The project title: Demonstration of Active Optical Stochastic Cooling of 1GeV electron beam in CESR

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## Background and Introduction

### Background

The luminosity of a high energy collider determines the production rate of the particles of interest to the high energy physicist. Luminosity is directly proportional to electron beam brightness, and thus brightness is the one of most critical beam figures of merit for high energy collider design. In such machines, brightness is ultimately limited by the dilution of the particle beam phase-space with increasing particle beam density from to intra-beam scattering (IBS) and beam-beam effects.

Electron cooling and conventional stochastic cooling, both methods of boosting hadron beam brightness, are ineffective at very high energies. The former is extremely difficult to implement at ultra-relativistic energies; a notable example is the electron cooling system with 4.3 MeV electrons in Fermilab’s Recycler which is used to cool 8 GeV anti-protons prior to injection into the Tevatron [1]. Stochastic cooling, invented by Simon Van der Meer [2] and for which he shared the 1984 Nobel Prize for cooling anti-protons used in CERN’s Proton-Antiproton collider, is ineffective at the large particle beam densities in a collider. This is due to the limited bandwidth of pickup and kicker. (A state-of-the-art stochastic cooling system operates at about 8 GHz [3]). New technologies are required to increase brightness in high energy hadron storage rings. To that end, Optical Stochastic Cooling (OSC) and Coherent-electron-Cooling (CeC), are being explored [4].

The OSC, first suggested Mikhailichenko and Zolotorev [6] (and later refined by Zolotorev and Zholents [7]), is similar in concept to the ordinary stochastic cooling but with a transition from microwave to optical wavelengths and an accompanying dramatic increase of the absolute operating bandwidth of the cooling system by approximately 4 orders of magnitude. This is accomplished by replacing the pickup and kicker plates with undulators tuned to an optical frequency. In the transit-time version of the OSC a particle passes through the “pickup” undulator (PU) where it radiates a wave-packet with a pulse duration of a few 10’s of femtoseconds. Upon exiting the PU the particle is propagated through some fraction of the machine arc and/or a dedicated bypass-chicane, and into the Kicker-Undulator (KU). The wave-packet meanwhile is transported through optical amplifier and lenses and imaged in the KU. The wave-packet meets its parent particle in the KU and their interaction gives a small change in energy to the particle.

Since the sign and amplitude of the energy change is determined by the relative arrival time of the particle and wave-packet, the total path length of both the optical system and chicane are arranged so that the kick will decrease the momentum error and the betatron amplitude of the particle. The design of the bypass is such that this corrective process is simultaneously occurring for all particles in the bunch and thus the momentum spread and horizontal emittance of the beam is reduced.

OSC can significantly enhance performance of high energy hadron beams. It was estimated that had the Tevatron (proton-antiproton collider) been equipped with an OSC system to mitigate dilution of the phase space of the antiprotons during a store, a **doubling of integrated luminosity** could have been achieved [8].

**The goal of this proposal is to demonstrate the OSC in the Cornell Electron Storage Ring (CESR) with amplifier gains required for hadron or heavy-ion cooling**. Presently there are two attempts at a proof-of-principle demonstration of the OSC with electrons; in CESR and also in the Integrable Optics Test Accelerator (IOTA) at Fermilab. Both groups are interested in first demonstrating the ‘passive’ cooling, where the undulator wave-packet is simply refocused into the KU without amplification. Such a demonstration is a critical first step but **a passive OSC scheme would not be effective in a collider** where theory predicts an amplifier gain of 20-30dB is required.

A road block towards effective amplification in the current approaches is they rely on a relatively short delay between the light and particles, which puts severe restrictions on the amplifier design; most notably the amount of optical delay that can be afforded to the amplifier. To overcome this, we propose taking advantage of the existing storage ring arc to extend the path length of the charged particles with respect to the light, obviating the need for a chicane bypass. The differential path length is increased from a few mm to nearly 60 cm, relaxing the constraints on the amplifier so that 20-30dB of gain is achievable.

Successful OSC requires extreme synchronization of the time of arrival of the light and electrons. **For this scheme to be successful we must first demonstrate stability of the light path to the single fs level,** which will be accomplished by feeding back on an interference pattern generated with a narrow-band laser propagating through the light path. WIth this complete, **passive OSC can be demonstrated. The optical amplifier will be developed** in parallel with the previous steps, and will installed in the tunnel **to demonstrate high-gain active OSC in CESR**.

### Unique role of Cornell for the proposed research

**The Cornell Electron Storage Ring (CESR)** is uniquely instrumented for the study of innovative storage ring optics and dynamics of electron and positron beams [10]. The 768m circumference ring operates with beam energy ranging from 1GeV to 6GeV with full energy injector. The ~100 independently powered quadrupoles and sextupoles permit a tremendous variety of lattice configurations. The nearly 120 beam position monitors collect turn-by-turn (and bunch-by-bunch) position data, and thus yield measurements of orbit, betatron phase advance, transverse coupling, and dispersion and damping rates. The bunch-by-bunch feedback is completely configurable allowing the setting of any combination of the 1281 available 2-ns RF buckets in CESR for feedback or excitation. The sophisticated control system interface software facilitates real time analysis, modeling and interpretation of beam data, and implementation of optimization and tuning algorithms. The accelerator complex is available for the machine experiments for 2-4 hours each week, depending on requirements of the CHESS x-ray program.

**An existing NSF grant** supports an experimental program to demonstrate and explore passive optical stochastic cooling in CESR. That support has enabled: (1) Demonstration of injection and storage of low energy (1GeV) electron beams without damping wigglers. The low beam energy greatly simplifies the requirements of OSC instrumentation and is essential to our test. Prior to these tests CESR had never operated below 4 GeV without damping wigglers. (2) Conceptual and engineering design of a helical undulator to serve as OSC pickup and kicker with first harmonic of 800 nm at 1GeV beam energy. The helical geometry attains the requisite wavelength at a lower field than a conventional planar design. (3) Design of chicane style bypass with differential path length of electron beam and undulator radiation of 2 mm. (4) Simulation modeling of *all* relevant light and electron beam dynamics, including as generation, propagation, and interaction with radiated electromagnetic fields, which permits detailed simulation of cooling dynamics. This analysis can include study of sensitivities to mis-alignments, instabilities, field errors, field variation, etc. (5) assembly and training of a team of talented young scientists with the expertise to perform this exquisite experiment. This proposal is entirely distinct in its scope, but seeks to build upon and extend what has been already accomplished and enabled by the previous NSF grant.

**Complementarity with other efforts worldwide.** Fermilab is also pursuing a proof-of-principal demonstration of the OSC in the Integrable Optics Test Accelerator (IOTA). Their proposal represents an exciting and well-developed plan for demonstrating the OSC in a passive mode (no optical amplifier) on 100 MeV electrons [11]. At this low energy the OSC damping rate can be made to be approximately an order of magnitude faster than synchrotron damping, which in the absence of OSC is balanced by the growth in emittance from quantum excitation; and hence will result in a dramatic reduction of the stored beam emittance. However, at 100 MeV the IBS growth rate prevents storage of a beam with more than approximately 106 electrons. At this relatively low charge the beam density is too low for the important effects of the incoherent (heating) kicks of neighboring particles to contribute to the OSC process. The presence of incoherent heating is not only well known from ordinary stochastic cooling and warrants study in its optical analog, it will be a factor in any realistic implementation of OSC on high intensity hadron beams. Study of this effect can be done in CESR. Although an active test of the OSC in IOTA is planned, the short bypass used in the demonstration puts serious constraints on the amplifier design, preventing the development of one with gain sufficient for application to high energy hadrons. Since in this proposal we aim to develop a long bypass – which lifts these constrains – **CESR is uniquely poised to develop a high-gain amplifier for the OSC,** a definite prerequisite for the technique to be used in the cooling of hadrons or heavy-ions.

**Importance to education and future workforce development.** Cornell University is a participant of the Center for Bright Beams, an NSF Science and Technology Center involving a large number of institutions across the country: Arizona State 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 beyond. CBB is devoted to the development of novel concepts, simulation tools, and materials without connection or support for any specific single accelerator or major hardware development. 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. While **the CBB has no component or funding to develop the accelerator hardware**, it provides a platform to engage top PhD students and broad community of specialists in advanced research topics of accelerator science. In addition to 1 PhD student and 1 postdoc budgeted in this proposal, this grant will provide a unique opportunity for a hands-on research in the area of optical stochastic cooling for **an additional 1 PhD student and 1 postdoc that would represent an in-kind support from the CBB** (including a new CBB postdoc, Matthew Andorf, who has worked extensively on the optical stochastic cooling scheme at IOTA as a part of his PhD research). The PI’s on this proposal (Bazarov and Maxson) coordinate two out of three research themes in the CBB (Beam Production and Beam Storage and Transport) and are committed to realizing and taking full advantage of the potential represented by the opportunity to demonstrate active optical stochastic cooling.

### Overview of the proposed research

The research of this proposal will culminate in the **first** **demonstration of both passive and active OSC with optical path and amplification procedures applicable toward high energy hadron cooling**. Toward this end, we will first install the pickup and kicker undulators in the CESR ring, along with specialized dipole chambers with onboard mirrors which allow the extraction of the synchrotron light from the vacuum to the in-air amplifier. OSC requires extreme stability in the time of flight for both the electrons and photons (single fs-scale and better). Thus, after construction of the optical path, which includes evacuated transport tubes and an enclosed amplifier table, an active phase and position feedback system will be tested using interferometry of an external long coherence length laser in the actual path of the OSC photons. This **active feedback will enable the first demonstration of passive OSC**, in which feedback will be performed on the spatiotemporal overlap between the pickup and kicker synchrotron radiation. In parallel, a high gain Ti:Sapphire amplifier will be developed using an external laser source. Once complete the amplifier will be integrated into the CESR OSC optical path, and the first experiments will be performed on amplified synchrotron light.

## Multiple Investigators

### Synergies between the (co)-PI’s

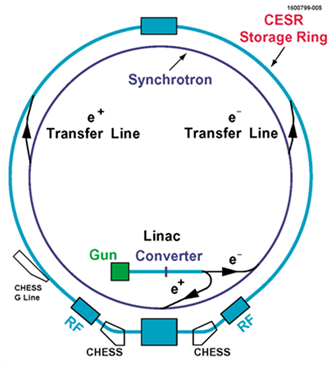
Given that optical stochastic cooling is inherently interdisciplinary, this proposal brings together PIs with expertise which span a wide swath of accelerator physics and photonics, including nonlinear storage ring dynamics, accelerator modeling and optimization, high brightness electron and photon beam instrumentation, ultrafast science, laser physics, and electron-photon interactions.

**PI Ivan Bazarov** is an expert in high power, high brightness electron beam physics, as well as the production and characterization of synchrotron light. Ivan is also an innovator in the field of electron and photon beam modeling and optimization, being among the first to introduce multiobjective genetic optimization to high brightness electron beam simulations, which have led to drastic improvements in simulated and achieved beam brightnesses in both linacs and storage rings. Bazarov has also pioneered multiple methods in 3D spatiotemporal laser shaping for high brightness accelerators. Having garnered expertise in both electron beam physics and photonics, PI Bazarov is both the technical lead of the project and the bridge between the photonics and electron beam development.

**PI David Rubin** is an expert in storage ring design, optimization, and operation. He brings many years of expertise with CESR and its modification and upgrading, as he has served as the director for CESR storage ring accelerator physics program and the CESR Test Accelerator research program. Additionally, Rubin was responsible for the concept and design of the CHESS upgrade that is currently nearing completion in Wilson lab, which will result in a significant brightness increase for the storage ring as a whole. Given this experience, Rubin leads the OSC storage ring modification efforts, including beam transport modeling and optimization, as well as the installation of undulators and light-guiding vacuum chambers.

**PI Jared Maxson** is an expert in ultrafast (sub-picosecond) electron and laser optics. He brings years of experience in the design and commissioning of ultrafast optical systems, synchronization schemes, laser-electron interactions in vacuum, and high brightness electron beam dynamics and diagnostics. PI Maxson is the lead of the photoemission bright beams laboratory, which houses an ultrafast laser development lab space which will be used for OSC amplifier development. Maxson will lead the amplifier construction and testing, as well as the interferometric spatiotemporal overlap feedback system.

**Fig. 1**. ***The Wilson Lab accelerator complex on the campus of Cornell Univ.*** *consists of a Linac injector, synchrotron booster and the 768 m circumference Cornell Electron Storage Ring (CESR).*



### CESR

The Wilson Laboratory accelerator complex (see **Fig. 1**) includes a linac capable of accelerating electrons to 300 MeV, and producing and accelerating positrons to 150 MeV. The beam energy is increased to as high as 6 GeV in the synchrotron booster. High energy beams of electrons and/or positrons are transferred to the 768 m circumference Cornell Electron Storage Ring (CESR), where they circulate for many hours. In the high energy/high current mode, CESR is a source of x-rays for the Cornell High Energy Synchrotron Source (CHESS). Low energy operation is reserved for beam physics studies. The storage ring is instrumented with high bandwidth and high precision beam position and beam size monitors, as well as dozens of specialized detectors for measuring the beam dynamics and characterizing the beam environment.

The storage ring has been reconfigured many times since commissioning in 1979 as an electron-positron collider operating in the center of mass energy of the Upsilon system. Subsequent upgrades included modification of interaction region optics, implementation of multiple bunch operation with electrostatic separation, replacement of room temperature with superconducting RF cavities, installation of superconducting wigglers to enhance radiation damping, compact narrow gap undulators for x-ray science and most recently rearrangement of the interaction region to accommodate multiple x-ray insertions. In addition to operation for users as collider and x-ray source, the storage ring has served as a laboratory for accelerator physics and studies of beam dynamics.



**Fig. 2**. ***The long bypass in CESR to enable active OSC.*** *(Top) The section of the ring showing pickup and kicker undulators. Light bypass is indicated schematically by arrows. (Bottom) An example of optical functions which provide cooling in both longitudinal and transverse planes.*

### Detailed modeling of OSC in CESR

In preparation for a demonstration of optical stochastic cooling in the Cornell Electron Storage Ring (CESR) we have developed a particle tracking simulation to study the relevant beam dynamics. Optical radiation emitted by an electron in the pickup undulator gives a momentum kick to that same particle in the kicker undulator. The optics of the electron bypass from pickup to kicker couples betatron amplitude and momentum offset to path length, so that the coherent momentum kick serves to reduce betatron amplitude and momentum spread. Nearby electrons contribute photons, which given their random phase relationship with the test particle, are a source of incoherent noise. The simulation enables determination of cooling rates and their dependence on bunch and lattice parameters of bypass optics, effects of coherent kicks and incoherent noise, as well as time dependent (and static) magnet alignment and field errors.

The particle tracking code makes extensive use of Bmad, a subroutine library for relativistic charged-particle dynamics simulations [11]. In an typical simulation, the bunch is modeled as a distribution of 1000 macroparticles with some initial emittance (typically the equilibrium emittance as determined by radiation damping and/or intra-beam scattering), and tracked through a CESR lattice for many turns. At every turn the 6-dimensional phase space of each particle is recorded at the location of the pickup, to construct the sigma matrix, from which the normal mode emittances in three planes are computed [12]. Quantum excitation and damping (stochastic emission of photons) can be turned on or off as desired. On every turn, each macroparticle receives both coherent and incoherent kicks when exiting the kicker undulator. The incoherent contribution depends on the number of real particles (as opposed to macroparticles), in the bunch. We have developed a computationally efficient method for including the incoherent contribution.

The momentum kick received by each particle in the kicker undulator is given by Eq. 1 where G is the gain, the relative phase of electron and light for the ith electron, and e relative phase of the light from the j nearby electrons.



(1)

## Cooling (coherent) kicks

The first term on the right hand side of Eq. 1is the kick that cools by correcting momentum offset. It is straightforward to apply this so-called coherent kick to the macroparticles. The path lengthening of each particle from the pickup to the kicker (center to center) is computed: , where and are the same-turn longitudinal coordinates of the particle at the middle of the kicker and pickup undulator, respectively. The phase shift . The system gain G depends on undulator parameters, bypass beam optics and amplifier gain.

## Noise (Incoherent) Kicks

The second term in the right of Eq. 1 describes the noise or heating effect from kicks that are due the radiation of nearby particles in the pickup undulator. The most straightforward way to implement the incoherent kicks would be to count the number of particles trailing the reference particle within the range , (Radiation of particles outside of that range (slice) will not arrive in the kicker undulator in time to interact with the reference particle.), and sum their contributions directly. This method is however impractical, as it requires tracking the entire population the bunch (107 to 108 particles).

We find empirically that if the number of particles in the longitudinal slice is large (> 6), the probability distribution of noise(incoherent kick) is Gaussian with width proportional to . The details are determined numerically. The incoherent kick is then randomly chosen from a Gaussian distribution with the appropriate width.

The total longitudinal kick, the sum of the coherent and incoherent parts, is then applied to the particle at the exit of the kicker undulator on every turn, thus simulating the OSC cooling process. The contribution from the incoherent kicks increases with the number of particles in the slice, and in the bunch. It is essential to include this dependence in the simulation in order to learn how the measured cooling rate will depend on bunch population.

The simulation has been used to quantify cooling rates and ranges, and to determine dependencies for the lattice with chicane bypass. The layout of the chicane bypass is shown in Fig. Recall that the differential path length of light and electrons in the chicane bypass is only 2mm.



Figure 3 Layout of the chicane bypass. Note the very different horizontal and vertical scales. The differential path length for electrons and light is 2mm.

The results of a simulation of the cooling for the chicane bypass is shown in Figure 3. The simulation includes radiation damping and excitation, coherent as well as incoherent kicks, and dipole field variation. We assume 10 million electrons in a 10mm long bunch. The dipole field variation is a combination of a 60Hz modulation and white noise and is based on measurements of the CESR dipole. Each curve in the Figure 4 shows the horizontal emittance versus turn number, for a different value of the gain system gain. The gain depends on the undulator characteristics, the chicane beam optics, and amplification. In the absence of amplification (passive cooling), the gain for the chicane bypass configuration is about 2e-10. Beam energy is 1.0 GeV.



Figure 4 Simulated horizontal emittance versus turn number for a bunch of 1e7 electrons, for a range of system gain. The simulation is for the chicane bypass configuration. Beam energy is 1GeV.

Preliminary simulations for the lattice configured with the longer arc bypass, (**Fig. 2**) are shown in Figure 5 and cooling is indeed evident. Work is underway to improve the passive gain by further optimization of the beam optics and undulator parameters, and as noted above, the arc bypass configuration is characterized by differential electron/light path length of 63cm (as compared to 2mm in the chicane bypass), thus affording space for active amplification.



Figure . Simulated damping of horizontal emittance for the lattice configure with arc bypass (63cm differential delay)

[11] D. Sagan, Nucl. Instrum. Methods Phys. Res. A 558, 356 (2006).

[12] A. Wolski, Phys. Rev. ST Accel. Beams 9, 024001 (2006).

### Laser Expertise at Cornell

**Lasers for accelerators expertise.** Over the past decade and half, Cornell Laboratory of Accelerator Sciences and Education (CLASSE) has become a world leader in innovation of developing lasers for accelerators primarily in the area of bright electron sources. Leveraging its close relationship to the strong optics research at Cornell’s Physics and Applied Physics Departments a number of unique laser systems have been developed to drive Cornell’s photoinjector requiring a high-power ultrafast pulses that are both well stabilized in position and in phase and correctly synchronized with the accelerator RF [12]. We currently operate two state-of-the-art laser systems (see Fig. xxx [Jared to add the photo]) that are used as the drive lasers for two separate photo-accelerators, both of which are able to achieve ~100 fs level of synchronization between RF and laser. One of the systems was built from the ground up at Cornell, including all stabilization feedback hardware and software, and has been used regularly for the past 10 years. The optical path and laser stability requirements in this proposal are a natural extension of the work that we have already accomplished at Cornell and are achievable with similar methods.

## Proposed Research and Methods

### OSC Bypass Requirements for Electrons, including undulators

The electron beam circulates counter clockwise in the storage ring. Radiation emitted by electrons in the pickup undulator (centered at 35m,240m in **Fig. 2**) is extracted from the bend chamber downstream of the pickup, transported across the ring arc, and injected into the bend chamber upstream of the kicker undulator where it transmits a momentum kick to the electrons. The length of the path of the electrons is about 60cm longer than that of the radiation, allowing introduction of optical elements along the flight path, such as lenses and mirrors to focus the light and an amplifier to increase system gain. The propagation time of the light is tuned so that it is coincident with the radiating electrons in the kicker. The 60cm differential propagation length in the arc bypass is to be compared to the 2mm differential length in the conventional chicane bypass in our earlier design as well as in the planned experiment at Fermilab. The extended differential delay allows the possibility of more sophisticated optical elements and a more powerful amplifier.

|  |  |
| --- | --- |
| Pickup & Kicker Undulator | |
| Length [m] | 4.55 |
| Period [m] | 0.325 |
| Geometry | Helical |
| Wavelength[nm] (@1.4kG, 1GeV) | 800 |

Table 1. Undulator Parameters

The momentum kick to the electron in the kicker undulator depends on the arrival time of the electron with respect to the phase of the electric field of the radiation. The optics of the electron transport are designed to couple horizontal betatron amplitude and momentum offset in the pickup to the path length so that the momentum kick in the kicker effects damping. We find that the existing bend and quadrupole magnets in the arc between pickup and kicker permit design of satisfactory cooling parameters. (We may add sextupoles to compensate nonlinearity). Indeed the required modifications to the storage ring are straightforward. The lattice and bypass and pickup and kicker undulator parameters are summarized in Table 1 and Table 2. The undulators will be installed in existing straights (recently vacated by electrostatic separators). The bend chambers adjacent to the undulator straights will be modified with in-vacuum mirrors on the outer wall and window on the inner wall for transmission of the undulator radiation.

|  |  |
| --- | --- |
| Beam Energy [GeV] | 1 |
| Horizontal emittance [pm] x | 0.99 |
| Momentum spread [%] p/p | 0.037 |
| Horizontal cooling range [nm] x | 28.4 |
| Longitudinal cooling range [%] p/p | 0.927 |
| Ratio of horizontal and longitudinal cooling rates x/z | 13.02 |

Table 2. Cooling and lattice parameters.

The ring lattice and linear bypass optics for the arc-bypass configuration that is the basis of this proposal (**Fig. 2**) require no additional magnets and no modifications to the CESR ring. Commissioning will begin in Spring 2019 and continue in the first year of the award. Tests will be conducted at the 1GeV beam energy that we anticipate for the demonstration of optical stochastic cooling. As noted above, injection and storage into a 1GeV test lattice was achieved nearly one year ago. However a sextant of the storage ring arc has since been reconfigured as an improved x-ray facility. Our first task will be to recover 1GeV operation. Because of the relatively long radiation damping time of about 0.6 seconds at 1GeV, (as compared to 13ms at 6 GeV), the rate at which beam is transferred from synchrotron injector to storage ring is necessarily reduced by that ratio, from 60 Hz to 1Hz. Injection times are therefore longer, total current is lower, and we will be obliged to develop new techniques to characterize the ring optics with bunch current that is a fraction of a mA. That characterization will include measurement and correction of orbits, beta-and dispersion functions in order to insure that the bypass optics satisfy design specifications for cooling and that the equilibrium beam size is near the design value. Compensation of nonlinear path lengthening through the bypass will require installation of additional sextupoles, and tests of the effectiveness of that compensation and associated dynamic aperture will be scheduled during the first year of the award.

### OSC Bypass Requirements for Light

Matt to add a new figure with all major optical components.

A critical first step in the demonstration of high-gain OSC in CESR is the stabilization of the light path connecting the PU and KU. We envision doing this by feeding back on a Michelson-like interferometer; with one leg comprising the OSC light path while the other, much shorter leg, consists of a single mirror. Jitter in the obtained interference pattern directly measures a change in the OSC light-path length and can be registered on a photo-diode. The photo-diode signal then drives a piezo-electric transducer on one of the mirrors in the light path, adjusting the path length as needed.

Ideally the time-of-flight for the reference particle, traveling from PU to KU, and the light path are equal. A path length error Δse results in a reduction in damping rates by a factor cos(kΔse) where k=2π/λ is the zero-angle wavelength of the undulators, which for this proposal is 800nm. Path length error can either occur from fluctuations in the dipoles making up the bypass or from vibrations in the mirrors comprising the light path.

Vibrations in the mirrors are assumed to be gaussian-random uncorrelated errors. In order to achieve a damping rate of 80% of the ideal (error-free) rate the mirrors must be stabilized so that the rms path-length error of the light does not exceed 85 nm. The light path will require 8-9 mirrors and therefore each mirror must be stabilized to (in the direction perpendicular to the light-path) 15 nm. With a feedback system the permitted rms path-length error relaxes to λ/2 increasing the required stability to 70 nm for each mirror. Although severe, we note the stability tolerances of femtosecond-scale enhancement cavities are even tighter than this but none-the-less can be achieved with interferometric feedback techniques [13].

Since the two legs of the interferometer will be different by approximately 160 m we require a laser with a longitudinal coherence length that exceeds this difference. Fortunately, there are commercially available rack mounted fiber lasers with linewidths of 20 KHz. This corresponds to a coherence length of more than 10 km which is well past our path length discrepancy.

The light path and corresponding optics will be kept in vacuum, isolated from the CESR vacuum, to eliminate noise related to local fluctuations in air temperature and pressure. We anticipate most noise coming from vacuum pumps and other components related to the accelerator which will occur at 60 Hz and its first few harmonics. We therefore estimate the required bandwidth of the feedback system to be less than 1 kHz.

For both the passive and active demonstrations of the OSC in CESR, we can use coherent interference between the PU and KU from the entire beam, a direct result of the cooling process, to obtain information on the path length error between the reference particle and the PU wave-packet as described in [14]. Thus, the feedback system developed here can be repurposed for stabilization during cooling.

### Laser amplifier for OSC

The necessity of a laser amplifier for making the OSC a viable cooling method for hadron and heavy-ions was already explained above. Here we discuss the specifics of the amplifier to be implemented under this proposal. For the gain medium we select Titanium-sapphire (Ti:sapph) which boasts an operating bandwidth of 100 THz as well as excellent thermal handling properties and has often been considered a superb candidate gain medium for the OSC for these reasons [15][16]. Ti:Sapphire has a peak wavelength of 790 nm; originally considered for the active test in IOTA [17] it was ruled out since its use would result in too small a fraction of the beam being cooled – a limitation arising from the short length of the bypass in IOTA. Instead an amplifier based on Cr:ZnSe, with a peak wavelength of 2490 nm, was selected. This gain medium has an exceptional bandwidth of 50 THz but suffers from extreme thermal effects and provides limited gain [18]. A major advantage of the long bypass considered for the OSC in CESR is it allows for the use of a shorter wavelength allowing us to exploit the full potential of Ti:Sapphire.

A Continuous-Wave (CW) diode laser at 532 nm can be used to excite a population inversion in the crystal necessary for gain. Adapting the formulas presented in [18] to Ti:Sapphire we estimate a pumping intensity of 1 MW/cm2  is needed for 10 dB of amplifier gain. Pump wavelength absorption constants as high as 10 cm-1 are readily available, so a 3-mm long crystal results in over 95% absorption of the pump energy. To achieve the required pump intensity the radiation will be focused to a 30 µm spot radius in the crystal center giving a Rayleigh range of 3.5 mm- a value which is longer than the crystal and therefore ensures amplification of the radiation throughout it. The crystal can be cooled either cryogenically or thermoelectrically.

The long-arc bypass can easily accommodate 2-3 stages of amplification yielding a total amplification of 20-30dB. These gain values are significant on two fronts. First it allows the OSC experiments in CESR to probe into a high gain regime where the incoherent (heating) contributions of neighboring electrons counteract the coherent (cooling) kicks of the electrons interaction with its own radiation. This balance between heating and cooling results in an optimal gain and is inherent in any stochastic cooling scheme (including CeC); thus, it represents an OSC system brought to its full fruition allowing all aspects of its theory to be explored. Second, and broader in impact, 20-30dB is the amount of gain needed to combat the phase-space dilution from deleterious effects like IBS in eRHIC and TeV scale hadron colliders making the OSC a viable cooling option.

## Project Objectives

Here we give a concise summary of the specific objectives/aims of the proposed project.

### Reduced Test of Interferometric Stability (AB, MA)

We will begin by constructing a benchtop setup to test the hardware and software for position and phase stability feedback. Next, during access to the CESR tunnel, we will install laser optics and the associated safety systems. After installation, the first milestone is to achieve position stability across the entire light-path, which will allow the phase to be measured. The final milestone will be to achieve position and phase stability simultaneously, and to produce a measure of the final phase stabilization that is achievable.

### Preparing CESR for OSC configuration (DR)

During the first year of the award we will establish injection and storage of 1GeV in the lattice with bypass optics. Optical functions and orbits will be measured and corrected and instrumentation to monitor beam emittance and damping times will be commissioned. With installation of the additional sextupoles in the bypass, we will explore the effectiveness of the compensation of nonlinear path lengthening by measuring dependence of global orbit shifts on sextupole strength. Dynamic aperture will be determined by measuring amplitude dependent tune shift and tolerance to beam excitation.

### Install and Characterize Undulators (DR)

The pickup and kicker undulators will be installed in an existing long straight and there will be essentially no impact on storage ring operation. With installation of the undulators and the adjacent bend chambers near the end of the first year of the award, we will store beam and develop methodology for aligning the beam in the undulators and the in-vacuum mirrors in the bend chambers, for extracting the radiation. Characterization of the undulator spectra will allow precise tuning of the magnetic field. Alignment of the beam trajectory will be guided by precision beam position monitors located at entrance and exit of the undulators.

### Demonstration of Passive Cooling (DR, MA)

I.e. able to achieve the required optical phase stability.

### Laser Amplifier (AB, MA)

A bench test of the amplifier can proceed in parallel to the previous steps. Upon acquiring the amplifier materials (pump laser, gain crystal) an existing laser system belonging to one of the Co-PI’s, tunable from UV-mid-IR, can be used for seeding. A gain curve will be measured over wavelength range matching the bandwidth expected from the PU.

### Demonstration of Active Cooling (DR, MA)

Ultimate victory.

## Proposed Resources (DR – CESR, IB – non-CESR,)

Identify the resources needed to meet the objectives of the proposed project and accomplish the research goals. Requests for support of any resources in the budgets submitted with the application should be consistent with the scope of research efforts identified in the narrative. Reviewers will be asked to consider if the proposed budgets are reasonable and appropriate to carry out the proposed work and adequately estimated and justified.

This seems like a summary of the budget justification?

The Cornell Electron Storage Ring and injector are critical resources for the proposed research. The proposed cooling bypass fits neatly into the layout of the storage, (by design), so that beam instrumentation can be installed with minimal disruption of ongoing operations. Preliminary studies of operation of the accelerator in the 1GeV regime, (the low energy regime where the experiments will be performed) have been conducted with zero impact on x-ray operations and we intend to preserve the capability for efficient transition from operational to experimental conditions. The project will rely on the sophisticated lattice design capability that has been developed over decades of operations and that has enabled various beam physics experiments, as well as the extensive beam instrumentation and diagnostics that is the product of prior support. The experiment will benefit from the maturity of the control system and the associated analysis software. Finally, local experts will be available to support the program.

Our computing facility is well equipped to address the demands of lattice design, magnet modeling, and simulations.

The engineering and technical staff at CLASSE, have extensive experience with design, fabrication and installation of the type of equipment that is required for the experiment.

## Timetable of Activities

This section outlines all the major activities and phases of our project year-by-year.

Year 1.

Undulator installation & characterization

Bend chambers manufactured

Test of the bypass optics in CESR 1 GeV lattice with beam

Setup the light path from pickup to kicker locations

Year 2.

Bend chambers installed during downtime

Reduced demonstration of the optical path spatiotemporal stability

Demonstration of passive cooling in the 1 GeV CESR configuration

Laser amplifier built

Year 3.

Laser amplifier installed in tunnel

Demonstration of active cooling in CESR

## Appendix 1: Biographical sketches

## Appendix 2: Research Scientists

## Appendix 3: Current and Pending Support

## Appendix 4: Bibliography and References Cited

1. S. Nagaitsev, et al., Phys. Rev. Lett. 96, 044801 (2006).
2. S. van der Meer. Stochastic Damping of Betatron Oscillilations in the ISR. Geneva, Switzerland (1972).
3. R. J. Pasquinelli., JINST 6 T08002 (2011)
4. V. N. Litvinenko, et al. in Proceedings of the International Workshop on Beam Cooling and Related Topics (COOL'17), Bonn, Germany, p. 77 (2017).
5. V. A. Lebedev et al., in Proceedings of the North American Particle Accelerator Conference (NAPAC'13), Pasadena, CA, USA, p.422 (2013).
6. A. A. Mikhailichenko, M.S. Zolotorev, Phys. Rev. Lett. 71, 4146 (1993).
7. M. S. Zolotorev, A. A. Zholents, Phys. Rev. E 50 3087 (1994).
8. V.A. Lebedev, ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams HB2010, Morschach, Switzerland (2010).
9. D.L. Rubin, “The Challenges of Ultra-Low Emittance Damping Rings,” in *Proceedings of the 2011 International Particle Accelerator Conference, San Sebastián, Spain*, 2011, p. 956-960.  [PDF (JACoW)](http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/tuyb02.pdf)
10. D.L. Rubin, “CESR Test Accelerator,” in *Proceedings of Snowmass on the Mississippi 2013, Minneapolis, MN*, SNOW13-00115, [Preprint (arXiv:1308.2325)](http://arxiv.org/abs/1308.2325)
11. Jarvis18
12. Zhao, Zhi & Bartnik, Adam & Wise, Frank & V. Bazarov, Ivan & Dunham, Bruce. (2014). High-power fiber lasers for photocathode electron injectors. Physical Review Special Topics - Accelerators and Beams. 17. 10.1103/PhysRevSTAB.17.053501
13. I. Pupeza, Power Scaling of Enhancement Cavities for Nonlinear Optics. Springer Books. New York, (2012).
14. M.B Andorf et al., in the Proceedings of the North American Particle Accelerator Conference (NAPAC'16), Chicago,IL, USA. p.3024 (2015).
15. A. Zholents and M. Zolotorev, in the proceedings of Particle Accelerator Conference (PAC’97), Vancouver, B.C. Canada, p. 1804 (1997).
16. M.B. Andorf et al, in the proceedings of the International Particle Accelerator Conference (IPAC’16), Busan, Korea, p. 3024 (2016).
17. V.A. Lebedev, at al, in the proceedings of the North American Particle Accelerator Conference (NAPAC’13), Pasadena, CA, USA, p. 422 (2013).
18. M.B. Andorf et al, in the proceedings of COOL’15, Newport News, VA, USA, p. 128.

## Appendix 5: Facilities & other resources

The Wilson Laboratory accelerator complex includes a linac capable of accelerating electrons to 300 MeV, and producing and accelerating positrons to 150 MeV. The beam energy is increased to as high as 5.6 GeV in the synchrotron booster. High energy beams of electrons and/or positrons are transferred to the 768 m circumference Cornell Electron Storage Ring (CESR), where they circulate for many hours. The storage ring operates over an energy range of 1.5 GeV to 5.6 GeV with circulating currents up to 500 mA. In the high energy/high current mode, CESR is a source of x-rays for the Cornell High Energy Synchrotron Source (CHESS). Low energy operation is reserved for beam physics studies. The storage ring is instrumented with high bandwidth and high precision beam position and beam size monitors, as well as dozens of specialized detectors for measuring the beam dynamics and characterizing the beam environment. All operation and measurements are integrated into the state-of-the-art control system.

## Appendix 6: Equipment

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## Appendix 7: Additional Budget Requirements

N/A

## Appendix 8: Data Management Plan

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## Appendix 9: Other Attachments

N/A