Performance of GridPIX Detector in Magnetic Field with low mass and high efficiency CO_2 cooling

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We propose to extend the GridPIX Detector investigation which was funded via generic EIC R&D-FY22. For the FY-23 R&D call we would like to include two crucial components which were not included in the previous proposal: namely, the tracking and PID performance in the magnetic field of the tertiary beam line, and a low mass, high efficiency CO_2 cooling to significantly reduce the material budget in the hadron going direction. This proposal significantly leverages the existing funds from FY22 program and the infrastructure from both CO_2 cooling and the sPHENIX-TPC. Both CO_2 cooling and the use/configuration of the tertiary beam line at FNAL with magnet can have wide range of benefits for other detector subsystems for the EIC second detector.

1 Motivation

The introduction to the GridPIX technology, conceptual design and anticipated performance for aGridPIX based TPC in the context of an upgrade option for the existing detector or/and for an envisioned new detector at IP8 is described in the proposal for FY2022 which was approved for funding (Tracking and PID with a GridPIX Detector). For the FY22 proposal, funds were requested to perform mainly the PID capability of GridPIX TPC at FNAL test beam facility with secondary and tertiary beams. Further it was proposed to go to Argonne National Lab in the next R&D cycle (if funded) to test the tracking performance with cosmics inside a magnetic field. This would provide a field up to 4 Tesla, but would be limited in statistics due to using cosmic rays as the particle source. Here we discuss two new studies that will enable a high statistics tracking performance assessment and low mass studies. These are both new topics as compared to last year's proposal.

1.1 High Statistics Performance Studies in a Field

At the time of that writing, there was no possibility of having a functional magnet of a size that can accommodate the TPC prototype at FNAL. During our recent visit to FNAL (Hemmick and Garg) we were shown that a 0.7 T dipole magnet, so called "Jolly Green Giant" (Fig.1), has been recently refurbished and the GridPIX TPC prototype can fit in easily. However, in order to use the GridPIX TPC inside the magnet additional tracking detectors will be required (upstream and downstream of the TPC) to study the tracking performance.

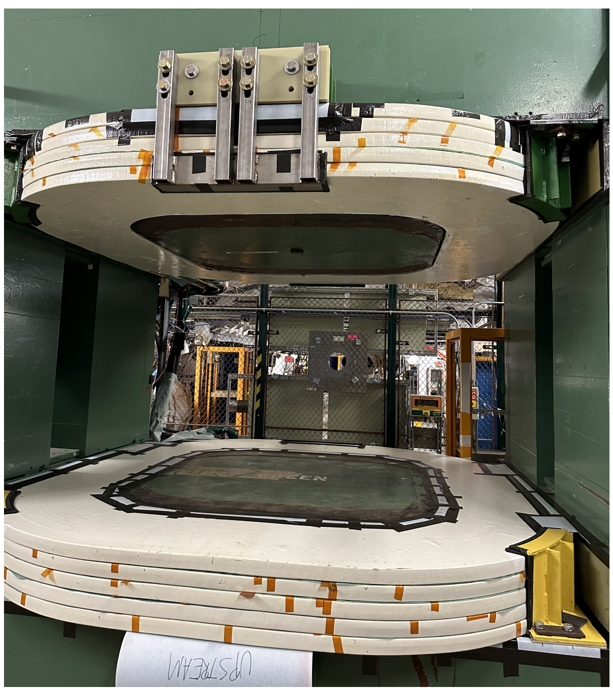

Figure 1: The so called "Jolly Green Giant" dipole magnet (up to 0.7 T) at FNAL MCenter test beam area.

1.2 Development of CO_2 Based Cooling

Another motivation is to work towards a reduction of the material budget at the readout end in the hadron going direction. Figure 2 shows the basic layout of a single sided TPC, where the electron going direction is a thin low material cathode already. Since the heat load of GridPIX chips is not negligible, it poses challenges to cool the electronics while maintaining the low material budget.

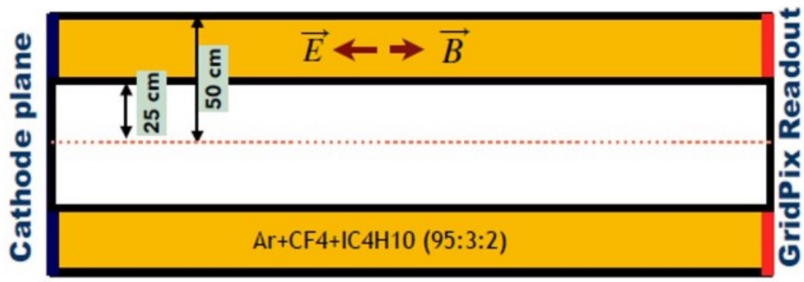

Figure 2: The basic layout implements a single-sided TPC volume with a negative cathode at negative η and a GridPIX readout plane at the positive eta end.

Further, conventional methods of water cooling don't result a uniform temperature inside the gas volume. Since GridPIX relies on individual electron counting, this can have a particularly detrimental effect.

Purdue University and Yale University will collaborate on various aspects of a CO_2 cooling setup, with a clear deliverable of a small scale system able to provide R&D capabilities at Purdue and Yale University to study aspects of low mass, high efficiency cooling. This particular cooling scheme might be beneficial for other detector subsystems, e.g. for the AC-LGAD time-of-flight system in hadron going direction for ePIC. The material budget is expected to reduce significantly by implementing such a CO_2 cooling technique.

2 Implementation

2.1 Conceptual Design

The process of ionization in a gas is a multi-step phenomenon. First, interactions between the charged particle and the surrounding gas produce ionizations known as "primary" electrons. The statistics of primary ionization are purely Poisson in nature and, if directly countable, would have a $\frac{dE}{dx}$ precision that scaled with $\sqrt{N_{primary}}$. Alas, nature is not so kind and each primary ionization also produces some number of secondary ionizations (2-4 typically). The fluctuations in the secondary yield generate the long high-side Landau tail which is the bane of the existence of all detectors that attempt to measure $\frac{dE}{dx}$ as a PID technique. The two basic approaches to fighting the Landau tail up to this point are:

- Truncated mean
  - Split the ionization trail into many small samples along the length.
  - Reject all measurements that are a factor higher than the mean of the others.
  - Average the remaining samples.
- Distribution Fit
  - Split the ionization trail into many small samples along the length.

- Fit the probability distribution of all the samples to a Landau curve.
- Use the most probable value from the fitted Landau function as $\frac{dE}{dx}$

Both of the traditional methods require the the ionization trail be divided into as many small samples as is practical. Macroscopic pads in a traditional pad plane are rather large as compared to the typical distance between ionization, and thereby always measure the integral of charge from a large but unknown number of primary ionizations. A sort of ”Holy Grail” has been the concept to move from samples of many clusters to so-called cluster counting [1]. This quest has been one of the driving factors in the development of the GridPIX chip, which is in many respects ideally suited for PID at low momentum at the EIC.

Additionally, when coupled to a low diffusion gas in magnetic field, the GridPIX technology will act as a high resolution tracker competitive with all silicon systems.

GridPIX chips have already undergone multiple development stages, the most recent of which is GridPIX 4 [2] [3] [4][5][6][7][8][9] [10][11]. The progression from the individual chip to the functioning tracker, is depicted in Fig.3. Single chips are mounted into a ”quad”, several of which make a ”module” that is finally coupled to a gas volume to form a GridPIX tracker. The event show here is especially illustrative of the power of the high pixellation as applied to the PID task. A large ”blob” that is possibly a delta ray, is clearly visible near the center of the track. This can be removed topologically, thereby producing a substantial improvement in PID performance over conventional readout.

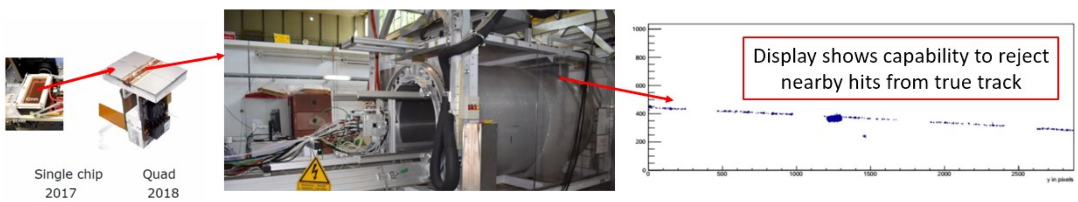

Figure 3: Building a set of chips into an array suitable for a test beam experiment.

2.2 Anticipated Performance

As mentioned previously, the task of PID via $\frac{dE}{dx}$ is typically easiest at the lowest momenta. The reason for this fact is neatly summarized in Fig. 4. Notice that the axes of the figure are plotted logarithmically. The region to the left of the thick purple line indicates momenta below 0.5 GeV/c the pion/kaon/proton separation is quite clear. We are not, however, proposing to build the STAR TPC with its 2 meter track length and roughly 100 samples along each track. Nonetheless, we can use the measured $\frac{dE}{dx}$ from STAR (which uses a dominantly Argon-based gas) and use known techniques to scale the resolution as a function of detector length.

Figure 5 shows in the left hand panel a so-called Lehraus plot. This analysis accumulates the measured $\frac{dE}{dx}$ for all known TPC experiments as a simple function of the length of the measured ionization trail. The world's TPC data indicates a $\sim$universal scaling of the energy resolution with path length. Using both the 1983 and the 2021 scaling laws, we can extrapolate the resolution prediction to our proposed detector length (25 cm) and thereby calculate with the STAR data the number of sigma separation we expect in the low momentum regime. The result is remarkable in the a worst case of 20 σ separation is observed. We take this rather optimistic result as a worst case since the Lehraus scaling applies to conventional TPC readout and the GridPIX should perform in a far superior manner. In any case, we can anticipate superb hadron ID for all low momentum hadrons with only a 20 cm path length.

As a final note, Fig. 6 shows the diffusion as a function of electric and magnetic fields for the gas mixture used in most GridPIX studies. This gas exhibits exceptionally low diffusion at high

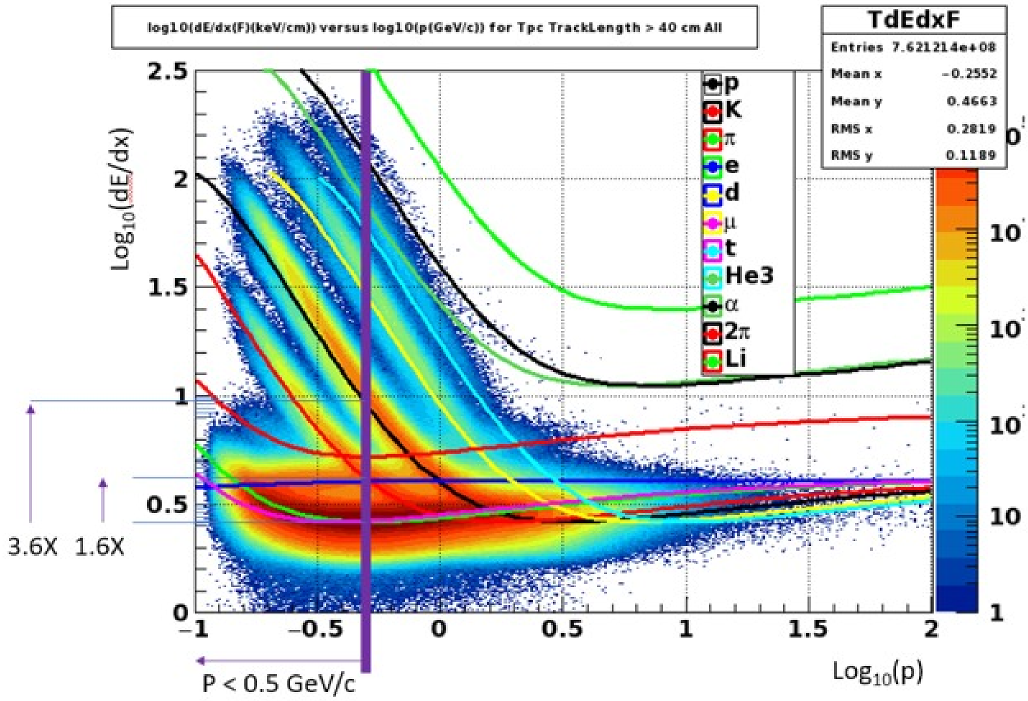

Figure 4: $\frac{dE}{dx}$ measured in the STAR TPC. The figure illustrates that the although $\frac{dE}{dx}$ measurements can be challenging in the region of the relativistic rise, the low momentum regime is comparatively simpler.

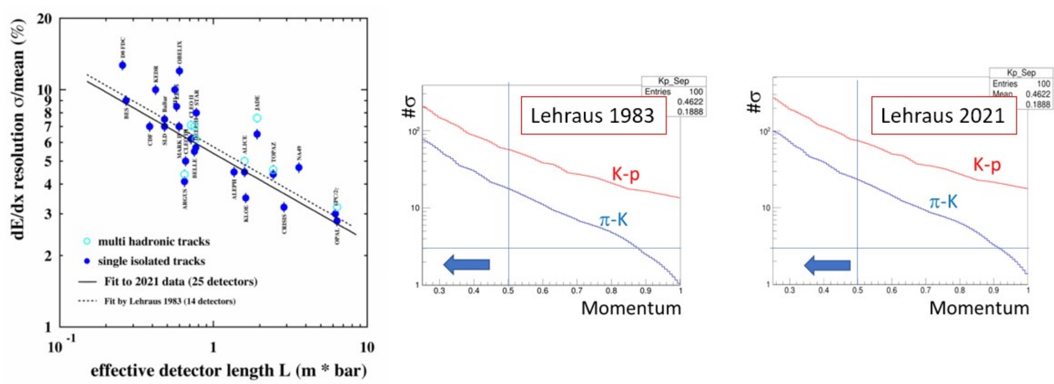

Figure 5: Lehraus has shown that all past TPC efforts lie along a universal curve correlating resolution with detector length. The parameterization of this performance allows one to extrapolate to a mini-TPC device to predict its efficacy.

field and thereby makes a positive contribution to overall tracking resolution. For this reason, we anticipate that implementations wherein a GridPIX system were embedded into a silicon system like those considered by ATHENA and ECCE would overall likely have a positive impact on the momentum resolution. We note that it would certainly have a major positive impact on pattern recognition by providing thousands of points along each track. This latter consideration would certainly become more important as the machine luminosity increases over the years.

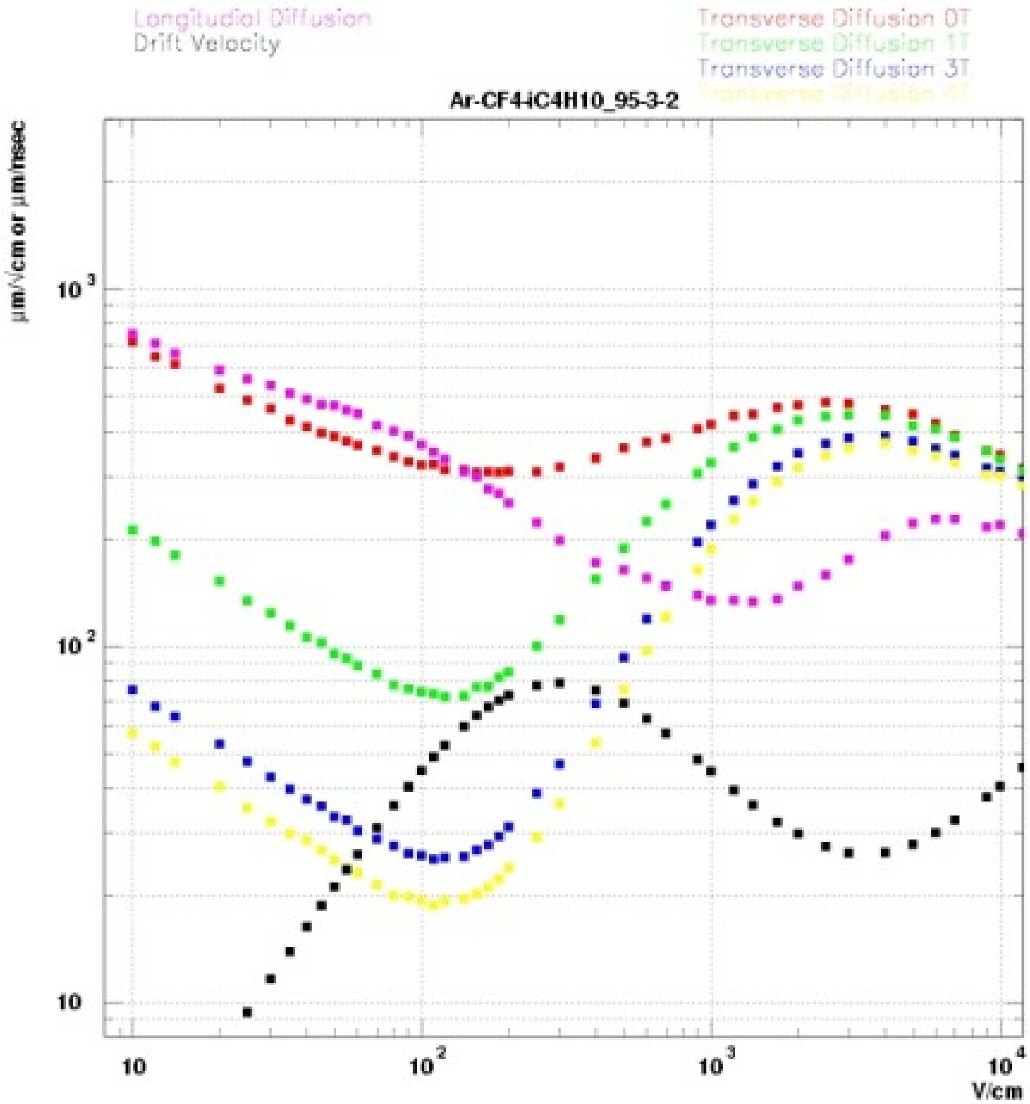

Figure 6: Transverse diffusion as a function of drift field for a variety of magnetic field values.

3 R & D Plans

The groups collaborating on the GridPIX project have varied and often complementary experience with detector R&D. Stony Brook has experience with gas Cerenkov detectors for EIC and the sPHENIX TPC, Yale has experience in many technologies including state-of-the-art pad segmentation strategies, whereas Nikhef and Bonn are long time developers and users of the GridPIX. Purdue has a long experience from CMS on mechanical structures and cooling.

Our basic strategy would be to initiate our R&D efforts through reuse of existing parts from past R&D's. In particular, we would imagine combining the existing TPC prototype field cage from the sPHENIX studies with the quad GridPIX modules into a functioning single ended TPC. The external trackers for this test will also be managed through local resources. Most of the request for FY23 will be towards cooling R&D and to cover personal expenses to travel and stay for the test beam duration.

We will have huge advantage for FY23 as the R&D funds from FY22 will help us in many ways. The MCenter beam line operates rather differently than MTest. MCenter experiments are anticipated as longer term occupants and typically equipment is either left untouched between runs or rolled to the side. Thus, our heavy equipment will not need to be transported again using the FY23 funds.

It is to be noted that the magnetic field at FNAL is only about 0.7T. By using Eq.1 we can extrapolate the resolution at any other magnetic field by knowing the diffusion coefficient from Garfield++ calculations.

$$\sigma_{total}^2 = \sigma_{pixel}^2 + \frac{D_t^2}{N_{eff}} L \tag{1}$$

Here, σ_{pixel} is the resolution because of pixelation, D_t is the transverse diffusion at a given magnetic field, L is the drift length and $N_{effective}$ is the effective number of electrons.

3.1 Thermal Management with CO_2 Cooling System

The Purdue HEP group has resources for studying thermal properties of advanced light-weight materials (including composites) available that allow advanced thermal and mechanical FEAs, measurement of thermal conductivity, as well as a CO2 cooling setup with a cold box (see Fig.7) for testing cooling structures. Apart from the hardware Purdue also has extensive capabilities for finite element analysis of thermal & mechanical properties of composite structures, including composite materials (ANSYS), Solidworks, and Autodesk design (CAD).

Also, the renovated Wright Lab at Yale allows the group access to large detector test and assembly areas, professional and student machine shop, CAD computers with latest versions of several design programs and prototyping shop with 3-D printers, a large water jet cutter, and a large laser cutter. So the idea would be to build a portable CO_2 cooling system at Yale, which can be shared with other EIC subsystems if they wish to use it, with the help of expertise from Purdue. Purdue will also upgrade their system to carry out thermal performance studies, which will benefit R&D projects for the LGAD TOF system as well. Once the CO_2 cooling setup is fully commissioned and matched to the needs of the testing, it will be adopted for the GridPIX readout plane.

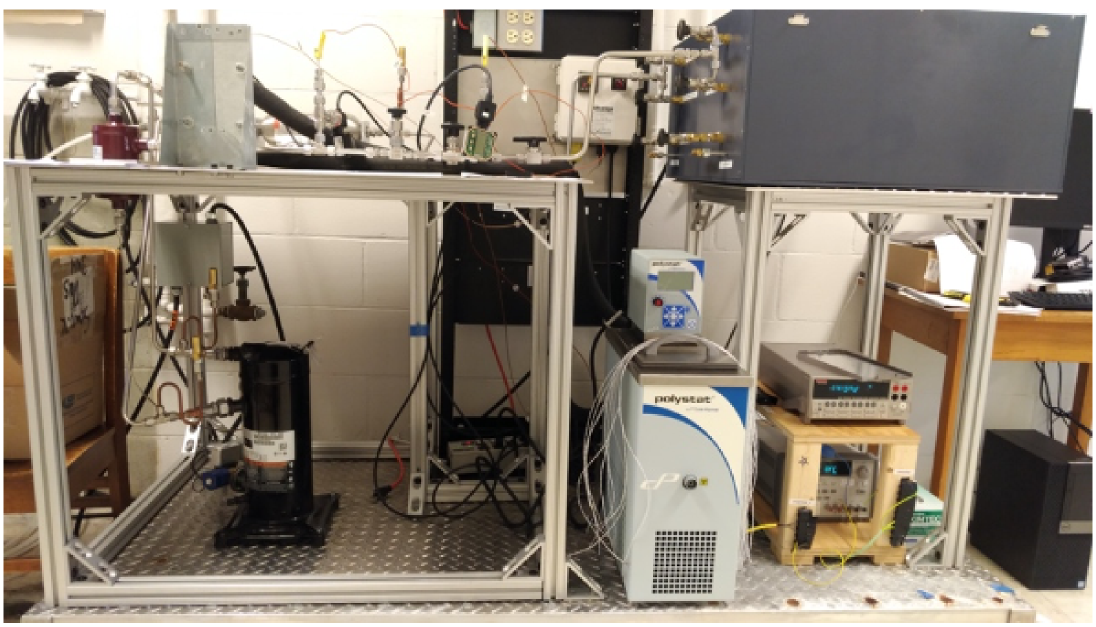

Figure 7: Cold box setup in the PSDL mechanics lab with compressor, refrigeration, storage tank, cold box itself, and a Keithley-based readout system connected to a PC at Purdue.

3.2 Test Beam at FermiLab inside Magnetic Field

In the US, the Fermilab test beam is the best source of mixed particle type beams at low momentum. This makes Fermilab the principle facility of interest for our initial run. Figure 8 shows the sPHENIX TPC prototype installed at the Fermilab Test Beam facility. The field cage and surrounding accoutrements would be reused for the initial GridPIX run. The machining of the new end plate for the TPC that accepts GridPIX grad modules instead of quad GEM stacks is already funded through FY22. The only major additional part we will need would be two trackers for tracking performance studies, we are only requesting money for gas bottles. In addition we would like to integrate the CO_2 cooling system at the end-plate of our readout plane of GridPIX and test the effect on track resolution.

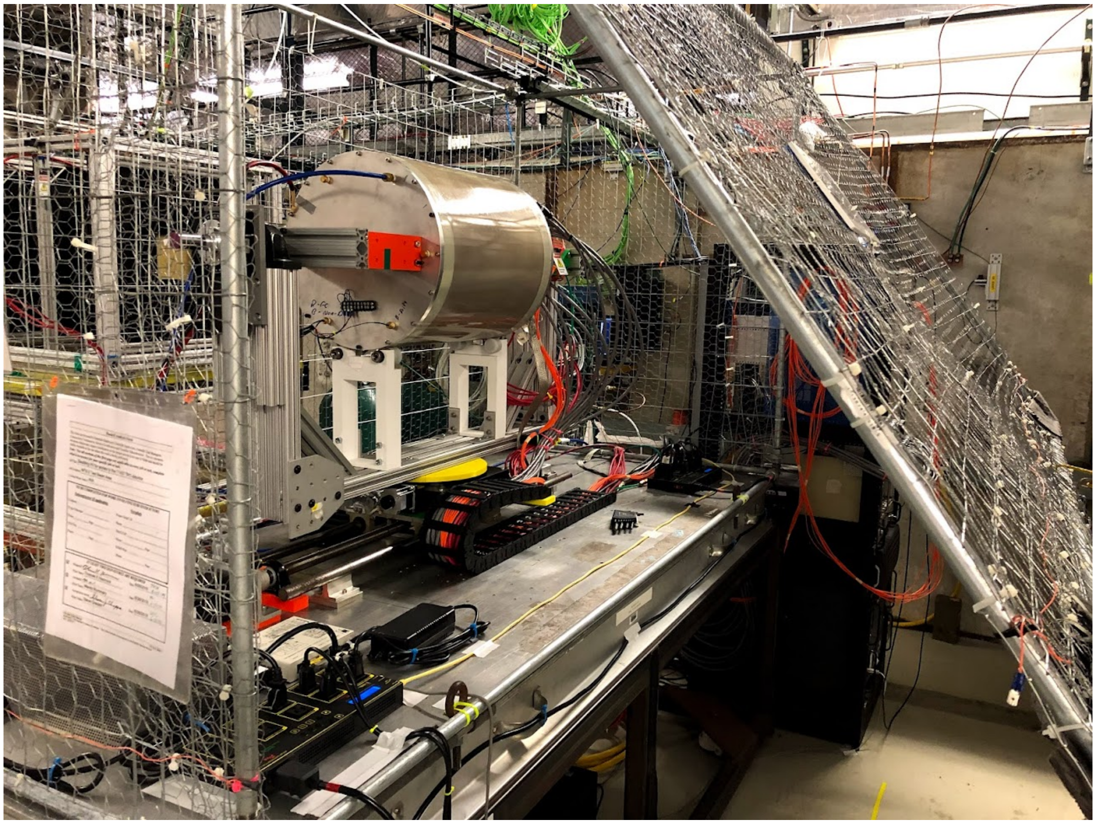

Figure 8: The sPHENIX TPC prototype set up in test beam in 2019. The field cage and all mechanical motion apparatus would be reused for the GridPIX experiment.

3.3 Cost Effectiveness

Through the heavy reuse of existing equipment and FY22 funding, the equipment costs of the proposal are rather low. It will be dominated by the CO_2 cooling system and personnel travel.

4 Budget

Table 1 shows our estimated costs for the FY23 of the project as well as a response to how we will continue in the case of reduced funding. To understand the scaling, it is important to understand the input assumptions. Our FY23 funding request is focused on the a single test beam run with a marriage of the sPHENIX TPC prototype field cage with the existing quads from Nikhef and the resources from FY22 funds and equipment for the cooling studies. Since there is no way to scale down significantly the costs of cooling equipment, our only options are travel reduction and support for an undergraduate student at Purdue. Hence, to produce reduced cost scenarios, we have been forced to search elsewhere for savings. The major category for savings is therefore the travel costs.

Item	Description	Nominal	20% down	40% Down
1	CO_2 Cooling	$50,000	$45,000	$35,000
2	Gas	$1,000	$1,000	$500
3	Travel (SBU)	$15,063	$11,633	$7,017
4	Travel (Yale)	$8,950	$6,170	$4,455
5	Travel (Purdue)	$5,180	$2,590	$1,295
	Total	$ 80,193	$ 66,393	$ 48,267
	Reduction		-17.2%	-39.8%

Table 1: Three funding scenarios are presented. The variations are whether we have a full or partial crew to run the experiment and how long the test beam campaign will last.

The details of how the travel budget is estimated are listed in Table 2. The vehicle costs are difficult to understand without explanation. Figure 8 showed the TPC detector set up at Fermilab for a past beam test. This detector includes not only the field cage cylinder, but a remote control positioning apparatus allowing the detector to be repositioned for various drift distances, rotated around the vertical axis to simulate non-zero eta tracks, and around its own axis to simulate low momentum tracks. These are unusual motions and are not provided by the facility itself. Therefore, our apparatus stands directly on the floor, raises the detector to beam height, and is very heavy. Since the detector will be moved to FNAL from FY22 funds, that saves a lot of money for transportation.

We propose to bring many young students to the test beam (see Figure 9), and we have found that having this crew drive a minivan or SUV from SBU is much more cost effective than buying plane tickets. Finally, it is necessary when running 24 hour shifts to have two vehicles for ferrying people back and forth to the hotel. Thus we require two rental cars (minivan driven from SBU and a second car rented in Chicago) for managing transportation to and from the hotel.

Item	Description	Cost
1	Vehicles and Fuel (14 day)	$ 7,724
2	Vehicles and Fuel (7 day)	$ 3,862
3	Hotel Rate per Room	$ 155
4	per diem	$ 30
5	Airfare/person (Yale)	$ 190

Table 2: Assumed rates used to calculate expenses.

Table 3 shows how the reductions from the original estimate are calculated. To achieve a roughly 25% reduction in cost we must trim the personnel who travel for test beam.

The final opportunity for cost reduction is to reduce the test beam duration from two to one week. Users who are familiar with the Fermilab test beam will recognize that runs are quantized by weeks. However, the available useful beam time does NOT scale linearly. The first few days of any run are dedicated to setup and safety inspection. The last days are dedicated to packing. Therefore the loss in running time by changing from a two week run (likely to be successful) to a one week run (risk of failure) is close to a factor of three. The savings, do not quite achieve the total loss of 40% but we do not see any further options to reduce the cost.

Item	Description	Request	20% Down	40% Down
1	Test Beam Duration	14 days	14 days	7 days
2	SBU Senior Personnel	2	2	2
3	SBU Junior Personnel	4	1	0
4	Yale Senior Personnel	2	2	2
5	Yale Junior Personnel	2	1	1
6	Purdue Senior Personnel	1	1	1
7	Purdue Junior Personnel	1	0	0

Table 3: Scenarios for Reduced Budgets.

5 Diversity, Equity, and Inclusion

Stony Brook University has been engaged in diversity, equity, and inclusion practices since before the term came into common use. We are among the top few percent of school in the country for the high percentage of students who are first-in-family to attend college. We are also a university the strives to get undergraduates involved in research. Indeed, the general education curriculum requires every undergraduate to get a non-classroom experience before they may graduate. The result of these policies is shows pictorially in Figure 9.

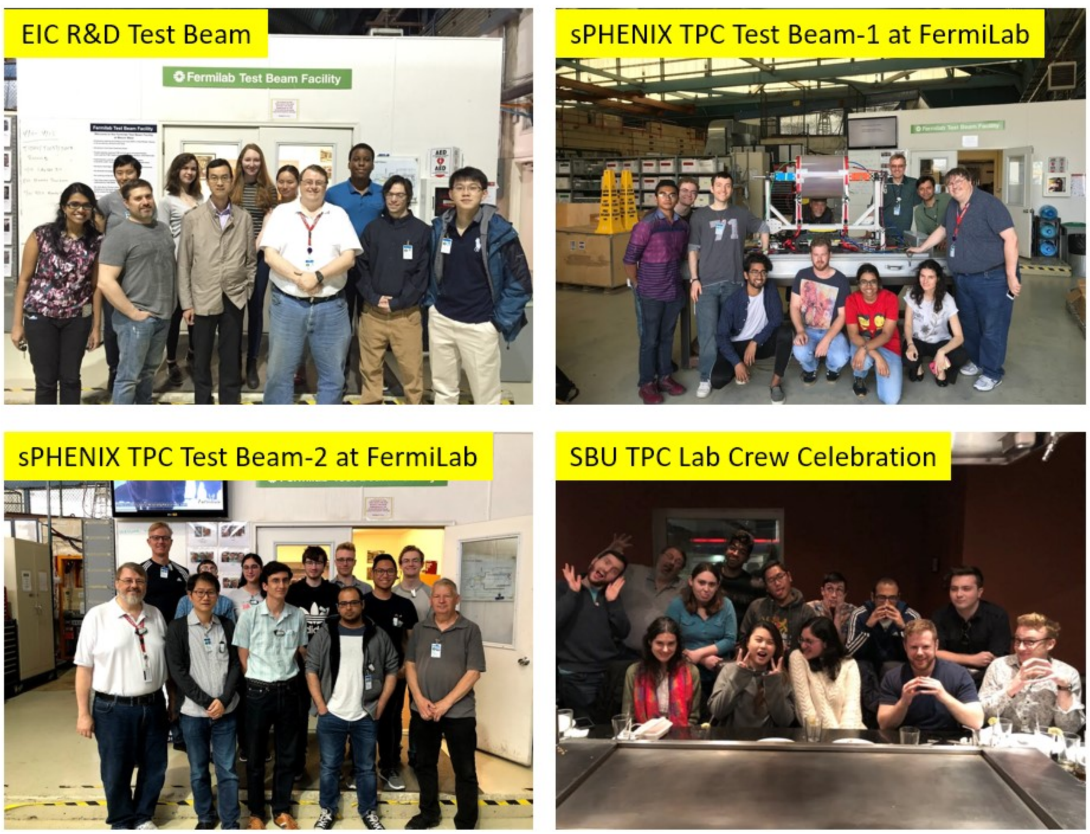

Figure 9: Stony Brook has a long tradition of supporting diversity, equity, and inclusion. These panels show the photos of the faculty, staff, and students present at our most recent three test beam campaigns. Additionally, the panel in the lower right shows the at home SBU crew celebrating a milestone in TPC construction.

Figure 10: RHI group at Wright Lab, Yale University. The Yale group has also a long tradition of supporting diversity, equity, and inclusion. Picture shows some of the current faculty, staff, postdocs, graduate and undergraduate students.

Our test beam efforts have always included many young students with backgrounds as diverse as our undergraduate classes. Additionally, PI Hemmick was a member of the committee that wrote the ATHENA charter which included a detailed policy for nurturing DEI.

6 Progress Report

Because of the delay in receiving funds for FY22, a beam test campaign has delayed. We have been active to organize and plan during our weekly meetings and some of the accomplishments are as follows:

- Nikhef refurbished and repaired DAQ computer.
- Nikhef wrote DAQ documentation and trained all the other groups how to run it.
- Nikhef tested and verified the functionality of the module.
- Nikhef packed the module for shipping.
- A draft of the loan agreement was written and is approved by Nikhef and under review at SBU.
- SBU and Yale traveled to Fermilab to inspect MCenter.
- Yale is negotiating with TOAD time-of-flight regarding use of beamline PID detectors.
- We have added Purdue University as a new collaborator for the purpose of developing cooling technology.
- Some of the possible gas mixtures have been identified by Yale group.

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