ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLM21

OPTICAL STOCHASTIC COOLING PROGRAM AT FERMILAB'S INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

Beam cooling enables an increase of peak and average luminosities and significantly expands the discovery potential of colliders. Optical Stochastic Cooling (OSC) is a high-bandwidth cooling technique that will advance the present state-of-the-art, stochastic-cooling rate by more than three orders of magnitude. A proof-of-principle demonstration with protons or heavy ions involves prohibitive costs, risks and technological challenges; however, exploration of OSC with electrons is a cost-effective alternative for studying the beam-cooling physics, optical systems and diagnostics. The ability to demonstrate OSC was a key requirement in the design of Fermilab's Integrable Optics Test Accelerator (IOTA) ring. The IOTA program will explore the physics and technology of OSC in amplified and non-amplified configurations. We also plan to investigate the cooling and manipulation of a single electron stored in the ring. The OSC apparatus is currently being fabricated, and installation will begin in the fall of 2019. In this contribution, we will describe the IOTA OSC program, the upcoming passive-OSC experimental runs and ongoing preparations for an amplified-OSC experiment

INTRODUCTION

The precise control of a relativistic charged particle using its own spontaneous radiation may have broad implications ranging from the science reach of future colliders to a deeper understanding of radiative processes in storage rings. The necessary capabilities for a research program in this area are provided by the physics and technology of Optical Stochastic Cooling (OSC), a high-bandwidth, beam-cooing technique that represents a more than three-order of magnitude advance in the state-of-the-art stochastic-cooling rate [1,2]. The physics of the OSC principle does not depend on the type of charged particle in any fundamental way, engineering challenges notwithstanding; therefore, the physics results, and some technology elements, of a cost-effective research program with electrons are universal and could be readily applicable to future systems for protons, heavy ions or muons [3,4].

Van der Meer's Nobel-winning Stochastic Cooling (SC) was vital in the accumulation of antiprotons and in the delivery of the beam quality required for the discovery of the W and Z bosons [5,6]. In a SC system, signals from electromagnetic pickups, operating in the microwave regime with a bandwidth on the order of several GHz, are used in negative feedback systems to reduce the phase-space volume of a circulating beam in all degrees of freedom [5-10]. SC systems have been successfully implemented at a number of facilities around the world, most recently at the Relativistic Heavy Ion Collider, where bunched-beam cooling was used to boost the collider's luminosity [11,12].

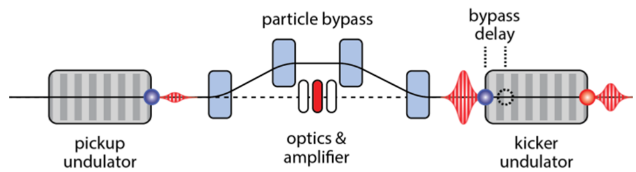

Figure 1: Simplified conceptual schematic of a transit-time OSC insertion.

Optical Stochastic Cooling

Extension of the SC principle to optical frequencies could increase cooling rates by three to four orders of magnitude and would be a significant advance in beam-cooling physics. 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 [1,2]. OSC's greatest strength, its high-bandwidth phase-space sampling, also presents a challenge; very stringent tolerances must be met in design, engineering and experimental execution due to the short wavelength of the radiation. Several variations on the original OSC concept have been proposed, and its use has been suggested for hadron, heavy-ion, electron-ion and muon colliders and also controlling emittance growth in electron storage rings [13-19]. Simplified proof-of-principle demonstrations have also been proposed at several facilities over the last decade or so [4,18-20].

In the transit-time method of OSC, shown schematically in Fig. 1, a particle's deviations from the reference particle are encoded in its arrival time at the kicker system by transiting a magnetic bypass [2]. The particle (an electron for purposes of discussion) first emits a radiation packet while traversing a pickup undulator (PU). The radiation packet is transported with or without amplification to a kicker undulator (KU) where it interacts with the same electron. Between the pickup and kicker, the electron traverses a bypass (chicane), which is designed such that a reference particle at the design energy will arrive at the KU simultaneously with the head of its radiation packet. The energy of the reference particle is unchanged by its interaction with the radiation field in the KU; however, in the linear approximation, all other particles will have a delay change that is proportional to their momentum deviation $\Delta p/p$, and will receive corresponding corrective kicks towards the design

* Fermi National Accelerator Laboratory is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
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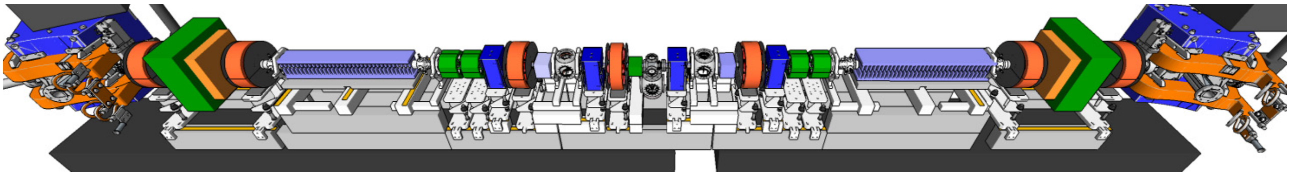

Figure 2: Integrated model of the OSC insertion in the full configuration; chicane dipoles (blue), OSC quads (small green), coupling quad (small green at center), sextupoles (orange), correctors and OSC undulators (light blue).

energy. Coupling of the cooling to all three degrees of freedom is straightforwardly achieved using a coupling quad in the electron bypass and operation on an x-y coupling resonance

OSC AT IOTA

The Integrable Optics Test Accelerator (IOTA) ring, recently commissioned at the Fermi National Accelerator Laboratory (FNAL), is a unique test facility for advanced beam-physics concepts and technologies [21]. IOTA's scientific program targets fundamental advancements in beam optics, beam cooling and space-charge compensation, and a robust capability to demonstrate OSC physics was used as a key requirement in the ring's design. The IOTA OSC concept is unique in that the OSC-damping rate will dominate the ring's synchrotron-radiation (SR) damping by a factor of ~20-40x in the absence of any optical amplification (SR: τ_x~1s, τ_s~0.5s; OSC: τ_x~26 ms, τ_s~28 ms for x-y uncoupled). This means that the physics of OSC can be thoroughly explored early in the experimental program, decoupled from the technological challenges related to high optical gain. R&D for a high-gain, amplified-OSC experiment will follow the initial passive experiments.

Experimental Apparatus and Program Plan

The initial experiments will be conducted in this "passive" (i.e. non-amplified) configuration at a nominal wavelength of 950 nm. The system, which is pictured in Fig. 2, consists of identical pickup and kicker undulators, a precision magnetic bypass (chicane), collider-style optics in the bypass (for maximizing horizontal cooling range), a coupling quad for mixing the longitudinal cooling into the horizontal plane, a primary optics chamber and two diagnostics chambers. To accelerate studies and minimize risk, the passive-OSC experiment will be conducted in two phases: minimal configuration and full configuration. The minimal configuration does not include the bypass sextupoles, which are used to correct nonlinear path lengthening in the chicane, and the OSC undulators. However, an existing undulator is available for insertion alternately at the PU and KU locations and can be used to fully validate the optical beamlines and diagnostics prior to the full OSC experiment. Initial experiments in the minimal configuration are set to begin in ~Nov. 2019, and experiments in the full configuration will follow in the ~Feb./Mar. 2020 timeframe.

We plan to operate at low intensities ($N_e<10^6$) to avoid excessive emittance growth due to multiple intrabeam scattering and beam losses due to Touschek scattering. Additionally, residual-gas scattering will knock beam particles out of the OSC cooling range, and ultra-high vacuum of $<10^{-10}$ Torr is required to mitigate this loss. The vacuum upgrades for achieving this goal are underway at IOTA. They will benefit both the OSC and the proton science programs. Particles scattered out of the OSC cooling range may accumulate at higher-order cooling zones and can be returned to the beam core by momentarily turning off OSC and allowing the particle to damp via SR.

Finally, fluctuations in the main bending fields or in the chicane dipoles will generate effective momentum errors relative to the fixed optical delay of the OSC bypass. To ensure that these errors do not confound the OSC process, the main bending and chicane fields will be stabilized to $\sim10^{-4}$ and $\sim10^{-5}$, respectively.

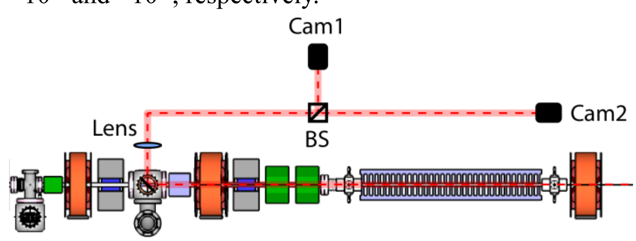

Figure 3: Alignment scheme for the e-beam and radiation in the PU; similar configuration is used for the KU.

Alignment and Diagnostics Systems

The nominal optical axis of the system will be defined using a laser-based alignment with two surveyed pinholes (~+/- 100 μm). To ensure good overlap of the e-beam and radiation in the KU, we require spatial alignment of <100 μm, and angular alignment of <100 μrad between the e-beam and the reference optical axis. This precision is achieved by imaging the radiation from two locations (upstream and downstream) in each undulator; a small pickoff mirror is inserted in the case of the PU. Knowing the transfer matrix for the light optics, we infer the error of the closed orbit at the center of the undulator (*dx,dy,dx',dy'*) relative to the reference optical axis. When fully aligned, the radiation spots overlap each other and the optical axis (HeNe laser). Full Synchrotron Radiation Workshop [22] simulations demonstrate that an imaging resolution of ~10s of μm and 10s of μrad is achievable over a range of +/- 5 mm and +/- 5mrad. Final spatial alignment of the PU radiation in the KU will be achieved by fine tuning the position of the optical lens (in the center vacuum chamber); if needed, the PU radiation can be imaged subtractively in the kicker diagnostics line by repeatedly inserting and removing the pickoff mirror shown in Fig. 3. This OSC alignment system also increases the number of sync.-light beam-position monitors by 50% (8 from the main IOTA dipoles and 4 from the OSC alignment system).

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Longitudinal alignment of the PU and KU radiation will be achieved using independently rotating, precision delay plates. A control algorithm maps the two rotational degrees of freedom onto the optical delay and the vertical offset of the PU radiation, and the system is capable of rapid inversion of the cooling zones (~10 ms; i.e. short compared to the OSC time). When the system is nearly aligned and the delay is swept, the total first harmonic radiation power from the undulators will be heavily modulated (~100%) as the PU and KU wave-packets coherently interfere; this signal is an unambiguous sign that OSC is underway.

PRELIMINARY EXPERIMENTS

IOTA's initial commissioning and science run was completed in April, 2019. While the facility was primarily configured for studies in nonlinear integrable optics (NIO), a low-emittance (LE) test lattice, which emulates many of the properties of the OSC lattice, was designed so that IOTA could be tested in the OSC regime and valuable operational experience could be gained. This LE lattice, shown in Fig. 4, was designed for pc=100 MeV, betatron tunes of Q_x=Q_y=5.3, and an uncoupled equilibrium emittance of ε_x=1.65 nm. For convenience, the lattice functions at the injection point were matched to those of the primary NIO lattice; this minimized the amount of injection tuning that was required when changing lattices.

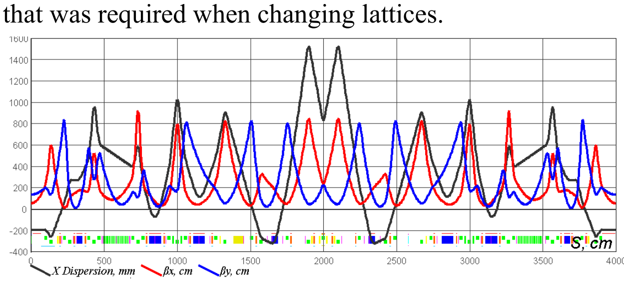

Figure 4: Lattice functions for the LE test lattice in IOTA.

The first-generation electronics for IOTA's electromagnetic beam position monitors (BPM) were optimized for high-charge operation and short bunches and could not be used for lattice correction at the lower intensities supported by the LE lattice. The coming upgrade to the IOTA BPM system will address this issue, and with the improved performance, LOCO corrections at low charge will be possible. Furthermore, all BPMs will be equipped with preamplifiers, and will support turn-by-turn capability that will enable tune and optics measurements at the upper end of the OSC charge range.

All orbit and lattice corrections for the current experiment were performed using 7 of the 8 IOTA sync.-light BPMs. The decay of the stored beam in the corrected lattice (driven primarily by Touschek scattering), as measured on one of the sync.-light BPMs, is shown in Fig. 5. To support the BPM upgrade, preamplifiers were installed on two of the IOTA BPMs. This enabled the tune measurements at low bunch charge. Also, a prototype π-mode, vertical-emittance diagnostic was successfully tested in preparation for measuring the small beam sizes during OSC. Sample results from these measurements are shown in Fig. 6. The minimum tunes split achieved on the coupling resonance was limited to ΔQ=0.014 due to the small number of available SR BPMs and power-supply limitations for IOTA's skew-quad corrector magnets. Recent upgrades to IOTA's power systems and the availability of the BPMs described above should significantly improve the quality of correction for the actual OSC lattice.

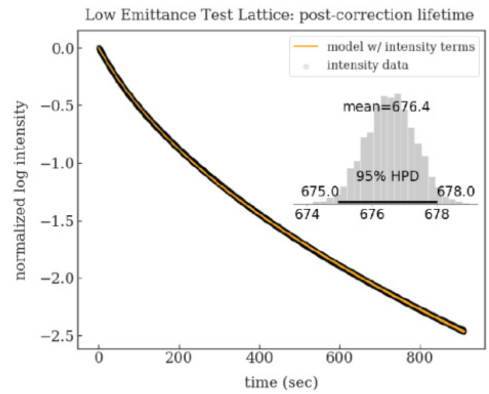

Figure 5: Beam decay in the corrected LE lattice; (inset) posterior distribution for the low-charge lifetime.

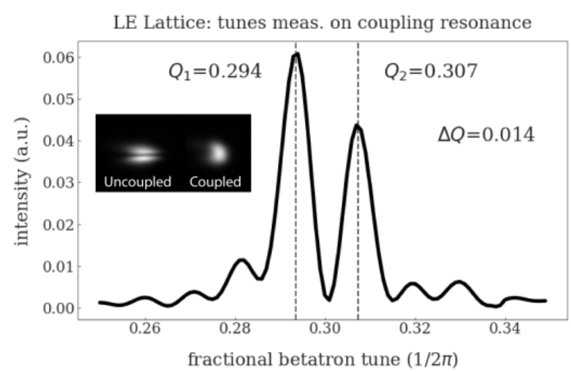

Figure 6: Tunes measurement for the corrected LE lattice; inset shows π-mode SR images both on the coupling resonance (right) and with the tunes split (left).

Finally, during these preliminary experiments, we successfully demonstrated the on-demand injection, storage and characterization of single (or few) electrons in the LE lattice for long periods of time (~10 min). Figure 7 shows SR images of a single electron as it undergoes large betatron oscillations excited by collisions with gas molecules. This is an important step towards single-electron OSC, which may enable a variety of unique quantum-science experiments to be carried out at IOTA.

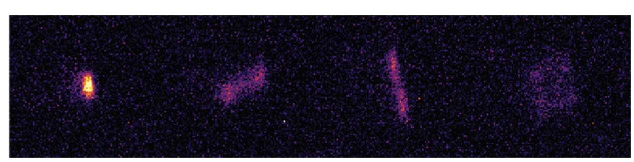
Figure 7: SR images of an individual electron undergoing large betatron oscillations in IOTA due to residual-gas scattering. (from left to right) fully damped single electron; large amplitude horizontal, vertical, and mixed betatron oscillations.

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