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

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Funding Opportunity FOA Number: DE-FOA-0001961

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HEP research subprogram(s) as identified in Section I of this FOA:

Innovations in optimization and control of accelerators using methods of differential geometry and genetic algorithms

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## Background and Introduction

Explanation of the importance and relevance of the proposed work as well as a review of the relevant literature. A brief description of research activities conducted by the Principal Investigator and his/her group, including specific roles and responsibilities in collaborative research efforts, and accomplishments and impacts made during the recent past (typically the past three years), is also encouraged. Investigator(s) proposing to conduct research across multiple HEP research subprograms are encouraged to provide their overall plan for such activities, including any transition of effort.

### Background

Introduction on cooling in general and optical stochastic cooling in particular; challenges, motivation (**MBA, DLR**) – less than a page.

The luminosity of a high energy collider determines the production rate of the particles of interest to the high energy physicist. Luminosity is ultimately limited by the dilution of the particle beam phase-space with increasing particle beam density, due to intra-beam scattering (IBS) and beam-beam effects.

Electron cooling and conventional stochastic cooling are ineffective at very high energy beams. For the former it is extremely difficult to implement at ultra-relativistic energies with a notable example being the electron cooling system with 4.3 MeV electrons in Fermilab’s Recycler 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 combat emittance in high energy 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 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 Kicker-Undulator (KU). The wave-packet meets its parent particle in the KU and their interaction gives a small kick in energy to the particle.

Since the sign and amplitude of the energy kick 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 at least in principle significantly enhance performance. 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 attempts is they rely on a relatively short bypass 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.

For this scheme to be successful we must first demonstrate stability of the light path which can be accomplished by feeding back on an interference pattern generated with a narrow-band laser propagating through the light path. Having done this the passive OSC can be demonstrated and finally the amplifier, developed in parallel with the previous steps, can be inserted to demonstrate high-gain active OSC in CESR.

### Unique role of Cornell for the proposed research

Uniqueness of CESR: DLR – each a paragraph

The Cornell Electron Storage Ring (CESR) is uniquely instrumented for the study of innovative storage ring optics and dynamics of electron and positron beams. The ring 768m circumference 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 to inform 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 nsec 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.

References are included like so [1][2]. Go to Insert -> Cross-references, select Reference type: Numbered item; Insert reference to: Paragraph number.

Previous NSF funding: DLR

An existing NSF grant supports development of an experimental program to demonstrate and explore 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 4GeV without damping wiggles. (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 2mm. (4) Computer model of relevant beam dynamics, as well as generation, propagation, and interaction with radiated electromagnetic fields, that permits detailed simulation of cooling dynamics, including sensitivities to mis-alignments, instabilities, field errors, field variation, etc. (5) assembly of a team of talented young scientists with the expertise to perform this exquisite experiment.

**Relation to 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 [cite Jarvis18]. 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 incoherent (heating) kicks of neighboring particles to contribute to the damping rate. The presence of incoherent heating is well known from ordinary stochastic cooling and warrants study in its optical analog; and can be done in CESR. Although an active test of the OSC in IOTA is planned, the short bypass used in the demonstration puts a serious constraint on the amplifier design preventing the development of one with significant gain. Since in this proposal we aim to develop a long bypass -that lifts these restrictions- CESR is in a unique situation 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.

Synergy with the Center for Bright Beams: IVB

### Overview of the proposed research

Basically, a summary of what’s proposed **(JMM)**

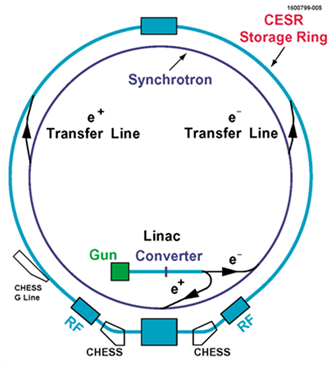
## Multiple Investigators

In applications with more than one senior investigator, the accomplishments, milestones, and plans of each senior investigator must be clearly identified. Reviewers will be asked to apply the review criterion to the information provided for each senior investigator and these evaluations will be used as input to the funding decisions.

### Synergies between the (co)-PI’s

A short spiel about why 3 PI’s and what each one brings to the table - **JMM**

**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).*



[Some old text follows] This proposal brings together accelerator science experts and a computational physics theorist with the common goal of extending the way that accelerators are controlled and optimized. The combined expertise includes: in-depth understanding of beam dynamics, not only of storage rings [1], … development of powerful accelerator simulation and optimization tools [3] numerous theoretical tools from statistical… Well instrumented accelerator – the large scale CESR ...

### CESR & Beam Dynamics Modeling

**DLR -** 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.

### Laser Expertise at Cornell

A paragraph on laser expertise at Cornell. – **ACB**

## Proposed Research and Methods (MBA & others)

Identify the hypotheses to be tested (if any) and details of the methods to be used including the integration of experiments with theoretical and computational research efforts.

### OSC Bypass Requirements for Electrons, including undulators

DLR, MBA





The electron beam circulates counter clockwise in the storage ring. Radiation emitted by electrons in the pickup undulator (centered at 35m,240m in the figure) 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.

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 pathlengh 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 Tables I and II. 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.

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

Table . Undulator Parameters

|  |  |
| --- | --- |
| 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 . Cooling and lattice parameters

### OSC Bypass Requirements for Light

MBA, DLR

### Stability Requirements for the Long Bypass

MBA

### Laser Path Feedback

ACB, MBA

### Laser Amplifier

ACB, MBA

## Project Objectives

This section should provide a clear, concise statement of the specific objectives/aims of the proposed project.

All (PIs)

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

### Reduced Test of Interferometric Stability

Using a dedicated laser to demonstrate ability to stabilize the light path down to 100 nm.

### Install and Characterize Undulators

Period? Number of poles? Planar vs helical?

### Demonstration of Passive Cooling

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

### Laser Amplifier

Proceeds in parallel with the above.

### Demonstration of Active Cooling

Ultimate victory.

## Proposed Resources

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?

## Timetable of Activities

This section should outline, year-by-year, all the important activities or phases of the project, including any activities planned beyond the project period. Successful applicants must use this project timetable to report progress.

DLR

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

Year 1.

Undulator installation & characterization

Bend chamber manufactures

Setup the light path from pickup to kicker locations

Year 2.

Install bend chambers during the downtime

Reduced Test of Interferometric Stability

4.2 Install and Characterize Undulators

4.3 Demonstration of Passive Cooling

4.4 Laser Amplifier

4.5 Demonstration of Active Cooling

Year 3.

.

## Appendix 1: Biographical sketches

## Appendix 2: Research Scientists

## Appendix 3: Current and Pending Support

## Appendix 4: Bibliography and References Cited

1. 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)
2. 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)
3. D. Sagan, I.V. Bazarov, J.Y. Chee, J.A. Crittenden, G. Dugan, K. Finkelstein, G.H. Hoffstaetter, C.E. Mayes, S. Milashuk, D. L. Rubin, J.P. Shanks, and R. Cope, "Unified Accelerator Modeling Using the Bmad Software Library", Proceedings of the 2011 International Particle Accelerator Conference, San Sebastian, Spain, (2011) 2310-2
4. S. Nagaitsev, et al., Phys. Rev. Lett. 96, 044801 (2006).
5. S. van der Meer. Stochastic Damping of Betatron Oscillilations in the ISR. Geneva,

Switzerland (1972).

1. R. J. Pasquinelli., JINST 6 T08002 (2011)
2. V. N. Litvinenko, et al. in Proceedings of the International Workshop on Beam Cooling

and Related Topics (COOL'17), Bonn, Germany, p. 77 (2017).

1. V. A. Lebedev et al., in Proceedings of the North American Particle Accelerator

Conference (NAPAC'13), Pasadena, CA, USA, p.422 (2013).

1. A. A. Mikhailichenko, M.S. Zolotorev, Phys. Rev. Lett. 71, 4146 (1993).
2. M. S. Zolotorev, A. A. Zholents, Phys. Rev. E 50 3087 (1994).
3. V.A. Lebedev, ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-

Brightness Hadron Beams HB2010, Morschach, Switzerland (2010).

## 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