# Award 1734189 - Annual Project Report

Reporting Period: 09/01/2017 - 08/31/2018

## **Accomplishments - What was done? What was learned?**

### **What are the major goals of the project?**

[List the major goals of the project as stated in the approved application or as approved by the agency. If the application lists milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion. Generally, the goals will not change from one reporting period to the next. However, if the awarding agency approved changes to the goals during the reporting period, list the revised goals and objectives. Also explain any significant changes in approach or methods from the agency approved application or plan.]

Optical stochastic cooling (OSC):

1. Code to model the optical stochastic cooling mechanism in CESR that enables simulation of the equilibrium parameters of the cooled beam. The simulation will be used to explore dependencies such as cooling range and range, on details of the bypass, beam parameters, beam energy, kickup and kicker undulator parameters, bunch current, bunch length, lattice parameters, etc, and to guide the design of the delay bypass and the experimental method.
2. Operation and characterization of beam dynamics in the storage ring (CESR) operating at the low energy and low bunch current required for the OSC test
3. Design, fabrication, installation and tests of the delay bypass and pickup and kicker undulators
4. Measurement of the radiation spectrum from pickup and kicker undulators and interaction of electron beam in kicker undulator with radiation emitted by the pickup. Demonstrate passive cooling.

### **What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

[For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive and negative); and 4) key outcomes or other achievements. Include a discussion of stated goals not met.

As the project progresses, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.]

**Major Activities:**

***Optical Stochastic Cooling (OSC) Simulation***

*During this past year we developed an elaborate particle tracking simulation of the dynamics of optical stochastic cooling in CESR.*

The simulation includes; measurement of position in pickup undulator, propagation of the particles through the delay bypass, interaction with radiation in the kicker undulator, and finally propagation around the CESR ring. Radiation excitation and damping is also included, as are nonlinearities from sextupoles and edge effects. The simulation results are consistent with theoretical expectations and are used to guide and inform design of lattice and bypass.

We are in process of incorporating radiation and propagation of electro - magnetic fields from pickup to focusing optics and then interaction with electrons in the kicker undulator, enabling a complete ’end-to-end’ simulation of beam cooling.

***Operation of CESR at low energy for OSC***

*We identified the optimum beam energy for the experiment and demonstrated in dedicated machine studies that the storage ring can be operated at that energy.*

The beam energy and lattice properties for the demonstration of OSC are chosen to maximize our sensitivity to the cooling effect at a wavelength (800 nm) for which optical amplifiers are readily available.

1. We maximize passive gain by minimizing equilibrium emittance of the lattice (in the absence of OSC). Emittance generated by radiation increases with beam energy, while the contribution to emittance from intra-beam scattering decreases with energy (defining an energy range).
2. The magnetic field of the pickup and kicker undulators consistent with first harmonic radiation at 800 nm, increases with beam energy (lower energy is advantageous).
3. Radiation damping time decreases with increasing energy (higher energy is preferred).

Our lattice is designed to satisfy the constraints imposed by OSC at 1GeV.

The nominal operating energy of the CESR ring for the CHESS xray program is 5.3 GeV. Operation at low energy (1GeV) is challenging for the following reasons.

1. Radiation damping time increases from 20ms at 5.3 GeV to 1 second at 1 GeV. The injection repetition rate therefore is necessarily reduced from 60 Hz to <1 Hz.
2. There are a dozen permanent magnet undulators and wigglers (x-ray sources) with fixed field. The good field region of the compact undulators is very narrow. Sensitivity to fringe fields and nonlinearities increases rapidly with decreasing beam energy. (The narrow gap undulators are the source of x-rays for the CHESS program. The OSC lattice is designed for compatibility with the undulators in order to minimize overhead transitioning from operation for CHESS to studies of OSC.)
3. Magnet power supplies regulate poorly at very low excitation.

During the past year 67 hours of machine time was dedicated to learning to inject and store beam at 1 GeV and to characterize beam quality. We established the sensitivity of the beam position monitor system, and beam size monitors to the very low beam currents at which the cooling experiments will be performed.

To inject at 1GeV, beam was extracted from the synchrotron part way through the ramp, rather than at the peak of cycle, as has been our practice. The fast timing system was configured to kick the bunch from synchrotron to storage ring at the appropriate energy and into a well defined storage ring RF bucket. As beam is accumulated in CESR using off axis injection, the transfer repetition rate can be no higher than the radiation damping rate. The radiation damping time is 20 ms at 5.3 GeV, as compared to ½ second at 1.0GeV. Accumulation at 1GeV limited the injection repetition rate to 0.5 Hz.

The optical stochastic cooling mechanism depends on bunch charge. Intra-beam scattering blows up the equilibrium emittance, limiting the cooling range. In addition, the stochastic cooling rate scales inversely with the number of particles in the bunch. Sensitivity to the cooling phenomenon therefore increases with decreasing bunch charge. The experiment will be performed with the minimum bunch charge sufficient to measure bunch size. We developed and tested techniques for characterizing (and correcting) the ring guide field, orbit and lattice functions, with as little as 50 micro-amps (~109) electrons. We demonstrated that our visible light beam size monitor, and streak camera can resolve size of a bunch with as few as 107 electrons.

In summary, we demonstrated viability of a test of optical stochastic cooling in CESR at 1GeV.

***Lattice and bypass***

*We designed a storage ring lattice and delay bypass, consistent with passive cooling in both transverse and longitudinal dimensions operating at optical wavelength of 800 nm.*

The lattice is based on the layout of the storage ring that includes the CHESS (x-ray) narrow gap insertion devices. Design energy is 1 GeV. The bypass delays the electron bunch with respect to propagating radiation by 2-5mm. The design defines the guide field of the bypass and informs the engineering design of the bypass magnets and vacuum chambers, which is just now beginning.

**Specific Objectives:**

1. Demonstrate viability of operating the storage ring at 1GeV with 0.5 sec radiation damping time
2. Develop numerical model of cooling dynamics as basis for simulation and characterization of lattice and bypass.
3. Design of lattice and bypass with appropriate sensitivity to demonstrate passive cooling
4. Specification of guide field of delay bypass as basis for engineering design

**Significant Results:**

1. Successful test of the operation of storage ring at low energy and long radiation damping time.
2. Numerical model of cooling dynamics that is used to characterize lattice and bypass
3. Design of lattice and bypass and characterization with simulation
4. Specification of optics of delay bypass

**Key Outcomes or Other Achievements:**

### **What opportunities for training and professional development has the project provided?**

[Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.]

Graduate students and postdocs participated in machine studies to explore low energy behavior of the storage ring, as well in other unrelated studies, thus providing hands on control room experience. With guidance from scientific staff, students developed specialized tools to collect and analyze beam data, and to manipulate the storage ring guide field through the accelerator control system. Students and postdocs worked one on one with a senior accelerator scientist to implement new modules in our accelerator code library, extending the reach of our simulations. Young scientists regularly present findings in group meetings and at accelerator conferences.

### **How have the results been disseminated to communities of interest?**

[Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.]

Results of the OSC project are relatively new and have yet to be shared outside of the laboratory. During the next year we anticipate presentations at accelerator conferences.

### **What do you plan to do during the next reporting period to accomplish the goals?**

[Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.]

*Complete end to end simulation*

The complete simulation will have two components; particle tracking, and emission, propagation and interaction with electromagnetic radiation. The tracking component is complete. The electromagnetic radiation component will be completed in the next reporting period, enabling a complete simulation of the OSC process.

*Fabricate components of delay bypass*

The magnetic optics and layout of the pickup and kicker undulators and the delay bypass are complete. Components will be designed and fabricated during the next reporting period*.*

*Test 1GeV operation of reconfigured storage ring*

The storage ring is being reconfigured (summer-fall 2018) with additional xray beam lines and insertion devices. The new layout will require a new low energy lattice. The 1GeV lattice compatible with the upgraded layout will be tested during the next reporting period.

## **Products**

**Journals / Juried conference papers**

[All published journals, including papers from juried/peer-reviewed conference proceedings, will need to be deposited in the NSF Public Access Repository (NSF-PAR). Once deposited and validated, the publications will then be automatically included in your project report under the Products section.]

**Other conference paper / presentation**

**Technologies and Techniques**

**Thesis / Dissertation**

**Website**

Documentation including presentations in group meetings, design parameters, description of lattice and bypass, results of simulations, etc., are accessible at

<https://www.classe.cornell.edu/~dlr/osc/documentation/osc.html>

**Other products**

## **Participants / Organizations**

### **What individuals have worked on the project?**

[Provide the following information for each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation.

Provide the name and identify the role the person played in the project. Indicate the nearest whole person month (Calendar, Academic, Summer) that the individual worked on the project. Show the most senior role in which the person has worked on the project for any significant length of time. For example, if an undergraduate student graduates, enters graduate school, and continues to work on the project, show that person as a graduate student, preferably explaining the change in involvement.

Describe how this person contributed to the project and with what funding support. If information is unchanged from a previous submission, provide the name only and indicate "no change".

Identify whether this person is collaborating internationally. Specifically is the person collaborating with an individual located in a foreign country and whether the person had traveled to the foreign country for this award as part of that collaboration and duration of stay. The foreign country(ies) should be identified.

For NSF purposes, this should read: Identify whether this person is collaborating internationally on this project.

Example:

Name: Mary Smith Project Role: Graduate Student Nearest person month worked: 5 Contribution to Project: Ms. Smith has performed work in the area of combined error-control and constrained coding. Funding Support: The Ford Foundation (Complete only if the funding support is provided from other than this award.) Collaborated with individual in foreign country: Yes Country(ies) of foreign collaborator: China Traveled internationally for this award: Yes If traveled internationally, duration of stay: 5 Months]

Name: Michael Ehrlichman

Project Role: Post doctoral research associate – 4 FTE months

Contribution: Dr. Ehlrichman designed the delay bypass and contributed to the OSC machine studies

Name: Robert Meller

Project Role: Research Associate – 1 FTE month

Contribution: Dr. Meller configured the fast timing system to enable extraction of low energy beam from the synchrotron and participated in the OSC machine studies.

Name: Alexander Mikhailchenko

Project Role: Research associate – 4 FTE months

Contribution: Dr. Mikhailichenko worked on the fundamental physics of OSC, the design of the bypass, and to the design of an optical amplifier

Name: Suntao Wang

Project Role: Postdoctoral research associate – 4 FTE months

Contribution: Dr. Wang wrote the program that simulates the cooling dynamics and used it to characterize our evolving design. He made essential contributions to OSC machine studies and beam instrumentation

Name: Will Bergan

Project Role: Graduate student – 6 FTE months

Contribution: Mr. Bergan worked on the analysis of the OSC feedback mechanism. He computed the radiation in the pickup undulator, propagation of the electro-magnetic radiation through the optical telescope, and absorption of the radiation by in the kicker undulator. He also participated in all of the OSC machine studies

Funding Support: NSF graduate fellowship

Name: Robin Bjorkquist

Project Role: Graduate Student – 4 FTE months

Contribution: Ms. Bjorkquist developed methodology for measuring injection trajectories in the storage ring and collating multiple low current beam position measurements to achieve resolution necessary to correct orbit and optics. She participated in all of the OSC machine studies.

Funding Support: This award

Name: David Rubin

Project Role: Co-Principle Investigator – 2 FTE months

Contribution: Professor Rubin provides leadership and direction

### **What other organizations have been involved as partners?**

[Describe partner organizations - academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) - that have been involved with the project. Partner organizations may provide financial or in-kind support, supply facilities or equipment, collaborate in the research, exchange personnel, or otherwise contribute.]

### **What other collaborators or contacts have been involved?**

[Some significant collaborators or contacts within the recipient's organization may not be covered by "What people have worked on the project?" Likewise, some significant collaborators or contacts outside the recipient's organization may not be covered under "What other organizations have been involved as partners?"

For example, has there been any: collaborations with others within the recipient's organization; especially interdepartmental or interdisciplinary collaborations; collaborations or contact with others outside the organization; and collaborations or contacts with others outside the United States or with an international organization. It is likely that many recipients will have no other collaborators or contacts to report.]

## **Impact**

### **What is the impact on the development of the principal discipline(s) of the project?**

[Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research and/or pedagogical methods in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style). How the field or discipline is defined is not as important as covering the impact the work has had on knowledge and technique. Make the best distinction possible, for example, by using a "field" or "discipline", if appropriate, that corresponds with a single academic department (i.e., physics rather than nuclear physics).]

Techniques developed for low energy/low current operation of the storage ring, especially methodology for measuring properties of low current beams will be of general application in electron storage rings.

The modules created for simulation of the OSC dynamics are applicable to investigation of systems where there is self-interaction of the particle beam with electro-magnetic radiation.

A successful demonstration of the concept of optical stochastic cooling in CESR will likely lead to proposals to incorporate OSC in high energy proton and heavy ion storage rings to enhance their performance.

### **What is the impact on other disciplines?**

[Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.]

Insofar as electron storage rings are the source of x-rays for countless experimental investigations in chemistry, biology, materials science, and physics, enhanced techniques for measuring and characterizing particle beams in storage rings will impact those disciplines

Optical stochastic cooling can reduce emittance and enhance performance of proton and heavy ion colliders, thus benefiting particle and nuclear physics.

### **What is the impact on the development of human resources?**

[Describe how the project made an impact or is likely to make an impact on human resource development in science, engineering, and technology.]

The project provides a rare opportunity for students and young scientists to get hands on accelerator experience and training in accelerator physics and technology, an increasingly important technology for many fields of research, medicine and industry.

### **What is the impact on physical resources that form infrastructure?**

[Describe ways, if any, in which the project made an impact, or is likely to make an impact, on physical resources that form infrastructure, Including physical resources such as facilities, laboratories, or instruments.]

A delay bypass will be fabricated, installed in the storage ring and commissioned and tested, thus enhancing the physical resources of the accelerator complex.

### **What is the impact on institutional resources that form infrastructure?**

[Describe ways, if any, in which the project made an impact, or is likely to make an impact, on institutional resources that form infrastructure]

### **What is the impact on information resources that form infrastructure?**

[Describe ways, if any, in which the project made an impact, or is likely to make an impact, on information resources that form infrastructure,]

### **What is the impact on technology transfer?**

[Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use. Including: transfer of results to entities in government or industry; instances where the research has led to the initiation of a start-up company; or adoption of new practices.]

### **What is the impact on society beyond science and technology?**

[Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world. For example, in areas such as: improving public knowledge, attitudes, skills, and abilities; changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or improving social, economic, civic, or environmental conditions.]

The project trains young scientists in the technology and operation of particle accelerators. Accelerators are an increasingly important tool for research, medicine, and industry. A trained workforce is essential to maintain leadership in this critical field.

## **Changes / Problems**

### **Changes in approach and reasons for change**

[Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.]

### **Actual or Anticipated problems or delays and actions or plans to resolve them**

[Describe problems or delays encountered during the reporting period and actions or plans to resolve them.]

### **Changes that have significant impact on expenditures**

[Describe changes during the reporting period that may have a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.]