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ELECTRON BEAM SHAPING TECHNIQUES USING OPTICAL STOCHASTIC COOLING*

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Abstract

Optical Stochastic Cooling (OSC) has demonstrated its ability to reduce the three-dimensional phase-space emittance of an electron beam by applying a small corrective kick to the beam each turn. By modifying the shape and timing of these kicks we can produce specific longitudinal beam distributions. Two methods are introduced; single-pulse modulation, where the longitudinal profile of the OSC pulse is amplified by some function, as well as multiple-turn modulation, where the overall strength or phase is varied depending on the synchrotron oscillation phase. The shaping techniques are demonstrated using a model of OSC developed in the ELEGANT particle-tracking code program.

BACKGROUND

Optical Stochastic Cooling (OSC) is a beam cooling technique which uses a pair of undulators to correct the deviation in momentum of each particle [1, 2]. In the passive-OSC scheme, undulator radiation is focused directly from the pickup into the kicker undulator [3]. In the active-OSC scheme, the radiation is first amplified before being recombined with the particle beam. The amplification is typically performed uniformly (i.e. is constant along the bunch and on a turn-by-turn basis) to increase the cooling rate while reducing the emittance and increasing the beam lifetime by counteracting intra-beam scattering (IBS) effects. However, by modulating the amplification on a turn-by-turn basis or along the bunch and controlling the optical delay, OSC can be used to tailor the longitudinal phase space (LPS).

THEORY

There are two implementations enabling the OSC mechanism to be used to control the LPS distribution of an electron beam. One option is to implement a multiple-pass control of the corrective kick strength where the gain of the optical amplifier is dependent on some variable such as synchrotron oscillation phase. Another method is to control the temporal distribution of the laser amplifier so to apply a kick $\kappa(s)$ dependent on the bunch longitudinal coordinate.

The longitudinal OSC mechanism reduces each particle's deviation in momentum by a small fraction each pass, gradually reducing the energy spread and bunch length. A particle traces an ellipse in LPS (s, p) so a particle with high deviation in momentum and low spatial deviation $\phi = \pi/2$ later will have low momentum deviation and high spatial deviation. Unlike for the case of betatron motion, this varies relatively slowly and can be used as the independent variable in beam shaping techniques.

Multiple-Pass Control

Multiple-pass control uses time-dependent amplification of the undulator radiation to shape the longitudinal beam distribution. The main motivation for multiple-pass control is using this periodic behavior to reduce the longitudinal deviation of the beam in only one degree of freedom. That is, to reduce the momentum spread while leaving the bunch length unchanged (or vise versa depending on at what phase in the synchrotron period they are measured). This is achieved by applying the OSC kick at the same point every synchrotron period.

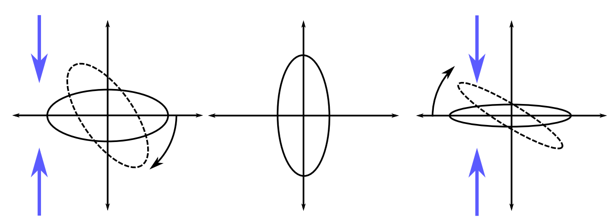

Figure 1: Synchrotron Phase

Figure 1 depicts this method implemented to "flatten" the beam LPS. The kick is applied and reduces the momentum spread. $\pi/2$ later, the beam has rotated so that what was the bunch length has converted into the momentum spread. The kick is turned off here so there is no reduction in the original bunch length. Finally, as the bunch rotates $\pi/2$ back to the minimum energy spread, the kick is turned back on thereby continuing to flatten the beam in one dimension only.

Single-Pass Control

The next tool for shaping electron beams with OSC is single-pass control of the amplification function. This relies on temporally shaping the amplification of the undulator radiation pulse. In traditional OSC, the pulse is amplified uniformly to reduce the phase-space emittance of the beam; see Fig. 2(a). This uniformly increases the electric field all particles in the bunch experience in the kicker. An amplification pulse with temporal (e.g. along s) dependence can be used to control specific slices within the bunch separately; Fig. 2(b). By applying a non-uniform amplification function

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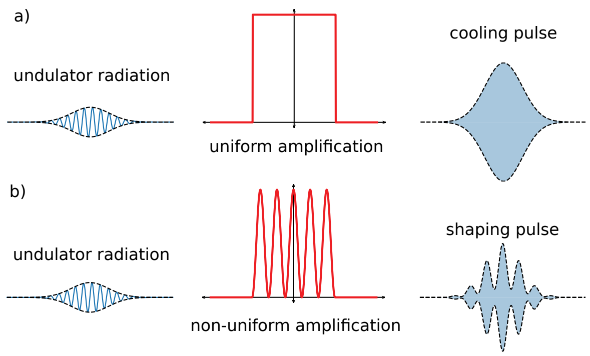

Figure 2: Conventional (a) and non-uniform (b) undulator-radiation amplification.

in time, only specific slices of the beam will be cooled (or heated depending on the introduced delay).

APPLICATIONS

We investigate two applications of the proposed shaping techniques: (*i*) single-dimension flattening of LPS distribution and (*ii*) the formation of beamlets via bunch splitting.

Energy Spread Reduction (Multi-Pass)

Using the concept described earlier in Fig. 1 the OSC mechanism flattens the beam. The corrective kick of the active-OSC scheme is defined as a function of synchrotron oscillation phase ϕ so that,

$$\delta p/p = \kappa(\phi)\sin(\omega(t_i - t_0) + \psi) \tag{1}$$

and, with

$$\kappa(\phi) = \kappa_0 \cos(\phi)^n, \tag{2}$$

where κ_0 is the maximum corrective kick and n is some large, even integer. For smaller values of n, the OSC force will reduce the bunch length alongside the energy spread. The sin() term represents the kick of the transit-time model of OSC.

Micro-bunch Formation (Single-Pass)

OSC can also be used to focus cooling on specific parts of the beam by non-uniformly amplifying the undulator radiation pulse. In our investigation, we attempt to use this method to form micro-bunches by amplifying by a cosine-squared function with wavelength less than the bunch length and sweeping between heating and cooling. This is shown in Fig. 2(b). For such an implementation we consider the amplification to be of the form

$$\kappa(\phi) = \kappa_0 \cos(\phi)^n \cos(\omega_s t + \phi/4)^2, \tag{3}$$

where the first cosine term comes from the multi-pass shaping, the second is the $\cos^2()$ "comb" which alternates between heating and cooling due to the $\phi/4$ term, and ω_s controls width of the micro-bunches.

DEMONSTRATION

The first experimental demonstration of OSC was recently conducted at Fermilab's IOTA ring [4, 5]. The experiment cooled low-charge bunches of 100 MeV electrons using two undulator magnets [3]. This experiment provides a lattice on which we may test the practical limits of these techniques.

Toy Model

The motion of particles turn-to-turn in a storage ring can be quickly calculated using a transfer-matrix approach. A simple toy model of the IOTA lattice is represented using three transfer matrices; one between the pickup and the kicker undulators, one from the kicker undulator to the RF cavity, and one from the RF cavity to the pickup undulator. Each particle's position is recorded at the pickup and is used to apply a kick in momentum at the kicker defined by the function $\delta p/p = -\kappa\sin(\omega(t_i - t_{avg}) + \psi)$ where $t_i - t_{avg}$ is the difference in the time of flight between pickup and kicker of the *i*th particle and the average, ω is the angular frequency, and ψ is the optical delay. The RF system is modeled as a kick in momentum as well as a reduction in the transverse momentum to account for synchrotron radiation. Together this provides a quick computation tool to test beam shaping techniques with considerable accuracy.

This "toy model" is used for quick simulations and can also produce phase-space attractor plots. These are plots in which particles are uniformly placed in phase-space and their trajectories at the beginning of every synchrotron period are mapped; see Fig. 3. The attractor plot shows regions where

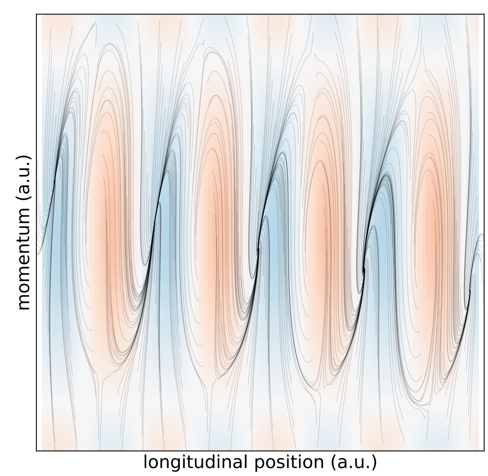

Figure 3: Attractor plot example. The blue and red regions show the relative cooling/heating force of every point in phase space integrated over a single synchrotron period. The black lines track the evolution of particles undergoing the single-pass shaping scheme.

particles are pushed towards and away from as well as how they get there. This can help design shaping techniques that need to avoid certain regions of phase space.

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ELEGANT

The toy model has obvious short comings. A full tracking simulation was done using ELEGANT[6] implementing a high-fidelity model of OSC we developed[7]. This more accurately simulates SR effects, scattering, and particle dynamics.

First, looking at the energy spread reduction, we applied an OSC kick according to Eq. (2), with n=100. The synchrotron frequency of the IOTA ring is $f_0 = 426$ Hz (corresponding to ~ 17600 turns). Figure 4(a) presents the corresponding beam evolution over ~ 17 synchrotron periods. The minima correspond to the energy spread reached when the beam is at the longest bunch length. As the beam rotates in phase space, however, the bunch length converts to energy spread. The maximum oscillations remain relatively constant while the minimum momentum spread decays. Such a behavior indicates the beam getting flatter in only one degree of freedom and can be seen on the LPS plots in Fig. 4(b,c,d).

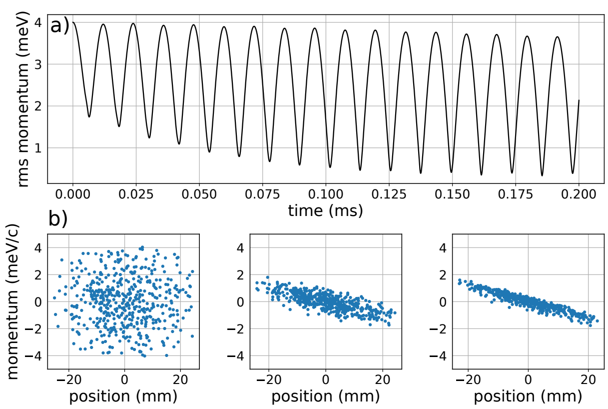

Figure 4: Energy spread reduction using multipass gain modulation. The top plot shows the r.m.s. momentum spread. The lower plots are the LPS distributions at synchrotron periods 1, 8, and 17.

In the second we attempted to form micro-bunches within a beam. By amplifying the OSC kick according to Eq. (3). A similar simulation was run for this method using 1000 macroparticles for 8 synchrotron periods. Figure 5 shows a waterfall plot of evolution of the corresponding longitudinal bunch distribution. As the beam rotates though the phase-space the bunch length grows and shrinks but the initial Gaussian distribution eventually splitting into about 9 beamlets; see final LPS in Fig. 6. The spread of the beamlets are tunable with the lower limit most likely limited by space-charge and intra-beam scattering effects. Figure 6 shows the longitudinal distribution of the beam in the final synchrotron period. The particles have formed into micro-bunches but many particles still remain far from the attractors. This can be further improved by alternating between the beam shaping and beam flattening techniques. It should be noted that that the bunch spacing correspond to ~ 1 ps while the bunchlet duration is below ~ 500 fs in this example. Such capabilities could support the generation of narrowband tunable radiation pulses in the THz and beyond [8].

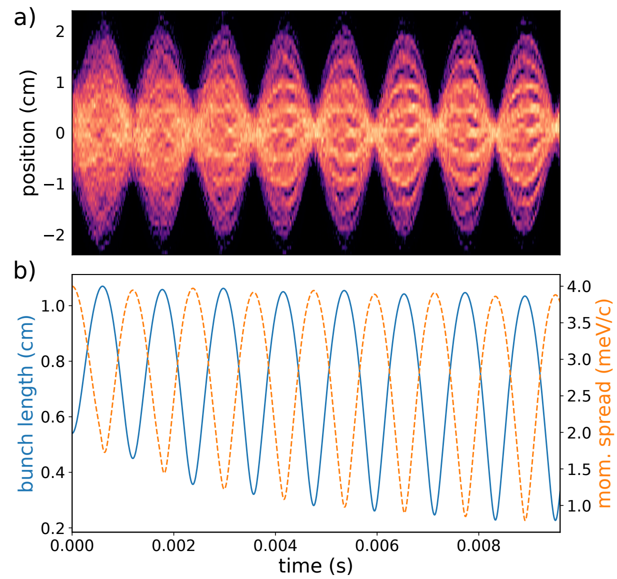

Figure 5: Demonstration of microbunch formation. Waterfall plot of the evolution of the longitudinal bunch distribution (top), and corresponding rms bunch length and energy-spread evolution over 10 ms (bottom).

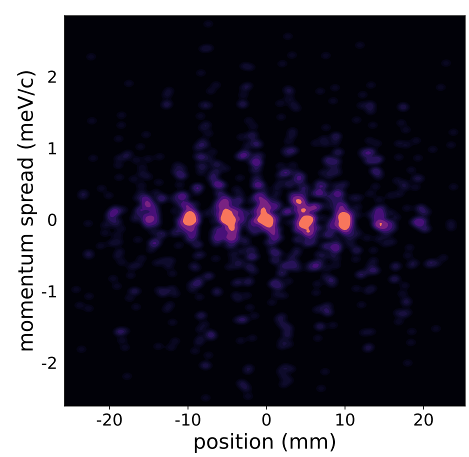

Figure 6: LPS distribution obtained at $t \simeq 9$ ms in Fig. 5.

CONCLUSION

We have investigated two methods for shaping the longitudinal distribution of beams in storage rings using optical stochastic cooling. These methods are effective in reducing a single dimension of the LPS and targeting cooling on specific longitudinal slices. Future investigations will look into the physical limits of these methods and potential applications given available laser-shaping methods [9]. Applications could include tunable light sources or experiments which require specific distributions. It may also be possible to shape the transverse profile of beams by coupling the longitudinal and transverse degrees of freedom.

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