MRI Consortium: Development of a multi Time Projection Chamber (mTPC) for Jefferson lab Tagged Deep Inelastic Scattering (TDIS) experimental program

3. Project Description

a. Information about the proposal

a1. Instrument Location and Type: Instrument Location: Experimental Hall A, Thomas Jefferson National Accelerator Facility (Jefferson Lab), Newport News, Virginia.

The instrument to be developed is a multiple Time Projection Chamber (mTPC) for detecting and measuring the momenta of low energy proton tracks under high rate conditions in nuclear physics experiments.

a2. Justification for submission as a Development proposal:

How will the end result of the effort be a stable shared-use research instrument? The proposed mTPC is developed to be the key instrument needed to realize the Jefferson lab experimental Hall A high luminosity spectator tagging experimental program. There are already two approved Jefferson lab experiments in the TDIS experimental program which will use this device. In addition, there is another experiment being developed currently to measure Deeply Virtual Compton Scattering (DVCS) on the neutron using the proposed device. Furthermore, the proposed device will become part of Jefferson lab experimental hall A setup and will be available for experiments by the entire Hall A collaboration of over 250 physicists. It is expected that this powerful device will enable many exciting experiments in the future.

What significant new capabilities, not available in an instrument provided by a vendor, will the new instrument provide? The proposed mTPC is a cutting edge pioneering experiential device not available from any vendor. Compared to other similar devices previously developed, the proposed device will provide significantly higher background rate capability and wider range of detected proton momenta.

Does the instrument development effort build capacity for instrument development activities within an MRI submission-eligible organization(s)? Yes, the University of Virginia group currently has the expertise and capability for developing large area Gas Electron Multiplier (GEM) trackers. The proposed project will allow this group to extend its expertise into the new area of GEM based Time Projection Chambers. Furthermore, the proposed project will significantly enhance the detector development capabilities at Hampton University (HU).

In what way does the instrument development require design and development work that must be undertaken or has been undertaken in-house, rather than through readily available/published designs found in the literature? The proposed device is based on novel design concepts to meet the unprecedented requirements imposed by the TDIS physics program. As such most of the design, development, fabrication, testing and optimization work for this project will be done in house at the collaborating institutions, UVa, HU and Jefferson Lab. The only main components not fabricated in house are the GEM foils, which will be manufactured at the CERN GEM shop per designs developed by this collaboration and the readout electronics components which will be based on the electronics developed for the ALICE TPC device at CERN.

To what extent does the instrument development require/benefit from a team of scientists/engineers/technicians that bring a variety of skills to the project? This ambitious detector development project requires diverse specialized skill sets on many fronts. The UVa group brings in their GEM technology, detector design and fabrication expertise. The HU group, which is a leading institution in the BONUS RTPC project, bring in its TPC and cylindrical geometry detector expertise. The Jefferson lab readout electronics experts contribute to the readout development of the project. Monte-Carlo simulation experts from the wider TDIS collaboration also bring in their skills to this project.

For what activities does the instrument development require a significant number of person-hours, more so than simple "assembly" of purchased parts? The activities requiring a significant number of person-hours include design, prototyping, testing and optimization cycles, as well as the fabrication and testing of the final device.

To what extent does the instrument development require time-frames for completion that are longer than are required for plug-and-play or assembled instruments? The estimated time frame of 2 years for the proposed project is significantly longer than what is required for just the assembly of an instrument. Based on our experience from previous large instrumentation projects, we estimate that about 2/3 of the allocated time will be used for design, prototyping, testing and optimization cycles.

Does the instrument development require the use of a machine shop or a testbed to fabricate/test unique components? Yes, manny of the components of the proposed device such as the mTPC body components, pressure vessel components etc., as well as assembly fixtures, will be fabricated at the UVa physics machine shop.

Does the instrument development effort involve risks in achieving the required specifications, and what is the risk mitigation plan? The main risks associated with the project include GEM foil failures and readout electronic module failures. The risk mitigation plan includes building the mTPC as a modular device so that a single faulty TPC module can be replaced with a spare, fabricating and maintaining two spare TPC modules, and having approximately 20% spare electronics modules.

b. Research Activities to be Enabled.

The proposed mTPC device, combined with Jefferson lab Super Bigbite Spectrometer [2], allows precision measurements of high luminosity electron scattering off effectively free pion, kaon and neutron targets through the spectator tagging technique. This will allow the measurement of some of the most sought after quantities in particle physics such as Deeply Virtual Compton Scattering (DVCS) on the neutron, elastic form factors for pions and kaons at high Q^2, and structure functions for pions and kaons. Currently there is no or very little data for most of these reactions.

TDIS experimental program: The first use of the mTPC will be as the key instrument needed to realize Jefferson lab TDIS experimental program, E12-15-006 [4]. The physics motivation for the TDIS program is to pioneer a measurement of the Deep Inelastic Scattering (DIS) cross section, while tagging low-momentum recoil and spectator protons for the purpose of probing the elusive mesonic content of the nucleon structure function. A second experiment, C12-15-006A [5], which has been already approved by the Jefferson Lab PAC to be a part of the TDIS program will explore the structure of the Kaon, in addition to the structure of the pion.

The virtual meson "cloud" of the nucleon plays an important role in the understanding of the nucleon-nucleon interaction and the pion cloud in particular has always been considered critical to understanding the nucleon's long-range structure. At shorter ranges, the role of mesons in electron-nucleon deep inelastic scattering (DIS) has also been investigated. In 1972 Sullivan [8] suggested that some fraction of the nucleon's anti-quark sea distribution may be associated with this pion content of the nucleon. For many decades this and numerous other theories that describe and/or utilize the meson cloud of the nucleon have advanced significantly (see [10, 11, 12] for some review). From partially conserved axial current to the success of chiral quark models, it is considered known that the nucleon has an associated meson cloud. In very stark contrast to the substantial body of theory associated with the meson cloud, however, experimental results remain few and far between.

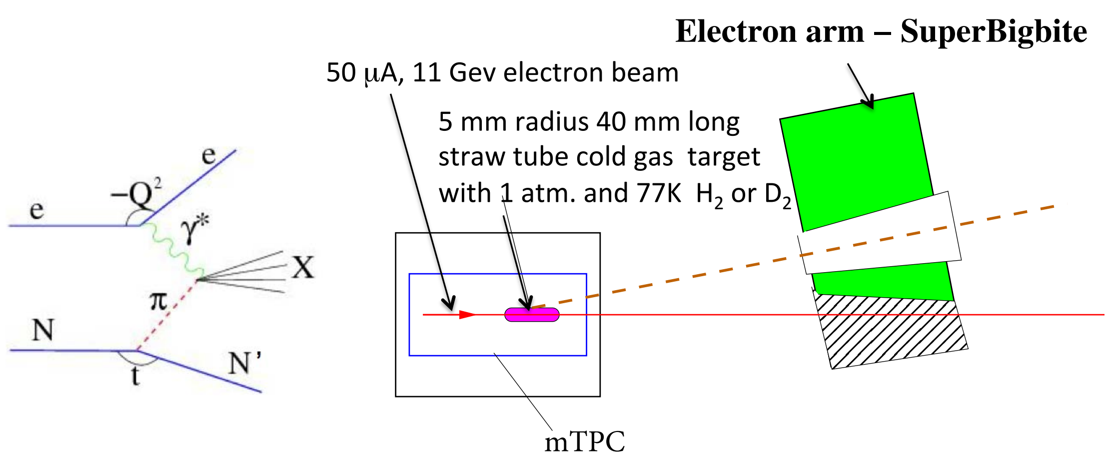

Figure 1: Left: Feynman diagram for electron scattering from the pion cloud of the nucleon N, with the initial nucleon at rest (the Sullivan process). Right: Schematic layout of the proposed experiment. Note that this sketch is not to scale.

The 12 GeV upgrade of JLab presents new opportunities to study the mesonic structure of the nucleon. One such technique is to measure the contribution to electron Deep Inelastic Scattering (DIS) off the meson cloud of a nucleon target, as pointed out by Sullivan [8] (Fig. 1-left).

In the TDIS experiment we plan to measure semi-inclusive reactions $H(e, e'p)X$ and $D(e, e'pp)X$ in the deep inelastic regime of $8 < W^2 < 18$ GeV^2, $1 < Q^2 < 3$ GeV^2, and $0.05 < x < 0.2$, for very low proton momenta in the range of 60 MeV/c to 400 MeV/c. The key to this experimental technique is to measure the low-energy outgoing "recoil" proton in coincidence with a deeply inelastically scattered electron from the hydrogen target. In the deuterium case, an *additional* low energy spectator proton will be identified at backward angle to identify the neutron target. The inclusive electron kinematics determine that a DIS event has occurred, i.e. that the reconstructed Q^2 and missing mass, W^2, of the recoiling hadronic system are sufficiently large. However, unlike the standard inclusive case, the low momentum protons N' measured in time and vertex coincidence with the DIS event ensure that the deep inelastic scattering occurred from partons within the meson cloud (here identified as a pion) surrounding the nucleon. This can be achieved by employing the Super Bigbite Spectrometer to detect the scattered electrons in time and vertex coincidence with low momentum proton(s) measured in the low mass mTPC device proposed here.

The idea of considering the meson cloud as a virtual pion target was used at the HERA $e-p$ collider to measure the pion structure functions at low-x in a hard diffractive process [9], where forward-going neutrons or protons were tagged in coincidence with the DIS events, as shown in Fig. 1-left. While the HERA experiments have provided very interesting first data on the extraction of pion structure functions using the Sullivan process, there are many reasons for extending such measurements to JLab energies. The pion, being the lightest and simplest hadron, has a central role in our current description of nucleon and nuclear structure. The pion has been used to explain the long-range nucleon-nucleon interaction, making it a fundamental component of the Standard Model of Nuclear Physics [13, 14, 15]. The pion is also used to explain the flavor asymmetry of the quark sea in the nucleon. Moreover, the masses of light mesons such as the pion are believed to arise from dynamical chiral symmetry breaking [16], and thus models of the pion must account for both its role as the Goldstone boson of quantum chromodynamics (QCD) and as a quark-antiquark system.

In the TDIS experiment, a 50 μA, 11 GeV electron beam from Jefferson lab CEBAF accelerator will be incident on a 5 mm radius 40 mm long straw tube target with 1 atm. hydrogen or deuterium gas maintained at 77 K. The scattered electron will be detected in the Hall A Super Bigbite Spectrometer, while the low momentum recoil proton will be detected, in time and vertex coincidence, by the mTPC device proposed here. The target and the mTPC will be placed in a strong 4.5-Tesla magnetic field created by a large bore solenoid. The solenoidal magnetic field causes the proton tracks to curve, depending on the proton momenta, allowing for the determination of the momentum and energy of each detected proton. This combined system, along with Jefferson lab high current continuous wave electron beam, leverages the high luminosity and unique kinematics required to access the proposed physics.

The Super Bigbite Spectrometer (SBS), currently under commissioning, was funded by DOE, consists of a large dipole magnet and a modular detector package. For the TDIS experiment the SBS magnet (front face of the yoke) will be placed 2.0 m from the target allowing for a 50 msr solid angle around a 12° central angle. The large out-of-plane angle of SBS provides significant coverage in azimuthal angle (about 20% of 2π). In the TDIS configuration, SBS large GEM tracker will be used as the main tracker. This tracker covers a 60 cm x 200 cm area providing a spatial resolution of 60-70 μm. The combination of an electromagnetic calorimeter and a threshold gas Cherenkov counter will be used for trigger and particle identification purposes.

The Measurement of Kaon Structure Function through TDIS: The TDIS experimental program also allows investigation of the kaon structure function using high Q^2 electrons scattered from a hydrogen target in coincidence with low momentum recoiling Λ hyperons reconstructed from decay protons and pions. Jefferson Lab Program Advisory Committee approved the TDIS run group experiment C12-15-006A [5] for this measurement in 2017. In this experiment, the tagging technique allows for probing the strangeness content in the nucleon through its meson cloud, through the Sullivan process. This will be the first ever measurement to explore the kaon structure function.

Simple quark models form a picture of the nucleons structure in terms of its valence u- and d-quark constituents. The subsequent development of QCD clarified this picture to also include the contribution of the sea of virtual quark-antiquark ($q\bar{q}$) pairs and gluons, which made the nucleon a far richer and more dynamic environment. The structure of the nucleon structure in this context should not be limited to the light-quark $q\bar{q}$ sea, but also include local contributions of heavier quarks such as the strange or even charm quarks to the internal nucleon dynamics.

Chiral symmetry breaking in QCD is a fundamental feature of the nonperturbative dynamics of the $q\bar{q}$ sea, including strange (s) and anti-strange ($\bar{s}$) quarks. While the generation of $s\bar{s}$ pairs through perturbative gluon radiation typically produces symmetric s and $\bar{s}$ distributions (at least up to two loop corrections [19]), any significant difference between the momentum dependence of the s and $\bar{s}$ parton distribution functions (PDFs) would be a clear signal of nonperturbative effects. In fact, insights from chiral symmetry breaking in the non-strange sector led to the prediction [21] of an excess of $\bar{d}$ over $\bar{u}$ in the proton, which was spectacularly confirmed in DIS [22],[23] and

Drell-Yan [24], [25] experiments more than a decade later. A similar mechanism, which can be intuitively realized in the form of a pseudo-scalar meson cloud surrounding a valence-quark nucleon core, was subsequently used [26] to demonstrate the natural emergence of a nonzero $s\bar{s}$ asymmetry from the breaking of the chiral SU(3) symmetry of QCD. A recent study [27] provided full details of the calculation of the kaon loop contributions to the strange-quark PDF and its moments in the chiral effective theory. From the theory point of view, substantial studies have been discussed in terms of the formal derivation of the convolution representation, the various contributions from the lowest order diagrams, various regularization procedures that preserve the chiral and gauge symmetries of QCD, and form factors at hadronic vertices. From the effective chiral Lagrangian for parton distributions in the nucleon, twist-two quark operators with the hadronic operators are matched in the effective theory. The matrix elements of these operators are then related through the operator product expansion in QCD to moments of the PDFs.

In striking contrast to the sophisticated theoretical approaches, there is little experimental information at all on the parton distribution of the quark sea in the kaon. The results of the approved Kaon-TDIS measurement will contribute vital information to resolve the question if the valence distributions of the strange and non-strange quarks in the kaon are different and allow for comparing valence distributions in the kaon and pion.

Projected results The full range of results expected from TDIS experiments are presented in the experiment proposals [4].[5]. Among many other results, the TDIS program will provide access to the pion and kaon structure functions via the Sullivan process. Experimental knowledge of the partonic structure of the pion is currently very limited due to the lack of a pion target, and most of the current knowledge of the pion structure function in the valence region is obtained primarily from pionic Drell-Yan scattering [17]-[20]. Currently there is no data available for kaon structure functions.

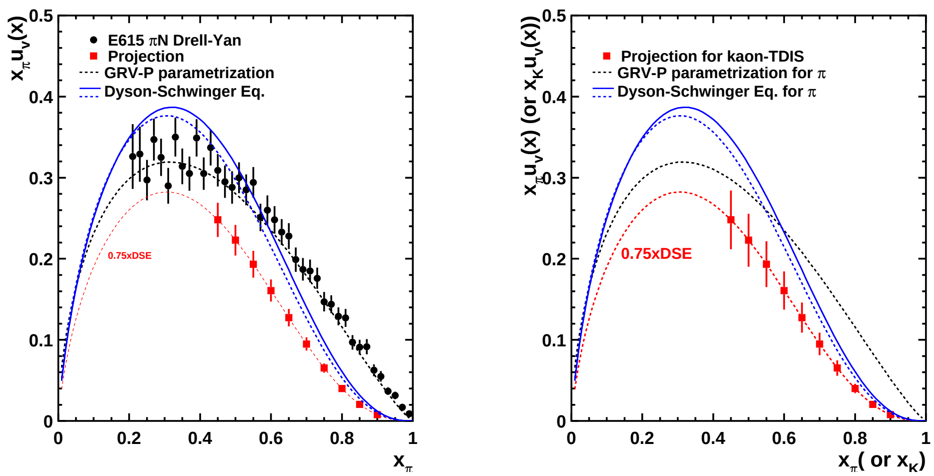

Figure 2: Projected pion (left) and kaon (right) structure function results (red solid squares). Also shown are the results from the pionic Drell-Yan experiment E615, the GRV-P parametrization and a Dyson-Schwinger equation based calculation from Ref. [28]. The projected points are shown along a curve which is 0.75×DSE, in order to demonstrate the potential for shape discrimination. It is important to note that the existing data from the Drell-Yan process are limited to charged pions, while the proposed experiment will also include the neutral pion and provide a check of the validity of isospin symmetry and any dynamical effects that differ between neutral and charged pions.

Fig 2 shows the projected pion and kaon structure function that can be extracted from the TDIS experiment. As can be seen the figure, the proposed data nicely complement the Drell-Yan data and will fill in the heretofore unprobed moderate x range. Moreover and importantly, measurements of pion parton distributions using the Drell-Yan process are limited to charged pions, while the proposed experiment will also include the neutral pion and provide a check of the validity of isospin symmetry and any dynamical effects that differ between neutral and charged pions.

Tagged Neutron DVCS Measurement: Another major research area made possible by the proposed detector is tagged neutron Deeply Virtual Compton Scattering (DVCS). The theoretical advances since mid 1990s allow us to study the internal structure of nucleons in a whole new way by carefully mapping out the three-dimensional spatial distributions of individual partons (i.e., quarks and gluons), which are normally given in term of Generalized Parton Distributions (GPD) [29, 30, 31, 32]. At leading twist, each quark/gluon flavor has eight GPDs, including $H^{q/g}$, $E^{q/g}$, $\tilde{H}^{q/g}$, $\tilde{E}^{q/g}$, and their corresponding transverse component, $H_T^{q/g}$, $E_T^{q/g}$, $\tilde{H}_T^{q/g}$, $\tilde{E}_T^{q/g}$. Individual GPDs give different internal dynamic correlations of partons and their contributions to the nucleons properties, for example, how the spins and orbital angular momenta of partons contributes to the nucleon spin [30]. GPDs also provide a link between the well measured electromagnetic form factors and parton distributions within the same formalism [33, 34].

There are multiple hard exclusive reactions that allow us to probe GPDs. Among them DVCS is the golden channel to experimentally study GPDs [34]. In electron scattering off nucleons with sufficient large momentum transfer, one measures the hard-exclusive photons produced in the Bethe-Heitler (BH) and the DVCS processes as well as their interference, and isolates the DVCS amplitude which is correlated to corresponding GPDs. The DVCS amplitude is normally composed by the mixture of different GPDs coupled to kinematic quantities. To separate all GPDs for individual quarks and gluons, we not only need to perform the measurement over a wide range of kinematic phase-space, but must also do the measurements with both proton and neutron targets to perform flavor separation. Moreover, the DVCS on unpolarized neutron is more sensitive to the GPD E.

Because of the low production rate and strict requirements in term of kinematic coverage and experimental precision, there have been only a handful DVCS measurements on protons in the last 20 years; and the measurements on neutrons are even more rare. One of the main difficulties of performing neutron DVCS measurements is the lack of free neutron targets. Deuteron targets have been commonly used as effective neutron targets but they carry strong nuclear effects, such as Fermi motion of the neutron inside the nucleus. Furthermore, the subtraction of contribution from scattering off the proton inside the deuteron introduces large systematic uncertainties, and the separation of the coherent DVCS on deuterium contribution by only relying on the calorimeter resolution has not been possible. The Hall-A experiments, E03-106[35] and E08-025, were the first experiments to measure neutron DVCS cross sections and beam-helicity asymmetries with high precision, but the kinematic coverage of the data was very limited. In the Jefferson Lab 12-GeV era two Hall B CLAS12 experiments have been approved to measure nDVCS; E12-11-003 measuring neutron DVCS with Deuteron targets using the Central Neutron Detector for 80 days at $10^{34} cm^{-2} s^{-1}$ per nucleon[36], and E12-17-012B using the ALERT detector to detect the spectator recoil proton for 20 days with similar luminosity.

We planing to do a short pilot measurement of the neutron DVCS in parallel with the already approved TDIS program taking advantage of the planned luminosity of 3×10^{36} $\text{cm}^{-2}\text{s}^{-1}$, which is significantly higher than what is achievable in CLAS12, and the simpler optics of the spectrometers. This short, 6-day measurement is expected to be competitive with the much longer Jefferson Lab Hall B CLAS12 nDVCS measurement. The proposed mTPC device enables us to directly measure the low-momentum spectator proton when the beam electron knocks out the neutron inside the Deuteron nucleus. The recoil proton detection will not only ensure that the scattering process happens on the neutron but can also directly probe the neutron Fermi momentum by knowing the proton momentum and applying momentum conservation. This will also give a handle on the coherent DVCS contribution by unambiguously distinguishing the final state. We will utilize SBS to measure the scattered electrons, same as in the TDIS setup. On top of the existing TDIS configuration, we plan to add an Electromagnetic Calorimeter (ECal) to the left-hand side of the beamline, to detect the real photons coming from the target. We will share the online setup and the data set with the TDIS, and perform offline analysis to isolate the DVCS events by forming the coincidence between the scattered electrons measured by SBS, the recoil protons by mTPC and the real photon by ECal. We will reconstruct the neutron missing mass spectrum to further suppress the background events. We are currently preparing the proposal for this pilot measurement. We expect that the success of this measurement will spur on a large experimental program based on the proposed mTPC to measure neutron-DVCS over a large range of x and Q^2.

Sources of funding for research enabled by the proposed instrument and research personnel to benefit from the proposed instrument: Beyond the funds requested in this proposal for the development of the mTPC device, funds for the mounting and running of the TDIS experimental program will be provided from the Jefferson lab operations budget allocated by the US Department of Energy (DoE). The support for individual researchers participating in the TDIS experiments will be coming from the those researchers' research grants from domestic funding agencies (DoE and NSF in the case of US researchers).

All research personnel who will use the proposed mTPC device for their research as part of the TDIS program are in the area of nuclear physics. The TDIS experiment research personnel anticipated to benefit from the proposed instrument include 52 senior personnel, approximately 10 postdoctoral fellows, approximately 15 graduate students and approximately 25 undergraduate students. In addition to these, the proposed device will be available for nuclear and particle physics experiments by the entire Jefferson Lab hall A collaboration of over 250 physicists.

Results from Prior NSF Support: The base research support for co-PI Dr. Eric Christy comes from NSF. Award Number:1508272; Dates: 08/01/2015 - July 31, 2018; Award Amount:$224,998.00; Experimental Studies of Nucleon Structure: Commissioning Jefferson Lab Halls A and C; PI: M. Eric Christy.

Intellectual Merit: Funding provided by Dr. Christry's current NSF grant has supported the groups efforts on a commissioning experiment in Jefferson Lab Hall A, E12-07-108 (the GMp12 experiment), to measure the electron-proton elastic scattering cross section at large 4-momentum transfer, Q^2. Dr. Christy is serving as a co-Spokesperson and analysis coordinator for this experiment, which was proposed to measure the elastic scattering cross section from protons to better than a factor of three better than previous measurements at $Q^2 > 12$ $(\mathrm{GeV/c})^2$. The experiment had a data taking run in Spring of 2015 and Fall 2016, as well as beamline commissioning during Fall 2015. The Hampton University group has had responsibility for a number of calibration and analysis tasks for the experiment, including beamline instrumentation such as the the beam position monitors (BPMs) and beam current monitors (BCMs).

For the last year Dr. Christy has been leading the BONuS12 Detector Design Group, which has met weekly. The design of this TPC detector is also based on the GEM technology proposed for the mTPC in the present proposal.

Broader Impacts: These grant funds have been used for training graduate and undergraduate students at Hampton University. The graduate student Mr. Thir Guatam, who is a dissertation student on the experiment under the supervision of the PI. In addition, Mr. Gautam has also analyzed the beam current dependence of the cryogenic hydrogen target density, as well as spectrometer acceptance studies. Progress on the analysis of these items has been presented regularly at the weekly GMp12 analysis group and results for both the Fall 2015 and Spring 2016 run periods have been presented at the weekly Hall A meeting and at the Hall A collaboration meeting held twice a year. And the graduate student Ms. Ms. Aruni Nadeeshani is currently working on the BoNUS RTPC design.

No publications have produced under this award so far.

No reserch products from this award have been made available so far

None of the other PIs on the current proposal has participated as PIs or co-PIs in NSF awards with a start date within the past five-year period.

c. Description of the Research Instrument and Needs

The proposed mTPC device will be located in the bore of a superconducting solenoid magnet, with a 400-mm warm bore, a total length of 152.7 cm, and a 4.7 T magnetic field in the center of the magnet. This magnet belongs to the UVa group; it has already been moved to Jefferson Lab in preparation for the TDIS program.

The detection of low energy proton tracks in the TDIS experiment is complicated by the large intensity of the secondary electrons, photons, pions and other particles produced in the interaction of the electron beam with the target. Extensive Monte-Carlo simulation work carried out by the TDIS collaboration within the GEANT-4 simulation framework has indicated that the background rates at the TPC detector location will be as high as 670 MHz; this is significantly higher than the rates handled in similar size TPCs before. Therefore, the success of the TDIS program relies on the development of a precision detector that could operate under extremely high background conditions. Much of the development effort in the proposed project is aimed at realizing a time projection device that is capable of operating under these harsh high rate conditions. Some of the features proposed to meet this high rate challenge are:

- use of a composite TPC device consisting of multiple TPC modules instead of a single TPC detector. Each TPC unit of the composite mTPC will be be exposed to a fraction of the background rate, while a single TPC would have to deal with the full rate.
- keep the drift electric field parallel to the solenoidal magnetic field , as opposed to the perpendicular field configuration used in a radial TPC. The longitudinal electron drift parallel to magnetic field minimizes the Lorentz force on drift electrons leading to significantly simplified track reconstruction and reduced drift times.

• Use the strong solenoidal magnetic field to confine most of the background δ-electrons created in the target so that they do not enter the TPC ionization region.

The modular mTPC design and the magnetic field parallel electron drift allows the maximum drift distances to be around 5 cm, leading to maximum drift time of the order of 1 μs. This is a major reduction in drift time, down by about a factor of 20-40, compared to a radial TPC of a similar size. This reduced drift time directly translates into a reduction in the number of background tracks recorded by the detector.

The configuration of the proposed mTPC, as modeled in the Geant-4 simulation, is shown in Fig. 3. The mTPC will consist of 10 cylindrical TPC units. The entire detector will be 55 cm long with an annulus of inner radius of 5 cm and an outer radius of 15 cm. The gas mixture inside the detector will be maintained at 0.1 Atm pressure and around 90 K temperature. The low pressure of 0.1 Atm is required to keep the material thickness at low. The low temperature of 90 K is needed because the target has to be kept cold to maintain the required density and the target can not be thermally isolated from the drift volume of the detector.

The electrons liberated in the ionization by a proton track drift against the electric field lines towards the readout detector disks. The amplification and detection of the drifting electrons will be achieved by Gas Electron Multiplier (GEM) foil based readout disks.

The (GEM) technology, which was invented by F. Sauli [37] at CERN in 1997, has been widely used as the electron amplification stage of TPCs. A single GEM layer consists of a 50 μm thick poly-amide foil coated on both sides with a 5 μm copper layer and punctured with 70 μm holes. The distance between these holes is about 140 μm. By applying a voltage in the range of 200 V to 300 V across the two copper layers a very high electric field is formed inside the holes. The GEM action is based on gas avalanche multiplication of electrons entering this strong electric field within GEM holes. Most the created electrons are guided forward by the drift field between GEM foils while most of the created positive ions are captured by the copper surface on the back of the GEM foil. Several GEM foils (amplification stages) can be cascaded to achieve high gain and stability in operation.

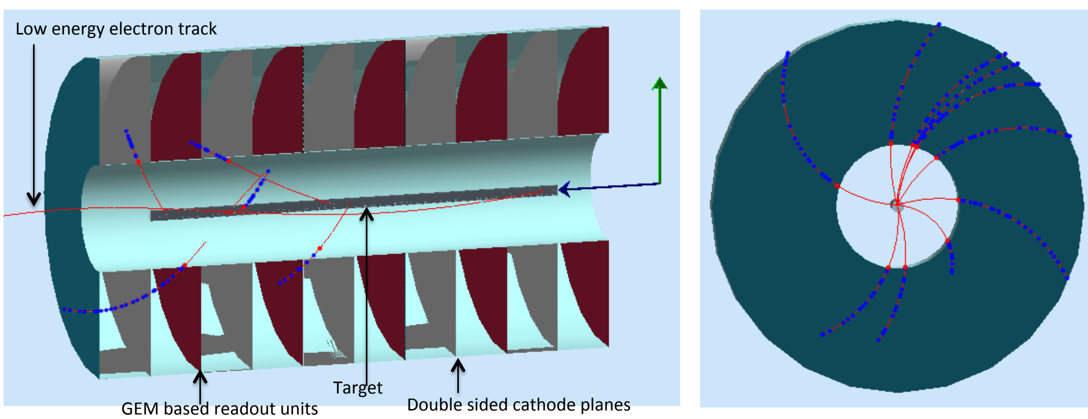

Figure 3: The cross-sectional view (left) and the end view (right) of the proposed mTPC device configuration from the GEANT-4 simulation model of the experiment. The simulated protons tracks, originating in the target and curving in the strong longitudinal magnetic field, are shown in red. When the proton travels through the Helium gas filling the detector volume, it loses energy ionizing gas atoms along the way, the blue dots show the ionization clusters. The red disks represent the GEM based readout assemblies, where the readout is maintained at ground voltage. The gray disks indicate thin cathode foil planes maintained at negative high voltage; the voltage gradients the between cathodes and the readouts generate the drift electric fields, parallel or anti-parallel to the magnetic field, in the TPC units. The inner and outer cylindrical walls will contain thin gold printed circuit traces (not shown in the figure) which will form the sides of the drift field cage to ensure uniform longitudinal electric field throughout each TPC volume.

We have developed a detailed CAD model for the mTPC; a 3D rendition of the mTPC within this model is shown in Fig 4. The mTPC will be constructed as 10 separate TPC volumes which will be assembled together to form the mTPC. The connecting of the modules will done using o-ring sealed flanges to ensure gas tightness. The outer cylindrical wall, made of a rigid fiberglass materiel, and the front and back end-caps will form the pressure vessel of the mTPC. The four readout disks in the middle region of the mTPC will be double sided structures while

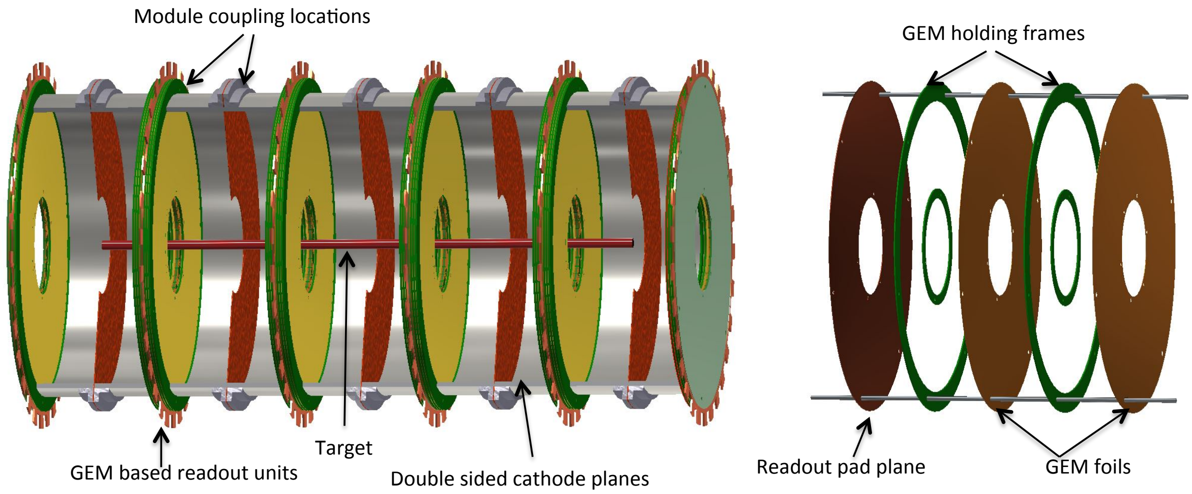

Figure 4: Left:The CAD design for the mTPC. The inner cylindrical wall, made of a 2 μm Kapton foil with gold circuit traces, is not shown for clarity. The mTPC will be constructed as 10 separate TPC volumes which will be assembled together to form the TPC. The outer cylindrical wall, made of a rigid fiberglass materiel, and the front and back end-caps (not shown) will form the pressure vessel of the mTPC. Right: The expanded view of the CAD design for a single amplification-readout unit of the mTPC. The four double sided readout structures of the mTPC will be made of two assemblies as this, connected back to back. The GEM holding frames will be machined out of Permaglas ME-730 material from Resarm corporation in Belgium. The readout board will be a 50 μm Kapton foil with copper readout pads on one side and connecting traces on the opposite side.

the two end disks will be single sided. As shown in Fig 4-Right, a readout facing a TPC drift volume consists of two GEM layers, each mounted on a 2 mm thick holding frame, followed by a readout surface containing conducting pads connected to readout electronics through traces on the back of the readout and then through a flex circuit strip. Each readout pad will have an area of 5 x 5 mm^2 separated by gaps of 100 μm, yielding approximately 2500 pads per readout. This arrangement gives position resolution of approximately 1.5 mm.

mTPC gas mixture selection: There are a few important factors we need to consider when selecting the TPC gas for our detector.

- The material thickness in the target and the mTPC volume has to be minimized to prevent energy loss of the protons and to reduce the rate of secondary background production.
- The atomic number (*Z*) of the drift gas atoms has to be minimized to reduce the rate of secondary background production, especially through photo production and Compton process due to low energy photon background.
- The drift time has to be kept low, ideally below 2 μs to keep the background track numbers at manageable levels.
- The gas mixture should be able to operate at low temperatures down to 90 K.

The need for low thickness and low *Z* makes Helium the clear choice as the drift gas and methane (CH_4) as the quencher gas. A study of GEM operation with low pressure He-based mixtures has been demonstrated in the reference [38]. As for the quencher, in addition to its low density and low *Z* of its constituents, another reason which makes CH_4 ideal for this TPC is its low boiling point; at 0.1 Atm, the boiling point of CH_4 is around 90 K. This makes it possible to operate the mTPC with a mixture such as 90% He and 10% CH4 at the proposed setting. We used a detailed simulation with Garfield++ used as an interface to Magboltz to study the properties of gas mixtures under the proposed conditions of the mTPC. Sample results from this study are shown in Fig 5. As the electron drift velocity plot shows, one downside to using a 90-10 He-CH4 mixture is its relatively short drift velocity of about 1.5 cm/μs at the proposed drift voltage of 200 V/cm at 0.1 Atm. This will lead to a drift time of nearly 3 μs, which is too long. On the other hand a 70-30 He-CH4 mixture, while somewhat denser and higher effective Z, gives a drift velocity of 3 cm/μs and a drift time of 1.7 μs, which is better. From a drift time point of view an even better choice is the 70-30 Ne-CH_4 mixture which give a drift time under 1 μs, however the density and effective Z for this mixture is significantly higher than for the 90-10 He-CH_4 mixture.

The transverse diffusion coefficient for all three gas mixture mentioned here, under the proposed conditions, is

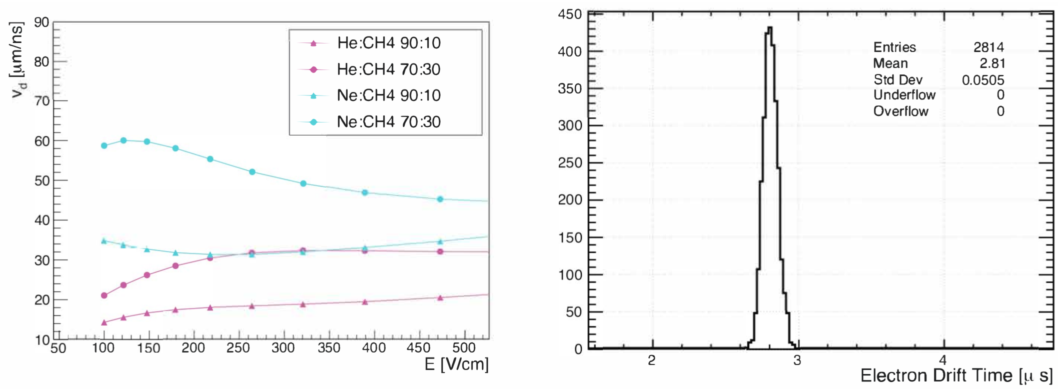

Figure 5: Sample results from the Garfield++/ Magboltz gas drift properties simulation for the proposed setup. The simulation was performed at the proposed experimental conditions of 4.7 T longitudinal magnetic field and 0.1 Atm pressure. (left) electron drift velocities for a few low density gas mixtures capable of operating at 90 K. (right) The arrival time distribution for a ionization cluster created at the maximum drift distance of close to 5 cm, for a 90-10 He-CH_4 mixture operating with a drift electric field of 200 V/cm.

around 0.01 $\sqrt{\mathrm{cm}}$, while the longitudinal diffusion coefficient for these mixtures are in the rage of 0.03 $\sqrt{\mathrm{cm}}$ to 0.06 $\sqrt{\mathrm{cm}}$. Given the relatively short drift distance of 5 cm, the electron cluster broadening due to these diffusion is well within the resolution needs of the proposed device. The final time resolution achievable with the 90-10 He-CH_4 gas mixture is presented on the left side of Fig 5. This time broadening, calculated by the Garfield++/ Magboltz setup, includes contributions from diffusion effects as well as angular effect. The resulting time resolution of 1.8% (in this case, a sigma of 0.05 μs out of a drift time of 2.75 μs) is sufficient to meet the TDIS program requirements.

As part of the development effort related the proposed project, we will continue to study the gas properties for different mixtures with the Garfield++/ Magboltz setup and then to use the selected gas mixtures in the Geant4 simulation to evaluate the effects due to density and Z. Finally, we will measure the properties of the selected gas mixtures in experimental conditions in the first level prototype detector before choosing the best gas mixture for the mTPC meeting the criteria listed above.

Ion flowback consideration: The flowback of positive ions into the drift volume, which causes electric field distortions leading to increased tracking uncertainties, is an important consideration in the TPC design. From this point of view, GEM is an ideal electron amplifier for a TPC because most of the positive ions created in the gas avalanche are collected on the conducting surface of the GEM and are removed from the detector, minimizing the ion flowback issues. However, even with a GEM readout, a small fraction of positive ions can flow back into the drift volume causing problems. Recently, the ALICE TPC upgrade collaboration studied the ion flowback issues in GEM readouts and showed that with a triple GEM stack the flowback level could be reduced to about 2.5% , while a carefully optimized four GEM stack could lower this number to be around 1% [39]. For the proposed mTPC, we are proposing to use double GEM stacks for electron amplification. Our preliminary measurements have indicated the best case ion flowback rate for a double GEM stack will be around 5%. While this is a relatively high number, the low drift distance of the proposed mTPC makes this level of ion feedback acceptable. In fact, the effects on the final track resolution due to ion flowback goes down as the square of the drift distance; a short drift distance cuts down the time the positive ions spend drifting in the TPC volume, while the electric field distortions due to space charge in the drift volume lead to a multiplicative uncertainty factor that affects the electron drift distances.

The calculations show that for the proposed setup operating at a rate of 70 MHz charged particle tracks per module, with a GEM gain factor of 2000 and an ion flowback level of 5%, the electric field distortions will be at the 1% level, which is more than adequate to achieve the required track resolution. As part of the development effort related the proposed project, results from Geant4 and Garfield++ simulation tools for the charge flowback related issues will be checked and optimized with the prototype detector.

mTPC momentum resolution and efficiency: The proposed modular design allows the mTPC to handle high background rates. This high rate capability comes at the cost of reduced efficiency and reduced momentum resolution due to the presence of readout disks in the middle of the active area. These disks affect the momentum resolution by reducing the track lengths in the drift volume; any track with a momentum uncertainty of over 10% is rejected leading to decreased efficiency. However, detailed Geant4 simulations of the proposed mTPC show that it will have an efficiency in the range of 50% to 70% for detecting proton tracks with momenta in the range of 50 MeV/c to 300 MeV/c with a transverse momentum resolution of 10% or better. For tracks in the momentum range of 300 MeV/c to 400 MeV/c, this efficiency is higher than 20%. These available inefficiencies are sufficient to meet the physics goals of the TDIS program. The efficiency profiles for a few momentum settings are shown in Fig. 6-right , while a sample momentum resolution plot is shown in Fig. 6-left. Path length distributions for proton tracks in the TPC volume for two sample proton momenta are given in Fig. 7. These path lengths depend on proton momentum dependent factors such as absorption in the drift gas, absorption in the readout structures, and curving in the magnetic field, as well as the geometry of the track. All these factors have been carefully modeled in the Geant4 simulation.

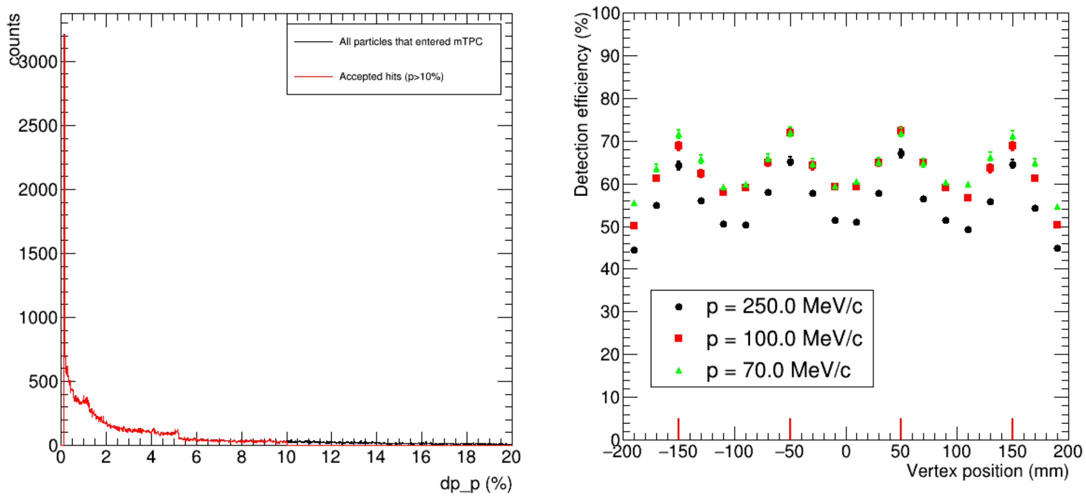

Figure 6: Left: The simulated momentum resolution for 100 MeV/c protons in the mTPC. Right: Efficiency profiles for proton track of three sample momenta. Efficiency is defined as the ratio of the number of tracks yielding a momentum resolution better than 10% to the total number of tracks generated in the target with the corresponding momentum.

mTPC Calibration: The mTPC efficiency profile calibration requires careful consideration.

Some initial calibration can be done by using the copious proton tracks from elastic electron-proton scattering. At production luminosity there will be several accidental elastic proton tracks distributed evenly along the target for every $e-p$ DIS event. These protons are well separated from the protons of interest because, to be at the same momentum but generated by elastic events, they are necessarily kinematically directed almost perpendicular to the beam.

It will be particularly productive to use quasi-elastic electron scattering from the deuteron for the mTPC calibration. The energy and direction of the spectator proton may be determined in a quasi-elastic reaction using a scattered electron in the SBS in combination with a neutron measured with the (relocated) SBS Hadron Calorimeter (HCAL). This movable HCAL detector will be placed on the beam right (opposite side from SBS) at optimum kinematics to record neutrons for this calibration measurement. Using this method we can predict the distribution of protons of energy, for instance 5-27 MeV (or momentum 100-225 MeV/c), in the directions required for the mTPC calibration. A comparison between the measured proton spectra and the proton distributions expected in the mTPC from quasi-elastic neutrons in HCAL will provide a check on the mTPC proton acceptance and efficiency corrections.

The proposed calibration will be performed at an electron-nucleon luminosity of 0.3×10^{36} Hz/cm^2 with an electron beam energy 4.4 GeV and SBS angle at the same angle of 12 degrees as during the production TDIS run. The projected rate of electron-neutron quasi-elastic events in SBS is around 1000 Hz. The average neutron momentum will be 970 MeV/c. Using HCAL located at a distance of 15 meters (60 degrees relative to the beam direction) we have calculated that the coincidence $e-n$ rate will be approximately 70-80 Hz. Neutron momentum will be within a cone with an average angle relatively the beam of 60° an opening of $\pm 4°$. At such a low luminosity the spectator protons will be easy to identify and use for mTPC calibration. One day of such a measurement provides

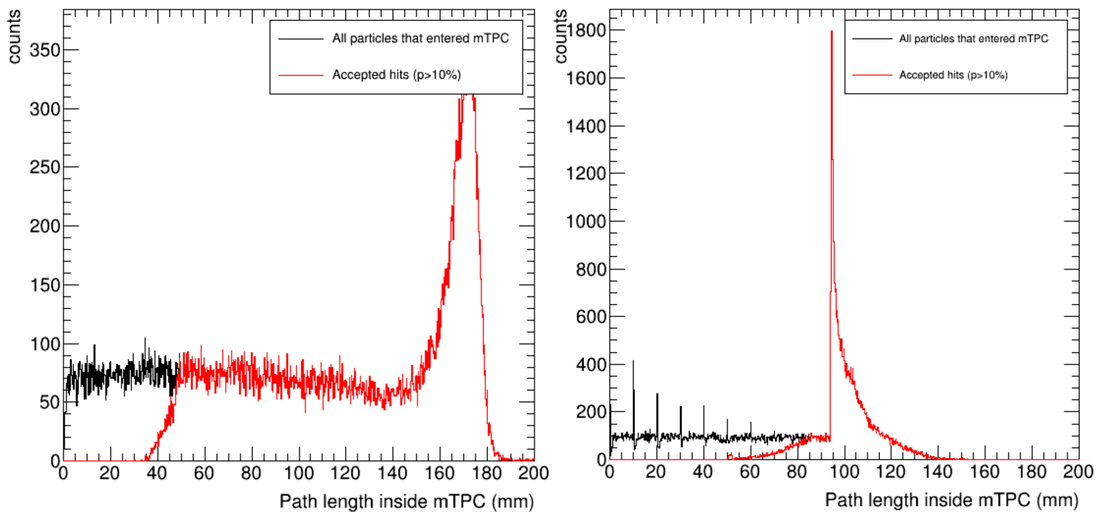

Figure 7: Two sample path length distributions for protons in the mTPC. Left: path length distribution for 70 MeV/c protons. The very short path lengths, down to 0, correspond to the absorption of these low momentum protons in the drift gas and and in the readout structures. The very low path length tracks (shown in black) yielding worse than 10% momentum resolution are removed from the efficiency calculation. The large number of tracks reaching long path lengths around 170 mm are due to the strong curving of these low energy protons in the magnetic field. Right: path length distribution for 250 MeV/c protons. The sharp peak around 100 mm corresponds to many of these relatively high momentum protons making it all the way from the inner boundary of the mTPC at 50 m radius m to the outer cylindrical surface at 150 mm.

more than 6 million tagged proton events which would allow detailed study of mTPC.

Readout electronics: The readout electronics of the mTPC will be based on the design of the SAMPA chip centered readout electronics chain used for the ALICE TPC at CERN [40] (Fig. 8). While we will have to adapt this readout to the architecture of our mTPC, using this design allows us to benefit from the considerable development work the ALICE and LHCb collaborations have put into this readout system. The adaption of this system to Jefferson lab DAQ environment and to the mTPC architecture will proceed as a part of the ongoing streaming readout development effort by Jefferson lab Data Acquisition Group. The acquisition, assembly and testing of the mTPC readout system will be carried out by the Hampton University group in close collaboration with data acquisition experts from Jefferson lab.

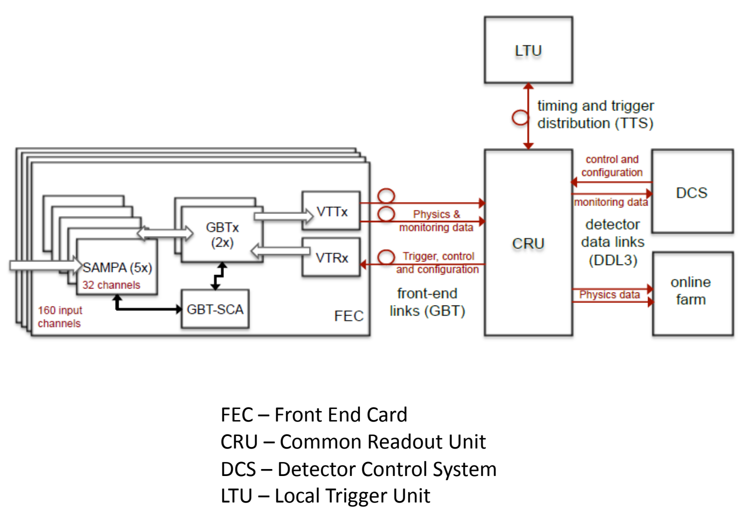

Figure 8: Schematic of the ALICE readout system

In the proposed configuration, the Front-End Card (FEC) houses the SAMPA chips and contains the complete readout chain for amplifying, shaping, digitizing, processing, and buffering the TPC signals. The FEC will be connected to the detector readout using a flex circuit cable with a length up to 25 cm. The SAMPA ASIC chip, developed by the University of Sao Paulo group [41], processes the data from 32 individual front-end channels concurrently. The first stage of the SAMPA is a charge-sensitive preamplifier and shaping amplifier, which transforms the currents induced in the readout pads into differential semi-Gaussian voltage signals. These analog signals are continuously digitized, at a rate of 10 MHz or 20 MHz, by an ADC with 10-bit dynamic range. The digitized signals are further processed by an on-chip Digital Signal Processor (DSP) which implements pedestal subtraction, digital filtering and data compression using zero suppression. Concurrently, the acquired data are transferred to the GBTx ASIC [42], which multiplexes them and transmits them via an optical link components [43] to a Common Readout Unit (CRU) [44]. The CRU serves as interface to the online farm, trigger and detector control system, and is situated off-detector in shielding hut.

This readout system can operate in both continuous and triggered modes. In the triggered mode the processing of the continuously sampled data stream starts upon arrival of a first-level trigger; only the data corresponding to the detector drift time is frozen in the data memory and read out. For the TDIS experiment the expected trigger rate is around 5 kHz.

The SAMPA chip preamplifier/shaper has a two peaking time modes, 160 ns (available in the current configuration) and 80 ns (possible in the future). While both modes are acceptable for the TDIS program needs, we are considering the possibility of using the 80 ns mode to improve high rate capability of the system. Given the readout pad size of 5x5 mm^2 and a trace length up to 25 cm to front end card, the estimated detector capacitance is approximately 20 pF; given this capacitance, the expected equivalent noise charge (ENC) level is $670e$.

Pileup and occupancy considerations The design of the mTPC has been optimized to work under elevated background rates expected during the TDIS program while keeping effects of pileup to an acceptable level. The current mTPC configuration is segmented in 10 chambers with 5 cm each in length, allowing the operation of the DAQ at a reduced trigger window (on the order of 1 μs). With that, and considering the sampling period of 50 ns and the signal shaping time of the SAMPA chips, we estimate a mean occupancy of the readout to be on the order of 55 % for the highest luminosity proposed for the experiments. In this condition, there will be on the order of 19 % of the readout elements with two or more hits within this trigger window, although most of those multiple hits could still be disentangled by timing and trajectory information when reconstructing the particles track in the detector.

Data rates and bandwidth considerations: The data acquisition from the MTPC will be done through the already developed Super BigBite DAQ system. This system was designed for high luminosity form Factor Experiments which will run at a luminosity up to $10^{38} cm^{-2} s^{-1}$ Furthermore, this DAQ system is designed to be able to handle trigger rates up to 6 KHz with data rates up to 2 GB/s. The TDIS experiment will operate at a much lower luminosity of $3.10^{36} cm^{-2} s^{-1}$. During TDIS, the the total data volume, including data from the mTPC, is estimated to be less than 500 MB/s which is well within the capacity of the SBS DAQ.

d. Broader Impacts

The proposed mTPC device is truly novel detector which in turn will facilitate a bold and pioneering suite of spectator tagging measurements at Jefferson Lab. The techniques pioneered here and proposed science is being explored to facilitate an additional, new potential program for the future Electron Ion Collider. In addition to being the key instrument for the TDIS program, the proposed device will become part of Jefferson lab experimental hall A setup and will be available for experiments by the entire Hall A collaboration of over 250 physicists. It is expected that this powerful device will enable many exciting experiments in the future. In fact, this expectation is based on the previews project outcome experience of this collaboration. Under his previous MRI instrumentation project (MRI grant PHY-0216351)), the lead PI of the present proposal, Dr. Liyanage, led the design and construction of the Multi-Wire Drift Chamber (MWDC) package for BigBite spectrometer in Jefferson Lab Hall A. At the time that MRI proposal was submitted, Bigbite spectrometer was intended for one approved experiment only. However, since the successful completion of that project, Bigbite spectrometer has been used for five highly rated experiments which have yielded numerous publications. Furthermore, the results from those experiments and the novel experimental approach that was demonstrated by the success of the Bigbite spectrometer, led to a development of the Super BigBite (SBS) project, a major Jefferson lab experimental program for the 12 GeV era.

Furthermore, the proposed instrumentation project provides an ideal research-intensive learning environment to educate undergraduate and graduate students. The GEM technology is based on simple physics concepts which are well within the grasp of undergraduate and junior graduate students, and yet have far reaching applications in cutting-edge research projects and in industry. Since we plan to design and build the proposed device in-house "from scratch", the students will have the opportunity to participate in every step of building a major research instrument. The students will play a major role in mTPC chamber simulations, prototyping, construction and testing. We plan to recruit 2 graduate students and about 6 undergraduate students over the next 2 years for prototyping, fabrication and testing of the mTPC modules and readout electronics. In addition to these students, post-doctoral associates and graduate students participating in experiments using the mTPC will benefit from the requested MRI grant. Based on many exciting measurements that will become possible with the mTPC, we expect that there will be at least 5 major Jefferson Lab experiments using this device in the future. From this, we estimate that there will be about 25 undergraduate students, 15 graduate students and 10 post-doctoral associates using the mTPC for their research.

Two of the institutions leading this project, HU and VUU, are minority universities. This project will provide advanced and internationally-competitive scientific training for African-American students in a field where they are sorely under-represented. All collaborating groups have a very strong track record in involving both graduate and undergraduate students in their research activities. In fact, one of the UVa undergraduate research assistants on the Bigbite MWDC MRI project, Andrew Puckett, went on to become one of the best young researchers at Jefferson lab; Andrew went to MIT for graduate studies with an MIT President's fellowship, after completing his PhD there, he was awarded a highly coveted director's fellowship at Los Alamos National Lab for his post-doctoral work. Following that he served as a staff scientist at Jefferson Lab for one year before accepting a faculty position at the University of Connecticut in 2013 where is he is currently an assistant professor of physics. He received a prestigious DOE Early Career Research Program grant in 2015.

e. Management Plan

1. Organizational Structure: The mTPC consortium consists of University of Virginia (UVa), Hampton University (HU), Jefferson Lab (JLab), Virginia Union University (VUU) and University of Glasgow (UG). UVa and HU are requesting NSF funding in this consortium proposal. The consortium will be led by Nilanga Liyanage from UVa. The UVa sub-group (UVa in collaboration with JLab and UG) will be responsible for the development, construction and assembly of the mTPC in UVa GEM detector lab, and for testing the mTPC at Jefferson Lab. The HU-JLab sub-group (HU and JLab in collaboration with VUU) will be responsible for the development of the readout electronics system for the mTPC. Both sub-groups will coordinate through the Project Leader, Dr. Liyanage, who will communicate with JLab management and the TDIS experimental program leadership. Currently the leader of the TDIS collaboration, Dr. Thia Keppel, is also the leader of the JLab experimental halls A and C.

UVa sub-group: The UVa group, in collaboration with JLab and University of Glasgow, will develop the mTPC design through simulating, CAD designing, prototype constructing, testing, and design optimizing cycles. After finalizing the design with two such prototyping cycles, the UVa group will construct the final mTPC consisting of 10 TPC modules as well as two spare modules. The prototypes as well as the final mTPC will be tested using cosmic rays and x-rays at UVa, as well as in beam tests at Jefferson lab. Finally, the UVa group will work together with the two collaborating institutions and Jefferson lab to commission the mTPC. The mTPC development work will be carried out in the UVa GEM Detector Lab, a 15 x 15 m^2, well equipped nuclear physics detector development lab that has been used for the development, construction, and testing of some of the world's largest GEM detectors. Recently, the fabrication and testing of 48 large area GEM detectors for Jefferson lab SBS polarimeter trackers was successfully completed in this facility.

The UVa PI, Prof. Nilanga Liyanage, is an expert in tracking detectors, especially GEM detectors, who previously led the successful projects to develop the polarimeter GEM trackers for SBS and the large MWDC tracker for the Bigbite spectrometer. Both these major instrumentation projects were completed on time and on budget. In the proposed project, Dr. Liyanage will be responsible for:

- the overall supervision of the project.
- coordination with NSF, collaborating institutions, Jefferson lab management and the TDIS experiment collaboration.

- leading the design and development of the proposed mTPC device

UVa research scientist Dr. Kondo Gnanvo is a widely recognized GEM detector expert with extensive expertise in GEM detector design and GEM chamber readout electronics. In the proposed project Dr. Gnanvo will be responsible for the design and development of the mTPC, for coordinating GEM components design and fabrication at CERN, and leading the testing effort of the prototype and final devices. The post-doctoral research scientist Dr. Huong Nguyen is highly skilled in the fabrication of GEM detectors. She recently completed the successful fabrication of the large area GEM modules for the SBS project. In the proposed project, Dr. Nguyen will be responsible for:

- the fabrication of the proposed mTPC device and its prototypes.
- testing of the prototypes and the final mTPC device.
- the day-to-day supervision of graduate and undergraduate students participating in the project.

The UVa team will closely collaborate on the Geant-4 simulation modeling of the mTPC with Jefferson lab post doctoral associate Dr. Marco Carmignotto and Jefferson lab staff scientist Dr. Bogdan Wojtsekhowski. Dr. Wojtsekhowski is an acknowledged world expert in detector technology. He has overseen the design and construction of many large detector packages over the last three decades and has been the physicist in-charge of experimental Hall A detectors since the inception of the hall.

University of Glasgow Senior Research Fellow Dr. John Annand and research associate Dr. Rachel Montgomery will be responsible for the Garfield++/Magboltz simulations to optimize drift gas mixtures for the mTPC.

HU-JLab sub-group: The HU-JLab sub-group be responsible for the development of the readout electronics system for the mTPC. This includes:

- the adaption and optimization of the ALICE TPC readout design for the proposed mTPC architecture,
- acquisition and fabrication of all readout components.
- testing and quality assurance of the readout components.
- assembly and commissioning of the full readout system.

The co-PI Dr. Eric Christy at Hampton University will lead this effort in collaboration with JLab staff scientists Dr. Alexandre Camsonne and Dr. Ed Jastrzembski, as well as VUU faculty member Dr Narbe Kalantarians. Dr. Christy is an expert in tracking detectors and in large instrumentation projects; he was the lead PI of the MRI consortium project (PHY0723062) for the detector package of Hall C SHMS spectrometer. At present, he is leading the development of BONuS12 rTPC. Dr. Camsonne is the experiential hall A data acquisition expert. Dr Jastrzembski is a digital electronics expert who has been in charge of Custom hardware and electronics design at the JLab data acquisition group for many years. Dr Kalantarians has many years of detector and instrumentation experience, having Managed construction and initial testing of drift chambers for Hall C SHMS spectrometer and being a member of the core group that developed Jefferson lab BONuS6 radial TPC device.

Currently there is a program underway at Jefferson lab to develop streaming readout capabilities for future Jefferson lab experiments; SAMPA chip based readout is an important part of this program. The development and fabrication work for the mTPC readout will be carried out as part of this larger program.

2. Schedule of the project: The schedule of the project, year-by-year expenditures and manufacture or activity and deliverables are presented in Table 1.

Once the completed mTPC is moved to Jefferson lab, it will be housed in the GEM clean-room located in Jefferson lab test-lab building for commissioning. When the time comes for the TDIS experimental program, the mTPC will be moved into experimental hall A, installed and commissioned in its operational position in the hall. During periods between experimental programs when the mTPC is not used, it will be stored in operation ready conditions in the test-lab clean room. A statement by Jefferson lab halls A and C leader Dr. Thia Keppel indicating Jefferson lab's commitment to house the mTPC is included with this proposal. While at Jefferson lab, the mTPC will be operated by the trained and authorized members of the TDIS collaboration.

Group	months	Purchase	Activity	Deliverables
UVa	1-6	Components for a single prototype TPC module $ 10,000 (3 GEM foils, 1 readout plane, TPC body components, GEM frames, supplies)	Finalize prototype design, Construct a single cell prototype TPC module, test the prototype and optimize design	single cell prototype TPC
UVa	7-12	Components for a 4-cell mTPC prototype $ 26,800 (12 GEM foils, 4 readout plane, GEM frames, supplies)	Develop and test 4-cell mTPC optimize the design for final mTPC	4-cell prototype mTPC
UVa	13-24	Final mTPC components $ 79,400 (36 GEM foils, 12 readout plane, GEM frames, supplies)	Construct and test the final mTPC construct 2 spare modules	final mTPC, 2 spare modules
HU-JLab	1-12	Front End Card (FEC) set $ 194,625 FEC power supply set $ 18,730 CRU set $ 120,000 Fiber optic cable set $ 10,000	Fabrication of 2500 chan. prototype readout test with prototype TPC finalize the design	prototype readout system, finalized readout design
HU-JLab	13-24		Fabrication of the final readout test with prototype mTPC	Final readout system with 10% spare channels

Table 1: Period-by-period expenditures and manufacture or activity

3. Risks associated with the project and risk mitigation: The main risk associated with the construction of a large and delicate tracking device is due to possible damage to detector elements during construction, installation and operation of the detectors. We will take extra care and follow strict safety procedures to minimize damage to sensitive elements. The effectiveness of the precautions and safety procedures followed at the UVa detector facility is indicated by the fact that all 48 large area GEM modules constructed at UVa for the SBS project are fully operational meeting all design requirements.

In order to prepare for the possibility of damaged detector elements, we will procure and store spares at the level of 20% or higher over the required amounts for all sensitive elements of the mTPC modules including GEM foils, readout planes, and all specialty connectors. The cost of these spares is already built into the budget presented here. In addition to the 10 TPC modules for the mTPC, two fully operational spare modules will be produced. The spare modules will be moved to JLab and stored there when the completed mTPC moves to JLab. Stand-by facilities will be setup in the Jefferson lab clean-room to replace a module in case of damage during operation.

4. Knowledge Transfer: The mTPC we are proposing to build here will be the highest rate capable TPC in the world. Therefore, the success of the proposed project would signify a major new advancement in TPC technology. Furthermore, the experience gained in the development, construction and operation of the high rate mTPC will be crucial for the future instrumentation projects related to the JLab, Electron Ion Collider and for radiation detection technology in the U.S. Therefore, we will ensure that the knowledge gained and the technology developed are transferred quickly to other instrumentation groups at National Labs and Universities in the U.S. This will be done by publishing technical documents, designs and reviews related to the project on JLab web-site. We also plan to publish several articles in the journal Nuclear Instrumentation and Methods in Physics Research A based on the development of the high rate mTPC at the conclusion of different stages of the project.

References

[1] http://www.jlab.org/.

[2] The Super-Bigbite Spectrometer (SBS) Conceptual Design Report and SBS Technical review report can be found on the web-page http://hallaweb.jlab.org/12GeV/SuperBigBite/MRI/CDR/.

[3] Accardi, A., Albacete, J.L., Anselmino, M. et al. Eur. Phys. J. A (2016) 52: 268. https://doi.org/10.1140/epja/i2016-16268-9

[4] Measurement of Tagged Deep Inelastic Scattering (TDIS), T. Keppel, D. Dutta, P. King, B. Wojtsekhowski (spokespersons), Jefferson Lab experiment e12-15-006, (2015).
https://www.jlab.org/exp_prog/proposals/15/PR12-15-006.pdf

[5] Measurement of Kaon Structure Function through Tagged Deep Inelastic Scattering (TDIS), K. Park, T. Horn,R. Montgomery, (spokespersons), Jefferson Lab experiment C12-15-006A, (2015),
https://misportal.jlab.org/pacProposals/proposals/1348/attachments/98383/Proposal.pdf

[6] K. Gnanvo, N. Liyanage, V. Nelyubin, K. Saenboonruang, S. Sacher, and B. Wojtsekhowski, Nucl. Inst. Meth. **A782**, 77-86 (2015).

[7] K. Gnanvo X. Bai, C. Gu, N. Liyanage, V. Nelyubin, Y. Zhao, Nucl. Inst. Meth. **A808**, 82-92 (2016).

[8] J.D. Sullivan, Phys. Rev. **D5**, 1732 (1972).

[9] HI Collaboration, C. Adloff *et al.*, Eur. Phys. J. **C6**, 587 (1999); V. Andreev *et al.*, arxiv:1312.4821.

[10] J. Speth and A.W. Thomas, Adv. Nucl. Phys. 24, 83 (1998).

[11] P.L. McGaughey, J.M. Moss, and J.C. Peng, Ann. Rev. Nucl. Part. Sci. 49, 217 (1999).

[12] S. Kumano, Phys. Rep. 303, 183 (1998).

[13] R. Holt and C. Roberts, Rev. of Mod. Phy. **82**, 2991 (2010).

[14] S. C. Pieper and R. B. Wiringa, Ann. Rev., Nucl. Part. Sci. **51**, 53 (2001).

[15] R. B. Wiringa, Phys. Rev. **C73**, 034317 (2006).

[16] P. Maris, C. D. Roberts, P. C. Tandy, Phys. Lett. **B420**, 287 (1998).

[17] J. S. Conway *et al.*, Phys Rev. D **39**, 39 (1989).

[18] J. Badier *et al.*, Z. Phys. **C18**, 281 (1983).

[19] S. Catani *et al.*, Phys. Rev. Lett. **93,** 152003 (2004).

[20] B. Betev *et al.*, Z. Phys. **C28**, 9 (1985).

[21] A. W. Thomas, Phys. Lett. 126B, 97-100 (1983).

[22] M. Arneodo *et al.*, Phys. Rev. **D** 50, 1 (1994).

[23] K. Ackerstaff *et al.*, Phys. Rev. Lett 81, 5519 (1998).

[24] A. Baldit *et al*, Phys. Lett. **B 332**, 244 (1994).

[25] R. S. Towell *et al.*, Phys. Rev. **D64**, 052002 (2001).

[26] A. I. Signal and A. W. Thomas, Phys. Lett.**B 191,** 205 (1987).

[27] X. G. Wang *et al.* arXiv:1610.03333 Oct. (2016).

[28] M. B. Hecht, C. D. Roberts, and S. M. Schmidt, Phys. Rev. **C63**, 025213 (2001).

[29] D. Muller, D. Robaschik, B. Geyer, F.-M. Dittes and J. Hoeji, Fortsch. *Phys. 42, 101 (1994) [hepph/9812448].*

[30] X.-D Ji. *Phys. Rev. Lett. 78, 610 (1997).*

[31] X. -D. Ji, *Phys. Rev. D 55, 7114 (1997).*

[32] A.V. Radyushkin. *Phys. Rev. D 56, 5524 (1997).*

[33] M. Diehl. *Phys. Rep. 388, 41 (2003).*

[34] A. V. Belitsky and A. V. Radyushkin, *Phys. Rept. 418, 1 (2005).*

[35] M. Mazouz, *et al. Phys.Rev.Lett. 99 (2007) 242501.*

[36] Jefferson Lab CLAS12 experiment E12-11-003, *Deeply Virtual Compton Scattering on the Neutron with CLAS12 at 11 GeV".*

[37] F. Sauli, Nucl. Inst. Meth. **A386**, 531 (1997).

[38] S.K. Das, Y. Mizoi, T. Fukuda, K. Yamaguchi, H. Ishiyama, M.H. Tanaka, Y.X. Watanabe, H. Miyatake, Nucl. Instrum. Meth. A **625**, 39-42 (2011).

[39] ALICE Collaboration. Upgrade of the ALICE Time Projection Chamber. Technical Design Report, CERN-LHCC-2013-020, ALICE-TDR-016. 2013. `https://cds.cern.ch/record/1622286/files/ALICE-TDR-016.pdf`

[40] ALICE Upgrade of the Readout & Trigger System V Technical Design Report, `http://cds.cern.ch/record/1603472/files/ALICE-TDR-015.pdf`

[41] SAMPA Chip: the New 32 Channels ASIC for the ALICE TPC and MCH Upgrades, `http://iopscience.iop.org/article/10.1088/1748-0221/12/04/C04008/pdf`

[42] The GBT, a Proposed Architecture for Multi-Gb/s Data Transmission in High Energy Physics, `https://cds.cern.ch/record/1091474/files/p332.pdf`

[43] A Versatile Link for high-speed, radiation resistant optical transmission in LHC upgrades, `https://doi.org/10.1016/j.phpro.2012.03.753`

[44] Common Readout Unit (CRU) V A new readout architecture for the ALICE experiment, `http://iopscience.iop.org/article/10.1088/1748-0221/11/03/C03021/pdf`

10. Data Management Plan

Summary: This plan outlines the management of scientific data generated in the research program proposed in this document. The Jefferson Lab experimental programs proposed here will be carried out in Experimental halls A and B at Jefferson lab. All data generated in these experiments are covered by the Jefferson lab data management plan:

`http://scicomp.jlab.org/DataManagementPlan.pdf`,

and by the data management plans of experimental halls A and B:

`https://data.jlab.org/drupal/?q=system/files/Data_Management_Plan_Hall-A.pdf`,

`https://data.jlab.org/drupal/?q=system/files/Data_Management_Plan_Hall-B_0.pdf`.

The rest of this document presents the management plan for the data generated locally by the UVa-Liyanage group in its mTPC development described in this proposal.

Responsibilities: With the assistance of the UVa physics department computer support team, UVa-Liyanage group is responsible for the management of the experimental data it generates locally at UVa. The PI, Dr. Liyanage, has the overall responsibility to ensure the proper management of this data according to the plan outlined below. The Co-Investigator, Dr. Kondo Gnanvo is responsible for the supervision of organization, recording and backing up of the generated data. The UVa physics department IT manager, Dr. Bryan Wright, is responsible for the management of the UVa physics department central Unix servers used to backup the generated data.

Data Management Process: The experimental data generated in the UVa mTPC detector R&D program include the following:

- Digital drawing files for mTPC detectors and their components in machine readable formats (.DXF and .274x) as well as in human viewable .pdf format.
- Digital pictures of mTPC detector construction steps.
- mTPC detector component characterization data files (mTPC foil high voltage scan data and microscope images).
- Raw data from mTPC detector test runs (in binary form).
- Databases used for processing the raw data.
- Processed data for mTPC detector test runs (root tree files and histogram files).
- Data used to create graphs presented in published articles and technical reports.

All these data items are written, organized and cataloged, by the detector name, detector number and the date, into local disks mounted on Linux and Widows computers in the lab. All data in these disks are backed up daily into the physics department central Unix server (galilio). All data elements are available to the research community upon request.

Quality Assurance: As indicated above, the data management plan process is overseen by the PI. Periodic reviews of data management are made every month by going over and checking the integrity of randomly selected files from local disks as well as from the backup server.

8. Facilities, Equipment, and Resources

- **UVa GEM Detector Lab:** The GEM detector lab operated by Dr. Liyanage's group at UVa is a 15 x 15 m^2, well equipped detector development lab that has been used for the development, construction, and testing of many large area GEM detectors. The lab consists of a 7 x 4 m^2, level 1,000 clean room, especially set up for the GEM chamber construction. The lab contains specialized GEM construction equipment worth over $ 200,000.

  The facilities in the the lab include:

  - Equipment needed for GEM detector fabrication.
    - Mechanical Stretching systems with tension load monitoring for large area GEM foil foils.
    - High power optical microscope for GEM foil inspection.
    - Picoammeters for GEM foil testing and characterization.
    - Large volume dry N_2 boxes for GEM foil testing.
    - Large capacity ultra-sonic bath for GEM frame cleaning.
    - Laminal flow racks for GEM foil storage.
    - Particle counter for clean room monitoring.
  - GEM readout system based on APV25-S1 electronics: a state of the art, 10,000 channel GEM readout system based on APV25-S1 electronics (this is the readout system used for GEM R&D activities in the lab; new separate new readout system with 127,000 channels is being set up for SBS). APV25-S1 is a fast pipeline readout chip used for COMPASS GEM trackers, CMS silicon stripe detectors, and STAR FGT GEM chambers. The capacity of this system is sufficient to readout prototype GEM trackers.
  - Wiener-Iseg multi-channel High Voltage system: The UVa GEM group owns a Wiener-Iseg2 multi-channel High Voltage system that is especially suited to provide high voltage to sensitive tracking chambers. This system currently has 16 channels and can be expanded to 40 channels.
  - A GEM detector testing station equipped with a high-flux x-ray tube and radioactive sources. This setup is located within a large, walk in cabinet shielded with lead.
  - A cosmic ray test stand equipped with large area scintillators for trigger.
  - A CODA (Jefferson lab DAQ architecture) based Data Acquisition system.

- **Machine shop:** The UVa Physics department machine shop has a staff of three full time machinists and spans eight rooms (3,760 sq. ft.), including a User shop available to researchers who have completed the shop course. The machine shop equipment suite includes nine mills (some with digital readout and CNC), eleven lathes (one CNC), numerous drill presses, grinders, shapers, and wood working tools. Of special note is the welding shop (featuring Oxy-Acetylene, MIG, and TIG welding systems) and its demonstrated expertise in the welding of high vacuum systems.

- **Electronics shop:** The UVa Physics department electronics shop has a full time electronics engineer with particle and nuclear physics instrumentation expertise and an electronics technician skilled in laboratory instrument construction and repair. The shop provides in-house electronics development, prototyping, fabrication, and optimization services.

- **Computer support:** UVa physics department computer support team includes a full time Computer Systems Senior Engineer and a full time Programmer/Analyst. In addition to providing support for standard workstations, they also help develop and manage research systems (data acquisition and analysis). Departmental computer resources include a Beowulf-class supercomputing cluster and various other Linux and Windows servers.

- **Jefferson Lab facilities:** As the host institution for the proposed mTPC, Jefferson lab will be providing needed facilities, expertise and skilled manpower for this project. These resources include: Jefferson lab clean rooms, experimental hall A facilities, skilled mechanical, electrical and electronics technicians from the Jefferson lab physics division, Jefferson lab staff scientist electronics and data acquisition experts from hall A and data acquisition groups.