# INTRABEAM SCATTERING AND TOUSCHECK LIFETIME FOR THE OPTICAL STOCHASTIC COOLING EXPERIMENT AT THE MIT-BATES SOUTH HALL RING

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*Abstract*

A proof-of-principle experiment of Optical Stochastic Cooling (OSC) at the MIT-Bates South Hall electron storage ring (SHR) has been proposed. To produce convincing cooling results, the ring will be run near 300 MeV. Beam emittance growth caused by Intrabeam scattering (IBS) is a major concern for the design of experiment. Touschek scattering imposes a dominant limit on beam lifetime. Evaluation of these effects is part of the design optimization process. Simulation analyses of cooling for a viable OSC experiment are presented.

## INTRODUCTION

Transit-time Optical Stochastic Cooling is a uniquely, promising cooling mechanism for high-brightness, high-energy hadron beams [1]. The first proof-of-principle experiment of OSC at the MIT-Bates SHR has been proposed recently [2]. To test the OSC principle on an electron ring has two major advantages. First, the OSC cooling rate for electron beams is much faster and cooling effects are much easier to be observed. Secondly, the cost to conduct such test is much lower than in a high-energy hadron ring.

The Bates SHR has two long straight sections, one for injection and the other available for an OSC insertion of a length of around 10 meters. A small-angle electron beam magnetic bypass chicane is proposed combined with a state-of-art optical amplifier to achieve cooling objectives with significant technical simplicity and reliability.

The SHR dipoles have a large bending radius (9.144 m). Operating at 300 MeV as proposed, the synchrotron damping is slow ($\tau_x$ is ~5 seconds) which is desirable for OSC observation. However at this low energy, beam emittances in both transverse and longitudinal phase space are predominantly defined by the balance between IBS growth and synchrotron radiation damping. Touscheck scattering loss becomes a primary limit of beam lifetime which has to be long enough for meaningful cooling measurements.

To counter IBS growth and Touschek loss, an 'OSC lattice' was developed, which produces a large natural beam emittance (about 10 times that of normal SHR operation). Special optical design for large dispersion functions at the OSC insertion straight is also required for transverse OSC.

The IBS and Touschek effect evaluations were part of the optimization process for the OSC experimental design.

## IBS AND OSC CALCULATIONS

The IBS growth rates and equilibrium emittances without cooling are calculated using *elegant* [3] which employs the same formalism as described in ZAP code [4]. We assumed a fixed X-Y coupling coefficient of 0.1.

The optical stochastic cooling formalism is described in [1], reformulated and extended to general bypass designs in [5]. In the OSC insertion, particles pass through two undulators at the entrance and exit of a horizontal magnetic bypass chicane. At the first undulator, each particle emits an EM wave packet of length $\lambda N_\mu$ which is amplified optically and sent to the second undulator. There, each particle interacts with its own amplified wave and the waves of all particles traveling within a coherent slice of length $\lambda N_\mu$. $N_\mu$ is the number of undulator periods. The wave number of the EM wave is $k=2\pi/\lambda$; $\lambda=[\lambda_\mu(1+K^2/2)]/2\gamma^2$ is the undulator wavelength, $\lambda_\mu$ is the undulator period, K is the undulator parameter, and $\gamma$ is the Lorentz factor. The particle path length increase through the bypass chicane is

$$\Delta l = R_{51}x+R_{52}\theta+h\delta,\ \ h=R_{51}\eta + R_{52}\eta' + R_{56} \ . \qquad (1)$$

where $R_{i,j}$ are inverse bypass matrix elements; x, $\theta$, $\delta$ are transverse betatron position, angle, and momentum deviation at exit of the OSC insertion. The phase shift of the particle with respect to its own amplified light pulse is $\Delta\phi\equiv k\Delta l$. The cooling rates for a Gaussian beam are:

$$\begin{aligned}\alpha_T &\equiv -\frac{1}{2}\left(\frac{\Delta\langle x^2\rangle}{\langle x^2\rangle}+\frac{\Delta\langle\theta^2\rangle}{\langle\theta^2\rangle}\right) \\ &= Gk(h-R_{56})\exp\left\{-\frac{\langle\Delta\phi^2\rangle}{2}\right\} - G^2N_s\nu^2/(2\langle\delta^2\rangle)\end{aligned}\ , \qquad (2)$$

$$\alpha_\delta \equiv -\frac{\langle\Delta\delta^2\rangle}{\langle\delta^2\rangle} = -2Gkh\exp\left\{-\frac{\langle\Delta\phi^2\rangle}{2}\right\} - G^2N_s/(2\langle\delta^2\rangle)$$

with $$G = g\frac{qE_0N_u\lambda_uK}{2c\gamma p}\ , \qquad \textbf{(3)}$$

and $$\nu^2 \equiv \left(\frac{\eta^2}{\langle x^2\rangle}+\frac{\eta'^2}{\langle\theta^2\rangle}\right)\langle\delta^2\rangle/2\ , \qquad \textbf{(4)}$$

$$\langle\Delta\phi^2\rangle = k^2\left(R_{51}{}^2\langle x^2\rangle + R_{52}{}^2\langle\theta^2\rangle + h^2\langle\delta^2\rangle\right)$$

where *g* is the amplication factor of the optical amplifier, *q* is the particle charge, $E_0$ is the initial amplitude of the one particle EM wave, *P* is the particle momentum, and $N_s$ is the particle number within the coherent slice of $\lambda N_\mu$. In an equilibrium state, the emittance growth (damping) rates of IBS, OSC, synchrotron radiation damping and quantum excitation satisfy the relations:

$$g_{IBS-x} + g_{x,syn}\left(\frac{\varepsilon_{x0}}{\varepsilon_x} - 1\right) + f_0\alpha_{x-OSC} = 0 \quad , \qquad \textbf{(5)}$$
$$g_{IBS-\delta} + g_{l,syn}\left(\frac{\delta_0^2}{\delta^2} - 1\right) + \frac{f_0\alpha_{\delta-OSC}}{2} = 0$$

where $f_0$ is the particle revolution frequency in the ring.

The cooling rate of the longitudinal phase space is half of $\alpha_\delta$ calculated for $<\delta^2>$ in equation (4), as a consequence of mixing in the longitudinal phase space [6].

In the cooling calculations, the beam phase space evolution is obtained by iterating instantaneous growth rates and beam emittances in all phase planes until an equilibrium state is reached. The IBS growth rates as functions of $\varepsilon_x$, $\delta^2$, and bunch charges are pre-calculated as inputs for interpolation in the iteration process.

## COOLING OBSERVATIONS

The initial OSC experimental parameters have been carefully chosen to optimize cooling effects, and to be technically (for undulator, bypass chicane, optical amplifier, cooling measurement etc.) feasible [2] [7]. The cooling effects will be observed by measuring changes of beam profile (transverse and longitudinal) in equilibrium before and after cooling. The parameters for the proposed transverse cooling test are listed in Table 1.

Table 1: SHR & OSC Insertion parameters

| | Natural | IBS effect |
|---|---|---|
| SHR Energy (MeV) | 300 | |
| RF Voltage (kV) | 14 | |
| Particles/bunch, bunch number | $1\times10^8$ ,12 | |
| Average current (mA) | 0.3 | |
| Beam emittance, εx (nm) | 49 | 96 |
| Energy Spread | 8.5e-5 | 1.67e-4 |
| rms bunch length (mm) | 5.1 | 9.8 |
| SR damping τx (sec.) | 4.83 | |
| Touschek lifetime (min) | 0.67 | 1.45 |
| Lattice para. at OSC Insertion | β=3m, η= 6m, η′=η/β | |
| Chicane: L/max. bend angle | 6m / 65 mrad | |
| Chicane: R51/R52/R56 | $8.6\times10^{-4}$ / 2.52 mm / -12 mm | |
| Undulator: L / period/λ | 2m / 20cm / 2μm | |

The optical amplification factor can be adjusted to optimize the cooling process. The optimal G to maximize the total cooling rate $\alpha = \alpha_T + \alpha_\delta$ is:

$$G_m = -k\langle\delta^2\rangle(h+R_{56})\exp\left\{-\frac{\langle\Delta\phi^2\rangle}{2}\right\}/\left(N_s\left(1+\nu^2\right)\right) \quad . \qquad (6)$$

and $\alpha = \frac{1}{2}\left[k(h+R_{56})\exp\left\{-\frac{\langle\Delta\phi^2\rangle}{2}\right\}\right]^2 \langle\delta^2\rangle/\left(N_s\left(1+\nu^2\right)\right)$

As $G_m$ is a function of beam profiles, it should be adjusted during the cooling process.

Figure 1 shows the horizontal beam size reduction during the cooling process. The horizontal rms beam size including IBS effects is 0.54 mm. Starting from the equilibrium state, cooling is expected to reduce $\sigma_x$ by ~40% to 0.34 mm in less than 2 seconds with optimal optical amplification variations. If the optical amplification is fixed at an optimal value corresponding to the initial beam profiles, the reduction is only 13%.

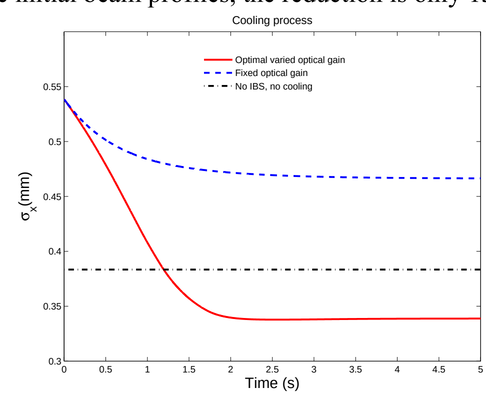


Figure 1. Transverse beam size reduction due to OSC.

Various growth (damping) rates during the OSC cooling process are plotted in Fig.2. In this experiment, the IBS and OSC are the two dominant mechanisms to define the beam transverse emittance.

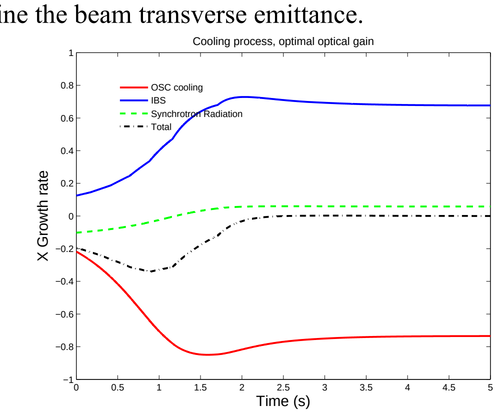


Figure 2. The ½ transverse growth rates during cooling.

However in longitudinal phase space (Figure 3), after an initial minor compression, the momentum spread (and the bunch length) increases by ~25%. The increasing radiation damping counteracts a stronger IBS growth due to horizontal size reduction. The 25% length change of a 20 mm long bunch can be easily detected with a streak camera in the SHR [8].

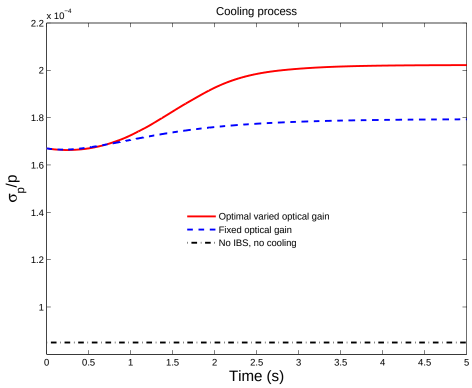


Figure 3. Energy spread variations during cooling.

The required variation of the optical amplification is a quite moderate 30% increase in 2 seconds as shown in figure 4.

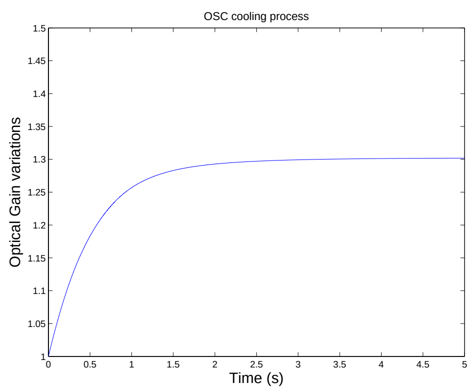


Figure 4. The optimal optical amplification variations

## TOUSCHEK LIFETIME

The OSC lattice has a large natural beam emittance, and a large momentum compaction ($\alpha$=0.05). The energy acceptance for this lattice is dominated by the RF acceptance. The actual momentum aperture around the ring was determined by 6D tracking with *elegant* [9]. It verified that the RF aperture limits the energy aperture (at $V_{rf}$=14 kV, $\varepsilon_{RF}= \pm 5.7\times10^{-4}$). The 6D tracking gives a slight asymmetry of positive and negative acceptance ( $5.25\times10^{-4}$, $-5.75\times10^{-4}$ ) due to non-linear synchrotron motion.

The Touschek lifetime for the table-1 setting is short. For equilibrium (with IBS), it is only 90 seconds (See Fig. 5). Still it is acceptable to make beam profile measurements without significant bunch intensity loss.

One can reduce bunch intensity to increase Touschek lifetime which also helps the cooling. However, a limited optical amplifier repetition rate limits the bunch number in the ring to 12, and the average stored current to 0.3 mA for a bunch intensity of $10^8$ particles. It will be difficult for beam diagnostics to operate at even lower current.

The other way to increase Touschek lifetime is to raise $V_{rf}$, up to 140 kV for the RF cavity in the SHR. This will reduce the bunch length as $\sigma_l \propto (V_{rf})^{1/2}$, and therefore increase $N_s$ and reduce the cooling rate. Combined with increased IBS rates, the observed cooling effect would be drastically reduced.

A proper experimental procedure may be to inject and stack beam at high RF voltage with longer Touscheck time (~ 10 minutes), and then switch to low RF voltage for cooling and measurements.

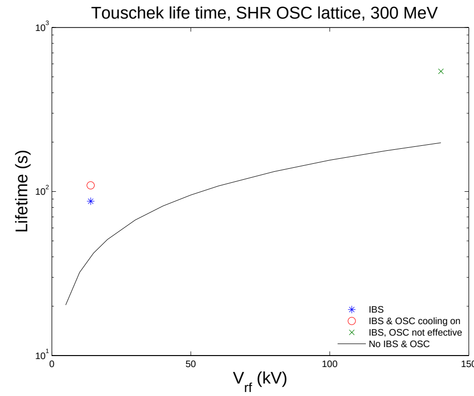


Figure 5. Touschek lifetime vs. $V_{rf}$.

## SUMMARY

IBS-caused emittance growth and the Touscheck lifetime limit are of major concerns to the design of OSC experiment at the MIT-Bates SHR. Evaluation of these effects have been incorporated in the design for optimized cooling. Initial cooling simulations show that OSC can be demonstrated through large transverse beam size reduction and bunch length changes with the proposed OSC apparatus and SHR parameters.

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