**Proposal for FY2021 Laboratory Directed Research and Development Funds**

**Title: The EIC on a Table Top**

**Topics: Advancing high performance computing and quantum information science**

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| **Mentor (if needed)** |  |
| **Proposal Term:** | **From:** 10/2020  **Through:** 09/2023  **If continuation, indicate year (2nd/3rd)**: new proposal |

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# **Abstract**

We propose a research collaboration between JLab and the AMO group of Olivier Pfister at UVA to adapt and enhance their optics-based Quantum Computing (QC) system to enable the calculation of Doubly-Deeply Virtual Compton Scattering amplitudes relevant for JLab12 and the EIC program. It is envisioned that high-performance computing techniques will be required to prepare the necessary states for the matrix elements. In partnership with UVA, JLab will provide the technical expertise to enhance the current system, and explore significantly scaling it to become a unique and powerful resource.

# **Summary of Proposal**

## **Description of Project**

This proposal explores the possibility of using near-term Quantum Computers (QC) to determine lepton-ion reactions directly from Quantum Chromodynamics (QCD) and Quantum Electrodynamics (QED). As they serve as a window into the inner structure of nucleons and nuclei, these reactions lie at the core of the present-day JLab 12GeV program and the planned [Electron Ion Collider (EIC)](https://www.bnl.gov/eic/). In particular, we focus our attention on the possibility of determining doubly-deeply virtual Compton scattering (DDVCS) of the proton as well as light nuclei, from which one may obtain their generalized parton distributions (GPDs).

Presently, the only reliable tool at our disposal to study QCD non-perturbatively is lattice QCD. Due to technical points, DDVCS may not be accessed directly using Euclidean based lattice QCD. However, a recent study by our group (Briceno, 2020) explains how DDVCS-like amplitudes, where each of the two currents have arbitrary virtuality, may in principle be accessed using near-term QCs.

This project will create a collaboration between JLab and the AMO group of Olivier Pfister at UVA to enhance and scale their existing optics-based QC system to enable such calculations by quantum simulation. The lab’s expertise in electronics, cryogenics, and detector technologies will be required to achieve these goals.

The project will proceed in three phases. The first is to demonstrate a complete small-scale quantum simulator using the present system. We will initiate the necessary theory collaboration between JLab and UVA to establish how lattice QCD calculations should be formulated for this continuously-variable QC system, and UVA will work with the theorists and experimentalists to make the current system workable for the envisioned calculations. The second open is to show that scaling-up the system by a factor of 10 is possible. In a third phase we will investigate how the system can be scaled by another factor of 10 to 1000.

This project covers two of the main FY21 focus areas of the JLab LDRD program - Advancing high performance computing, and Quantum computing.

## **Expected Results**

Continuous-variable QC based on quantum optics provides a new and powerful, but relatively unexplored, avenue for simulations of lattice field theories. We will establish a theory collaboration program with UVA that will investigate their formulation. We will produce a document describing the impact for nuclear theory computing, considering the present system, and scaling the number of modes accessible within the system by x10, x100, and greater than x100.

In year 1, we will pave the way to a complete quantum simulation system by automating the current system, improving its stability, adding electronic quantum-gate control features, and enhancing the electronic data acquisition and processing. A report detailing the improvements will be provided.

In year 2, utilizing the improvements from year 1, we aim to show a complete quantum simulation on a small scale while showing that scaling up the system by x10 is possible. It is anticipated that further enhancements of the electronic and measurement systems, as well as cryogenic systems, will be required. We anticipate providing a report on the activities and prospects within year 2. Given a successful result showing the viability of our plan for scaling, we will begin the acquisition of a new measurement system late in the year.

In year 3, we will complete the acquisition of the new measurement TES system and demonstrate the scaling of the system by x10 along with a report on the activities. We will report on a plan to further scale the system by x10 up to x100.

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# **Proposal Narrative**

## **Purpose/Goals**

One of the primary goals of Jefferson Lab is to understand the inner structure of nature’s building blocks. By understanding how quarks and gluons arrange themselves into hadrons, including light nuclei, we hope to answer some of the more pressing questions of nuclear physics: “What is the origin of the mass of matter?”, “What is the role of gluons?”, “How do partons hadronize?”.

The connection between partons and hadrons is quantified in terms of a variety of partonic distributions functions. These are non-perturbative objects, which until recently could only be accessed indirectly from experimental lepton-hadron data. Recently, there has been tremendous progress to access these distribution functions directly from theory of quark and gluons, namely quantum chromodynamics (QCD), using the only systematic non-perturbative tool in the market, lattice QCD. In fact, the Lab’s theory group, including some of the members of this proposal, have been playing a primary role in making this a reality. Despite the progress of lattice QCD, it is limited in scope because it is defined in a Euclidean spacetime. This is a limitation that may be circumvented with the advent of quantum computers.

This proposal builds upon an on-going exploratory research to use quantum computers to study nuclear reactions that are imperative for the EIC program and are presently inaccessible using classical computers, including deeply virtual Compton scattering of light nuclei. This is a tall order but not obviously impossible.

In order to understand if or how quantum computers may be of use in the study of nuclear reactions, it is necessary to understand particularities of how the underlying equations of nuclear physics may be cast onto quantum devices. This project brings experts from Nuclear theory, Computer Science and AMO physics to address the outstanding obstacles to access nuclear reactions from QCs.

With this goal in mind, the feasibility of accessing Doubly-Deeply Virtual Compton Scattering (DDVCS) using QCs has recently been explored (Briceño, 2020). While QCs may in-principle give access to real time observables, these calculations necessarily are confined to a finite spacetime where asymptotic states are absent. Given that scattering theory requires the existence of asymptotic states in order to define reactions, naively nuclear reactions may not be possible to access using QC. Briceño et al. present a practical solution to this shortcoming and present a proof that DDVCS amplitudes may be obtained from finite-volume Minkowski observables determined using QCs. Part of the proposal aims to extend this observation and investigate the outstanding details to bring to a reality in practice.

The continuous-variable “qumode” approach used in the UVA/QC system opens up a new and powerful avenue for the simulation of quantum field theories, in particular gauge theories like QCD (Marshall, 2015; Yeter-Aydeniz, 2018). We will establish a research collaboration amongst UVA, JLab, ODU and W&M to formulate a quantum field theory using the cluster-state approach (Chen, 2014) advocated by UVA. The prepared input and output states for the proposed lattice QCD matrix element calculations will be generated using high-performance, but “classical”, computer systems. In a fully realized version of the system with ~106 qumodes, we anticipate large-scale computing resources will be required.

At present the UVA/QC team has demonstrated the entanglement of 60 quantum fields, or qumodes, in a cluster state suitable for quantum simulations. Qumodes are the equivalents of qubits and the basic units of a simulation, the available degrees of freedom that can be used to encode QFT. The optics-based approach scales well, due to the use of the spectral domain, and it is expected that that there are actually about 104 spectral modes generated on the table (Wang, 2014) which can scale to 106 and beyond by also employing a sequential, time-resolved approach (Alexander, 2016); however, the measurement system to implement quantum gates is not yet in place. A goal of this project is to leverage the lab’s expertise in electronics, cryogenics and detector technology to scale up the measurement capacity of the system.

## **Approach/Methods**

The only non-perturbative, systematically improvable method available to make predictions from QCD is the lattice formulation, which is the technique used in this project. The calculations must be made with a finite lattice box size as well as some finite, non-zero, lattice spacing. Discretization effects can be systematically removed. More importantly, the restriction to finite spatial volume turns out to be a powerful tool that allows us indirect access to scattering amplitudes, such as in DDVCS. The application of finite-volume techniques, coupled with high-performance computing, has enabled significant progress in the determination of hadron spectroscopy and structure. This formalism relates finite volume calculations, available with the finite number of degrees of freedom in HPC systems, with infinite volume Minkowski scattering amplitudes that we can compare to experiment. This approach is well matched to present Quantum Computing systems which have only a finite number, possibly continuous, degrees of freedom such as in the UVA/QC system.

The UVA/QC system provides a platform where we can apply these finite-volume techniques directly in Minkowski space. In this approach, QCD is formulated as a Hamiltonian system acting on some input state, evolving that state to a later time, and contracting with some suitable out-going state. In the case of many-body, e.g. multi-nucleon, these states can be provided using spectral information gathered in an HPC calculation of QCD in Euclidean space. A part of the theory program is developing the suitable formulation of quantum field theories within the UVA setup.

There are several aspects of these Minkowski based calculations (Briceno, 2020) that require further investigation, as outlined below. Fortunately, the steps for testing the theory match well onto the stages of this project. We will formulate and test simplified versions of quantum field theories, such as the **𝛟**4 model where there are site based interactions, in finite volume utilizing the limited number of qumodes available. As the system is scaled, we will check that model based calculations agree with those available from the UVA/QC system.

The two principal challenges to reaching practical QC are achieving scalability (reaching a large enough number of qubits to enable nontrivial computations) and eschewing decoherence (that turn quantum state superpositions into statistical mixtures). As a QC platform, light yields record-size quantum processor prototypes while helping with decoherence, photons being non-interacting bosons. This LDRD quantum simulator project leverages the experimental demonstration by the Pfister group of a highly scalable experimental platform for quantum information in which traditional discrete-variable (two-state) qubits are replaced with continuous-variable (CV) quantized electromagnetic fields, or **qumodes**. The qumodes are the resonant modes of an optical resonator that contains a two-photon-emitting nonlinear crystal whose function is to generate quantum entanglement between qumodes. The resulting device, an optical parametric oscillator (OPO), has been used by the Pfister group to demonstrate large-scale (60-qumode, extensible to 104-mode) entanglement in specific quantum states, called **cluster states** (Pysher, 2011; Chen, 2014), which form the mathematical substrate of **measurement-based QC**, a.k.a. **one-way QC**. These scalable cluster states form the experimental backbone of this proposal, which will investigate their use, as universal QC resources, for the simulation of quantum field theory (QFT), following the CV generalization (Marshall, 2015) of an initial proposal over qubits (Jordan, 2012). The Pfister lab has mastered the generation of large-scale cluster states. What’s missing is the ability to perform quantum gates by implementing specific measurements of cluster states. The goal of this LDRD effort is to address this in so as to pave the way toward quantum advantage, i.e., quantum simulation regimes inaccessible to classical computers.

The thrusts of this proposal are as follows, all in collaboration involving JLab, UVA, W&M, and ODU:

1. EXPERIMENT (JLab and UVA)
   1. Develop all components of a **complete quantum simulator**. (“x1 stage.”)
      1. Prepare a QC-universal 2D-graph cluster state. Note that theory work will inform on different, more specific cluster states that could also be used.
      2. Develop Gaussian[[1]](#footnote-1) heterodyne parallel processing technology (“quantum FM”) for realistic **large-scale** quantum simulation.
      3. Develop the one- to few-qumode non-Gaussian quantum gates that enable **exponential** QC speedup (e.g., **𝛟**4 evolution gates) and quantum error correction. They rely on photon-number-resolving (PNR) detection, implemented by superconducting transition-edge sensors (TESs).
   2. **Scale the quantum simulator** **size**
      1. **x10 stage**. Implement all components of x1 stage together. Increase the number of TESs by 10 to scale up non-Gaussian gates. (Gaussian gates should already be large-scale after 1.1.2.)
      2. **x100 stage**. Produce a plan for scaling the number of TES by 100. This may require a complete upgrade of cryogenics, with a new refrigerator.
2. THEORY (JLab, UVA, W&M, and ODU)
   1. Develop QFT models. Identify and develop QFT models and problems, especially of interest to JLab and EIC, that would benefit the most from the associated experimental effort on quantum simulation.
   2. Map the quantum circuits known to simulate QFT, e.g. site-based interactions including **𝛟**4 and link-based interactions including gauge theories, into cluster states and one-way QC.

**1. EXPERIMENT** The present experimental system is composed of two main components, on two separate optical tables. One produces the optical beam that is in the cluster state, and implements interferometric (homodyne/heterodyne) measurements which characterize entanglement and enact part of the quantum simulation. All such field (wavelike) measurements are Gaussian and easy to simulate. The other table implements photon-number-resolving (PNR, particle-like) measurements which project the light into non-Gaussian Fock states, an operation which can be leveraged, in principle, to yield **𝛟**4 gates (Lloyd, 1999; Gottesman, 2001). Any difficult-to-simulate operation must involve both large-scale and non-Gaussian gates.

**1.1** **Quantum simulator build.** In the first phase (x1), the two tables will be coupled to perform non-Gaussian gates on a large-scale Gaussian cluster state, a requirement for a complete quantum simulator. With help from the JLab electronics group, the stability control of the first table, as well as the data acquisition and processing of both tables will be automated, per the following milestones:

**1.1.1 Improved optical servos:** This is crucial to realizing a 2D-graph cluster state and operating it stably, beyond the previous UVA work which focused solely on cluster-state characterization. The experiment uses ultrastable laser and OPO cavities, controlled by servo loops. In order to achieve long-term stability, these servos need to be improved (broader bandwidth, separate slow and fast gain channels) as well as automated so as to relock themselves after jumping out of lock due to thermal drifts, acoustic noise spikes, etc. This could be done using commercial components, such as Vescent D-125 loop filters or Moku:Lab by Liquid Instruments, and FPGA design by JLab. There is a research opportunity with JLab electronics, and possibly also the JLab source group, to consider a more custom solution using lab expertise.

**1.1.2 Real-time heterodyne data processing:** The encoding of the qumodes is in the frequency domain, in the optical frequency comb (OFC) of the OPO. This provides a unique opportunity for parallel processing (patent pending). In order to take advantage of this, heterodyne optical measurements of the OFC against a monochromatic local oscillator (LO) need to be demodulated at a number of different frequencies simultaneously. A powerful way to do this is real-time FFT of the whole heterodyne signal. The real-time component is needed to implement post-measurement feedback on unmeasured qumodes, which implements Gaussian quantum gates in one-way QC. This will be designed and implemented by JLab using FPGAs to acquire and process the UVA multi-heterodyne signal. The number of FFT points will need to be at least the number of qumodes, the whole spectral range being reciprocal to the measurement time. In order to test this procedure, we will use dense spectral encoding of qumodes 10 kHz apart (the mode spacing in previous experiments was 1 GHz), which is allowed by our use of 1 kHz-bandwidth pump and LO lasers.

**1.1.3 Real-time PNR data processing:** The measurement system on the second table uses cryogenic superconducting Transition-Edge-Sensor (TES) calorimeters, which provide a unique high-quantum-efficiency PNR measurement system. The UVA system was developed by SaeWoo Nam’s group at NIST, Boulder, with whom the Pfister group collaborates. Direct signals from the TES can give counts up to 5 photons; however, using fast signal integration, counts up to 15-20 photons can be obtained. Here again, such PNR measurements need to be used in feed-forward to electro-optic components in order to implement non-Gaussian gates such as the cubic and quartic phase gates (Gottesman, 2001). JLab has developed flash ADCs that appear to meet the requirements for scaling the number of photons detected on the TES to 15-20 photons, and provides a software framework for generating suitable signals to be used in downstream electronics on the table.

In this first phase, we will apply both of these approaches to demonstrate increased automation of the system. In this phase, lab members will gain the necessary experience to tackle the next steps.

**1.2 Scaling stage.** The second phase of the project consists in bringing all milestones of Stage 2.1 together to demonstrate a “toy mode” QFT simulator over tens of qumodes. Note that the Gaussian part of the simulator, the quantum OFC, should already be at this stage due to the initial number of 104 entangled qumodes and the heterodyne FFT processing. The challenge here will be to scale the non-Gaussian resources, in particular the number of TESs. A 10-qumode quantum simulator is likely to require, at the very least, 10 PNR measurements as part of 10 **𝛟**4 gates and 10 other final PNR measurements to deliver the final evaluation of the QFT scattering amplitude. This means 20 TES operating simultaneously. The current capability of the UVA lab is 8 TES, with 3-6 operating simultaneously (due to electronic readout issues and different temperature biases per device). A first step will be to bring all these together in order to demonstrate a “toy model” quantum simulator on a few qumodes. The increase of the TES numbers involves two efforts: first, acquiring them and we are considering a commercially available system from Xanadu in Toronto. Second, the cryogenic capability needs to be assessed. This presents an opportunity for JLab’s expertise in cryogenics to assess the limit of the current UVA adiabatic demagnetization refrigerator (ADR) and the need for a more powerful system such as a dilution refrigerator.

The current TES system has 16 device slots, 12 of them filled, 8 of them by 1064nm-wavelength devices in use (the other 4 operate at 1550 nm). The operational temperature of the TES system is 100 mK with an estimated total heat load of less than 1 𝝁W. However, the noncontinuous cooling nature of the ADR limits the available measurement time to about two days. Recycling the ADR requires approximately two hours. Scaling the number of TESs above a factor or two or more will severely impact the time available for measurements, and greater refrigeration capacity will be needed. The largest 3He-4He dilution refrigerators commercially available provide continuous cooling capacities up to about 1 mW at 100 mK. At face value, such systems could support more than a thousand TESs, although a more careful analysis of the complete heat budget is required before making a definitive statement. The 100x system may actually require a custom-designed dilution refrigerator that is optimized to provide increased capacity not only at 100 mK, but also at higher temperatures where ancillary electronics such as SQUIDs are located. The JLab Target Group has experience in this area, having designed and constructed a dilution refrigerator for a frozen spin polarized target in Hall B with a cooling power in excess of 10 mW at 100 mK. In year one of this proposal, a Target Group staff scientist (C. Keith) will make a detailed analysis of the existing system at UVA and determine appropriate cooling requirements for both 10x and 100x scalings. Procurement of a commercial dilution refrigerator may commence in year two. We have a quote for a basic mid-sized dilution refrigeration system from BlueFors – the LD400 for $400k - that may serve the needs of the intermediate system. Alternatively, Target Group personnel (C. Keith and one engineer/designer) could begin designing a high cooling power dilution refrigerator capable of supporting even more TESs. The choice between these two avenues will clearly depend upon the availability of funds and the results from the rest of this project.

Another key requirement of the scaling effort is the procurement of the TES themselves. These are uniquely sophisticated optically coated W chips, coupled to single-mode optical fibers. The exquisite TES resistance variation per photon absorption are detected by SQuIDs and preamplified, all at cryogenic temperatures. The current TES devices and their SQuIDs in the UVA system are manufactured by SaeWoo Nam’s group at NIST Boulder, with whom Pfister’s group has collaborated. Xanadu in Toronto has provided a quote for a 12, 24 and 36 channel commercial version of these systems. The package optionally includes a FPGA DAG with software designed to control the system. The speed of the DAQ system is below that of the JLab fADCs, and the latter might be required to meet our measurement requirements. The system also optionally includes cryostat wiring for a pre-supplied cryostat. The cryostat would be purchased separately. The quote for the 12-channel TES+SQuID assembly without cryogenics (since the Pfister lab is already equipped with an ADR) but including the DAQ and cryostat wiring is $425k for a 12 channel system. The project’s experience on the phase 1 system will leave us prepared for this next phase. Preliminary measurements on a Xanadu system will allow us to further tailor our developments, and upon integration into the JLab-UVA system, demonstrate scaling before the end of the project.

The ultimate stage at which the quantum simulator can be expected to reach quantum advantage, i.e., to outperform state-of-the-art lattice-gauge QCD calculations, will likely require “optics-on-a-chip” (implementing all optics from source to detection of a photonic waveguide device). The method is being pursued at Harvard, Yale, Purdue, Arizona, Virginia, and elsewhere as well as in the industry, see (Pfister, 2019) for references, and could potentially scale to 106 qumodes, but likely will not be considered in this project. Possibly another project, involving NSF or a DoE center, is appropriate.

**2. THEORY.** Theory methods can be tested on these intermediate stages. Even with the present system, we can consider the efficacy of the new approaches in toy models requiring few degrees of freedom. As the system is scaled, the methods, relying on finite-volume scaling, can be studied. As the system grows, more sophisticated models nearing the proposed matrix elements can be studied, allowing us to validate the efficacy of the approach.

# **Year 1:** in collaboration with UVA, the theory effort will focus on the interface between the QFT simulation goals as defined by JLab/ODU/WM and the UVA quantum optics simulator platform. This effort will be spearheaded by the UVA postdoc and will be two-pronged: mapping the quantum-circuit model of QFT simulation of (Marshall, 2015) onto cluster states and integrating this mapping to specific QFT simulation models, in particular the classical simulation software of the Orginos group.

The development of the formalism for finite-volume Minkowski matrix elements (Briceno, 2020) provides a proof of principle that DDVCS amplitudes may indeed be accessible within this framework. There are several formal outstanding feasibility questions that have been raised in this work that should be addressed. One particularly important is regarding the need of a smearing parameter. Ultimately, the physical observables must be independent of this parameter, but there are practical costs in making this too small. With this in mind, Briceño will be working with the PD and the ODU graduate student to quantify and mitigate these sources of systematics. The new graduate student will begin training.

The general framework of a CV quantum computing device contains the setup of continuous-variable states that evolve in time with a specific Hamiltonian. It is known that in such devices one can implement hamiltonians that are arbitrary polynomials of the canonical variables. For a small number of qumodes one can compute the behavior of the system on a classical computer. We propose to investigate the design of a software package, written in C++ and Python, that would allow us to simulate the quantum computation on a classical computer. Such packages already exist for the case of qubit based quantum computers. Orginos and collaborators intend to design a software package that implements the basic operations allowed by the underlying “hardware”.

The UVA postdoc will work on mapping quantum simulation circuits originally proposed in (Marshall, 2015) to cluster states, which are the scalable QC resource Pfister lab produces. Because cluster states are QC-universal, we know such a mapping exists. The longer-term goal is to integrate both the quantum circuit and the cluster architectures with the Orginos code.

Close coordination with the UVA team will be established so that we can begin to think about implementations of the theoretical models on the UVA system. The JLab postdoc will begin working with the UVA team.

**Year 2:** having laid out the framework for studying DVCS using QCs for single-particle states, Briceño and collaborators plan to investigate the possibility of considering DVCS of loosely-bound states, like the deuteron. From experience with developing finite-volume formalism for lattice QCD, it is expected that these observables will suffer from additional finite-volume systematics. This requires understanding the properties of the desired amplitudes and their finite-volume counterparts, which will be considered first in 1+1 dimensional spacetime.

Orginos and collaborators will continue the investigation of simple field theories with O(600) qumodes. These studies will be done with the simulator software and will aim to further understand finite volume corrections by varying the size of the box in a wide range of box sizes. Orginos and collaborators will provide a progress report on the performance of the simulator software. Orginos and collaborators will provide a progress report on implementations of simple field theories on the UVA system. Experience on these implementations using results from the simulator software will be presented in this report.

**Year 3:** we will investigate state preparation for bound states. HPC resources will be needed to prepare such states in a finite-volume. Results of these investigations will be reported.

We will do initial investigations of field theories with fermions such as the Schwinger model in 1+1D. These investigations will be generalized to field theories in higher dimensions. We will consider scalar QED in 2+1 and 3+1 dimensions. At this point, our new and larger system will be available (scaled up number of qumodes) and such models may be possible to be considered for implementation on the JLab-UVA system. Reports on formulations of fermionic and non-abelian gauge theories will be presented.

Investigations of matrix element calculations, at first in low rank theories, using the JLab-UVA system will be carried out. These steps will require the preparation of initial and final states. Results will be reported along with the prospects for scaling these calculations to systems like QCD.

**Goals for FY2021**

* Quarter 1
  + Theory: design a software package that implements the basic operations allowed by the underlying “hardware” will be written.
  + Electronics: First interfacing of JLab f-ADC with UVA TES signals and characterization of photon-number measurements, in collaboration with the UVA graduate student..
  + Cyrogenics: Keith will visit Pfister Lab at UVA to examine and detail the existing cryostat in its disassembled state.
* Quarter 2
  + A prototype code will be developed following the design in quarter 1. Coordination with the UVA team (postdoc) will make sure that the code faithfully represents the capabilities of the physical device.
  + The cluster-state architecture will be integrated into the Orginos code. We will start modeling experimental imperfections (decoherence) to assess their effect on the quantum simulation.
  + Orginos and collaborators will begin the investigation of simple field theories using the qumode implementation. Low dimensional simple theories such as scalar φ^4 and scalar QED in 1+1 dimensions will be considered for implementation on a system with a small number of qumodes.
  + Electronics: integration of f-ADC into UVA PNR measurement chain. First interfacing of f-ADC with heterodyne signals from the UVA QOFC.
  + Keith: Generate heat budget for existing system and compare it to data.
* Quarter 3
  + Continue the investigation of simple field theories and begin implementation on simulator software by Orginos and collaborators.
  + Electronics: Use of the TES f-ADC system in quantum tomography and quantum gate experiments. Possibility of publishable results on quantum state engineering. Implementation of FPGA-FFT on heterodyne QOFC signals.
  + Keith: Scale heat budget from Quarter 2 to 10x, 100x, etc. Identify satisfactory refrigeration for each.
* Quarter 4
  + Briceño and collaborators will present findings on the dependencies on the smearing, time extent and lattice size dependence of the finite-volume formalism to the collaboration in this time period.
  + If successful, in formulating simple field theories with qumodes and simulating them with our software simulator a manuscript will be written by Orginos and collaborators.
  + Electronics: Successful demonstration of a scalable 2D cluster state parallel-processed by FPGA-FFT (publishable).
  + Keith: As required, identify vendors and obtain quotes for a cryogenic refrigerator commensurate with 10x and 100x systems.

## **Required Resources**

It is anticipated that some computing time on the JLab HPC systems will be required for the theory program development. Some small percentage of the system time is reserved for the lab, and as such, small allocations are available.

Beyond this, suitable lab space is available for the project members.

## **Anticipated Outcomes/Results**

Quantum field theory (QFT) lattice methods provide a powerful tool to gain insight into Quantum Chromodynamics, and have become well established in the Nuclear Physics community. The Euclidean based formulation is highly suited to High Performance computing, and with access to upcoming Exascale computing platforms, will provide new predictions from QCD that will guide and impact the experimental program of Jefferson Lab, as well as future directions within Nuclear Theory. However, there are limitations to the method. In particular, the theoretical formulation of QCD in Euclidean space significantly complicates how one can probe the deep inelastic scattering (DIS) of quarks and gluons. A new approach, provided by Quantum Computing platforms, presents a revolutionary method whereby the theory can be recast in Minkowski space allowing, for the first time, a non-perturbative investigation of QCD directly in the DIS regime.

This project brings together the extensive theoretical progress and understanding that has been made in conventional QCD formulations, in particular from members of the Jefferson Lab Theory Center, with the rapid developments and expertise available in Quantum Computing. While there are many aspects of this new formulation that are familiar, more theoretical development is needed to realize the full potential of the approach. As the program begins investigating the computation of matrix elements with extensive initial and final states, classical calculations using High Performance Computing systems are expected to contribute. Over the course of the project, the theory formulations will match the stages in the development of the hardware providing a crucial synergy between both theory and experimental developments.

While there have been very recent experimental advances on qubit-based quantum simulation using trapped ions and trapped Rydberg atoms, this project would bring about the first experimental quantum simulator of quantum field theory, especially as applied to the problems of interest to Jefferson Laboratory, such as deeply virtual Compton scattering. The use of continuous-variable quantum fields, i.e., qumodes, to simulate quantum fields is also a much more natural choice than that of the discrete-variable qubits, one that can reach additional simulation power. The unique advantage of qumode encoding is its demonstrated scalability in quantum optics, which is unmatched by any known qubit platform.

The project would both validate the approach by demonstrating complete QFT simulation, say site or link based interactions, albeit on a limited scale initially and then up of tens of qumodes, before paving the way to larger scale quantum simulations which can lead to quantum advantage of over lattice-QCD based approaches. While quantum advantage will necessitate other advances outside the scope of this LDRD (such as integrated optics), we believe that the LDRD work will build a compelling foundation for a next-stage proposal at the center level with either DoE or NSF.

Another aspect is the exploitation of measurement-based quantum computing (MBQC), which utilizes large-scale cluster states, as the fundamental principle. While MBQC has been theoretically proven to be a universal QC approach, its use for quantum simulation still represents new scientific territory whose exploration will be spearheaded by this LDRD project.

It is also important to note that building a universal quantum simulator isn’t required to blaze a trail to quantum advantage. The simulation of QFT presents a variety of certifiably hard problems and our effort can be focused on attacking just one of them, privileging *ad hoc* experimental approaches and solutions over the more challenging program of building a universal quantum computer. Finding these specific problems and building the right quantum machine for them will leverage Jefferson Lab’s expertise in theory and experiment, both empowering and unifying academic efforts at UVA, W&M, and ODU.

The extensive cooperation required between theory and experiment will provide a new direction for the lab to extend its expertise. Over the course of the project, as the team gains confidence in the understanding of the UVA system and the challenges that are involved, the system will be expanded and made more robust. These steps are anticipated to feedback into the lab in the form of new capabilities in cryogenics, electronics, and theory.

## **Accomplishments in Previous Years**

Not applicable

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# **Budget Explanations**

**Theory @ JLab, ODU, W&M:**

* Years 1, 2, 3
  + Purchases/procurements:
    - None
  + Personnel:
    - 0.25 FTE/year for R. Edwards as the PI, management, and participant in the theory developments for formulating LQCD in the UVA framework.
    - 2.5% FTE of R. Briceno at ODU and 2.5% FTE of K. Orginos at W&M. These faculty members will supervise their students working on the project, and participate in discussions amongst the theory groups. They will also interact with the postdoc at JLab and the UVA staff.
    - Request funding for 3 years of two (current) graduate students at ODU (supervised by R. Briceno) and W&M (supervised by K. Orginos) to work with their supervisors and R. Edwards on the formulation and implementation of quantum field theories within the UVA framework. In the fall, these students would be at the correct point in their graduate career to take on such a project. In particular, we anticipate these students will work directly with UVA to implement toy models on the existing and scaled systems. One student project will involve developing the mechanisms for input and output state preparation for the simulator. Another project is understanding the finite-volume and time-evolution scaling of toy models within the UVA framework.
    - Request funding for 3 years of a postdoc at JLab. The postdoc will help coordinate the efforts between JLab, ODU and W&M on the development of the lattice QCD formulation for the QC system. The postdoc will help with extending the finite-volume formalism for bound-state nuclei, and also extend these finite-volume calculations to the UVA framework. There is currently a postdoc, Juan Guerrero, at ODU working part time on a project in QCD global data analysis, and part-time with Raul Briceno on developing the Minkowski-space finite-volume formalism. He is a co-author on the first study of the formalism in the 2020 paper with R. Briceno listed in the references. This initial study, the basis for the theory component of this project, has considered DDVCS for a virtual photon and proton. Later extensions will consider nuclei. J. Guerrero is a candidate for the proposed postdoc position in JLab Theory. This PD will work closely with the UVA experimental group. J. Guerrero is a candidate for the proposed postdoc position in JLab Theory.
  + Travel:
    - Travel by team members to UVA (experimental work in the lab, weekly meetings with the theory team － which can also take place at JLab)
  + Needed hiring:
    - There is no need for hiring outside of the JLab orbit.

**UVA:**

* Years 1, 2, 3:
  + Purchases/procurements:
    - Year 1: automation of present system (phase 1)
      * Vescent D2-125 auto-relocking loop filters for servo loops $3.5k/box and 6 boxes ~$21k
    - Years 2 & 3: demonstration of scaling by 10x (phase 2)
      * Transition-Edge-Sensor system from Xanadu. One unit of 12 TES+SQuID elements. Total cost quoted is $425k. Split costs over years 2 & 3.
  + Personnel:
    - Requesting 1 month/year of summer salary of Olivier Pfister to work on the project in connection with JLab.
    - Request funding for 3 years of a postdoc to work with the JLab-centered groups on the development of the theory for the QCD system as well as the JLab experimental groups.
    - Request funding for 3 years of a graduate student. The student will work with the JLab experimental group on the implementation of techniques to improve the stability and scaling of the UVA system.
* Travel:
  + Travel by team members to JLab (experimental work at Pfister labs; theory work on interfacing QFT and quantum optics for quantum simulation)
* Needed hiring:
  + The Pfister group currently has graduate students on the experiment who would be available for this project. On the theory side, one postdoc, Dr. Carlos González-Arciniegas has been with the group for 1.5 years and enjoying a very productive spell in theoretical research in quantum information (González-Arciniegas, 2019). He would be an ideal candidate for the job.

**JLab electronics:**

* Year 1: automation of present system (phase 1)
  + Purchases/procurements:
    - Stand-alone fADC devices are $3.5K each - 16 Channels
  + Personnel:
    - 0.25 FTE - Hai Dong[FEDAQ] and John McKisson[RDI] are two people that will spend about a month each to handle new requests needed for optimizing DAQ for the TES devices.
* Year 2: plan for scaling the system for 10x:
  + Purchases/procurements:
    - Add cost for more fADC to match quantity of TES devices. [Use $3.5K/16-Channels]
    - Scaling up may need new firmware/software as discovered during the previous year.
  + Personnel:
    - Makes sense to increase manpower to 0.5FTE because more research will be needed to identify and/or design new laser cavity lock electronics to include FPGA PID loop control
* Year 3: plan for scaling system for 100x:
  + Personnel:
    - 0.4 FTE {Electrical Engineer/Software/Firmware} and 0.2 FTE (Senior Staff Scientist).
* Travel:
  + Travel by team members to UVA - estimate 3 weeks integrated per year

**JLab cryogenics:**

* Year 1 - scaling system for 10x & 100x:
  + Purchases/procurements
    - N/A
  + Personnel:
    - 0.1 FTE (Chris Keith) to develop heat budget and cooling requirements for increasing the current number of TESs to a number commensurate to x10 and x100 scaling.
  + Travel:
    - Travel (Chris Keith) to UVa to examine existing cryostat in disassembled state, one trip of two days.
* Year 2 - scaling system to x10, x100:
  + Purchases/procurements:
    - TBD based on Year 1 results. Possible procurement of a cryogenic refrigeration system commensurate with the heat budget determined in Year 1. **The amount has not been budgeted into the spreadsheet**.
  + Personnel:
    - TBD based on Year 1 results. If necessary, commence design of a custom cryogenic system commensurate with the heat budget determined in Year 1. 0.15 FTE (CK) + 0.4 FTE (designer).
* Year 3: plan for scaling system for 100x:
  + Purchases/procurements:
    - NA
  + Personnel:
    - TBD based on Year 1 results. If necessary, complete design of a custom cryogenic system commensurate with the heat budget determined in Year 1. 0.15 FTE (CK) + 0.4 FTE (designer).

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1. From here on, “Gaussian” refers to the Wigner function of quantum states/gates. [↑](#footnote-ref-1)