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Amplifier for Optical Stochastic Cooling

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Abstract: The amplification of electromagnetic radiation emitted from charged-particle beams can be used for beam cooling. We discuss our progress to develop such a system using undulator radiation.

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1. Introduction

In Optical Stochastic Cooling a particle emits radiation in a pickup undulator. The light from the pickup is then transported to a kicker undulator located downstream and identical to the pickup undulator. Therefore the particle follows a curved path in a magnetic bypass chicane such that it arrives at the entrance of the kicker just as the light from the pickup is also arriving [1,2]. Depending on the energy of a particular particle it will be delayed or advanced in the bypass chicane relative to a reference particle. This additional longitudinal displacement gives rise to a phase, between the pickup and kicker light, correlated to each particles energy. Thus a particle will appropriately constructively or deconstructively interfere with its own radiation giving it a corrective kick. Over many turns in the accelerator this leads to a decrease in the longitudinal phase space of the entire particle beam. Additionally the presence of beam dispersion in the kicker can result in reduction of the horizontal beam emittance. Coupling the horizontal and vertical phase spaces outside of the cooling insertion results in full 6-D phase space cooling. A comprehensive overview of the technique is given in [3]. Fermilab is currently pursuing a proof-of-principle test of the OSC with 100 MeV electrons in the Integrable Optics Test Accelerator (IOTA) [4].

An important figure of merit for an OSC system is the damping decrement (betatron and synchrotron amplitudes) per turn and is proportional to the amplitude of the pickup light arriving in the kicker. Thus including an amplifier in the light optics transport system will increase the damping decrements. Unfortunately the design of such an amplifier is constrained to be single pass and can only afford an optical delay of a few mm's.

The amplifier must be capable of amplifying pulses as long as the bunch length at high repetition rates ($\approx$ 500 ps at 7.5 MHz in IOTA) and have sufficient bandwidth to preserve the time structure of each particles individual radiation ($\approx$ 100 THz) within the bunch. Furthermore to obtain sufficiently large cooling ranges OSC must take place in the Mid-IR regime. The above considerations lead us to consider an amplifier based on Cr:ZnSe crystal, which has a mid-band wavelength $\lambda_a = 2.49$ μm and an bandwidth $\Delta\omega_a \approx 2\pi * 50$ THz, pumped with a CW Thulium laser at 1.908 μm.

2. Cr:ZnSe as an OSC amplifier in IOTA

The circumference of IOTA is 40 m and will have 77 cm long undulators consisting of 7 periods and an undulator parameter $K = 1.04$. This corresponds to an average power of 60 fW per electron per undulator. During demonstration of the OSC we will use bunches with $\approx 10^6$ particles. The average power is then on the order of 10's of nw's with the peak power only about 250 times larger. Thus calculations for gain can be done in the steady state and completely neglect the presence of the undulator radiation. At the pump laser frequency, ν_p, Cr:ZnSe has both an absorption cross section σ_{pa} and an emission cross section σ_{pe}. The pump beam intensity, I_p, can be found by numerically integrating [5]

$$\frac{dI_p}{dz} = -I_p N_t \left(\frac{(1+I_p\sigma_{pe}A)(\sigma_{pa}+2\sigma_{pe})}{I_pA(\sigma_{pa}+2\sigma_{pe})+1} - \sigma_{pe} \right) \tag{1}$$

where N_t doping concentration and $A = \tau_2/h\nu_p$, h is Plank's constant and τ_2 is the fluorescence time and is taken to be 5 μs for our calculations. The total change in the pump intensity over a crystal length of L, $\Delta I_p = I_p(z=0) - I_p(z=L)$

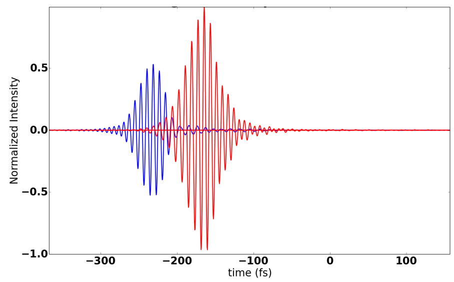

Fig. 1. **The original pulse reconstructed from light from an undulator alongside the amplified pulse (red) constructed from the modified spectrum using Eq.3.**

relates to the signal gain (in power) as

$$G = e^{\frac{\sigma_s \tau_2}{h\nu_p}\Delta I_p} \tag{2}$$

where σ_s is the emission cross section at λ_a. With a 1 mm long crystal doped with a concentration of $N_T = 2.0 * 10^{19}$ cm^{-3} and a pumping intensity of 100 kW/cm^2 yields G=7 dB at the mid-band wavelength. This gain can be used to calculate the amplitude growth of the electric field emitted from a single classical electron. However we must additionally account for (i) Dispersion from the host material, (ii) Gain narrowing of the pulse due to a finite amplifier bandwidth and (iii) A phase shift that occurs during amplification. We calculate the modification of the field harmonic using [6] [7]

$$E_2(\omega, z) = E_1(\omega)\exp[i(z\beta + \phi_{amp})]G^{\frac{1}{2(1+\Delta x^2)}}. \tag{3}$$

with ϕ_{amp} given by

$$\phi_{amp} = \frac{\Delta x}{(1+\Delta x^2)}\ln(G), \tag{4}$$

where $\Delta x = 2\dfrac{\omega - \omega_a}{\Delta\omega_a}$ and $\omega_a = 2\pi\dfrac{c}{\lambda_a}$. $E_1(\omega)$ was found by simulating undulator radiation with Synchrotron Radiation Workshop [8]. A time domain plot of the pulse from a single electron before and after amplification is shown in Fig 1. Finally the increase in cooling decrement is found by taking the maximum of the correlation function between the initial and amplified pulse and multiplying by $\sqrt{G}$. It is then expected that the amplifier described above will increase the cooling decrement by a factor 2.

3. Conclusions

An amplifier based on Cr:ZnSe is sufficient to demonstrate OSC for electrons. Initially the OSC was suggested for high luminosity hadron colliders. However to be useful for this purpose an amplification of 20-40 dB is required. In this case usage of Cr:ZnSe does not look promising because the required gain cannot be achieved simultaneously with required small delay of the signal. An alternative is to use an OPA with the pump pulse circulating in a resonant cavity to mitigate the high average power needed to operate a high repition rate, high duty cycle OPA. The resonant cavity is a tenable solution since, even at high single pass gain, the pump remains undepleted.

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