OPTICAL STOCHASTIC COOLING EXPERIMENT AT THE MIT-BATES SOUTH HALL RING

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Abstract

Optical stochastic cooling (OSC) is a technique formulated for very fast cooling of charged particle beams of high energy and high brightness which has yet to be experimentally realized. An experiment to demonstrate the principle of OSC has been designed using electrons at 300 MeV in the MIT-Bates South Hall Ring (SHR). The SHR is a particularly suitable location for studying OSC physics due to its layout, energy range, and availability for dedicated use. The experiment will operate the SHR in a configuration designed for simultaneous transverse and longitudinal cooling. The cooling apparatus including a magnetic chicane, undulator system, and optical amplifier has been designed for compatibility with existing technology. Such studies are a necessary prerequisite to implementation in a high-energy collider environment.

INTRODUCTION

Many of the proven techniques for beam cooling diminish in effectiveness for beams of high energy and high brightness. Stochastic cooling [1], a beam-based feed-forward technique for cooling of stored particle beams, encounters limits on the cooling time of very intense bunched beams due to the bandwidth of RF amplification systems. The use of higher bandwidth feed-forward systems would effectively divide bunches into a larger number of samples with fewer particles in each to be cooled, thereby allowing for more rapid cooling.

The yet-to-be-demonstrated technique of optical stochastic cooling [2] combines aspects of microwave stochastic cooling with techniques developed for coherent radiation in light sources. Based on an ultra-broadband feed-forward system, OSC would significantly reduce the bandwidth-limited cooling time present for microwave stochastic cooling. The transit-time method of OSC, formulated by Zolotorev and Zholents [3], would provide momentum kicks to a stored charged particle beam via interaction with its own amplified radiation while traversing a magnetic undulator for reduction of the emittance. Successful implementation of the OSC technique is expected to yield fast cooling of protons/antiprotons and heavy ions at energies in excess of several hundred GeV per nucleon.

The OSC technique, shown schematically in Figure 1, entails construction of a nearly isochronous magnetic delay line for charged particles, installation of two undulators, development of a high gain optical amplifier, and use of fast diagnostic and feedback systems. Estimates of OSC times and design parameters have been made for existing facilities, including RHIC [4], and the technique has been considered for future facilities such as a muon collider.

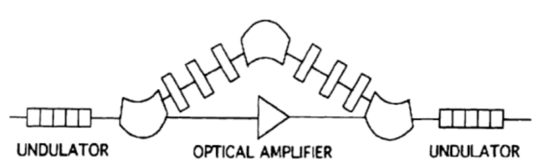

Figure 1: Schematic of an optical stochastic cooling insertion in a storage ring.

There are significant technical challenges in producing a working OSC system. The costs and time required for implementation of such systems in a new or existing high-energy hadron machine will be high. For hadrons or ions, presently achievable optical amplifier output power would necessitate operation of an OSC system well below optimal gain, thereby limiting the achievable cooling time. The development of necessary OSC diagnostic techniques could proceed more readily in a system in which OSC can be achieved in real time. Thus, a demonstration of OSC physics using electrons, which can be much more quickly cooled than high-energy hadrons, is an essential step prior to implementation at a high-energy facility.

A unique opportunity for such a study presently exists using the MIT-Bates South Hall Ring (SHR), shown in Figure 2, which has a particularly suitable geometry. For an OSC experiment with electrons, it is essential to operate at an energy at which the ring's synchrotron radiation damping time is long compared to the expected OSC cooling time. Because of the large radius of curvature (9.1 m) in its dipole arcs, operation of the SHR near 300 MeV yields a beam with a synchrotron radiation damping time of approximately 5 seconds. This synchrotron damping time and the counteracting growth rate of the beam due to intrabeam scattering (IBS) are both long compared to the cooling time for an OSC system operating at optimal gain. The SHR contains two long straight sections with sizable gaps between magnetic elements for installation of the OSC experimental apparatus. The location permits placement of beam diagnostics for the experiment in a shielded area of the SHR northern arc. Furthermore, an experiment to study OSC physics can be performed as a dedicated experiment without impacting ongoing operations. Although beam operations for nuclear physics experiments at MIT-Bates ceased in 2005, a recent test run of the accelerator established the continuing viability of stored beams in the SHR for this energy regime.

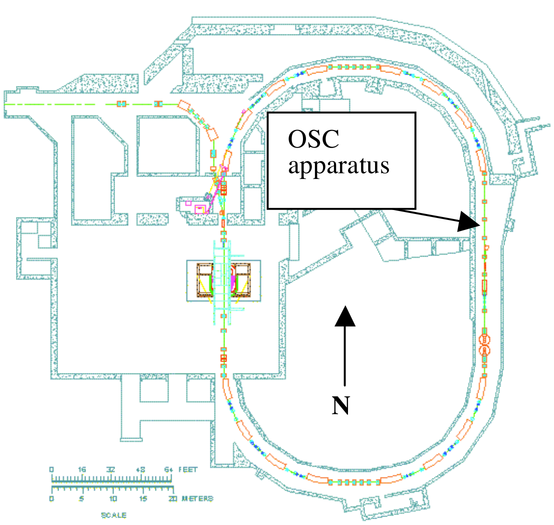

Figure 2: Layout of the South Hall Ring. The OSC experiment will be located in its eastern straight section.

EXPERIMENT

The primary goal of this experiment is to demonstrate optical stochastic cooling for the first time. A secondary goal is to produce apparatus with the potential for scaling to the high-energy high-brightness regime. Hence beam conditions and features of the experimental apparatus have been chosen specifically so as to maximize the chance of a successful demonstration of OSC. The strategy for this experiment will be to observe effects of cooling on equilibrium properties of a stored beam.

Electron Beam

An overview of design parameters for the electron beam for the OSC experiment is given in Table 1. Previous experimental studies of SHR lattices have confirmed the accuracy of past models of the SHR beam to a high degree [5].

Table 1: Design SHR beam parameters for an OSC demo.

Beam Property	**Design Value**
SHR Energy (MeV)	300
RF Voltage (kV)	14
Particles/bunch	1×10^{8}
Average current (mA)	0.3
Equilibrium emittance, ε_x (nm)	96
Energy Spread	1.67×10^{-4}
rms bunch length (mm)	9.8
Synchrotron damping τ_x (sec.)	4.83
Touschek lifetime (min)	1.45
Lattice para. at OSC Insertion	β=3m, η= 6m, $\eta'=\eta/\beta$

One of the challenges in observing OSC with electrons is to separate its effect from other beam heating and cooling forces, which act on a comparable time scale. While the damping effects due to synchrotron radiation can be readily controlled with low energy operation, heating due to intrabeam scattering must be carefully modeled as a function of bunch intensity. The effects of intrabeam scattering for the SHR have been calculated [6] using *elegant* [7] and are included in Table 1. The cooling effects will be observed by measuring changes of beam profile (transverse and longitudinal) in equilibrium before and after cooling.

The calculations also consider the effect of Touschek scattering on the beam lifetime for low-energy stored electron beam equilibrium properties. During the most recent SHR study, stored electron beams were established at 325 MeV with average intensities comparable to those which will be needed for the OSC experiment. Sustained SHR operation at energies near 300 MeV appears to be feasible and not to be prohibited by Touschek lifetime considerations.

The OSC experiment will use a few-bunch pulsed mode for beams circulating in the SHR, with up to 12 (out of 1812) RF buckets populated with electrons. Each bunch traverses the OSC apparatus at the SHR revolution frequency of 1.576 MHz. Operation of the electron beam in pulsed mode permits the use of pulsed amplification for the cooling system. It also reduces the effects of multi-bunch instabilities, which can affect the beam profile. The bunch structure of the SHR electron beam will be set to match the maximum repetition rate for the OSC amplifier system to allow efficient cooling. A mode-locked laser system [8] has been developed to serve as a new driver for the Bates photoinjector to be phase locked to the accelerator RF systems and to the OSC amplifier. This system will provide considerable freedom to vary the bunch intensity through stacking. A nominal initial bunch intensity of $1.0*10^8$ particles has been chosen.

An OSC lattice has been designed with a horizontal equilibrium emittance of ε_x=96 nm for this intensity. This relatively large value mitigates the initial effect of intrabeam scattering. An x-y coupling of 10% is chosen. The OSC lattice has been designed with a high dispersion (η=6m) at the exit of the OSC apparatus to couple longitudinal and transverse cooling. In combination these two features should permit strong transverse damping of the beam.

OSC Apparatus

The OSC demonstration will utilize a compact experimental apparatus. A summary of selected parameters for the apparatus is given in Table 2.

Table 2: Parameters for the OSC apparatus.

Parameter	**Value**
Chicane length (m)	6
Chicane dipole bend (mrad)	65
Chicane Optics: R51/R52/R56	8.6×10^{-4} / 2.52 mm / -12 mm
Undulator length L_u (m)	2.0
Undulator periods	10
Radiation wavelength λ (μm)	2.06

Its centerpiece is an ultra- broadband short pulse optical parametric amplifier [9] for the undulator radiation, which has several virtues. Optical stochastic cooling requires an ultra-broad optical amplification bandwidth, which is present with well- established nonlinear optical materials. Short pulse OPA relies on the beating of a signal pulse and pump pulse with an idler to produce large gain within a very short medium. Power gains in excess of 10^3 are readily achievable in only a few millimeters of crystal length and these amplifiers can be scaled to yield large average power output. They also introduce minimal phase delay in the amplification and the phase delay over the optical bandwidth can be controlled to a fraction of an optical cycle as needed to achieve OSC.

The low delay time required for this method of amplification permits the design of a compact magnetic chicane for the electron beam with fixed optics, shown schematically in Figure 3. The bypass must preserve a small well-defined correlation between particle momentum and transit time to define the path length difference between electrons in the bypass and the amplified radiation from the first undulator to a fraction of the wavelength of the undulator radiation. Calculations of electron optics for the magnetic bypass have been performed using TRANSPORT for a small angle (ψ=65mrad) chicane including four dipole magnets and a split lens quadrupole. The optical amplifier will be housed within the same enlarged vacuum chamber as electrons traversing the magnetic bypass.

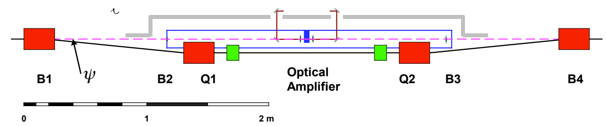

Figure 3: Schematic design for the OSC chicane.

The installation of a chicane for electrons effectively changes the circumference of the SHR. The total change in electron path length introduced by this chicane is only about 6 mm. Such a change can be accommodated with slight modifications (Δf=90 kHz) to the RF frequency of the SHR cavity (f_0 = 2856 MHz) and the injection linac, as was successfully demonstrated in a recent test. The chicane design also does not require sextupoles to control the chromaticity. Power supply accuracy and stability ($\Delta I/I \sim 10^{-4}$ over 1 hour) requirements for the magnets are at a level which can be met by commercially available devices. Alignment tolerances for the chicane magnets are also modest.

The OSC experiment requires fabrication and installation of two identical planar permanent magnet undulators. The undulator design includes adjustable operating gaps which will be tuned to yield radiation peaked at a wavelength of 2.06 µm. The overall gain of the cooling system depends on the undulator parameter and the gain of the optical amplifier. Estimates have been made for the amplifier requirements to achieve OSC of a 300 MeV beam in 500 ms have been based on two dipole undulators with 200 mm period with 2.0 m total length. For cooling a single bunch of 10^8 particles circulating in the SHR, an amplifier with gain of less than 40 dB and output power below 100 mW will suffice for an initial demonstration of OSC. The design of the optical system, which uses a direct pump source, is shown in Figure 4.

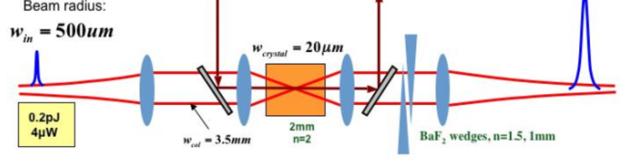

Figure 4: Layout of the optical amplifier.

Operation at a wavelength where the amplified signal is at about twice the pump wavelength, ensures ultra-broadband amplification. The pump laser will consist of a femtosecond Yb:fiber laser at 1030 nm with a fraction of the output pulse stream tapped off and stretched to 20-100 ps in single-mode fiber. The pulses can than be directly amplified with a robust amplifier [10].

The amplifier optical line will be instrumented with a thin set of barium fluoride wedges permitting finely controlled variation of the phase shift between the amplified radiation and electrons from the chicane. Interferometry between amplified radiation from the first undulator and radiation produced in the second undulator can be performed by variation of the relative phase. In the limit of a nearly isochronous chicane and a low gain amplification system, the phase shift needed for OSC to occur can be optimized using the interference signal from a power detector with a spectrometer used as a filter to suppress background. With the amplifier operating initially in a low-gain regime, the experiment will seek to demonstrate correlation of the interference signal with the establishment of OSC. Feedback techniques to optimize the amplifier phase and gain during the OSC process will be studied.

Measurements

The OSC experiment will perform accurate measurements of cooling rates as a function of initial bunch intensity, transverse size, and momentum spread of the beam. Figure 5 shows the expected horizontal beam size reduction during the OSC process for a bunch intensity of 10^8 particles. The red curve represents a case in which the gain of the OSC system is dynamically optimized as the beam cools. Starting from the equilibrium state, cooling is expected to reduce σ_x from 0.54 mm to a new equilibrium of 0.34 mm in under 2 seconds. For the second case (blue curve) the optical amplification is fixed at a value corresponding to the initial beam profile, resulting in a reduction of only 13% in horizontal size. Development of techniques for dynamical gain adjustments during the cooling process will be pursued as a central part of the experimental program.

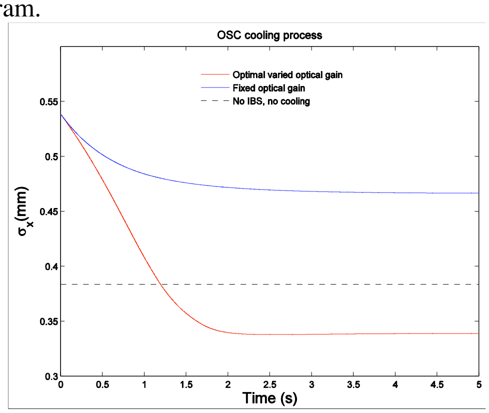

Figure 5: Calculated transverse size change due to OSC.

The required time-dependent variation of the optical gain to achieve optimal cooling is shown in Figure 6. An increase in gain of approximately 30% over the course of 2 seconds suffices to achieve optimal cooling. Similar results can be calculated for the momentum profile of the beam as a function of time as it cools, with the effects of cooling strongly dependent on the choice of chicane and lattice parameters.

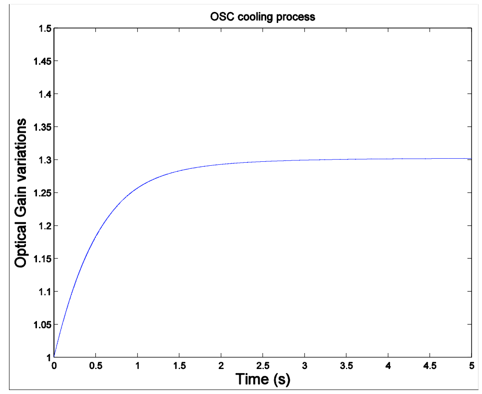

Figure 6: Optimal optical gain as beam cools

Confirmation of OSC will enable a host of additional measurements including investigation of the effects of changes in bunch intensity, lattice parameters, and beam energy.

SUMMARY

An experiment to demonstrate the principle of optical stochastic cooling using stored electrons is underway. The experiment will study the extension of cooling formalism to the optical regime with a desired reduction in cooling time depending inversely on the bandwidth of the cooling system. Recent design studies and beam development studies have reinforced the approach of carrying out this experiment in the MIT-Bates South Hall Ring with a compact apparatus based on existing technology. Such a demonstration will provide a firm basis for evaluating the applicability of this technique in higher power regimes as needed for high-energy hadron beams.

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