Proposal for the GENERIC EIC-RELATED DETECTOR R&D PROGRAM

Precise Timing with a Micro Pattern Gaseous Detector

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We propose to build upon the MicroMegas based PICOSEC device, an improved version that is is overcoming the presently existing shortfalls of this technology aimed for precise timing applications in an EIC detector.

Contents

1 Introduction

In the scope of the EIC physics program, semi-inclusive deep inelastic scattering (SIDIS) reactions in e-p and e-A collisions play an important role regarding the spin of the proton, Fragmentation Functions (FF), Transverse Momentum Distributions (TMDs) by means of flavor tagging through hadron type, measuring Kaon asymmetries and cross sections, measuring strangeness Probability Distribution Functions (PDFs), amongst others. This, in turn requires $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range in pseudorapidity, $|\eta| < 3$. It needs to cover the entire kinematic region in p_t and z, needs excellent particle identification (PID) and excellent momentum resolution at forward rapidities. TMDs need full azimuthal coverage around the virtual photon and a wide p_t coverage.
In the barrel region ($\eta < |1|$) particles have to be identified that are abundantly created with momenta below 1 GeV/c (refer for pions to Fig. 1). At present, the devices being considered for particle identification in the barrel region are based on DIRC technology as well as based on TOF technology. DIRC is capable of performing PID and can identify pions and protons down to $p_T \sim 250$ MeV/c and $p_T \sim 850$ MeV/c, respectively. Notwithstanding, the momenta ranges as just mentioned might have to be complemented by additional technologies such as Time-of-Flight (TOF) techniques.
In the present planning TOF devices that will be implemented in the Detector-1 design are

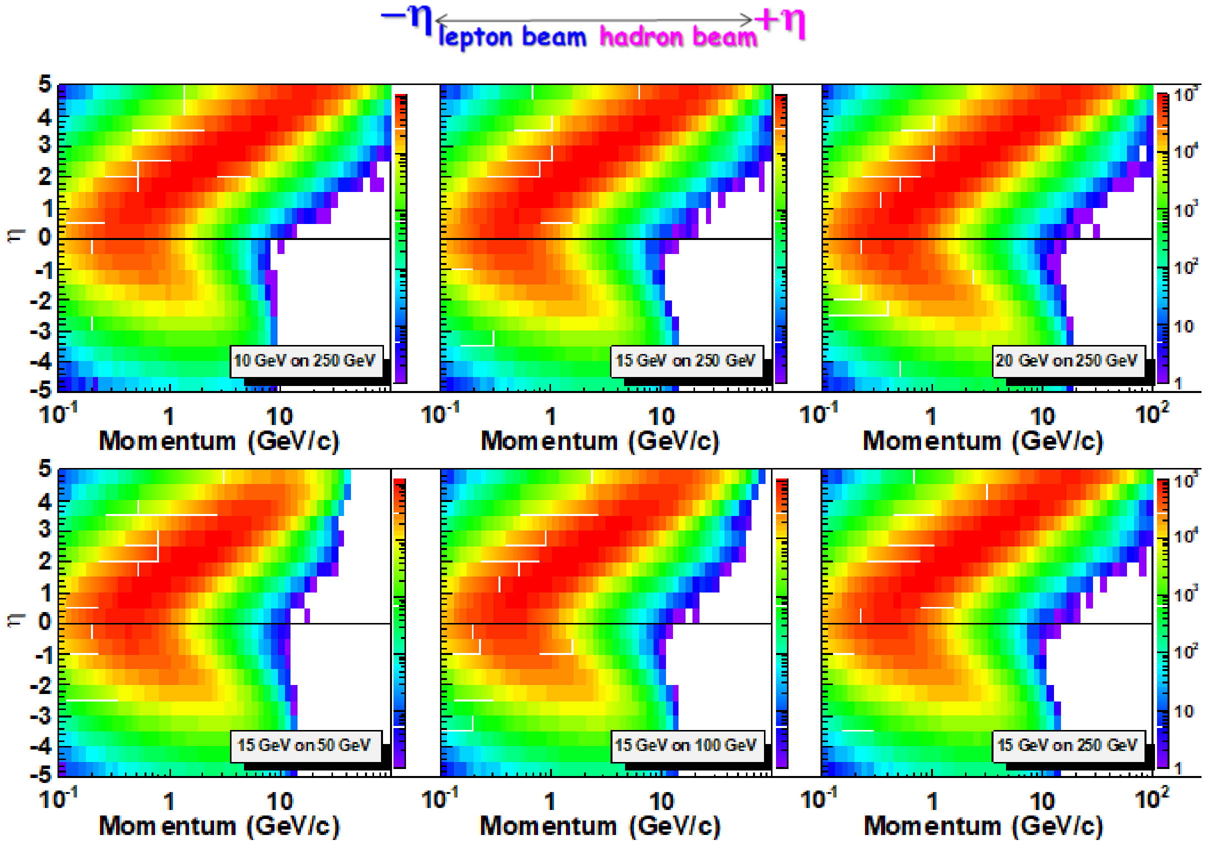

Figure 1: Pion kinematics in SIDIS. Upper: collisions with increasing lepton-beam energy and fixed hadron-beam energy, where hadrons are more and more boosted toward negative pseudorapidities. Lower: collisions with increasing hadron-beam energy and fixed lepton-beam energy, where hadrons' momentum at fixed pseudorapidities increases. It shall be noted that other hadron species beside $\pi^{\pm}$, like $K^{\pm}$ and $p^{\pm}$ show the same kinematics.

based on Si detectors which makes use of the Low Gain Avalanche Detector (LGAD) technology [1]. This detector technology provides promising performance features with very good timing resolution as well as position resolution. Several investigations have yet to be performed regarding sensor technology as well as for readout electronics issues. To reduce the risk of a single technology it is advantageous to perform investigations toward detector technologies that would provide similar capabilities and would therefore supply an alternatives. The TOF capability as well as the tracking capability of gaseous based technologies would provide similar performance compared to the LGAD technology. It will be discussed in the following sections. This technology is known under the term -Micro Mesh Gaseous Device (MicroMegas) based PICOSEC- detector [2].

The MicroMegas based PICOSEC detector technology, from now on Picosec, has been used within a prototype project and performances have been shown that are very promising for the application as indicated above. Fig. 2 shows an example of that performance: timing resolutions of $\mathcal{O}$(20 ps) can be achieved. Based on its timing performance the Picosec device can be well

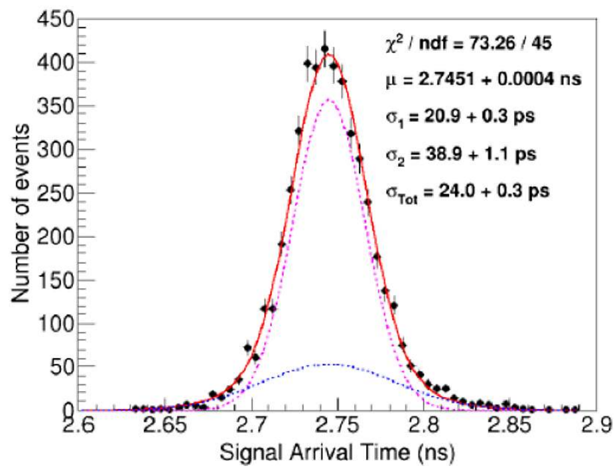

Figure 2: Timing resolution measured with a Picosec prototype at the SPS-H4 test beam line at CERN.

integrated into the EIC detector concepts, acting as TOF detectors in the barrel as well as in the forward regions. A further promising feature for the Picosec is to use it as a tracking detector with very good position resolution. As an application beside, the Picosec could also be established as a very fast photo-detector which requires the collection of electrons converted from the single photons to be detected. The latter requires very good photon conversion efficiencies and well delivered amplification thereof.
The improvement in detector stability as well as efficiencies and consequently its performance is the main task of this proposal.

2 The PICOSEC Concept

2.1 Introduction

The Picosec technology was motivated and initiated from the requirements of the LHC high luminosity upgrade (HL-LHC), for differentiating events occurring from multiple interaction within a single bunch crossing. This in turn warranted a high temporal resolution of a possible detector application.
Gaseous detecting devices based on Micro Pattern Gaseous Detectors (MPGD) generally provide good timing resolution, however, not sufficient to disentangle events from an HL-LHC event. Timing resolutions of sub-100 ps are required. The idea is to use a MicroMegas based amplification scheme and combine it with an instantaneous electric signal provider. Such signal provider can be obtained with Cherenkov photons. The Picosec detector combines a Cherenkov

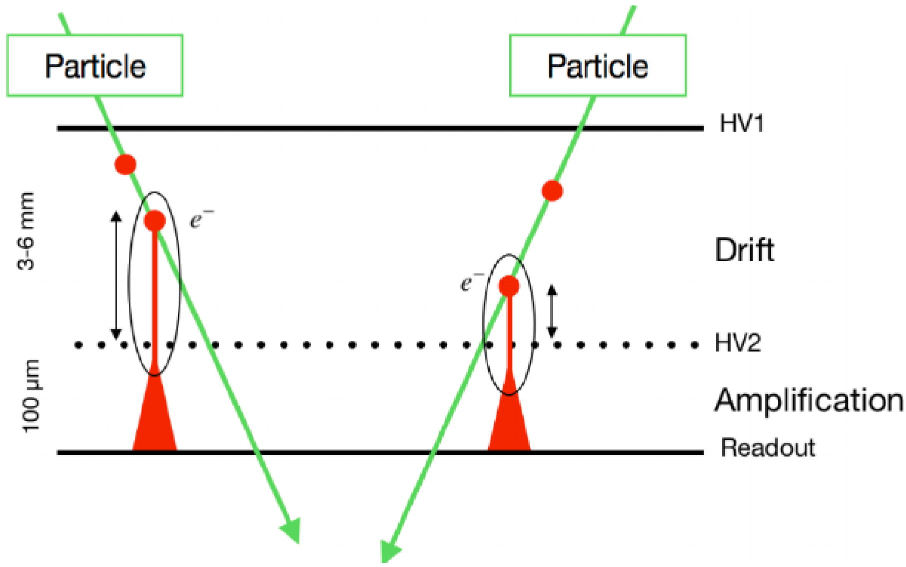

Figure 3: The working principle of a MicroMegas device. The timing uncertainty arise with the unknown location of the signal creation as well as a relatively long drift length.

radiator, a photocathode and a MicroMegas-based amplification stage into a high-precision timing detector. Incoming particles create Cherenkov photons in the radiator, which are converted to primary photoelectrons at the photocathode. These electrons are pre-amplified in a drift region and finally amplified by the MicroMegas. A time resolution of the order of 20 ps for Minimum Ionising Particles (MIPs) has been measured in several test beam campaigns in recent years. The principle of the signal formation can be seen in Fig. 4. It is important to recognize that the photo-electrons have to be released at the same position in a plane with respect to distance to the amplification structure, therefore removing variations in timing by ionization statistics along the particle path and subsequent drift length differences prevalent in other detectors . The prototype efforts presented here were led by the GDD group[1] at CERN who will participate in the proposal as described here. The present prototype studies provided a proof-of-principle result. The results, however, demonstrated that various areas need significant improvements. The areas under consideration are

1. mechanical stability for providing uniform performance
2. multi-pad readout structure for covering larger areas
3. photocathode studies for improving the photon yield
4. radiator studies for improving photon yield

[1]https://gdd.web.cern.ch/

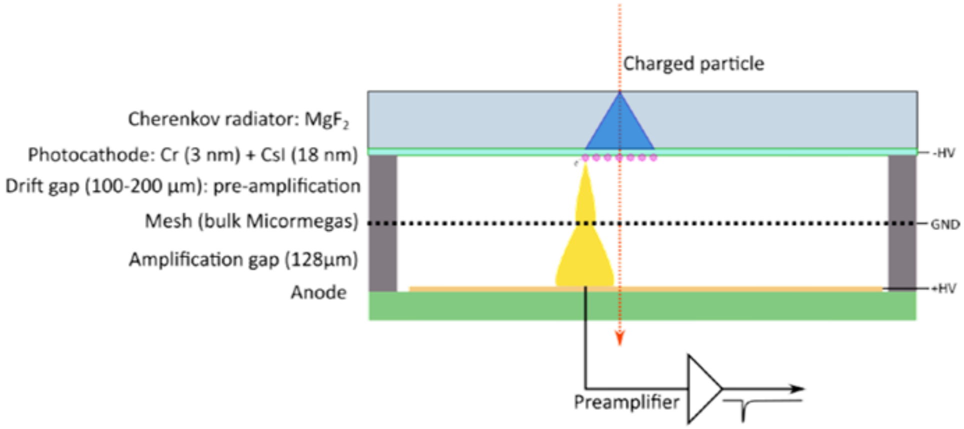

Figure 4: Schematics of the MicroMegas based Picosec device. A radiator for minimum ionizing particles "generates" the photons that are converted into electrons at the photocathode and undergoing pre-amplification as well as amplification in a gas volume. The electrons for the signal are all generated at the the same drift position.

Planarity is crucial for the operation of the Picosec device. It has been found that a variance in the height of 15μm will result in an error of 100 ps in the timing resolution. Fig. 5 shows the result of a scan over the surface which show visible deformations and is not restricted to certain regions. The mechanical stability can be improved with two different approaches. The first ap-

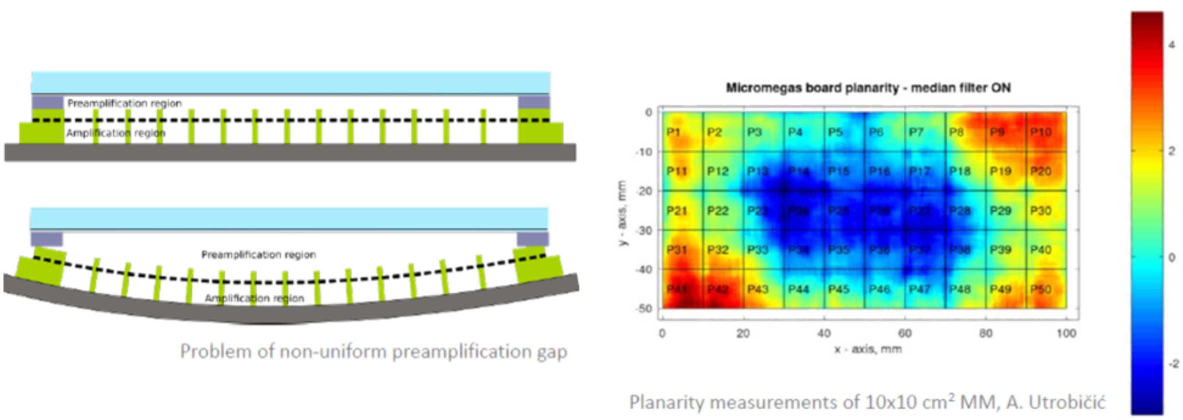

Figure 5: Deformation of the readout board which is consequently introducing a non-uniform gap across the device. Non-planarities of up to 30 μm have been observed.

proach is to support the fragile structure with stiff materials, for instance, with ceramic planes. This would certainly improve the planarity, however, it has to be studied to what degree the increased radiation length might have an impact. The second approach would be to move away from a Micromegas as the amplification structure and toward an alternative MPGD structure. The μRWell structure (Fig. 6) would be such device as it inherently provides a stable surface

structure and can be operated in a similar way as the Micromegas, see Fig. 7.
Larger multi-pad readout structures can be accomplished once the mechanical stability issue has been overcome. The size of the readout pads and the channel count has to be considered. Smaller pad sizes result in less charge to be accumulated on the individual pads. It has to be investigated how the gain structure has to be adjusted in order to compensate for that effect.

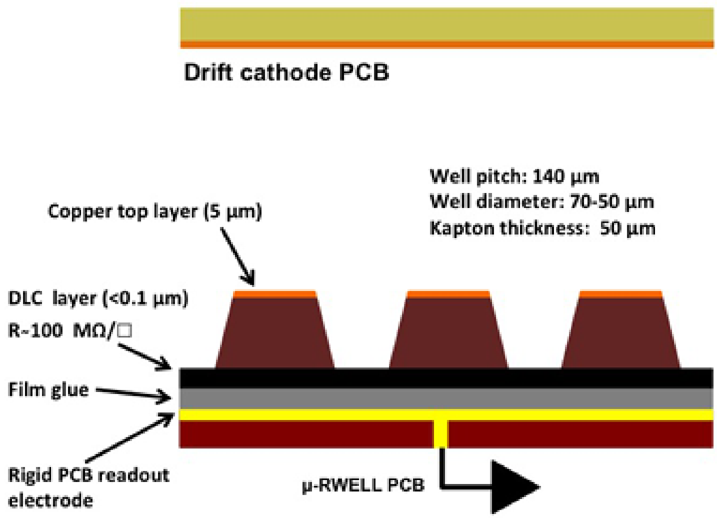

Figure 6: Sketch of a micro-resistive well device. The rigidity of this device is provided because of the combination of a GEM-like structure attached to a rigid PCB readout board structure. This would not add to an increase in radiation length.

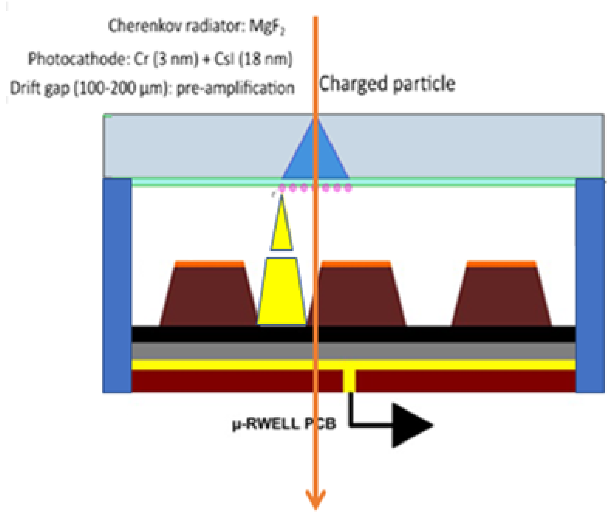

Figure 7: Adapted Picosec device with a μRWell structure as amplification provider.

Furthermore, readout electronics has to be developed that can cope with the fast signal struc-

ture and can be scaled to an increased channel count. The timing resolution in any case, either TOF and photo-detector will significantly improve when the number of participating photons is enhanced. This is true if the number of photons that are converted to electrons is maximized. This implies that the photocathode as the photon to electron converter should have a quantum efficiency (Q.E.) of 100%. This is desirable but in reality cannot be accomplished. Nevertheless, if materials can be implemented such that the Q.E. approaches 100% as much as possible it would be as much desirable. Presently, the photocathode material that offers the highest Q.E. in the Picosec applications is based on Cesium-Iodide CsI. This material has several advantages but also give disadvantages.
Advantages are the relatively high quantum efficiency for photons in the VUV wavelength regime which are most abundantly created with the Cherenkov effect, for any material since $dN_\gamma \propto 1/\lambda^2$. The wavelength range, however, does also pose restrictions on the photon yield efficiency as it requires transparency of the traversed media. In addition, CsI is hydrophobic and is very sensitive to any water content in the environment as it changes its crystal structure which changes its Q.E. dramatically. The same happens when it is exposed to Ion Backflow as well as discharges which are created in the gas amplification process. It is therefore critical to investigate alternative materials that can overcome these restrictions. Possible alternative materials that show promising results are metallic photocathodes, diamond like Carbon (DLC) structures, and Boron Carbides (B4C). Possible solutions might also emerge from the field of meta-materials that the P.I. is investigating. The Cherenkov radiator material might also promise

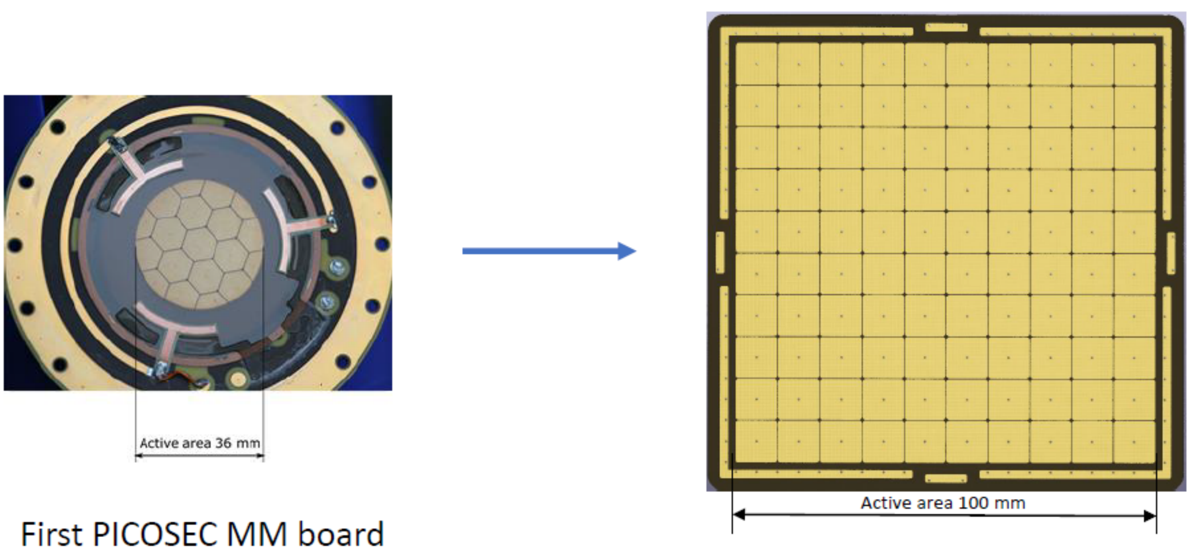

Figure 8: Design studies: from a few-pad readout to multi-pad (100 channels) readout for the Picosec.

a timing improvement if appropriate materials can be found that increase the photon yield. In addition, if the photons exiting the radiator toward the photoconversion border can be focused it will be an improvement in the timing resolution as well as position resolution.

2.2 Proposed studies

2.2.1 Mechanical Stability

We are proposing to investigate the improvement in stability with the least compromise toward the radiation length of the device. At present it is suspected that the attachment of the Micromegas board to the housing as well as the attachment of the radiator are causing the mechanical issues toward the inhomogeneous surface distribution within the Picosec device. In addition, we will investigate the support of the readout PCB by means of low radiation length material, for instance, with honeycomb Nomex structures sandwiched within glass-fiber layers. Eventually, we will be investigating a Picosec device based on a μRWell amplification structure which might inherently provide the mechanical stability as desired. The latter studies will be performed on 10 cm $\times$ 10 cm large structures with a pad size that provides a 100-channel readout.

2.2.2 Multi-Pad Readout Structure

As indicated in Sec. 2.2.1 we will be using Picosec devices that offer a readout structure of 100 and more readout pads. At present the default readout chain consists of a few-channel count and expensive instruments (Fig. 9). This is not only impractical but also prohibitively expensive. We

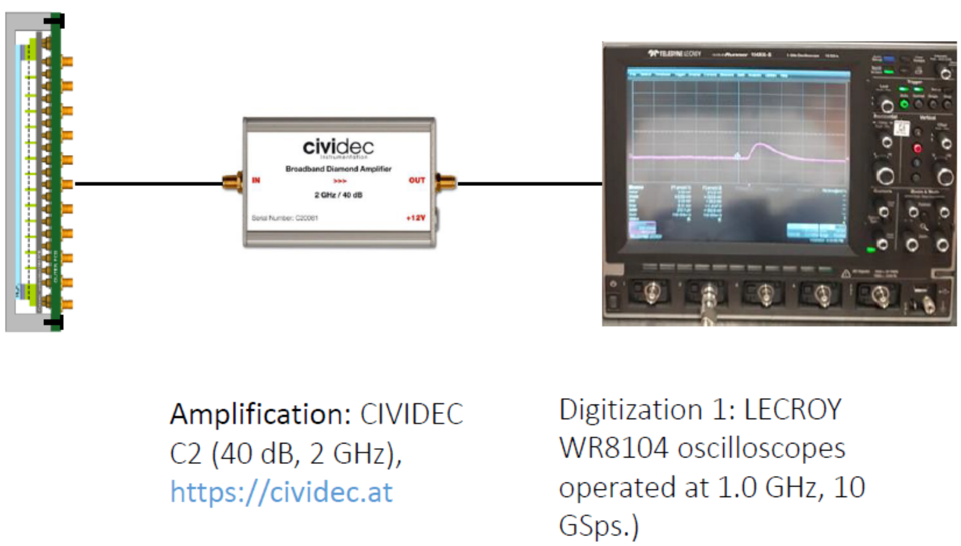

Figure 9: Few-channel readout chain for present Picosec test beam campaigns.

are aiming to keep the readout board and amplification structure separable so that PCBs with different configurations can be investigated (Fig. 8). For reading out electronically a 100+ pad configuration we will be asking the colleagues from the GDD group to produce pre-amplifier devices and procure a digitizer unit of 128 channel based on the SAMPIC chip [3] from a group at Saclay (Fig. 10). The pre-amplifier is in the development stage and under testing. The

Figure 10: Multi-channel SAMPIC digitizer.

SAMPIC is working with a 8.5 GS/s sampling frequency; stacking multi-channel mezzanine modules and going toward 256 ch; with a bandwidth 1.6 GHz; with internal FPGA algorithms for signal processing. It has been tested in a test beam environment with 6.4 and 8.5 GS/s and is used with a Sigmoid fit and CFD (20%).

2.2.3 Photocathode Studies

The SBU group has a facility with which the photocathode evaporation for all the HDB-GEM detectors with CsI had been performed. We have upgraded this facility, an UHV evaporator unit with an ion-beam assisted physical vapor deposition instrument, based on an electron-gun evaporator. Our experience with this facility will allow us to evaporate a variety of materials as photo-cathode layers on appropriate surface blanks and study these materials according to their Q.E. properties.

2.2.4 Radiator Studies

The radiator is one of the main components for a TOF device when measuring the velocity of MIPs. Its properties are crucial for the performance in terms of timing. Ideally, radiators with high index of refraction n_r are preferred as they provide a larger photon yield: $dN_\gamma \propto \sin^2(\theta_{Ch})$, but also $dN_\gamma \propto 1/\lambda^2$. However, this indicates rivaling effects. On one hand a higher n_r increases the photon yield, on the other hand, it increases the spatial distribution of the photons created. The latter, in turn, degrade the signal because the photoelectrons spread out and consequently, degrade the timing resolution. To compensate for the spreading we are investigating the implementation of focusing elements, either on the radiator level by means of lenses or by means of electric field focusing element for focusing the converted electrons. In addition we will be reviving studies that we performed in a previous project that is dealing with the development of meta-materials. Meta-materials, if found with the right properties, are the ultimate solutions.

3 Scope of Work

The tasks described in the previous sections will be performed by a graduate student at the Ph.D. level. The student will be supervised by the P.I. as well as the additional personnel from the author list. The personnel from Stony Brook University will be responsible for supervising the student on campus and in addition, the personnel as listed from CERN will be supervising the student while present at CERN during a test beam campaign.
The test beam campaigns should be performed at the CERN-SPS test beam area H4. The GDD group has a sophisticated test beam setup at this facility and it will enable us to travel only with the detector under test (DUT) plus its readout electronics to the test beam area.
It should be noted that although the call for proposals at this time requires the funding requests only for the coming year, this project will be a multi-year project. We have therefore included additional tables with funding requests for the two following FY.

3.1 Deliverables

The project aims in the first year to assemble a large area, multi-pad Micromegas based Picosec detector and apply the proposed electronics readout chain to it. Bench tests will be performed at SBU to gain an understanding of the DUT first hand. Based on the shortcomings as described above we will investigate thereafter the improvement of the mechanical stability of the detector and verify with bench tests its improved performance. The verification process will be finalized with a test beam campaign at the SPS-H4 beam line at CERN. The whole chain described above will be accomplished in the first year of this project.

3.2 Cost Effectiveness

The equipment that needs to be acquired as described in this proposal will be produced by well established sources, like the PCB workshop at CERN and the University of Zagreb. This allows us to forego paying NRE costs since every piece of equipment is standard equipment. Furthermore, the use of the CERN-SPS test-beam facility which accommodates a complete technical environment for the investigation of the device(s) in this proposal will save us from constructing the same supporting environment when, for instance making use of the Fermilab test beam facility (FTBF).
The employment of a graduate student is advantageous in two aspects. The work can be accomplished with lower personnel costs and will provide a junior researcher to get them familiarized with instrumentation research on the highest level.

3.3 Diversity, Equity, and Inclusion

The work described in this proposal will allow any interested junior researcher to be trained in the field of instrumentation. This is a unique opportunity to foster young academics and for them to take over the responsibility in this field. There is a lack of experts in the field of instrumentation and that is exactly one of the big advantages of research chances like this. The P.I. and the team understands the need for instrumentation workforce in the future and is capable to train the student as they were enthusiastically performing this work in the past.

4 Budget

Although the call for proposals requests us to ask for funding in the coming fiscal year we have compiled a set of budget requests that reach out into the following fiscal years. As mentioned above this project is aimed toward a three-year operation and, in particular requires a multi-year commitment of a graduate student to get trained for future instrumentation applications. We therefore list a budget table for FY'23 only as well as budget tables for the following years. All budget tables consider also a nominal budget request as well as 20% and 40% reduced budgets, respectively.

4.1 Baseline funding request FY'23

Our baseline funding request compared to baseline - 20% and baseline - 40% request for FY'23 is summarized in Table 1.

Item	Budget **FY'23**	Nominal	Nominal - 20%	Nominal - 40%
1	Salary Ph.D. student	$ 61,525	$ 46,144	$ 30,763
2	Travel costs (Test Beam)	$ 7,975	$ 4,417	$ 859
3	Picosec Amplification Structure	$ 4,080	$ 4,080	$ 4,080
4	Radiator	$ 1,224	$ 1,224	$ 1,224
5	Sapphire window	$ 510	$ 510	$ 510
6	Aluminum housing	$ 1,020	$ 1,020	$ 1,020
7	Outer PCB	$ 1,530	$ 1,530	$ 1,530
8	Preamplifier	$ 4,590	$ 4,590	$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240	$ 12,240	$ 12,240
	Total	$ 94,694	$ 75,755	$ 56,816

Table 1: Nominal—Nominal - 20%—Nominal - 40% funding request for FY'23 for SBU. Line item 1 and 2: fully loaded.

4.2 Reduced funding request

Two reduced funding request scenarios are described and listed in tables 2 and 3. In both cases the request for Ph.D. student support has to be reduced to 75% and 50%, respectively plus reduction in travel costs. The requested funding for hardware needs to stay at the same level because it cannot be compromised. The reduced student's salary support would make the project extremely difficult if not impossible.
Please note that the amounts listed in tables 2 and 3 have been also included in Table 1 for direct comparison.

Item	Nominal Budget -20%	FY'23
1	Salary Ph.D. student	$ 46,144
2	Travel costs (Test Beam)	$ 4,417
3	Picosec Amplification Structure	$ 4,080
4	Radiator	$ 1,224
5	Sapphire window	$ 510
6	Aluminumhousing	$ 1,020
7	Outer PCB	$ 1,530
8	Preamplifier	$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240
	Total	$ 75,755

Table 2: Nominal funding request -20% for FY'23. Line item 1 and 2: fully loaded.

Item	Nominal Budget - 40%	FY'23
1	Salary Ph.D. student	$ 30,763
2	Travel costs (Test Beam)	$ 859
3	Picosec Amplification Structure	$ 4,080
4	Radiator	$ 1,224
5	Sapphire window	$ 510
6	Aluminumhousing	$ 1,020
7	Outer PCB	$ 1,530
8	Preamplifier	$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240
	Total	$ 56,816

Table 3: Nominal funding request -40% for FY'23. Line item 1 and 2: fully loaded.

4.3 Budget requests for FY'23/'24/'25

Our baseline funding request for year 1 to 3 is summarized in Table 4.

Item	Nominal Budget	**Year 1**	**Year 2**	**Year 3**	**Total**
1	Salary Ph.D. student	$ 61,525	$ 63,201	$ 64,927	$ 189,653
2	Travel costs (Test Beam)	$ 7,975	$ 15,950	$ 15,950	$ 39,875
3	Picosec Amplification Structure	$ 4,080	$ 4,250		$ 8,330
4	Radiator	$ 1,224	$ 1,500		$ 2,724
5	Sapphire window	$ 510			$ 510
6	Aluminum housing	$ 1,020			$ 1,020
7	Outer PCB	$ 1,530	$ 1,530		$ 3,060
8	Preamplifier	$ 4,590			$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240			$ 12,240
	Total	$ 94,694	$ 86,431	$ 80,877	$ 262,002

Table 4: Nominal funding request for three years for SBU. Line item 1 and 2: fully loaded. Line items 3 and 4 are two different amplification structures.

4.4 Reduced funding request

Two reduced funding request scenarios are described. In both cases the request for Ph.D. student support has to be reduced to 75% and 50%, respectively plus reduction in travel costs. The requested funding for hardware needs to stay at the same level because it cannot be compromised. The reduced student's salary support would make the project extremely difficult if not impossible.

Item	Nominal Budget -20%	Year 1	Year 2	Year 3	Total
1	Salary Ph.D. student	$ 46,144	$ 47,401	$ 48,695	$ 142,240
2	Travel costs (Test Beam)	$ 4,417	$ 14,464	$ 16,007	$ 34,888
3	Picosec Amplification Structure	$ 4,080	$ 4,250		$ 8,330
4	Radiator	$ 1,224	$ 1,500		$ 2,724
5	Sapphire window	$ 510			$ 510
6	Aluminumhousing	$ 1,020			$ 1,020
7	Outer PCB	$ 1,530	$ 1,530		$ 3,060
8	Preamplifier	$ 4,590			$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240			$ 12,240
	Total	$ 75,755	$ 69,145	$ 64,702	$ 209,602

Table 5: Nominal funding request -20% for three years. Line item 1 and 2: fully loaded. Line items 3 and 4 are two different gain structures.

Item	Nominal Budget - 40%	Year 1	Year 2	Year 3	Total
1	Salary Ph.D. student	$ 30,763	$ 31,601	$ 32,464	$ 94,827
2	Travel costs (Test Beam)	$ 859	$ 12,978	$ 16,062	$ 29,899
3	Picosec Amplification Structure	$ 4,080	$ 4,250		$ 8,330
4	Radiator	$ 1,224	$ 1,500		$ 2,724
5	Sapphire window	$ 510			$ 510
6	Aluminumhousing	$ 1,020			$ 1,020
7	Outer PCB	$ 1,530	$ 1,530		$ 3,060
8	Preamplifier	$ 4,590			$ 4,590
9	Digitizer SAMPIC 128 CH	$ 12,240			$ 12,240
	Total	$ 56,816	$ 51,859	$ 48,526	$ 157,200

Table 6: Nominal funding request -40% for three years. Line item 1 and 2: fully loaded. Line items 3 and 4 are two different gain structures.

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