Experimental Demonstration of Optical Stochastic Cooling at the Integrable Optics Test Accelerator

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Year Doctorate Awarded: 2009
Number of Times Previously Applied: 1

Topic Area: Accelerator Science and Technology Research and Development in High Energy Physics
DOE National Laboratory Announcement Number: **LAB 19-2019**

The proposed research program constitutes the world's first experimental demonstration of the physics and technology of Optical Stochastic Cooling (OSC), a high-bandwidth, beam-cooling technique that will advance the state-of-the-art, stochastic-cooling rate by more than three orders of magnitude. OSC is an enabling technology for next-generation discovery-science machines, including hadron, electron-ion and muon colliders. At present, a proof-of-principle demonstration with protons or heavy ions would involve prohibitive costs, risks and technological challenges [1]; however, demonstration of OSC with medium-energy electrons is a cost-effective alternative that enables detailed study of the beam-cooling physics, optical systems and diagnostics [2]. The proposed experimental program is well matched to DOE/HEP's mission, the scope and scale of an Early Career Award and the expertise, facilities, operations schedule and mission of the Fermi National Accelerator Laboratory (FNAL).

Beam cooling compresses a beam's phase space by damping incoherent particle motions. It is a principal means of increasing achievable luminosity, preventing emittance growth due to intra-beam scattering (IBS) and other effects, reducing beam losses and improving energy resolution. Beam cooling is an indispensable element of modern storage rings and colliders and has enabled fundamental breakthroughs in accelerator-based discovery science. For example, van der Meer's Nobel-winning stochastic cooling (SC) was vital in the accumulation of antiprotons and the delivery of the beam quality needed for the discovery of the W and Z bosons [3,4].

In a SC system, signals from electromagnetic pickups are used in negative-feedback systems to reduce the phase-space volume of a circulating beam in all degrees of freedom. If each individual beam particle's deviation from the reference particle could be sensed and corrected, then the total error in the beam could be removed in a single pass; however, in practice, the bandwidth of such a system determines the granularity of the phase-space sampling, and therefore the rate at which the incoherent particle motions can be damped. With a limited bandwidth on the order of several GHz, conventional SC systems become ineffective for the high-density beams of modern colliders and storage rings. The realization of higher-bandwidth cooling techniques, and their translation into operational systems, will be instrumental in achieving the performance targets, increasing economic feasibility and extending the discovery potential of future machines.

An extension of the SC principle to optical frequencies (~10^{14} Hz), termed OSC, would increase achievable cooling rates by three to four orders of magnitude. Moreover, OSC can provide powerful cooling over a large range in proton energy where no beam-cooling solutions presently exist (few hundred GeV to a few TeV). OSC was first suggested in the early 1990s by Zolotorev, Zholents and Mikhailichenko, and replaced the microwave hardware of SC with optical analogs, such as wigglers and optical amplifiers [5]. OSC's greatest strength also presents its principal challenge; very stringent tolerances must be met in design, engineering and experimental execution due to the short wavelength of the radiation. In the transit-time method of OSC, which is shown schematically in Figure 1 and upon which the proposed program is based, a beam particle emits an electromagnetic wavepacket while traversing a pickup undulator. This wavepacket is subsequently transported, with (active OSC) or without (passive OSC) amplification, and focused into a kicker undulator where it interacts resonantly with the same particle. Between the pickup and kicker, the particle traverses a magnetic bypass so that sufficient delay is created for the optical system and such that the particle's arrival time in the kicker, relative to the wavepacket, is proportional to its momentum deviation; thus the interaction in the kicker will drive the particle's momentum toward the design value. Specially introduced coupling between the horizontal and longitudinal degrees of freedom provides horizontal cooling, and subsequent coupling of the transverse dimensions yields cooling in all degrees of freedom.

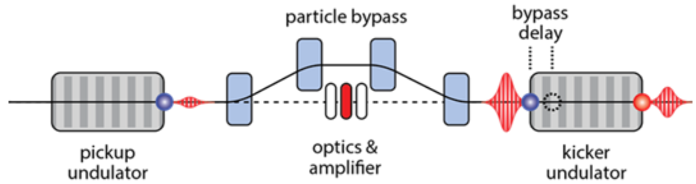

Figure 2: Simplified conceptual schematic of an optical stochastic cooling section.

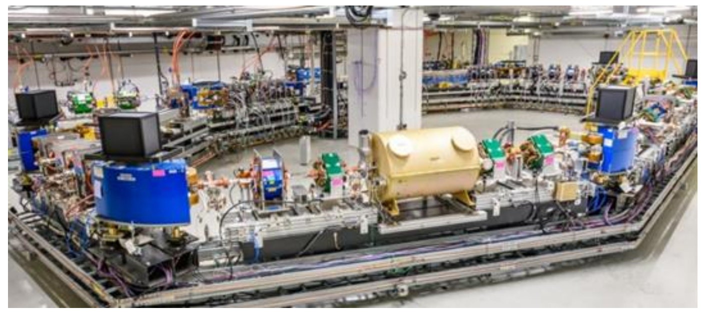

Figure 1: The IOTA ring at Fermilab's FAST facility

The demanding requirements of OSC were accounted for in the design of FNAL's recently commissioned Integrable Optics Test Accelerator (IOTA) ring, which is located at the Fermilab Accelerator Science and Technology facility (FAST) and pictured in Figure 2. As a result, it is the only machine capable of effectively demonstrating OSC in the near future. In particular, the IOTA OSC concept has the unique advantage that, in a passive configuration, the OSC rate will dominate synchrotron-radiation (SR) damping by nearly two orders of magnitude. This will provide an early and unambiguous demonstration of this transformational cooling physics. OSC demonstrations at other candidate facilities would require high levels of optical-power amplification to achieve comparable contrast with the SR damping. Note that such passive-OSC systems could be viable, state-of-the-art cooling solutions for proton rings operating between ~500 GeV and several TeV, and potentially for rapid cooling of the electron beam in an electron-ring cooler.

The proposed ECA program will dramatically expand the existing OSC research at FNAL and will produce important world's-first results in each of its three major thematic components: 1) passive-OSC demonstration, 2) active-OSC development and demonstration, 3) single-particle OSC and related quantum-science experiments.

Passive-OSC Demonstration

With its simplified optical system, the passive-OSC experiment significantly accelerates the timeline along which the fundamental cooling physics can be observed and explored; furthermore, it provides an opportunity to validate the performance of the magnetic lattice, electron bypass, undulators, radiation and beam diagnostics, vacuum and precision-motion systems and alignment procedures prior to the more complex active-OSC experiment. By the start of the ECA research program, the passive-OSC apparatus, which is shown in Figure 3, will have been installed in the IOTA ring. We will begin the program with a four to six-month operations period during which the lattice will be established and corrected, the light-optics aligned and all diagnostics validated. This run will culminate in the world's first demonstration of OSC, and a thorough exploration of the cooling physics will be compared against theory and simulations. We will also explore advanced modes of phase-space manipulation using the OSC physics and hardware.

Active-OSC Development and Demonstration

In this program component, we will develop suitable optical amplifiers for the active-OSC experiment and demonstrate their performance, first in the FAST laser laboratory and subsequently with undulator radiation on the FAST high-energy beamline. The optical amplifier will then be integrated with the OSC apparatus, installed in IOTA and used to demonstrate active OSC for the first time. Most hardware elements in the passive-OSC apparatus were designed to have forward compatibility with an active-OSC demonstration; however, some magnetic and vacuum elements must be redesigned to accommodate the modified accelerator lattice of the active program while still providing optimum OSC

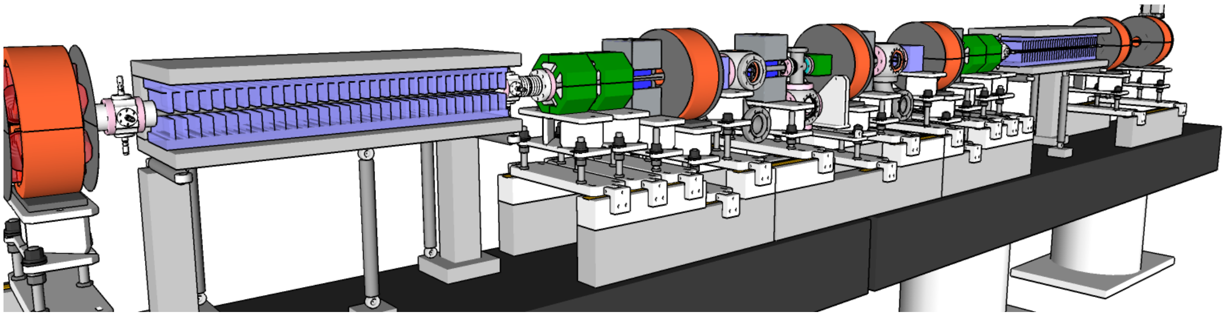

Figure 3: Solid model of the passive-OSC apparatus in IOTA.

performance. The initial active-OSC demonstration will take place at ~2 μm and use an amplifier based on Cr:ZnSe to increase the cooling rate by approximately a factor of two. Additional development will focus on methods and technologies needed to enable high-gain amplification for OSC.

Single-Particle OSC and Quantum-Science Experiments

During IOTA's commissioning, it was demonstrated that a single electron could be reliably injected, on demand, and characterized via SR for an extended period of time (~10 minutes). This capability, when combined with our OSC hardware, presents fundamental research opportunities that are unavailable at any other facility in the world. We will experimentally investigate the OSC physics of a single-particle, including quantum effects in emission and absorption and possibly radiation-reaction effects [6]. Furthermore, we will be able to study the nature and effect of quantum noise in the OSC process and demonstrate advanced phase-space manipulation of a single particle with its own radiation. Ancillary opportunities may be available such as the first demonstration of the emission of light with orbital angular momentum by a single-particle [7].

Since joining FNAL as a Peoples Fellow in 08/2017, the PI of this proposal has focused on the development of all aspects of the IOTA OSC concept: low-emittance lattice design and testing; simulation of the generation and transport of the undulator radiation; the design and engineering of critical experimental hardware, including magnetic elements, vacuum chambers, light optics and precision-motion and beam-diagnostic systems; and systems integration of the full experimental apparatus. FNAL also has a deep heritage in beam optics, SC, OSC and related areas, and its personnel and infrastructure are ideally suited for the proposed program; furthermore, this ECA is fully congruent with the IOTA science program and the schedule of its planned operations.

This DOE Early Career Award will support the development of a broad experimental program in OSC, and will produce groundbreaking results in passive, active and single-electron modes of operation. This program will improve the viability of OSC in future accelerators and could create substantial value for DOE via increased efficiency, performance and discovery potential of high-energy, high-intensity colliders. We are also establishing a variety of strategic partnerships, centered on IOTA's unique OSC capabilities, that provide exciting opportunities for cross-office benefit within DOE-SC (HEP, NP, BES); this includes technology development for a future EIC, techniques for advanced phase-space control, and quantum science with small numbers of stored electrons.

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