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BYPASS DESIGN FOR TESTING OPTICAL STOCHASTIC COOLING AT THE CORNELL ELECTRON STORAGE RING (CESR)

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Abstract

Optical Stochastic Cooling (OSC) is a promising method for cooling very dense stored particle beams through the interference of radiation created in an upstream 'pickup' wiggler and a downstream 'kicker' wiggler. By correlating a particle's path length via a bypass between the two wigglers with its betatron coordinates in the pickup, the particle will receive a kick in energy which, through coupling introduced by non-zero horizontal dispersion in the kicker, can reduce its betatron amplitude, thus cooling the beam. A proof-of-principle test of this technique is being planned at the Cornell Electron Storage Ring (CESR). In addition to maintaining standard requirements such as a large dynamic aperture and acceptable lattice functions throughout the ring, the design of the bypass is guided by the mutually competing goals of maximizing the cooling rate while maintaining a sufficiently large cooling acceptance with properly-corrected nonlinearities. We present a design of such a bypass and ring optics so as to best achieve these objectives.

INTRODUCTION

Stochastic cooling at microwave frequencies has proven effective at reducing the emittance of hadron beams. The promise of optical stochastic cooling (OSC) is to operate at frequencies in the visible region of the spectrum ($\sim$ 400 THz), corresponding to an increase of bandwidth of 10^4 [1]. We will focus our attention on transit-time OSC [2]. This method uses two wigglers with separate paths in between them for the travel of the light and the beam. The beam produces radiation in the first wiggler (the pickup), and subsequently travels along the beam bypass to the kicker, while the radiation travels through the light bypass, which may include an optical amplifier. We choose the lengths of the beam and light bypasses so that a particle travelling on the reference trajectory will arrive in the kicker at the zero-crossing of its own radiation, and so will not receive any energy kick. The optics of the beam bypass are arranged so that if the electron does have some transverse phase space offset, it will traverse the bypass either faster or slower than the ideal particle, and so will see a non-zero electric field in the kicker wiggler from its own radiation. This will provide either a positive or negative energy kick, which, when coupled to the transverse phase space through dispersion, will tend to cancel out the particle's initial offset. Repeated passage through such a device will provide a net cooling effect to the beam.

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In order to demonstrate the feasibility of such a method, an OSC system will be installed in the Cornell Electron Storage Ring (CESR). Although the storage ring has recently been upgraded to operate at 6 GeV as a light source [3], its flexible optics enable it to be used at lower energies as a testbed for accelerator technology. We will install two helical wigglers in the northern portion of the ring and use the existing intervening magnets as the beam bypass, providing a total bypass length of 71 meters between the centers of the wigglers, as seen in Fig. 1. Our test of OSC will take place at 1 GeV. At this energy, the OSC damping rate is comparable to the damping rate from synchrotron radiation and we therefore expect a measurable reduction in the beam emittance. Additionally, the beam current is set low enough to avoid the inchorent kick contributions [4] while still having sufficient charge for beam instrumentation. We use wigglers with a period of 32.5 cm and field strength of 0.14 T, providing radiation of 800 nm, well-suited for amplification by a Titanium-sapphire amplifier [5].

In transit-time OSC, the optics of the beam bypass are critical to achieving proper performance. In addition to providing the required path lengthening between pickup and kicker, the bypass optics also introduce dispersion in the kicker, which is necessary for horizontal cooling as discussed above. These parameters must be chosen to provide cooling from the OSC process that we can distinguish from the omnipresent radiation damping. Moreover, due to the sinusoidal nature of the radiation, the kick will switch signs when the particle's path length is changed by more than half a wavelength. Thus, for a given set of bypass optics, there is a maximum amplitude that will be cooled [6, 7]. The delay in the bypass will depend not just on the horizontal phase space coordinates of the particle, but also on its energy, which imposes an energy acceptance. These acceptances have both linear and nonlinear components. Nonlinear path lengthening is compensated by sextupoles within the bypass [8], and these sextupoles inevitably impact the dynamic aperture of the ring.

LINEAR OPTICS

In transit time OSC, the quantities of interest, such as the transverse cooling rate and the energy and emittance acceptances, are derived in [9]. In the case of transverse cooling, the energy acceptance is

$$(\Delta p/p)_{max} = \frac{\mu_0}{k(M_{56} + M_{51}\eta + M_{52}\eta')} \tag{1}$$

the emittance acceptance is

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$$\epsilon_{max} = \frac{\mu_1^2}{k^2\left(\beta M_{51}^2 - 2\alpha M_{51} M_{52} + \gamma M_{52}^2\right)} \tag{2}$$

and the cooling rate is

$$\begin{aligned}\lambda_x &= k\xi(M_{51}\eta + M_{52}\eta') \\ &\times J_0\left(\mu_0 \frac{\Delta p/p}{(\Delta p/p)_{max}}\right) J_1\left(\mu_1\sqrt{\epsilon/\epsilon_{max}}\right)\end{aligned} \tag{3}$$

where k is the wavenumber of the radiation, M_{ij} are the elements of the transfer matrix from the pickup to the kicker, η and η' are the ring dispersion and its derivative at the pickup, μ_0 and μ_1 are the first zeros of the Bessel functions J_0 and J_1, respectively, ξ is the maximum fractional energy kick provided by the radiation to the beam in the kicker wiggler, and all optics functions are evaluated at the pickup. In order to achieve a large energy acceptance, we have a small value of $M_{51}\eta + M_{52}\eta' + M_{56}$, which leads to a small value of the longitudinal damping rate. This allows us to neglect longitudinal heating or cooling, leading to a looser constraint on the transverse acceptance than reported in [9]. If we have symmetric bypass optics and a phase advance of an odd multiple of π from pickup to kicker, we find that the expressions for the acceptances and cooling rate may be written in terms of the dispersion and Twiss parameters at the pickup:

$$(\Delta p/p)_{max} = \frac{\mu_0}{k(M_{56} - 2\alpha\eta^2/\beta - 2\eta\eta')} \tag{4}$$

$$\epsilon_{max} = \frac{\mu_1^2}{k^2}\sqrt{\frac{\beta}{4\eta^2}} \tag{5}$$

$$\begin{aligned}\lambda_x &= k\xi(-2\alpha\eta^2/\beta - 2\eta\eta') \\ &\times J_0\left(\mu_0 \frac{\Delta p/p}{(\Delta p/p)_{max}}\right) J_1\left(\mu_1\sqrt{\epsilon/\epsilon_{max}}\right)\end{aligned} \tag{6}$$

We see that, in order to obtain a large transverse acceptance, we need large β and small dispersion in the wigglers. This in turn requires a large derivative of dispersion in the wigglers to get significant cooling, and so requires $M_{56} \sim 2\eta\eta'$ to get a large longitudinal acceptance. Reducing M_{56} to this level requires negative dispersion in the center of the bypass. Based on this analysis, we used Tao's built-in-optimizers [10] to obtain a 3π phase advance through the bypass, small dispersion in the wigglers, and negative dispersion in the center of the bypass. This provides us with a sufficiently good starting point that we may optimize directly on the longitudinal and transverse acceptances as well as the damping rate. We also constrain the optics functions throughout the ring consistent with apertures and injection requirements, and bring the tunes near the CHESS-U operating point to simplify transitions to the 6 GeV CHESS-U lattice. The results of this optimization are shown in Fig. 1, and summarized in Table 1.

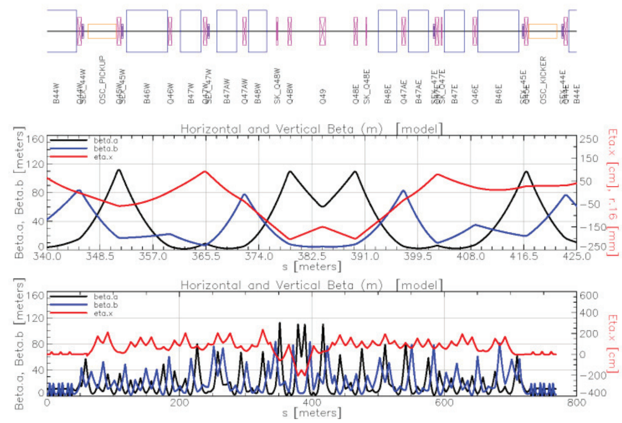

Figure 1: Layout of the OSC bypass, as well as the linear optics within the bypass and in the full ring.

Table 1: OSC and Lattice Parameters

Beam Energy	1 GeV
Bypass Length	71 m
Radiation Wavelength	800 nm
Emittance Acceptance	6.9 nm
Horizontal Emittance	1.0 nm
Linear Energy Acceptance	1.1×10^{-2}
Nonlinear Energy Acceptance	1.6×10^{-3}
Fractional Energy Spread	3.7×10^{-4}
Maximum Fractional Energy Kick	4.5×10^{-10}
Horizontal Damping Time with OSC	0.7 sec
Horizontal Damping Time without OSC	1.3 sec

NONLINEAR OPTICS

Beyond the linear optics necessary for proper operation of OSC, there are also nonlinear contributions to the acceptances. The nonlinear path lengthening due to transverse offsets is provided in [11] and [12] as:

$$\begin{aligned}\sigma_L^2 &= \epsilon^2[2(T_{511}\beta - T_{512}\alpha + T_{522}\gamma)^2 \\ &+ (T_{512}^2 - 4T_{511}T_{522})]\end{aligned} \tag{7}$$

A similar derivation leads to the nonlinear path lengthening due to energy offsets:

$$\begin{aligned}\sigma_L^2 &= \sigma_\delta^2(T_{511}\eta^2 + T_{512}\eta\eta' + T_{522}\eta'^2 \\ &+ T_{516}\eta + T_{526}\eta' + T_{566})^2\end{aligned} \tag{8}$$

The nonlinearities in Eqs. 7 and 8 can be partly compensated by introducing sexupoles into the bypass. The results

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of this procedure are shown in Fig. 2. Unfortunately, this inevitably introduces sextupoles which are nearly an order of magnitude stronger than the chromatic sextupoles in the ring.

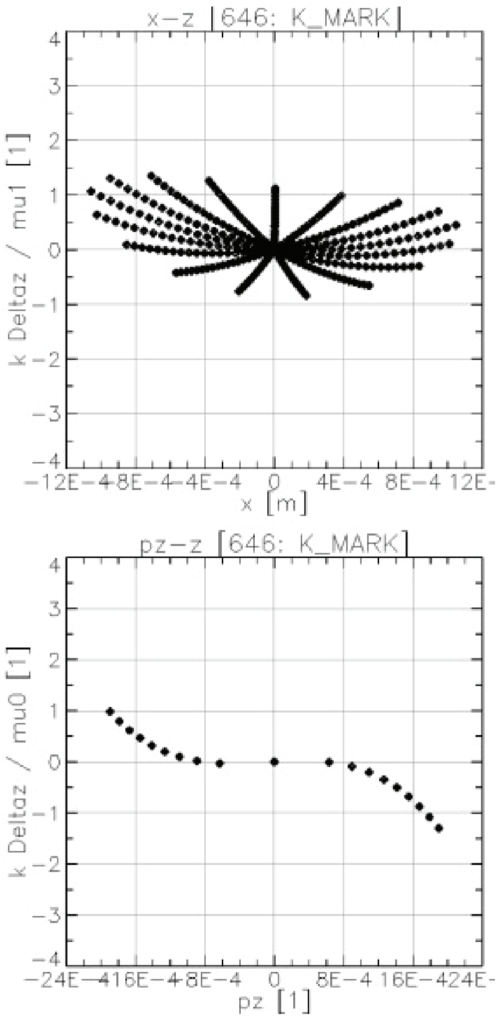

Figure 2: The nonlinear transverse and energy acceptance. No cooling will occur for particles with $|k\Delta L/\mu_1| > 1$ due to a transverse offset or $|k\Delta L/\mu_0| > 1$ due to an energy deviation. Three standard deviations in the beam size and energy spread are plotted.

DYNAMIC APERTURE

The strong sextupoles required in the bypass necessitate a significant reoptimization of the sextupole distribution in the rest of the ring in order to obtain an acceptable dynamic aperture and chromaticity. In order to achieve this, we have used a method based on Bengtsson's resonance driving terms [13]. We first solve the linearized equations which give the first-order driving terms as functions of the strengths of the various sextupoles to obtain a good starting point for optimization. We then use Tao's built-in optimizers to minimize the first and second-order driving terms and amplitude-dependent tune shifts, as well as to bring the chromaticities in both planes to unity. The results of this optimization are shown in Fig. 3.

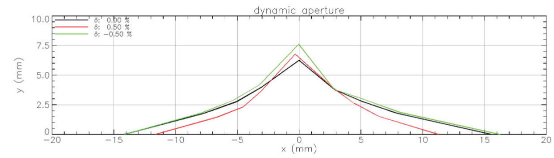

Figure 3: The dynamic aperture of the OSC lattice to be used for testing the OSC process itself.

Variable Sextupole Distribution

The dynamic aperture and injection efficiency obtained with the above optimization are significantly worse than those for the 6 GeV CHESS lattice. However, we note that the good dynamic aperture and injection efficiency are most important during injection, while the optimization of the nonlinear OSC optics is only important when we wish to observe cooling. It therefore makes sense to use one sextupole distribution, optimized for injection efficiency, for injection and switch to a second distribution, optimized for maximizing the OSC nonlinear acceptance, to actually measure damping rates. The distribution for the latter case is what we had discussed in the preceding sections. The dynamic aperture corresponding to the injection sextupole distribution is shown in Fig. 4.

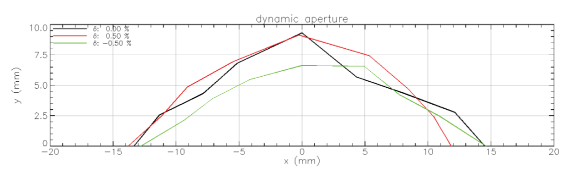

Figure 4: Dynamic aperture for the sextupole scheme used for injection. Since we do not constrain the bypass sextupoles to maximize the nonlinear acceptance, their strengths may be reduced and the dynamic aperture improved.

CONCLUSIONS

We have designed a lattice which will enable the testing of the OSC process at CESR. This includes good longitudinal and transverse acceptances and transverse cooling rate. It overcomes issues with poor injection efficiency by using one sextupole scheme with good dynamic aperture for injection and another with good nonlinear OSC acceptances for the experiment itself.

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