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To achieve nuclear fusion using glass laser systems, broadband infrared laser beams must be converted to the ultraviolet using a series of crystals. The tuning angles of these crystals, especially the "triplers", are of paramount importance to their conversion efficiency. Given the measured UV spectrum of a laser beam, I developed a systematic method to determine how to adjust each of the tripler angles to obtain optimal conversion efficiency. This method will be implemented on the two-tripler OMEGA system in Rochester, NY. It also removes a major obstacle to an extension of OMEGA to a four-tripler system.

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1. Background

1.1. Inertial Confinement Fusion

One among many research institutions worldwide investigating laser-induced inertial confinement fusion (ICF) is the University of Rochester Laboratory for Laser Energetics (LLE) [1]. In its OMEGA laser system, LLE researchers use a spherical target. This target is a plastic shell one millimeter in diameter containing a frozen layer of deuterium and tritium that is 0.1 mm thick. The 60 beams in the system transfer extremely high amounts of energy to this target, ionizing the atoms of the shell and thus creating a dense plasma layer around the fuel. As the plasma is heated, it expands outwards at approximately 1,000 kilometers per second, freeing itself from the rest of the pellet. In accordance with Newton's Third Law – every reaction has an equal and opposite reaction – the pellet implodes to a radius 20-30 times as small as that of the original pellet [1]. The imploded pellet is now under conditions of extremely high temperature and pressure; the combination of the two causes the deuterium and tritium to fuse, releasing high-energy neutrons. The ultimate hope of LLE researchers as well as many others in the scientific community is that laser-induced ICF will produce more energy from fusion than is input through laser energy; in doing so, a tremendous new energy source would be available.

The neodymium-doped glass amplifiers present in OMEGA and other laser systems produce beams with an infrared frequency (wavelength of 1.053 nm). Upon directing these infrared beams on the pellet, however, researchers in the late 1970s noticed that less than half of the energy emitted by the lasers was absorbed by the pellet. Moreover, a significant portion of the energy absorbed by the pellet was carried away by suprathermal electrons, which pass freely through the pellet and heat the fuel before it can be compressed [1]. In doing so, they prevent the pellet from reaching the densities needed for fusion. However, researchers noticed that this problem was significantly reduced when the pellet was heated by higher-frequency laser beams. Thus, it became necessary to convert the beams from infrared to ultraviolet to achieve maximum target performance.

1.2. Frequency Conversion

Scientists at LLE currently use a series of KDP (potassium dihydrogen phosphate) crystals to convert the infrared pump to ultraviolet (see Fig. 1). Three crystals are in use in this process, termed "frequency conversion". The "doubler" serves to double the frequency of the input wave, and two subsequent "triplers" act together to triple the original frequency. Thus, the frequency conversion currently in use on OMEGA can triple the frequency of an incoming beam when its crystals are properly oriented. Proper orientation of the crystals is very difficult to achieve and maintain; my work proposes an improved way of doing this.

The crystals operate by splitting the laser pulses into two components, one aligned with the *e* (extraordinary) axis of the doubler and the other aligned with the *o* (ordinary) axis of the

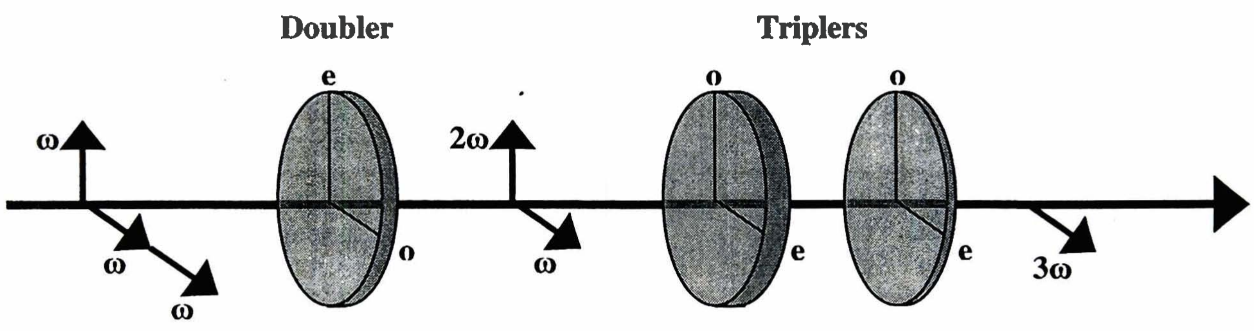

Figure 1 Frequency conversion process for a two-tripler system: an IR photon (ω) polarized in the *e* direction combines with two IR photons polarized in the *o* direction in the doubler to produce one green photon (2ω) and one *o*-polarized IR photon. These two combine in the triplers to produce one UV photon (3ω).

doubler [2]. When a laser pulse polarized at 35° to the doubler's *o* axis enters the doubler, two photons aligned with the *o* axis and one photon aligned with the *e* axis, all of which are at the original frequency (ω), are combined to produce an *e*-polarized photon at twice the original frequency (2ω) and an *o*-polarized photon at the original frequency. The 2ω photon is said to be at the second harmonic frequency and is green (wavelength of 527 nm).

Next, the laser pulse encounters the triplers, where the *o* and *e* axes are switched in orientation. The first tripler combines the second-harmonic *o*-polarized photon (relative to the triplers) with the first-harmonic *e*-polarized photon to produce one *e*-polarized ultraviolet photon, said to be at the third-harmonic frequency (3ω) [2]. The second tripler works on residual second-harmonic and first-harmonic photons, combining them through the process discussed above into more of the third-harmonic ultraviolet photons.

1.3. Two-Tripler vs. Four-Tripler System on OMEGA

A highly effective method introduced to improve target performance was smoothing by spectral dispersion (SSD) [3,4]. By creating smooth, focused laser beams, SSD results in a more evenly distributed, and thus more effective, contact between the beams and the target. However, to implement SSD, it is important to have the greatest range of wavelengths converted to the ultraviolet. Scientists refer to this range of wavelengths converted as "bandwidth". Wavelengths outside this range do not convert to the ultraviolet because they are not phase-matched – that is, the component waves travel at different speeds in the crystal, causing them to move out of phase [5].

Oskoui recommended the two-tripler system to replace the previous single-tripler system on OMEGA after concluding that the conversion bandwidth would increase from 4 Å to 14 Å

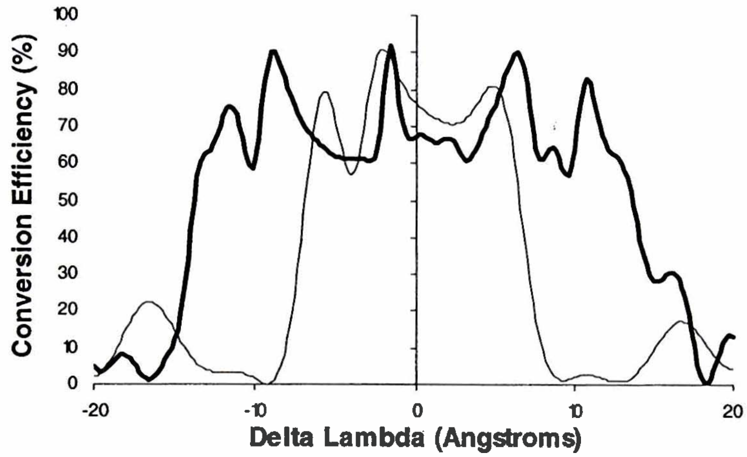

Figure 2 Comparison of conversion efficiency on two- and four-tripler systems as a function of wavelength deviations from the central IR wavelength: OMEGA's current two-tripler conversion efficiency (thin line) and the proposed four-tripler system conversion efficiency (thick solid line). The conversion bandwidth of the two-tripler system is 14 Å, as compared to the 30 Å conversion bandwidth of a four-tripler system.

[5]. A tripler was added to each of the 60 OMEGA beams following his research, resulting in the two-tripler system that exists today. Rounds concluded that an addition of two extra triplers, making four in all, would significantly broaden the conversion bandwidth to 30 Å (see Fig. 2) [6]. Expansion to the four-tripler system would therefore improve SSD, and, in turn, target performance.

1.4. Project Goal

Critical to frequency conversion are the angles at which the crystals, especially the triplers, are tuned. External influences sometimes tilt the triplers away from their optimal angles, drastically lowering the conversion efficiency of the system. As a result, less of the beam is converted to the ultraviolet frequency, and target performance ultimately suffers.

On a two-tripler system, the tuning of the triplers is straightforward. A fairly efficient method is currently in use on the OMEGA system to readjust detuned systems with a few shots of the laser. However, the possibility of a four-tripler system makes this tuning method unfeasible. Thus, a major obstacle to the establishment of a four-tripler system on OMEGA and similar laser systems worldwide is the lack of a means by which engineers can quickly tune the triplers to restore optimal conversion efficiency to a detuned system. This problem would be encountered as soon as the initial setup of the four-tripler system, and would surely be faced regularly thereafter.

Consequently, the goal of my project was to develop a method by which engineers could tune the proposed four-tripler system given the UV spectrum produced by the detuned system and restore the conversion efficiency to within 1% of the optimum. The successful accomplishment of this goal brings the establishment of a four-tripler system on OMEGA one step closer to realization. The method I propose also has immediate use on the current two-tripler system, as it can tune the triplers after just one shot of the laser after the new UV spectrometer is installed that will provide spectra of all 60 beams [7].

2. Methodology

2.1. Calculating the UV Spectrum

Essential to my tuning algorithm is the calculation of the UV spectrum. This three-step process is summarized in Figure 3. First, the IR spectrum is calculated. Second, the conversion efficiency is calculated. Third, the spectral power at each wavelength of the IR spectrum is multiplied by the conversion efficiency at that wavelength to obtain the spectral power of the UV spectrum. A detailed explanation of each step follows.

The first step is to calculate the IR spectrum produced by the laser. The SSD system

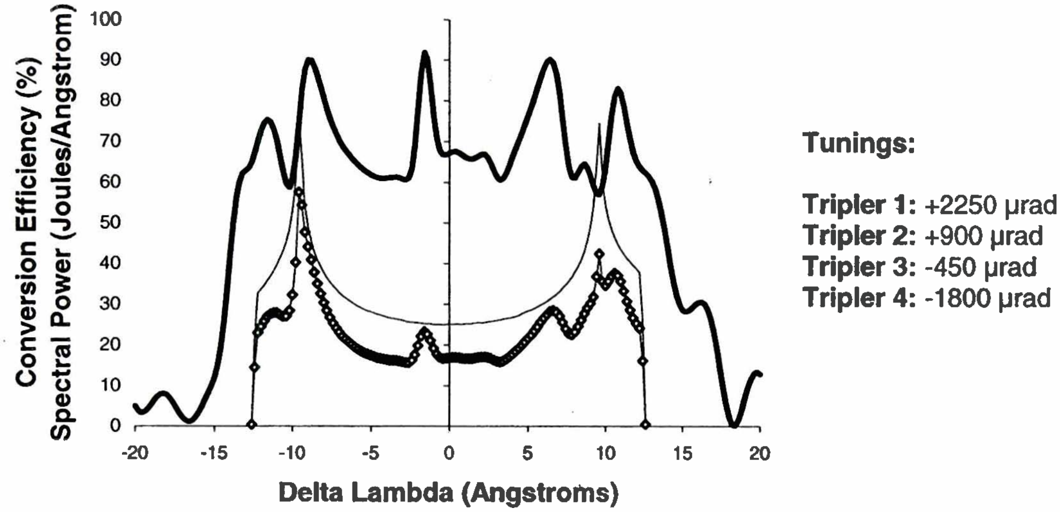

Figure 3 The proposed four-tripler system conversion efficiency (thick line), the OMEGA IR spectrum (thin line), and the optimal UV spectrum (open diamonds). At each wavelength, the UV spectral power is equal to the IR spectral power times the conversion efficiency. This spectrum is produced with the given optimal tunings.

produces a wavelength deviation ($\Delta\lambda$) across the beam [4] that varies as a function of x, y, and t, where x and y are spatial variations in the two axes of any cross-section of the beam and t is the time:

$$\Delta\lambda(x,y,t) = \Delta\lambda_1\cos(\omega_{M1}t - \alpha_1 x + \varphi_1) + \Delta\lambda_2\cos(\omega_{M2}t - \alpha_2 y + \varphi_2). \quad (1)$$

$\Delta\lambda$ is the deviation from the central IR wavelength (1.053 nm). ω_{M1} is a constant equal to $2\pi f_{M1}$, where f_{M1} is the frequency of the wave produced by the first of two electro-optic phase modulators and is equal to 3.3 GHz in OMEGA. Similarly, ω_{M2} is a constant equal to $2\pi f_{M2}$, where f_{M2} is the frequency of the wave produced by the second phase modulator and is equal to 10 GHz in OMEGA. α_1 and α_2 are constants that arise from diffraction gratings used on OMEGA to impose a sinusoidal variation of wavelength across the beam (approximately one cycle in each direction), and they are equal to 23.3 m^{-1} and 19.3 m^{-1}, respectively. φ_1 and φ_2 represent the phases of the two modulators. Since they are unknown, I set both to zero. Note that other values of φ_1 and φ_2 produce virtually the same spectra as is produced when both are set to zero. $\Delta\lambda_1$ and $\Delta\lambda_2$ are the bandwidths imposed by the phase modulators used. For the two-tripler system, they are equal to 5.5 Å and 0.72 Å, respectively. For the four-tripler system, each value is doubled. The sum $\Delta\lambda_1 + \Delta\lambda_2$ is equal to the laser bandwidth.

The spectrum is formed by splitting the beam into 100^2 spatial cells (N_x and $N_y = 100$) at each of 150 time slices ($N_t = 150$). This produces a total of $N_xN_yN_t$ contributions to the spectrum. I also split the wavelength axis of the spectrum into 200 equal intervals.

At each cell that was within the bounds of the laser beam (within the 13.5-cm radius), I calculated the quantity:

$$\Delta\text{energy} = I\Delta x\Delta y\Delta t. \qquad (2)$$

"I" corresponds to the intensity of the laser beam ($1.5 * 10^{13}$ W·m^{-2}·s^{-1}); Δx, Δy, and Δt are equal to the intervals for x, y, and t, respectively. After calculating $\Delta\lambda$ from Equation 1, I used a technique of linear interpolation to split up Δenergy between the two nearest bandwidth intervals according to how far the $\Delta\lambda$ value for that particular Δenergy was from each interval midpoint. By doing so, I obtained a histogram of the spectral power (J/Å) vs. $\Delta\lambda$. The IR spectrum was plotted using the midpoints of the bars of the histogram.

The second step in creating a UV spectrum is to determine the conversion efficiency as a function of wavelength. The conversion efficiency code of Rounds [6] (an extended version of Oskoui's code [5]) was used. This code is based on the frequency conversion equations [2, 8]:

$$\frac{dE_1}{dz} = -{}^1/_2\gamma_1 E_1 - iK_1E_3E_2^*\exp(-i\Delta k\cdot z), \qquad (3)$$

$$\frac{dE_2}{dz} = -{}^1/_2\gamma_2 E_2 - iK_2E_3E_1^*\exp(-i\Delta k\cdot z), \qquad (4)$$

$$\frac{dE_3}{dz} = -{}^1/_2\gamma_3 E_3 - iK_3E_1E_2\exp(i\Delta k\cdot z). \qquad (5)$$

E_n represents the electric field of a photon at the n^{th}-harmonic frequency. The γ_n terms refer to the absorption coefficient of the waves as they pass through the crystals, but are of little significance for this experiment because only a few percent of the laser energy is absorbed. The K_n terms are nonlinear constants reflective of the material properties of the KDP crystals used. Δk, known as the wave-vector mismatch, is described below. Finally, z is the direction in which the wave travels through the crystals.

Since E_3 is the electric field of the wave at the 3^{rd}-harmonic frequency, the growth of E_3 (described in Equation 5) is critical because it represents the creation of UV photons, the essence of frequency tripling. dE_3/dz is the rate of change in the UV electric field as the wave travels through the crystals. The product $-iK_3E_1E_2$, which is at the heart of the equation, describes the growth of the electric field; that is, the conversion of E_1 and E_2 to E_3. Note that Equations 3 and 4 give reductions in E_1 and E_2 which produce the matching increase of energy in E_3 described here. Finally, the phase terms, as represented by $i\Delta k \cdot z$, track the difference in phases between the different waves when the crystals are detuned. Tuning angles ($\Delta\theta$) are central to Δk because of the following equation:

$$\Delta k = \frac{d\Delta k}{d\theta}\Delta\theta + \frac{d\Delta k}{d\lambda}\Delta\lambda, \qquad (6)$$

where $d\Delta k/d\theta$ and $d\Delta k/d\lambda$ are properties of the KDP crystals used [8]. When Δk is zero, conversion occurs optimally as E_3 continues to grow with z. When Δk does not equal zero, conversion is reduced, and when $\Delta k \cdot z$ is π, the growth term switches signs, leading to reconversion. In Rounds' design, each crystal is tilted to a specific $\Delta\theta$ to make Δk equal to zero for a specific $\Delta\lambda$. The precise setting of $\Delta\theta$ for each tripler is the goal of this project.

The third step in creating a UV spectrum is the multiplication of the conversion efficiency at each of the wavelengths and the IR energy at these wavelengths. Thus, by inputting the optimal tripler tunings into the Rounds-Oskoui code, I obtained the optimal UV spectrum for both two and four triplers. By comparing experimental spectra taken from detuned systems to these optimal spectra, it should be possible to diagnose how to adjust the tripler angles to restore optimal efficiency. Proposed algorithms to accomplish this are discussed in the following sections.

2.2. Bin Search for a Two-Tripler System

A detailed description of my tuning algorithm will be given for a two-tripler system, but this algorithm is easily extended to a four-tripler system as well. The first step is the "Bin Search," illustrated in Figure 4(a). In this search, I created a grid of possibilities of detunings for the triplers. Since nearly all of the tuning errors in the OMEGA system occur well within +/-500 μrad, I chose these as the bounds of error for both triplers 1 and 2 in my Bin Search. In addition, I used an increment of 100 μrad error for both triplers. Next, I calculated the UV spectrum for each of the possible 121 combinations of error in triplers 1 and 2 (using the method described in

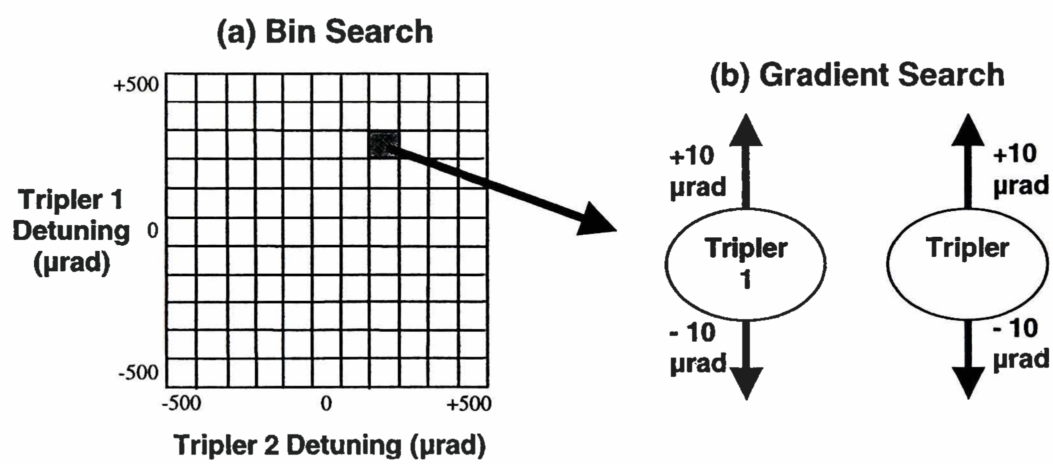

Figure 4 The tuning algorithm for two triplers: both the Bin Search and the subsequent Gradient Search try to minimize the RMS error with respect to the optimal UV spectrum. The Bin Search checks the combinations of detunings in a grid, while the Gradient Search proceeds by increasing and decreasing each tripler's angle and evaluates the resulting RMS error.

Sec. 2.1). I compared each of these 121 UV spectra with the optimal UV spectrum by calculating the root-mean-square (RMS) difference between the two spectra. This resulted in a series of 121 RMS values corresponding to the 121 combinations of tripler error. Selecting the combination of detunings which produced the minimum RMS error, I used these detunings as the starting point of a "Gradient Search".

2.3. Gradient Search for a Two-Tripler System

In the "Gradient Search", the second step in my tuning algorithm and illustrated in Figure 4(b), I created four temporary scenarios by increasing and decreasing each of the two tripler detunings by 10 μrad. I then calculated the UV spectrum for each of the four scenarios, and the corresponding RMS error values with respect to the optimal spectrum. Choosing the step which produced the lowest RMS error value, I modified the calculated detunings of the system and iteratively ran the Gradient Search. I continued this process until none of the four scenarios would lower the RMS error value; at this point, the Gradient Search was complete. The detunings of the two triplers were honed to +/-10 μrad at this stage, more than enough accuracy. However, I chose to further improve the accuracy to +/- 5 μrad by submitting the detunings I had found to a secondary Bin Search that searched through a grid with bounds of +/-10 μrad and increments of 5 μrad. At the conclusion of the algorithm, detunings were found which were far more accurate than necessary to restore conversion efficiency to within 1%.

2.4. Extension to the Four-Tripler System

The algorithm for the four-tripler system is very similar. The Bin Search present in the two-tripler algorithm searched through 11^2 possible detunings; in the four-tripler algorithm, 11^4

would be prohibitive. As a result, I used two successive Bin Searches in the four-tripler algorithm. The first searches through bounds +/-500 μrad for all four triplers with an increment of 250 μrad for each. The second searches through bounds +/-200 μrad about the chosen detunings from the first Bin Search, with an increment of 100 μrad. The Gradient Search is run with 8 possible scenarios, increasing and decreasing each of the four triplers by 10 μrad, and at its completion the detunings of the four triplers should be accurate to within +/-10 μrad of their actual values. The Bin Search that narrows the detunings down to +/-5 μrad in the two-tripler algorithm is skipped here in the four-tripler algorithm in the interest of runtime. At the completion of the four-tripler algorithm, the conversion efficiency has been restored to well within 1%.

2.5. Comments on the Tuning Algorithm

Two comments must be made regarding the tuning algorithm. First, the bounds and increments which are chosen in the Bin Search(es) and Gradient Search for the two- and four-tripler systems are both important and deliberate. The range of +/-500 μrad for the primary Bin Search in the algorithm for both systems is representative of the actual tuning errors that happen in the OMEGA system. Choices of range and increments for further searches in the algorithm were chosen based on a balance of accuracy and runtime. Second, the order of the searches is critical to the algorithm. A series of Bin Searches without a Gradient Search would be impractical as runtime would be far too high. A Gradient Search without a Bin Search introduces the possibility of narrowing down to a combination of detunings that produces an RMS error with respect to the optimal spectrum that is a false or local minimum. The Bin Search must come before the Gradient Search so that a general location of the correct detuning is established before it is narrowed further.

3. Results

3.1. Two-Tripler Trials on Computer-Generated Experiments

Ten computer-generated trials were conducted on the algorithm designed to tune a two-tripler system. They were "computer-generated" because the detuned spectrum was produced with user-entered detunings of the two triplers. The tuning algorithm was then run on the detuned UV spectrum. Detunings were in the range of –600 μrad to +600 μrad for each of the two triplers. These detunings were chosen outside the +/-500-μrad bounds of the Bin Search to test the capability of the Gradient Search to extend beyond these bounds. An example of one trial is given in Figure 5. The virtual overlap of the actual detuned spectrum and algorithm-calculated detuned spectrum is representative of all ten trials. In fact, the difference between the algorithm-derived detuning and the actual detuning was less than or equal to 6 μrad in each trial

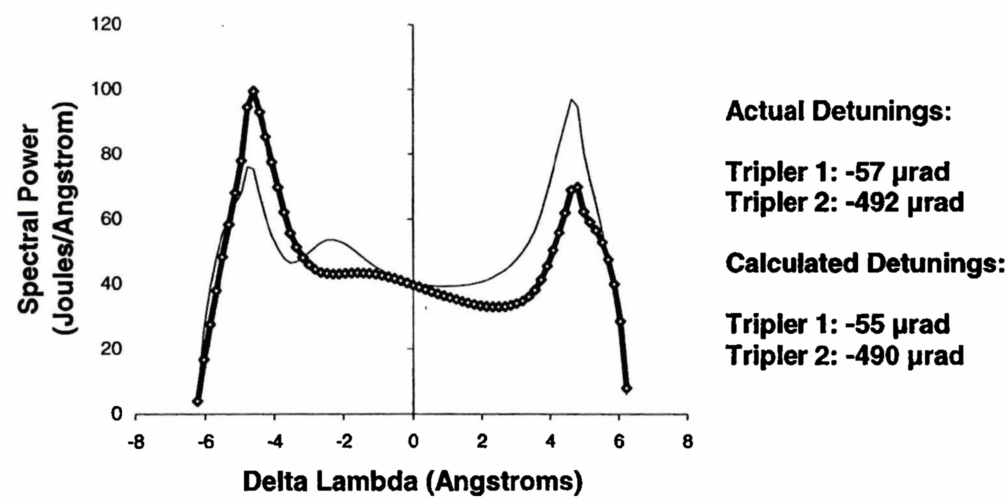

Figure 5 Trial 1 of computer-generated detunings of two triplers: the optimal UV spectrum (thin line), the actual detuned spectrum (thick line), and the detuned spectrum calculated by the algorithm (open diamonds). The accuracy of the algorithm is evident by the virtual overlap of the thick line and the diamonds.

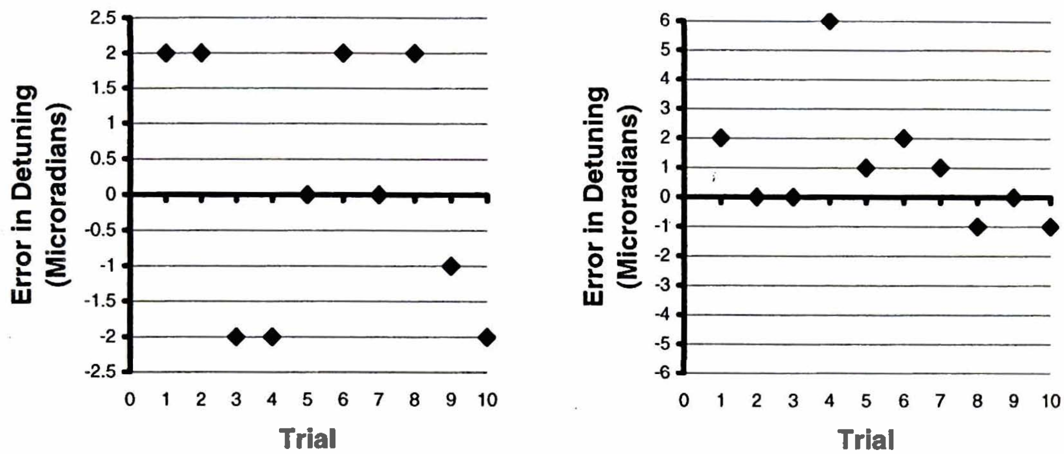

Figure 6 Algorithm errors in the detuning of triplers 1 (left) and 2 (right) for ten trials: the error for triplers 1 and 2 never exceeds 6 μrad for any of the trials. This is well within the desired restoration of conversion efficiency to within 1%.

for each tripler, as can be seen in Figure 6. Correspondingly, conversion efficiency was restored to well within the desired 1% in each trial.

3.2. Four-Tripler Trials on Computer-Generated Experiments

Ten computer-generated trials were also carried out on the four-tripler algorithm. Detunings were in the range –650 μrad to +650 μrad for each of the four triplers. The bounds of the Bin Search remained at +/-500 μrad. The spectra of one trial, seen in Figure 7, show a virtual overlap of the actual detuned spectrum and the algorithm-calculated detuned spectrum. The difference between the algorithm-derived detuning and the actual detuning was less than 8 μrad in each trial for each tripler (see Fig. 8). Again, the conversion efficiency was restored to within 1% for each of the ten trials. Note that in all my tests, not only on four triplers but also on two triplers, I never encountered two different combinations of detunings that gave the same spectrum. The uniqueness of the structures (peaks and valleys) present in the spectra is the likely cause for this.

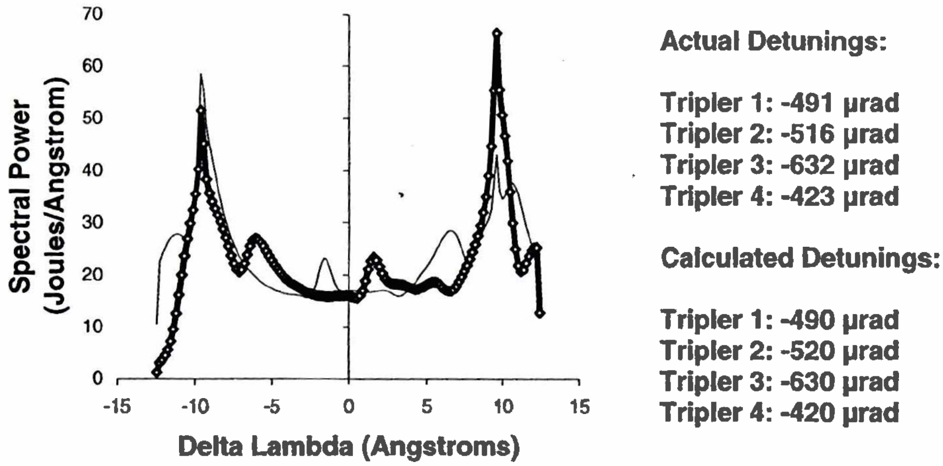

Figure 7 Trial 1 of computer-generated detunings of four triplers: the optimal UV spectrum (thin line), the actual detuned spectrum (thick line), and the detuned spectrum calculated by the algorithm (open diamonds).

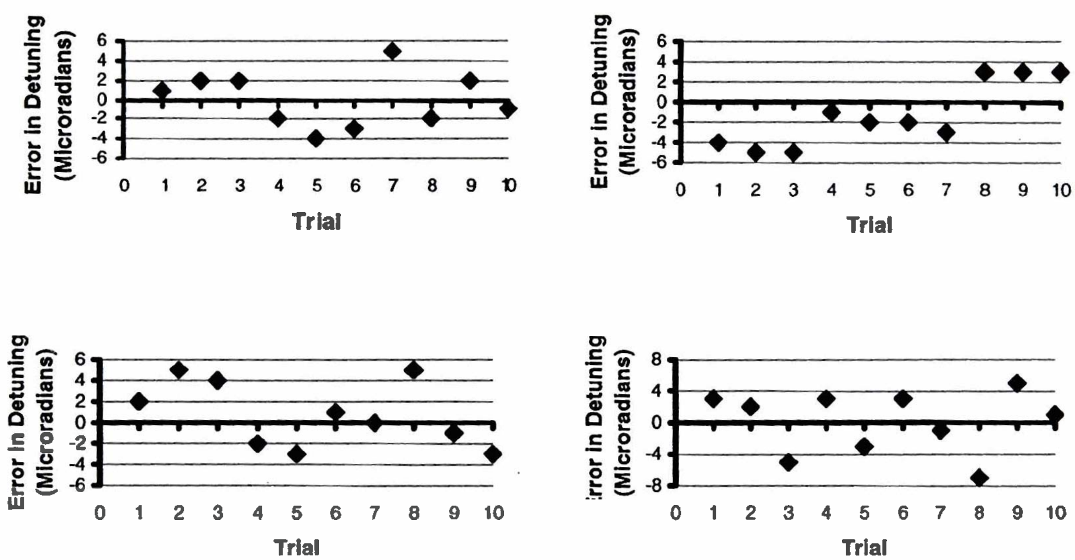

Figure 8 Algorithm errors in detunings of four triplers (triplers 1-4 arranged clockwise) for ten trials: the error for each tripler never exceeds 8 µrad for any of the trials. This is well within the desired restoration of conversion efficiency to within 1%.

3.3. Shot 28152, Beams 35 and 54

The tuning algorithm was also blind-tested on real OMEGA experimental data (for two triplers). Given the UV spectra of beams 35 and 54 on shot 28152, I used my two-tripler algorithm to calculate the detunings of the triplers in each beam. The only information I was given beforehand was that the detuning would be no larger than 2000 μrad for either tripler (though it was later discovered that the second tripler was detuned by a much larger amount). Correspondingly, I adjusted the bounds of the Bin Search to +/-2000 μrad. I also changed the increment of the Bin Search to 200 μrad so that the runtime would not increase drastically. The algorithm produced a calculated UV spectrum that matched the experimental UV spectrum very well, as seen in Figure 9. The algorithm error for the detuning of tripler 1 was -120 μrad in Beam 35 (Fig. 9) and –10 μrad in Beam 54. Since a 1% conversion efficiency loss corresponds to 100 μrad of detuning error, readjustment of beam 35 by the calculated amount would have restored the conversion efficiency to approximately 1% of its ideal value. Furthermore, the "actual" detunings quoted may only be accurate to 100 μrad anyway.

The detuning of tripler 2 was approximately 10 mrad, a magnitude so great that the tripler had no significant effect on the conversion efficiency and the UV spectrum. Thus, the algorithm could only find the detuning of tripler 1. Note that the detunings of both triplers were deliberately very large for testing purposes in an unrelated area. The close match for tripler 1 gives confidence that the algorithm would work very well for the smaller detuning errors that

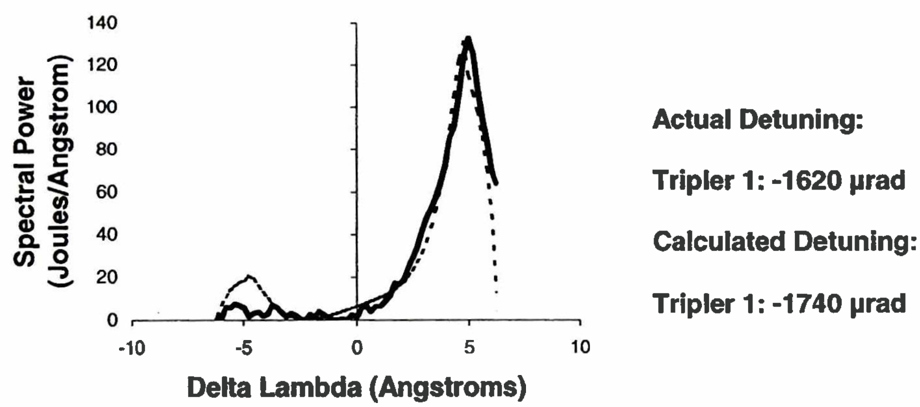

Figure 9 UV Spectra of shot 28152, beam 35: the experimental spectrum (thick solid line) and the detuned spectrum calculated by the algorithm (dashed line). Tripler 2 was detuned to such a degree that it had virtually no effect on the UV spectrum.

would normally be encountered.

3.4. Shot 30390, Beam 54

Blind experimental tests were also conducted on beam 54 of shot 30390. Again I was told that the detuning would be no larger than 2000 μrad for either tripler. Consequently, I used the same bounds and increments as I used for the trials on Shot 28152. The calculated spectrum again agreed very closely with the experimental spectrum (see Fig. 10). The algorithm-calculated detuning of tripler 1 had an error of –45 μrad, within the 100-μrad accuracy.

The error of the algorithm in tuning tripler 2 was –320 μrad. As seen in Figure 10, the spectrum produced by the "actual" tuning error – the thin line – is obviously a poor fit to the experimentally measured detuned spectrum. The excellent fit of the calculated detunings suggests that the experimental detunings were not known well. This illustrates the potential of using the spectrum as a better way of determining how the crystals are tuned than the method in use currently.

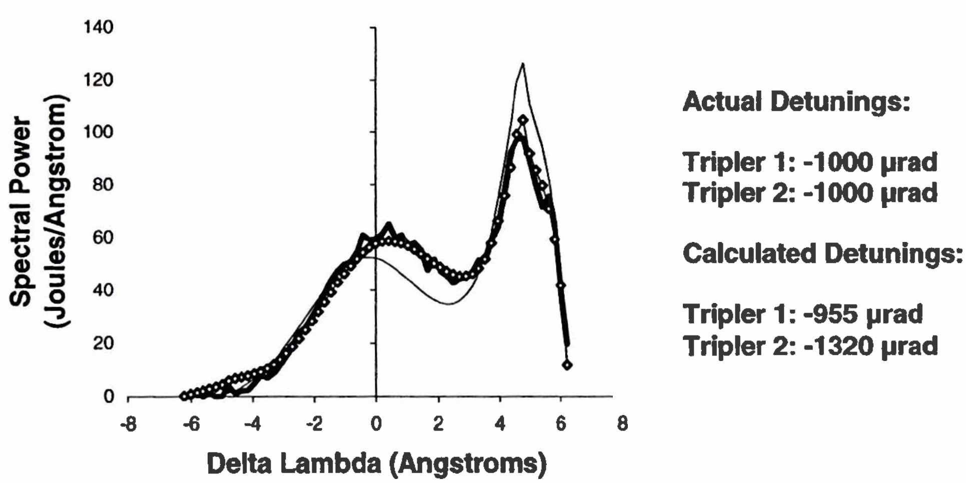

Figure 10 Tuning of shot 30390, beam 54: the experimental spectrum (thick line), the detuned spectrum calculated by the algorithm (open diamonds), and the spectrum of the given "actual" detunings (thin line).

4. Conclusions

I developed a systematic method to tune multiple triplers using the spectra produced by a UV spectrometer. Tests using computer-generated spectra proved that the algorithm works extremely well for both two- and four-tripler systems. Testing of the algorithm on experimental spectra produced spectra that matched the experimental spectra very well. Based on these results, it is planned to implement this algorithm on OMEGA when a new UV spectrometer is added that will measure the spectra of all 60 beams.

Furthermore, the outlook for tuning multiple triplers is promising. As a result, the establishment of a four-tripler system that can double the existing bandwidth is one step closer to reality at LLE as well as at other research facilities worldwide.

5. Acknowledgements

I would like to thank Dr. R. S. Craxton for allowing me to participate in the summer research program at LLE. I would also like to thank him for the invaluable guidance he has given and continues to give me with my project. I am also indebted to Dr. William Donaldson, who was and still is instrumental in my experimental testing. Finally, I would like to thank my fellow high school researchers who made the program an enjoyable, fun, and memorable experience.

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