# OPTICAL PARAMETRIC AMPLIFIER TEST FOR OPTICAL STOCHASTIC COOLING OF RHIC

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*Abstract*

Optical Stochastic Cooling (OSC) of gold ions in the Relativistic Heavy Ion Collider (RHIC) operating on wavelength ~12μm has been proposed by Ilan Ben-Zvi and use of Optical Parametric Amplifier (OPA) for OSC was suggested by Max Zolotorev [1, 2]. We have tested the performance of the OPA suggested to be used in OSC for RHIC. Our OPA is based on a single $CdGeAs_2$ crystal that has been pumped by a second harmonic of pulsed $CO_2$ laser system. Particle emission was emulated by output of another hybrid $CO_2$ laser operating in single longitudenal mode regime at wavelength 9.552 μm. The maximum amplification was achieved at a pump intensity value of $9.2\times10^6$ W/cm$^2$. Further increase of the pump intensity caused amplification quenching which we attribute to nonlinear multiphoton absorption of the pump beam. We also performed interferometric measurements that demonstrate that amplification of the radiation in OPA preserves its coherence.

## INTRODUCTION

Optical Stochastic Cooling [3] has been proposed as a method of dumping of the beam emittance that appears due to the intrabeam scattering (IBS) in the RHIC [1]. The basic idea of the OSC can be described as follows: a charged particle radiates while passing through the pickup undulator. This radiation carries information about the particle trajectory, is collected, amplified and then sent into the kicker undulator. The cooling occurs when the particle from the beam interacts in the kicker undulator with its own amplified radiation coming with a 180° phase shift. It is worth noting that the interaction of a particle with the amplified radiation of another particle results in heating. The compromise between cooling and heating imposes requirements on the optical amplifier gain and bandwidth [3].

The feasibility of OSC for RHIC has been theoretically proven [3, 4]. The cooling rate scales as a square root of wavelength. Thus, the optimal operation wavelength for optical stochastic cooling lies in the far IR range. It has been proposed [1, 2] to use OPA based on a nonlinear crystal operating at $\lambda$ = 12 μm being pumped by the second harmonic of a pulsed $CO_2$ laser. The amplification results from the nonlinear process of conversion of the 5.3 μm pump beam energy into the energy of the 12 μm idler beam and 9.552 μm signal beam. It has been shown that a reasonable cooling rate of gold ions in RHIC can be reached within an hour with the output power of the amplifier about 16 W and its bandwidth at least 100 cm$^{-1}$ [2].

Keeping this consideration in mind, we built and tested an OPA based on a single $CdGeAs_2$ crystal, which we anticipated could potentially be scaled up to meet the above requirements. Figure 1 shows the dependence of the OPA gain on the photon energy of amplified radiation. Unfortunately, we did not have a source of 12 μm radiation available. We tested the amplifier performance with a 9.552 μm seed and the idler wavelength in this case would be 12 μm.

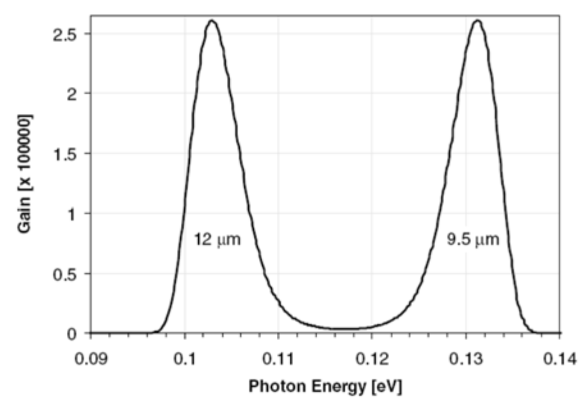


Figure 1: Dependence of the OPA gain on the photon energy of amplified radiation calculated using formulae from [5]

It is important that for the OSC setup to operate properly, the information about the state of the charged particles in the storage ring carried by the radiation emitted from the pickup undulator is not lost when the radiation is amplified. That is why we also checked how well the coherence of the radiation is preserved during the amplification.

## EXPERIMENTAL

Layout of the optical parametric amplifier (OPA) for the proposed optical stochastic cooling setup is shown in Figure 2. The OPA is based on a single crystal ($CdGeAs_2$) pumped by the second harmonic of the amplified output of hybrid $CO_2$ laser #1. The laser was tuned to the wavelength of 10.591 μm and produced ~300 ns long pulses. The Pockels cell (*PC1*) and thin film polarizer (*TFP1*) have been used to reduce the duration of the pulse down to 22 ns. The shortened pulse then was amplified by the 2-atm $CO_2$ amplifier.

The amplifier output was frequency doubled by the



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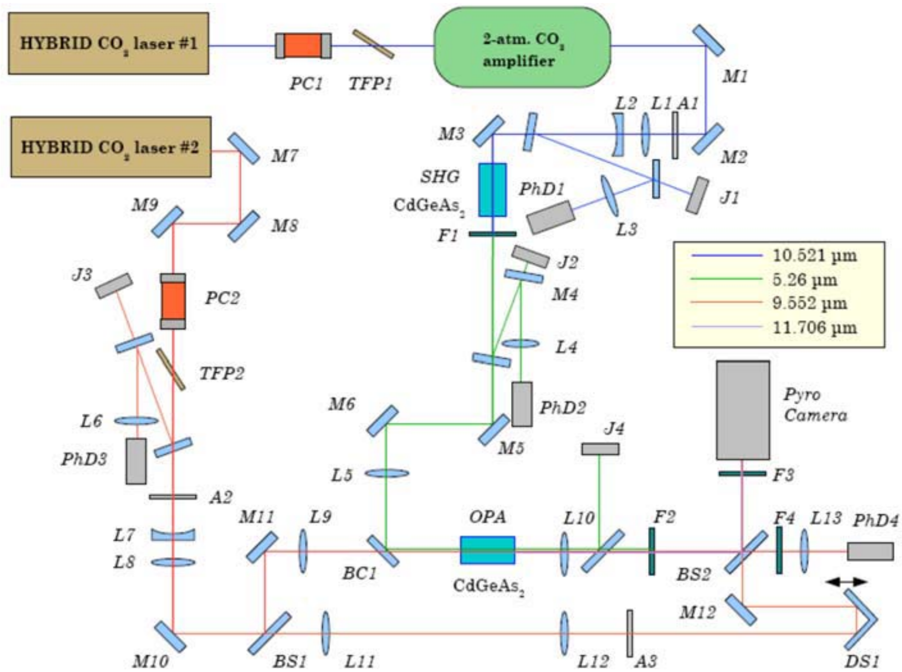


Figure 2: Layout of the OPA setup. Refer text for details.

$CdGeAs_2$ SHG crystal. The crystal has dimensions 6×6×8.2 mm and cut at the angle $\theta$ = 30.0°, which corresponds to Type I [5] mixing scheme for frequency doubling. With help of a telescope consisting of lenses *L1* and *L2* the pulse beam size and divergence were optimized to maximize the second harmonic output energy. The energy of the pulse entering the SHG crystal was varied with an attenuator *A1*. A small portion of the fundamental picked off after the attenuator *A1* by the beam splitter (*BS1*) was sent to photo diode (*PhD1*) and the pyroelectric detector used for energy and beam profile measurements. These measurements showed that the beam shape of the fundamental harmonic pulse was close to Gaussian. A four millimeter thick $MgF_2$ filter *F1* was used to block the fundamental frequency radiation.

The other hybrid $CO_2$ laser was used to emulate the emission of the ions going through pickup undulator. This laser was tuned to a wavelength of 9.552 μm and generated smooth pulses with a duration of about 1.25 μs reduced to 10 ns by the assembly consisting of the Pockels cell *PC2* and the polarizer *TFP2*. In a similar manner, a small portion of the beam was picked off after the attenuator *A2* for output power measurements.

The OPA crystal has the same dimensions and the phasematching angle as the doubling crystal. The phase matching angle of the OPA is close to the one required for doubling frequency phase matching. The OPA crystal was cooled by liquid nitrogen. The idler beam was dumped by filters *F3* and *F4* made of 3mm thick $CaF_2$ plates. Each of these plates reduces the intensity of the 12 μm radiation more than 20 times, while the intensity of the seed beam is reduced by a factor of 1.4.

Mirrors *M11* and *M12*, beam splitters *BS1* and *BS2* and the delay stage *DS1* form Mach-Zehnder interferometer used for coherency measurements. Beam splitter *BS2* and interference filter *F2* completely blocked the 5.3 μm pump beam. The intensities of reference and amplified beam were balanced with attenuator *A3* and filter *F4*. The interference pattern was imaged by a pyroelectric camera sensitive at this wavelength region.

## RESULTS AND DISSCUSSION

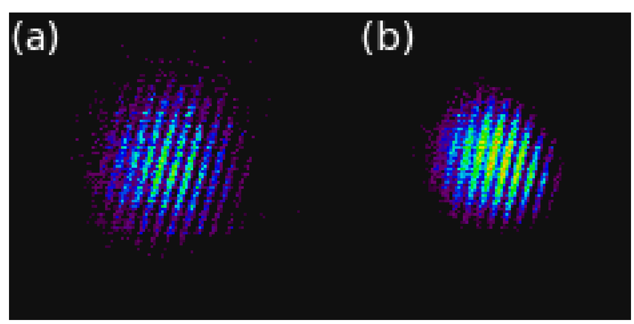


Figure 3: Interference pattern of non-amplified (a) and amplified (b) beam (at gain equal to 4.0)

Figure 3 shows the interference pattern between the reference and the seed beams with (b) and without (a) amplification. In the later case the pump beam was blocked. The modulation amplitude of the interference pattern corresponded to the non-amplified beam is close to 100%. The modulation amplitude in the other case is about 85%. This shows that the amplification preserves the phase of the seed beam. Moreover, the interference pattern of the amplified seed beam is not shifted relative to the pattern of the non-amplified seed beam. Thus, the

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wave mixing process in the OPA does not add any phase shift to the amplified seed beam.

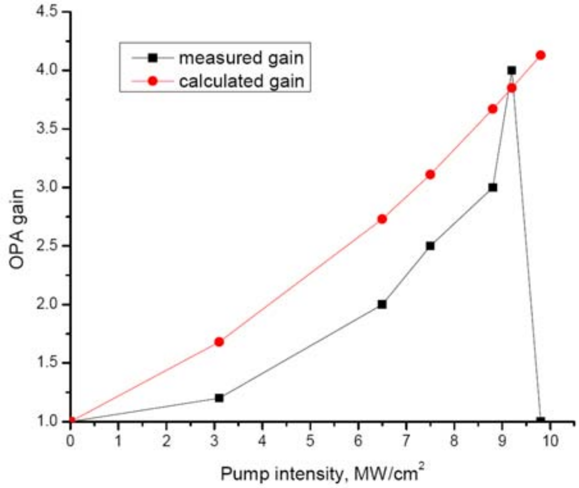


Figure 4: Measured (black) and calculated (red) dependence of the OPA gain upon the pump intensity.

The measurements of the dependence of the amplification efficiency showed that the gain grows smoothly with the pump intensity until the value of 0.19 $J/cm^2$ ($9.2\times10^6$ $W/cm^2$) was reached. At this point the gain is equal to 4.0. When the pump intensity was increased above this value the intensity of the amplified pulse suddenly drops. The interference pattern of the amplified and the reference beam disappeared. This happens because the pump radiation start absorbing strongly after the certain value of the pump intensity is reached. Time resolved measurements of the transmitted pump intensity support this hypothesis. One of the possible explanations of this phenomenon could be two photon absorption of the pump beam. Two-photon absorption of $CdGeAs_2$ crystal at shorter wavelength has been observed previously [6]. The band gap energy of $CdGeAs_2$ $E_g$ = 0.57eV [7] is greater than the doubled energy of the pump radiation photon $2h\nu$. However, presence of impurities or non-linear interaction of the pump radiation with the crystal medium may cause lowering of the band gap energy, facilitating the transition.

## CONCLUSIONS

We have built and tested an OPA based OSC setup to be used to damp beam emmitance of the gold ions in RHIC. Our OPA is based on a single $CdGeAs_2$ crystal pumped by the second harmonic of a pulsed $CO_2$ laser system. Another $CO_2$ laser has been used to emulate radiation of the golden ions in pickup undulator.

We have verified that the amplification of the radiation in the OPA preserves its coherency. The maximum gain value of 4.0 has been obtained at the pump intensity equal to $9.2\times10^6$ $W/cm^2$. Further increase of the pump intensity does not lead to higher gain, possibly due to two-photon absorption of the pump radiation in the crystal medium.

## ACKNOLEDGEMENTS

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