Project Description

1. Introduction

This program, which would span three years beginning in September 2017, will implement innovative accelerator concepts in pioneering working devices. These are: stochastic cooling in storage rings, superconducting RF photoelectron sources employing cold beam generation, very compact and efficient SRF accelerating structures, and low-emittance, high current recirculated beams. Using the expertise of the Cornell accelerator team and its unique infrastructure, we plan to address these grand challenges facing accelerator science and to expand Cornell's record of training future leaders in accelerator physicists through hands-on participation in all aspects of the proposed research.

This program is complementary to that of the Center for Bright Beams (CBB), which is an NSF Science and Technology Center established in Fall 2016 with Cornell as the lead institution. CBB seeks to develop concepts enabling brighter beams by employing the expertise of materials scientists, surface chemists, condensed matter physicists and mathematicians; it focuses on first principles understanding using an interdisciplinary approach. By contrast, the program proposed here is directed at realizing pioneering ideas in functional devices. All infrastructure and accelerator advances made within this award will become available as testbeds or application points for cutting-edge concepts developed either at CBB or elsewhere by the broader accelerator community.

1.1 Research Program Overview

The research program builds on the technical expertise and depth of Cornell's accelerator team and has the following overarching goals: 1) novel accelerator techniques and paradigms realized in hardware, 2) hands-on training of young scientists within the operational accelerator environment. Our proposed work will focus on the following areas:

- **Optical stochastic cooling** (led by Prof. David Rubin). Optical stochastic cooling promises many orders of magnitude faster cooling rates than the conventional stochastic cooling systems that operate in the microwave regime. OSC can enhance luminosity in proton and heavy ion colliders like the LHC and RHIC and reduce emittance in low energy electron rings. We propose a first demonstration OSC in the Cornell Electron Storage Ring (CESR).
- **Beam instabilities in high power linacs** (led by Prof. Georg Hoffstaetter). Many future accelerators, including eRHIC, JLEIC, LeHC and PIP-II, require high current, but beam instabilities in that regime are largely unexplored. We will deploy dedicated instrumentation in a test ERL now under construction at Cornell (CBETA) to analyze the beam distribution in phase space and quantify beam instabilities resulting from all dominant high-current effects.
- **High-efficiency, high-frequency microwave superconductivity** (led by Prof. Matthias Liepe). We propose the development of very compact high-frequency SRF cavities, which will enable completely new SRF-driven accelerators for small-scale university, industrial, national security, and medical applications, by offering robust, compact, energy efficient, and high beam power capable accelerating structures.
- **Lifetime of photocathodes and their suitability to operate in cryogenic environment** (led by Prof. Ivan Bazarov). The subject of photocathode lifetime is one of the most pressing issues in the accelerator field. The Cornell group has achieved the highest average current delivered from a photocathode with a record lifetime, and recently demonstrated the benefits of cooling the antimonide photocathodes to reduce their intrinsic emittance [48]. This program seeks to advance the field through improving the cathode lifetime as well as

operating cathodes at record low cryogenic temperatures in transmission mode for smallest laser spots and emittances – all by enhancing the unique infrastructure and techniques developed at Cornell.

- **Compact SRF gun for cold beams** (led by Prof. Ivan Bazarov and Prof. Matthias Liepe). We propose to combine our SRF, photocathode, and beam dynamics expertise to design and build a new platform – a compact SRF photoemission gun. Such a gun promises unprecedentedly low emittances for linac-based high-brightness electron accelerators (colliders, XFELs, as well as stand-alone compact electron imaging setups).

Broader impact summary statement: The work proposed here will have impact not only on accelerators in basic research but also on accelerators in industry. In particular, accelerators to which we contribute are critical tools for industry, medicine, national defense, and may offer a path to safe nuclear energy. Annual sales of industrial accelerators, for example, exceed $2B, and are growing at an estimated 10% per year [67]. Our past research has been transferred to industry (e.g. a turn-key SRF accelerator module) and has led to several SBIR's. We anticipate that the research proposed here will have similar impact on industry. This research also strengthens the education of undergraduate and graduate students in cutting-edge science, engineering and technology as urgently needed for the U.S. workforce. During summers, we will mentor students from community colleges in research in an environment that would otherwise be unavailable to them. About 1800 members of the general public tour Cornell's accelerator lab annually, and we will enhance these popular outreach tours with new virtual lab tours.

Student training: Cornell is a leader in doctoral education in accelerator science. The graduate student experience at Cornell may be unique: the students work with leaders in the field, on problems of great interest, and they work extensively and hands-on with accelerators and accelerator hardware. As a result of this training, they are in enormous demand when they graduate. Funded under this award, 7 graduate students would work at the frontier of pioneering accelerators science and technology, with strong intellectual interconnections across this program, and to the Center for Bright Beams.

1.2 Connections to and Synergies with the Center for Bright Beams

As mentioned earlier, the Center for Bright Beams is a newly funded effort that involves a large number of institutions: Cornell University, the University of Chicago, the University of California Los Angeles, the University of Florida, the University of Maryland at College Park, Brigham Young University, Morehouse College, Clark Atlanta University, and Chicago State University along with contributions from Lawrence Berkeley National Laboratory, Fermi National Accelerator Laboratory, the University of Toronto, and TRIUMF. CBB concentrates on investigating three broad synergistic themes: Beam Production, Beam Acceleration, and Beam Transport and Storage by involving non-accelerator physics experts from broad community of material science, theoretical physicists, mathematicians, chemists, and so on. CBB is devoted to the development of novel concepts, simulation tools, and materials without connection or support for any specific single accelerator. A large part of the center's goal is generating new ideas which are later to be tested or applied in a specific accelerator setting. As such, CBB has no component to develop the accelerator hardware.

In contrast to CBB, this program is specifically tailored to demonstrating novel approaches in-working devices. It seeks to realize breakthroughs in specific areas of the accelerator physics via implementing innovative yet practical hardware and techniques by employing the state-of-the-art accelerator capabilities at Cornell University. Therefore, CBB and this program enjoy synergistic roles without an overlap in the proposed work.

Previously, we have been awarded ~$10.6M over 3 years (~$3.5M/year) by the NSF Accelerator Science program for accelerator research (NSF PHY 1416318), of which this proposal is a chronological continuation. CBB support for the entire Cornell accelerator team totals approximately $0.9M/year, and is dedicated almost entirely to student support, with no equipment funds. The rest of the CBB budget supports researchers at other institutions, in different disciplines, or broader impacts activities. The funding requested in this proposal, approximately $2.9M/year on average for the next 3 years, is lower than our award previous funding cycle (~$3.5M/year), in recognition of the new support from CBB. The increase in total funding is justified because XXXXX.

1.3 The Structure of this Proposal

Sections 2 to 6 describe this research program in more detail, including its goals (in italics) and milestones (bold). The goals describe the thrust of the program, while the milestones indicate specific targets and the date by which we hope to achieve them, indicated by the quarter of the calendar year (e.g. Q1-2018). Section 7 covers results from previous grants and section 8 discusses the broader impacts of the proposed research, including an exciting outreach program.

2. Optical Stochastic Cooling

The sole Nobel prize awarded an accelerator physicist was to Simon van der Meer in 1984 for the invention of stochastic cooling at CERN, where it was used to collect and cool antiprotons. Stochastic cooling was further developed at Fermilab to cool antiprotons in the accumulator ring and then in the larger recycler. More recently, three dimensional stochastic cooling of 100GeV/nucleon gold beams has been implemented at RHIC to enhance luminosity.

Stochastic cooling is a high bandwidth feedback that measures and then corrects intra-bunch displacement of particle energy and/or position. In the ideal stochastic cooling system, the damping (cooling) rate scales with the bandwidth of the feedback system, and inversely with the number of particles in the bunch. Stochastic cooling as implemented in hadron rings operates at microwave frequencies, and the achieved damping times in antiproton rings are on the order of hours. The generalization of stochastic cooling from the traditional microwave regime to optical wavelengths, and the corresponding ~four orders of magnitude increase in bandwidth and anticipated cooling rate, was suggested nearly a quarter century ago by Mikhailichenko and Zolotorev[10]. OSC cooling times are measured in fractions of a second (rather than hours), and are comparable to radiation damping times in electron rings. OSC could be used to enhance the performance of very high energy proton colliders like LHC and an FCC, and to mitigate the effect of intra-beam scattering (IBS) emittance growth in low energy rings. And a very high frequency OSC system could be used to compensate IBS in ‘ultimate’ storage ring light sources.

We propose to develop and demonstrate optical stochastic cooling (OSC) in CESR. The OSC system will consist of pickup and kicker undulators, delay line chicane, and optical amplifier. The necessary equipment will be installed in the 18-meter-long straight section in CESR that is currently instrumented with electron cloud diagnostics. The chicane insert will be designed with zero impact on operation of the storage ring for CHESS (x-ray light source). Initially, we will develop the theory, and detailed simulations of the phenomena, then we will design the bypass beam line and insertion devices, and finally, demonstrate cooling in CESR. The work will be done by graduate students and post docs. We plan to repurpose existing damping wigglers as undulator pickup and kicker.

A number of experimental tests of optical stochastic cooling have been proposed [2][12][20][21][22]. There is a plan to implement OSC to mitigate emittance dilution due to intra-beam scattering and space charge in the conceptual design of the Laser Electron Storage Ring (LESR) Tsinghua University[24]. There is a well-developed plan for a test of OSC in the IOTA ring at Fermilab[22]. We propose here to investigate both science and technology of OSC. We plan to collaborate with Fermilab scientists in the development of simulations, lattice design, optical amplifier, and system tests. The timescale for the test of OSC at IOTA is somewhat longer than is here proposed for CESR. We have the advantage of an operating and extremely well understood machine. IOTA has yet to be commissioned. Implementation of OSC as practical cooling system in a hadron collider or synchrotron light source will demand a level of technical sophistication well beyond what is required for a simple test of the basic principle. A demonstration at CESR is a first step. We anticipate that the tests at IOTA will benefit from our experience at CESR and further advance the state of the art.

2.1 OSC Basics

We imagine the idealized OSC system as an undulator pickup, transducer-amplifier, and undulator kicker[3] The length of the bypass from pickup to kicker is about 16m.

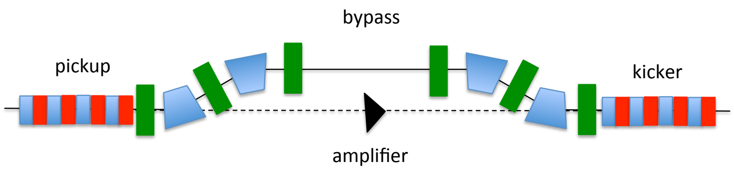

Figure 1. OSC beamline with undulator pickup, optical amplifier and kicker. The bypass delays the particle beam with respect to the electromagnetic radiation emitted in the pickup by about 2mm.

The undulator pickup emits radiation synchronized with particle passage and in some cases with amplitude proportional to transverse displacement. The transducer amplifies and delays the signal that is then coupled via kicker to correct particle energy or position or both. Let's follow the progress of electron and radiation in a bit more detail. The pickup undulator drives a transverse oscillation of the particle. The oscillating particle radiates in the forward direction at the wavelength determined by undulator period and particle energy. The electron loses energy to the radiation field. In the kicker undulator, the particle is again forced to oscillate, and the transverse electric field of the radiation emitted in the pickup undulator (and since amplified) will add or subtract to the energy of the particle depending on the relative phase. If the particle was on energy and on axis in the pickup, the phase is set so that particle is at the zero crossing in the kicker and no energy is exchanged. Transit time of high(low) energy particles through the bypass is a bit shorter(longer) and they will lose(gain) energy in the kicker. Indeed, the path length through the bypass can in general be arranged to depend on transverse displacement and angle of the particle as well as energy in the pickup, so that it is possible to damp both transverse and energy offsets.

The emittance is reduced to zero in a single pass through such an idealized system. The finite bandwidth of both pickup and kicker preclude detection and correction of the trajectories of individual particles. In a practical stochastic cooling[1] system, the distribution is subdivided into M macro-particles, each comprised of N individual particles. The macroparticle is detected by the pickup and its offset corrected at the kicker. If the distribution is completely mixed before it is again sampled and corrected, then it is damped in N passes.

It is straight-forward to estimate N, and thus the cooling time in an electron storage ring. The number of detectable macro-particles in a bunch is given by $M \sim k\sigma_z$ where σ_z is the bunch length and $k=2\pi/\lambda$ is the bandwidth of the detector. In an electron storage ring, bunch length σ_z ~10 mm and at optical wavelengths, ($\lambda_{osc} \sim 1\mu$m), then $M \sim 10^4$ and assuming 10^9 electrons/bunch, $N = 10^5$ and $\tau \sim 10^5$ turns, comparable to the radiation damping time. Noise in pickup, kicker and amplifier, nonlinearity of the bypass line, dependence of damping rate on emittance and energy spread, will decrease the achievable cooling rate. But studies suggest that optical stochastic cooling can be effective for high energy protons[5] and heavy ions[6], low energy electrons[24] and in a muon collider [7].

2.2 Research Plan

As noted above, optical wavelength of 1μm, and practical bunch charge and emittance in an electron ring, corresponds to cooling rate of 10^5 turns. We propose to configure CESR so that the radiation damping time is a bit longer than 10^5 turns, to ensure sensitivity to the effect of the OSC. This is accomplished by suitable choice of beam energy, lattice parameters, RF accelerating voltage and damping wiggler fields as discussed below.

Simulation (year 1) During the first year, grad student Will Bergen will extend our accelerator modeling code Bmad[89] to include emission and absorption of radiation in pickup and kicker undulators to enable detailed simulation of the cooling process. The simulation will be used to guide design of the ring lattice and cooling configuration for optimal experimental sensitivity to OSC.

Chicane Bypass (year 1) We describe instrumentation that with optical bandwidth, samples macroparticle position and phase (the pickup) and following amplification and appropriate delay interacts (kicker) with the same sample to reduce its betatron and energy oscillation. Undulators serve as both pickup and kicker[10]. The electromagnetic wave radiated by the macroparticle in the pickup is amplified and then coupled to that same macroparticle as it passes through the kicker as shown in Figure 1. A chicane bypass delays the particle beam to compensate the propagation time through the index ~ 2 optical crystal. The phase space coordinates of the macroparticle are encoded for correction in one of two ways. Grad student Will Bergen will explore designs for both configurations.

In the isochronous delay line method, the pickup is a gradient undulator [5]. The amplitude of the radiated electromagnetic wave is proportional to the displacement of the macroparticle from the design orbit. The delay line is isochronous so that transit time is independent of phase space coordinates of the particle in the pickup. In particular, the bypass transfer matrix elements satisfy $R_{5i}=0$ for all i. The ring lattice is designed with finite dispersion in the kicker undulator. The amplified wave couples to the macroparticle in the kicker wiggler to increase (or decrease) its energy and to reduce the betatron amplitude by shifting onto the dispersive orbit as shown in Figure 2. If Δx is the offset in the pickup, then the energy added by the kicker is $\Delta E/E = \Delta x/\eta$, where η is the dispersion in the kicker. Here, the cooling mechanism is a reverse of the process of quantum excitation that generates emittance from stochastic noise. The information about the packet is encoded in the amplitude and phase of the electromagnetic wave generated in the gradient undulator pickup. The effectiveness of this scheme depends on the purity of the isochronicity of the bypass condition of the bypass to a fraction of the optical wavelength [9].

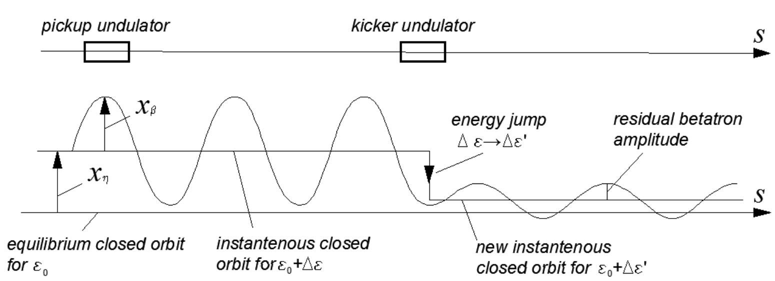

Figure 2. An energy change effects cooling of both transverse emittance and energy spread.

In the transit time method, dipole undulators serve as both pickup and kicker. The amplitude of the radiation emitted in the pickup wiggler is independent of macroparticle offset and energy. In this case, it is the transit time of the bypass that depends on horizontal offset, and angle, and energy of the macroparticle. In terms of the transport matrix of the bypass, $R_{5i}x_i = \delta l$, where $x_1=x$, $x_2=p_x/p$, … $x_6=\Delta E/E$. The delay line is tuned so that the radiation of the particle on the appropriate energy dependent closed orbit in the pickup is $\pi/2$ out of phase with its own radiation in the kicker and there is no energy gain or loss. As in the case of the isochronous delay line, the kick corrects energy error and increments particle energy to place it onto the dispersive closed orbit and thereby reduce betatron amplitude.

Undulators (year 1) In year 1, postdoc Steve Proprocki and graduate student Will Bergen will work together to optimize the undulator parameters. In an OSC system an undulator serves as pickup. The parameters of the undulator, and the beam energy determine the operating wavelength. As noted above, cooling rate scales inversely with wavelength. However, acceptance of the bypass, and the initial emittance and energy spread, are bound from below by the wavelength and as we will see, a longer wavelength system is more forgiving. Finally, the wavelength is necessarily compatible with available of optics and amplifiers. We consider $\lambda=1\mu$. The wavelength of the first harmonic of an undulator with period λ_u is $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{1}{2}K^2+\gamma^2\theta^2\right)$ where the $K=\frac{eB_{max}\lambda_u}{2\pi mc}$ and $\gamma = E/mc^2$. Power is peaked at the first harmonic in the forward direction for K~1. At beam energy of 500 MeV, $\lambda=1\mu$ corresponds to undulator period of 0.5m, and K= 2.4. Evidently, wavelength of the first harmonics shrinks rapidly with beam energy, thus favoring the very low energy extreme of the CESR operating range.

CESR Lattice (year 1) The OSC bypass will be installed in the 18 meter straight in the 'north' area of the storage ring. An example of bypass chicane layout and optics, with parameters suitable for an experimental test of the transit time method is shown in Figure 3. The energy kick is $\delta p/p = -\xi\sin(k\Delta s)$ where $\Delta s = \Sigma_i R_{5i} x_i$. Because of the nonlinear dependence of kick on Δs, there is a limited range of emittance and energy spread over which there is effective cooling. If the spread of betatron amplitudes of the particles in the packet defined by the bandwidth wavelength, is such that $R_{51}\sigma_x + R_{52}\sigma_x' + R_{56}\sigma_E > \lambda$, or $R_{56}\,\sigma_E > \lambda$ then a significant fraction of the particles are outside the cooling region. The maximum emittance and energy spread within the cooling region for bandwidth wavenumber k are given by [23,9] $\varepsilon_{max} = \frac{\mu_0^2}{k^2(\beta R_{51}^2 - 2\alpha\, R_{51}\, R_{52} + (1+\alpha^2)R_{52}^2)}$, $\left(\frac{\Delta p}{p}\right)_{max} = \frac{\mu_0}{k|\,\tilde{R}_{56}\,|}$ where μ=2.405 is the first root of the bessel function $J_0(x)$ and k =optical wave number. Defining $n_x = \sqrt{\frac{\varepsilon}{\varepsilon_{max}}}$ and $n_s = \frac{\left(\frac{\Delta p}{p}\right)_{max}}{\sigma_s}$, we see that the tolerable bandwidth scales inversely with the equilibrium emittance and energy spread.

A number of considerations inform the choice of ring lattice parameters suitable for a cooling demonstration. The CESR lattice and control system offers the requisite flexibility. Radiation damping time can be tuned independently of beam energy using the installed superconducting damping wigglers. The 100 ring quadrupoles (and sextupoles) are all independently powered allowing a wide range of lattice parameters. For the low emittance rings program (CesrTA),

Table 1. Test lattice and cooling parameters

Beam Energy [GeV]	0.5	$(\Delta p/p)_{max}$ X 10^{-4}	3.7 (n_s= 1.85)
ε [nm-rad] (radiation)	0.5	Wiggler period [m]	0.43
$(\Delta p/p)$ X 10^{-4}	2.01	Wiggler peak field [T]	0.07
Radiation damping times [s]	2.9/1.4	OSC Undulator parameter [K]	2.8
B_{max} (Damping Wigglers) [T]	0.5	Radiation wavelength λ [nm]	1130
Chicane delay [mm]	2.0	Particles/bunch	2 X 10^9
$R_{51}/R_{52}/R_{56}$ X 10^{-4}	3.7/-7.2/24.4	Bunch length [mm]	10
ε_{max} [nm-rad]	16 (n_x = 32)	OSC cooling time τ_x/τ_z [sec]	3.5/0.5

CESR operated from 1.8GeV to 5.3GeV. The OSC test will be at somewhat lower energy, and we give an example 0.5GeV lattice, shown in Figure 3(right) with the corresponding bypass layout in Figure 3(left). The relevant lattice and bypass parameters are shown in Table 1. The emittance can be increased by as much as an order of magnitude, as required by the experimental program, by simply introducing dispersion into the wiggler straights. The relatively long radiation damping time (~2 seconds) is convenient as it enhances sensitivity to the effect of the stochastic cooling. In year 1, grad student Will Bergan will explore lattice configurations and refine and optimize the design parameters.

Fabrication of Bypass Components (year 2) We anticipate that spare CESR 1.6m damping wigglers can be used for OSC pickup and kicker undulators with minor modification. Ring quadrupoles will become available in the second year with the replacement of the existing south arc with double bend achromats for the CHESS upgrade. In summary, we plan to build the bypass with materials already in house, including power supplies and vacuum system components. The bypass will be designed by the postdoc Poprocki for compatibility with operation at high energy (5.3-6 GeV) with CHESS and CHESS U.

Design of Optics and amplifier (year 2) Electromagnetic radiation generated in the pickup undulator is focused onto a crystal that amplifies the signal. The output is focused into the kicker undulator where it couples to the same particles that were the source of the radiation. The crystal is pumped with a laser. Titanium sapphire is a good candidate crystal for our experiment due to availability of materials and relatively simple engineering as amplifier. The lifetime of the excited state τ_L ~ 3.5 μs, and 1mm absorption length are a good match to our requirements. The power required to pump the crystal is about 7W. Amplification of a factor of nearly 400 can be achieved in two stages of total length 2mm. A single 2mm long crystal could be be pumped transversely. A second graduate student, yet to be identified, will work with Mikhailchenko to design the optical system.

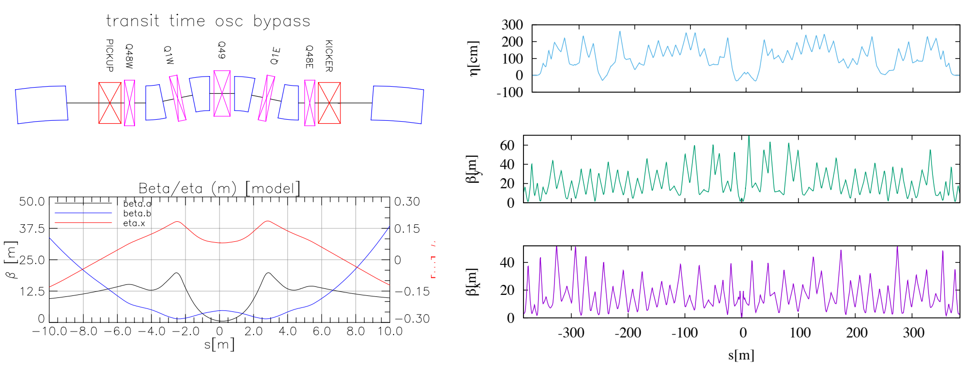

Figure 3. CESR north area transit time bypass. Quadrupoles Q48 and Q49 are part of the ring lattice. The bypass requires addition of two pair of gradient dipole magnets and a pair of quadrupoles. Total delay lenth is 2.7mm with displacement of 9.2cm. Ring lattice for test of optical stochastic cooling

Implement and Characterize CESR lattice (years 1-2) In the first year of the award we will design, and then implement and commission the 0.5GeV lattice in CESR during six days of dedicated accelerator studies. The excercise will include measuring and correcting betatron phase and coupling, measuring emittance, bunch length, intra-beam scattering, threshold for single bunch instability, and radiation damping times. We will establish minimum bunch charge required for measuring orbit, horizontal beam size with interferometer and vertical size with x-ray detector. We will explore dependence of horizontal emittance on dispersion in the damping wiggler straights. Graduate student and postdoc (with the help of accelerator physics staff) will perform the study.

Install and commission bypass (years 2-3) The OSC bypass will be installed in the storage ring near the end of the second year. After demonstrating the integrity of the bypass for CHESS operation at high energy, we will measure the properties of the bypass at 0.5 GeV, including amplitude and energy dependence of path length (R_{51}, R_{52}, and R_{56}) and amplitude dependence of all R_{5i}.

Characterize magnetic and optical properties of OSC insert (year 3) During a week of dedicated machine time, the graduate students will measure the properties of the bypass at 0.5 GeV, including amplitude and energy dependence of path length (R_{51}, R_{52}, and R_{56}) and amplitude dependence of all R_{5i}. They will characterize optical as well as magnetic properties of the bypass by measuring interference of radiation from pickup and undulator. We will demonstrate constructive and destructive interference as the length of the bypass is tuned through an optical wavelength.

Assemble test and install laser system and amplifier (years 3-4) Optical components will be assembled and tested by postdoc and students with guidance from Mikhailichenko to demonstrate optical path and measure gain and output power to establish cooling rates. The optical components will be installed and tested in situ near the end of year 3.

Measure dependence of damping time on amplifier gain and phase (years 3-4) Near the end of year 3, the 0.5GeV lattice suitable for tests of optical stochastic cooling will be established for routine operation, in the same tradition that the low emittance, low energy, conditions were so successfully exploited for CesrTA experimental program. The components of the stochastic cooling system will have been installed and tested, including chicane bypass, pickup and kicker undulators, and optical amplifier. Cooling experiments will be conducted by graduate students with assistance from laboratory accelerator scientist staff.

Goal: Complete simulation of beam dynamics and electromagnetic radiation in ring and OSC bypass chicane insert.

Goal: Design of bypass and ring lattice compatible with high energy operator for x-ray program

Goal: Design of optics and optical amplifier

Milestone Q2-2018: Implement low energy OSC lattice in CESR and test in machine studies

Milestone Q2-2019: OSC bypass components ready for installation in CESR.

Milestone Q2-2020: Install, commission and characterize OSC bypass with CESR machine studies

Milestone Q4-2020: Assemble test and install optics and optical amplifier

Milestone Q4/5-2020: Demonstrate cooling

2.3 CESR Accelerator Complex

The CESR accelerator complex is well suited for this research program. It has operated from as low as 1.8 to over 5.3 GeV as required. Twelve superconducting damping wigglers with peak field of 2.1 T are available to transform CESR to a unique wiggler dominated configuration. The maintenance and operation of this finely tuned apparatus, and the flexibility with which it can be transformed from dedicated x-ray source to various experimental configurations, depends on the expertise of electrical, RF and software engineers, specialists in accelerator hardware and operation, digital electronics, vacuum science, cryogenics, with technical support and machine operators.

3. Energy-Recovery Linac studies at Cornell's CBETA

The here proposed work utilizes the world's first multi-turn SRF Energy-Recovery Linac (ERL), which is currently under construction at Cornell University for fundamental beam-dynamic research pertinent to ERLs and to other high-current and high-brightness accelerators. It is referred to as CBETA [80], the Cornell-BNL ERL Test Accelerator, and is being constructed in collaboration with BNL using funds provided by New York State (NYSERDA office). Because of the construction funding from other sources, the here proposed accelerator-physics studies are very cost efficient and highly leveraged.

ERL technology is increasingly widespread [37]. Currently, ERLs are under development at Cornell University, the Helmholtz Zentrum Berlin (HZB), Orsay in France, KEK in Japan, and TJNAF. Large-scale ERLs are being designed for high-energy physics, as in the LeHC, for Nuclear physics, as in eRHIC [82], for x-ray light sources, and for bunched-beam electron cooling, as in eRHIC and the MEIC. The here proposed research at Cornell's CBETA will benefit all these projects and will also help high-current linear accelerators to understand their sources of particle loss and the phase-pace dynamics when their intense beam interacts with its environment. A prime example is particle loss and the beam dynamics in PIP-II.

The CBETA ERL uses sophisticated components that were developed, constructed, and commissioned at Cornell University under NSF funding. These components include the photo-emitter DC gun with the world's largest current, the SRF injector linac for minimal emittances [83,84], a 10m long SRF linac for high-current continuous wave (CW) beams, an ERL merger and a phase-space diagnostics section with a high-power beam stop. CBETA will prototype components and develop principles for eRHIC, and will be ideal for accelerator studies benefiting other ERLs as well as of other high-current accelerators whose beam-loss mechanisms need to be understood.

Besides being an ideal setup for accelerator-physics experiments, it will produce beam-parameters relevant for nuclear physics experiments that utilize medium-energy, high-current beams [85] and for a compact hard-x-ray source based on Compton back scattering [86].

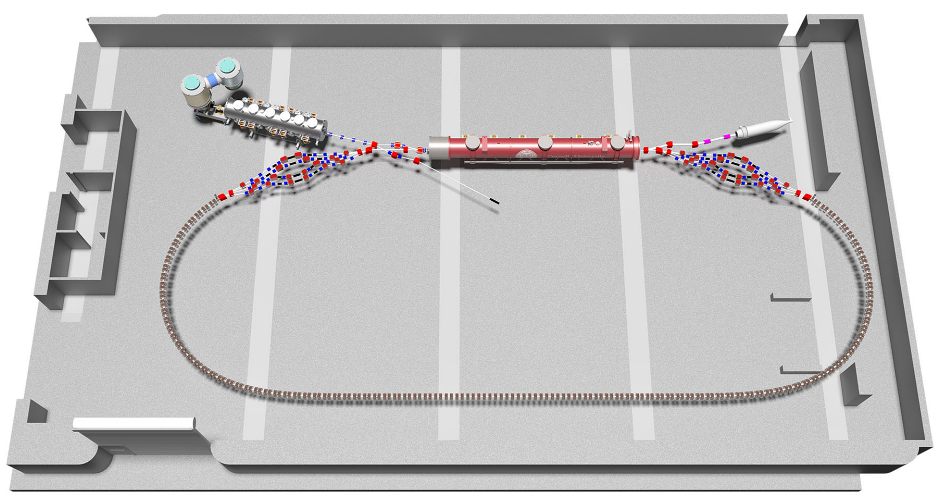

Figure 4: CBETA installation in Cornell's hall L0E. The DC gun (top left) sends electrons through the injection linac into the main ERL cryomodule (red) or the diagnostics line to it's right. After the ERL cryomodule, the beam goes into the return loop for energy recovery or into the beam stop (top right).

CBETA construction will be completed in July 2019 and commissioning will continue until May 2020. During the first two years of this award, from October 2017 to October 2019, the studies outlined here focus on computation, on experiment simulation, and on the construction of dedicated detectors and data acquisition, which will occur during beam times in August 2017 and

April 2018. This will be carried out by graduate students William Lou (focusing on BBU and micro-bunching instabilities) and Nilanjan Banerjee (focusing on particle loss), postdoc Colwyn Guilliford (focusing on impedances and space charge), and Michael Ehrlichman (focusing on post-mortem analysis). Graduate Steven Full has prepared studies on ion-accumulation. He will graduate in May 2017 and a new graduate student will continue ion studies for CBETA. During the last year, this new student, William Lou, and Nilanjan Banerjee will perform the experimental studies on the accelerator under guidance of Colwyn Guilliford, who has gained much operational experience with Cornell's ERL injector already.

Beam-dynamics simulations for accelerator-physics experiments in CBETA

High current accelerators like ERLs are limited by the beam's interaction with itself and its environment, characterized by impedances. These influence the phase-space dynamics of the charge distribution and drive instabilities. Both cause particle loss and change in the beam-size, and both will be studied. High currents limit the diagnostics that can be used and we focus on fast wire scanners [87] for beam-size studies and photo-multipliers for particle-loss analysis. We will equip the particle-loss system, the BPMs and the SRF system with a post-mortem data-analysis system that analyzes the last several 1000 data points before beam abort. To analyze the impedance due to ion-accumulation and its remedies, two ion-clearing electrodes [88] will be installed. The BPM and particle-loss system are part of the construction project and are not included in the budget of this proposal.

Specific activities that will be carried out under this award are:

- Beam-Breakup simulations, predictions of threshold currents and optics remedy to increase thresholds. Analysis of frequency in the post-mortem particle loss signal indicative of the BBU instability. This will be part of William Lou's PhD thesis.
- Particle-loss simulations due to Rest-Gas Scattering, Touschek Scattering, and dark current. Simulation of the loss-mechanisms' impact on characteristics of the particle-loss signals.
- Coherent-Synchrotron Radiation simulations, including micro-bunching; simulation of increases in beam size and in particle loss rates.
- Impedance budget analysis and 6-D phase space simulations with realistic impedances; determination of their impact on the energy spread after deceleration and beam-size increase before the beam-stop.
- Ion accumulation, defocusing by ion columns, and ion instabilities. Determination of the beam size increase due to ion accumulation and of ion-oscillation signals in the particle-loss rate. This will be part of Steven Full's PhD thesis.
- Space charge simulations about differences between the beam in CBETA's diagnostic line and the beam in the accelerator itself.
- The DC gun and SRF injector linac can produce extremely large brightness. An emittance growth analysis along CBETA will show whether this brightness can be preserved. The latter two topics will be attended to by Post Doc Colwyn Gulliford.

Development of beam diagnostics for high-current beams and post-mortem particle loss analysis

CBETA will be equipped with a large number of view screens for first turn steering of low-current beam, with beam position monitors (BPMs) that can resolve every turn of the ERL's accelerating and decelerating beams. As required for machine protection, particle-loss monitors are mounted around the accelerator. These tools are essential for commissioning the accelerator and are part of the construction budget.

Additional diagnostics are needed to study the beam dynamics that is the topic of this proposal.

For high-current phase-space analysis we will rely on 5 wire scanners installed at critical locations. The scanners are fully designed and one prototype has been tested already. Two ion-clearing electrodes are also part of the here-proposed budget, which have been fully designed already. For time-resolved particle-loss analysis, we will rely on a post mortem analysis of the particle-loss measurements. These will be provided by two PicoDigitizers (125-Series from Nutaq), which provide 125Mega-samples per second. PhD student Nilanjan Banerjee will establish and use the post-mortem system. These diagnostic devices are all not needed for the Key Performance Parameters (KPPs) of CBETA, which does not rely on low emittances and has too low current (1mA) to suffer from ion accumulation. These devices are therefor not included in the construction budget of CBETA. Their procurement is therefore part of this proposal.

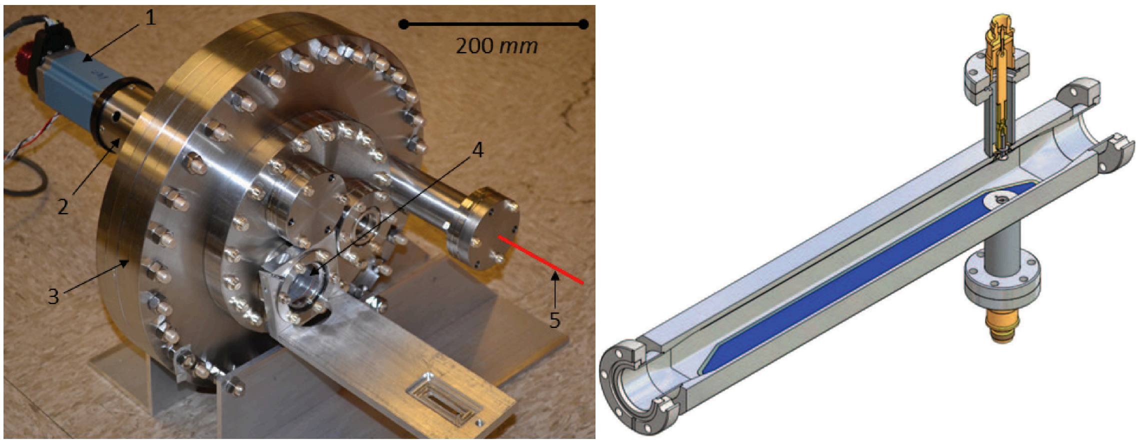

Figure 5: Compact fast (20m/s) wire scanner (left) and low-impedance ion clearing electrode to be installed in CBETA.

Goal: Simulate beam-dynamics in CBETA to design experiments about phase-space evolution, instabilities, and particle-loss mechanisms when an ERL's beam interacts with its environment.

Goal: Develop and construct instrumentation to perform the simulated beam-dynamics experiments: wire scanners and ions-clearing electrodes.

Goal: Develop buffered data acquisition so that post-mortem analysis after beam-aborts is available for the particle-loss detectors.

Milestone Q1-2018: Finish simulation of Beam-breakup and its manipulation by optics changes. Finish simulation of CSR as a function of bunch charges, determining measureable changes in beam size.

Milestone Q3-2018: Finish particle-loss simulations, correlating particle loss characteristics with loss mechanisms. Finish beam dynamics simulations with vacuum chamber impedances.

Milestone Q1-2019: Finish phase space dynamics with ions as a function of beam current and determine measurable characteristics, including beam sizes and particle loss locations. Finish simulations of space charge dynamics, comparing the diagnostics line and the accelerator line, determining measurable differences in beam size.

Milestone Q3-2019: Construct and install 5 wire-scanner setups at critical diagnostic locations.

Milestone Q6-2019: Construct and install the servers for post-mortem analysis of the particle-loss mechanism and particle-loss locations.

Milestone Q3-2020: Measure characteristics in the time-resolved particle loss data for the BBU instability, for different particle loss mechanisms, e.g. Touscheck scattering, rest-gas scattering, dark current, and ion accumulation. Measure characteristic beam-size changes with the wire scanners for space charge, CSR, and ion accumulation, and beam-pipe impedances.

4. High-Frequency, High-Efficiency, Compact SRF Cavities

Superconducting RF (SRF) cavities are the gold-standard for acceleration of charged particle beams [68], but complexity, size, and cost of the current SRF technology have limited SRF cavity application to primarily large-scale scientific accelerators. For the work proposed here, we point out that the transverse size of an SRF cavity (and thereby the transverse size of a SRF cryomodule) is directly proportional to the inverse of the operating RF frequency. Therefore, high-frequency (multi-GHz) SRF cavities could in principle allow for very compact SRF accelerators, but only if the RF surface resistance R_s can be kept low enough at high frequency (i.e. the cavity quality factor Q_0 high enough; $Q_0 \propto 1/R_s$) to maintain feasible cryogenic cooling loads and to prevent maximum field limitation from global thermal instability. Unfortunately, the BCS surface resistance increases rapidly (quadratically) with frequency. This is the key reason why standard niobium SRF cavities *in the past* typically have been limited to frequencies below 1.5 GHz, even in low beam current operation [68] (a notable exception are 3.9 GHz 3rd-harmonic cavities, though these were not fully optimized for highest efficiency).

This frequency limit now needs to be reevaluated. Several important recent developments have resulted in drastic reductions of the temperature-dependent part of the RF surface resistance (the surface resistance R_s can be separated into a sum of the temperature-dependent “BCS resistance” R_{BCS} and the temperature-independent “residual resistance” R_{res}: $R_s = R_{BCS} + R_{res}$). A positive Q-slope phenomenon (“anti-Q-slope”) was discovered in 2013 by Grassellino et al. at Fermilab in niobium doped with nitrogen [69] and by Dhakal et al. at Jefferson Laboratory [70], in which the BCS surface resistance decreases with increasing applied surface field strength. Significant progress is now emerging in understanding the underlying science of the nitrogen-doping benefit [71] - [74]. Very recently, Cornell has shown that niobium doped at low temperatures (~160C) with carbon and oxygen impurities shows low BCS surface resistance very similar to that of N-doped Nb, thereby greatly increasing the parameter space available for optimization of high Q_0 cavity treatment protocols. Continued fundamental research on impurity doping using small material samples will be an important focus of the STC Center for Bright Beams (CBB). Thin-film Nb_3Sn, with a critical temperature of almost twice that of niobium (~18K instead of 9.2K), offers the potential for very low BCS surface resistances at typical SRF cavity operating temperatures (1.8K to 4.5K). Cornell’s Nb_3Sn initiative has led to 1.3 GHz Nb_3Sn cavities (coated via tin vapor diffusion into niobium) with world-record low BCS surface resistances at typical CW accelerating fields (~16 MV/m) [76][77].

Figure 6 shows the drastic impact these new high Q_0 niobium doping treatments and the emerging alternative material Nb_3Sn have on the question of optimal RF operating frequency. Frequencies well above 1.5 GHz now become not only feasible, but optimal for maximizing cryogenic efficiency, allowing for a new generation of high-frequency, very compact SRF cavities. Developing, prototyping, and studying such high-frequency SRF cavities is the ultimate goal of the SRF R&D program we propose here.

We emphasize that the proposed SRF work does not overlap with the STC Center for Bright Beams, which does not provide any funds for applying the new high Q_0 treatments

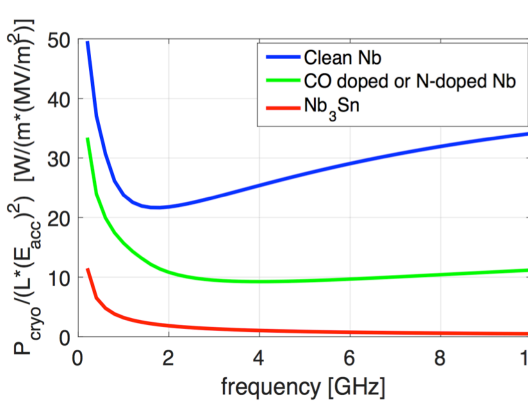

Figure 6. ***Predicted*** normalized (per active length) AC power required to cool differently prepared SRF cavities at optimal temperature [1.6K to 4.5K] as function of RF frequency (for (R/Q)/cell=115 Ω and 2 nΩ residual surface resistance). Shown are three cases: (1) clean niobium, (2) doped niobium, and (3) Cornell Nb_3Sn films.

to full SRF cavities, and for studying their high-frequency performance. The SRF work proposed here however has strong synergies with the proposed compact SRF gun program. Once fully developed, the high frequency SRF cavities will enable completely new SRF-based accelerators for small-scale university, industrial, national security, and medical applications by offering robust, compact, efficient, and high beam power capable accelerating structures.

4.1 Advanced High Frequency SRF Cavity Design and Prototyping

To successfully explore the high frequency regime, we will develop and prototype high frequency SRF cavities with operating frequencies in the 2 to >6 GHz range. These will then be used to systematically study high-frequency SRF performance after various high-Q_0 preparations, including studying field-dependence of the surface resistance (BCS and residual surface resistance), global thermal effect, and maximum achievable fields.

The compact SRF cavities will require using smaller beam-pipe apertures, potentially limiting maximum beam currents due to Higher-Order-Mode (HOM) effects below desirable values. Fortunately, the compact size at high frequency, combined with high cryogenic efficiency, will allow for employing novel SRF cavity designs, aiming at maintaining multi-mA CW beam current handling capabilities, even at high RF operating frequencies. Our new graduate student Thomas Oseroff will therefore develop and optimize high-frequency single-cell and multi-cell cavity designs, e.g. based on “HOM-free” elliptical [78] and photonic bandgap concepts [75] (see Figure 7), using advanced multi-variable RF design methods we have developed [79]. Prototypes of the most promising designs will be fabricated, spanning operating frequencies in the 2 to >6 GHz range.

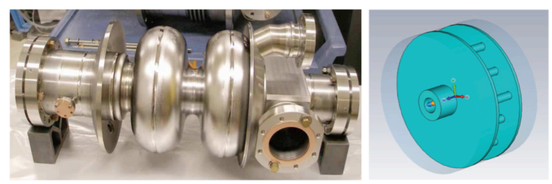

Figure 7. Left: Cornell ERL injector “HOM-free” SRF 1.3 GHz cavity [78]. Right: Photonic bandgap structure computer model [75].

Goal**:** Develop high-frequency SRF cavity design capable of accelerating CW beam currents >5 mA at an operating RF frequency >4 GHz.

Milestone Q4-2018: Complete fabrication of three optimized prototype high-frequency SRF cavities with RF frequencies in the 2 to >6 GHz range.

4.2 Advanced High Frequency SRF Cavity Performance Studies

Following fabrication, the RF surfaces of the prototype high-frequency cavities will be prepared using the new high-Q_0 treatments discussed above (impurity doping using N, C, and O, as well as thin-film Nb_3Sn coating). The systematic study conducted by one SRF graduate student on the high-frequency SRF performance of these compact cavities will focus on several critical questions:

- How does the BCS surface dependence and its surface field dependence (e.g. the anti-Q-slope) scale with frequency in the multi-GHz range?
- What are the dominant sources contributing to the residual surface resistance in the multi-GHz range? How do these scale with RF frequency ω? RF losses from trapped magnetic flux are predicted to scale as ω^α, with α=0.5 – 2, so can become significant at high frequencies. How do magnetic shielding and cool-down procedures need to be modified/improved for the compact, high-frequency cavities to achieve highest efficiency?
- Which effects limit the maximum achievable fields high-frequency cavities? Are the achievable surface resistances low enough to prevent global thermal instability even at highest RF frequencies (~6GHz)?

- How do practical issues like potential field emission effect the achievable performance of the prototype high-frequency cavities? How can the High-Pressure-Rinsing (HPR) system used to clean SRF cavities be adopted for the small transverse size of the high-frequency cavities?

Goal: Determine dominant contributions to the RF surface resistance and their frequency and surface field dependence for operating RF frequencies in the 2 to >6 GHz range.

Goal**:** Demonstrate efficient operation of the compact cavities at typical operating fields (~16 MV/m) for operating RF frequencies >4 GHz.

Milestone Q4-2019: Perform 15 cryogenic RF performance test of the high-frequency SRF cavities.

Milestone Q3-2020: Complete technical development of a compact, high-frequency cavity, ready for application in small-scale accelerators.

5. Beam Research with Photocathodes

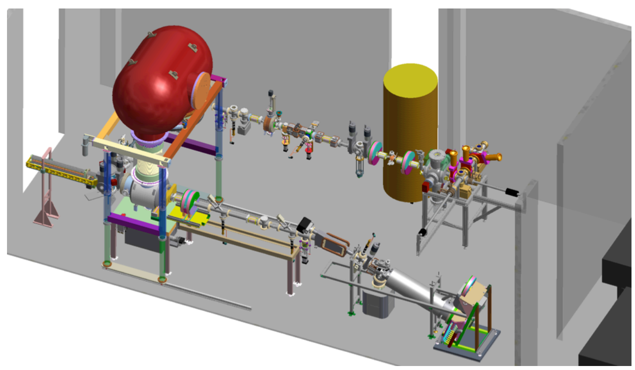

Figure 8. Two guns with respective beamlines as they are being set up in the new Cornell high brightness source development lab. The 400 kV gun is seen in the foreground, whereas the 200 kV gun is in the background with their respective beamlines facing the opposite way.

As a part of our high brightness development effort, the Cornell team has built up unique capabilities in photoemission sources. We have developed two low emittance HV DC guns equipped with a loadlock photocathode system: a 400 kV high voltage DC gun previously used in the ERL photoinjector, and a more compact photoemission 200 kV DC gun, capable of cooling down the photocathode holder to about 30-40 K, which is presently in the commissioning stage. By the summer of 2017, each gun will be moved to a new home in Newman Lab on the Cornell campus and equipped with its own beamline with diverse beam instrumentation mostly using previously built beamline components. The new home for the Laboratory of High Brightness Sources will form the backbone for numerous research activities, including those listed in this proposal. In particular, the “small” gun is designed to push beam brightness for small bunches (0.1 pC/bunch with 100 fs duration) as well as to serve as a testbed for novel photocathodes developed under other proposals. The “big” gun, on the other hand, is well suited for high current operation and lifetime studies of photocathodes. We note that this important research devoted to the lifetime studies is not presently a part of any other Cornell proposal. We envision to remain at the forefront of bright beam research addressing two key areas enabled by these guns (refer to Figure 8).

5.1 Cathode lifetime research

Cornell has previously demonstrated important advances in improving the photocathode lifetime and presently holds the world record for the best achievable lifetime [25]. Yet, there still exists need to understand the exact mechanisms which limit the performance of photocathode lifetime. Even though the needs of many projects requiring non-polarized beams can already be addressed using technology we have developed at Cornell (NaKSb), the lifetime remains a pressing issue for others, in particular those requiring beam polarization [2]. Also, despite various studies [27][28], the interplay of various phenomena limiting the lifetime remains poorly understood.

To better understand the physics of how back-streaming ions damage the photocathode, we plan to retrofit the “big” gun with a biased anode, which will allow us to study lifetime degrading phenomena as a function of the blocking voltage that shuts off ions backstreaming from after the gun [29]. A collaborator (John Smedley of BNL), will perform postmortem analysis of degraded photocathodes that we will provide using a suite of X-ray capabilities that he has developed at CHESS to determine the exact nature of the damage caused by ion backbombardment. Other important lifetime experiments will include studies of its dependence upon the substrate material and different excitation laser wavelengths. These new data are essential for multiphysics modeling, which can quantitatively explain the lifetime performance of various cathode materials.

Since operating HV DC gun at a high average current always causes the ion creation from the residual gas, we plan to pin down the rate of ion creation using clearing electrode measurements [30]. An inexpensive flying wire will additionally provide us with useful information about beam cross-section and to allow a cross-check between the ion effect as expected from full or partial beam neutralization by the ions [31]. A graduate student will carry out all theoretical and experimental aspects of this project.

Goal**:** Understand the role of ions for the cathode lifetime.

Goal**:** Obtain a qualitative agreement between the expected and measured lifetime via multiphysics modeling.

Milestone Q2-2018: Retrofit the 400 kV gun with a biased anode after.

Milestone Q2-2020: Perform lifetime studies at various parameters, such as the laser wavelengths and substrate material, including postmortem analysis.

Milestone Q3-2010: Perform ion creation rate measurements and measure the beam width as a function of current using a fast flying wire.

5.2 Ultracold beam production

As new photocathode materials become available, the need to introduce them and integrate with an actual low emittance photoemission gun becomes more critical. A number of critical phenomena such as disorder or laser induced heating [32][33], as well as the more familiar beam optics aberrations and space charge, can all dilute the beam phase space density potentially negating all photocathode improvements.

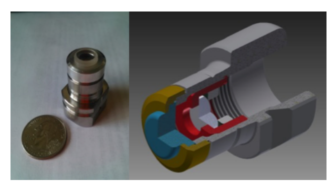

Figure 9. A cross-section of a compact puck that allows a tight laser focus using back-illumination for the transmission mode photocathode.

Recently we have developed a new transmission mode photocathodes [34], which we plan to combine with low temperature operation in order to further reduce the intrinsic emittance at the cathode (Figure 9). Our new proposal includes testing a specially engineered photocathode puck, which allows tight focus (~10-micron diameter) of the laser using back illumination and should enable us to demonstrate record small emittances (potentially well below 1 nm-rad). Measuring such emittances will require new diagnostics capabilities, which we plan to address by introducing new high resolution beam imaging similar to [35] to the small gun, which will give us an ability to resolve beam waist down to few micron sizes.

Additionally, our beamline is equipped with an RF bunch compressor and deflecting cavities, which, combined with the precision slits will allow us to perform sub-100fs slice emittance measurements (such a method was demonstrated by us previously [36]). This capability will prove essential in understanding new phenomena such as laser heating of electrons [33], an effect that takes place very quickly (few 10's of fs), but that can later be magnified to ~1ps scale by the space charge repulsion (or compressed further back via the bunch compressor). We plan to study new emittance degrading phenomena that may appear due to the new physics such as laser and disorder induced heating in/near the photocathode. This work will be spearheaded by a new graduate student whom we expect to take on board in summer 2017.

Goal**:** Achieve record low emittances using transmission mode cathodes with laser back illumination.

Goal**:** Understand and measure effects due to new physics that dilute the phase space density using time-resolved emittance measurements.

Milestone Q3-2018: Improve beam instrumentation to resolve sub nm-rad beam emittances.

Milestone Q3-2020: Combine phase space diagnostics with the RF deflector to achieve emittance slice measurement capability (2nd year) with a sub 100-fs resolution and perform beam measurements with it (3rd year).

6. Compact SRF Gun for Cold Beams

The future Electron Sources Workshop [37], which met at SLAC in September of 2016, has recently identified Superconducting RF guns as a primary vehicle to achieving next generation bright beams. Despite their significant promise, the SRF guns have yet to live up to their widely-held reputation of the next frontier photoemission guns despite some significant effort in this area. For example, pulsed electron sources have been largely dominated by the normal conducting RF guns given their simplicity and excellent performance, whereas CW operation at 100 pC/bunch level was recently established be comparable to that of SRF guns for photoinjectors based on HV DC gun technology in both simulations [38] and beam measurements [39][40][41]. Beam demonstrations from SRF guns have therefore been modest up till now, with a sole exception of a recent result from a quarter-wave SRF gun at BNL [42], which, though looking very promising, is yet to be fully understood and characterized in terms of its beam brightness performance. The BNL gun was developed for ~nC scale bunches suitable for applications such as nuclear physics, rather than for low bunch charge applications such as ultrafast electron diffraction (UED) or microscopy (UEM).

Before going forward, it is therefore instructive to understand some of the reasons behind the lack of progress in the SRF guns as well as the causes for significant emittance improvement from DC guns by more than a factor of 5 over the last decade. These reasons also underlie the unique position of the Cornell accelerator team to realize the full potential of an SRF-based photoemission source. First, beam dynamics simulations coupled with the SRF gun geometry optimization are needed, yet have been lacking with the sole exception of [38], for which the SRF gun was optimized for a specific beamline arrangement and a bunch charge range (around 100 pC). By contrast, the modest gradient available in DC guns (around ~5 MV/m at the cathode), was put to its full potential via full featured beamline optimizations [43], and was able to realize its full potential, as demonstrated at Cornell [36]. This history suggests that the entire package of gun-cathode-laser must be treated as a single whole in order to realize the potential of high brightness beams ultimately available with the SRF gun technology. Another recent advancement is the use of special photocathodes in DC guns, which are designed to have low record intrinsic emittances together with fast sub-picosecond response time [44].

Brightness limit investigations have shown that the maximum available brightness in the best scenario is determined by the cathode field E_{cath} and photocathode's intrinsic mean transverse energy (MTE) in the absence of space charge: $B \propto E_{\mathrm{cath}}^{n}/\mathrm{MTE}$, where the power $n \geq 1$ and depends on such specifics as the initial laser pulse duration and subsequent bunch compression scheme following the gun [45][46]. Cornell University has done pioneering research in both of these areas, increasing available accelerating field and pushing intrinsic photocathode emittance

(MTE) to its fundamental limits. More specifically, Cornell holds a world record for E_{acc} in a single cell SRF cavity [47]. Recently, we have pioneered the field of cryogenically cooled antimonide photocathodes, with the lowest MTE measured so far at 18 meV from a cryo-cooled photocathode (roughly corresponding ~200K temperature of electrons with the actual substrate temperature of ~100K) [48].

Here we propose the development and prototyping a novel compact SRF gun, which would have the following features: 1) fully optimized gun geometry based on powerful genetic algorithm optimizations of full beam dynamics, 2) cryogenically cooled photocathode, capable of LHe temperatures, and 3) allow introduction via a field-emission-free insertion mechanism of the most promising photocathodes capable of operating inside the SRF gun environment. Our goal is to reach 40MV/m for usable E_{cath} field, which, combined with the potential for the lowest MTE of 2-3 meV for cryogenically cooled photocathodes can potentially improve the beam brightness by x100 compared to the best available electron sources. The majority of the SRF gun R&D work will be done by two new graduate students in close collaboration: one with the SRF group and one within the photocathode/injector group. A postdoc will help coordinate advanced simulations, including multiobjective optimizations of the SRF gun geometry and the beam dynamics.

We emphasize that the work proposed here does not overlap with the STC Center for Bright Beams (CBB), which does not provide any funds for hardware accelerator development. On the contrary, this frontier SRF gun would greatly compliment the CBB work and provides an important outlet as well as a key platform for a number of innovations addressed at a conceptual level in the areas of lower emittance photocathodes, SRF technology improvements, and understanding of bright beam dynamics limits that the CBB brings to the accelerator community in its own separate program.

Specifics of our work will include optimizations for ~0.1-1 pC charge regime as emphasized by the need for compact sources suitable for small scale applications (UED, UEM). A successful SRF gun will undoubtedly be important for a larger bunch charge operation, including running at high average current and possible beam polarization for applications suitable for future colliders or perhaps polarized ultrafast electron microscopy, but these additional possibilities will not be the focus of our initial study proposed here.

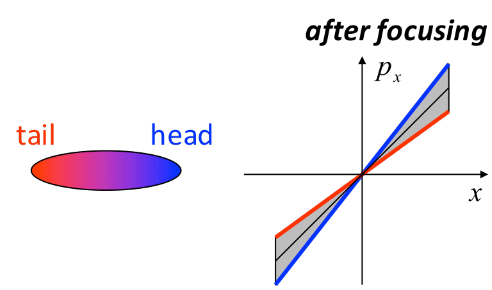

Figure 10. Transverse phase space demonstrating chromatic aberrations that appear after focusing intense electron bunch, whose tail has larger energy than its tail due to the strong space charge.

One key reason identified in the previous study [38] that can greatly limit the emittance from the SRF gun is chromatic aberrations that inevitable arise due to solenoid focusing coupled with the space charge induced energy growth near the photocathode. The solenoid focusing is essential to control the beam envelope and perform emittance compensation, but it also translates the energy spread growth acquired by the bunch (the head gaining energy while the tail losing it due to the space charge) into emittance growth, see Figure 10. Such emittance growth, though correlated along the bunch slice, is difficult to remove afterwards, once the beam is either further accelerated or run significantly off-crest in an N+½-cell style (S)RF gun. Instead, we propose to realize an aberration-free focusing system similar to the approach that we have shown to work extremely well for DC gun based photoinjectors, capable of achieving unprecedented levels in emittance compensation [38]. The basic idea is to sandwich another RF cavity buncher between two or possibly more solenoids. The incoming beam will have a positive correlation in energy due to strong space charge exiting the SRF gun (which would be run close to the on-crest condition and be a hybrid quarter-wave-like structure, having the transit time between the cathode to the anode to be a relatively small fraction of the RF cycle). This energy correlation's sign is then flipped by the RF buncher, which in turn undoes the chromatic aberrations imposed on the beam by the first focusing solenoid after it goes through the subsequent focusing lenses. In other words, such an arrangement represents a focusing system free of the first order chromatic aberrations, which focuses the beam both transversely and longitudinally further compressing the bunch and performing the required emittance compensation. Such scheme has already demonstrated excellent beam performance in numerical studies recently undertaken at Cornell for a DC gun system specifically designed for UED/UEM-like applications [49].

In summary, we plan to capitalize on the higher gradient and CW operation (which also naturally implies better field stability and more flexible bunch timing pattern) available with the superconducting RF gun technology. An important feature of the design will be its capability to cool photocathodes down to the LHe temperatures. Such low temperatures put us in an uncharted territory with regards to photocathode materials' performance at 4K.

Transfer of photocathodes into the SRF gun without degrading its performance will be an important design goal. We plan to grow such photocathodes on special pucks and modify our photocathode systems, making them compatible with the transfer mechanism. Following the beam-dynamics and RF optimizations of the SRF gun geometry, we will fabricate a prototype niobium SRF gun, prepare its RF surface using state-of-the-art high-gradient protocols, and verify high field performance initially without an actual photocathode present. In the third year of the proposed work, we will conduct a systematic study on the impact of the photocathodes on the high-field SRF performance, using an iterative process to arrive at a field-emission-free insertion mechanism for the most promising photocathodes.

We further propose to investigate suitability of various materials for 4K photocathode operation. For example, only lead and niobium were studied as potential (superconducting) photocathodes for operation inside SRF guns, though with emittance far from the small MTE values that we envision. These materials have prohibitively low quantum efficiencies (QE), especially when going to the threshold of their photoemission in order to reduce the intrinsic emittance. 4K operation of other promising materials that we grow routinely at Cornell hasn't been explored either. These materials hold much promise both due to their much larger density of states and corresponding QE, as well as demonstrated reduction of the intrinsic emittance by cooling these materials. One important question in regards to the antimonide-based photocathodes is a potential freeze out of the available carriers at such low temperatures, which could limit the available average current that can be extracted from such materials. This problem could be addressed via obtaining degenerate materials that don't experience any carrier freeze out at low temperature, e.g. by varying the stoichiometry of the grown material.

Goal**:** Realize beam dynamics and RF modeling to allow design and optimization of the novel SRF gun geometry and its subsequent beamline so that the final emittance is dominated by the photocathode.

Goal**:** Understand and resolve the mechanisms that plague SRF guns equipped with a load lock with field emission problems and minimize their causes.

Goal: Identify suitable photocathodes for operation at 4K temperature.

Milestone Q4-2018: Finish genetic optimization and RF design of the novel SRF gun and beamline.

Milestone Q3-2019: Fabricate cold SRF structure and perform initial vertical performance test.

Milestone Q3-2019: Perform Hall probe and other related measurements of suitable photocathodes to verify their ability to operate at 4K temperatures.

Milestone Q3-2020: Realize a cryo-cooled cathode puck translation mechanism which is free from generating field emission, and verify Q_0 vs. E_{peak} in the SRF gun with and without the puck insertion.

7. Results from Prior NSF Support

7.1 Cornell Program for Student-Centered Accelerator Science (NSF PHY 1416318)

Dates: 9/1/2014-8/31/2017, Amount: $10,597,786, PI: David Rubin co-PIs: Ivan Bazarov, Georg Hoffstaetter, Donald Hartill, Matthias Liepe

Intellectual Merit

This research award funds R&D on photoemission sources, on emittance-limits in storage-rings, and on niobium cavity RF superconductivity. Monte-Carlo simulations for a layered photocathode were in excellent agreement with measurements, and experimental evidence of the effectiveness of the photo-emissive sample cooling for reducing the intrinsic cathode emittance was demonstrated. A weak-strong model of incoherent emittance growth of positrons due to the electron cloud was found to be in good agreement with measurements of horizontal and vertical emittance growth and tune shifts in trains of positron bunches. Emittance growth was observed to depend on charge in the witness bunch (pinch effect) as well as density of the electron cloud. Observation of vertical-longitudinal crabbing of an electron bunch due to interaction with an asymmetric (top-down) impedance, as that induced by a scraper or orbit displacement in a narrow gap chamber was consistent with predictions of a model based on calculation of the wakefield with finite element code. A dedicated bunch by bunch and turn by turn xray beam size monitor (and associated source wiggler magnet) with 60 deg tilted detector was installed and commissioned at both 5.3 GeV and 2 GeV and is now available for routine measurement and diagnostics of positron beams in both CHESS and CesrTA operation. A quadrupole with electron flux and electron density detector (microwave), was installed adjacent to a standard lattice quadrupole enabling an experimental program to measure dependence of electron trapping for the first time as a function of quadrupole gradient.

With prior NSF support we have produced nearly 200 publications and reports including 3 PhD thesis and dozens of REU reports. All three of the PhD graduates are now employed at accelerator labs. The complete bibliography of CesrTA publications and reports is available at [50]. The conversion of CESR from colliding beam machine to a laboratory for the study of the physics of beams in low emittance storage rings is documented in the 448 pages of "The CESR Test Accelerator Electron Cloud Research Program: Phase I Report" [51].

As part of the SRF activities, we have discovered that nitrogen doped SRF cavities have increased sensitivity to residual surface resistance from trapped ambient magnetic fields due to their much-reduced mean-free electron path. We further demonstrated that this effect can be counteracted by cavity cool down with large spatial thermal gradients. Our work resulted in the development of optimized cool-down procedures for SRF cavities to achieve highest quality factors, and initiated improvements in the shielding of the Earth's magnetic field in the LCLS-II SRF linac. Our recent discovery of very high Q_0 oxygen and carbon doped niobium SRF cavities has greatly increased the parameter space available for optimization of the cavity treatment protocol [52] for highest cryogenic efficiency. The full utilization of this new C/O doping treatment for very compact, high frequency SRF accelerator cavities is part of the work proposed in this proposal. Our results on critical fields and maximum fields achievable in SRF cavities show that metastable fields above the lower critical fields can be reached in niobium cavities, showing that the lower critical field is not a fundamental limit for SRF cavities for high-quality surfaces. Results have been published in [53] - [64].

Broader Impacts

This program provides training of undergraduate and graduate students in cutting edge science, engineering and technology as urgently needed for the U.S. workforce. In the first year, 7 graduate students, 11 undergraduate students, and 2 postdocs participated. Results have been extensively presented to a wide audience at six conferences, in many cases by the graduate students. The photoemission source work directly impacts the accelerator field by enabling lower emittance relativistic beams. The emittance-limits in storage-rings work helps determine current limits in high intensity rings, and requirements for bunch by bunch feedback systems, and will inform the design of accelerators that are used in chemistry, biology, materials science, condensed matter physics and industry. The SRF niobium cavity research funded by this project impacts all uses of SRF technology where highest Q_0 is essential, especially in CW applications, e.g. future proton linacs (PIP-II, neutrino factories, a muon collider, and Accelerator-Driven-Systems for energy generation and nuclear waste transmutation), future CW operated electron linacs (Energy-Recovery Linacs and SRF driven FELs like LCLS-II), as well as ion linacs (FRIB).

7.2 IMR: Phase 1B Energy Recovery Linac (ERL) Technology R&D (NSF DMR 0807731)

Dates: 10/1/2010-12/31/2015, Amount: $30,948,000, PI: Georg Hoffstaetter co-PIs: Ivan Bazarov, Joel Brock, Matthias Liepe

Intellectual Merit

This award led to the development of the key accelerator science and technology necessary to build a successful full-scale ERL-based hard x-ray light source, including DC electron gun, photocathode, SRF linac, beam dynamics, beam instrumentation, and undulator R&D. We designed, built and tested an SRF driven injector that achieved 75 mA average current at 1300 MHz repetition rate, and a normalized emittance of 0.3 μm at a bunch charge of 77 pC, meeting the needs of an ERL. The current is far beyond the previous record from a photoemission electron injector of 32 mA. We designed, built and tested SRF cavities suitable for an ERL main linac. They have high Q, low field emission, strongly damped higher-order modes and a high beam-breakup threshold. Extensive computer modeling of 7-cell cavities led to the designs to meet these goals, as well as all of the requirements for industrial production of the cavities. Seven cavities have been constructed and all meet the requirements for Q and gradient. One cavity was tested in a horizontal cryostat, and achieved a world-record Q of 1×10^{11} at 1.6 K. Six cavities have be built into a cavity string and mounted in a prototype cryomodule for the ERL main linac, which is currently under extensive performance testing. These results are useful not only for us at Cornell, but for many other proposed machines that need high-brightness, high-power electron beams and high efficiency SRF linacs. The ERL Phase 1B project has led to over a 100 journal and conference papers and 3 PhD theses [65].

Broader Impacts

Community engagement: Graduate students have been involved in several high-impact outreach activities: participating in the workshop on the Science of Sound at the 2011 Expanding Your Horizons Program; presenting at the New York State Fair, which offered over 2000 visitors the opportunity to explore concepts related to electron excitation through hands-on activities; networking with Ithaca City School District (ICSD) science teachers as part of the ICSD-Cornell University Resource Fair; sharing CLASSE resources, materials and ideas that educators can use in their classrooms; helping to facilitate a session on magnetism to a group of 40 middle-school science teachers as part of the biannual Cornell Science Sampler Series hosted at Weill Medical College in Manhattan. All of our graduate students regularly provide tours of research facilities. Approximately 200 visitors, ages 8-80, tour the ERL prototype and control room each year, led by RA's and graduate students.

Summer Research for Community College Students: Sixteen students from local community colleges joined us in research through Summer Research for Community College Students, a program initiated by the PI. This program, which started in 2010 under Liepe's NSF CAREER award, has attracted about 10 applications for every open slot. The effect has been extremely positive, and nearly all of the participating students have gone onto 4-year colleges studying topics in science, math and engineering.

8. Broader Impacts of the Proposed Work

8.1 Impact on Accelerators and Industry

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 [66]. By improving the performance of key accelerator components, this proposal will benefit all of these. It will also make them more cost effective to build and operate.

Today's accelerators are also a critical tool for industry, medicine, national defense, and research, and may offer a path to safe nuclear energy. Annual sales of industrial accelerators, for example, exceed $2B, and are growing at an estimated 10% per year [67]. Our research will directly impact the feasibility of high-performance, high-power/intensity, robust accelerators for industrial applications. For example, the compact, high-frequency, high-efficiency SRF cavities we will develop are an ideal match for industrial applications, supporting high beam current in continuous operation, and thus fulfilling critical needs for future CW operated electron linacs for industry (e.g. for lithography near the atomic limit; in-line X-ray metrology/wafer inspection; radiation crosslinking; ion implantation), for medical applications (e.g. for radionuclide production; sterilization of medical equipment), for environmental conservation (radiation processing of polluted water and flue gas emissions), and for national security (e.g. for cargo x-ray imaging). Nearly all linac-based high-brightness electron accelerators (colliders, XFELs, as well as stand-alone compact electron imaging setups) could potentially benefit from improved low emittance electron sources and rugged photocathodes as outlined in this proposal. We expect that much of the technology we will develop as part of the work proposed here can be transferred rapidly to industry. Our past research has been transferred to industry (e.g. a turn-key SRF accelerator module) and has led to several SBIR's. We anticipate that the research proposed here will have similar impact on industry.

The PI's will continue to serve on advisory and executive committees to accelerators around the world.

8.2 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 specific fields of accelerator science and technology, the graduate students will receive broad training in beam physics and cutting-edge science. They will have the experience of leading a complex experiment. To develop presentation skills, as well as experience in collaborative research, the graduate students will regularly present their work in group meetings, collaboration meetings, and at conferences, and will also be well connected to the CBB research. Undergraduate students both from Cornell as well as those participating in our SRCCS program discussed below will participate in the proposed research. Each undergraduate student will have his/her own mentor, and will be asked to give scientific presentations during group meetings to develop communication skills.

8.3 Outreach

This proposal has a two-pronged outreach program, building upon the successes of our previous NSF funded outreach activities. 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.

8.3.1 Summer Research for Community College Students (SRCCS)

Cornell University in Upstate New York is surrounded by 2-year community colleges located in primarily rural and economically depressed regions. 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 it 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 lab's Research Experience for Undergraduates (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 continues a very successful program that was begun by the PI (Liepe) under his now expired CAREER award.

8.3.2 Engaging and Informing the General Public

Accelerators have very broad impact on society, but the general public mostly is unaware about the importance of accelerators. To help engage and inform the general public about accelerators, the Cornell accelerator lab gives facility tours to approximately 1800 visitors each year, many of them school children who come on field trips. Here we propose to extend and strengthen our facility tours in several ways.

We plan to produce new virtual lab tours for online use and/or display during facility tours. These will describe and explain the technologies used in accelerators as well as show examples of their usage and impact on society. We will provide paid positions for undergrad and graduate students to generate these virtual tours, as students not only have the knowledge to generate these, but also have fresh ideas on how to best make them attractive to a young audience.

Currently, the demand for tours exceeds the staff's ability to provide guided tours of the research facility. In order to significantly increase the number of visitors that can tour our accelerator, we will choose one of the accelerator–science graduate students as tour-guide coordinator (providing a 10h/week paid position to this student for her/his leading role) to train and oversee a small group of graduate students providing the guided tours of our facilities. These activities will be done under the guidance of Lora Hine, a professional science educator.

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