Cover Page

The project title:	High intensity CBETA tests for electron cooling
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COVER PAGE SUPPLEMENT

Lead Institution: Brookhaven National Laboratory (BNL)	
PI: Stephen Peggs	Accelerator physicists & engineers to support enhanced study and commissioning.

Collaborating Institutions	
Name and Institution	**Facilities, Equipment and Resources**
PI: Georg Hoffstaetter, Cornell University	CBETA accelerator and infrastructure. Accelerator physicists & engineers to support enhanced study and commissioning.
PI: Steve Benson, Jefferson Laboratory	Accelerator physicists & engineers to support enhanced study and commissioning.

Budget table ($ in thousands)

Collaborative Application Information					
Title	**Names**	**Institution**	**Year 1**	**Year 2**	**Total Budget**
Lead PI	Stephen Peggs	Brookhaven National Laboratory	$480k	$495k	$975k
Co-PI	Georg Hoffstaetter	Cornell University	$703k	$1,297k	$2,000k
Co-PI	Steve Benson	Jefferson Laboratory	$550k	$430k	$980k

Leadership Structure:

Brookhaven National Laboratory is the lead laboratory for the proposed work, in close collaboration with Cornell University and Jefferson Laboratory. The three PIs report on this work directly to the funding agency, as required. Quarterly updates to the DOE funding officer and more substantial annual reports are envisioned. Communication and coordination between the three groups is maintained by weekly phone meetings of the PIs and co-PIs. Stakeholders of the three laboratories also receive updates about the work of each group.

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Project Narrative

1.0 Introduction

The unique foundation for the proposed work is the Cornell-BNL ERL Test Accelerator, CBETA, the world's first multi-turn SRF ERL. This proposal highly leverages previous funding by the National Science Foundation (NSF) for existing Cornell University equipment, and single-shot funding by New York State Energy Research and Development Agency (NYSERDA) for the construction of CBETA.

The major challenge in reaching luminosities of $L=10^{34}cm^{-2}s^{-1}$ and higher in an electron-ion collider (EIC) is the realization of strong hadron cooling with electron beams. The most efficient way of producing the strong CW electron beams needed for cooling is through the use of energy recovery linac (ERL) technology. However, the state of the art in ERL technology falls short by a factor of 10 to 100 in intensity, compared to what is needed for strong hadron cooling. We propose to address the necessary development of ERL technology by studying the accelerator physics and technological issues using the CBETA facility, which will begin to be available for experimental beam tests in 2019. The community panel on R&D priorities for EIC recommended that such studies to be performed with highest priority.

Construction of CBETA, an accelerator capable of 4-pass ERL operation, will be completed in 2019. Commissioning to achieve the relatively modest Key Performance Parameters shown in Table 1 will continue until April 2020 [1]. This proposal covers a program of CBETA work over the two-year period from October 2018 to October 2020, with the central goal of understanding and increasing the average current and single bunch charge limits for the different electron-cooling concepts for EICs. Initially the program focuses on simulation studies, beam diagnostics development, and Low Level RF (LLRF), evolving towards enhanced commissioning and extraction design during the second year.

Table 1: Key Performance Parameters (KPP) defined in the construction contract with NYSERDA, and ultimate anticipated design parameters.

Parameter	Unit	KPP	Design
Electron beam energy	MeV		150
Electron bunch charge	nC		0.123
Electron source current	mA	1	40
Bunch repetition rate (source)	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV		6
RF operation mode			CW
Number of ERL passes		1	4
Energy aperture of arc		2	4

Limits for the average current and the bunch charge in CBETA are expected to be set by:

a. Higher-Order Mode (HOM) absorber heating in the Main Linac Cryomodule (MLC).
b. Beam-Breakup Instability (BBU).
c. Halo losses and associated equipment damage and radiation exposure.
d. Emittance degradation for high bunch charges.
e. LLRF control issues with a very high ratio of circulating beam power to installed RF power.

These same processes will limit the current and bunch charge in any ERL-driven electron cooler for the EIC. CBETA is therefore an excellent – and unique – test-bed accelerator.

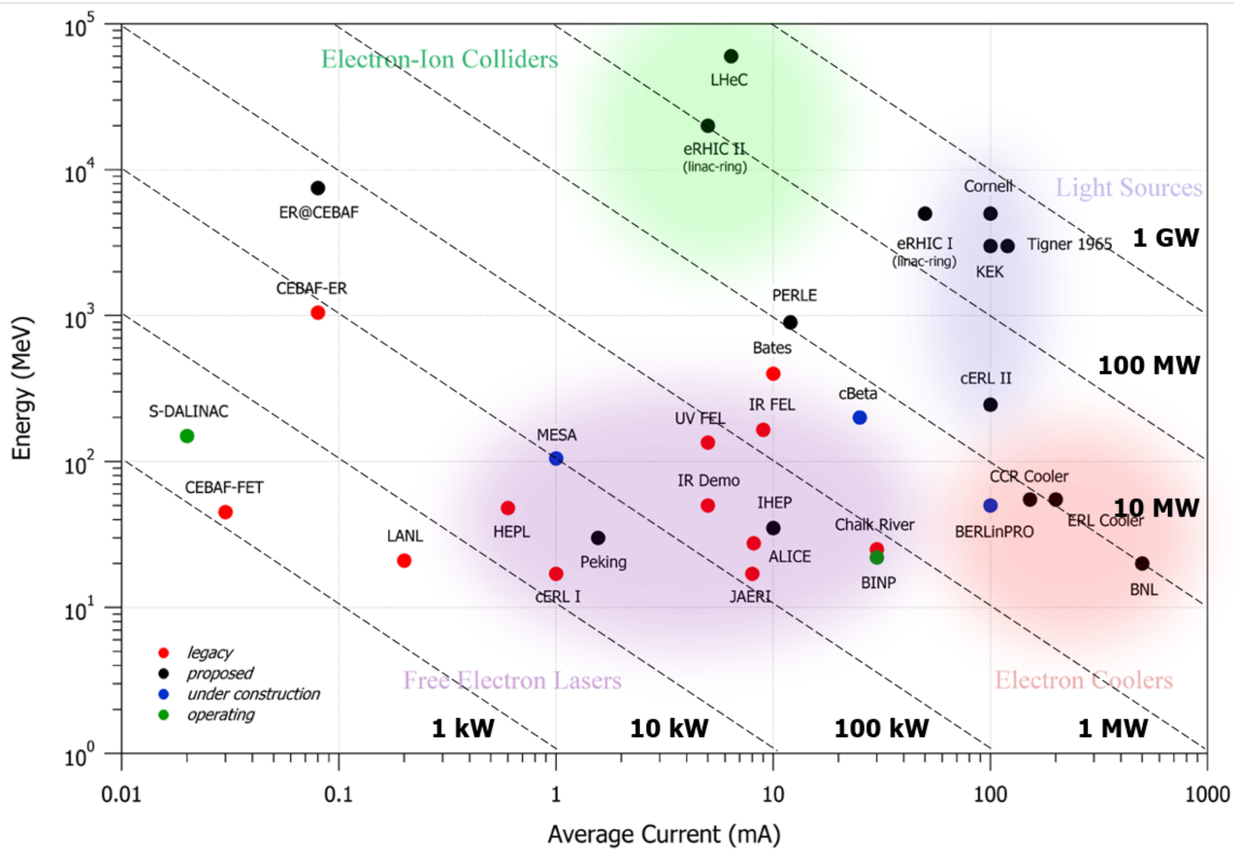
CBETA is designed for a 150 MeV electron beam with a bunch repetition rate of 1.3 GHz. The maximum average current is anticipated to be 40 mA, based on:

1. an extrapolation of HOM heating measurements obtained by sending an electron beam through a single MLC cavity, and
2. simulating the BBU instability under beam loading in the 6 cavities of the MLC, assuming realistic errors.

Further CBETA studies are needed, including:

a. HOM heating of other beamline components.
b. Simulations of longitudinal and the quadrupole BBU.
c. Beam loss due Touschek and rest-gas scattering.
d. Halo losses from space charge forces and field emission.
e. Coherent Synchrotron Radiation (CSR).
f. Microbunching.
g. Nonlinear dynamics.
h. RF control of the SRF cavities with strong reactive beam loading.

Figure 1: The ERL landscape, showing the location of CBETA in the trend towards higher average beam power. The single bunch charge is also an important parameter in EIC cooler applications. (Graphic by courtesy of C. Tennant).

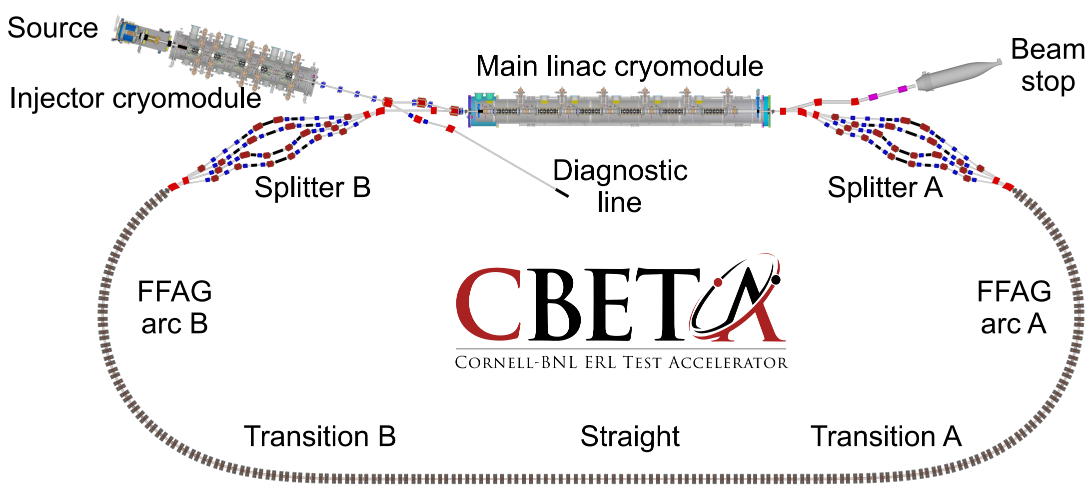


Interest in ERL technology is becoming widespread in both development and design, as shown by the ERL landscape plot shown in Figure 1. Other state-of-the-art ERLs that are also currently in construction, at the Helmholtz Zentrum Berlin (BerlinPRO) and in Mainz (MESA), will begin commissioning significantly after CBETA. It is likely that a collaboration between Orsay and CERN will eventually take the PERLE@Orsay design into construction, although it is currently only at the proposal stage.

Large-scale ERLs are being considered for high-energy physics applications (such as the LHeC), for nuclear physics (eRHIC) [2], for X-ray light sources, and for bunched-beam electron cooling, as in eRHIC and the JLEIC. The research program proposed here will benefit all of these ERLs. It will also help high-current conventional linear accelerators (such as PIP-II and ESS) to understand their sources of particle loss and their phase-space dynamics.

A unique feature of CBETA is the use of very strong focusing optics in a return arc to enable a single beam pipe to transfer electrons with a broad range of energies – 42, 78, 114, and 150 MeV – from the exit of the MLC back to its entrance for another acceleration (or deceleration) pass. This is illustrated in Figure 2, which shows the racetrack layout created by connecting splitters A and B on either end of the MLC to two fixed field alternating gradient (FFAG) arcs A and B, thence to a straight section on the opposite side of the ring. The return beam line uses Halbach type permanent magnet quadrupoles in a non-scaling fixed field alternating gradient configuration that adiabatically matches the arcs to the straight section, parallel to the linac. Electron energy recovery and acceleration is controlled by adjusting the time-of-flight and the R_{56} matrix element (which measures the rate of change of path length with respect to the relative momentum deviation), using the electromagnets in splitters A and B.

Figure 2: CBETA installation in experimental hall L0E at the Cornell Laboratory for Accelerator StudieS and Education. The DC gun and source sends electrons through the 6 MeV injector cryomodule into the main linac cryomodule or the beam diagnostics line. After passing through the MLC on each of 4 passes the beam enters the return loop for further acceleration or energy recovery, eventually ending in the beam stop.



The scaling fixed field alternating gradient principle, which was developed during the 1950's in the MURA (Midwest University Research Association) group and independently in Russia and Japan [3, 4, 5], allows acceleration with extremely large momentum dynamical aperture, zero chromaticity, fixed horizontal and vertical tunes. Non-scaling fixed field alternating gradient optics allow for the magnets to be reduced in size by an order of magnitude, as in CBETA [6, 7]. The Electron Model for Multiple Applications (EMMA), built in Daresbury Laboratory in the UK, was the first non-scaling fixed field accelerator [8]. More recently a momentum acceptance aperture of ± 60% was achieved in a non-scaling fixed field alternating gradient beam line experiment at the BNL ATF [9].

CBETA uses sophisticated components that were developed, constructed, and commissioned at Cornell under NSF funding. These pre-existing components, shown in Figure 2, include the world's highest current (75 mA) DC photocathode gun, the minimal emittance 6 MeV SRF injector linac [10, 11], the 10 m long SRF MLC for high-current continuous wave (CW) beams, an ERL merger between injector and the MLC, and a phase-space diagnostics line with a high-power beam stop. Besides being an ideal venue for accelerator physics studies, CBETA will also produce beam parameters potentially relevant for nuclear physics experiments that need medium-energy, high-current beams [12] and for a compact hard-X-ray source based on Compton back scattering [13].

1.1 Collaborative Structure

The program will be performed in a collaboration of three peer institutions: Brookhaven National Laboratory (BNL), Cornell University (CU), and Jefferson Laboratory (JLab). The team members will work largely at their home institutions, but will send a significant workforce to Cornell during times of CBETA commissioning and operation.

The BNL-CU collaboration that planned, designed, and is now building CBETA was formed in the summer of 2014, wrote a white paper in December 2014, began receiving construction funding from NYSERDA in November 2016, and will use this grant to commission to Key Performance Parameters by spring 2020. The BNL-CU collaboration functions by holding weekly internet meetings of the full team, by regular and as-needed phone meetings of subgroups, by biannual collaboration meetings, and by a significant amount of travel. We will continue and develop these modes of exchange – of simulation results, component design, operation plans, and labor sharing – when JLab members join the team.

There is considerable joint interest and coordinated activity on common topics between the three labs, following from the tight collaboration that is already in place between BNL and CU, for the construction and initial commissioning of CBETA. Nonetheless, the three labs have leading interests.

BNL will simulate strong electron cooling in eRHIC for parameters that can be achieved in CBETA, will participate in beam dynamics simulations, will send people to CBETA commissioning runs, and will work on extraction designs. BNL will further analyze how CBETA intensities can be increased towards the values required for eRHIC cooling.

Cornell University, where CBETA is located, is responsible for maintaining and operating the facility. CU scientists will put together the core operations team, will simulate beam dynamics and instabilities, halo losses and collimation, and will implement new diagnostics components into the accelerator and the control system. CU engineers will implement LLRF and microphonic suppression and will push the DC gun current and bunch charge as high as permitted by radiation limits. Cornell will simulate CBETA operation at high currents and large bunch charges, and will push CBETA commissioning to the highest possible currents.

JLab will design and develop high-current and beam-halo diagnostics. JLab personnel will participate in beam dynamics simulations, and in CBETA commissioning runs. JLab will simulate and analyze magnetized beam transport through CBETA. No hardware development for magnetized beams is included in this proposal, as the Cornell DC photo-emitter gun cannot be replaced in the timeframe of this proposal. However, a follow-up proposal may address such hardware installation and beam operation. The incoherent electron cooling proposed for JLab requires very large currents at 100 MeV. CBETA runs at this reduced energy are therefore proposed, while pushing the beam current to the highest possible values.

2.0 Project Objectives

The research program builds on the technical expertise and depth of the accelerator teams at BNL, Cornell, and JLab.

BNL brings expertise in beam simulation and accelerator operation, including very strong focusing permanent magnet optics. BNL also has significant experience with high charge and high current electron guns, SRF cryomodules, HOM simulation, microphonic control and remediation, and precision LLRF.

Cornell brings expertise in design, simulation, construction, and operation of electron guns, SRF cryomodules, and ERLs.

JLab brings essential expertise in the operation and simulation of DC electron guns, magnetized beams, and operations of the JLab IR Upgrade Free Electron Laser (FEL).

We propose to work on five main tasks:

1) Simulations
    a. Develop halo simulations to compare loss mechanisms with experiments.
    b. Simulate bunch-charge limitations for CBETA
    c. Design a chicane and simulate beam studies of the microbunching instability.
    d. Simulate a CBETA magnetized gun, possibly with a round-to-flat transformer to allow transport through the FFAG lattice.
2) Diagnostic development
    a. Develop halo diagnostics for high current and high bunch-charge operations.
    b. Develop coherent synchrotron radiation and microbunching diagnostics.
    c. Develop time-resolved diagnostics for post-mortem analysis of beam loss mechanisms.
3) Low Level RF
    a. Construct a model of the RF system to simulate the behavior of noise and transient behavior over a range of beam currents.
    b. Optimize the loop gains and frequency response to provide stable operation at the highest possible CW and pulsed currents.
    c. Test the RF control system on the MLC using pulsed and CW beams to benchmark the simulations. Re-optimize as needed to maintain stability.
4) Commissioning to high-intensity
    a. Push to the highest possible current in 4-pass ER mode with an energy of 150 MeV.
    b. Optimize LLRF controls for stable high current operation with headroom for beam noise.
    c. Operate with increased single bunch charge, pushing toward 1 nC per bunch.
    d. Find where halo is lost with high (1 nC) single bunch intensities.
5) Extraction design
    a. Design one or more 150 MeV beam-extraction lines.
    b. Drive the high-energy beam (alone) to large orbit oscillations in beam-extraction studies.
    c. Demonstrate 110 MeV operation in 3-pass ER mode for later JLEIC cooling studies.
    d. Push the beam current to the largest possible values (50 mA?) in 3-pass ER mode.

3.0 Proposed Research and Methods

This section describes the five main topics of proposed work in more detail. Section 4 discusses the "Broader Impacts of the Proposed Work", while the milestones associated with the topical goals are described in Section 5, "Timetable of Activities".

3.1 Simulations

Future ERLs and linacs require high currents, including those in eRHIC, JLEIC, LHeC, PIP-II and ESS. However, beam instabilities in the high-intensity regime are largely unexplored. This topic focuses on the simulation of CBETA current limits, with the general goal of using simulations to design experiments to study phase-space evolution, instabilities, and particle-loss mechanisms when beam interactions with the environment dominate.

The current in CBETA will be limited by the interactions of the beams with itself and with its environment, characterized by impedances that influence the phase-space dynamics of the charge distribution and drive instabilities. Both types of interaction cause particle loss and increase the emittance, and both will be studied. BBU simulations of threshold currents and potential optical remediation to increase thresholds will be simulated and studied as part of William Lou's PhD thesis research.

Particle-loss mechanisms will be simulated, including residual gas scattering, Touschek scattering, and dark current effects. Simulations will include a study of the impact of each loss mechanism on characteristics observable in available beam diagnostics. Coherent synchrotron radiation simulations will include microbunching, the study of beam emittance and beam-size increases, and particle loss rates.

Beam loss

Goal: Develop halo-simulations to compare loss mechanisms, including ghost pulses from the laser, field emission at the cathode and in cavities, and Touschek (residual gas) scattering.

It is of primary importance to diagnose and control unintended light that is incident on the photoinjector cathode. Stray light at the level of one part in a thousand can come from a single scratched, dirty, or otherwise poorly chosen optical element in the laser path, limiting CBETA performance through electron beam losses at high currents. This effect is primarily controlled by restricting the size of the active area of the photocathode to be only slightly larger than the laser spot, so that stray light does not directly lead to photoexcited electrons. However, single or multiple reflections in the surrounding vacuum chamber or nearby optical elements make it possible for light to hit even this small active area, at an unintended time. Such "ghost" pulses excite electrons, which are then accelerated.

Ghost pulses may be accelerated through the rest of the machine, but are likely to be lost due to an energy or betatron mismatch within the lattice. In addition to photo-emitted ghost pulses, electrons that are field-emitted from the cathode or from the RF cavities can similarly lead to beam losses after acceleration. Studying these effects and estimating the location and amount of beam loss is straightforward, using an end-to-end model of the accelerator and a detailed model of the laser flight path.

Residual gas interactions

A second mechanism for beam loss is electron interactions with residual gas molecules, either through elastic scattering or bremsstrahlung. Elastic scattering changes the trajectory of the electrons and excites betatron oscillations. If the scattering angle is larger than an angle aperture set by a collimator, the electron is lost transversely at the collimator [14, 15]. In the process of bremsstrahlung, an electron scattering off a gas nucleus emits a photon and suffers an abrupt energy change. If the energy change is too large, the electron is lost longitudinally.

Analytical estimates have been made for electron beam losses through elastic scattering and bremsstrahlung, as a function of the transverse or longitudinal aperture. Different gas species are assumed for initial commissioning and for later routine operations. If the limiting transverse aperture is at the last linac pass, the analytical estimates show that in the initial operation stage, the beam loss due to elastic scattering ranges from 2.16 pA (2.5 cm aperture) to 13.4 pA (1 cm aperture) and the beam loss due to bremsstrahlung ranges from 0.22 pA (0.1 MeV energy aperture) to 0.14 pA (1 MeV energy aperture). At the stable operation stage, the beam loss due to both processes reduces by a factor of 2. Further simulation work will focus on more accurate estimates achieved through element-by-element simulation with detailed lattice design and environment parameters.

High-bunch-charge

Goal: Simulate bunch-charge limits for CBETA, including coherent synchrotron radiation, microbunching, longitudinal space charge, and wakes.

Nearly all ERLs built and operated so far have been used to drive an FEL by leveraging the ability to run high repetition rates in SRF cavities to generate high beam powers while operating with modest bunch charges. Electron coolers, on the other hand, require aggressive bunch charges of several nanoCoulombs. Investigating the high-charge limits of CBETA operation is therefore vital to bridging the gap between the bunch charges that have successfully run in past ERLs (of order 0.1 nC) and those necessary for coolers (of order 1.0 nC). Experience at the Jefferson Laboratory ERL-driven FELs (the IR Demo, IR Upgrade and UV) provided ample opportunity to observe, measure and diagnose a variety of collective effects at bunch charges of around 0.1 nC. With an order of magnitude increase required for electron coolers, one of the primary challenges is to understand and control collective effects, to maintain and deliver beam of the quality needed at the cooling channel. The three effects that pose the biggest challenge are CSR, space charge and the microbunching instability.

CBETA is ideally suited to investigate these issues by virtue of its multi-turn capability – a feature no other SRF ERL currently possesses (or will possess in a reasonable time frame). For example, the evolution of CSR can be studied over many turns-worth of bending, and the multiple passes provide long transport distances over which space charge can accumulate. And finally, the presence of both CSR and space charge, together with a small energy spread within the bunch, provides the potential to seed the microbunching instability.

Other important beam dynamical processes, such as Touschek scattering, halo, intrabeam scattering and other loss mechanisms are discussed elsewhere. Here we consider only the ways in which the beam interacts with itself.

Coherent synchrotron radiation

Coherent synchrotron radiation poses a significant challenge for high brightness accelerator beams. When a bunch travels along a curved orbit, fields radiated from the tail of the bunch can overtake and interact with the head. Because the interaction takes place in a dispersive region, the energy redistribution is correlated with the transverse positions in the bend plane, potentially leading to projected emittance growth. Further, because the tail loses energy while the head gains energy, CSR leads to a distortion of the longitudinal phase space. This is particularly problematic for cooler applications where the energy spread must remain very small.

CSR-induced transverse emittance growth can be managed with careful lattice design [16]. The CSR wake-induced distortion in the longitudinal plane, however, is more difficult to ameliorate. We propose to simulate and understand how these effects scale with bunch charge and with the number of recirculations, and to understand how lattice adjustments can be used to mitigate them. This will provide much needed guidance in cooler lattice design.

Space charge

Recent work has shown that space charge is not particularly detrimental during the traversal of a single, generic recirculation arc, even at single bunch charges of several nanoCoulombs [17]. However, space charge may become problematic after multiple recirculations, because it is an integrated effect. Once again, CBETA offers an attractive test bed for understanding the degradation of beam quality due to space charge, as it is the only SRF ERL with multi-turn capability. We propose to study and understand how much space charge can be tolerated over multiple recirculations.

Microbunching instability

In the microbunching mechanism an initial density modulation, either from shot noise or from the drive laser, is converted to energy modulations through short-range wakefields such as space charge and CSR. The energy modulations are then transformed back to density modulations through the momentum compaction (R_{56}) of the lattice. Danger arises when a positive feedback loop is formed, and the initial modulations are enhanced. This phenomenon has been studied extensively, both theoretically and experimentally, in bunch compressor chicanes. However, only recently has there been a concerted effort to study the microbunching instability in recirculating arcs [18].

ERLs are particularly susceptible to microbunching, in part because of the native momentum compaction of the lattice (in arcs, splitters, chicanes, et cetera). Low energy injected beam is influenced by space charge forces. Multi-pass energy recovery with substantial bending ensures that ERLs are subject to CSR effects that – unlike space charge – do not diminish at high energy. CSR can drive the microbunching instability; in addition to its potential for emittance and energy spread growth.

Simulating the microbunching instability in the time-domain (via particle tracking) presents multiple challenges. The initial density modulation needs to be small enough to remain in the linear regime but large enough to overcome numerical artifacts. This requires tracking a large number of particles. Due to the computational burden, it becomes difficult to exercise parametric studies and/or model an entire accelerator complex. On the other hand, a semi-analytical Vlasov solver that works in the frequency-domain and models relevant collective effects such as LSC, CSR and linac geometric effects using analytic impedance expressions has led to insights on lattice constraints in controlling the microbunching instability [19]. The development of a fast Vlasov-solver has been an invaluable asset in the design and development of arc lattices.

Preliminary estimates using the Vlasov code show a modest microbunching gain for a single CBETA pass [20]. However, the gain will grow exponentially with each additional pass, up to a maximum of 4 passes. Therefore very high bunch charges may not be necessary to observe and measure the microbunching instability. Regardless of the bunch charge, a more thorough analysis of the instability is required.

Magnetized beam-transport simulation

One of the most critical features of JLEIC is the luminosity, which requires cooling the ion beams. In the proposed design, this is achieved when an electron beam and ion beam of the same average velocity but different temperatures co-propagate. The cooling rate such an interaction achieves can be improved by approximately two orders of magnitude if the interaction occurs within an appropriate solenoid field [21]. The design of the Circulating Cooling Ring (CCR), consequently, intends for the cooling to occur in four long solenoids. One difficulty in effecting electron cooling is the fringe field the electron beam encounters upon entering a long solenoid. Derbenev [22] suggested that the detrimental impact of the fringe field on the cooling rate is removed if the electron beam is created in a similar field; this is called a magnetized electron beam.

While magnetized electron beams have been studied at the Fermilab Photoinjector Laboratory [23, 24, 25], none are a CW beam of high average current that is required for the CCR, which is supplied by a magnetized electron beam ERL. Currently, magnetized electron beams are being studied at JLab. While the experiments and simulations contribute to the understanding of magnetized beam dynamics and demonstrate an agreement between simulation and measurements, the necessary CW, high average current beam has not been demonstrated [26]. The opportunity to produce a magnetized electron beam fulfilling these criteria would be provided by installing a DC high voltage photogun and solenoid (such as the magnetized gun currently in use for the JLab beam experiments) at the beginning of the CBETA injector. The magnetized beam could then be passed through the injector and the merger.

Such an undertaking requires thorough simulation work to ensure that the beam will travel through the beamline while remaining magnetized, as well as determining the proper scope of the experiment. The simulation work can be separated into three successive phases: the injector, the merger, and the FFAG arcs. If simulations fail to successfully pass a magnetized beam through a given section, the design of that section will be altered until a magnetized beam is successfully transported or until the design features that prevent a transport are clearly identified. The experimental desire would be to measure the magnetization of the beam, which requires additional space.

The main obstacle to simulating a magnetized injector is the limitation of the existing construction. Simulations that have already been performed demonstrate a magnetized electron beam passing through a typical ERL injector, modeled on the JLab FEL. The difficulty comes in the form of magnet strengths, cavity voltage limits, and physical room in the beamline for either additional magnets or diagnostics, especially before the merger.

If an experimental set-up can be created that allows for a magnetized beam to retain its characteristics while passing through the merger, this would allow for thorough beam characterization to be performed on the diagnostic beamline in the existing CBETA layout. The challenge in this section is that the merger is not axially symmetric – a known source of degradation for magnetized beams [27]. This is first challenge likely to degrade the magnetization of the beam. Even if that degradation were unavoidable, an opportunity to quantify the degradation experienced in relation to the axial asymmetry of the beamline would provide valuable information on the beam dynamics of magnetized beams. A comparison of flat beam properties will be made for transporting a magnetized beam through the merger, performing a flat beam transform and transporting a flat beam through the merger.

After successfully designing a merger section that makes the required net bend and retains beam magnetization, the beam will be tracked through the main MLC and at least one FFAG arc. However, as beam magnetization is unlikely to be preserved without significant modification, the goal of this phase is to identify the sources of magnetization degradation and, if possible, determine requirements for an FFAG design that will retain beam magnetization. A full re-design is not the goal, nor is it possible in the proposed timeline. Simulations for the evolution of a flat beam through the MLC and FFAG arc will be performed.

The total anticipated time spent on the entire magnetized beam simulation design is 12 weeks – 4 weeks on each section – during FY19, in three successive phases:

1. Modify the existing CBETA injector until a magnetized beam is successfully transported in simulation.
2. Simulate the magnetized beam from the altered injector design through the merger.
3. Simulate the magnetized beam from the altered merger design through the MLC and at least one of the FFAG arcs.

Nonlinear dynamics

Maintaining a high-quality longitudinal distribution is important for avoiding particle loss and maintaining energy recovery efficiency. The longitudinal dynamics are controlled by the RF force, by the dependence of time-of-flight on energy created by the return loop, and by collective effects such as wake fields and coherent synchrotron radiation. The fixed field alternating gradient return arc has a significant second-order contribution to time-of-flight. Further, the compact nature of the splitter lines requires them to have significant second-order terms in order to match the linac to the return arc. Very short magnets also contribute significant nonlinear terms due to magnet end effects.

We will compute time-of-flight as a function of energy including nonlinear and magnet end effects. Combining this with the linac, we will produce a model for the longitudinal dynamics of the full machine, and use this model to study the impact of the RF phase choices on the longitudinal dynamics.

As the current increases during enhanced commissioning, coherent synchrotron radiation and wakefields modify the longitudinal dynamics of the system. These effects will be included in the longitudinal modeling, to determine how best to adjust the RF phasing scheme as a function of current, and to determine whether they limit the current. If so, we will explore lattice design changes that could raise the current limit. For instance, nonlinear magnets could be added to the splitters to correct higher order optical terms.

The very high chromaticity of CBETA may have an impact on transverse instabilities. This will also be studied, for comparison with beam studies experiments.

3.2 Diagnostic development

Both setup and benchmarking of an accelerator require comprehensive diagnostics that allow the beam physicists to set up the machine and to compare the beam behavior with simulations. In a high current ERL with a bright beam, several important beam properties cannot be measured with typical accelerator diagnostics (viewers, beam position monitors, scanning wires, et cetera.). This effort will develop and install diagnostics that are uniquely useful to a high current ERL, in three topical areas.

Halo diagnostics

Though some models allow halo predictions, they are usually not effective in predicting the halo for any given machine. One must therefore measure halo as carefully as possible. Conventional diagnostics typically do not have the dynamic range or noise floor to see current densities that are four to six orders of magnitude below the core beam density. But, since this halo has a much larger area, it might have a net current of microamperes, which is much more than can be lost anywhere in the accelerator.

A High Dynamic Range (HDR) transverse beam profile monitor was developed for both the Jefferson Lab FEL and for the running of the Dark Light experiment at JLab FEL [28]. A version of this device is proposed to image the tails of the core beam by having it pass through a hole in the center of the Optical Transition Radiation (OTR) and only image the halo. This system will also be evaluated for use of a YAG screen with or without a hole. A stepped fork in the transverse plane has been successfully used at the JLab FEL, in an arrangement that allows a variable-size aperture to be used with a CW beam. This device also allows the core of the beam to pass unimpeded, while imaging the halo. The forks can be either phosphor coated or direct OTR. The HDR beam viewers, which come with a telescope to remove the video camera from the plane of the beam path, allow the beam loss sources to be located.

CSR and microbunching diagnostics

ERL beams start with very bright beams, which are very susceptible to microbunching. The relatively high charge also leads to an enhancement in coherent synchrotron radiation that can lead to a growth in both the energy spread and transverse emittance. Standard emittance measurements may be used to get some idea of the emittance growth and BPMs at a dispersive location can characterize the energy loss due to CSR [29]. The best way to see microbunching is to look for the coherent radiation enhancement at short wavelengths. A spectrometer can be used to characterize the short wavelength fall-off in the coherent radiation for comparison with the models.

The CSR effects can be imaged CW with synchrotron light, the effect is seen and the electron beam begins to separate out to distinct filaments. Passing the signal into a visible/near IR spectrometer can quantize the effect. These devices use a tangential port and telescope for a video imaging camera & a fiber optic collection system that diverts the CSR signal to a small spectrometer, Ocean Optics are an example [30].

Time-resolved beam-loss diagnostics for machine protection post-mortem analysis

Machine protection systems must prevent damage from the extremely high power densities in the core beam. Instabilities can cause the beam to trip off when losses suddenly rise. The problem of determining the cause of the beam loss can be aided by "first fault" capability in the machine protection system logic chain, but it can be determined even more sensitively by monitoring some key parameters with sampling scopes and triggering on a loss event. One can then look back to the time before the trip to see what led to the event.

This effort by JLab, in collaboration with a Cornell graduate student, will provide expertise and engineering support for the development of this beam loss monitor. A beam loss monitoring system was developed during operation of the JLab FEL that allowed for archiving the last faults, using 12 channel VME boards (x4 for 48 channels) that gave warning alarms prior to faults and captured the sequence of beam loss pattern around the machine. An updated copy of this system is proposed. Based on Photo-Multiplier Tubes (PMT), the integration constant is fixed and controlling the high voltage sets the gain. The system is periodically calibrated with known beam conditions, to counteract PMT aging issues.

3.3 Low Level RF

RF Stability in the Injector Cryomodule (ICM) and the Main Linac Cryomodule (MLC)

ERL operation is similar to electron time of flight spectrometers [31]; consequently stability of electric fields in the SRF cavities is an important issue. Amplitude and phase stabilities of better than 1×10^{-4} and 0.1° have been targeted for CBETA operations in the presence of very high beam loading. This calls for the development of advanced field control and fast detuning compensation algorithms to be incorporated in its low level RF control system. The major factors affecting stability are vibrations of the SRF cavities, beam loading and noise coming from the RF power sources.

Vibrations result in transient deformations of the cavity walls leading to microphonics detuning. Strong microphonics place large transient RF power demands in order to maintain stable accelerating field in the cavities. Both the injector and the main linac cryomodules incorporate fast tuners based on piezo-electric actuators to compensate for transient detuning. Microphonics compensation algorithms monitor cavity detuning and vibration signals from sensor piezos to calculate actuation signals used by the fast tuner. Feedback control based on two ideas – digital filter banks [32] and Least Mean Square techniques [33] – are under development and will be used in CBETA operation to compensate for detuning and significantly reduce peak power demands, especially on the MLC cavities.

Large beam currents in both pulsed and CW operation will induce ripples in the accelerating fields, due to high beam loading. Detailed simulations will be performed incorporating these effects, including microphonics and noise from various sources, in order to understand the behavior of the cavity field and to optimize the LLRF for maximum stability.

"Perfect" energy recovery would be ideal but is not always possible [34]. Imperfect energy recovery drives the need for excessive RF power or the need to vary the tuner as a function of beam current. Additionally, there is an issue of beam "slippage" between the injected beam at about 5 MeV, and the decelerated beamlets at more than 40 MeV.

Lastly there is the issue of path length drift. Path lengths changes as small as 0.6 mm are probably sufficient to exceed the available RF power limitations. Detailed simulations will be performed to better understand the effect of imperfect energy recovery that can be calculated as a function of beam current and cavity location in the linac. Analysis will be performed as to the need for, and the design of, a feedback system that would stabilize the path length to an acceptable level.

Tune up beam is generally a macro pulsed beam of some tens of microseconds long (necessary for diagnostics such as beam position monitors) at some 10 Hz (in order to eliminate the risk of burn through) with a micro pulse repetition rate of 42 MHz or about 2.6 mA of peak current. RF loading due to this beam is further complicated by the concept of interceptive beam diagnostics. Thus if one were to put a viewer in the beam line just after the last accelerating pass, then the linac will have 4 times the tune beam current in the linac. The concept of beam loading under such conditions also needs to be simulated and may require reduction in the micropulse repetition rate of 42 MHz, or implementation of a feedforward beam loading compensation algorithm in the LLRF.

Ramping the DC current up to the maximum value will present important problems with beam scraping and halo, as well as with beam loading. The approach used at JLab in their moderate current ERL was to first tune with a pulsed beam of 2 Hz 250 us beam, then to change the pulse repetition rate from 2 Hz to 60 Hz, and finally to increase the pulse width until achieving good transport without tripping the beam loss monitor system. Additionally, JLab had a vernier control on the micro pulse repetition rate. For example if one had a 42 MHz bunch repetition rate with a maximum bunch repetition rate of 1300 MHz one would put one pulse every 23.8 ns. One can increase the current by adding another 770 ps pulse every 23.8 ns, ramping up to full current in 30 steps. The first activity is to review the drive laser system to determine if this approach can be implemented.

The project will develop a beam mode table that defines all of the required time structures and bunch charge parameters. This is necessary to define the machine protection system and to understand the RF drive requirements.

3.4 Commissioning to high-intensity

Commissioning to the highest intensities requires a variety of skill sets spread across many people. Some of those people are naturally resident at Cornell: for example those with specialized support roles for cryogenics, vacuum, injector, ion mitigation, and controls. In other cases, expert collaborators from BNL and JLab will be effective in the control room, in data analysis, and in importing hardware such as beam diagnostics. External collaborators from BNL and JLab need travel support, especially in recognition of the need to avoid inefficient short-term participants.

BNL personnel performed much of the lattice design work for CBETA; therefore their participation in commission and operations of CBETA is essential. This is particularly important when machine configurations change as required to achieve the proposed goals.

Experience at Jefferson Lab has shown that three classes of activity are vital for successful high-power ERL operation: operations planning, RF drive analysis on optimization, and power flow management. The RF drive analysis was discussed in the last section. Jefferson Lab will carry out studies necessary to define operational procedures and characterize the power flow management.

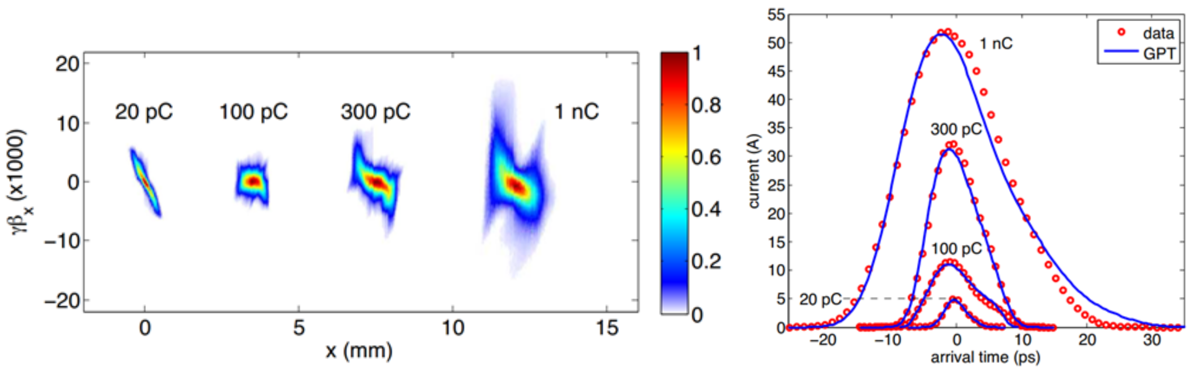
Integrated planning of high-power operations is needed to insure that project goals are consistent with the installed machine, to reduce risk, and to ensure safe operation. The team will – at the outset – develop a set of operational goals that can be met within the operational envelope using existing hardware and generate a beam operations plan that will serve as a framework supporting activities in pursuit of these goals. The information provided by subsequent activities will be codified in test plans and procedures on which actual beam operations will be based.

At high beam powers, beam halo and synchrotron radiation (primarily coherent synchrotron radiation) can result in substantial power deposition. Control of these effects is critical to successful operation of any nonequilbrium system, and the effort involved consumes much – or even most – of the beam time devoted to high power operation. Before high power operation commences, an assessment of halo sensitivities [35], CSR effects [36], and associated operational implications [37] must be performed. Collimation may be required and – given the multivariable couplings involved in FFAG transport – care must be taken in the development of the tuning algorithms used to mitigate halo losses.

Operating with a 1 nC bunch charge at a reduced repetition rate

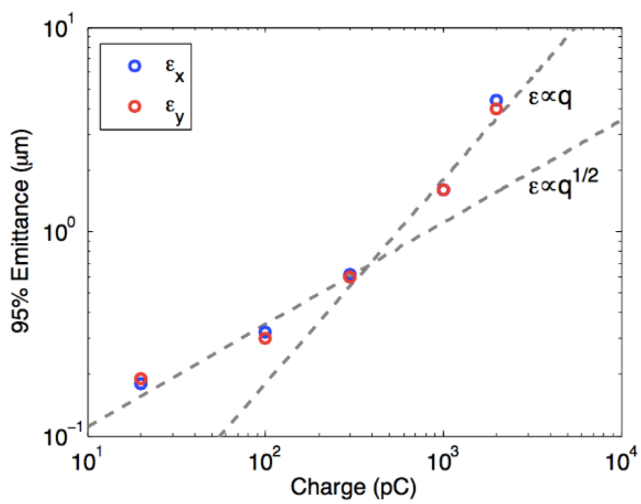
Our strategy in pushing for high average current includes first demonstrating that we can transport a high bunch charge beam (of about 1 nC) around CBETA, with and without energy recovery. A reduced repetition rate of high charge bunches will serve as a perfect test of beam halo diagnostics prior to pushing for higher average currents, in addition to being directly relevant to electron cooling.

Figure 3: Left: Longitudinal current profiles for corresponding bunch charges. Right: Horizontal phase spaces for bunch charges from 0.02 nC to 1 nC.



Previously, the Cornell photoinjector has produced low emittance bunches with charges up to 2 nC per bunch at about 9.5 MeV. Figure 3 shows the measured (horizontal) phase spaces and longitudinal current profiles for bunch charges up to the desired 1 nC targeted in this proposal. Bunches with a charge of 2 nC tended to have significantly larger tail than 1 nC bunches. The injector settings for these measurements were established using detailed multiobjective genetic algorithm optimizations of the 3D space charge dynamics in the injector using the space charge code General Particle Tracer (GPT) [38, 39]. All electromagnetic fields in the injector were modeled using realistic field maps, and all relevant laser and injector parameters (such as laser spot size, longitudinal shape, and magnet and cavity settings) were varied during the optimization. Figure 4 shows the best emittances measured over a wide range of bunch charge Q on a logarithmic scale. Low bunch charges (Q) the trend.

Figure 4: Trend of emittance versus bunch charge out of the Cornell photoinjector.



The emittance scales like $Q^{1/2}$ at low charges, and roughly linear with Q at higher charges. A charge of about Q = 0.3 nC separates the two regimes. The final emittance is dominated by the intrinsic emittance of the photocathode below 300 pC, with noticeable contributions from optical aberrations (mostly emittance compensating solenoids and SRF cavities) at higher charges. The 95% and 100% emittances at 1 nC are 1.6 and 2.3 microns (consistent with CBETA design specification), with the formation of large halo tails that become even larger with 2 nC bunches [39].

CBETA operation with nanocoulomb bunches will require re-optimizing the injector optics, to account for the lower injector energy of 6 MeV, and for the fact that the second ICM is turned off in this configuration, because this cavity reaches its frequency tuning range limit. The plan is to accelerate 1 nC low repetition rate beam in a 1-pass ERL configuration, as well as in a 4-pass recirculation configuration in which high energy beam is dumped in a Faraday cup (small) beam stop. We may also attempt 4-pass energy recovery at either 1 nC or at a reduced bunch charge, as limited by beam losses.

Care must be taken in constraining the bunch length and the longitudinal tails delivered by the injector to be compatible with the downstream optics, including potential energy recovery. The resulting optimized 1 nC bunches will then be tracked through the single pass ER CBETA lattice using BMAD, which includes a relativistic Gaussian space charge model and CSR effects as well as the final 4-pass configuration. End-to-end tracking will establish where beam losses are expected to occur, including (if possible) energy recovery after the MLC. If necessary, full 3D space charge tracking of the final 6 MeV beam transport will be performed from the MLC to the main beam stop using GPT.

The first step in experimentally realizing 1 nC bunches in CBETA will be upgrading the CBETA drive laser system. We will re-install the existing rod amplifier into the laser system to boost the laser power and will set up the long set of longitudinal shaping crystals and mirrors to lengthen the laser pulse to the values of about 25 ps rms required for nC bunches. A high performance multi-alkali photocathode is also required, with a large centered active area, when operating at reduced duty factor for the initial production of 1 nC bunches.

Once the laser upgrades and cathode production and installation are completed, the injector will be tuned to the optimized 1 nC optics setting. The beam will then be characterized using the emittance measurement system that is located in the diagnostic line before and adjacent to the MLC, directly measuring both the transverse and the longitudinal phase spaces, in turn providing a measurement of the transverse emittance and Twiss parameters as well as the longitudinal emittance.

Then the beam will be accelerated though the MLC, threaded through the first splitter line (set for single pass ER mode) and injected into the return loop. Beam losses will be monitored along the beam line using BLMs and radiation monitors. Similarly, the 4-pass CBETA configuration will later be explored with 1 nC beams. Beam losses will be characterized using the beam loss monitoring system that consists of numerous discrete radiation monitors and a network of scintillating fibers connected to PMTs around the transport loop.

Pushing to the highest possible current in the 1-pass ERL configuration at 42 MeV

The highest average current in superconducting ERLs achieved to date is 9.1 mA, demonstrated at the JLab IRFEL-DEMO [40]. At Cornell, CBETA is uniquely poised to explore the regime of higher average currents, with CW currents of more than 50 mA already demonstrated in the Cornell photoinjector. As a first goal, we will push to the highest possible average current with CBETA set up as a single pass, 42 MeV ERL.

By running in a single pass mode configuration, we benefit from a simpler bunch time structure, so diagnostics will not have to deal with multiple spatially overlapping beams. The control system will be able to fine-tune the machine optics for a single beam without worrying about the optics at other energies, as will be necessary in multipass running. The complex requirements on the bunch pattern structure required to prevent temporal overlap of multi-pass beams are also essentially removed. Under these conditions we can use a 1.3 GHz bunch train, allowing for the same high current operation at significantly reduced bunch charges, as compared to bunch repetition rates of tens of MHz.

Reduced bunch charge operation mitigates the issues related to increased radiation levels originating from unwanted beam losses. The primary strategy to increase the electron beam current will focus on this high repetition rate. Prior to these proposed experiments, all operations in CBETA will have been at a reduced repetition rate of about 42 MHz, chosen to allow multi-turn operation. At 1.3 GHz bunch charges can be reduced by a factor of 1300/42=31 for the same average current in the machine, mitigating both the long-term and short-term issues of operating permanent magnets in the presence of high radiation levels.

The permanent magnet arcs require a properly matched beam to achieve a transport that will not degrade the beam parameters to the point where they significantly affect the energy recovery efficiency. Initial experiments will be performed at a very low duty factor using the diagnostic line, to verify that the beam is correctly matched to the rest of the lattice, in order to fine-tune the machine settings.

Every change in bunch charge requires such a brief low-current tuning period. After that, the beam is threaded at low current through the rest of the arc, adjusting the path length to fully recover the energy, and guiding the beam into the beam stop. Then, increasing the laser duty factor gradually raises the average current. At 1.3 GHz the laser duty factor can be set anywhere in the range from 0% to 100%.

The laser spot on the photocathode is adjusted and matched to the active area on the cathode in order to minimize the radiation beam losses from halo. The active area is also sufficiently far from the electrostatic center to mitigate ion back bombardment effects that limit the cathode lifetime. Care is taken to ensure that the active area is positioned not too far off the center, in order to minimize beam aberrations while still allowing the drive laser to be cleanly reflected without inducing spurious reflections and contributing to the unwanted beam losses.

While increasing the machine duty factor, we will perform studies aimed at mitigating already known primary limitations in the production and transport of high average electron beam currents: the cathode degradation by ion back bombardment and vacuum trips induced by machine trips, ion trapping, long-range higher-order mode effects in SRF cavities, as well as radiation losses from beam halo or incomplete energy recovery. As we push into an unexplored high current territory we also anticipate facing new and unexpected challenges.

We hope to improve the cathode lifetime by operating the biasable anode on the new DC electron gun. This may reduce the gun trip rate at high currents. Ion accumulation is not expected to be a significant problem below average currents of 10 mA. Higher currents will present an opportunity to further explore ion clearing methods previously developed at Cornell [41]. Beam break up from higher-order modes in SRF cavities is not expected to be relevant until currents larger than 100 mA, although the heat dissipation from the HOMs is expected to be measureable at currents of less than 10 mA.

Finally, the largest impediment to high current is likely to be beam loss both from halo and incompletely energy-recovered beam (i.e. temporal tails). We detect these two effects using local radiation monitors and a network of scintillating fibers connected to PMTs around the recirculating arc. Understanding and mitigating beam losses will require guidance from the simulations as discussed elsewhere.

Some minor hardware modifications will be required in order to operate CBETA in this mode. Specifically, vacuum pipes will need to be replaced on the first splitter lines, to reach the correct path length required for energy recovery. Changes to the laser system are also required to produce the 1.3 GHz bunch rate. Both of these required modifications have been already designed and will not require any new infrastructure.

Pushing to the highest possible current in the 4-pass ERL configuration at 150 MeV

To date no multi-pass ERL has operated at significant levels – milliamps – of current. CBETA is uniquely poised to target this gap, due to its high intensity photoinjector and the large energy acceptance of its return loop. Multi-pass high average current operation is significantly more complicated than single-pass operation, due not only to the complexity of beam diagnostics that must work simultaneously on overlapping beams, but also to the inherent challenges in controlling orbits, energies, and beam halo losses of each individual beam when using a shared control system that affects them all. Our goal is to explore the challenges posed by multimode operation with as many as 4 passes, and to identify average current limitations. This will build not only on the experience with high-current single pass operation, but also on the high bunch charge operation detailed previously.

We will begin with a 2-pass configuration, incrementally activating additional one pass at a time. Two-pass operation is the simplest configuration that will introduce new issues, a necessary step for success with larger numbers of passes. Operation in a 3-pass configuration is of particular interest to JLab because its beam energy of 114 MeV is directly comparable to the energy required by the JLab high current electron source designed for strong hadron beam cooling.

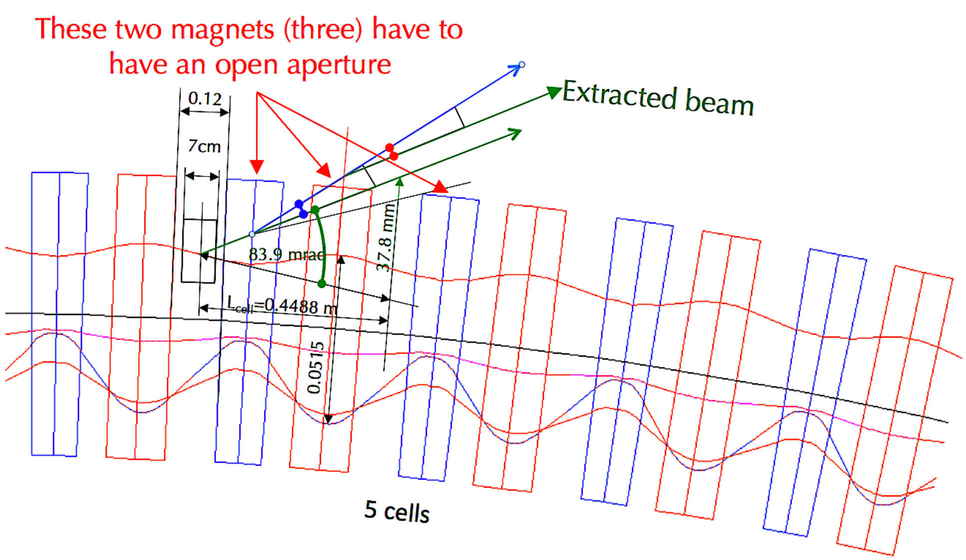
Each change in the number of passes requires dedicated vacuum hardware replacement to both splitters, to add or subtract the half RF wavelength of additional path length that is needed for energy recovery. However, no other hardware modifications or upgrades are required, and only minor changes to the beam optics settings are foreseen.

All multipass operations require the use of the existing 42 MHz laser to drive the photoinjector, in order to provide a bunch structure that is compatible with multiple beam diagnostics. At this lower frequency, the laser duty factor can be smoothly adjusted from 0% to 100% duty factor, increasing the average current at a fixed bunch charge.

3.5 Extraction design

CBETA will support 4-pass acceleration to 150 MeV, followed directly by 4-pass deceleration. At a later stage, after this proposal is complete, CBETA could be used for EIC R&D or other purposes in a configuration in which beam is extracted at 150 MeV, and also returned for subsequent energy recovery. A number of concepts have been proposed for high-energy beam extraction, but none of them have been developed far enough to evaluate their performance and practicality. The goal of this topic is to develop these concepts further, supported where possible by preliminary beam studies.

Figure 5: Concept of 150 MeV beam extraction from the CBETA return arc.



One concept for high-energy extraction is shown in Figure 5. Extraction from the arc to an experimental line is achieved by using a couple of special open mid-plane magnets. Prototypes of such open-midplane Halbach-style magnets have already been built and successfully tested at BNL.

4.0 Broader Impacts of the Proposed Work

As research tools, accelerators deliver X-rays, produce high-energy particles and create the conditions found in the center of stars and the early stages of our Universe. By one estimate, between 1939 and 2009, a Nobel Prize was awarded every 2.9 years for research made possible or carried out at least partially on an accelerator. By improving the performance of key accelerator components, this proposal will benefit all of these research accelerators – not just EIC-focused ERLs. It will also make them more cost effective to build and operate.

The five topics of work proposed here would have also a significant impact on accelerators that are critical tools for industry, medicine, national defense, and which may one day offer a path to safe and sustainable nuclear energy. Annual sales of industrial accelerators exceed $2B, and are growing at an estimated 10% per year. Past research in the SRF-ERL arena has already been transferred to industry (e.g. a turn-key SRF accelerator module) and has led to several Small Business Innovation Research projects. This proposal would have a similar impact on industry.

This research also strengthens the education of undergraduate and graduate students in cutting-edge science, engineering and technology. Through the outreach programs at CLASSE and through Research Experiences for Undergraduates (REU) programs, we will mentor students from community colleges and universities in a research environment that would otherwise be unavailable to them. About 1800 members of the general public tour the CLASSE labs annually, on visits that are enhanced by showing the CBETA accelerator during its construction.

4.1 Impact on accelerators and industry

Our research will directly impact the feasibility of energy efficient, high-performance, high-power, high-intensity, robust accelerators for industrial applications. For example, the compact, high-frequency, high-efficiency SRF cavities we will continue to develop are an ideal match for industrial applications, supporting high beam current in continuous operation, thus fulfilling critical needs for future CW operated electron linacs for industry. Industrial applications include lithography near the atomic limit; in-line X-ray metrology and wafer inspection; radiation cross-linking; and ion implantation. Medical applications include radionuclide production and the sterilization of medical equipment. Environmental conservation is enhanced by radiation processing of polluted water and flue gas emissions, and national security is addressed by cargo X-ray imaging.

Nearly all linac-based high-brightness electron accelerators (such as colliders, XFELs, and stand-alone compact electron imagers) would benefit from improved low emittance electron sources and rugged photocathodes. The technology that would be developed as part of this proposal could, for the most part, be transferred to industry.

4.2 Education

In addition to advancing accelerator science and technology, this project will provide much needed training of undergraduate students and graduate students in cutting-edge science, engineering and technology as urgently needed for the U.S. workforce. In addition to training in the specific field of accelerator science and technology, graduate students will also receive broad training in beam physics and cutting-edge science. They will experience how to lead a complex experiment.

Graduate students will regularly present their work in group meetings, collaboration meetings, and at conferences, learning how to develop presentation skills and how to participate in collaborative research. Undergraduate students from Cornell and from participating community colleges will take part in the proposed research. Each undergraduate will have his/her own mentor, and will be asked to give scientific presentations during group meetings to develop communication skills.

Currently there are 2.25 full time graduate students at Cornell working on CBETA, one for LLRF and feedback systems, and one for online accelerator modeling and data/simulation comparisons. Another student is working 25% on photocathode developments. Typically about twice as many Cornell undergraduates as graduates are already working on CBETA, although the fluctuations are much larger. About 6 REU undergraduates from other universities work on ERL topics each summer. Other graduates students from Cornell and elsewhere may join the collaboration.

4.3 Outreach

This proposal has a two-pronged outreach program; building upon the successes of previous NSF funded outreach activities at Cornell. One program brings local community college students into the lab to work with us in accelerator research. The other is directed towards engaging and informing the general public about the importance of accelerators for society.

Summer Research for Community College Students (SRCCS)

Cornell is surrounded by 2-year community colleges located in primarily rural and economically depressed regions of upstate New York. Research opportunities in the physical sciences are quite rare for students attending community colleges. We therefore propose to bring three community college students for an 8-week internship to Cornell each summer. The main focus of the internship will be research in accelerator physics, on the projects described in this proposal, but internships would also include specifically targeted seminars, lectures, tours of research facilities, social and recreational events, and building an interactive exhibit for the lab's outreach program. Some of these activities piggyback on programming already in place for the labs REU program. The community college students will be assigned a faculty mentor who defines the research project, guides the student's project, and provides one-on-one training. This very successful program was begun by a member of the proposal team (Liepe).

Engaging and Informing the General Public

The general public is mostly unaware of the broad impact that accelerators have on society. One way to engage and inform the general public is to enable visits to the facilities. CLASSE gives facility tours to approximately 1800 visitors each year; many of them school children who come on field trips. CLASSE proposes to extend and strengthen these facility tours, for example producing new virtual lab tours for online use and/or for display in during facility tours. These virtual tours will describe and explain the technologies used in accelerators, and will show examples of their use and impact on society.

5.0 Timetable of Activities

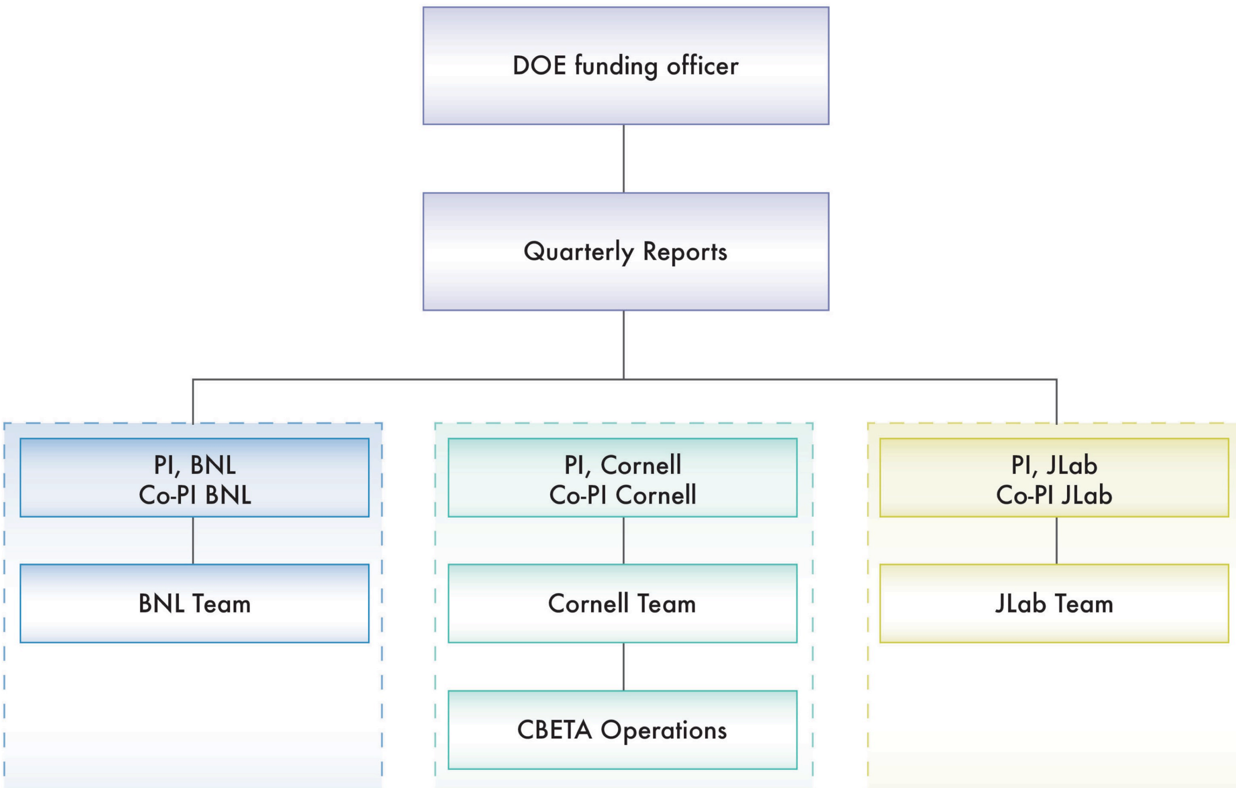
Figure 6: Timeline of activities for the tasks described in this proposal.

Task	Task	Year 1				Year 2			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
3.1	**Simulations**								
	3.1.1 Nonlinear longitudinal model	■	■						
	3.1.2 Impedance/CSR estimate or computation	■	■	■	■				
	3.1.3 Estimates of halo-generating effects	■	■	■	■				
	3.1.4 Magnetized beam simulated	■	■	■	■				
	3.1.5 Simulated halo effects			■	■	■	■	■	■
	3.1.6 Simulated high-charge dynamics			■	■	■	■	■	■
3.2	**Beam diagnostics design & construction**								
	3.2.1 Procure diagnostic hardware Milestone 1: Hardware procured	■	■						
	3.2.2 Install diagnostic hardware Milestone 2: Hardware installed			■	■				
	3.2.3 hardware commissioned Milestone 3: Diagnostics commissioned			■	■				
3.3	**Low Level RF**								
	3.3.1 Develop LLRF models and software Milestone 1: Models developed	■	■	■	■				
	3.3.2 Commission LLRF controls Milestone 2: Controls commissioned				■	■	■		
	3.3.3 Optimize LLRF with beam Milestone 3: LLRF controls done							■	■
3.4	**Commissioning to high-intensity**								
	3.4.1 High charge preparations Milestone 1: Lattice simulated; laser & diagnostics ready	■	■	■	■				
	3.4.2 Photoinjector setup with nC beam Milestone 2: Beam characterized up to nC bunch in DL					■			
	3.4.3 1-pass ERL run with nC bunches Milestone 3: Characterized losses with high charge low rep rate bunches					■	■		
	3.4.4 1.3 GHz laser for high current Milestone 4: Laser ready for beam	■	■	■					
	3.4.5 Push 1-pass ERL for hi avg cur Milestone 5: Beam data obtained						■	■	
	3.4.6 Push multipass ERL for hi cur Milestone 6: Beam data obtained							■	■
3.5	**Extraction design**								
	3.5.1 Analysis of alternative designs					■	■	■	■

6.0 Project Management Plan

The work performed by this proposal has clear tasks for each laboratory. While those tasks are coordinated by the PIs of that laboratory, it is important that vibrant communication is maintained between the labs on topics of mutual interest. The PIs and pertinent senior management personnel meet weekly in teleconferences and about twice a year in-person during semi-annual meetings of the collaboration at large. Information sharing and the distribution of minutes is arranged through a commonly accessible data site. Each PI shares information from the laboratory that they represent, and disseminates information received from the other PIs.

Figure 7: Organizational structures with individual reporting to DOE, communication between PIs, and updates to laboratory stakeholders



Cornell University is responsible for the day-to-day operations and maintenance of CBETA, including specialized sub-system support, organizing accelerator operation, and building the core of the operations team. Cornell will include personnel from BNL and JLab in accelerator runs as peers, when they are available, Cornell will install components that have been constructed for CBETA under this proposal.

Table 2. Project team members and their roles in this project

PIs and co-PIs	Project Role
Ivan Bazarov	Cornell co-PI
Steve Benson	JLab PI
Georg Hoffstaetter	Cornell PI
Mathias Liepe	Cornell co-PI
Stephen Peggs	BNL PI
Dejan Trbojevic	BNL co-PI

The participating institutions have a shared interest in maximizing the benefits of this research for the EIC. A Board of Stakeholders (BoS) will be routinely informed about progress. Members of the BoS are the chair of the BNL Collider-Accelerator Department, the CLASSE director, the CASA director, Cornell's vice provost for research, and the two coordinators for EIC research at BNL and at JLab.

Each of the three collaborating laboratories is funded separately, and each separately prepares quarterly financial and technical performance reports for the grant officer of the funding agency. Each lab also writes an annual report to the funding agency. These reports from the PIs will also be distributed to the BoS and to other appropriate parties.

APPENDIX 1: Biographical Sketches

Stephen Peggs | Senior Physicist
Collider-Accelerator Department | Brookhaven National Laboratory

Education and Training:

PhD, Accelerator Physics, Cornell University, Ithaca NY, 1981

BA, Physics, Oxford University, Oxford UK, 1973

Research and Professional Experience:

June 2016 – Present **Project Manager & Project Director, Brookhaven National Laboratory**

- Cornell-BNL Electron Test Accelerator project, a $25M collaboration between BNL and Cornell University, funded by the New York State Energy Research & Development Agency.

2015 – 2016 **Detailee in the DOE office of HEP, Germantown**

- Program Manager of the Proton Improvement Plan-II project (PIP-II), a collaboration of Fermilab and three Indian laboratories, with a total project cost of $650 million.

2013 – 2016 **Hadron Therapy Group Leader, Brookhaven National Laboratory**

- Principle investigator in a Cooperative Research And Development Agreement with Best Medical International, developing the BNL iRCMS medial accelerator design for hadron therapy.

2009 – 2013 **Deputy Head of Accelerator Division, European Spallation Source, Lund**

- Jointly grew the ESS Accelerator Division from two original members to about 30, while on secondment from BNL. Executive Editor of the ESS Technical Design Report.

2008 – 2009 **Sabbatical leave, CERN, Geneva**

- Became involved in developing the ESS conceptual design while at CERN to participate in LHC commissioning and in the UA9 crystal collimation experiment.

2004 – 2008 **LHC Accelerator Research Program Leader, BNL/Fermilab**

- Founding leader of the U.S. LHC Accelerator Research Program, a collaboration of 4 U.S. laboratories (BNL, FNAL, LBNL & SLAC). Joint BNL/FNAL appointment.

1999 – 2004 **Associate Head, Collider Accelerator Department, BNL**

- Lead the BNL-industrial consortium that wrote the RCMS Technical Design Report, awarded a 2008 patent. Lead the beam dynamics efforts within the U.S. LHC Construction Project.

1992 – 1999 **Head, RHIC Accelerator Physics Group, Brookhaven National Laboratory**

- RHIC accelerator design and high level controls. Lead the commissioning to first beam in 1999.

1989 – 1992 **Head, Accelerator Physics Department, Fermilab**

- Main Injector lattice, nonlinear dynamics experiment E-778, controls software, database schema.

1984 – 1989 **Accelerator Physicist, SSC Central Design Group, Berkeley**

- Contributed to diverse aspects of the Superconducting Super Collider design, at LBL.

Representative Publications:

1. S. Peggs & T. Satogata, "An Introduction to Accelerator Dynamics", Cambridge University Press, 2017.

2. S. Peggs (Editor), Aschenauer et al, "Report of the eRHIC Ring-Ring Working Group", technical note eRHIC/46, BNL, 2015.
3. S. Peggs (Editor), Bazarov, Ben-Zvi et al, "A white paper: The Cornell–BNL FFAG-ERL Test Accelerator", unpublished, 2014.
4. S, Peggs (Executive Editor), "European Spallation Source Technical Design Report", technical note ESS-doc-274, Lund, 2013.
5. S. Peggs, T. Satogata, J. Flanz, "Survey of hadron therapy accelerator technologies", PAC07 MOZAC02, 2007.
6. U. Iriso & S. Peggs, "Maps for electron clouds", & "Maps for coupled electron and ion clouds", PRSTAB-8-90024403 & PRSTAB-9-071002, 2005 & 2006.
7. S. Peggs, "Fundamental limits to stereotactic proton therapy", Trans. Nucl. Sci., 51-3, 2004.
8. I. Ben-Zvi, J. Kewisch, J. Murphy, S, Peggs, "Accelerator physics issues in eRHIC", NIMA 463 94, 2001.
9. T. Satogata et al, "Driven response of a trapped particle beam", PRL 68 12, 1992.
10. D. Andrews et al, "Observation of three upsilon states", PRL 44 17, 1980.

Patents:

2008, "Rapid cycling medical synchrotron and beam delivery system", US 20070170994 A1

Synergistic Activities:

1. Chair, MICE Project Board, STFC, UK.
2. External Advisory Board, UTSW Medical Center, Dallas.
3. Science Advisory Committee, International Institute for Accelerator Applications, Huddersfield.
4. Fellow, American Physical Society.
5. Visiting Scientist, Cornell University.

Collaborators and Co-editors:

G. Hoffstaetter (Cornell), collaborator, PI on the CBETA NYSERDA project.

R. Michnoff (BNL), collaborator, project manager on the CBETA project.

C. Montag (BNL), co-author, "The eRHIC Ring-Ring Design".

T. Satogata (JLab), text book co-author, "An Introduction to Accelerator Dynamics".

K. Smolenski (Cornell), collaborator, deputy project manager on the CBETA project.

D. Trbojevic (BNL), collaborator, PI on the CBETA project.

Graduate and Postdoctoral Advisors and Advisees:

Graduate advisor: Richard Talman, Cornell University.

Graduated students: N. Cook (Radiasoft), T. Satogata (JLab), C. Tang (High school teacher), J. Cardona (U. of Bogota), R. Calaga (CERN), R. Fliller (BNL), U. Iriso (CELLS), A. Warner (FNAL).

Adam C. Bartnik
Cornell University

Education and Training:

Cornell University, Ithaca, NY	Physics	B.A.	2002
Cornell University, Ithaca, NY	Physics	Ph.D.	2010

Research and Professional Experience:

Research Associate, Cornell University	2011-present

Publications:

Most related to proposal:

L Cultrera, C Gulliford, A Bartnik, H Lee, I Bazarov, *Ultra low emittance electron beams from multi-alkali antimonide photocathode operated with infrared light*, Appl. Phys. Lett **108**, 134105 (2016).

A Bartnik, C Gulliford, I Bazarov, L Cultera, B Dunham, *Operational experience with nanocoulomb bunch charges in the Cornell photoinjector*, Phys. Rev. ST AB **18**, 083401 (2015).

C Gulliford, A Bartnik, I Bazarov, B Dunham, L Cultrera, *Demonstration of cathode emittance dominated high bunch charge beams in a DC gun-based photoinjector*, Applied Physics Letters **106**, 094101 (2015).

Z Zhao, A Bartnik, FW Wise, IV Bazarov, BM Dunham, *High-power fiber lasers for photocathode electron injectors*, Phys. Rev. ST AB **17**, 053501 (2014).

DL Hall, A Bartnik, MG Billing, R Eichhorn, GH Hoffstaetter, MLC Mayes, et al., *Beam-based HOM Studies of the Cornell Energy Recovery Linac 7-cell SRF Cavity*, Proc. of the 2014 Intern. Conf. on Lin. Acc., Geneva, Switzerland 869 (2014).

Closely related:

JM Maxson, AC Bartnik, IV Bazarov, *Efficient and accurate laser shaping with liquid crystal spatial light modulators*, Applied Physics Letters **105**, 171109 (2014).

T Moore, NI Agladze, IV Bazarov, A Bartnik, J Dobbins, B Dunham, S Full, et al., *Fast wire scanner for intense electron beams*, Phys. Rev. ST AB **17**, 022801 (2014).

L Cultrera, S Karkare, B Lillard, A Bartnik, I Bazarov, B Dunham, W Schaff, et al., *Growth and characterization of rugged sodium potassium antimonide photocathodes for high brilliance photoinjector*, Appl. Phys. Lett **103**, 103504 (2013).

B. Dunham, J. Barley, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, G. Hoffstaetter, B. Johnson, R. Kaplan, S. Karkare, V. Kostroun, Y. Li, M. Liepe, X. Liu, F. Loehl, J. Maxson, P. Quigley, J. Reilly, D. Rice, D. Sabol, E. Smith, K. Smolenski, M. Tigner, V. Vesherevich, D. Widger and Z. Zhao, *Record high-average current from a high-brightness photoinjector*, Appl. Phys. Lett **102**, 034105 (2013).

C. Gulliford, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, B. Dunham, F. Gonzalez, S. Karkare, H. Lee, H. Li, Y. Li, X. Liu, J. Maxson, C. Nguyen, K. Smolenski and Z. Zhao, *Demonstration of low emittance in the Cornell energy recovery linac injector prototype,* Phys. Rev. ST AB **16**, 073401 (2013).

Synergistic Activities:

Research Experience for Undergraduates mentor, Wilson Lab, Cornell University

Collaborators and Co-Editors:

J. Barley, I. Bazarov, L. Cultrera, J. Dobbins, B. Dunham, F. Gonzalez, C. Gulliford, G. Hoffstaetter, B. Johnson, R. Kaplan, S. Karkare, V. Kostroun, H. Lee, H. Li, Y. Li, M. Liepe, X. Liu, F. Loehl, J. Maxson,

C. Nguyen, P. Quigley, J. Reilly, D. Rice, D. Sabol, E. Smith, K. Smolenski, M. Tigner, V. Vesherevich, D. Widger and Z. Zhao (all from Cornell University)

Graduate Advisors and Post-Doctoral Sponsors:

Graduate Advisor: Frank Wise, Cornell University, Ithaca, NY

Post-doctoral Advisors: Bruce Dunham and Ivan Bazarov, Cornell University, Ithaca, NY

Ivan B. Bazarov
Cornell University

Education and Training:

Far Eastern State University	Vladivostok, Russia	Physics	M.S.	1998
Far Eastern State University	Vladivostok, Russia	Physics	Ph.D.	2000
Cornell University (post-doc)	Ithaca, NY	Accelerator Physics		2000-03

Research and Professional Experience:

Associate Professor of Physics, Cornell University		2013-present
Assistant Professor	of Physics, Cornell University	2007-13
Research Associate	Cornell University, Laboratory for Elementary-Particle Physics	2003-07
Post Doctoral Assoc., Cornell University, Laboratory of Nuclear Studies		2000-03

Publications:

Demonstration of low emittance in the Cornell energy recovery linac injector prototype, C. Gulliford, I.V. Bazarov et al., Phys. Rev. ST Accel. Beams **16** (2013) 073401, http://prstab.aps.org/pdf/PRSTAB/v16/i7/e073401

Monte Carlo charge transport and photoemission from negative electron affinity GaAs photocathodes, S. Karkare, I. Bazarov et al., Journal of Applied Physics **113** (2013) 104904*,* http://dx.doi.org/10.1063/1.4794822

Growth and characterization of rugged sodium potassium antimonide photocathodes for high brilliance photoinjector, L. Cultrera, I. Bazarov et al., Applied Physics Letters **103** (2013) 103504 *,* http://link.aip.org/link/doi/10.1063/1.4820132

Record high-average current from a high-brightness photoinjector, B. Dunham, I. Bazarov et al., Applied Physics Letters **102** (2013) 034105, http://dx.doi.org/10.1063/1.4789395

Cornell ERL: Project Definition Design Report, A. Bartnik, I.V. Bazarov et al.*, Eds. G.H. Hoffstaetter, S.M. Gruner, M. Tigner, Cornell (2013,* http://erl.chess.cornell.edu/PDDR/PDDR.pdf

Fundamental Photoemission Brightness Limit from Disorder Induced Heating, J. Maxson, I. Bazarov et al., New Journal of Physics **15** (2013) 103024, http://dx.doi.org/doi:10.1088/1367-2630/15/10/103024

Cathode R&D for future light sources,D.H. Dowell, I. Bazarov et al., Nucl. Instr. Meth. Phys. Res. A **622** (2010) 685, http://dx.doi.org/10.1016/j.nima.2010.03.104

Maximum achievable beam brightness from photoinjectors, I.V. Bazarov et al., Physical Review Letters, **102** (2009) 104801, http://dx.doi.org/10.1103/PhysRevLett.102.104801

Experimental investigation of multibunch, multipass beam breakup in the JLAB FEL Upgrade Driver, D.R. Douglas, K.C. Jordan, L. Merminga, E.G. Pozdeyev, C.D. Tennant, H. Wang, T.I. Smith, S. Simrock, I.V. Bazarov, G.H. Hoffstaetter, Phys. Rev. ST Accel. Beams, **9** (2006) 064403*,* http://prst-ab.aps.org/pdf/PRSTAB/v9/i6/e064403

Multivariate optimization of a high brightness dc gun photoinjector, I.V. Bazarov and C.K. Sinclair, Phys. Rev. ST Accel. Beams, **8** (2005) 034202*,* http://prst-ab.aps.org/pdf/PRSTAB/v8/i3/e034202

Synergistic Activities:

Research Experience for Undergraduates co-PI, Wilson Lab, Cornell University

US Particle Accelerator School lecturer

Scientific program committees of various Particle Accelerator Conferences and workshops

Collaborators and Co-editors:

S. Belomestnykh (BNL), D. Dimitrov (Tech-X), D.H. Dowell (SLAC), K. Harkay (ANL), C. Hernandez-Garcia (TJNAF), R. Legg (TJNAF), H. Padmore (LBNL), M. Poelker (TJNAF), T. Rao (BNL), J. Smedley (BNL), W. Wan (LBNL)

Graduate and Postdoctoral Advisors and Advisees:

Graduate Advisor: Prof. O.A. Bukin, Far Eastern Branch of Russian Academy of Science

Thesis Advisees and Postgraduate Scholar Sponsor

Thesis Advisees: C. Gulliford (New College of Florida), J. Maxson (Cornell), S. Karkare (Cornell), H. Wang (Cornell), H. Lee (Cornell), F. Hannon (JLAB)

Postgraduate Scholars Sponsored: Tsukasa Miyajima and Luca Cultrera

Stephen Benson, Senior Scientist

Center for Advance Studies of Accelerators, Jefferson Lab

Education and Training:

University of Maryland, College Park, MD	Physics	B.Sc.	1972-1976
Leland Stanford Junior University, Stanford CA	Physics	Ph.D	1979-1985

Research and Professional Experience:

1992-Present Staff Scientist/Senior Staff Scientist, Jefferson Lab

- Design and commission a high current injector for an energy recovering linac (ERL).
- Design, install and commission five ERL based free-electron lasers (FELs).
- Assist in the design of high power and short wavelength FEL driver accelerators.
- Coordinate the design of an electron cooling system for the Jefferson Lab Electron Ion Collider (JLEIC)

1988–1992 Research Assistant Professor, Duke University

- Re-installed and re-commissioned the Mark III Free-electron laser in the Duke Free-electron laser Lab (DFELL).
- Set up a user program for the DFELL.

1986–1988 Research Associate, Stanford University

- Installed and commissioned the Mark III Free-electron laser at the Stanford Photon Research Center.
- Ran the user program and technology development program at Stanford University for the ONR Navy Medical FEL program.

Representative Publications:

1. S. V. Benson and J. M. J. Madey, “Demonstration of harmonic lasing in a free-electron laser”, Phys. Rev. A, **39** 1579–1581.
2. M. S. Curtin, G. Bennett and R. Burke, S. V. Benson, J. M. J. Madey, “First Demonstration of a Free-electron Laser Driven by Electrons from a Laser Irradiated Photocathode” Proc. of the Int. Conf. on Lasers ‘88 (Lake Tahoe NV, Dec. 1988) Eds. R. C. Sze and F. J. Duarte, p. 196.
3. S. V. Benson, “Tunable free-electron lasers”, in Tunable Lasers Handbook, copyright 1995 Academic Press, Inc. pp. 443–470.
4. S. V. Benson, P. S. Davidson, R. Jain, P. K. Kloeppel, G. R. Neil, and M. D. Shinn, “Optical modeling of the Jefferson Laboratory IR demo FEL”, *Nucl. Inst. and Meth. in Phys. Res.* **A407** (1998) 401–406
5. G. R. Neil, C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, “Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery”, *Physical Review Letters*, **84**, (2000) 662.
6. S. Benson, D. Douglas, M. Shinn, K. Beard, C. Behre, G. Biallas, J. Boyce, H. F. Dylla, R. Evans, A. Grippo, J. Gubeli, D. Hardy, C. Hernandez-Garcia, K. Jordan, L. Merminga, G. R. Neil, J. Preble, T. Siggins, R. Walker, G. P. Williams, B. Yunn, S. Zhang, H. Toyokawa, “High Power Lasing in the IR Upgrade FEL at Jefferson Lab”, Proceedings of the 2004 FEL Conference, Trieste, Italy, 229 (2004).
7. S. Benson, G. Biallas, K. Blackburn, J. Boyce, D. Bullard, J. Coleman, C. Dickover, D. Douglas, F. Ellingsworth, P. Evtushenko, C. Hernandez-Garcia, C. Gould, J. Gubeli, D. Hardy, K. Jordan, M. Klopf, J. Kortze, R. Legg, M. Marchlik, W. Moore, G. Neil, T. Powers, D. Sexton, M. Shinn, C. Tennant, R. Walker, A. Watson, G. Williams, G Wilson & S. Zhang, “Demonstration of 3D effects with high gain and efficiency in a UV FEL oscillator”, Proceedings of PAC 2011, New York, USA p. 2429 (2011).

8. S. V. Benson, D. Douglas, G. Neil, M. D. Shinn and G. P. Williams, "A synchronized VUV/THz Light Source at Jefferson Lab", Proceedings of IPAC'12, New Orleans, LA May 20-25, p. 1789 (2012).
9. R. Alarcon, et al., "Transmission of Megawatt Relativistic Electron Beams through Millimeter Apertures", Phys. Rev. Lett. 111, 164801, 16 October 2013

Relevant Patents:

- D. Douglas and S. Benson, "*Use of Incomplete Energy Recovery for the Energy Compression of Large Energy Spread Charged Particle Beams*", U.S. Patent Number 7,166,973 (January, 23, 2007)
- S. Benson, G. Biallas, D. Douglas, K. Jordan, G Neil, M. Shinn, and G. Williams, "*Magnetic Chicane for Terahertz Management*", U.S. Patent Number 7,859,199 (December 28, 2010)
- D. Douglas, S. Benson, D. Nguyen, C. Tennant, and G. Wilson, "*Bunch Length Compression Method for Free Electron Lasers to Avoid Parasitic Compressions*", U.S. Patent Number 9,040,936 (May 26, 2015)
- S. Benson, F. Marhauser, D. Douglas and L. Ament, "*Linear Accelerator Accelerating Module to Suppress Back-Acceleration of Field-Emitted Particles*", U.S. Patent Number 9,629,230 (April 18, 2017)

Synergistic Activities:

- Technical reviewer for DoE, NSF, Physical Review
- Fellow, American Physical Society

Collaborators and Co-editors:

See above lists of publications and patents; in addition: Dr. Vadim Banine (ASML), Mr. Peter Bartray, (ASML), Dr. Seth Brussaard (ASML), Dr. Teis Coenen (ASML), Dr. Patrick de Jager (ASML), Dr. Henry Freund (NoVA consulting), Dr. Olaf Frijns (ASML), Dr. Dennis Grimminck (ASML), Dr. Geoff Krafft (Jefferson Lab), Mr. Robert Legg (Jefferson Lab), Dr. Fanglei Lin (Jefferson Lab), Dr. Erik Loopstra (Carl Zeiss), Dr. Peter McIntyre (Texas A&M), Dr. Vasiliy Mozorov (Jefferson Lab), Dr. George Neil (consultant) , Dr. Andrey Nikipelov (ASML), Dr. Willem op 't Root (ASML), Dr. Michael Phillips (consultant), Dr. Fulvia Pilat (Oak Ridge), Dr. Matthew Poelker (Jefferson Lab), Dr. Yves Roblin (Jefferson Lab), Dr. Henry van Rooijen (ASML), Dr. Todd Satogata (Jefferson Lab), Dr. Peter Smorenburg (ASML), Dr. Michael Spata (Jefferson Lab), Dr. Riad Suleiman (Jefferson Lab), Dr. Amy Sy (Jefferson Lab), Dr. Balsa Terzic (ODU), Dr. Nico ten Kate (ASML), Dr. Neil Thompson (ASTeC Daresbury), Dr. Alan Todd (consultant), Dr. Jeroen van Helvoort (ASML), Dr. Michiel Vervoordeldonk (ASML), Dr. Haipeng Wang (Jefferson Lab), Dr. Roy Whitney (BNNT, Inc.), Dr. Peter Williams (ASTeC Daresbury), Dr. Richard York (MSU/FRIB), Dr. He Zhang (Jefferson Lab), and Dr. Yuhong Zhang (Jefferson Lab)

Scott Berg
Brookhaven National Laboratory

Education and Training:

Cornell University, Applied and Engineering Physics, BS, 1989.

Stanford University, Physics, Ph.D., 1996.

European Organization for Nuclear Research (CERN), scientific associate, 1996–1997.

Research and Professional Experience:

Brookhaven National Laboratory, physicist, 1999–. Beam dynamics in and design of particle accelerators, particularly focusing ono muon accelerators and fixed field alternating gradient accelerators.

Indiana University, assistant professor, 1997–1999.

Publications:

J. S. Berg, S. Brooks, F. Méot, D. Trbojevic, N. Tsoupas, J. Crittenden, Y. Li, and C. Mayes, "CBETA FFAG Beam Optics Design," to appear in the proceedings of the 59th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL 2017), Geneva, Switzerland, June 18–23, 2017. BNL report BNL-114414-2017-CP. http://www.osti.gov/scitech/biblio/1408698

J. Scott Berg, "Optimizing the design of linear non-scaling fixed field alternating gradient arcs for the electron rings of eRHIC," in *Proceedings of IPAC'2016, Busan, Korea,* 2475–2478 (2016). http://www.jacow.org/ipac2016/papers/wepmw025.pdf

V. Ptitsyn *et al.*, "The ERL-based design of electron-hadron collider eRHIC," in *Proceedings of IPAC'2016, Busan, Korea*, 2482–2485 (2016). http://www.jacow.org/ipac2016/papers/wepmw027.pdf

S. Machida, D. J. Kelliher, C. S. Edmonds, I. W. Kirkman, J. S. Berg, J. K. Jones, B. D. Muratori, and J. M. Garland, "Amplitude-dependent orbital period in alternating gradient accelerators," Prog. Theor. Exp. Phys. **2016**, 033G01. DOI: 10.1093/ptep/ptw006

D. J. Kelliher, S. Machida, C. S. Edmonds, I. W. Kirkman, J. K. Jones, B. D. Muratori, J. M. Garland, and J. S. Berg, "Orbit correction in a linear nonscaling fixed field alternating gradient accelerator," Phys. Rev. ST Accel. Beams **17**, 112806 (2014). DOI: 10.1103/PhysRevSTAB.17.112806

S. Machida *et al.*, "Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA," Nature Physics **8**, 243–247 (2012). DOI: 10.1038/nphys2179

R. Barlow *et al.*, "EMMA—The world's first non-scaling FFAG," Nucl. Instrum. Methods A **624**, 1–19 (2010). DOI: 10.1016/j.nima.2010.08.109

J. S. Berg, "The EMMA main ring lattice," Nucl. Instrum. Methods A **596**, 276–284 (2008). DOI: 10.1016/j.nima.2008.08.068

J. Scott Berg, "Minimizing longitudinal distortion in a nearly isochronous linear nonscaling fixed-field alternating gradient accelerator," Phys. Rev. ST Accel. Beams **9**, 034001 (2006). DOI: 10.1103/PhysRevSTAB.9.034001

Synergistic Activities:

Organizing committee, fixed field alternating gradient workshop series.

Collaborators and Co-editors:

Elke Aschenauer, BNL; Adam Bartnik, Cornell University; Ilan Ben-Zvi, BNL; Michael Blaskiewicz, BNL; Stephen Brooks, BNL; John Cintorino, BNL; James Crittenden, Cornell University; John Dobbins, Cornell University; Bruce Dunham, SLAC; Chris Edmonds, University of Liverpool; Wolfram Fischer, BNL; Richard Gallagher, Cornell University; James Garland, European Organization for Nuclear

Research (CERN); Colwyn Gulliford, Cornell University; Yue Hao, BNL; Georg Hoffstaetter, Cornell University; James Jones, Daresbury Laboratory; Stephen Kahn, Muons Inc.; David Kelliher, Rutherford Appleton Laboratory; Val Kostroun, Cornell University; Yulin Li, Cornell University; Chiyu Liu, BNL; William Lou, Cornell University; Yun Luo, BNL; Shinji Machida, Rutherford Appleton Laboratory; George Mahler, BNL: Christopher Mayes, SLAC; François Méot, BNL; Robert Michnoff, BNL; Michiko Minty, BNL; Christoph Montag, BNL; Bruno Muratori, Daresbury Laboratory; David Neuffer, Fermilab; Robert Palmer, BNL; Brett Parker, BNL; Ritchie Patterson, Cornell University; Stephen Peggs, BNL; Vadim Ptitsyn, BNL; Thomas Roser, BNL; David Sagan, Cornell University; Karl Smolenski, Cornell University; Diktys Stratakis, Fermilab; Steven Tepikian, BNL; Peter Thieberger, BNL; Dejan Trbojevic, BNL; Nicholaos Tsoupas, BNL; Sam Tygier, University of Manchester; Peter Wanderer, BNL; Ferdinand Willeke, BNL; Holger Witte, BNL

Graduate and Postdoctoral Advisors and Advisees:

Ronald D. Ruth, SLAC.
Robert Warnock, SLAC.

Stephen Brooks | Accelerator Physicist
Brookhaven National Laboratory

Education and Training:

D.Phil., Particle Physics, University of Oxford, Oxford, United Kingdom, 2010

M. Math. Mathematics, University of Oxford, Oxford, United Kingdom, 2003

B.Sc., Applied Mathematics, The Open University, Buckinghamshire, United Kingdom, 2001

Research and Professional Experience:

10/2013 – present Physicist, Brookhaven National Laboratory

- Magnet design and tuning for the CBETA 4-turn ERL-FFAG.
- Design, construction and operation of a 4x energy range non-scaling, permanent magnet FFAG beamline at the BNL ATF-1 facility (experiment AE-79).
- Lattice design for the eRHIC accelerator, using FFAGs.

09/2003 – 10/2013 Accelerator Physicists, Rutherford Appleton Laboratory

- Research topics currently include: beam dynamics and magnetic field simulations in FFAG (fixed-field) particle accelerators; heat deposition and yield of particle beam targets. Previously worked on the Neutrino Factory "muon front end" design, including setting up a public distributed computing project to run the simulations and optimize the design automatically.

2007 – 2003 Associate Lecturer in Physics, The Open University

- Tutored the course "S357: Space Time and Cosmology" for two years at distance learning university, with ~20 students in the class. Syllabus included classical mechanics, special and general relativity and cosmology.

Summer 2000 – Spring 2003 Vacation Studentships, Rutherford Appleton Laboratory

- Developed graphics for interactive particle beam transport simulations.

Publications:

CBETA Design Report, Cornell-BNL ERL Test Accelerator, G.H. Hoffstaetter *et al.* (ed. Chris Mayes), available from https://arxiv.org/abs/1706.04245 (2017).

Production of Low Cost, High Field Quality Halbach Magnets, S.J. Brooks, J. Cintorino, A.K. Jain, and G.J. Mahler, in *Proc. IPAC2017*, pp. 4118--4120, Copenhagen, Denmark, May 2017, paper THPIK007, available from http://jacow.org/ipac2017/papers/thpik007.pdf or https://doi.org/10.18429/JACoW-IPAC2017-THPIK007 (2017).

Vertical Orbit-excursion Fixed Field Alternating Gradient Accelerators (V-FFAGs) and 3D Cyclotrons, S.J. Brooks, Proc. IPAC’14.

Vertical Orbit Excursion Fixed Field Alternating Gradient Accelerators, S.J. Brooks, Phys. Rev. ST Accel. Beams **16**, 084001 (2013).

Acceleration in Vertical Orbit Excursion FFAGs with Edge Focussing, S.J. Brooks, Proc. HB2012.

Vertical Orbit Excursion FFAGs, S.J. Brooks, Proc. HB2010.

Extending the Energy Range of 50Hz Proton FFAGs, S.J. Brooks, Proc. PAC’09.

Muon capture schemes for the neutrino factory. DPhil. University of Oxford. Stephen Brooks, (2010). http://ora.ox.ac.uk/objects/uuid:7b724028-e4ef-4248-9d42-505e571c9e19

Extrapolation of Magnetic Fields from a Curved Surface, S.J. Brooks technical note (2014) available from http://stephenbrooks.org/ap/report/2014-2/offsurface.pdf

eRHIC Design Study: An Electron-Ion Collider at BNL, E.C. Aschenauer *et al.*, pre-print (2014) available from http://arxiv.org/abs/1409.1633

Synergistic Activities:

In 2017, Dr. Brooks operated a permanent magnet non-scaling FFAG of the same sort as used in CBETA at an experimental beamline on the ATF-1 facility at BNL (ATF experiment# AE79). This beamline bent electrons from 18-70MeV energy by a 40 degree angle, with optical parameters measured and as expected. He also designed the magnets, lattice and specified the survey data for this beamline.

Dr. Brooks is involved in the design team of the eRHIC accelerator at BNL, which is also an FFAG. His code (MUON1 [19]) has been used extensively in producing new baseline designs, as well as being benchmarked against other widely used codes to verify correctness. The eRHIC project [17] also required evaluation of different magnet and vacuum vessel technologies and co-optimization of those with the beam optics.

Dr. Brooks gave an invited talk at IPAC'14 (the main international accelerator conference) about VFFAGs and 3D cyclotrons [1, 21], suggesting the idea of an electron model at the end.

Dr. Brooks was an invited consultant at the Radiatron machine design review held at RadiaBeam Technologies in July 2014. The Radiatron is a small electron FFAG with few-MeV beam energy for industrial X-ray production.

Collaborators and Co-editors:

Nikolai Avreline, RadiaBeam Technologies

Salime Boucher, RadiaBeam Technologies

Christopher Mayes, Cornell University

Alex Murokh, RadiaBeam Technologies

Stephen Webb, RadiaSoft LLC

Graduate and Postdoctoral Advisors and Advisees:

John Cobb, University of Oxford

Christopher Prior, STFC Rutherford Appleton Laboratory

Luca Cultrera
Cornell University

Education and Training:

Salento University (former University of Lecce) Lecce, Italy Physics M.S. 2000

Salento University (former University of Lecce) Lecce, Italy Physics Ph.D. 2004

National Institute of Nuclear Physics Rome, Italy Accel. Physics Postdoc 2005-07

Research and Professional Experience:

Senior Researcher Associate, Cornell University, CLASSE 2010 - present

Collaborated to the commissioning and operation of the Cornell ERL photoinjector prototype and on the development of high QE semiconductor photocathodes to be operated in high voltage DC gun to generate high intensity high brightness electron beam.

Researcher, National Institute of Nuclear Physics, Rome, Italy 2007 - 2010

Collaborated to the commissioning of the SPARC photoinjector at INFN in Frascati (ITALY) and worked on R&D of magnesium and yttrium metallic photocathodes grown using pulsed laser deposition.

Publications:

1. L. Cultrera, J. Maxson, I. Bazarov, S. Belomestnykh, J. Dobbins, B. Dunham, S. Karkare, R. Kaplan, V. Kostroun, Y. Li, X. Liu, F. Loehl, K. Smolenski, Z. Zhao, D. Rice, P. Quigley, M. Tigner, V. Veshcherevich, K. Finkelstein, D. Dale, B. Pichler, *"Photocathode Behavior During High Current Running in the Cornell ERL Photoinjector", Phys. Rev. ST Accel. Beams* **14** (2011) 120101
2. B. Dunham, J. Barley, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, G. Hoffstaetter, B. Johnson, R. Kaplan, S. Karkare, V. Kostroun, Y. Li, M. Liepe, X. Liu, F. Loehl, J. Maxson, P. Quigley, J. Reilly, D. Rice, D. Sabol, E. Smith, K. Smolenski, M. Tigner, V. Vesherevich, D. Widger and Z. Zhao, "*Record high-average current from a high-brightness photoinjector"*, *Appl. Phys. Lett.* **102**, 034105 (2013).
3. L. Cultrera, S. Karkare, B. Lillard, A. Bartnik, I. Bazarov, B. Dunham, W. Schaff, K. Smolenski, *"Growth and characterization of rugged sodium potassium antimonide photocathodes for high brilliance photoinjector", Appl. Phys. Lett.* **103** (2013) 103504
4. L. Cultrera, I. Bazarov, A. Bartnik, B. Dunham, S. Karkare, R. Merluzzi, M. Nichols, *"Thermal emittance and response time of a cesium antimonide photocathode", Appl. Phys. Lett.* **99** (2011) 152110
5. I.V. Bazarov, L. Cultrera, A. Bartnik, B. Dunham, S. Karkare, Y. Li, X. Xianghong, J. Maxson, W. Roussel, *"Thermal emittance measurements of a cesium potassium antimonide photocathode"*, *Appl. Phys. Lett.* **98** (2011) 224101
6. C. Gulliford, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, B. Dunham, F. Gonzalez, S. Karkare, H. Lee, H. Li, Y. Li, X. Liu, J. Maxson, C. Nguyen, K. Smolenski, Z. Zhao, *"Demonstration of Low Emittance in the Cornell Energy Recovery Linac Injector Prototype", Phys. Rev. ST Accel. Beams* **16** (2013) 073401
7. C. Gulliford, A. Bartnik, I. Bazarov, B. Dunham, L. Cultrera, *"Demonstration of cathode emittance dominated high bunch charge beams in a DC gun-based photoinjector", Appl. Phys. Lett.* ***106*** (2015) 094101

8. L. Cultrera, H.Lee, I. Bazarov, *"Alkali antimonides photocathodes growth using pure metals evaporation from effusion cells"*, *J. Vac. Sci. and Tech.* **B 34** (2016) 011202
9. J. Maxson, L. Cultrera, C. Gulliford, I. Bazarov, *"Measurement of the tradeoff between intrinsic emittance and quantum efficiency from a NaKSb photocathode near threshold", Appl. Phys. Lett.* **106** (2015) 234102
10. L. Cultrera, C. Gulliford, A. Bartnik, H. Lee, I. Bazarov, *"Ultra low emittance electron beams from multi-alkali antimonides photocathodes operated with infrared light"*, *Appl. Phys. Lett.* **108** (2016) 134105

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B.S., Physics, Rensselaer Polytechnic Institute, Troy, New York, 2011

Research and Professional Experience:

2017 – Present **CASA Post-Doctoral Fellow, Jefferson Lab**

- Beam dynamics simulation of magnetized electron beam through existing Jefferson Lab Free Electron Laser (JLab FEL) injector
- Beam dynamics simulation and design of an Energy Recovery Linac for a magnetized electron beam
- Simulation work to estimate electron cloud effects in ion ring of proposed Jefferson Lab Electron-Ion Collider (JLEIC)
- Work towards machine impedance budget for JLEIC

2012 – 2017 **Graduate Research Assistant, Old Dominion University**

- Start-to-end beam dynamics simulation and design of Inverse Compton Light Source, including SRF gun, SRF linear accelerator, and magnetic focusing.
- Design of SRF reentrant gun

Publications:

1. G. A. Krafft, E. Johnson, K. Deitrick, B. Terzić, R. Kelmar, T. Hodges, W. Melnitchouk, and J. R. Delayen, Laser pulsing in linear Compton scattering, Phys. Rev. Accel. Beams **19**, 121302 (2016).
2. S. U. De Silva, K. Deitrick, H. Park, and J. R. Delayen, Beam Dynamics Stuides of 499 MHz Superconducting RF-Dipole Deflecting Cavity System, in *Proceedings of the 2015 International Particle Accelerator Conference, Richmond, Virginia, USA* (2015), p. 3564.
3. B. Terzić, K. Deitrick, A. S. Hofler, and G. A. Krafft, Narrow-Band Emission in Thomson Sources Operating in the High-Field Regime, Phys. Rev. Lett. **112**, 074801 (2014).
4. C. S. Hopper, K. Deitrick, and J. R. Delayen, Geometry Effects on Multipole Components and Beam Optics in High-Velocity Multi-Spoke Cavities, in *Proceedings of the 2013 North American Particle Accelerator Conference, Pasadena, California, USA* (2013), p. 868.
5. S. Ahmed, G. A. Krafft, K. Deitrick, S. U. De Silva, J. R. Delayen, M. Spata, M. Tiefenback, A. Hofler, and K. Beard, Beam dynamics studies for transverse electromagnetic mode type rf deflectors, Phys. Rev. ST Accel. Beams **15**, 022001 (2012).

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Research and Professional Experience:

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- Design, tolerance specification, beam dynamics analysis, and commissioning for CEBAF
- CEBAF-ER concept, design, and operation
- Design, tolerance specification, beam dynamics analysis, commissioning, and operation of IR Demo, IR Upgrade, and UV FEL driver ERLs
- Design, tolerance specification, and beam dynamics analysis for multiple next-generation nonequilibrium systems, including ONR INP IR FEL, ASML EUV FEL, and JLEIC electron cooling system

1982-1985 Staff Scientist, Lawrence Berkeley Laboratory

- Advanced Light Source (lattice design, error analysis, dynamic aperture/tracking)
- SSC Reference Design Study and Central Design Groups (lattice design, dynamic aperture/tracking)

Representative Publications:

1. G. R. Neil *et al.*, "*Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery*" Phys. Rev. Lett. 84, 662-665 (2000)
2. P. Piot, D. Douglas, and G.A. Krafft, "*Longitudinal Phase Space Manipulation in Energy Recovering Linac-Driven Free-Electron Lasers*", Phys. Rev. ST Accel. Beams 6, 030702 (2003)
3. Lia Merminga, David R. Douglas, and Geoffrey A. Krafft, "*High-Current Energy-Recovering Electron Linacs*", Annual Review of Nuclear and Particle Science, 53, Page 387-429, Dec 2003
4. C. Tennant, K. Beard, D. Douglas, K. Jordan, L. Merminga, E. Pozdeyev, and T.I. Smith, "*First Observations and Suppression of Multipass, Multibunch Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade*", Phys. Rev. ST Accel. Beams 8, 074403 (2005)
5. R. Alarcon, *et al.,* "*Transmission of Megawatt Relativistic Electron Beams through Millimeter Apertures*", Phys. Rev. Lett. 111, 164801, 16 October 2013
6. C. Hall, S. Biedron, A. Edelen, S. Milton, S. Benson, D. Douglas, R. Li, C. Tennant, and B. Carlsten, "*Measurement and Simulation of the Impact of Coherent Synchrotron Radiation on the Jefferson Laboratory Energy Recovery Linac Electron Beam*", Phys. Rev. ST Accel. Beams 18, 030706 (2015)
7. C.-Y. Tsai, S. Di Mitri, D. Douglas, R. Li, and C. Tennant, "*Conditions for Coherent-Synchrotron-Radiation-Induced Microbunching Suppression in Multibend Beam Transport or Recirculation Arcs*", Phys. Rev. Accel. Beams 20, 024401 (2017)
8. C.-Y. Tsai, Ya. S. Derbenev, D. Douglas, R. Li, and C. Tennant, "*Vlasov Analysis of Microbunching Instability for Magnetized Beams*", Phys. Rev. Accel. Beams 20, 054401 (2017)
9. J.A.G. Akkermans, S. Di Mitri, D. Douglas, and I.D. Setija, "*Compact Compressive Arc and Beam Switchyard for Energy Recovery Linac-Driven Ultraviolet Free Electron Lasers*", Phys. Rev. Accel. Beams, 20, 080705 (2017)

10. D. Angal-Kalinin *et al*., "*PERLE. Powerful Energy Recovery Linac for Experiments. Conceptual Design Report*", J. Phys. G: Nucl. Part. Phys., http://iopscience.iop.org/article/10.1088/1361-6471/aaa171

Relevant Patents:

- D. Douglas, "*Linac Focused by Graded Gradient*", U.S. Patent Number 6,642,677 (Nov. 4, 2003)
- D. Douglas and B. Yunn, "*Passive, Achromatic, Nearly Isochronous Bending System*", U.S. Patent Number 6,737,655 (May 18, 2004)
- D. Douglas, "*Compaction Managed Mirror Bend Achromat*", U.S. Patent Number 6,956,218 (Oct. 18, 2005)
- D. Douglas and G. Neil, "*Achromatic Recirculated Chicane with Fixed Geometry and Independently Variable Path Length and Momentum Compaction*", U.S. Patent Number 6,885,088 (April 26, 2006)
- D. Douglas and S. Benson, "*Use of Incomplete Energy Recovery for the Energy Compression of Large Energy Spread Charged Particle Beams*", U.S. Patent Number 7,166,973 (January, 23, 2007)
- D. Douglas, "*Skew Chicane Based Betatron Eigenmode Exchange Module*", U.S. Patent Number 7,858,951 (December 28, 2010)
- S. Benson, G. Biallas, D. Douglas, K. Jordan, G Neil, M. Shinn, and G. Williams, "*Magnetic Chicane for Terahertz Management*", U.S. Patent Number 7,859,199 (December 28, 2010)
- D. Douglas, "*Use of Off-Axis Injection as an Alternative to Geometrically Merging Beams in an Energy-Recovering Linac*", U.S. Patent Number 8,093,840 (January 10, 2012)
- D. Douglas and C. Tennant, "*A Method for Controlling Coherent Synchrotron Radiation-Driven Degradation of Beam Quality During Bunch Length Compression*", U.S. Patent Number 8,217,596 (July 10, 2012)
- D. Douglas, S. Benson, D. Nguyen, C. Tennant, and G. Wilson, "*Bunch Length Compression Method for Free Electron Lasers to Avoid Parasitic Compressions*", U.S. Patent Number 9,040,936 (May 26, 2015)
- D. Douglas, "*Separated-Orbit Bisected Energy-Recovered Linear Accelerator*", U.S. Patent Number 9,125,287 (September 1, 2015)
- D. Douglas and C. Tennant, "*Method and Apparatus for Control of Coherent Synchrotron Radiation Effects During Recirculation With Bunch Compression*", U.S. Patent Number 9,184,022 (November 10, 2015)
- D. Douglas and C. Tennant, "*Method and Apparatus for Recirculation With Control of Synchrotron Radiation*", U.S. Patent Number 9,408,290 (August 2, 2016)
- D. Douglas and L. Ament, "*RF Kicker Cavity to Increase Control In Common Transport Lines*", U.S. Patent Number 9,629,230 (April 18, 2017)
- D. Douglas and L. Ament, "*Electron Beam Control For Barely Separated Beams*", U.S. Patent Number 9,629,230 (April 18, 2017)
- S. Benson, F. Marhauser, D. Douglas and L. Ament, "*Linear Accelerator Accelerating Module to Suppress Back-Acceleration of Field-Emitted Particles*", U.S. Patent Number 9,629,230 (April 18, 2017)

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Cornell University	Physics	Ph.D.	2013
Cornell University (post-doc)	Accelerator Physics		2014-16

Research and Professional Experience:

Research Assoc., Cornell University, CLASSE*	2016-present
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Publications:

*Multiobjective optimizations of a novel cryocooled dc gun based ultrafast electron diffraction beam line***,** C. Gulliford, A. Bartnik, I.V. Bazarov, Phys. Rev. Accel. Beams **19** (2016) 093402**,** http://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.093402

*Operational experience with nanocoulomb bunch charges in the Cornell photoinjector***,** A. Bartnik, C. Gulliford, I.V. Bazarov, L. Cultrera, Phys. Rev. Accel. ST Beams **18** (2015) 083401**,** http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.083401

Demonstration of cathode emittance dominated high bunch charge beams in a DC gun-based photoinjector, C. Gulliford, A. Bartnik et al., Applied Physics Letters **106** (2015) 10.1063,http://aip.scitation.org/doi/abs/10.1063/1.4913678?journalCode=apl

Demonstration of low emittance in the Cornell energy recovery linac injector prototype, C. Gulliford, I.V. Bazarov et al., Phys. Rev. ST Accel. Beams **16** (2013) 073401, http://prst-ab.aps.org/pdf/PRSTAB/v16/i7/e073401

Cornell ERL: Project Definition Design Report, A. Bartnik, I.V. Bazarov et al.*, Eds. G.H. Hoffstaetter, S.M. Gruner, M. Tigner, Cornell (2013)*, http://erl.chess.cornell.edu/PDDR/PDDR.pdf

Ultra low emittance electron beams from multi-alkali antimonide photocathode operated with infrared light, L. Cultrera, C. Gulliford, A. Bartnik, H. Lee, I.V. Bazarov, Applied Physics Letters, **108** (2016) 10.1063/1.4945091*,* http://aip.scitation.org/doi/10.1063/1.4945091

Measurement of the tradeoff between intrinsic emittance and quantum efficiency from a NaKSb photocathode near threshold, J. Maxon, L. Cultrera, C. Gulliford, I.V. Bazarov, Applied Physics Letters, **106** (2015) 10.1063/1.4922146*,* http://aip.scitation.org/doi/abs/10.1063/1.4922146

*New method for generating linear transfer matrices through combined rf and solenoid fields***,** C. Gulliford, I.V. Bazarov, Phys. Rev. Accel. Beams, **15** (2012) 024002**,** http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.15.024002

*Asymmetric focusing study from twin input power couplers using realistic rf cavity field maps***,** C. Gulliford, I.V. Bazarov, S. Belometnykh, V. Shemelin, Phys. Rev. ST Accel. Beams, **14** (2011) 032002**,** http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.14.032002

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DESY	Accelerator Physicist	1998-2002
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Publications:

Cornell-Brookhaven ERL Test Accelerator (CBETA) Design Report, G. Hoffstaetter, D. Trbojevic (PIs), C. Mayes (Ed.) (2017)

Energy Recovery Linac Development, G.H. Hoffstaetter, APS Division of Physics of Beams Newsletter 2015 (2015)

The Cornell-BNL FFAG-ERL Test Accelerator: White Paper, Ivan Bazarov, John Dobbins, Bruce Dunham, Georg Hoffstaetter, et al., arXiv:1504.00588 (2015)

Science with an ERL, D.H. Bilderback, J.D. Brock, E. Fontes, G.H. Hofstaetter (Eds.), www.classe.cornell.edu/ERL/Images/Science_with_an_ERL.pdf CLASSE report (2013)

Cornell ERL: Project Definition Design Report, G.H. Hoffstaetter, S.M. Gruner, M. Tigner (Eds.) http://erl.chess.cornell.edu/PDDR/PDDR.pdf CLASSE report (2013)

Optics issues in ongoing ERL projects, S. Smith, B.D. Muratori, H.I. Owen, G.H. Hoffstaetter, V.N. Litvinenko, I. Ben-Zvi, M. Bai, J. Beebe-Wang, M. Blaskiewicz, R. Calaga, W. fischer, X.Y. Chang, D. Kayran, J. Kewisch, W.W. MacKay, C. Montag, B. Parker, V. Ptitsyn, T. Roser, A. Ruggiero, T. Satagata, B. Surrow, S. Tepikian, D. Trbojevic, V. Yakimenko, S.Y. Zhang, Ph. Piot, Nuclear Instruments and Methods in Physics Research A 557, 145-164 (2006)

Adiabatic invariance of spin-orbit motion in accelerators, G.H. Hoffstaetter, H.S. Dumas, J.A. Ellison, Physical Review ST-AB 8, 014001 (2006)

Orbit and Optics Improvement by Evaluating the Nonlinear BPM Response in the Cornell Electron Storage Ring, R.W. Helms, G.H. Hoffstaetter, Physical Review ST-AB 8, 062802 (2005)

Coherent beam-beam tune shift of unsymmetrical beam-beam interactions with large beam-beam parameter, L. Jin, J. Shi, G. H. Hoffstaetter, Physical Review E 71, 036501 (2005)

Beam-Breakup Instability Theory for Energy Recovery Linacs, G. H. Hoffstaetter, I. Bazarov, Physical Review ST-AB, Volume 7, 54401 (May 2004)

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Illinois Institute of Technology	Elect. Engin.		1978-1985
Old Dominion University	Elect. Engin.	BSEE	1987-1990

Research and Professional Experience:

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- CASA Diagnostics group leader
- FEL Chief Engineer Free Electron Laser
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1985-1987 Technischer Angesteller, Deutsches Elektronen-Synchrotron (DESY)

- SRF group, instrumentation for HERA SRF cavity development

1978-1985 Electronic Technician, Fermi National Accelerator Lab

- Assisted in the design & implementation of Energy Doubler vacuum system
- Electrical Engineering Support Group
- DC power supply support group

Representative Publications:

1. G. R. Neil *et al.*, "*Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery*" Phys. Rev. Lett. 84, 662-665 (2000)
2. G. Ciovati, Steven M. Anlage, C. Baldwin, G. Cheng, R. Flood, K. Jordan,P. Kneisel, M. Morrone, G. Nemes, L. Turlington, H. Wang, K. Wilson, and S. Zhang "Low temperature laser scanning microscopy of a superconducting radio-frequency cavity" Review of Scientific Instruments **83,** 034704 (2012)
3. V. Raffa, C. Riggio, M. W. Smith, K. C. Jordan, W. Cao, A. Cuschieri "BNNT-Mediated Irreversible Electroporation: Its Potential on Cancer Cells" Technology in Cancer Research and Treatment ISSN 1533-0346, 2012 March 28
4. M.W. Smith, K.C. Jordan, C. Park, J.-W.Kim, P.T. Lillehei, R. Crooks and J.S. Harrison "Very long single- and few-walled boron nitride nanotubes via the pressurized vapor/condenser method" Nanotechnology 20 (2009) 505604 (6pp)
5. S. Benson, *et al.,* "The 4th Generation Light Source at Jefferson Lab" Nucl. Instrum. Meth. A 582, 14 (2007).
6. C. Tennant, K. Beard, D. Douglas, K. Jordan, L. Merminga, E. Pozdeyev, and T.I. Smith, "*First Observations and Suppression of Multipass, Multibunch Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade*", Phys. Rev. ST Accel. Beams 8, 074403 (2005)
7. P. C. Eklund, B. K. Pradhan, U. J. Kim, and Q. Xiong , J. E. Fischer , A. D. Friedman and B. C. Holloway , K. Jordan, M.W. Smith, "Large-Scale Production of Single-Walled Carbon Nanotubes Using Ultrafast Pulses from a Free Electron Laser," Nano Letters, American Chemical Society, Volume 2, Issue 6 (June 12, 2002).
8. C. Park, K. E. Wise, J. H. Kang, J.-W. Kim, G. Sauti, S. E. Lowther, P. T. Lillehei, M. W. Smith, E. J. Siochi, and J. S. Harrison, and K. Jordan, "Multifunctional nanotube polymer nanocomposites for aerospace applications: adhesion between SWCNT and polymer matrix", Adhesion Society Meeting, Austin TX, Feb (2008)

Patents:

- Induction-Coupled plasma synthesis of Boron Nitride nanotubes, US 9,776,865 (Award 10/3/2017)
- Target holders, multiple incidence angle, and multizone heating for BNNT synthesis US 9,745,192 (Award 12/13/2017)
- Nano-Materials for adhesive-free adsorbers for bankable extreme high vacuum cryopump surfaces, US 9,463,433 (Award 10/11/2016)
- System for Instrumenting and Manipulating Apparatuses in High Voltage, US 9,362,802 (Award 6/7/2016)
- High kinetic energy penetrator shielding and high wear resistance materials fabricated with boron nitride nanotubes (BNNTS) and BNNT polymer composites, US 9,067,385(Award 6/30/2015)
- Magnesium doping of boron nitride nanotubes, US 9,059,361 (Award 6/16/2015)
- Efficient boron-carbon-nitrogen nanotube formation via combined laser-gas flow levitation, US 8,986,513 (Award 3/24/2015)
- Apparatus for the production of boron nitride nanotubes, US 8,753,578 (Award 5/28/2014)
- Integrated Rig for the Production of Boron Nitride Nanotubes via the Pressurized Vapor-Condenser Method, US 8,679,300 (Award 3/25/2014)
- Efficient boron nitride nanotube formation via combined laser-gas flow levitation, US 8,673,120 (Award 3/18/2014)
- Articulating feedstock delivery device, US 8,573,446 (Award 11/5/2013)
- Apparatus and method for fast recovery and charge of insulation gas, US 8,522,817 (Award 9/3/2013)
- Protective laser beam viewing device, US 8,334,899 (Award 12/18/2012)
- Laser Ablative Synthesis of Carbon Nanotubes, US 8,317,983 (Award 11/27/2012)
- Boron Nitride Nanotubes, US 8,206,674 (Award 6/26/2012)
- Magnetic Chicane for Terahertz Management, US 7,859,199 (Award 12/28/2010)
- Laser Ablation for the Synthesis of Carbon Nanotubes, US 7,692,116 (Award 4/6/2010)
- Laser Ablative Synthesis of Carbon Nanotubes, US 7,671,306 (Award 3/2/2010)
- Apparatus for Free Electron Laser Ablative Synthesis of Carbon Nanotubes, US 7,663,077 (Award 2/16/2010)

Synergistic Activities:

1. Awarded NASA Government Invention of the Year 2016
2. Scientific program committee member International Beam Instrumentation Conference
3. Winner R&D100 Award for Free Electron Laser

Collaborators and Co-editors:

See above lists of publications and patents; in addition: Dr. Vadim Banine (ASML), Mr. Peter Bartray, Dr. Jay Benesch (Jefferson Lab), (ASML), Dr. Tessa Charles (CERN), Dr. Patrick de Jager (ASML), Dr. Bruce Dunham (SLAC), Dr. David Dunning (ASTeC Daresbury), Dr. Wouter Engeln (ASML), Dr. Pavel Evtushenko (HZD), Dr. Arne Freyberger (Jefferson Lab), Dr. Henry Freund (consultant), Dr. Olaf Frijns (ASML), Dr. Dennis Grimminck (ASML), Dr. Rol Johnson (Muons Inc), Dr. Reza Kazimi (Jefferson Lab), Dr. Roelof Klunder (ASML), Dr. Geoff Krafft (Jefferson Lab), Dr. Fanglei Lin (Jefferson Lab), Dr. Erik Loopstra (Carl Zeiss), Dr. Christopher Mayes (SLAC), Dr. Peter McIntyre (Texas A&M), Dr. Vasiliy Mozorov (Jefferson Lab), Dr. Bruno Muratori (ASTeC Daresbury), Dr. Andrey Nikipelov (ASML), Dr. Willem op 't Root (ASML), Dr. Hywel Owen (U. Liverpool/ASTeC Daresbury), Dr. Michael Phillips (consultant), Dr. Fulvia Pilat (Oak Ridge), Dr. Matthew Poelker (Jefferson Lab), Mr. Thomas Powers (Jefferson Lab), Dr. Yves Roblin (Jefferson Lab), Dr. Henry van Rooijen (ASML), Dr. Todd Satogata (Jefferson Lab), Dr. Michael Spata (Jefferson Lab), Dr. Riad Suleiman (Jefferson Lab), Dr. Balsa Terzic (ODU), Dr. Neil Thompson (ASTeC Daresbury), Dr. Alan Todd (consultant), Dr. Jeroen van Helvoort (ASML), Dr. Michiel Vervoordeldonk (ASML), Dr. Haipeng Wang (Jefferson Lab), Dr. Roy

Whitney (BNNT, Inc.), Dr. Peter Williams (ASTeC Daresbury), Dr. Richard York (MSU/FRIB), Dr. He Zhang (Jefferson Lab), and Dr. Yuhong Zhang (Jefferson Lab)

Matthias Liepe
Cornell University

Education and Training:

Universität Hamburg	Hamburg, Germany	Physics	B.S.	1994
Universität Hamburg	Hamburg, Germany	Physics	M.S.	1998
Universität Hamburg	Hamburg, Germany	Physics	Ph.D.	2001

Research and Professional Experience:

Associate Professor of Physics, Cornell University	2013-present
Assistant Professor of Physics, Cornell University	2006-2013
Lecturer, Cornell University	2004-2006
Research Associate, Cornell University	2001-2006
Research Assistant, DESY, Germany	1998-2001
Visiting Scientist, Cornell University	1998-1999

Publications:

The importance of the electron mean free path for superconducting radio-frequency cavities, James Maniscalco, Dan Gonnella, and Matthias Liepe, J. Appl. Phys. 121, 043910 http://dx.doi.org/10.1063/1.4974909 (2017).

Theoretical estimates of maximum fields in superconducting resonant radio frequency cavities: stability theory, disorder, and laminates, Danilo B Liarte, Sam Posen, Mark K Transtrum, Gianluigi Catelani, Matthias Liepe and James P Sethna, Superconductor Science and Technology, Volume 30, Number 3, 033002 http://stacks.iop.org/0953-2048/30/i=3/a=033002 (2017).

Impact of nitrogen doping of niobium superconducting cavities on the sensitivity of surface resistance to trapped magnetic flux, Dan Gonnella, John Kaufman, and Matthias Liepe, J. Appl. Phys. 119, 073904 http://dx.doi.org/10.1063/1.4941944 (2016).

Proof-of-principle demonstration of Nb3Sn superconducting RF cavities for high Q0 applications, S. Posen, M. Liepe, D. Hall, Applied Physics Letters 106, Issue 8 http://dx.doi.org/10.1063/1.4913247 (2015).

Radio Frequency Magnetic Field Limits of Nb and Nb3Sn, S. Posen, N. Valles, and M. Liepe, Phys. Rev. Lett. 115, 047001 http://dx.doi.org/10.1103/PhysRevLett.115.047001 (2015).

Nitrogen-doped 9-cell cavity performance in a test cryomodule for LCLS-II, D. Gonnella, R. Eichhorn, F. Furuta, M. Ge, D. Hall, V. Ho, G. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears, V. Veshcherevich, A. Grassellino, A. Romanenko and D. A. Sergatskov, J. Appl. Phys. 117, 023908 http://dx.doi.org/10.1063/1.4905681 (2015).

Shielding Superconductors with Thin Films as Applied to RF Cavities for Particle Accelerators, S. Posen, M. K. Transtrum, G. Catelani, M. Liepe, and J. P. Sethna, Phys. Rev. Applied 4, 044019 http://dx.doi.org/10.1103/PhysRevApplied.4.044019 (2015).

Analysis of Nb3Sn surface layers for superconducting RF cavity applications, C. Becker, S. Posen, N. Groll, R. Cook, C. M. Schlepuetz, D. Hall, M. Liepe, M. Pellin, J. Zasadzsinski, and T. Proslier, Applied Physics Letters 106, Issue 8 http://dx.doi.org/10.1063/1.4913617 (2015).

Advances in development of Nb3Sn superconducting radio-frequency cavities, S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 https://doi.org/10.1103/PhysRevSTAB.17.112001 (2014).

Superconducting RF for Energy-Recovery Linacs, M. Liepe, J. Knobloch, Nuclear Instruments and Methods in Physics Research A 557, 354-369, https://doi.org/10.1016/j.nima.2005.10.099 (2006).

Synergistic Activities:

- Founder and PI of Summer Research for Community College Students Program 2010-2013
- Faculty Innovation in Teaching Program Award 2007
- Research Experiences for Undergraduates Mentor and Lecturer 2001-present
- Online physics video demonstration database: http://courses2.cit.cornell.edu/physicsdemos/
- Member of the Cornell Active Learning Initiative, developing a "flipped classroom" approach for physics courses

Collaborators and Co-Editors:

I. Bazarov (Cornell), C. Becker (ANL), S. Belomestnykh (FNAL), T. Buck (TRIUMF), G. Catelani (Jülich), G. Ciovati (JLAB), R. Cook (ANL), J. N. Corlett (Berkeley), P. Corlett (Daresbury Laboratory), A. Crawford (FNAL), P. Davies (Daresbury Laboratory), B.M. Dunham (SLAC), R. Eichhorn (Cornell), F. Furuta (Cornell), M. Gee (Cornell), Rong-Li Geng (TJNAF), S. Gheidi (TRIUMF), D. Gonnella (SLAC), A. Grassellino (Fermilab), N. Groll (ANL), D. Hall (Cornell), D. Hartill (Cornell), H. Hayano (KEK), A. Hocker (FNAL), G. H. Hoffstaetter (Cornell), Y. Iwashita (Kyoto University), T. Jones (Daresbury Laboratory), R. Kiefl (TRIUMF), T. Kimura (SLAC), J. Knobloch (HZB), K. Ko (SLAC), Peter Koufalis (Cornell), O. Kugeler (HZB), M. Kuriki (Hiroshima University), R. Laxdal (TRIUMF), H. Lee (SLAC), D. Li (LBNL, Berkeley), Danilo Liarte (Cornell), J. Maniscalco (Cornell), C. Mayes (Cornell), P. A. McIntosh (Daresbury Laboratory), O. Melnychuk (FNAL), S. Michizenko (KEK), A. Neumann (HZB), C.K. Ng (SLAC), H. Padamsee (FNAL), A. Palczewski (TJNAF), R. Patterson (Cornell), M. Pellin (ANL), L. Phillips (JLAB), R. Porter (Cornell), S. Posen (FNAL), T. Proslier (CEA), P. Quigley (Cornell), C. Reece (TJNAF), J. Reilly (Cornell) , A. Romanenko (FNAL), M. Ross (SLAC), A. Rowe (FNAL), C.M. Schlepuetz (ANL), J. Sears (Cornell), D. A. Sergatskov (FNAL), J. Sethna (Cornell), T. I. Smith (SLAC), S. Sibener (U of Chicago), N. Solyak (FNAL), J. Strachan (Daresbury Laboratory), N. Terunuma (KEK), M. Transtrum (BYU), B. Y. Trenikhina (FNAL), T. Smith (CCLRC Daresbury Laboratory), A.M. Valente (JLAB), N. Valles (Ratheon), V. Veshcherevich (Cornell), G. Wu (FNAL), L. Xiao (SLAC).

Graduate and Postdoctoral Advisors

Graduate Advisor: Peter Schmüser, Universität Hamburg, Germany
Postdoctoral Advisors: none

Graduate and Postdoctoral Advisees

Graduate Students: Daniel Gonnella (now at SLAC), Daniel Hall (Cornell), Peter Koufalis (Cornell), James Maniscalco (Cornell), Thomas Oseroff (Cornell), Ryan Porter (Cornell), Sam Posen (now at FNAL), Conrad Smart (Cornell) Nick Valles (now at Raytheon), Yi Xie (now at FNAL) **(total 10)**

Postdoctoral Advisees: none

Advisory Committees: LCLS-II Facility Advisory Committee (SLAC)

Thomas Powers, Senior Engineer

Superconducting Radio Frequency Institute, Jefferson Lab

Education and Training:

Old Dominion University, Norfolk, VA	Electrical Engineering	B.Sc.	1975-1980
Old Dominion University, Norfolk, VA	Electrical Engineering	MS	1985-1987

Research and Professional Experience:

1980 – 1985 Navigation Systems Engineer, Naval Sea Systems Command, Norfolk Detachment.

- Provided in-service engineering support for conventional navigation systems that were used on board US Navy Ships.

1987-Present Staff Engineer/Senior Staff Engineer, Jefferson Lab

- Developed maintained, and upgraded production RF test systems for superconducting radio frequency (SRF) cavity testing.
- Developed and led team that implemented the cryogenic controls for the JLAB vertical test systems.
- Was a member of the team that performed the production testing of SRF cavities for original CEBAF, SNS (Oak Ridge TN), the CEBAF 12 GeV upgrade, and LCLS II.
- Developed beam position monitor diagnostics for CEBAF.
- Was involved with original operational commissioning of the SRF systems for CEBAF.
- Was a member of the JLAB IR/UV FEL team for a number of years specializing in RF and diagnostics systems as well as drive laser synchronization systems.
- Extensive experience in measuring and mitigating microphonic vibrations in SRF systems.
- Extensive experience with RF systems used for operating and commissioning SRF and normal conducting cavities.
- Provided advice and hands-on guidance as to the testing and operation of SRF technology at other labs in the USA as well as internationally.

Representative Publications:

1. C. Hovater, et. al., “Operation of the CEBAF 100 MV Cryomodules,” Linac 2016, East Lansing, MI, Sep. 2016.
2. T. Powers and M. Morrone, “Jefferson Lab Vertical Test Area RF System Improvement.,” SRF 2015, Whistler, BC Canada, Sep. 2015
3. Z. Gao#, Y. He, W. Chang, S.H. Zhang, W.M. Yue, Z.L. Zhu, Q. Chen, IMP, CAS, Lanzhou, China, Tom Powers, JLab, Newport News, VA 23606, USA, “The Study on Microphonics of Low Beta HWR Cavity at IMP,” SRF 2015, Whistler, BC Canada, Sep. 2015
4. T. Powers, “Recent Improvements to the Software Used for Optimization of SRF Linacs,” Linac 2014, Geneva Switzerland, Sept. 2014.
5. J. Bisognano, et.al., “Wisconsin SRF Electron Gun Commissioning,” Proceedings of PAC2013, Oct. 2013.
6. J. Corlett, et.al., “Superconducting Linac Design Concepts for a Next Generation Light Source at LBNL,” Proceedings of the 2013 FEL workshop, New York, Aug. 2013
7. K. Davis, J. Matalevich, T. Powers, and M. Wiseman, “Vibration Response Testing of the CEBAF 12 GeV Upgrade Cryomodules,”, K. Davis, et.al. Proceedings of Linac 2012, Tel-Aviv, Israel, Sept. 2012
8. C. Hovater, J. Delayen, L. Merminga, T. Powers, C. Reece, “RF Control Requirements for the CEBAF Energy Upgrade Cavities,” XX international Linac Conference, Aug. 2000.
9. T. Powers, “RF Controls Experience with the JLAB IR Upgrade FEL,” ERL 2009, June 2009.
10. T. Powers, C. Tennant. “Implications of Incomplete Energy Recovery in SRF-based Energy Recovery Linacs,” ERL 2007, May 2007.

Collaborators and Co-editors:

See above lists of publications and patents; in addition: Dr. Pavel Evtushenko (HZD), Dr. Rol Johnson (Muons Inc), Dr. Reza Kazimi (Jefferson Lab), Dr. Geoff Krafft (Jefferson Lab), Mr. Robert Legg (Jefferson Lab Dr. Roy Whitney (BNNT, Inc.), Dr. Peter McIntosh (ASTeC Daresbury), Dr. Richard York (MSU/FRIB), and Dr. Yuhong Zhang (Jefferson Lab), Dr. Jean Delayen, ODU/JLAB, Dr. Subashini De Silva, ODU.

Chris Tennant | Staff Scientist III

Center for Advanced Studies of Accelerators | Jefferson Laboratory

Education and Training:

B.A. Physics, Ithaca College, Ithaca, NY (2001)

M.S. Physics, The College of William & Mary, Williamsburg, VA (2002)

Ph.D. Physics, The College of William & Mary, Williamsburg, VA (2006)

Research and Professional Experience:

Staff Scientist III (2015 – *present*), Jefferson Laboratory

Staff Scientist II (2011 – 2014), Jefferson Laboratory

Staff Scientist I (2006 – 2014), Jefferson Laboratory

- Start-to-end modeling and analysis of collective effects for multiple ERL-driven systems: Jefferson Laboratory IR and UV FELs, Office of Naval Research INP IR FEL, ASML EUV FEL, and the Jefferson Laboratory Electron Ion Collider (JLEIC) electron cooling system
- Modeling and analysis of Polarized Electrons for Polarized Positrons (PEPPo) transport line
- Simulation and analysis of cumulative beam breakup (BBU) in cavities for an inverse Compton source
- High power beam operation for the DarkLight experiment at the Jefferson Lab FEL Driver
- Design and simulation of coherent synchrotron radiation (CSR) managed bunch compression systems
- Analytical study and simulations of the effects and implications of incomplete energy recovery on high power ERLs utilizing superconducting radio-frequency (SRF) cavities.

Publications:

1. C. Tennant and D. Douglas, *"Analysis of a "Simple Arc" for Use in the CCR for Strong Cooling in JLEIC"*, Jefferson Laboratory Technical Note 18-001 (2018).
2. C.-Y. Tsai, Ya. S. Derbenev, D. Douglas, R. Li, and C. Tennant, *"Vlasov analysis of microbunching instability for magnetized beams",* Phys. Rev. Accel. Beams **20**, 054401 (2017).
3. C.-Y. Tsai, S. Di Mitri, D. Douglas, R. Li, and C. Tennant *"Conditions for coherent-synchrotron-radiation-induced microbunching suppression in multibend beam transport or recirculation arcs"*, Phys. Rev. ST Accel. Beams **20**, 024401 (2017).
4. C.-Y. Tsai, D. Douglas, R. Li, and C. Tennant *"Linear microbunching analysis for recirculation machines"*, Phys. Rev. ST Accel. Beams **19**, 114401 (2016).
5. C. Tennant (2016), Novel Accelerator Ideas: Energy Recovery Linacs, in (eds. O. Bruning, S. Myers) *Challenges and Goals for Accelerators in the XXI Century* (pp. 741-766). Singapore, World Scientific.
6. C. Hall, S. Biedron, A. Edelen, S. Milton, S. Benson, D. Douglas, R. Li, C. Tennant, and B. Carlsten, *"Measurement and Simulation of the Impact of Coherent Publications Synchrotron Radiation on the Jefferson Laboratory Energy Recovery Linac Electron Beam"* Phys. Rev. ST Accel. Beams **18**, 030706 (2015).
7. D. Douglas, S. Benson, A. Hutton, G. Krafft, R. Li, G. Neil, Y. Roblin, C. Tennant, and C.-Y. Tsai, "*Control of Coherent Synchrotron Radiation, and Microbunching Effects during Transport of High Brightness Electron Beams"*, arXiv:1403.2318v1 (2014).

8. R. Alarcon, et al., *"Transmission of Megawatt Relativistic Electron Beams through Millimeter Apertures"* Phys. Rev. Lett. **111**, 164801 (2013).
9. C. Tennant, D. Douglas *"Overview of Existing Energy Recovery Linacs"* ICFA Beam Dynamics Newsletter, No. 58 (2012).
10. C. Tennant, K. Beard, D. Douglas, K. Jordan, L. Merminga, and E. Pozdeyev, *"First observations and suppression of multipass, multibunch beam breakup in the Jefferson Laboratory free electron laser upgrade",* Phys. Rev. ST Accel. Beams **8**, 074403 (2005).

Relevant Patents:

- D. Douglas and C. Tennant, "*A Method for Controlling Coherent Synchrotron Radiation-Driven Degradation of Beam Quality During Bunch Length Compression*", U.S. Patent Number 8,217,596 (July 10, 2012)
- D. Douglas, S. Benson, D. Nguyen, C. Tennant, and G. Wilson, "*Bunch Length Compression Method for Free Electron Lasers to Avoid Parasitic Compressions*", U.S. Patent Number 9,040,936 (May 26, 2015)
- D. Douglas and C. Tennant, "*Method and Apparatus for Control of Coherent Synchrotron Radiation Effects During Recirculation With Bunch Compression*", U.S. Patent Number 9,184,022 (November 10, 2015)
- D. Douglas and C. Tennant, "*Method and Apparatus for Recirculation With Control of Synchrotron Radiation*", U.S. Patent Number 9,408,290 (August 2, 2016)

Synergistic Activities:

- Local Organizing Committee, ICFA Workshop on Future Light Sources (2012)
- Organized and co-instructed *"Beam Measurements, Manipulation and Instrumentation at an ERL FEL Driver"* course for USPAS (2011)

Collaborators and Co-editors:

Akkermans, Iwan (ASML), Ament, Luuk (IBM), Benson, Stephen (JLAB), Biedron, Sandra (CSU), Carlsten, Bruce (LANL), Douglas, David (JLAB), Edelen, Auralee (CSU), Hall, Chris (RadiaSoft), Hutton, Andrew (JLAB), Krafft, Geoff (JLAB), Li, Rui (JLAB), Milton, Stephen (CSU), Neil, George (JLAB), Powers, Tom (JLAB), Roblin, Yves (JLAB), Satogata, Todd (JLAB), Setija, Irwan (ASML), Tsai, Cheng-Ying (SLAC), York, Richard (MSU)

Graduate and Postdoctoral Advisors and Advisees:

- Dr. David Douglas (JLab)
- Dr. Keith Griffioen (W&M)
- Dr. Lia Merminga (SLAC)

Dejan Trbojevic | Senior Physicist
Collider-Accelerator Department | Brookhaven National Laboratory

Education and Training:

Ph.D., Physics, Georgetown University, Washington, D.C., 1984

M.Sc., Physics, Electro-Technical University, Belgrade, Serbia, 1980

B.A., Technical Physics, Electro-Technical University, Belgrade, Serbia, 1974

Research and Professional Experience:

2003 – Present Senior Physicist (tenured 2003), Brookhaven National Laboratory

- Principal Investigator at BNL of the CBETA project officially from November 2016
- Designed accelerator lattices and interaction regions for electrons and ions for electron ion collider – eRHIC
- Proposed a new solution with non-scaling fixed field accelerator (NS-FFAG) to reduce significantly the overall cost of the eRHIC project
- Inventor of new concepts: including fixed field accelerators with medical application to cancer therapy (five patents), and the transition-less accelerator lattice with a control of momentum compaction applied in the previous design of eRHIC and LHeC-Large Hadron electron Collider
- Recognized world expert in Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerators. Independently invented the triplet NS-FFAG accelerator during the international muon collider collaboration
- Chief Scientist of the ion Fast Cycling Medical Synchrotron (iRCMS http://www.ipac2011.org/pre_press/WEPS028.PDF). Designed original fast cycling synchrotron, lead scientific efforts in the CRADA collaboration and produced the iRCMS Pre-Conceptual Design Report

1992 – 2003 Accelerator Physicist, Brookhaven National Laboratory

- Expert in the field of accelerator physics design, commissioning, and operations at the Relativistic Heavy Ion Collider (RHIC).
- During the RHIC design and commissioning: developed a novel Transition Energy Jump; commissioned the permit link; the loss monitor system; supervised magnetic measurements; responsible for the magnet survey and alignment; designed the decoupling and octupole systems; reviewed and documented the vacuum system; designed and commissioned the abort and injection systems, etc. Success of these efforts resulted in my appointment as the Head Commissioner of RHIC (1999-2000) at the initiation of operations (http://conference.kek.jp/heacc2001/ProceedingsHP.html)

1986 – 1992 Physicist, Accelerator Division, Fermi National Laboratory, Batavia, IL

- Leader of the Main Ring group. Responsible for its operations as injector for Tevatron proton-antiproton collider. Participated in Tevatron commissioning, improved antiproton production and the Main Ring operation.
- Invented a novel method for dispersion matching and introduced the “normalized dispersion space” acknowledged in accelerator physics courses and textbooks. Applied the method in a design of the Fermilab Main Ring vertical overpass over the “D0” detector (http://dx.doi.org/10.1109/PAC.1989.72939). This lead to a new D0 overpass project. Became the Project Manager, lead a $40 million project from start to finish. Successfully completed and commissioned the project, early and under budget. Experimental measurements showed excellent agreement with predictions.

1984 – 1986 Post-Doctoral, Accelerator Division, Fermi National Laboratory, Batavia, IL

- The postdoctoral position started at the Fermi Switchyard Group. Major projects included: glow http://dx.doi.org/10.1109/TNS.1985.4334279 discharge improvements of electrostatic septa, Main Ring correction system characterization, participated in series of SSC (Super Conducting Super Collider) experiments with the synchrotron light desorption. A member of the team of scientists who reported a major restriction for operation of the future super collider due to continuous desorption from the cold pipe walls. An additional liner was proposed to solve the problem for the beam survival. This is a part of the present Large Hadron Collider (LHC) at CERN as well.

Research and Professional Accomplishments:

- Head of Brookhaven Cornell Test Accelerator R&D group 2015 - present
- Principal Investigator of the LDRD NS-FFAG for eRHIC 2012 – 2014
- Principal Investigator of the iRCMS CRADA 2009 – present
- Deputy of the Accelerator R&D group of the R&D Division 2008 – present
- Deputy of the Accelerator Physics group in the Accelerator Division 2006 – 2008
- Group Leader in the Accelerator Physics in the Accelerator Division 2004 – 2006
- Head Commissioner of the RHIC 1999 – 2000
- Key member of team designing and constructing RHIC 1992 – 1999

Patents:

1. 2015, "Scanning Systems for Particle Cancer Therapy", US 20140163301 A1, www.google.com/patents/US20140163301
2. 2009, "Gantry for medical particle therapy facility", D. Trbojevic, US Patent number: 7582886
3. 2012, "Gantry for medical particle therapy facility," D. Trbojevic, US Patent 8,173,981
4. 2012, "Non Scaling Fixed Field Alternating Gradient Permanent Magnet Cancer Therapy Accelerator," D. Trbojevic, Patent Submitted: Attorney Docket No.: S126140
5. 2012, "Innovative Scanning System for Ion Cancer therapy," D. Trbojevic
6. 2012, "Linear Fixed-Field Multipacks for recirculating Linear Accelerators", Bogacz, V. Morozov, and D. Trbojevic, 2166U (JSA)

Synergistic Activities:

Brookhaven Science and Technology Award (2014)

Brookhaven Town Board Award: Certificate of excellence for the design of the gantry for the carbon cancer therapy (2012)

American Physical Society (APS) Fellow, (2008 – present)

Reviewer, Physical Review Special Topics for Accelerators and Beams, on IEEE Transactions on Nuclear Science, and the Small Business Innovation Research (SBIR) for the DOE (2000 – present)

Collaborators and Co-editors:

Professor Ugo Amaldi (Italy), Dr. Jay Flanz Massachusetts General Proton Therapy facility, Dr. Marko Pullia - CNAO carbon therapy facility in PAVIA Italy

Graduate and Postdoctoral Advisors and Advisees:

Research Advisors: Prof. James Lambert and Prof. Paul Treado.

APPENDIX 2: Current and Pending Support

The Principal Investigator, Stephen Peggs, as well as senior investigators Scott Berg, Stephen Brooks, and Dejan Trbojevic are funded by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics (KB020201-1), to support accelerator operations and R&D at BNL's RHIC complex. This is collectively at about 43 person-months per year.

Other current or pending support requests for the PI and senior investigators are detailed below.

Current and Pending Support
Investigator: Stephen Peggs
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: New York State Energy Research and Development Authority
Award Number or Identifying Number: Contract ID 102192
Title of the award or activity: ERL Test Accelerator (C-Beta)
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $25,000,000 (FY17-FY20)
The number of person-months per year to be devoted to the project: 4.8

Current and Pending Support
Investigator: Kevin Jordan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: DOE BES
Award Number or Identifying Number: YN1901000SLAC125201
Title of the award or activity: LCLS II LERF Cryomodule test facility
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $3M
The number of person-months per year to be devoted to the project: 8

Current and Pending Support
Investigator: Chris Tennant
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: DOE NP
Award Number or Identifying Number: KB0102011
Title of the award or activity: Advanced machine development for JLEIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2.1M
The number of person-months per year to be devoted to the project: 5.5

Current and Pending Support
Investigator: Stephen Benson
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: DOE NP
Award Number or Identifying Number: KB0102011
Title of the award or activity: Advanced machine development for JLEIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2.1M
The number of person-months per year to be devoted to the project: 5.5

Current and Pending Support
Investigator: David R. Douglas
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: DOE NP
Award Number or Identifying Number: KB0102011
Title of the award or activity: Preliminary Accelerator Design for JLEIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2.1M
The number of person-months per year to be devoted to the project: 5.5

Current and Pending Support
Investigator: David R. Douglas
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: CERN
Award Number or Identifying Number: B&R for Perle
Title of the award or activity: PERLE project design
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $0.492M
The number of person-months per year to be devoted to the project: 0.9

Current and Pending Support
Investigator: Chris Tennant
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: CERN
Award Number or Identifying Number: B&R for Perle
Title of the award or activity: PERLE project design
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $0.492M
The number of person-months per year to be devoted to the project: 1.2

Current and Pending Support
Investigator: Tom Powers
Support: ☐ Funded ☐ Pending NONE
Sponsor or Source of Funding:
Award Number or Identifying Number:
Title of the award or activity:
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding:
The number of person-months per year to be devoted to the project:

Current and Pending Support
Investigator: Bartnik, Adam
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 3, 6 months

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0011643
Title of the award or activity: NEW METHODS TO PRODUCE AND EXTEND THE SPECTRAL RANGE OF PHOTOCATHODES FOR LARGE-AREA PHOTODETECTORS WITH MM-SCALE SPACE RESOLUTION
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $690,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: PHY-1416318
Title of the award or activity: CORNELL PROGRAM FOR STUDENT-CENTERED ACCELERATOR SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $10,597,786
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1461111
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $404,625
The number of person-months per year to be devoted to the project: 0.25

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0013571
Title of the award or activity: INNOVATIONS IN OPTIMIZATION AND CONTROL OF ACCELERATORS USING METHODS OF DIFFERENTIAL GEOMETRY AND GENETIC ALGORITHMS
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $470,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0014338
Title of the award or activity: ULTRA-LOW EMITTANCE PHOTOCATHODES FOR ACCELERATORS AND FEMTOSECOND ELECTRON DIFFRACTION
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $400,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0016203
Title of the award or activity: NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $280,000
The number of person-months per year to be devoted to the project: 0.25

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1757811
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $406,169
The number of person-months per year to be devoted to the project: 0.2

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High current electron sources for strong hadron cooling and polarized sources for EIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $537,006
The number of person-months per year to be devoted to the project: 1 month

Current and Pending Support
Investigator: Bazarov, Ivan
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: RMD Inc.
Award Number or Identifying Number:
Title of the award or activity: Manufacturing of Reliable Bialkali Photocathodes via Sputtering for the Electron-Ion Collider
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $133,503
The number of person-months per year to be devoted to the project: 0.25

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0011643
Title of the award or activity: NEW METHODS TO PRODUCE AND EXTEND THE SPECTRAL RANGE OF PHOTOCATHODES FOR LARGE-AREA PHOTODETECTORS WITH MM-SCALE SPACE RESOLUTION
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $690,000
The number of person-months per year to be devoted to the project: 9.0

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: PHY-1416318
Title of the award or activity: CORNELL PROGRAM FOR STUDENT-CENTERED ACCELERATOR SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $10,597,786
The number of person-months per year to be devoted to the project: 1.2

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1461111
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $404,625
The number of person-months per year to be devoted to the project: 1.0

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0016203
Title of the award or activity: NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $280,000
The number of person-months per year to be devoted to the project: 3.0

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1757811
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $406,169
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 0.5, 1

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High current electron sources for strong hadron cooling and polarized sources for EIC
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $537,006
The number of person-months per year to be devoted to the project: 6 months

Current and Pending Support
Investigator: Cultrera, Luca
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: RMD Inc.
Award Number or Identifying Number:
Title of the award or activity: Manufacturing of Reliable Bialkali Photocathodes via Sputtering for the Electron-Ion Collider
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $133,503
The number of person-months per year to be devoted to the project: 2

Current and Pending Support
Investigator: Gulliford, Colwyn
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 3, 6

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Chicago Operations Office DOE
Award Number or Identifying Number: DE-SC0008431
Title of the award or activity: RAISING SUPERCONDUCTING CAVITY GRADIENTS
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,540,000
The number of person-months per year to be devoted to the project: 0.5

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: PHY-1416318
Title of the award or activity: CORNELL PROGRAM FOR STUDENT-CENTERED ACCELERATOR SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $10,597,786
The number of person-months per year to be devoted to the project: 1.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1461111
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $404,625
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Institute for Basic Science
Award Number or Identifying Number: N/A
Title of the award or activity: R&D ON THE HALF-WAVE-RESONATORS (HWR) FOR THE RAON ACCELERATOR
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $1,630,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Fermi National Accelerator Laboratory
Award Number or Identifying Number: 619833
Title of the award or activity: ADVANCED CONCEPTS FOR MUON AND NEUTRINO SOURCES
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $47,900
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Faraday Technology Inc.
Award Number or Identifying Number: 1022
Title of the award or activity: ACID-FREE ELECTROPOLISHING OF SRF CAVITIES
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $404,071
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Brookhaven National Lab
Award Number or Identifying Number: 324118
Title of the award or activity: CORNELL-BROOKHAVEN ERL TEST ACCELERATOR (CBETA)
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $5,500,000
The number of person-months per year to be devoted to the project:

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Fermi National Accelerator Laboratory
Award Number or Identifying Number: 641538
Title of the award or activity: SRF R&D FOR THE ILC COST REDUCTION
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $300,000
The number of person-months per year to be devoted to the project:

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1757811
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $406,169
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: 0000232626
Title of the award or activity: **RAISING SUPERCONDUCTING CAVITY GRADIENTS**
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $1,650,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Hoffstaetter, Georg
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 0.8, 2

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Chicago Operations Office DOE
Award Number or Identifying Number: DE-SC0008431
Title of the award or activity: RAISING SUPERCONDUCTING CAVITY GRADIENTS
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,540,000
The number of person-months per year to be devoted to the project: 0.5

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: PHY-1416318
Title of the award or activity: CORNELL PROGRAM FOR STUDENT-CENTERED ACCELERATOR SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $10,597,786
The number of person-months per year to be devoted to the project: 1.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1461111
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $404,625
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Institute for Basic Science
Award Number or Identifying Number: N/A
Title of the award or activity: R&D ON THE HALF-WAVE-RESONATORS (HWR) FOR THE RAON ACCELERATOR
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $1,630,000
The number of person-months per year to be devoted to the project: 0.5

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Brookhaven National Lab
Award Number or Identifying Number: 324457
Title of the award or activity: NSLS-II 500 MHZ SUPERCONDUCTING VERTICAL TEST
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $283,350
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Ultramet
Award Number or Identifying Number: 16613
Title of the award or activity: CVD PROCESS DEVELOPMENT OF THIN-FILM TRINIOBIUM-TIN FOR SRF APPLICATIONS
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $33,817
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: DE-SC0017959
Title of the award or activity: ADVANCED ACCELERATOR TECHNOLOGY
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $170,000
The number of person-months per year to be devoted to the project:

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: PHY-1734189
Title of the award or activity: PROGRAM FOR DEVELOPMENT AND DEMONSTRATION OF PIONEERING ACCELERATOR TECHNOLOGY
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,500,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: Ultramet
Award Number or Identifying Number: 16644
Title of the award or activity: FABRICATION & TESTING OF COPPER SRF CAVITIES WITH WELL-ADHERED THICK-FILM NIOBIUM BY LOW TEMPERATURE CVD FOR HIGH GRADIENT APPLICATIONS, PHASE II
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding:$328,000
The number of person-months per year to be devoted to the project: 0.2

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☒ Funded ☐ Pending
Sponsor or Source of Funding: SLAC National Accelerator Laboratory
Award Number or Identifying Number: 179490
Title of the award or activity: LCLS-II CAVITY COOL-DOWN STUDIES
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $80,369
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Fermi National Accelerator Laboratory
Award Number or Identifying Number: 641538
Title of the award or activity: SRF R&D FOR THE ILC COST REDUCTION
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $300,000
The number of person-months per year to be devoted to the project:

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: National Science Foundation
Award Number or Identifying Number: 1757811
Title of the award or activity: REU SITE: ACCELERATOR PHYSICS AND SYNCHROTRON RADIATION SCIENCE
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $406,169
The number of person-months per year to be devoted to the project: 0.2

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number: 0000232626
Title of the award or activity: **RAISING SUPERCONDUCTING CAVITY GRADIENTS**
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $1,650,000
The number of person-months per year to be devoted to the project: 0.5

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Fermi National Accelerator Lab
Award Number or Identifying Number: N/A
Title of the award or activity: Advanced Accelerator Technology
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $170,000
The number of person-months per year to be devoted to the project: 0.0

Current and Pending Support
Investigator: Liepe, Matthias
Support: ☐ Funded ☒ Pending
Sponsor or Source of Funding: Department of Energy
Award Number or Identifying Number:
Title of the award or activity: High Intensity ERL Test at CBETA
The total cost or value of the award or activity, including direct and indirect costs. For pending proposals, provide the total amount of requested funding: $2,000,000
The number of person-months per year to be devoted to the project: 0.0

APPENDIX 3: References

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[2] E.C. Aschenauer, e. a. eRHIC Design Study: An Electron-Ion Collider at BNL. Technical report (2014)

[3] Symon, K. R., "Fixed-Field Alternating-Gradient Particle Accelerators." Physical Review, 103 (6), pages 1837–1859 (September 1956).

[4] Ohkawa, T. "FFAG Accelerator." Symposium on Nuclear Physics of the Physical Society of Japan (1953).

[5] Kolomenski, A. "Electron Ring Phasotron". Zhurnal Eksp. Teor. Fiz., 33 (298) (1957).

[6] Trbojevic, D., Courant E.D., and Garren A.A. "FFAG lattice without opposite bends." AIP Conf. Proc., 530, pages 333–338 (2000).

[7] Trbojevic, D., Courant E.D., and Blaskiewicz M.. "Design of a non-scaling fixed field alternating gradient accelerator. Phys. Rev. ST Accel.. Beams, 8, page 050101 (May 2005).

[8] Brooks Stephen, https://www.bnl.gov/rhic/news2/news.asp

[9] Machida, S., et al. "Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA," Nature Physics, 8 (3), pages 243–247 (January 2012).

[10] B.M. Dunham, e. a. Record high-average current from a high-brightness photoinjector. Applied Physics Letters, 034105 (102) (2013)

[11] C. Gulliford, e. a. Demonstration of low emittance in the Cornell energy recovery linac photoinjector prototype. Physical Review ST-AB, 73401 (16) (2013)

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APPENDIX 4: Facilities & Other Resources

The central piece of equipment is the CBETA accelerator itself, which is currently under construction and early commissioning, for example with the Fractional Arc Test occurring in February through April, 2018. The CBETA Project is funded by NYSERDA, the New York State Energy Research and Development Agency, for a total cost of $25M over a period of 42 months, beginning on October 31, 2016 and ending on April 30, 2020. The NYSERDA contract, for complete construction of a 4-pass capable ERL, specifies beam commissioning only to relatively modest Key Performance Parameters.

All three collaborating laboratories have extensive and well-known supporting facilities and resources. The NYSERDA project calls heavily on those capabilities at BNL and Cornell. This proposal calls on expert human resources at all three laboratories, but very little on their engineering facilities, since the only capital activity proposed is to build a small number of specialized beam diagnostics equipment.

APPENDIX 5: Equipment

The major piece of equipment for the proposed work is the CBETA accelerator, which is located in an experimental hall of the Cornell Laboratory for Accelerator ScienceS and Education (CLASSE). For more discussion please see Appendix 4, "Facilities and other Resources".

APPENDIX 6: Data Management Plan

We are committed to implementing a comprehensive data management plan. Our plan covers data collection, metadata, sharing, preservation, and dissemination of our results. The project may generate experimental data as well as simulated data from predictive computational models and metadata from either experimental or simulated data. Below we outline our strategy for the different data types:

Data types: Experimental data, simulation data and metadata

Experimental data is generated in the course of measurements at research facilities. Experimental data will be stored and preserved at Cornell with the research facility control system machine data. This data is regularly backed up within the control system, at no additional cost to the project. This will ensure that the data collected in the course of this project is properly archived and easily shared between the members of the team. Public access to the control system is not possible because of security concerns. Mirroring all experimental data to a public server is burdensome due to the possibly large volume of data.

Simulation data and metadata are generated as a result of simulation work and the analysis of either experimental or simulation data. Simulation data and metadata will be will be stored and preserved using the electronic archiving systems available at BNL, Cornell and JLab, at no additional cost to the project. This will ensure that the simulation data and metadata created in the course of this project are properly archived and easily shared between the members of the team. Mirroring all simulation data and metadata to a public server is burdensome due to the possibly large volume of data.

Data for published figures will be submitted as supplemental data for journals that allow it. These will include all relevant metadata.

Data disseminated to the public will not include any confidential or Personally Identifiable Information.

APPENDIX 7: Other Attachments