# 1 Research or technology development

## 1.1 The proposed research program and its innovative aspect

Much progress has been made toward unraveling the structure of the nucleon. It is well known that inclusive electron scattering at high momentum and energy transfer is governed by elementary interactions with quarks and gluons. But our understanding is fragmented, particularly in the confinement region of Quantum Chromodynamics (QCD). An outstanding major issue of modern physics is the better understanding of the confinement or non-perturbative region, where the quark-quark interaction is strong and QCD can only be used as a basis for either model development or numerical solutions such as Lattice QCD (LQCD).

One obstacle to our improved comprehension is that exclusive and semi-inclusive deep inelastic scattering studies at large $Q^2$ are difficult because they require continuous, high luminosity electron beams, and detectors with good particle identification and reproducible systematics. The Thomas Jefferson National Accelerator Facility (Jefferson Lab, or JLab), a world-leading nuclear physics laboratory located in Newport News, Virginia, has a Continuous Electron Beam Accelerator and four experimental halls needed to undertake these experiments. The recent JLab upgrade addresses these issues, with a doubling of the maximum electron beam energy to 12 GeV, and the construction of new experimental apparatus.

Compared to the non-perturbative regime in general, some simplification occurs in Deep Exclusive electron scattering, in the hard scattering regime where the QCD factorization theorem applies. Here, scattering amplitudes can be factorized in terms of a perturbatively calculable hard interaction between the electron probe and the struck parton, and a process-independent, non-perturbative soft contribution describing the interacting hadrons. For processes such as Deep Exclusive Meson Production (DEMP), this soft contribution can now be understood in terms of Generalized Parton Distributions (GPDs), which are universal non-perturbative amplitudes representing the correlations between different parton configurations in the hadron. GPDs cannot be calculated from first principles, but once determined, their universality promises a significant step forward in our understanding of QCD in the non-perturbative regime.

In recent years, much progress has been made in the theory of GPDs. Unifying the concepts of parton distributions and of hadronic form factors, they contain a wealth of information about how quarks and gluons make up hadrons. The key difference between the usual parton distributions and their generalized counterparts can be seen by representing them in terms of the quark and gluon wavefunctions of the hadron. While the usual parton distributions are obtained from the squared hadron wavefunction representing the probability of finding a parton with specified polarization and longitudinal momentum fraction $x$ in the fast moving hadron, GPDs represent the interference of two different wavefunctions, one where the parton has momentum fraction $x + \xi$ and one where this fraction is $x - \xi$. GPDs thus correlate different parton configurations in the hadron at the quantum mechanical level. A special kinematic regime is probed in DEMP, where the initial hadron emits a quark-antiquark or gluon pair. This has no counterpart in the usual parton distributions and carries information about $q\bar{q}$ and $gg$-components in the hadron wavefunction.

In order to access the physics contained within GPDs, one is restricted to the hard scattering regime. An important feature of hard scattering reactions is the possibility to separate clearly the perturbative and nonperturbative stages of the interaction. The presence of a hard probe allows one to create small size quark-antiquark and gluon configurations, whose interactions are described by perturbative QCD (pQCD). The non-perturbative stage of the reaction describes how the hadron reacts to this configuration, or how this probe is transformed into hadrons. This separation is the so-called factorization property of hard reactions. DEMP was first shown to be factorizable in Ref. [1]. This factorization applies when the virtual photon is longitudinally polarized, which is more probable to produce a small size configuration compared to a transversely polarized photon.

GPDs are universal quantities and reflect the structure of the nucleon independently of the reaction which probes the nucleon. At leading twist-2 level, the nucleon structure information can be parameterized in terms of four quark chirality conserving GPDs, denoted $H$, $E$, $\tilde{H}$ and $\tilde{E}$. $H$ and $E$ are summed over quark helicity, while $\tilde{H}$ and $\tilde{E}$ involve the difference between left and right handed quarks. $H$ and $\tilde{H}$ conserve the helicity of the proton, while $E$ and $\tilde{E}$ allow for the possibility that the proton helicity is flipped. Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter. In particular, leading order QCD predicts that vector meson production is sensitive only to the unpolarized GPDs, $H$ and $E$, whereas pseudoscalar meson production is sensitive only to the polarized GPDs, $\tilde{H}$ and $\tilde{E}$. In contrast, deeply virtual Compton scattering (DVCS) depends at the same time on both the polarized ($\tilde{H}$ and $\tilde{E}$) and the unpolarized ($H$ and $E$) GPDs. This makes DEMP reactions complementary to the DVCS process, as it provides an additional tool to disentangle the different GPDs [2].

The infrastructure requested here is in support of our research to determine the $\tilde{E}$ GPD. The first moment, $\sum_q e_q \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = G_P(t)$, where $G_P(t)$ is the pseudoscalar nucleon form factor. Although $G_P(t)$ is an important quantity, it remains highly uncertain because it is negligible at the momentum transfer of $\beta$-decay [3]. Because of partial conservation of the axial current (PCAC), $G_P(t)$ alone receives contributions from $J^{PG} = 0^{--}$ states [4], which are the quantum numbers of the pion. Thus, $\tilde{E}$ contains an important pion pole contribution. The measurements to determine $\tilde{E}$ carry a high scientific priority, as it cannot be related to any already-known parton distribution, and can provide new nucleon structure information which is unlikely to be available from any other source.

Frankfurt et al. [5] have considered a specific polarization observable which is the most sensitive observable to probe the spin-flip $\tilde{E}$. This variable is the single-spin asymmetry for exclusive charged pion production, $\vec{p}(e,e'\pi^+)n$ or $\vec{n}(e,e'\pi^-)p$, using a transversely polarized nucleon target and longitudinally polarized photons, known as $A_{LT}^{sin(\phi-\phi_s)}$. It has been shown in [5] that this asymmetry must vanish if $\tilde{E}$ is zero. If $\tilde{E}$ is not zero, the polarization asymmetry will display a $\sin(\phi-\phi_s)$ dependence, where $\phi$ is the azimuthal angle of the produced pion with respect to the electron scattering plane, and $\phi_s$ is the azimuthal angle of the polarized nucleon target. The asymmetry is required to vanish for pions detected along the virtual photon $\vec{q}$-axis, and grows in magnitude as the pion angle is moved away from $\vec{q}$ (larger Mandelstam $-t$).

Another factor in favor of these measurements is that there are strong theoretical reasons [5, 6] to expect $A_{LT}^{sin(\phi-\phi_s)}$ to display "precocious factorization," meaning that the $\tilde{E}$ information encoded in $A_{LT}^{sin(\phi-\phi_s)}$ may be accessible at values as low as $Q^2 = 2-4$ GeV$^2$. This precocious scaling arises from the fact that higher order corrections, which are expected to be significant at low $Q^2$, will likely cancel when one examines the ratio of two longitudinal observables. In contrast, the onset of scaling for the absolute cross section is only expected for much larger values of $Q^2 > 10$ GeV$^2$. The relatively low value of $Q^2$ for the expected onset of precocious scaling is important, because it will be experimentally accessible after the JLab 12 GeV upgrade. This places $A_{LT}^{sin(\phi-\phi_s)}$ among the most important GPD measurements that can be made in the meson scalar.

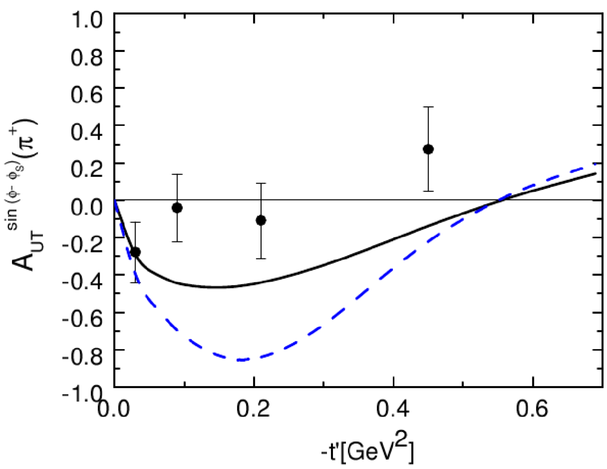



**Figure 1:** Predictions for $A_{UT}^{sin(\phi-\phi_s)}$ in the handbag approach [12], in comparison to the data from HERMES [13] at $Q^2 = 2.45$ GeV$^2$, $W = 3.99$ GeV. The independent variable is $-t' = |t - t_{min}|$. Dashed line: contribution from longitudinal photons only. Solid line: full calculation including both transverse and longitudinal photons.

Refs. [2] and [7] also point out that the study of the transverse target single-spin asymmetry is important for the reliable extraction of the pion form factor from electroproduction experiments. Investigations of hard exclusive $\pi^+$ electroproduction using a pQCD factorization model [8, 9] find that at $x_B = 0.3$ and $-t = -t_{min}$, the pion pole contributes about 80% of the longitudinal cross section. Since $A_{LT}^{sin(\phi-\phi_s)}$ is an interference between pseudoscalar and pseudovector contributions, its measurement would help constrain the non-pole pseudovector contribution, and so assist the more reliable extraction of the pion form factor. The upper $Q^2 = 6$ GeV$^2$ limit of our approved pion form factor measurements in the JLab 12 GeV program [10] is dictated primarily by the requirement $-t_{min} < 0.2$ GeV$^2$, to keep non-pion pole contributions to $\sigma_L$ at an acceptable level [9]. $A_{LT}^{sin(\phi-\phi_s)}$ studies versus $t$ may eventually allow, with theoretical input, the use of somewhat larger $-t$ data for pion form factor measurements, ultimately extending the $Q^2$-reach of pion form factor data acquired with JLab 12 GeV beam. The importance of such pion form factor measurements was highlighted in the recent "QCD and Hadron Physics White Paper" [11] that feeds into the new U.S. Long Range Plan for Nuclear Physics, providing yet another endorsement of the importance of these measurements.

### 1.2 How the proposed research complements comparable programs elsewhere

$A_{LT}^{sin(\phi-\phi_s)}$ is experimentally completely unknown, and except for the program described below, no other measurements are proposed worldwide. The closest related measurement (without an L–T separation), was published by the HERMES Collaboration in 2010 [13]. Their data were obtained for average values of $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV$^2$ and $\langle t' \rangle = -0.46$ GeV$^2$, subject to the criterion $W^2 > 10$ GeV$^2$. The six Fourier amplitudes in terms of the azimuthal angles $\phi$, $\phi_s$ of the pion-momentum and proton-polarization vectors relative to the lepton scattering plane were determined. Of these, at leading twist only the $sin(\phi - \phi_s)_{UT}$

Fourier amplitude receives a contribution from longitudinal photons. If one assumes that longitudinal contributions dominate, these $A_{UT}^{sin(\phi-\phi_s)}$ values can be compared to GPD models for $\tilde{E}$, $\tilde{H}$. However, indicated in Fig. 1, a considerable share of the unseparated cross section measured by HERMES [13] is due to contributions from transversely polarized virtual photons, which may dilute the observed asymmetry by about 50%.

Due to the conflicting experimental requirements, I envision the $A_{LT}^{sin(\phi-\phi_s)}$ program to consist of two parts: ($i$) A set of very high quality $\vec{n}(e,e'\pi^-)p$ measurements, from a transversely polarized $^3$He target, utilizing the SHMS+HMS magnetic spectrometers in JLab Hall C. These spectrometers are designed to measure small absolute cross sections with the small systematic uncertainties needed for reliable L–T separations, and with good missing mass resolution to isolate the exclusive final state. These measurements will investigate the $A_{LT}^{sin(\phi-\phi_s)}$ precocious factorization expectations at moderate $Q^2$, and determine whether the calculations of the dilution due to transversely polarized virtual photons are accurate. These proposed SHMS+HMS measurements [14] were reviewed by the JLab Program Advisory Committee (PAC), who recognized its high scientific importance but also its very challenging nature. ($ii$) Due to the limited SHMS+HMS angular acceptances, in part ($i$) it is only possible to perform measurements over a limited range of pion angles ($<4^o$) about the virtual photon $\vec{q}$. Measurements with full azimuthal coverage at larger angles, where $A_{LT}^{sin(\phi-\phi_s)}$ is largest, are unfortunately not possible. The second part of these measurements will use a large solid angle detector with full azimuthal coverage to access the larger asymmetry values at higher $-t$. Even if full L–T separation is not possible, the $A_{UT}^{sin(\phi-\phi_s)}$ measurements in part ($ii$) will overlap those in part ($i$), so that the theoretical corrections needed to determine $\tilde{E}$ will be highly constrained and enable access to the novel aspects of proton structure contained therein. Due to the high quality JLab electron beam and recent developments in detector technology, the part ($ii$) statistical uncertainties and kinematic coverage should be much better than the HERMES measurements.

### 1.3 Why it is important to pursue the research program at this time

Very recently, a new opportunity for future research has opened up. Due to my expertise in Deep Exclusive Meson Production (DEMP), I have been invited to join the SoLID Collaboration. SoLID is an acronym for Solenoidal Large Intensity Device, and when constructed will be located at JLab Hall A. A conceptual view of the detector is shown in Fig. 2. It is a next-generation tracking detector which will allow data to be collected at high luminosity ($> 10^{37}$ cm$^{-2}$s$^{-1}$) over a large angular range but moderate resolution. The proposed large acceptance, good particle identification, good vertex resolution, and high luminosity capabilities of SoLID make it ideally suited to the part ($ii$) measurements discussed in Sec. 1.2. The SoLID Collaboration prepared a detailed Preliminary Conceptual Design Report (pre-CDR) in 2014 [15], and has received approval to use the former CLEO-II magnet from Cornell for the device. The SoLID construction cost is expected to be in the neighborhood of US$50 million.

SoLID is now in the R&D stage, with the international collaboration performing additional studies and constructing prototypes to finalize the detector design and obtain detailed cost estimates. The intention is to submit proposals for construction of the detector once

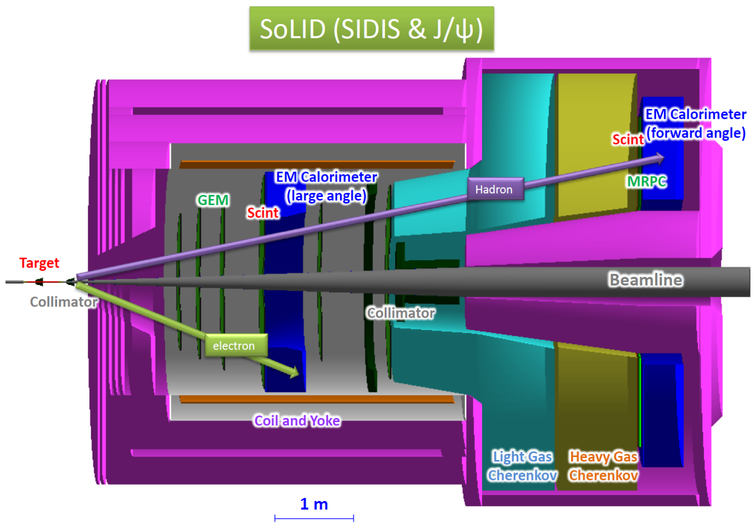



**Figure 2:** The Solenoidal Large Intensity Device (SoLID), planned for subatomic physics research studies using the Jefferson Lab 11 GeV electron beam. The Heavy Gas Čerenkov Detector is the second element from the right.

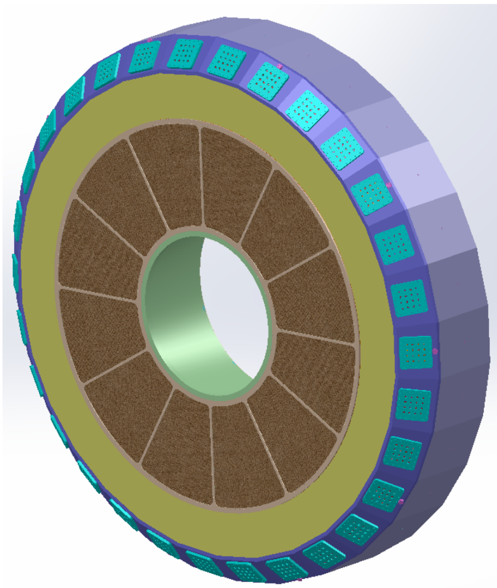
these studies are completed. This grant proposal is in support of the Heavy Gas Čerenkov (HGC) detector, as explained below. This request is timely because our prototyping studies need to be completed over the next 1-2 years, so that the SoLID HGC design can be finalized without causing delay to the rest of the project.

# 2 Need for the infrastructure

## 2.1 The requested infrastructure and how it will enable the proposed program

For our proposed measurements to meet their scientific goals, we must have a very reliable means to distinguish the various types of particles striking the detectors. For momenta above 2 GeV/c, it becomes increasingly more difficult to distinguish charged particle species by time of flight measurements, and one must rely on other means of particle identification. A primary technique is the detection of Čerenkov radiation, which is a form of blue to ultraviolet wavelength light that is emitted when a charged particle is moving very rapidly through a transparent medium. Two different types of Čerenkov detectors are planned for SoLID, one filled with a low density gas (Light Gas Čerenkov – LGC), and another filled with a high density gas (Heavy Gas Čerenkov – HGC). The conceptual design of the HGC detector is shown in Fig. 3. It consists of three basic components: (1) a light and gas tight cylindrical tank to hold the high density gas ($C_4F_{10}$); (2) UV-sensitive photomultiplers (PMTs) to detect the Čerenkov light; (3) aluminized mirrors and cones to reflect the Čerenkov light onto the PMTs.

Electron identification will be accomplished by use of energy measurements in an electromagnetic calorimeter (far right in Fig. 2), which will be supplemented with the Light



| | |
|---|---|
| Momentum Range | 2.5 – 7.5 GeV/c |
| Angular Range | 8 – 14.8$^o$ |
| Kaon Rejection Rate | ≥99% |
| Radiator Gas | $C_4F_{10}$ |
| Gas Pressure | 1.5 atm |
| Tank Diameter | 5.4 m |
| Tank Thickness | 1.0 m |
| Active area | 8.5 m$^2$ |
| Number of PMTs | 480 |
| Number of Spherical Mirrors | 30 |

**Figure 3:** The SoLID Heavy Gas Čerenkov (HGC) detector will help with the identification of both positive and negative pions at forward angles.

Gas Čerenkov detector just downstream of the tracking detectors. For our experiments, this device will be filled with $CO_2$ gas at standard atmospheric pressure.

For hadrons, efficient, high-confidence particle identification (PID) can be provided economically by the HGC.

- $\pi^{\pm}$: Charged pions with momentum $> 2.2$ GeV/c will trigger a HGC detector filled with 1.5 atm of $C_4F_{10}$ gas ($n = 1.0021$). The light collection is very efficient, with pions generating an average of 10-15 photoelectrons (depending on their angle).

- $K^{\pm}$: Charged kaons below 7 GeV/c momenta will not generate Čerenkov radiation, but can produce a false signal by scattering the gas atomic electrons, which can radiate. PMT light output cuts will be used to suppress this signal. e.g. For 3.0 GeV/c particle momentum, assuming that $K^{\pm}$ would produce at most 1 photoelectron below the Čerenkov threshold, a cut placed at 3 photoelectrons will result in a pion detection efficiency of 99.6% with kaon contamination no more than 0.8%.

The HGC detector discussed here is essential for reliable charged pion identification in SoLID. As such, it is a critical component of the research program discussed in Sec. 1, which requires reliable pion identification from 2–8 GeV/c. This detector is also an appropriate Canadian contribution to SoLID because it makes use of Regina expertise built up in earlier detector projects.

In comparison to the Super High Momentum Spectrometer (SHMS) HGC, for which the UofR was able to take sole responsibility, the SoLID HGC is much more complicated and costly and groups from several institutions are joining forces to perform the necessary studies.

The full HGC detector will cost approximately US$2.5 million to construct. Before we launch on such an ambitious endeavor, we need to be sure that all of the necessary design questions are addressed in detail and that the physics goals are met. This will be accomplished by constructing a Heavy Gas Čerenkov detector prototype for about 10% of this cost, and do various performance tests on it. This grant proposal is for funds to construct the Canadian share of the SoLiD HGC detector prototype, with the remaining funds to come from our international partners.

## 2.2 How the infrastructure will be fully utilized by the researchers

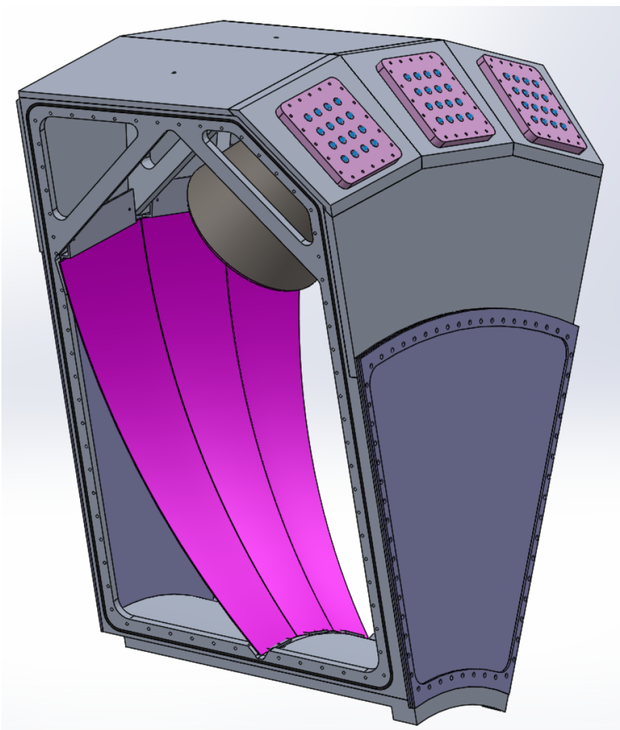


**Figure 4:** The SoLID HGC prototype detector consists of three detector segments, including PMT, mirror and light reflecting cones, to investigate the light collection efficiency and thin window performance. The enclosure is planned to be constructed at the UofR Science Machine Shop, with other components procured from specialized vendors. UofR researchers (faculty and students) will also contribute their expertise in mirror curvature and reflectivity measurements, gained from our prior experience building a similar HGC detector for the SHMS in JLab Hall C.

A conceptual view of the SoLID HGC detector prototype is shown in Fig. 4. The prototype enclosure is planned as one of 10 identical units in the final HGC detector, sealing against adjacent units at right and left. The prototype unit consists of 3 detector segments. The central segment will be fitted with 1 mirror, 1 light reflecting cone, and 16 Hamamatsu PMTs in a 4×4 matrix. Our collaboration partners have already purchased the PMTs for R&D studies. The UofR contribution is the detector enclosure, window, cone and mirror, with the remaining components provided by our U.S. collaborators. The HGC detector prototype components requested here will be utilized both by UofR and U.S. investigators. We will perform a number of initial tests on the detector components in Regina as described below. After we are satisfied with their performance and have written these results up as technical reports circulated within the SoLID Collaboration, the components will be shipped to the U.S. where they will be mated with the remaining components (e.g. photomultipliers) for additional tests. Thus, the items requested here will see significant use and are crucial for finalizing the design of the 30 segment SoLID HGC detector.

The detector enclosure is planned to be constructed at the UofR Science Machine Shop, making use of the expertise we have developed during our construction of the SHMS HGC detector. The enclosure will be manufactured from aluminum with dimensions of approximately

1847 mm×1641 mm×1011 mm. An important aspect of the enclosure which we need to test is its deformation at the 1.5 atm operating pressure. Since the spacing between the LGC, HGC and electromagnetic calorimeter is tight, there are strict requirements on the allowed deflection. The curved base of the enclosure will be milled from 6" thick aluminum sheet, and will be very strong. The shell and side frame parts are planned to be constructed from 1" thick 6061 aluminum alloy sheet and the top of the enclosure is covered by 1" thick 6061 aluminum cover plates.

The back of the enclosure (behind the mirrors in Fig. 4) has the conflicting requirements of needing to be thin (to avoid particle production affecting the downstream calorimeter) and strong (to reduced overall deflection). We anticipate needing to investigate several options, including different thicknesses of 6061 and 7075 alloy, or even carbon-fiber epoxy to achieve the necessary combination of thinness and strength.

Another design aspect which we need to test with the prototype is the performance of the O-ring seals against the two adjacent units. The left and right sides of the prototype will be blanked off with 3/8" thick aluminum 6061 side covers (not shown in Fig. 4) and the enclosure pressurized above the 1.5 atm operating pressure to check for leaks. Since we may have to make modifications to the design, the prototype enclosure frame will not be welded together. Instead, it will be bolted to allow easy disassembly, and sealed internally with RTV (Room Temperature Vulcanization) silicone adhesive. Once we are more confident in the design, we try welding the prototype frame parts together to see whether this causes any undesirable warping.

At the front of the detector (at right in Fig. 4) is a thin entrance window. It is important to ensure the thin window meets our goals for light and gas tightness, and not slip from the clamps over an extended period. Our requirements for the vessel entrance window are similar to those for the detector enclosure itself: (*i*) The window should be as thin as possible, as knock-on electrons produced by subthreshold particles traversing the windows will lead to false signals in the detector. These background events can be largely (but not completely) eliminated via a cut on the number of photoelectrons registered by the PMTs; (*ii*) The window must provide a good mechanical seal for an indefinite period without slipping or failing. Our initial design of the pressure vessel entrance window is based on a proven design from Brookhaven National Laboratory [16]. It consists of a layer of 0.43 mm Kevlar fabric sandwiched between two layers of 0.13 mm Mylar. It will be held firmly in place with two 1/4" thick trapezoidal-shaped clamps, which are bolted to the enclosure with an O-ring gas seal. An embedded aluminum wire in the window clamp flange serves as an aide in clamping, and the seal is made against a Viton O-ring on the vacuum vessel side. A new window material made from a Tedlar-Mylar-Tedlar sandwich holds the promise of improved performance with a significant reduction in thickness. This material is currently under investigation at JLab for the CLAS-12 Čerenkov detector and we plan to make use of the information gained in their studies.

The mirrors are of very specialized manufacture (carbon fiber reinforced polymer) and their coating optimized for high ultraviolet reflectivity (down to 200 nm). The reflecting cone is also a special design, consisting of a 0.125" low carbon steel outer layer and a 0.062" $\mu$-metal inner layer to shield the PMTs from magnetic field. Inside the shielding cone, there is an aluminized reflection layer to improve light collection efficiency. Tests will be performed to confirm that sufficient quantities of Čerenkov light are generated and detected by the photomultipliers to ensure reliable identification of pions and efficient rejection of kaons, so that our planned deep semi-inclusive and exclusive meson production studies yield the necessary scientific information.

### 2.3 Similar infrastructure available elsewhere

JLab's high quality electron beam, with variable energy between 1–12 GeV, beam current up to 100$\mu$A, and 100% duty factor, is unique in the world. The energy and intensity of the electron beams enable studies at very short distance scales ($< 10^{-15}$ m) and permit explorations of nucleon structure that are otherwise not possible. (In comparison, the Canadian Light Source probes atomic and molecular distance scales, which are more than $10^6$ times larger.) The SoLID project will develop a large acceptance spectrometer/detector system capable of handling very high rates. It is designed to satisfy the requirements of high-scientific rated experiments that require both high luminosity and large acceptance, such as the one described here. This is enabled by recent advances in detector technology, to yield a significant advance compared to the previous HERMES experiment at DESY. The HGC prototype detector R&D studies described here are absolutely crucial to the eventual success of the SoLID HGC detector and our planned measurements to determine the GPD $\tilde{E}$. There is no other facility elsewhere, either proposed or planned, that can perform these (or similar) measurements.

## 3 Researchers

### 3.1 The expertise and ability of the researchers to lead the proposed program

Dr. Huber is an active member of experimental collaborations at JLab and at the Mainz Microtron, each of which have 75–150 members.

My most significant contribution to the JLab program, for which I have received international recognition, is my significant leadership role in the pion form factor series of experiments. I am the co-spokesperson (with D. Gaskell, JLab) of an experimental program that aims to significantly improve our knowledge of the pion charge form factor in the space-like region. Because the pion has a relatively simple $\bar{q} - q$ valence structure, this observable is of particular interest – it is one of the most direct ways of testing QCD-based models in the non-perturbative regime. Thus, it is an observable that all QCD-based calculations use as a first test case (the 'positronium atom' of QCD). Using electron beams up to 5 GeV energy at JLab, we acquired data and published the first high-quality pion form factor data (with well-understood and quantified systematic uncertainties) since the seminal work of Brauel et al., at DESY, in 1979. Our data, spanning the range $Q^2$=0.6-2.45 GeV$^2$, are where theoretical calculations for $F_\pi$ begin to diverge and constrain the treatment of soft versus hard contributions to the pion wave function. The five publications from this work have had continued impact, to date gathering over 800 citations (source: inspirehep.net). As a result of the impact of this work, we have received the highest possible endorsement of the JLab PAC to continue these studies with the upgraded 12 GeV electron beam at JLab, including the awarding of A scientific priority in 2010, and being identified as a "high impact" experiment in a 2014 review of the JLab 12 GeV scientific program. As co-spokesperson and lead contact person, my role in all aspects of this work is significant.

Please note that authorship on JLab Halls A and C papers require a direct contribution to the publication, such as running a prescribed minimum number of data-taking shifts on the data included in the publication, acting as run-coordinator for one of the data-taking periods, participating in the data analysis or interpretation, or other significant intellectual contribution to the specific work. In order to encourage the active participation of Halls A and C users to its highest priority experiments, contributions to general-use equipment or software without also contributing to the work in question does not confer authorship-privileges. The ordering of the authors is usually that the core-group (2–5 people) responsible for the physics results and interpretation are listed first, followed by the rest of the co-authors in alphabetical order. I am listed in this core-group on all publications resulting from the pion form factor experiments, including 3 where I am first author.

### 3.2 The technical expertise of the candidate that will allow them to make the best use of the requested infrastructure

Over the last 25 years, the UofR group has constructed a number of Čerenkov detectors for use at JLab and TAGX (Tokyo, Japan).

In 1990, the UofR signed a Memorandum of Understanding with JLab for the design and testing of the silica aerogel Čerenkov detectors, plastic scintillator trigger counters, and associated analog electronics for the high resolution spectrometers ($HRS^2$) under construction in Hall A. As part of this agreement, funds from the U.S. Department of Energy (USDOE) were awarded to the UofR for the design and construction of the above equipment. The Aerogel Čerenkov detector consisted of a novel carbon-fiber epoxy enclosure with composite mirrors. My effort on this project was mostly with the design and performance testing of the Čerenkov detector, modeling the light collection characteristics of this Čerenkov detector using a modified version of the CERN GUIDE7 package, and optimizing the detector design for light collection efficiency and pulse rise-time. A prototype Čerenkov detector, based on this design, was constructed and tested with pion, muon and electron beams at TRIUMF. With the assistance of Italian Collaborators, it was also tested using the Saturne $SPES-IV$ spectrometer (CEA Paris), and at the Saskatchewan Accelerator Laboratory. One M.Sc. student (L. Alexa), who I co-supervised, analyzed these data, and made a detailed comparison of these results with the computer model, which resulted in a 1995 peer-reviewed publication. The full scale detector was installed at JLab Hall A and has been in continuous use for nearly the last 20 years. Two more peer-reviewed publications resulted, with the final one presenting the operational performance of the detector in its as-installed configuration. Following this extensive work, we constructed a simpler Gas Čerenkov detector for our work with the TAGX Collaboration in Japan.

Because of the success of our Čerenkov detector work for JLab Hall A, and the vital role that good $\pi/K$ particle separation will have upon the Pion Form Factor and other 12 GeV experiments that I lead, I was asked to develop the HGC for the new Super High Momentum Spectrometer (SHMS) as part of the upgrade of JLab Hall C. This has been my most significant hardware contribution to date. The HGC is a threshold Čerenkov detector using the heavy gas $C_4F_8O$ as a radiator at sub-atmospheric pressure, so that Čerenkov light from 3-11 GeV/c $\pi^{\pm}$ is efficiently detected, discriminating against $K^{\pm}$ and other sub-threshold particles. The funds for this detector came primarily from an NSERC RTI-1 grant awarded to me in the 2010 competition, with funding for mirror aluminization and some additional components provided by JLab. With the assistance of one M.Sc. student (W. Li) and several undergraduate student researchers (P. Selles, L. Sichello), we optimized the detector design for light collection efficiency and uniformity using both Geant4 Monte Carlo simulations, and specialized ray-tracing software provided by a U.S. collaborator.

Using the experience gained during our construction of the HGC for the SHMS spectrometer for JLab Hall C, we will perform a variety of curvature measurements on the prototype mirror, to confirm it was constructed to the required specifications. Two types of tests are planned: 1) we will use a lens to disperse laser light across the mirror surface and measure the size of the reflected spot versus position to directly determine the mirror focal length, 2) we will use a FaroArm digital sensor to obtain precise $(x, y, z)$ measurements for a grid of points across the mirror and use these data to investigate manufacturing imperfections, such as the variation of focal length across the mirror surface. Results from these tests were effective in selecting the best 4 mirrors (out of a sample of 15) for use in the SHMS HGC detector. This experience will be valuable for checking that the SoLID HGC mirrors have been built to the correct curvature specification. In addition, members of my group helped develop the JLab mirror reflectivity measurement facility as part of our SHMS HGC work, and this will be an additional UofR contribution to the SoLID R&D studies. Much of this work can be performed by UofR students (both graduate and undergraduate) and will make excellent thesis and honors projects.

Finally, with the assistance of the UofR Science Machine Shop, we prototyped a number of mirror mounting schemes for the SHMS HGC, including one making use of carbon-fiber epoxy mirror frames. Although that design was ultimately abandoned in favor of a simpler design, our in-house experience with carbon-fiber epoxy may prove useful for the prototype enclosure requested in this application. At the UofR, we also hydroformed the 2024-T3 aluminum windows for the SHMS HGC (1.282 m diameter) and provided to the JLab engineering staff the necessary information for the pressure certification of the windows.

The SHMS HGC was delivered to JLab in the summer of 2013. It was due to experiences such as these that I was invited to join the SoLID HGC project.

### 3.3 Existing collaborations and partnerships essential to the success of the program

With the capability to deliver variable energy electron beams between 1–12 GeV of unprecedented quality and stability, JLab is the world's largest nuclear physics user facility. Several groups of Canadian experimentalists and theorists perform research there, making it the largest center for offshore Canadian nuclear physics research. The Canadian contributions at JLab are very highly regarded and this proposal is a further contribution to these high-profile international contributions.

The SoLID Collaboration has more than 200 members from over 50 institutions in 11 countries. SoLID has attracted significant international attention, with many groups committed to make large detector contributions, including the GEMs and MRPC by Chinese groups. When constructed, SoLID will be located in Hall A of JLab and use the JLab electron beam to perform a variety of experiments over a period of 10-20 years. JLab provides significant oversight and technical support for the SoLID project. The inaugural SoLID Project Manager (PM) is Dr. Jian-Ping Chen, a JLab Research Scientist who is in charge of executing the project and reporting to JLab management. The SoLID Executive Board (EB) is elected by the Collaboration and makes decisions on scientific and organizational choices. The Chair of the EB is the principal contact between the Collaboration and JLab management/USDOE. The Chair, together with the PM, is responsible for the performance and assessment of all detector subsystems. Finally, the Technical Board (TB) advises the PM on all aspects of the project, including any changes in cost, scope or schedule. The TB consists of senior representatives from each detector subsystem, representing the full range of required technical expertise.

The HGC subgroup presently consists of members from Duke University (Dr. Haiyan Gao, Dr. Zhiwen Zhao, Mr. Gary Swift) and the UofR (myself and other members of my research group). Jointly, we are responsible for all aspects of the HGC to the broader SoLID Collaboration and JLab. Another key member of the SoLID Collaboration that we are working closely with is Dr. Tom Hemmick of the SUNY Stony Brook Physics Department. He has expertise with the PHENIX Ring-Imaging Čerenkov Detector at RHIC, and will be performing the aluminization of reflecting components for both the HGC and LGC.

Close collaboration with Duke University, JLab and members of the LGC subgroup is essential to the success of the specific project discussed here. Due to several conflicting technical requirements, such as very limited geometric space for the detector, and the potential adverse effect of the SoLID solenoidal fringe field, the proposed optical and mechanical design for the SoLID HGC are quite complex. The technical assistance of the JLab design and engineering staff, as well as scientific and engineering collaborators at Duke University are essential if we are to deliver a 30-segment HGC which meets all design parameters.

JLab engineering personnel have been helping with gas system evaluation and providing equipment for DAQ testing. Their effort will be increased in the next two years, especially when it reaches the final testing stage.

The UofR role, as presented above, is to deliver to our collaborators a tested prototype enclosure, including thin windows, which JLab and Duke engineers can later certify for U.S. safety standards. We will also provide our expertise regarding the optical tests of the HGC components, both in Regina and at Duke University/JLab.

We expect to continue our collaboration well past the completion of the HGC prototype studies. When built, SoLID will form a key component of JLab scientific apparatus, providing some of its most important measurements in the coming 2 decades. The collaborations formed as a result of the funding of this project will form a lasting legacy for ongoing Canadian contributions at JLab.

# 4 Training of Highly Qualified Personnel (HQP)

## 4.1 How the infrastructure will enhance the current training environment for HQP

The measurements described in this proposal make an excellent HQP training ground. Intermediate energy experiments represent a compromise between the large collaborations of high energy physics and the small groups of low energy nuclear physics. UofR students travel to JLab for the on-site portions of their research, making use there of the most modern experimental techniques, such as state-of-the-art data acquisition, beam polarimetry and polarized targets. Students gain direct experience working within an international collaboration, yet the project layout is still small enough that students and PDFs can be exposed to nearly all aspects of the experiment. The dedicated beamtime needed for an individual measurement is usually 2-6 months, with several years of analysis afterward. Experiments proceed in a staggered fashion, with students and PDFs working on various phases of these experiments in parallel, which gives them a more comprehensive education. This proposal, therefore, forms part of an integrated HQP training plan, providing the needed student experiences in detector design, prototyping and testing. These activities will complement those obtained during running experiments with beam at JLab, including data acquisition, debugging and analysis. The combination of these activities will allow them to become well-rounded scientists, capable of critical thinking, leadership, and teamwork in their future careers.

### 4.2 How the infrastructure will better prepare HQP for research and other careers

The infrastructure requested here will allow HQP to develop expertise in nuclear electronics, statistical analysis, experiment design, mechanical and optical prototyping and testing. The will also acquire computational skills required for detector simulations and data analysis. The funds for these HQP are expected to come from a combination of NSERC Subatomic Physics envelope and UofR funds.

**Undergraduate Student Researchers:** Over the last five years, I have directly involved eight undergraduates in my research. Summer projects included PMT gain testing for the SHMS HGC, optical coupling tests for 5" Hamamatsu PMTs, simulations for the SHMS HGC optical design, testing and rehabilitation of the HMS focal plane detectors, data analysis and background simulations. Of these, three undergraduates spent significant time at JLab (T. Fitz-Gerald, B. Davis-Purcell, E. Avila), obtaining hands-on, international research experience. The undergraduate research experiences offered provide motivation for the student to continue on to graduate studies, and about half of the students so-employed do so. The others have gone on to apply their experiences in industry, primarily computing-related (e.g. iQmetrix, Quadrant Newmedia). As part of our HQP training strategy, we encourage our students to publicly present the research they have been involved with, such as at the Canadian Undergraduate Physics Conference (CUPC).

**Graduate Students:** The UofR Physics Department is almost exclusively involved in subatomic physics research, allowing a strong group with a critical mass of research activity to be maintained in a relatively small department. I am currently supervising three graduate students on JLab and Mainz research projects (S. Basnet, W. Li, D. Paudyal). The environment in the Department is highly collaborative, with my graduate students often helping (and receiving assistance from) other students working on the T2K and GlueX experiments. This encouraging atmosphere helps their education through exposure to the different techniques used in these investigations.

As an example of the valuable research contributions and skills acquired by my graduate students, some detail follows on Wenliang (Bill) Li's research work to date, which includes both hardware and data analysis aspects. He has made many contributions to the SHMS HGC detector project, including Geant4 simulations to optimize the detector optical layout and make predictions of the detector's expected $\pi^+/K^+$ separation efficiency. Bill also worked with JLab technicians to help develop a set-up to measure HGC mirror reflectivities over a wide range of wavelengths, and helped write a manuscript on the use of this facility to measure the optical transmission of RTV. This facility has since been used by other JLab collaborations to check their Čerenkov mirrors, saving them many thousands of dollars in mirror refurbishment costs.

If funded, we will train future UofR students and PDFs on the development of the SoLID scientific apparatus and the exciting data that will follow from this new international collaboration. However, since these trainee costs are not a CFI-eligible expense, funds will be requested from NSERC to cover this amount.

# 5 Benefits to Canadians

## 5.1 Beyond knowledge creation and HQP training, the expected to benefits to Canadians and why they are significant

This application builds upon our already significant expertise in Čerenkov detectors, and opens up for us significant new scientific opportunities. The Saskatchewan government has given strong support to the development of peaceful applications of nuclear technology, through the founding of the Sylvia Fedoruk Canadian Centre for Nuclear Innovation. As a result of that initiative, the province has recently invested a bridge faculty position in nuclear physics and nuclear imaging within the UofR Physics Department. The UofR was selected for that investment specifically because of our expertise for building particle detectors such as the one described here. Thus, international work of this nature has already been recognized by the province of being of significant benefit. Furthermore, many of the technologies used in Čerenkov detection have other practical applications, such as in improved breast cancer screening techniques, which is a topic of active research interest of the new UofR faculty member recently hired as a result of the Fedoruk initiative. Investments in state-of-the art detection technology for fundamental research such as this are thus drivers of improved technology for practical use later on.

The HGC detector prototype project is technically challenging (e.g. pressure and optical testing), and it involves a number of very specialized components (e.g. custom aluminum 7075 components, polymer mirrors and Kevlar/Mylar or Tedlar/Mylar thin windows). While the results from this type of research are often difficult to predict, the technical challenges often place new constraints on established technology, due to unusually strict requirements for equipment reliability and performance. Unlike the prototype requested here, which is planned to be constructed primarily in-house, if we are to attract a sizable portion of the full-size HGC project to Canada it will have to be constructed by companies willing to participate in the needed technical skill transfer. My colleagues at the University of Manitoba have expressed their interest in contributing to the full-size HGC detector after our prototyping tests are completed, so I am hopeful that we will have a significant Canadian contribution to this high profile international project.

In its 2012 report on the State of Science and Technology in Canada, the Council of Canadian Academies identified nuclear and particle physics as one of only a few sub-fields where Canada is ranked #1 in the world in terms of Average Relative Citations. As a result of this strong expertise, Canadian researchers are valued international partners and reap rewards in terms of technological spin-offs and enhanced HQP training opportunities. This proposal is exactly the type of scientific infrastructure project that CFI has already invested in at other Canadian universities.

### 5.2 Potential end-users of the research results and plans for knowledge mobilization

Our previous Čerenkov development work for JLab Hall A resulted in three refereed publications. Our work for the JLab SHMS Čerenkov has so far resulted in two publications (one refereed) and eight Technical Reports. Our results were also disseminated in the form of progress reports presented at detector workshops and conferences. The publications and technical reports are publicly available at http://arXiv.org and the Hall C document database https://hallcweb.jlab.org/doc-public/. If funded, we propose to similarly disseminate our results in a public manner, so that they may be used in as broad manner as possible. This will include public repositories such as the arXiv, peer-reviewed journals such as the Journal of Instrumentation and Nuclear Instruments and Methods, and conferences such as the American Physical Society and Canadian Association of Physicists meetings.

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