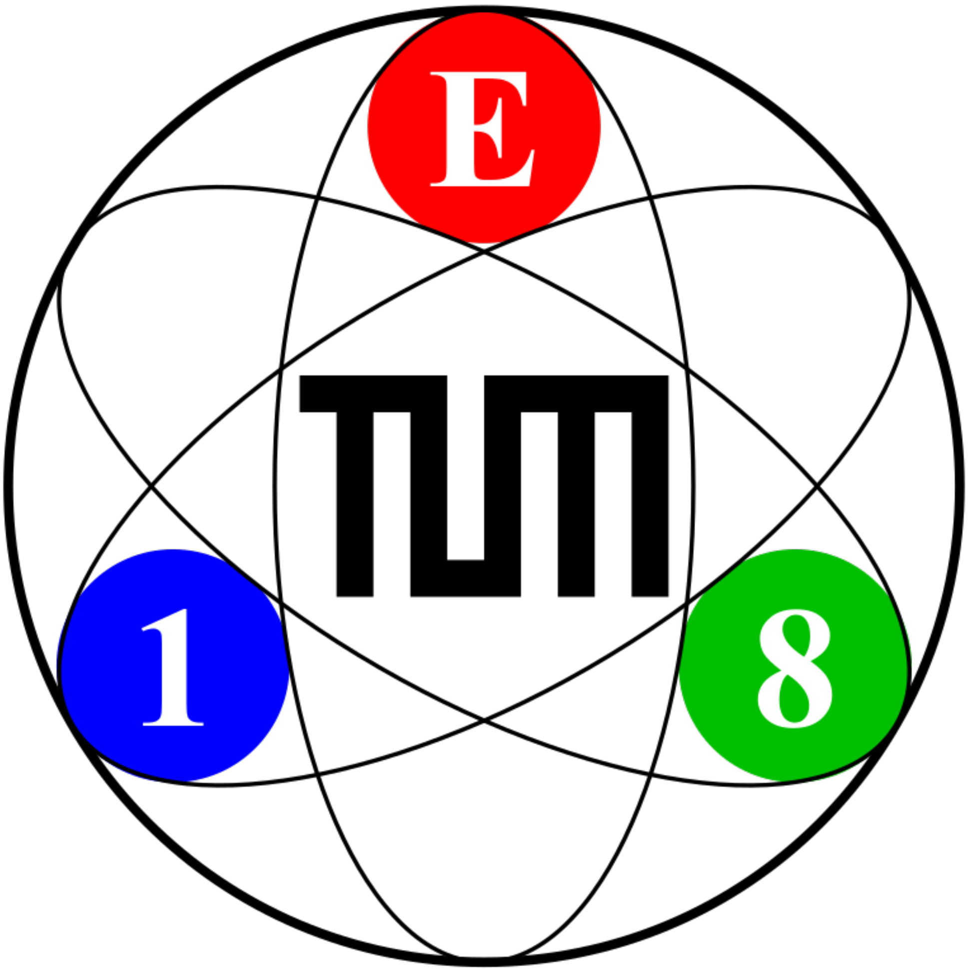

Figure 2.3.: Unified tracking station (UTS) with ALPIDEs and SFH

2.2.2. Scintillating fiber hodoscope(SFH)

The scintillating fiber hodoscope shown in picture 2.4, the detector for which the FPGA driven frontend electronics are developed in this thesis, is used to measure the precise

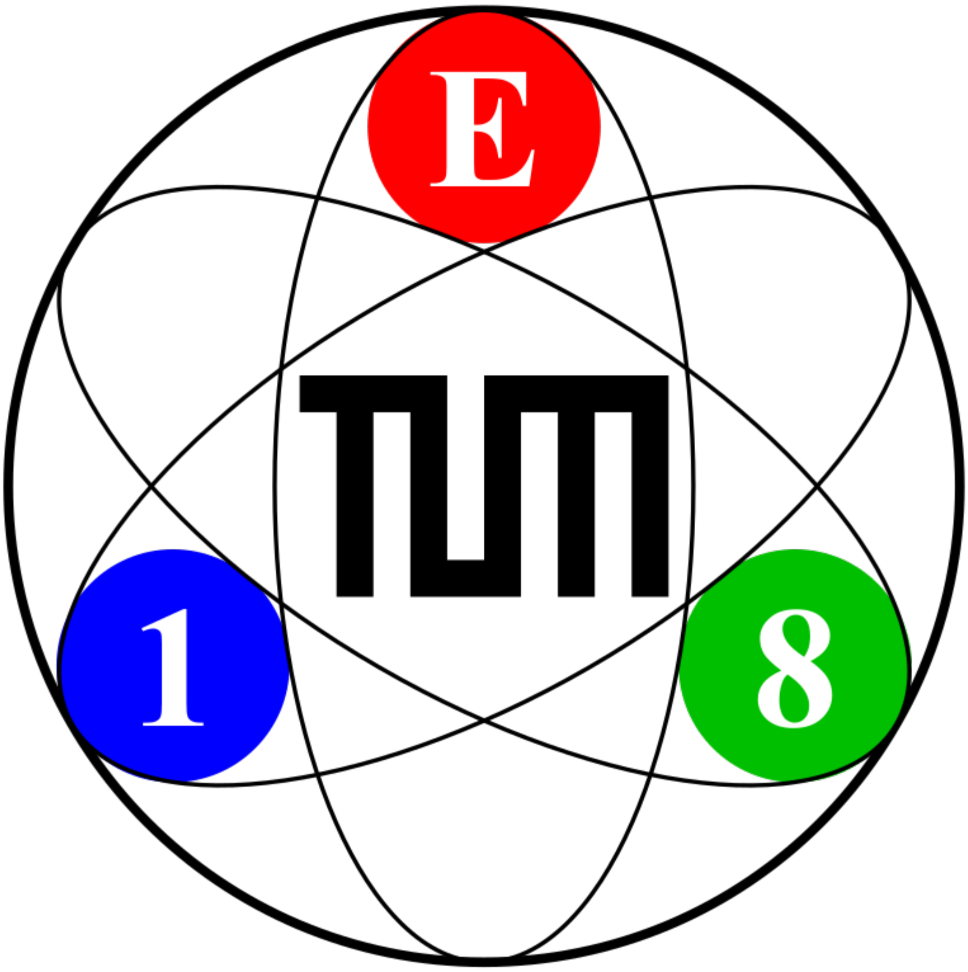

Figure 2.4.: Scintillating fiber hodoscope (SFH) with 4 layers of scintillating fibers

timing(300 ps[Fri22]) of the incoming and scattered muons.Every SFH contains four layers of scintillating fibers, two in x and two in y direction. Each layer is made up of 192[Fri22] fibers, 500 μm thick[The24],so in total 768 fibers per SFH. When charged particels, muons in this case, pass through a scintillating fiber they excite the scintillating material, which then emits photons.Both ends of every fiber are contected to a silicon photomultiplier (SiPM) which converts the photons into an electrical signal wich is then proccesed by the frontend electronics.

CHAPTER 3

Experimental Procedures

CHAPTER 4

Results

CHAPTER 5

Discussion

Discussion

CHAPTER 6

Conclusion and Outlook

6.1. Conclusion

Conclusion

6.2. Outlook

Outlook

APPENDIX A

Code

```
this is code
```

Bibliography

[Ada19] B. Adams, C. A. Aidala, R. Akhunzyanov, and et al. *Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS (COMPASS++/AMBER)*. 2019. arXiv: `1808.00848 [hep-ex]`. URL: `https://arxiv.org/abs/1808.00848` (cit. on pp. 4, 5).

[BAd19] e. a. B.Adams C. A. Aidala. *COMPASS++/AMBER: Proposal for Measurements at the M2 beam line of the CERN SPS Phase-1: 2022-2024*. Tech. rep. Geneva: CERN, 2019. URL: `https://cds.cern.ch/record/2676885` (cit. on pp. 1, 3–6).

[Fri22] J. M. Friedrich and O. Denisov. *AMBER Status Report 2022*. Tech. rep. Geneva: CERN, 2022. URL: `https://cds.cern.ch/record/2810822` (cit. on pp. 6, 7).

[KAR] E. KARL (cit. on p. 6).

[Pea89] B. M. Peake. "The discovery of the electron, proton, and neutron". In: *Journal of Chemical Education* 66.9 (1989), p. 738. DOI: `10.1021/ed066p738` (cit. on p. 1).

[The24] C. S. The AMBER Collaboration. *AMBER Status Report 2024*. Tech. rep. Geneva: CERN, 2024. URL: `https://cds.cern.ch/record/2907624` (cit. on p. 7).

Acknowledgement

I want to thank:

Tutor .

Professor .

Eidesstattliche Erklärung

Ich versichere hiermit an Eides statt, dass ich die von mir eingereichte Arbeit bzw. die von mir namentlich gekennzeichneten Teile selbständig verfasst und ausschließlich die angegebenen Hilfsmittel benutzt habe. Die Arbeit wurde bisher in gleicher oder ähnlicher Form in keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

Ort, Datum Unterschrift