Analysis of Auto- and Cross-correlator

Lee Teng Internship Paper

D. Gutierrez Coronel
Department of Physics, Illinois Institute of Technology
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Mentors: J. C. Dooling and Y. Sun
Accelerator Systems Division, Advanced Photon Source, Argonne National Laboratory

1 Abstract

We report the analysis and description of an auto- and cross-correlator optical system used to measure the pulse duration of the second and fourth harmonic wavelengths of the Advanced Photon Source Photocathode (PC) Gun Drive Laser System. The Drive Laser System is a Nd:Glass chirped-pulse amplification system that generates an IR wavelength at 1053nm that is frequency double into green at 527nm, and then into UV at 263nm, used on the PC gun. Work for the cross-correlator set up is still needed and the steps to complete it are discussed. Similarly, the effects of group velocity mismatch and the relation of power density between the fundamental and higher harmonics are discussed. The auto-correlation of IR was traced with an existing Single-Shot Auto-correlator, while the auto-correlator system was used for the second harmonic. Both profiles were fitted to Gaussian distributions, and the pulse duration sigma was seen to vary in the order of a few picoseconds, with the green pulse being broader in time. Overall, this provides relevant information on the UV longitudinal profile, that along with the transverse 3D profile, plays a key role in the PC gun electron emission. This measurements will be compared with previous measurements using a streak camera, to optimize the PC gun beam quality and minimize emittance.

2 Introduction

APS PC Gun Drive Laser System

The laser system is a generic Nd:Glass chirped-pulse amplification system. Such CPA system, generates a short pulse by first stretching, then amplifying, and finally re-compressing the laser pulse. The re-compressed output is an IR wavelength at 1053 nm, that then is frequency doubled twice two β-Barium Borate (BBO) Crystals. The resultant UV pulse is used on the PC gun to generate electrons.

The pulse duration of such ultra-short pulse laser can be measured from the auto- and cross- correlation of the laser beam. Although the auto-correlation measurements were demonstrated and verified, the steps to complete the cross-correlator set up will be described in the Discussion and Future Work. It is expected that the pulse duration of the higher harmonics is shorter than the fundamental given the nonlinear relation between their power densities. However, in cases were group velocity mismatch (GVM) is appreciable, it can broaden the higher harmonics pulse duration, which could be the case for the UV generation. Measurements done a year ago by J. Dooling using a streak camera showed the UV being shorter than the fundamental but slightly longer than the green wavelength pulse.

3 Theory

Second Harmonic Generation
The interaction of an intense light beam electric field with a given dielectric material may show a nonlinear material polarization, described by an expansion of the material polarization $\vec{P}$.

$$P_k = \epsilon_0 \left(\chi^{(1)}_{ik} E_i + \chi^{(2)}_{ijk} E_i E_j + ... \right) \tag{1}$$

The second order nonlinear polarization response, contains a component that radiates at twice the frequency of the input wave, showing second harmonic generation (SHG).

Optical Auto-correlation
Intensity Auto-correlation allows to measure the intensity vs time profile of ultra-short pulse lasers. This is done by focusing two identical copies of a beam with a variable time delay into a SHG crystal. The output signal is equal to the auto-correlation (convolution) of the input signal with twice the frequency. Cross-correlation may also be done by focusing two different beams into a crystal. For which, the output is equal to the cross-correlation of the input signal, making a longer output wavelength by difference frequency generation (DFG). The intensity measured is given by

$$I_{cc} = \int_{-\infty}^{\infty} I_1(t) I_2(t-\tau) dt \tag{2}$$

Where $I_1(t)$ and $I_2(t-\tau)$ are the temporal intensities for the two beams, and τ is the temporal delay between them [10]. In the case of auto-correlation $I_1(t) = I_2(t)$.

Thereafter the temporal profile for the beams can be obtained to measure the pulse length. For auto-correlation knowing the shape of the pulse, implies multiplying by a deconvolution factor. In the case of cross-correlation, by knowing one of the temporal profiles and measuring I_{cc}, the unknown beam profile can be obtained by numerical deconvolution [11]. Alternatively, assuming a Gaussian pulse shape and negligible effects of group velocity dispersion (GVD) and mismatch (GVM), the pulse duration σ_{cc} of the cross-correlation signal is related to the other two pulses by integration of equation 3.

$$\sigma_{cc} = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{3}$$

A model that considers GVM was derived by Weiner [9] and is used by Yang, et al. [10] to calculate the duration of the unknown pulse in cross-correlation measurements.

4 Experimental Arrangement

The pulse length was measured at varying and nominal compression of the IR pulse, by changing the horizontal retro-reflector (HRR) position in the drive laser system. The auto- and cross-correlator (ACC) optical system is shown in figure 1. Showing the conditions for the distances between the optical instruments for auto- and cross-correlation. A moving translation is set up to trace auto-correlation for different pulses with different time delays (different distance traveled by signal). The signal generated is measured using a Silicon PIN Detector ET - 2070.

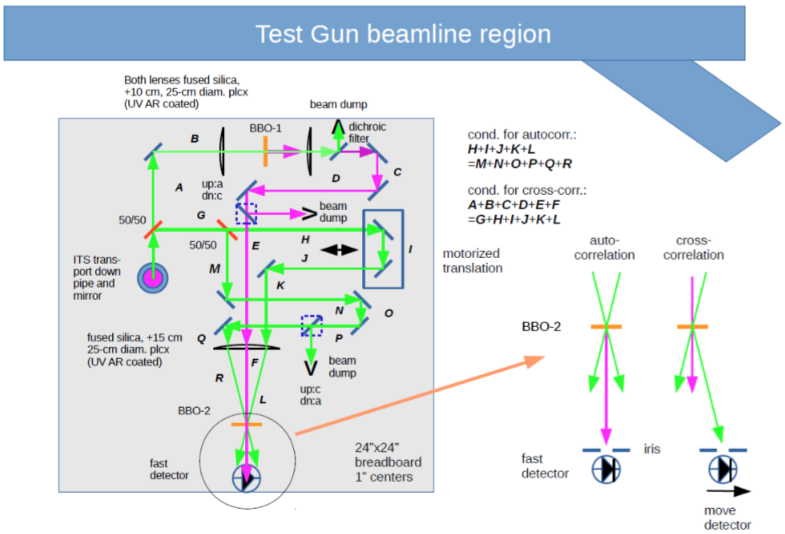


Figure 1: Optical Arrangement ACC.

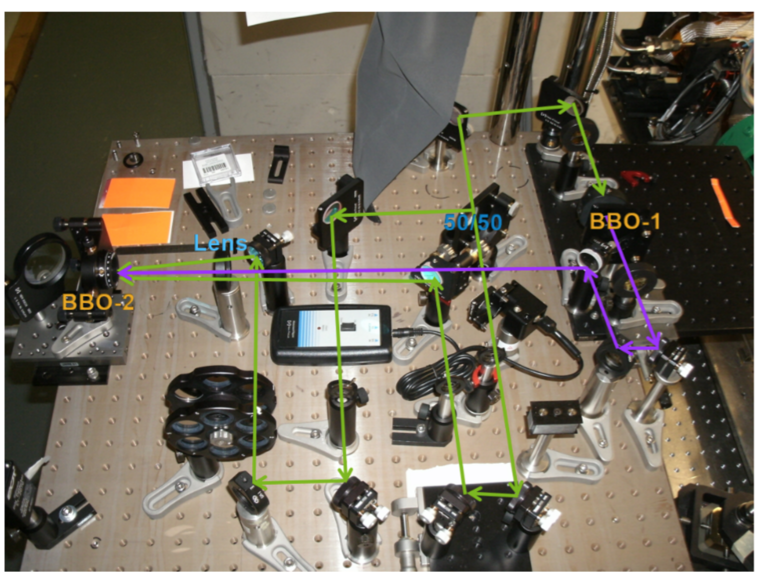


Figure 2: Picture Optical System.

The length of the green/AC legs were measured and equalized within ± 3 mm (± 0.125") to satisfy the conditions for temporal overlap for the AC. A pinhole of 25μm (Figure 3) was used to spatially overlap the beams. There was almost no appreciable difference for the AC path lengths of the beam, there is still a difference of less than an inch for the UV/CC path lengths.

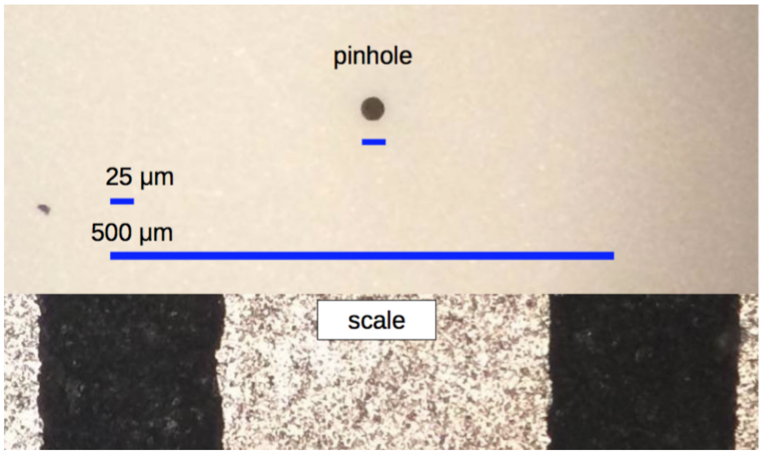


Figure 3: 25μm pinhole with 500μm scale .

For the auto-correlator the green wavelength coming from the laser system into the Injection Test Stand (ITS) is split in two using a 50/50 beam splitter, having one of the two paths have a translation stage to change the time delay of one of the beams. A SPX025 Fused Silica Plano-Convex Lens (with UV AR coating) with a diameter 25.4 mm and a focal length of 150mm, is used to focus the two beams into a BBO crystal (BBO-2, 2 mm thick, type-1 phase matched at $\theta = 25°$ and $\phi = 0°$). An UV auto-correlation signal was detected, and an UV mirror was used to assure none of the green signals were seen by the detector.

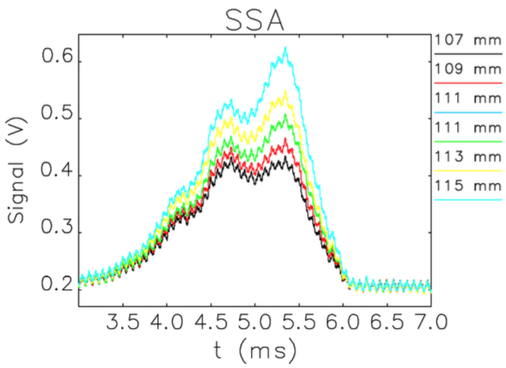
On the other hand, for the cross-correlator, the 527nm beam was split again and a BBO crystal (BBO-1 in figure 1) was used to generate the UV light (dumping the green light with a dichroic filter). Lenses were needed to focus the 527nm beam inside the crystal and a second lens is needed to compensate for the dichroism of the optical instruments, more specifically the over focusing of UV at the final fused silica lens.

The pulse duration of the IR wavelength was measured and verified using a Positive Light Model Single Shot Auto-correlator (SSA) available, that traces the auto-correlation by a single pulse based on the geometry of the interaction region of the two beams, whereas the ACC uses multiple pulses with different time delays (figure 1). The SSA can run in single-shot mode or it can be used to trace auto-correlation by multiple pulses.

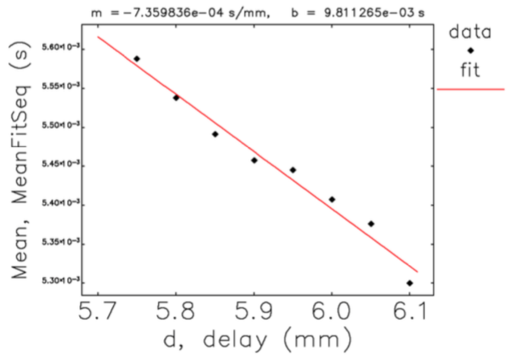
5 Measurements

IR pulse duration

The auto-correlation for the IR pulse for different compression (position of the HRR



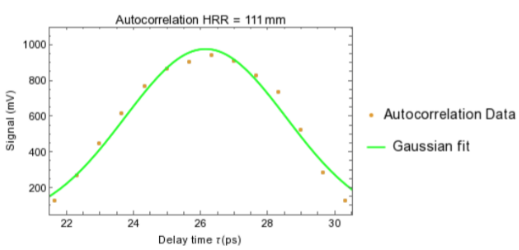
a: Autocorrelation IR for varying compression.



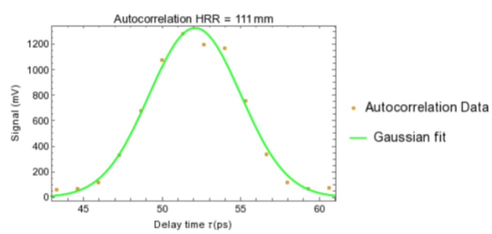
b: SSA calibration data

Figure 4: SSA data

in mm) can be seen in figure 4. Calibration data from the SSA (4) was used to find the actual pulse width.



a: $I_{set} = 160A$



b: $I_{set} = 170A$

Figure 5: Auto-correlation Green at nominal compression and Gaussian fit

The Auto-correlation of green was traced with the AC optical system at low power (IR pump current setting of $I_{set} = 160A$) and high power ($I_{set} = 170A$).

6 Results and Analysis

IR pulse duration

The SSA provided an auto-correlation, which was fitted to a Gaussian distribution. The sigma duration was extracted by multiplying by a calibration factor (4.5322e-09, which represents the real time difference over the scaled time difference) and by a deconvolution factor (for a Gaussian pulse is $1/\sqrt{2}$). At low power, the pulse duration sigma varied between 2.1 and 2.4 ps (4.9 and 5.7 ps FWHM) for maximal and minimal compression, respectively.

At high power the IR pulse was measured using the SSA in single-shot mode and multiple pulse auto-correlation. In single-shot, it was seen to vary between 1.6 and 2.0 ps (3.8 and 4.7 ps FWHM). Doing multiple pulse auto-correlation, it was seen to vary between 0.9 and 2.2 ps (2.1 and 5.1 ps FWHM)

HRR	σ_{IR}	σ_{green}
107	2.346	3.784
109	2.306	3.490
111	2.219	3.251
113	2.161	2.725
115	2.100	2.284

Table 1: Duration Sigma for varying compression at low power

HRR	single shot σ_{IR}	auto-correlation σ_{IR}	σ_{green}
107	2.001	2.161	3.386
109	1.930	1.749	2.704
111	1.826	1.501	2.055
113	1.730	1.169	1.554
115	1.583	0.885	1.189

Table 2: Duration Sigma for varying compression at high power

The same Gaussian fitting and deconvolution was done for the auto-correlation of green. The pulse duration sigma of the green wavelength was measured to vary between 2.3 and 3.8 ps (or 5.4 and 8.9 ps FWHM) for maximal and minimal compression respectively at low power. It varied between 1.2 and 3.4 (2.8 and 8 FWHM) at high power.

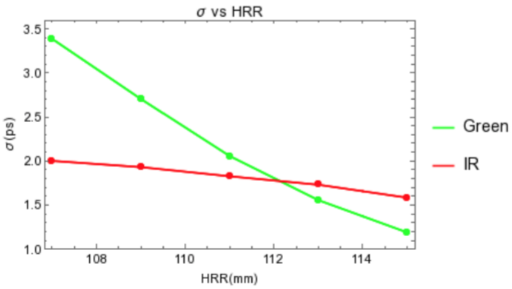
It is seen that the measurements of the single-shot mode of the SSA do not vary by much for different HRR positions. By fitting the SSA data in a linear fit it is seen that at low power it only varies by 0.032 ps/mm, and 0.0518 ps/mm at high power.

The results do not agree with the expected results, as the measurements show the Second Harmonic pulses being longer than the Fundamental. This may be foreseen for the green to UV conversion given the high group velocity mismatch for BBO, but from IR to green other factors may be affecting the results.

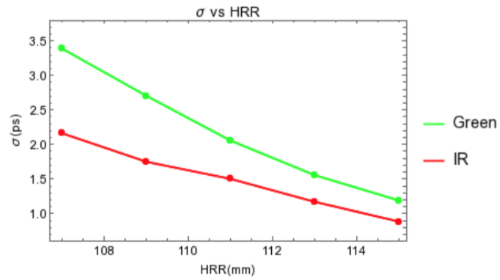
7 Discussion and Future Work

Cross Correlation Completion

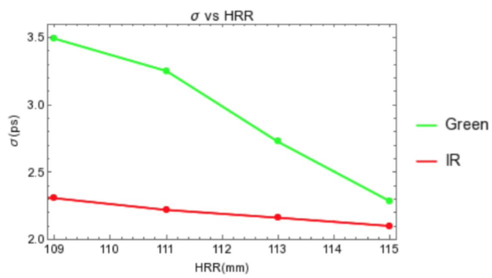
Finishing the cross-correlation system to get the cross-correlation signal is still needed. For this, four essential task must be completed.



a: $I_{set} = 170A$, auto-correlation IR



b: $I_{set} = 170A$, single shot IR



(c) $I_{set} = 160A$

Figure 6: Duration Sigma vs HRR

- First, alignment of the optical instruments is needed. The mirrors present in the leg C of the ACC diagram have to be moved 5 mm so as to equalize the UV and the delayed green beam path lengths. This is specially important for the beams to temporally overlap.
- Although the BBO-1 was installed and a UV signal was detected, assuring appropriate power from the UV signal is required. A PIN silicon detector may be used to optimize the signal.
- The third important task to complete, is to spatially overlap both beams, which can be done using a pinhole, just like for the auto-correlation [2].
- Finally installing the crystal in the position where both beams crossed the pinhole, and turning the crystal in the appropriate angle for phase matching conditions. Similarly dichroic filters and/or an iris can be added to make sure the correct signal is detected for cross-correlation.

After detecting a cross-correlation signal and measuring a simple approximation of the pulse can be done by equation 3. Numerical convolution can be done as well as using the model used by Yang, that takes into account GVM [10].

Estimation of pulse duration

Calculations using the relation between the power of the fundamental and the second harmonic (See 9 Appendix) were done to estimate the pulse duration of green and UV.

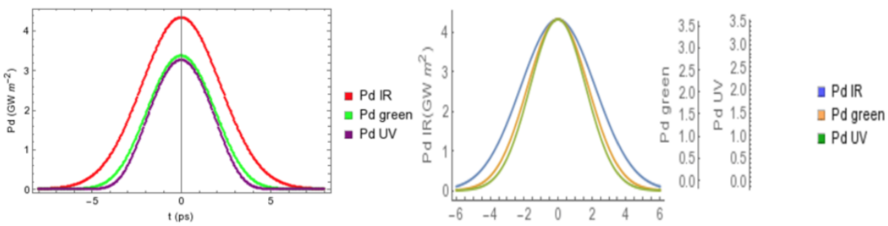


Figure 7: Intensity vs time profile for IR, green and UV.

It can be seen in figure 7, that the pulse length decreases as is expected given the nonlinear relation between the power densities of the fundamental and higher harmonics (equation 4). However, for conversion using a 2 mm crystal the pulse length of green does not differentiate as much from UV. This is does not agree with the results in the IR to green conversion.

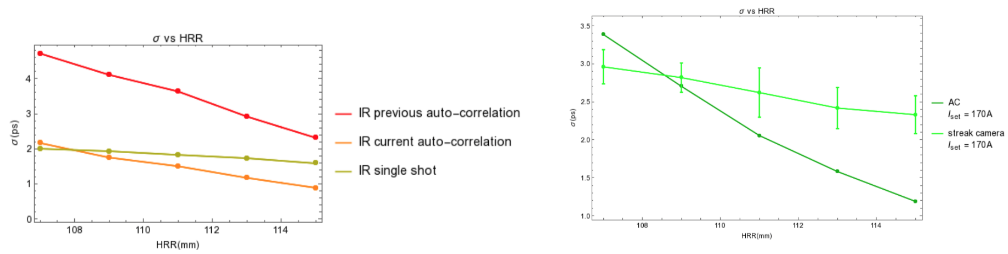
On the other hand, an estimation taking into account the group velocity mismatch (GVM) of the pulses was done as performed by Yang et al. [10]. For a 2 mm BBO crystal, the broadening of the UV pulse is expected to be $\delta t = L * GVM = 2mm * 0.475ps/mm = 0.95ps$. Using a 1 mm crystal for the green to UV conversion (BBO-1) would then give a broadening of 0.48 ps (See 9 Appendix) .

The effect of GVM is not as strong for the conversion from IR to green since for conversion from higher wavelengths the group velocity mismatch decreases drastically. (For instance, compare a calculated GVM of 44.6 fs/mm for conversion from 1053nm, to a GVM of 474 fs/mm for conversion from 527nm).

From previous measurements done using a streak camera by Dooling [1], the pulse of green was seen to vary from 3.0 to 2.0 ps for varying compression, while the UV pulse varied from 3.5 to 2.1 ps. Taking into account the effects of group velocity one would see a variation from 3.47 to 2.47 ps, which agrees to an percentage error of 0.85% and 17%, respectively.

Comparison Streak Camera Measurements

The results were compared with previous measurements of the IR and green pulse at an amplifier pump current setting (I_{set}) of 170 A. the IR pulse was calculated with an auto-correlator in the date seen in [1]. It is possible that a change in the laser system optics or the auto-correlator used to measure the pulse result in the shortening of the current measurements. Since the IR profile changed it is also possible that the same parameters for high power were not kept constant over time. In other words, a comparison of green has to be done after making sure the measurements at $I_{set} = 170A$ were done under the same conditions as the ones done a year ago.



a: IR at 1053nm

b: Green at 527nm

Figure 8: Comparison of duration sigma vs HRR for current and previous measurements done by J. Dooling using a Streak Camera

8 Conclusion

Alignment and work is still needed to complete the cross-correlation system. Appropriate focusing of the UV is needed given the dichroism of the optical instruments. When cross-correlation signal is seen the pulse of the UV can be extracted by knowing the profile of the green pulse by numerical deconvolution of the measured signal.

In the estimation of what the pulse lengths will be, the effects of the relation between the power density of the fundamental and higher harmonics was seen to be more appreciable for the conversion from IR to green. For the experimental results, the pulse length of green is longer and does not agree with this relation.

Moreover, the effect of group velocity mismatch dominates at shorter wavelengths, explaining the temporal broadening of the UV pulse for the conversion from 527nm wavelength. Therefore the UV pulse is expected to be longer in time by $\delta t = 0.95ps$.

Ultimately the results will be compared in more detail with previous streak camera measurements [1], in order to optimize the PC gun beam quality and minimize emittance.

Acknowledgements

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9 Appendix

Power Density Estimation

An estimation of the pulse length for the second and fourth harmonic was made using the relation between the power generated at second harmonic frequency 2ω to that of incident at fundamental frequency ω. This is found when Maxwell's equations in a nonlinear medium are solved for a coupled fundamental and second harmonic wave, which gives the following equation.

$$\frac{P_{2\omega}}{P_\omega} = tanh^2\left[lK^{1/2}\left(\frac{P_\omega}{A}\right)\frac{sin(\Delta kl/2)}{\Delta kl/2}\right] \tag{4}$$

Where l is the length of the crystal, A is the area of the fundamental beam, K is a parameter that contains the plane wave impedance, the frequency and the effective nonlinear coefficient of the nonlinear polarizability tensor [5]. Δk is the phase mismatch defined as $\Delta k = \frac{4\pi}{\lambda_1}(n_1 - n_2)$. These parameters were taken for a BBO crystal, 2 mm thick. [3].

Mathematica code was used to do this calculation. the Mathematica code also calculates the spatial Energy distribution by integrating the temporal power distribution over an specified area 9. From this the spot size of UV can be calculated, which is of particular interest when analyzing the effects on the PC gun electron emission.

Similarly it calculates the conversion efficiency from IR to green, from green to IR, and overall from IR to UV. Which was seen to decrease for shorter IR pulses. Thus increasing the compression (increasing HRR position and shortening the IR

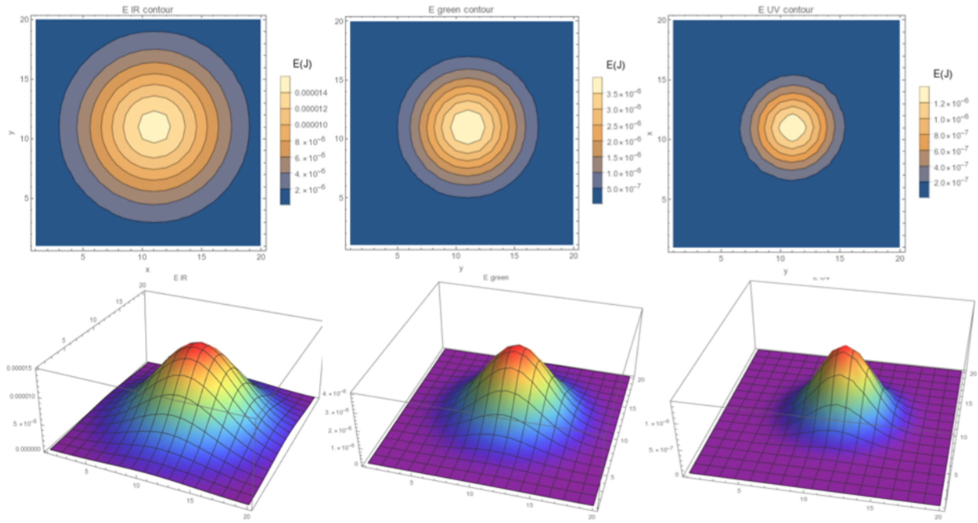


Figure 9: Contour plot and 3D plot of the spatial energy profile for IR, Green and UV.

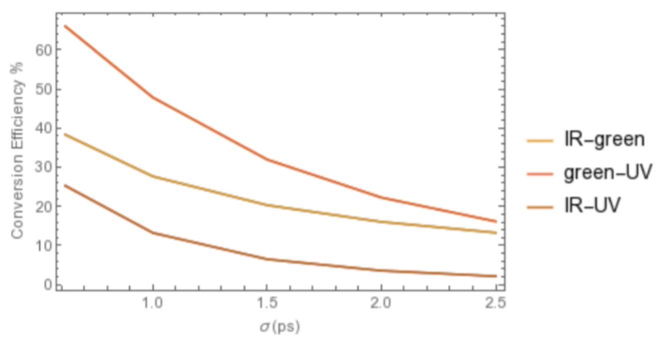


Figure 10: Conversion Efficiency vs duration sigma.

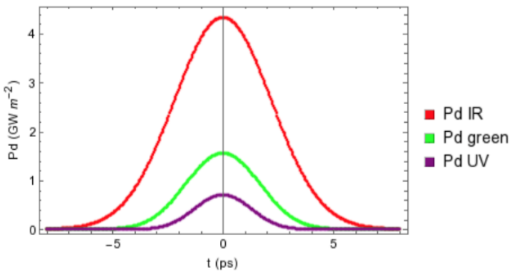
pulse) could possibly affect the output power of UV as the conversion efficiency is decreased.

Similarly, the length of the crystal affects conversion efficiency. It was seen that the conversion efficiency for a 2mm BBO crystal(28.5% overall conversion efficiency) was higher than that of a 1mm crystal (2.88%). Similarly for the thicker crystal the pulse duration of the higher harmonics did not vary (these calculations were done for an initial IR pulse of 1500 μJ and a pulse duration sigma of 2.2 ps).

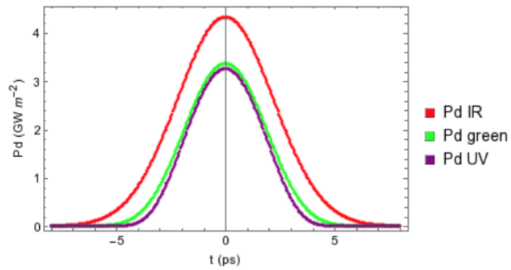
The Mathematica code, also extracts the pulse duration of the different components, as discussed in the Discussion and Future Work.

Group Velocity Mismatch Estimation

As a second harmonic is generated inside the crystal, the different frequency and polarization direction of the optical pulse results in a difference in group velocity, preventing a temporal overlap inside the crystal. GVM is given by



a: $l = 1mm$



b: $l = 2mm$

Figure 11: Power density vs time, showing the pulse length and relative power densities between the fundamental and the higher harmonics

$$GVM = \frac{1}{v_{g1}} - \frac{1}{v_{g2}} = \frac{\lambda_0}{c_0}\left[n'_o(\lambda_0) - \frac{1}{2}n'_e(\lambda_0/2)\right] \tag{5}$$

Calculation of the refractive indeces for the ordinary and extraordinary orientations and their change with respect to the wavelength (n'_e and n'_o, respectively, given for type 1 phase matching) can be calculated by using the Sellmaier Equations and the appropriate parameters for BBO [3].

Moreover, GVM broadens the pulse of the output signal by an amount $\delta t = L * GVM$, where L is the length of the crystal for a co-linear case. If the angle of incidence is not 0°, $\delta t = \frac{L}{cos(\theta)}GVM$, where θ is the phase matching angle.