Beam Physics with the MIT-Bates South Hall Ring

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R. Milner, T. Akdogan, D. Cheever, K. Dow, M. Farkhondeh, W. Franklin, E. Ihloff, J. van der Laan, C. Tschalär, E. Tsentalovich, Defa Wang, Dong Wang, F. Wang
Massachusetts Institute of Technology Laboratory for Nuclear Science
Cambridge, MA 02139
and MIT-Bates Accelerator Center, Middleton, MA 01949

F. Kärtner
M.I.T. Research Laboratory of Electronics, Cambridge, MA 02139

I. Ben-Zvi, P. Cameron, V. Litvinenko, A. Luccio, W. MacKay, T. Roser, V. Yakimenko
Brookhaven National Laboratory, Upton, NY 11973

S.Y. Lee
Indiana University Cyclotron Facility, Bloomington, IN 47405

M. Conte
INFN Sezione di Genova, Genova, Italy 16146

W. Barletta, A. Zholents, M. Zolotorev
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Abstract

We propose to carry out two experiments to investigate fundamental processes in beam physics. The processes to be studied have strong potential to yield new techniques for cooling and fast polarimetry/polarization, respectively, of stored particle beams. Each experiment will utilize features of the MIT-Bates South Hall Ring which make it particularly suitable for studying the underlying physics. Results from the experiments will have important implications for potential applications in nuclear physics experiments requiring high luminosity or highly polarized beams. Possible applications to the Relativistic Heavy Ion Collider will play a key role in defining the physics program.

1.0 OVERVIEW

The United States Department of Energy recently released a long-term plan for physics outlining a set of new facilities and major upgrades to existing facilities needed to accomplish the nation's highest scientific priorities. Many of these facilities require significant new developments in accelerator and beam physics in order to reach their goals. Normally, operational user facilities can devote only limited beam resources to such long-term developments without impacting their experimental programs.

Fortunately, an opportunity presently exists to carry out an accelerator research program focused on selected issues of importance to nuclear physics with the MIT-Bates South Hall Ring (SHR), a small facility with well-developed accelerator tools and beam diagnostics, where nuclear physics operations have recently ceased. MIT will own and operate the Bates accelerator for the duration of the proposed research, which would be administered within the Laboratory for Nuclear Science. The SHR provides a highly versatile electron beam at energies up to 1 GeV, which can be operated on a limited basis for accelerator studies. The proposed research program would be a strong attractor for MIT students to the field of accelerator physics.

This proposal discusses two experiments to study fundamental physical processes in the South Hall Ring with potentially important applications elsewhere. The first project would test a fundamentally new idea for beam cooling known as optical stochastic cooling (OSC). The program would focus on developing a working system and exploring beam physics relevant for the implementation of comparable approaches at other facilities, particularly the Relativistic Heavy Ion Collider (RHIC). The second explores an effect with the potential to yield new methods for fast polarimetry and polarization of relativistic charged particle beams. In addition to these two projects discussed in more detail below, a parallel proposal to utilize the SHR to study coherent synchrotron radiation in the terahertz frequency regime is being submitted to the Department of Energy's Office of Basic Energy Science. These proposals are complementary and joint approval would lower operational costs per project and yield other symbiotic benefits.

The cooling of charged particle beams plays a key role in the achievement of peak luminosity in high-energy colliders. Several planned facility upgrades require cooling systems beyond the bounds of what has been achieved to date. The presently undemonstrated idea of optical stochastic cooling holds promise in energy regimes where other techniques diminish in effectiveness. OSC has potential for fast cooling of protons/antiprotons and heavy ions at energies of several hundred GeV per nucleon. Presently, there is significant interest in using OSC to complement electron cooling for cooling of gold ion beams in RHIC. Demonstrating OSC with electron beams at 100-300 MeV would allow for the study of similar physics.

We propose to carry out an experimental program to demonstrate the physics of OSC using the Bates South Hall Ring. An OSC system would consist of two undulators, a magnetic bypass (delay) line with well-defined time-of-flight properties, and an optical amplifier. It is planned to install two undulators in the ring to serve as pick-up and kicker devices for the cooling system. A small electron beam bypass will be designed and installed in the east straight section of the SHR. An optical amplifier based on parametric amplification will be developed for this experiment. Sources of this type have been designed by the MIT Ultrafast Optics Group and have significant promise for OSC applications. A detailed description of the OSC experiment, including formalism, apparatus, and experimental program is provided in Section 2. Success of this program will establish the feasibility of a new cooling technique with a possible impact extending beyond application to RHIC. Future uses of OSC may include cooling of ions in the Large Hadron Collider (LHC) and cooling in a muon collider.

The Stern-Gerlach effect, based on the coupling of a particle's magnetic moment to an inhomogeneous magnetic field, is widely applied in polarizing low-energy atomic beams. It has also been shown theoretically that the transverse magnetic moment of a relativistic particle interacts with a transverse magnetic RF field with a strength proportional to the square of the relativistic factor, gamma. This interaction can cause a polarized beam to induce an RF field in a tuned cavity whose strength is proportional to the transverse polarization and thus provide a very fast polarimeter. Conversely, it can impart a momentum gain or loss to particles traversing a strong transverse RF field, depending on the particles' transverse spin states, and thus, potentially split an unpolarized beam into two polarized components with differing momenta. Both of these effects are orders of magnitude weaker than the coupling to the beam particles' electric charge. However, by tuning a cavity to a transverse electric RF mode, the Lorentz force is cancelled to first order and calculations show both the RF polarimeter and the "polarizing beam splitter" to be feasible. Both of these applications, particularly the polarizing beam splitter, are very exciting prospects for existing and future beam facilities such as RHIC, e-RHIC, and ILC.

As a first task, we propose to verify experimentally, for the first time, the existence and the properties of the relativistic Stern-Gerlach interaction by measuring the RF field induced by a polarized electron beam. A prototype RF cavity, designed and built by Brookhaven National Lab and MIT-Bates, was installed in the South Hall Ring in 2005 to search for this effect. A brief engineering test was used to establish the cavity response, commission electronics, and set up SHR beam conditions to enhance sensitivity to the polarization including single-turn on-axis injection and partial filling of the SHR. This experiment requires little new capital equipment, and utilizes the existing spin handling apparatus in the SHR including the Siberian Snake, spin flipper, and Compton polarimeter. The study will demonstrate the use of this technique for very fast polarimetry of energetic beams. Such a polarimeter would permit the SHR to be used as a test bed for ideas related to storage ring design for an electron-ion collider. The study will also evaluate the feasibility of applying it as part of a storage-ring spin splitter. A detailed description of the proposed program is given in Section 3.

The proposal concludes with a discussion of the integration plan and budget, given in Section 4. Costs associated with these experimental programs include those associated with operation of the Bates accelerator complex and those associated with procurement, fabrication, and installation of the experimental apparatus. A sum of approximately $1,000,000 will be required for equipment to accomplish the OSC and Stern-Gerlach experiments, with most of these costs incurred by the former project. We intend to pursue funding from the Small Business Innovation Research Program to cover some of these costs. In addition, funds to operate the Bates SHR on a limtied basis and to support personnel from MIT-Bates and the MIT Research Laboratory for Electronics needed for the experiments.. The inclusion of the initiatives in a joint proposal spreads the overhead cost associated with operating the machine over multiple projects. A detailed discussion of costs and the synergy of proposed projects is provided in Section 4. Funding will be requested for an initial three-year period in which time the basic techniques could be demonstrated.

2.0 OPTICAL STOCHASTIC COOLING

2.1 Introduction

The cooling of charged particle beams has been a subject of paramount importance in accelerator physics for the past several decades [Moh01]. Reduction of a beam's emittance plays a key role in maximizing storage ring lifetime, the achievement of peak luminosity in high-energy colliders, and the production of highly monochromatic beams for experiments with internal targets in nuclear physics. A variety of methods have been employed including radiation cooling, electron cooling, stochastic cooling, and laser cooling. The relative merits of these techniques depend on the specific properties of the beam to be cooled. Most modern accelerators, particularly storage rings, rely on some form of cooling with many employing multiple methods.

The stochastic cooling (SC) method, invented by S. van der Meer [Mee01], is applied primarily to stored beams and is known for its successful implementation in the antiproton cooling-accumulators for proton-antiproton colliders [Moh02]. Stochastic cooling involves feeding beam profile information forward from one location in a storage ring to an ensuing location where a correction is applied to each particle to reduce beam emittance. The correction is a superposition of coherent and incoherent components. The coherent component, which is responsible for damping, is proportional to the deviation of the particle under consideration from the equilibrium momentum or the reference orbit. The incoherent component, resulting from effects associated with other beam particles, averages out over multiple passes. A typical stochastic cooling system is composed of a pickup to acquire the beam profile at one location, an amplifier, and a fast kicker located at another position in the ring. While this technique has found many applications, there are limits on the cooling time which can be achieved using traditional RF amplifiers. Because the cooling time is inversely proportional to the amplifier bandwidth, it is desirable to work beyond present microwave-based systems which are limited to bandwidth of the order of 10 GHz.

Clear advantages could be gained by developing a SC system based on optical photons, where technologies associated with detection and amplification permit bandwidth of the order of 10^{14} Hz [Koe01]. However, an optical stochastic cooling (OSC) system requires very different techniques for beam profiling, amplification, and correction. The first plausible idea for an OSC system was invented by Mikhalichenko and Zolotorev [Mik01], who suggested using quadrupole and dipole wigglers as pickups and kickers. In their scheme, a particle radiates an electromagnetic wave in traversing a quadrupole wiggler. Mirrors guide this EM wave through an optical amplifier to a dipole undulator, where the amplified radiation again intercepts the charged particle beam. The dipole wiggler serves as a longitudinal kicker, with the interaction between the particle and the EM wave from its own radiation resulting in a change of the particle energy. If used at a high dispersion location it should be possible to damp betatron and synchrotron motion.

An alternative transit-time method for OSC was later invented by Zolotorev and Zholents [Zol01]. Their cooling technique resembles the transit-time method proposed for microwave stochastic cooling [Kel01]. The cooling system includes two undulators, an electron beam bypass, and an optical amplifier as shown in Figure 2.1. In this scheme, the amount of energy change due to the particle's interaction with its own EM wave depends on the phase of the EM wave when the particle enters the undulator. The variation of this phase from particle to particle is due only to the particle transit time in the bypass, since EM waves radiated by different particles propagate from the first undulator to the second undulator identically. The method relies on the ability to adjust the propagation time of the EM wave and the transit time of a particle with zero momentum deviation such that this particle will enter the undulator at a phase with a zero electric field, and thus will not undergo any energy change. To achieve cooling, the bypass optics must be designed such that particles with different momenta follow trajectories with different path lengths, thereby entering the second undulator with phase shifts (relative to the phase with zero electric field) proportional to their actual value of momentum deviation. A similar approach is also applicable to betatron motion.

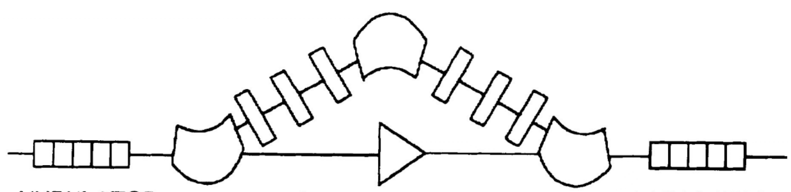

Figure 2.1: A schematic drawing of the cooling insertion in a storage ring for optical stochastic cooling.

As pointed out in the original paper [Mik01], the potential benefits of this type of cooling system are considerable, extending beyond proton-antiproton cooling. If demonstrated, the OSC technique could have implications for upgrading present facilities like the Relativistic Heavy Ion Collider (RHIC) [Ben01, Bab01] and the Fermilab Tevatron. In addition, OSC holds considerable promise for hadron colliders in the LHC and post-LHC era providing higher quality beams for very-large hadron colliders and muon colliders. However, while optical stochastic cooling appears theoretically viable, there are significant technical challenges in producing a working system. Because the cost and time required for implementation in a user facility is high, an important initial step would be to carry out proof-of-principle experiments.

We propose testing OSC feasibility through experiments using an electron beam. Since electrons are much lighter than protons, they can be more readily manipulated by light. Electrons also radiate light far more easily than protons. In order to produce radiation in the visible part of the spectrum, protons would need energy of several hundred GeV, whereas energy of 200-300 MeV would be sufficient for electrons. Since the physics of optical stochastic cooling does not depend explicitly on the particle species, experience gained studying cooling of electrons could be applied to muons, protons and heavy ions.

The experimental program to study the physics of OSC would use the MIT-Bates South Hall Ring (SHR). The SHR is an electron storage ring which provides intense beams at energies below 1 GeV. Nuclear physics operations at the facility have recently ceased, thereby making the ring available for dedicated use in beam physics studies requiring modest operating time. To carry out these studies, we plan to install two undulators in the ring to serve as pick-up and kicker devices in the cooling system. A small electron beam bypass will be installed in the east SHR straight section. An optical amplifier will be designed and tested offline prior to installation in the South Hall Ring. Details of these systems will be discussed in Section 2.3.

A challenge to implementing optical stochastic cooling in RHIC lies in producing a high average power broadband linear optical amplifier with excellent noise performance and time delay. Optical parametric amplification (OPA) is ideally suited for this purpose because the wavelength of amplification is limited not by the available active gain media, but rather by the availability of suitable nonlinear crystals. The MIT Ultrafast Optics Group has recently demonstrated a robust fiber-laser-based source with extremely low noise, delivering 500 fs pulses at 3 W of average power at 30 MHz repetition rate. A similar source scaled to 30 W of power and 20 ps pulses, together with a new concept known as cavity enhanced parametric chirped pulse amplification, enables construction of the desired parametric amplifier at relatively low cost and high efficiency. We propose to construct a cavity enhanced parametric amplifier based on a fiber laser system to study OPA operation in the context of electron cooling at Bates and ion cooling at RHIC. This study will evaluate different pump laser technologies (such as Yb/Nd:YLF-based pump lasers versus CO_2 laser based systems), the wavelength range and bandwidth over which amplification can be achieved, and the nonlinear optical crystals available at high quality for amplification to optimize the cooling processes for electrons and ions.

It should be noted that OSC proof-of-principle experiments using electrons have been previously proposed or seriously considered at other facilities, including Duke University and the Indiana University Cooler Ring. Although no such test was carried out, many of the physics considerations were initially worked out in the context of these proposals. Key results are presented in Section 2.2. Section 2.3 discusses the experimental apparatus in detail, and provides reasons why the Bates facility is particularly well suited for this program. Section 2.4 will discuss the experimental program being proposed. Detailed cost estimates for the project and discussion of the implementation plan are deferred until Section 4.

2.2. Physics Formalism

The formalism of optical stochastic cooling has been derived in detail [Zol01, Ben01]. This section will emphasize results of particular relevance for an experimental demonstration.

2.2.1 Transit Times in Optical Stochastic Cooling

Consider a test particle with a momentum deviation $\delta_i = \Delta P_i / P$, and the betatron phase space coordinates (x_i,x_i'). Neglecting higher order terms, the length of the trajectory of this particle in a bypass is $l_i=l_0+x_iI_1+x'_iI_2+\delta_iI_D$ [Ste01, Lee01]. Here l_0 is the trajectory length of the reference particle having zero momentum deviation and zero betatron coordinates and I_1, I_2, and I_D are

$$I_1=\int_{s_1}^{s_2}\frac{M_{11}(s,s_1)\,ds}{\rho(s)},\qquad I_2=\int_{s_1}^{s_2}\frac{M_{12}(s,s_1)\,ds}{\rho(s)},\qquad I_D=\int_{s_1}^{s_2}\frac{D(s)\,ds}{\rho(s)},\tag{1}$$

where $M_{11}(s,s_1)$ and $M_{12}(s,s_1)$ are transport matrix elements of the Hill's equation, ρ is the bending radius of the magnets, and $D(s)$ is the dispersion function. Each integral is carried out from the first undulator at s_1 to the second undulator at s_2 via the electron beam bypass.

In the first undulator, a test particle radiates an EM wave propagating in the z-direction: $E_i=E_0\sin(kz-\omega t+\phi_i)$ with electric field amplitude E_0 and phase ϕ_i. The wave number and frequency are $k=2\pi/\lambda$ and $\omega=kc$ with wavelength λ governed by undulator properties as discussed in Section 2.3. This radiation propagates to the optical amplifier, while the particle follows the bypass and traverses it in a time $\Delta t_i=l_i/c$.

The time Δt_0 required for radiation to pass all the way between undulators, including the amplifier delay, must be constrained and maintained by a feedback system to yield the condition $l_0- c\Delta t_0 = \lambda/4$. Thus, the particle arrives at the second undulator with a time delay $\delta(\Delta t)=\Delta t_i-\Delta t_0$ and with a phase shift $\Delta\phi_i=k(\ell_i-\ell_0)=k\left[x_iI_1+x'_iI_2+\delta_iI_D\right]$, relative to the phase with zero electric field. In the second undulator, the particle interacts with the electric field E_o of its own radiation and changes its momentum by [Pel01]

$$\delta P_i=G\sin(\Delta\phi_i),\qquad G=gq\,E_0\,M\,\lambda_u\,K/(2c\gamma),\tag{2}$$

where q is the particle charge, M is the number of undulator periods, g is the amplification factor of the optical amplifier, and δP_i is the amount of the momentum change related to the coherent longitudinal kick $\Delta\delta_i=\delta P_i/P$.

Let the dispersion function and its derivative at the second undulator be D_2 and D'_2. The changes of the particle betatron coordinates at the exit of the second undulator are $\Delta x_i=-D_2(\delta P_i/P)$ and $\Delta x'_i=-D'_2(\delta P_i/P)$ After passing the entire cooling insertion, the test particle has received coherent longitudinal and transverse kicks that are proportional to a linear combination of the particle's momentum deviation and betatron deviations. A proper choice of the parameters of the bypass lattice makes it possible to use these kicks to simultaneously damp transverse and longitudinal oscillations.

2.2.2 Cooling Rates

To a reasonable approximation, in a stochastic cooling system the cooling time is given by $\left(\tau_{\mathrm{cool}}\sim \mathrm{N_bF_B/\Delta f}\right)$, where N_b is the number of particles per bunch, C is the circumference, $F_B=(2\pi)^{-0.5}(C/\sigma_z)$ is the bunching factor, σ_z is the bunch length, and Δf is the bandwidth of the amplifier. A more detailed result for an OSC system can be found by considering the interaction of a test particle not only with the EM wave of its own radiation, but also interactions with the EM waves emitted by other particles moving behind it within a distance less than $M\lambda$. Such interactions constitute the incoherent component of the kick received by the particle. Assume that a test particle interacts with N_s electromagnetic waves (including its own wave) and consider again a change of the particle's momentum at the exit of the cooling insertion:

$$\delta_{ic} = \delta_i + G\sin\left(\Delta\phi_i\right) + G\sum_{k\neq i}^{N_s}\sin\left(\Delta\phi_i + \psi_{ik}\right), \qquad (3)$$

where δ_{ic} is the relative momentum of the i-th particle after the longitudinal kick, N_s is the number of particles in the sample, and $\psi_{ik} = \phi_I - \phi_k$. The contribution of the test particle to the total kick is subtracted from the sum, so that the sum depicts only the incoherent kicks.

Following references [Zol01, Lee02], the optimal gain and damping rate are

$$G = 2(I_D + I_\perp)\sigma_\delta^2 k \exp\left\{-\overline{\Delta\phi_i^2}/2\right\} / \left\{N_s\left[1 + (H_D\sigma_\delta^2/\varepsilon_x)\right]\right\}, \qquad (4)$$

$$\alpha_x + \alpha_\delta = 2(I_D + I_\perp)^2\sigma_\delta^2\left[k\exp\left\{-\overline{\Delta\phi_i^2}/2\right\}\right]^2 / \left\{N_s\left[1 + (H_D\sigma_\delta^2/\varepsilon_x)\right]\right\}, \qquad (5)$$

where $I_\perp$ is a function of betatron functions and the integrals I_1 and I_2 of the electron beam bypass, the rms phase shift of the sample is given by $\overline{(\Delta\phi)^2} = k^2[(\beta_1 I_1^2 - 2\alpha_1 I_1 I_2 + \gamma_1 I_2^2)\varepsilon_x + I_D^2\sigma_\delta^2]$, the betatron amplitude functions α_1, β_1, and γ_1 are evaluated at the first undulator, ε_x is the emittance of the sample, σ_δ is the rms fractional momentum width, and $H_D=\beta_2 D'^2_2+2\alpha_2 D_2 D'_2+\gamma_2 D_2^2$.

The maximum attainable damping rates occur when $k\exp\left\{-\overline{\Delta\phi_i^2}/2\right\}$ reaches its maximum $k/\sqrt{e}$ (e is the base of the natural logarithm) at $\overline{\Delta\phi_i^2} = 1$. Notice that the reduction of ε_x and σ_δ during the damping leads to a decrease of $\overline{\Delta\phi_i^2}$ and, correspondingly, to a decrease in the phase shifts of the individual particles. Since only coherent components of the kicks are responsible for damping, a decrease of $\overline{\Delta\phi_i^2}$ leads to a slowdown of the damping process. In a simplified optimal condition with equal decrements, the gain factor and the decrement are given by

$$G \approx \sqrt{\frac{2}{e}}\frac{\sigma_\delta}{N_s}, \qquad \alpha_x = \alpha_\delta = \frac{(1 + H_D\sigma_\delta^2/\varepsilon_x)}{2e\,N_s} \approx \frac{1}{eN_s}. \qquad (6)$$

In the cooling process, the number of passes through the cooling insertion required for a *1/e* reduction of the beam emittance (and the beam energy spread in the second power) is equal to eN_s. The sample size is equal to the number of particles in the bunch within the distance $M\lambda$, i.e.,

$$N_s \approx NM\lambda / \left(3F\ell_b\right), \qquad (7)$$

where N is a number of particles in the bunch, l_b is the bunch length, and F is ratio of the beam transverse area in the undulator to the transverse area of the light (or ratio of the beam angular spread to the opening angle of the undulator radiation). The damping time due to the optical stochastic cooling becomes $\tau_{x,\delta}=T_0[eN\lambda/(5\Gamma Fl_b)]$, where T_0 is the revolution period, and the factor $\Gamma=\Delta f/f$ is the ratio of the least of the bandwidths of the optical amplifier and the undulator radiation to the coherent laser frequency *(*$\Gamma=1/M$ [Kel01]).

2.2.3 Amplification

In order to determine the amplification factor of the optical amplifier one can relate G in Eq. (6) to that in Eq. (2). The unknown parameters are the amplification factor and the amplitude of the electric field E_0. We evaluate E_0 at the waist of the light beam, where the cross section of the coherent mode of the radiation is $A=2\lambda M\lambda_u$. During one pass of the undulator, the particle emits about $\pi\alpha q^2\xi[JJ]^2$ coherent photons, where α is the fine structure constant, $\xi=K^2/(2+K^2)$, and $[JJ]=J_0(\xi/2)-J_1(\xi/2)$. Therefore, we obtain

$$\varepsilon_0 E_0^2 Ac\Delta t_R/2 = \pi\xi[JJ]^2 kq^2/4\pi\varepsilon_0, \qquad (8)$$

where $c\Delta t=M\lambda$ is the length of the radiation pulse. Using Eq. (8) and substituting Eq. (7) for N_s, we find

$$g \approx 3\sqrt{2}\,\varepsilon\,\Gamma F/(2\pi r_0 N\xi[JJ]\sqrt{e}), \qquad (9)$$

where $r_0=q^2/4\pi\varepsilon_0 mc^2$ is the classical radius of the particle, m is the particle mass, and $\varepsilon_p=(2\pi)^{-0.5}\gamma l_b\sigma_\delta=\gamma\sigma_l\sigma_\delta$ is the rms invariant longitudinal emittance. Notice that ε_p in Eq. (9) represents the current emittance at each moment of the damping process. The equilibrium emittance is reached when all sources of damping are balanced by all sources of the emittance excitation. After that, the scheme remains stationary.

There are two additional parameters usually associated with the stochastic cooling technique. These are the noise of the amplifier and the so-called mixing – a process of the re-randomization of the beam on the way from the kicker to the pickup. The particles must not stay together with the same neighbors more than one turn, since otherwise the incoherent heating will grow [Moh02]. A complete re-randomization will occur if, during the passage from the second undulator to the first undulator, particles change positions inside the bunch on the order of $M\lambda$. Furthermore, randomization in the transverse phase space occurs if the beam emittance is larger than λ/π.

2.3 Experimental Apparatus

From the formalism in Section 2.2, it is clear that an OSC demonstration experiment requires very specific beam conditions and interplay between several systems. Requirements for the electron beam, and design parameters for an undulator system, electron beam bypass, and optical amplifier are discussed in this section.

2.3.1 Electron Beam

The MIT-Bates Accelerator Center, shown in Figure 2.2, produces a versatile electron beam. The facility includes a polarized photoinjector, a linac capable of accelerating electrons to energies up to 500 MeV, and a recirculator which can double the beam energy to 1 GeV. Beams from the linac are injected into the South Hall Ring, a ring suitable for long-lived stored beams.

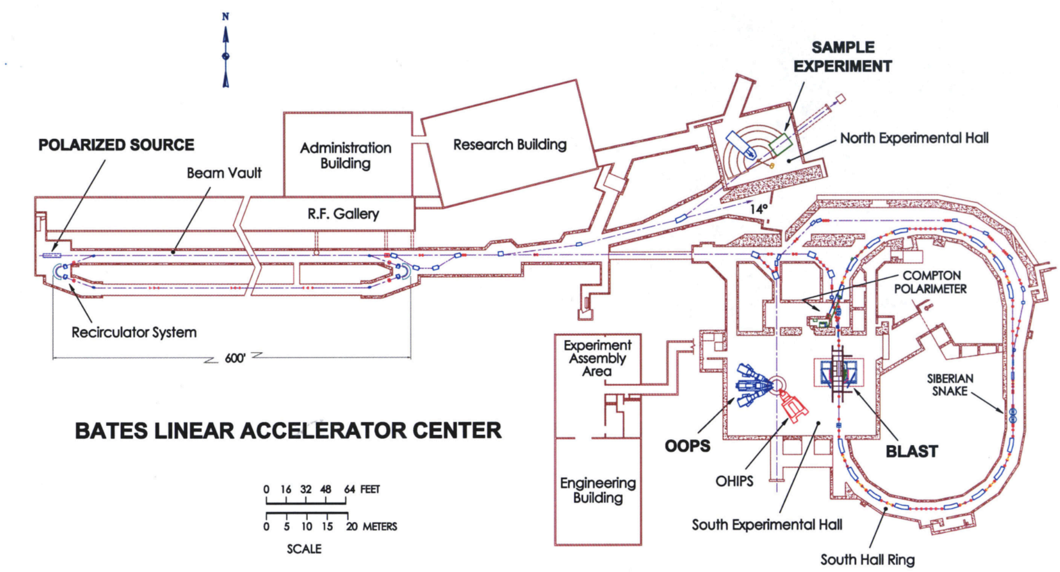

Figure 2.2: Layout of the Bates accelerator complex during nuclear physics operations in 2005 (prior to decommissioning of the SAMPLE, OOPS, and BLAST experiments). The South Hall Ring would house the OSC experiment in its east straight section, where space for the bypass beam line and undulator system exceeds 20m.

The SHR has several features making it very well suited to carry out an OSC demonstration experiment. These include ample space for a cooling insertion, suitable energy range, high frequency RF system, and a flexible lattice.

The SHR features a racetrack design with 190-m circumference and two long straight sections. Parts of these sections are presently devoid of beamline elements making them suitable for the installation of undulators and a cooling system. The straight sections also reside in tunnels at least 4 m wide, which formerly housed the decommissioned Extraction (X) Line and BLAST Spectrometer. The lack of severe spatial constraints allows for flexibility in the design of the electron beam bypass.

To accomplish an OSC demonstration, it is essential to operate SHR at an energy at which the synchrotron radiation damping time is long compared to the expected OSC damping time. Because of the unusually large radius of curvature (9.1 m) in its dipole arcs, this is quite feasible in the SHR. The synchrotron damping time as a function of energy is shown in Figure. 2.3. Below 300 MeV, the SHR synchrotron radiation damping time is greater than 1 second, which should be at least an order of magnitude greater than the OSC cooling time. The synchrotron damping time rises quickly as the energy is lowered, whereas the OSC time is expected to decrease. The SHR was designed primarily for higher energies, having operated extensively at 850 MeV for nuclear physics experiments with internal targets. Well-developed tunes also exist at other lower energies (569 and 669 MeV in particular). Although it has not been demonstrated, operation at 300 MeV or below should be achievable and lattices for the SHR have been calculated for this energy regime. A low-energy test run will be needed to investigate stored beam properties.

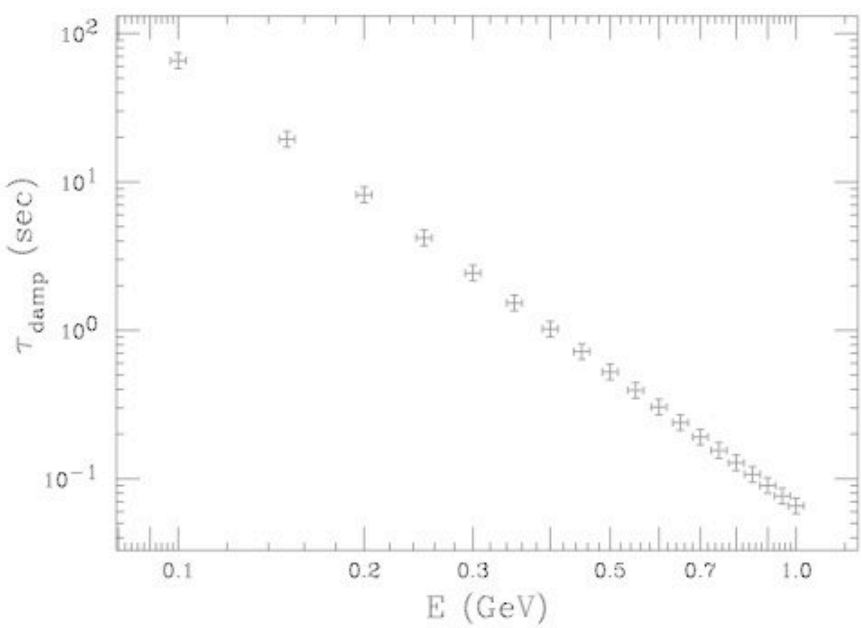

Figure 2.3: Synchrotron damping time for electrons in the SHR is shown as a function of energy.

The OSC application benefits from the SHR RF system, which consists of a single cavity operating at the high frequency of 2856 MHz. The installation of a bypass section for electrons effectively changes the circumference of the SHR. This necessitates either modification of the harmonic number of the SHR, alteration of the RF frequency, or both. Fortunately, modification of the harmonic number is relatively straightforward in the SHR. The SHR presently has a harmonic number of 1812 with interbunch separation of approximately 10 cm. The bypass can be designed to accommodate changes in bunch length of approximately 10 cm. There is sufficient flexibility in the RF system to tune finely the SHR RF frequency as necessary. Because the SHR is designed for significantly higher energy than the OSC experiment requires, the RF system has ample power to overcome additional losses due to additional bends from the electron bypass and undulator radiation.

Finally, the SHR features a very flexible lattice, having been designed to accommodate storage and extraction modes. Significant adjustments are possible, as was demonstrated recently during a test run in which the momentum compaction of the machine was adjusted from its usual value of $\alpha=3*10^{-2}$ to $\alpha\sim10^{-4}$ for a short bunch length study in the SHR. This flexibility will be needed to set up the electron beam bypass.

2.3.2 Electron Beam Bypass

The design of the electron beam bypass constitutes a significant challenge. The bypass must be designed with a high level of isochronism to permit OSC. A further issue involves compatibility with other uses of the machine, as it should be designed in such a manner that the system is consistent with the existing lattice. If this is not possible, it will be necessary to design the bypass such that the OSC system can be easily removed.

Although detailed lattice calculations must be done as part of the OSC design study, a rough draft of a bypass consistent with SHR can be provided. The bypass will utilize primarily existing electromagnets from the recently decommissioned SHR Extraction Line. Figure 2.4 shows an initial arrangement for a chicane consisting of four dipole magnets with each producing a 22.5^{o} bend with 4.6-m radius of curvature. The bypass will be approximately 8m in length and fits well into a portion of the east straight section presently devoid of beamline components. To avoid modifying the SHR RF frequency, the time delay induced by path length change for electrons in the chicane should be an exact multiple of 350 ps. For the design shown in Fig. 2.4, this is the case with the SHR harmonic number rising from 1812 to 1817. This corresponds to an electron delay of nearly 2 ns, which should be ample for the fast optical amplifier.

The bypass also includes six quadrupoles and four sextupoles to control the dispersion and isochronicity to the needed accuracy. The quadrupoles can be obtained from the X-Line; the sextupoles will have to be built. Detailed modeling of the Bates SHR has been carried out in the past using programs such as MAD and DIMAD. Studies of SHR lattices have confirmed the accuracy of these models to a high degree.

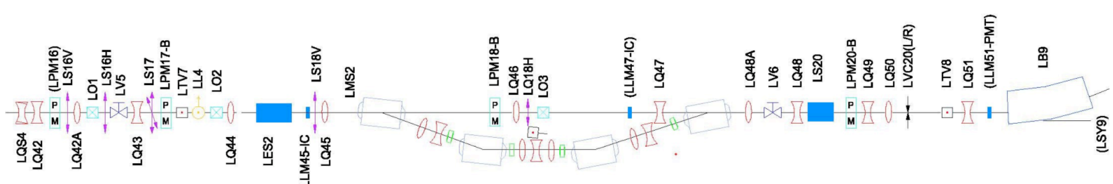

Figure 2.4: Schematic view of the electron beam bypass for the SHR.

Much of the vacuum hardware for the bypass can also be adapted from the X-Line. The vacuum system for the SHR was designed and built by the Bates Mechanical Group, and modifications will not be complicated. Some additional vacuum hardware will be required and the two dipoles along the SHR straight section will require vacuum box modifications to allow a wide aperture for undulator radiation to enter and exit the

OSC amplifier system. Modifications to the vacuum system of this sort have previously been made to synchrotron light ports on existing SHR dipoles, for example in the SHR Compton polarimeter.

2.3.3 Beam Instrumentation

Beam instrumentation will play an important role in setting up conditions in the cooling insertion and in observation of the occurrence of cooling. Beam instrumentation capable of measuring the beam profile rapidly and accurately will be essential to study cooling rates. Both transverse and longitudinal diagnostics are required. For transverse beam profiling, the SHR contains synchrotron light monitoring stations which provide detailed information at an update frequency of 30 Hz. Continuous information should be obtainable from high-order terms in the existing SHR beam position monitors (BPM's). An objective of the initial test run for this project will be to explore the accuracy to which SHR BPM's can yield profile information. Recently, Bates has also experimented with techniques for longitudinal profiles in the context of beam development for THz radiation studies [Wan01]. Measurements carried out by collaborators from Brookhaven National Laboratory's National Synchrotron Light Source using a Hamamatsu C6860 Streak Camera demonstrated the ability to resolve the SHR bunch profile at the sub-picosecond timing level. Such a device is essential for the complementary THz proposal and will be part of the Bates beam instrumentation if that proposal is approved. The OSC experiments will utilize a longer SHR bunch length and profile measurements can be carried out with fast diodes, which are included in the funding request.

A development needed for the OSC experiment involves improved control of the bunch-filling pattern for the South Hall Ring. The SHR has a single-cavity 2856 MHz RF system. In a standard storage mode, all RF buckets are filled with electrons in a uniform manner. The capability to control the filling pattern for individual RF buckets does not presently exist. However, this ability is highly desirable for the OSC experiment, where it is simplest to begin by studying the behavior of a single bunch circulating in the SHR. A detailed design for a bunch control system has been developed for the Bates photoinjector based on a mode-locked laser built by the MIT Ultrafast Optics Group [Buc01]. This system will permit control of the SHR filling pattern in a very flexible manner. The design of this system was also initially motivated by SHR THz radiation studies and is illustrative of the symbiotic effect of carrying out complementary projects in the SHR.

2.3.4 Undulator System

Another important aspect of the experiment is the design of a precisely machined undulator system. Important properties include strength, tunability, periodicity, and precision. The wavelength of the emitted undulator radiation is given by $\lambda = \lambda_u (1 + K^2/2)/2\gamma^2$, where γ is the Lorentz factor, λ_u is the undulator period, and $K = 0.934 B_u[\mathrm{T}]\lambda_u[\mathrm{cm}]$ is the undulator parameter. As an example, consider undulators with $\lambda_u = 10$ cm, a fairly standard value for undulators employed at light sources. Figure 2.5 plots the wavelength of the undulator radiation produced as a function of magnetic field strength. For radiation at 1 μm, the corresponding wiggler field varies from 0.18 T at 200 MeV to 0.57 T at 500 MeV electron beam energy. Since the gain of the OSC system (G) depends directly on the field strength, increasing the strength of the undulator field effectively lowers requirements for the gain of the optical amplifier system (g). This will be considered further in defining the amplifying medium.

The basic parameters of the undulator system will be comparable to those employed in a light source like the ALS. Initial cost estimates are based on design parameters for two dipole undulators with 10 cm period and 1.5 m length. A system is considered with adjustable electromagnets capable of reaching 1 T. The undulator system design parameters will be designed by the collaboration. Options for undulator fabrication are being explored both through commercial and academic sources.

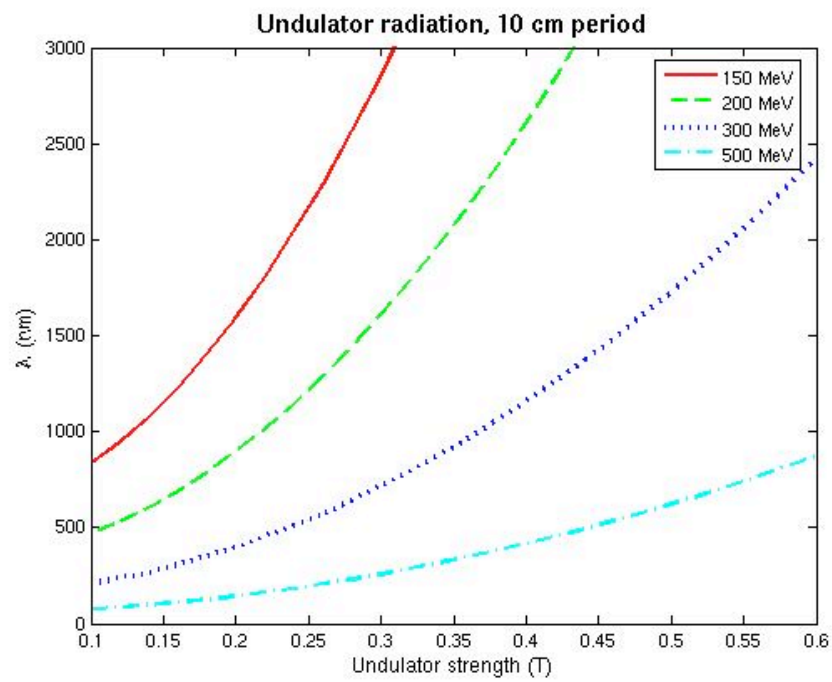

Figure 2.5: Undulator radiation wavelength vs. field strength for 10 cm period.

2.3.5 Amplifier

Calculations of the laser power needed from the amplifier to achieve particular OSC damping times have been carried out. Figure 2.6 shows the power which would be needed to cool the beam for typical conditions during a nuclear physics experiment at Bates with a stored electron current of 80 mA distributed over 1812 bunches. For such a beam, a laser system of order 1 W would be needed to cool the beam faster than the synchrotron damping time. The requirements for cooling with a single bunch circulating in SHR are significantly lower. An amplifier of order 1 mW will suffice for an initial demonstration of OSC with a single bunch stored in SHR. The dependence of OSC cooling time on bunch charge, multiplicity, and beam energy will be measured as part of the experimental program.

Various optical amplifier designs have been considered for use in this project.

Previous proposals have considered the use of Ti:sapphire, a medium well known for its tunability and large bandwidth. However, Ti:sapphire requires pumping from an external argon laser system, which is difficult to regulate, and is limited to the near infrared portion of the optical spectrum. Such a system could be adapted for the Fermilab energy range, but would not test many of the techniques needed for an OSC amplifier at RHIC. This proposal will emphasize development of a fiber system. Such amplifiers can be designed for specific wavelengths, are extremely stable, and are relatively cost-effective.

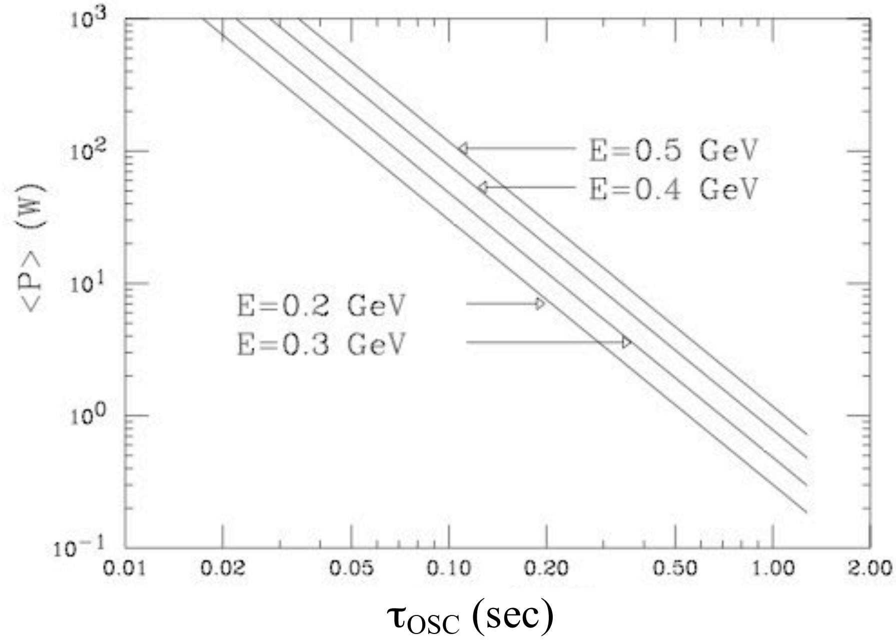

Figure 2.6: The required average laser power for optical stochastic cooling for a bunch intensity of 1.75 × 10^8 particles in a bunch and 1817 SHR RF buckets filled (*i.e.*, average beam current of 80 mA) as a function of cooling time. The average laser power will be reduced proportionally when the beam intensity or the number of bunches is reduced.

Operation of the electron beam in pulsed mode permits consideration of pulsed amplification for the cooling system, *i.e.*, the amplifier is only on over the duration of the electron bunch. Optical stochastic cooling requires an ultra-broad optical amplification bandwidth. In addition, it is advantageous to have scalability in central wavelength and average power. Also of importance is the phase delay over the wide optical bandwidth, which needs to be controlled to a fraction of an optical cycle. All these requirements are naturally supported by short pulse optical parametric amplification (OPA) [Ros01]. Due to the fact that ideally no energy is deposited in the amplifier crystal, these amplifiers can be scaled to large average power. Operation at a wavelength degenerate to the pump wavelength, *i.e.*, the amplified signal is at about half the pump wavelength, ensures ultrawide band amplification with very well developed and efficient nonlinear optical materials, such as Beta-Barium-Borate (BBO) and Periodically Poled Lithium Niobate (PPLN). In addition, OPA's can easily achieve a gain of 10,000 in only a few millimeters of crystal length in a single path. Therefore, they also introduce the least phase delay in the amplification, which can later be conveniently compensated for in a compact manner by specially designed chirped mirrors.

A hurdle for optical parametric amplification is the relatively high repetition rate that is relevant for RHIC optical stochastic cooling of about 28 MHz with a duration of 20 ps. To achieve large parametric amplification of 30-40 dB in crystals of reasonable length, i.e. <1cm, with 20 ps pulses, pulse energies on the order of 1-100 μJ are necessary. This pulse energy requires picosecond pump lasers with multiple 10 watt or even a kilowatt of average pump power, which are only commercially available in the multiple 10 watt range commercially available. The direct use of such a pump laser would be extremely wasteful, because only about 10W of laser power is necessary for achieving damping times on the order of 21ms at a bunch rate of 28 MHz. We recently introduced the concept of cavity enhanced parametric chirped pulse amplification [Ild01], where the pump pulse train is resonantly enhanced in an optical cavity. Experiments are currently underway in our laboratory to demonstrate this concept. The use of cavity enhanced OPA enables significant overall conversion factors from pump to signal wavelength. On average we expect up to 50% conversion with an intracavity conversion per pulse of less than 1%, which greatly reduces the cost of the laser system, because a lower power pump laser system can be used and it linearizes the gain. Such a system is shown in Figure 2.7:

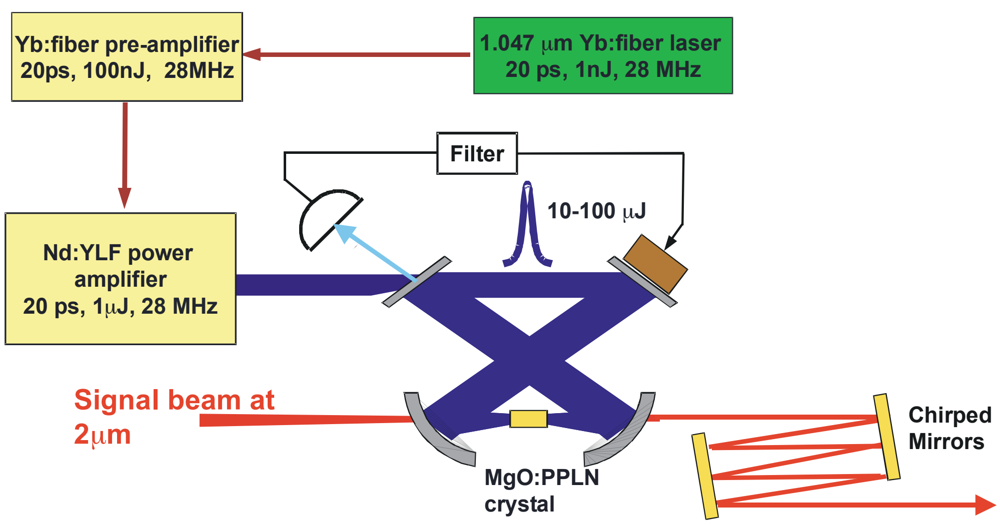

Figure 2.7: Layout of the cavity enhanced optical parametric amplifier.

We start with an actively modelocked 20 ps Yb:fiber laser at 1047 nm that is synchronized tightly with sub-picosecond precision to the 2856 MHz Bates microwave oscillator at its 102nd subharmonic, i.e. 28 MHz. This laser typically delivers 50 mW of average output power. The pulses can be directly amplified with a very robust and compact Yb fiber amplifier to the 3 W average power level, i.e. about 100 nJ pulse energy in each individual pulse. We previously demonstrated a very similar and easy to use fiber-laser-based source. The source delivers 500 fs pulses, when compressed, with 3 W of average power at 30 MHz repetition rate [Ild02]. All we will change here is to use a 20 ps seed laser to have a clean pulse shape. This is important for pumping of OPAs, especially if the OPA should work as a linear amplifier, an essential criterion for this application. For wideband optical parametric amplification, we will use MgO:PPLN with a poling period of 31.4 μm, which has a high damage threshold and a high nonlinear coefficient $d_{eff} = 18\text{pm/V}$. This relates to a parametric gain per unit length of

$$g = \frac{4\pi \cdot d_{eff}}{\lambda_s n_s} \sqrt{2 \cdot 377\Omega \cdot n_p \cdot I_p} \tag{10}$$

where $\lambda_s = 2\mu m$ is the signal wavelength, n_s and n_p are the index of PPLN at the signal and pump wavelength (about $n_s = n_p = 2.1$), and I_p is the intensity of the pump light. Eq. (10) can be evaluated as

$$g = \frac{7}{mm} \sqrt{\frac{I_p}{GW / cm^2}} \tag{11}$$

and therefore, the large signal gain of the amplifier is given by

$$G = \exp[g \cdot l] = \exp\left[7 \sqrt{\frac{I_p}{GW / cm^2}} \frac{l}{mm}\right] \quad , \tag{12}$$

where l is the crystal length. With $e^7 \approx 1100$ this formula shows that we achieve 30dB gain in a 2 mm long crystal at a peak intensity of about 0.25 GW/cm^2. We will not consider higher intensities because we want to operate far enough below the damage threshold of MgO:PPLN, which is expected to occur for this pulse length at about 5 GW/cm^2. With a spotsize of 100 μm^2 and a pulse length of 20 ps length we need a minimum pulse energy of 1.5 μJ. To achieve this pulse energy we need an amplification by a factor 15 of our output pulse stream from the fiber amplifier to boost the average power from 3 W to 45 W. Even then, this would leave us with no room for any loss, higher gain or pulse shaping to have homogenous gain over the 20 ps bunch length. Various companies provide Nd:YLF amplifier modules that boost the average power by a factor of 10, to 30 W or 1 μJ of pulse energy. To further enhance the pulse energy we send this beam into a resonant enhancement cavity, where the crystal is placed (see Figure 2.7), which enhances the optical power by a factor of 30-100, giving us pulse energies up to 100 μJ. This is enough energy to eventually go to longer pump pulses like 100 ps for achieving equal gain over the 20 ps bunch length as discussed before. The enhancement cavity allows us also to work in the limit of low conversion, i.e. the amplifier is not saturated and really operates as a linear amplifier, because we recycle the amplified pump light in the cavity and use it for many passes through the crystal. The use of a solid-state amplifier as the power amplifier in the last step, instead of another fiber amplifier, has the advantage that we can directly amplify the 20 ps pump pulses without the need for stretching and compression, which would be impossible to do in a fiber system because of the high nonlinearity. The locking of the cavity to the pulse stream will be done by the well known Haensch-Couillaud method [Hae01]. One of the cavity mirrors is mounted on a piezoelectric transducer (PZT) to scan the cavity length. Its position is controlled by the difference signal from a pair of photodiodes measuring the depolarization of the beam reflected from the cavity. This technique produces dispersion-like shaped resonances. This method has been used in many experiments involving an enhancement cavity, for example [Yan01], where enhancement by a factor of 10 and frequency doubling with conversion efficiencies up to 50% has been demonstrated.

For the pump wavelength of 1.047 μm the center frequency for degenerate parametric pulse amplification is 2.094 μm. The broadest phase matching bandwidth is expected at this wavelength. In fact, most recently such a system has been tested and Figure 2.8 shows the spectrum generated with such an OPA when seeded with broadband light generated from a Ti:sapphire laser by difference frequency generation [Fuj01]. These results clearly demonstrate that such an OPA can amplify spectra from 1.750 μm all the way out to 2.5 μm, corresponding to an amplification bandwidth of 51 THz.

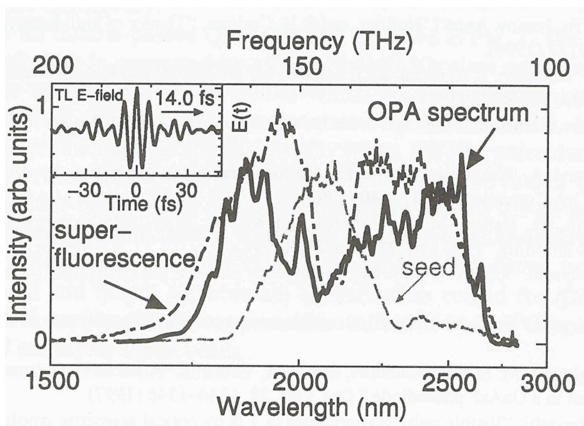

Figure 2.8: Broadband output spectrum of a 2 mm MgO:PPLN-OPA pumped at 1.047 μm when seeded with broadband light generated from a Ti:sapphire laser by difference frequency generation at the degenerate wavelength range around 2 μm.according to [Fuj01].

The amplifier is only suitable for optical stochastic cooling if it has the same group delay for all frequencies. Figure 2.9 shows the group delay variation in the 2 mm Lithium Niobate crystal in the wavelenth range of interest.

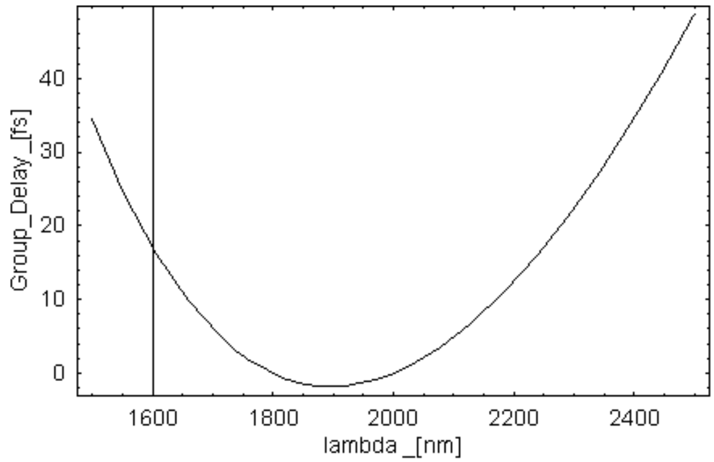

Figure 2.9: Group delay variation in 2 mm Lithium Niobate in the wavelength range of interest.

At 2.1 μm the optical cycle corresponds to 7 fs. Figure 2.9 shows that there is too much group delay variation over the wavelength range of interest and we have to compensate this group delay to about a 1/10 of an optical cycle. At the moment, there seems to be only one solution to compensate group delay variations over such large bandwidth with the required precision and that is via chirped mirrors [Szi01, Kär01, Kär02]. Over the last decade, our group has developed the most precise and wide band chirped mirror systems available, which we call double-chirped mirror pairs, to control group delay over one octave to a precision of less than 1 fs [Kär03]. However, the current mirrors have been developed for the Ti:sapphire wavelength range at 0.8 μm. Therefore, we need to measure the dispersion of the components involved in this new wavelength regime precisely, which we do routinely by whitelight interferometry. However, the current whitelight interferometer needs optics and detectors for this new wavelength range. We will work out a mirror design that is capable of taking all undesired group delay variations into account. Currently, there is only one company (Nanolayers, Optical Coatings, Rheinbreitbach, Germany), with whom we cooperate closely, that can fabricate these mirrors with the required precision. Depending on the bandwidth, half of an octave or a full octave, we can achieve dispersion compensation using only one type of double chirped mirrors or double-chirped mirror pairs, respectively. Each of these mirrors has up to 80 layers, which are monitored during growth and controlled effectively to a precision of 0.3 nm. Therefore, the growth process is very slow and one of these coating runs including substrates costs on the order of $30,000. We include at least one coating run in the budget. The precise dispersion compensation concludes the construction of the wideband optical parameteric amplifier for optical stochastic cooling.

2.4 Experimental Plan

Implementation of the optical stochastic cooling experiment will be carried out using a phased approach. Such an approach will allow a detailed design study to be pursued while continuing to develop the SHR beam for accelerator physics experiments. These phases correspond to roughly yearlong time intervals. It will be necessary to operate the South Hall Ring for at least one extended running period in each phase. A brief summary of the experimental goals for each phase is provided below. Bates operations are discussed in Section 4.

The initial phase will focus on a design and feasibility study. The following goals will be pursued during the initial phase: a) development of the optical amplifier; b) design of an isochronous electron beam bypass; c) undulator system design; d) low-energy run of the SHR to demonstrate storage at $E_e < 300$ MeV; and e) completion of beam instrumentation upgrades for the SHR. This includes particularly the bunch filling control scheme for the Bates Linac.

The second phase of the project will begin with construction of the magnetic chicane for the SHR. This will constitute a significant modification of the SHR. It will require a dedicated commissioning run to investigate the optics and develop lattice modifications needed for OSC. The run will also be used to investigate compatibility with other uses of the SHR. In the meantime, development of the optical amplifier system will continue in parallel and the undulator system will be built and delivered and installed in the SHR.

Phase 3 will involve a detailed study of optical stochastic cooling. This phase will begin with integration of all components in the SHR including the OSC undulators and optical amplifier. The initial goal will be to demonstrate optical stochastic cooling for the first time. As an unexplored territory in beam physics research, this study will permit exploration of a large set of topics. Research topics of the OSC study include the following: (1) low-noise optical transmission and amplification; (2) signal synthesis; (3) physics of inverse free-electron lasers; (4) space charge effects in low energy electron storage rings; (5) lattice function dependence of the OSC; (6) OSC cooling mechanism; (7) OSC cooling rate; and (8) the transverse mode effects [Kim01]. This will necessarily entail additional operation of the SHR in the third phase, reflected in the operations budget of Section 4.

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