Frequency Conversion Crystal Designs for Improved Ultraviolet Power Balance on the 60-Beam OMEGA Laser

Nathan Morse

Allendale Columbia School

Rochester, NY

Advisor: Mark Guardalben

Laboratory for Laser Energetics

University of Rochester

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Summary:

A Monte-Carlo-based method was developed and used to characterize the predicted performance of several different frequency conversion crystal designs for the 60-beam OMEGA laser located at the University of Rochester's Laboratory for Laser Energetics (LLE). The OMEGA laser is used to conduct implosion experiments and basic physics experiments in support of the National Inertial Confinement Fusion (ICF) program. A key element to achieving LLE's 100-Gbar implosion goal is improving the ultraviolet power balance of the OMEGA laser's 60 beams. The frequency conversion crystals (FCCs) on OMEGA convert an infrared laser pulse to an ultraviolet laser pulse using three crystals (a single doubler and two triplers), and were originally designed for higher laser input intensities and larger spectral bandwidth than are currently required. Less sensitivity of the ultraviolet laser power balance to beam-to-beam variations in the infrared energy and FCC angular alignment might be possible by using a different FCC design. A Monte-Carlo-based merit function was developed and used to characterize two different categories of FCC designs: 1) A reconfiguration of the current FCCs, and 2) FCC designs with alternative crystal lengths. Using an ultraviolet pulse designed for an 80-Gbar implosion campaign, improved power balance was achieved by eliminating OMEGA's second tripler. Additional improvement to power balance was obtained in a single-tripler design by changing OMEGA's crystal lengths from the current 12.2 mm to 15 mm.

I. Introduction

At the University of Rochester's Laboratory for Laser Energetics (LLE), scientists are attempting to create fusion in the laboratory using the 60-beam OMEGA laser. The method chosen, direct drive inertial confinement fusion, is performed by impacting a small spherical deuterium/tritium (DT) target with high-power ultraviolet lasers, compressing it with extreme acceleration. When the lasers hit the target, the outer shell explodes outwards. Newton's Third Law (every action must have an equal and opposite reaction) dictates that the rest of the target accelerates inwards and implodes. The radius of the target decreases by approximately a factor of 30, and the resulting high density and temperature within the target cause the DT fuel to fuse. The main goal of this research is to achieve ignition, at which point the energy output from the fusion process is greater than the energy of the impacting lasers.[1] The current goal of LLE is to achieve 100 Gbar of pressure on the target in a direct-drive implosion, a value that is required for ignition at National Ignition Facility (NIF) scale energies.

There are many challenges to direct-drive inertial confinement fusion. One of the main difficulties is achieving implosion uniformity. Small beam-to-beam variations in on-target irradiance can produce hotter and colder spots on the target's surface, causing the target to deform from an exact spherical shape as it implodes, inhibiting fusion.[2] Several possible sources of irradiation nonuniformity are being investigated at LLE, including the frequency conversion crystals (FCCs) that convert each of OMEGA's 60 beams from infrared (IR) to ultraviolet (UV) laser energy.

Each of the frequency conversion systems on OMEGA originally consisted of a doubler crystal and a single tripler crystal.[3] The doubler crystal converts some of the incoming IR light into green light, and the tripler crystal converts the green and residual IR light to UV light. A technique called Smoothing by Spectral Dispersion (SSD) is implemented in OMEGA to increase implosion uniformity on the target by phase modulating the IR light to increase its spectral bandwidth, and then angularly dispersing this bandwidth on the fusion target using diffraction gratings.[4] In order to efficiently convert all IR wavelengths within the bandwidth to the UV, a second tripler had been added to the frequency conversion system,[5,6,7] as shown in Figure 1. However, the current high-pressure implosion goal requires smaller bandwidth and lower IR intensities into the FCC than required for previous experiments.

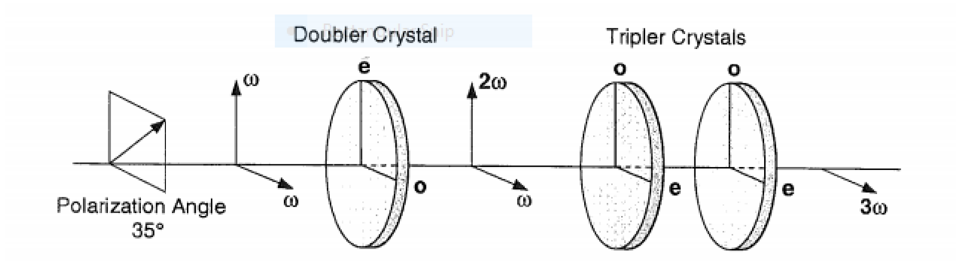

Figure 1: A diagram of the OMEGA frequency conversion system. The input IR beam has an electric field polarization that is at 35 degrees to the *o* (ordinary) axis of the doubler crystal and an angular frequency of ω. The frequency of the green beam is 2ω, and the frequency of the ultraviolet beam is 3ω. The polarization angle determines how the photons will be distributed to the *e* (extraordinary) and *o* axes of the doubler crystal. In the nonlinear frequency conversion process, each crystal produces an output beam of light with electric field along its *e* axis whose angular frequency is the sum of the frequencies of the crystal's inputs. Conversion efficiency is maximized by tilting each crystal to an appropriate angle about its *o* axis.

In order to achieve a precise pressure on all points of a spherical target, all 60 of OMEGA's beams must be approximately equal in power, or power balanced, throughout the temporal width of the laser pulse (typical pulse width is 1 – 3 nanoseconds). Preliminary simulations by LLE scientists suggested that improved beam-to-beam power balance might be possible while maintaining sufficient IR-to-UV conversion efficiency under current FCC-input beam requirements by removing the second tripler. In the work reported here, the frequency conversion process was simulated using the smaller IR bandwidth and lower IR intensity conditions, and a Monte-Carlo-based model was developed and used to calculate the expected temporally dependent UV power nonuniformity across all 60 of OMEGA's beams for several different FCC designs. This approach allowed the different designs to be compared based upon the sensitivity of each design to variations in IR input and FCC configuration (e.g., IR input energy and polarization angle, angular alignment of the FCCs and differential tripler angle, and width of the air gap between the two tripling crystals) and an optimized design to be chosen. Two categories of FCC designs were optimized: 1) A reconfiguration of the current FCCs, and 2) FCC designs with alternative crystal lengths.

In Section II, we describe the relationships between the parameters of the frequency conversion process and the ultraviolet pulse. In Section III, we discuss the Monte-Carlo method used to predict errors in UV power. In Section IV, we compare the best designs for OMEGA that were found using the Monte-Carlo method. In Section V, we show the process behind optimizing for crystal length, and observe the strengths and weaknesses of an FCC design with alternate length crystals. In Section VI, we conclude with a brief discussion of the impact of this study and future work.

II. Frequency Conversion Process

Figures 2 and 3 show how the efficiency of converting IR light entering the FCCs to UV light depends on the tilt angle of the doubler and tripler, respectively, for several different values of IR intensity. These plots represent a single-tripler FCC design with crystal lengths of 15 mm. Similar plots of conversion efficiency were generated for several different FCC designs using the harmonic generation code Mixette,[8] which provided the ratio of UV output intensity to IR input intensity for each FCC design investigated. Using these plots, “look-up” tables were formed that mapped a given IR intensity to a UV intensity for beam propagation in the forward direction through the FCC, while for backward propagation, the tables provided the UV-to-IR mapping. Backward mapping was used to determine the required IR pulse shape for a desired UV pulse shape. Linear interpolation between discrete values within these tables provided intermediate values of intensity, so that only a limited number of Mixette simulations were required. In this study, a desired UV pulse shape for the 80-Gbar shot campaign was used, as shown in Figure 4 with its corresponding IR pulse in the absence of any crystal detuning.

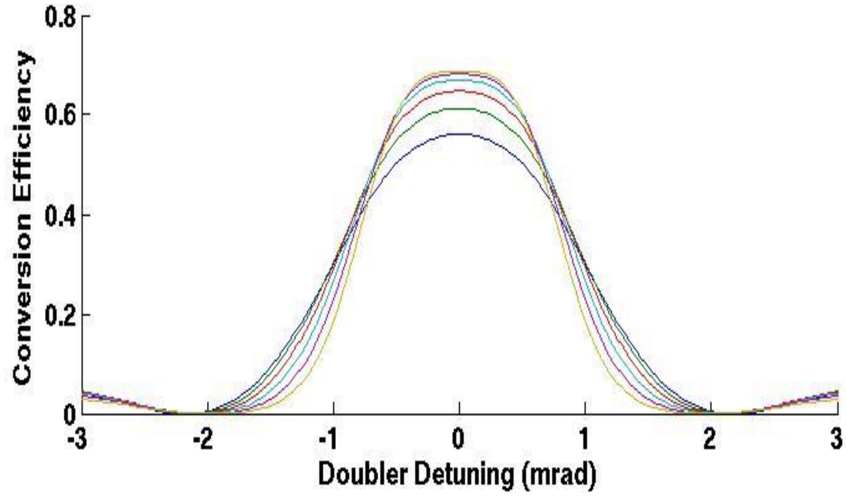

Figure 2: Graphs of IR to UV conversion efficiency v. doubler detuning for different IR intensities entering a 15-mm single tripler design. In this design, the second tripler was removed, and FCCs of 15 mm were used instead of the current 12.2-mm FCCs in OMEGA. A single IR intensity was used for each curve shown, with IR intensities ranging between 0.5 GW/cm^2 and 1.0 GW/cm^2 (inclusive), and an increment of 0.1 GW/cm^2 between curves. For this set of IR intensities, greater IR intensity corresponds to greater conversion efficiencies at 0° doubler detuning. As the doubler is detuned, conversion efficiency decreases nonlinearly, and differently for each IR intensity.

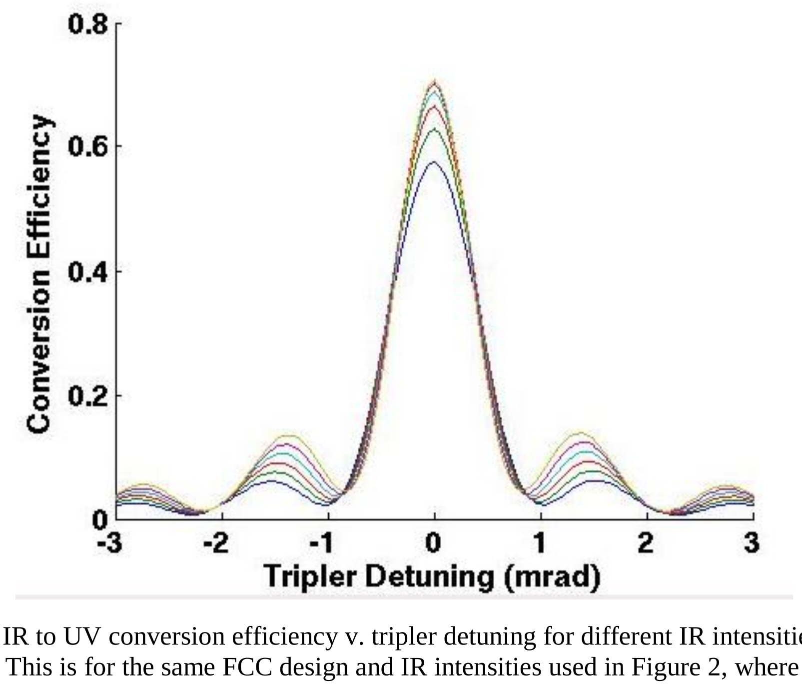

Figure 3: Graphs of IR to UV conversion efficiency v. tripler detuning for different IR intensities entering a 15-mm single tripler design. This is for the same FCC design and IR intensities used in Figure 2, where higher IR intensities also correspond to higher conversion efficiencies at 0° tripler detuning. Tripler detuning decreases conversion efficiency at a much greater rate than doubler detuning, as shown by the sharper efficiency peaks at 0° detuning in Figure 3 than in Figure 2. This implies that tripler detuning will be a larger source of error than doubler detuning.

Generation of an IR pulse that would, presuming no errors, convert to the desired UV pulse is necessary because the effects of frequency conversion parameters are dependent upon IR intensity. Among the FCC errors investigated, differential tripler detuning, IR polarization angle, and air gap distance were found to have less of an effect on the UV pulse than errors in IR energy, doubler detuning, and tripler detuning.

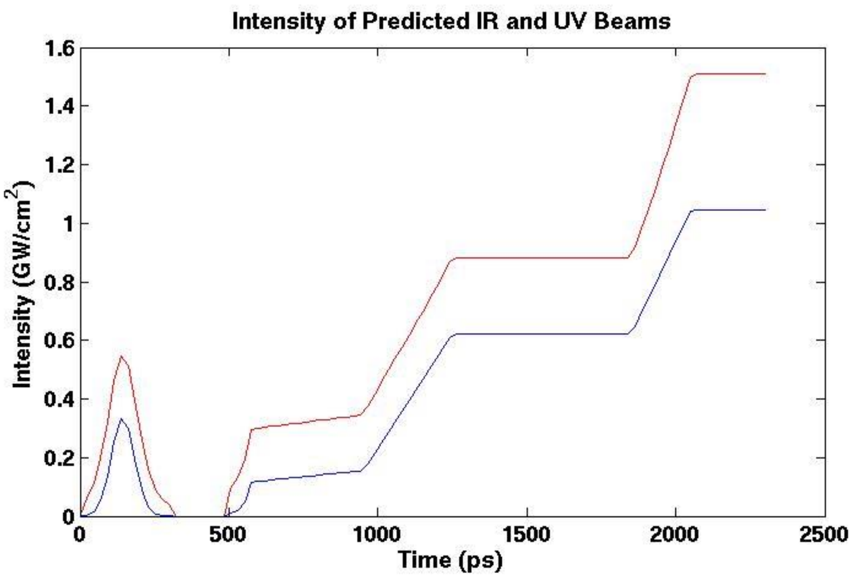

Figure 4: Desired pulse shape in IR (red) and UV (blue) for a 15-mm single-tripler design in the absence of crystal detuning. The relationship between the IR and the UV is nonlinear, shown clearly at the picket portion of the pulse (at ~200 ps). The relationship is slightly different for each FCC design, so a slightly different IR pulse is needed for each design to generate the same UV pulse.

III. Monte-Carlo Method

Measurements on OMEGA in the past have shown that beam-to-beam variations in crystal detuning and IR energy can be approximately described by Gaussian random distributions. In the Monte-Carlo method, the errors in IR energy and crystal detuning for each of 60 beams were randomly drawn from normal distributions whose standard deviations were taken from experimental data, as shown in Figure 5. The error in IR energy was described as a constant multiplier for each beamline, that multiplied the IR power at each temporal point throughout the IR pulse.

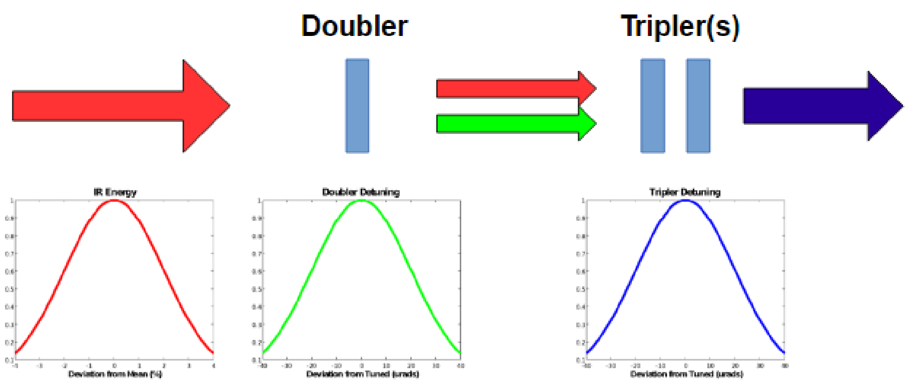

Figure 5: Visual depiction of Monte-Carlo error generation method used in the frequency conversion process. To represent the 60 beams of OMEGA, 60 samples from each Gaussian random distribution curve were drawn. The doubler and tripler detunings had a mean of 0 μrad and a standard deviation of 20 μrad. To model the IR energy error of each beam, an IR energy multiplier was drawn for each beam from a Gaussian random distribution with a standard deviation of 0.5% and mean value of 1.

The Monte-Carlo method assumes that each source of error independently contributes to the error in the UV pulse. For a given realization of 60 input IR pulses and FCC detunings, the look-up tables described in Section II were used to generate a set of 60 UV pulses. At each temporal point in the UV pulse, the variances of these three errors were added and the square root of this sum taken to obtain the root-sum-of-squares (RSS) error. This process allowed the calculation of the average UV pulse power and its standard deviation at each temporal point in the pulse across 60 OMEGA beams. This standard deviation is expressed as a percent of the UV power (RMS). The eventual goal of OMEGA is to achieve <1% RMS UV power imbalance.

IV. Configuration of Current FCCs

There were two main candidates for the optimized configuration of OMEGA's current FCCs: the single-tripler design, and the dual-tripler design. The single-tripler design was found to achieve better UV power balance overall, and roughly equivalent power balance at the picket, as shown in Figure 6. At low UV power, such as at the step portion of the pulse, the dual-tripler design has slightly lower RMS power imbalance than the single-tripler design. However, at greater UV power, such as at the drive portion of the pulse, the dual-tripler RMS power imbalance is much greater than that of the single tripler. The major source of error for the dual-tripler design in this region of the pulse is from crystal detuning. The dual-tripler design thus requires tighter control of crystal alignment than the single tripler design to reach LLE's eventual goal of <1% RMS UV power imbalance, so the single-tripler design is favored. As shown in Figure 6, the dual-tripler design was unable to achieve <1% RMS UV power imbalance for an IR energy error of only 0.5% RMS. Therefore, despite generating slightly greater power balance at the picket, the dual-tripler design is less suitable for use on OMEGA under current conditions.

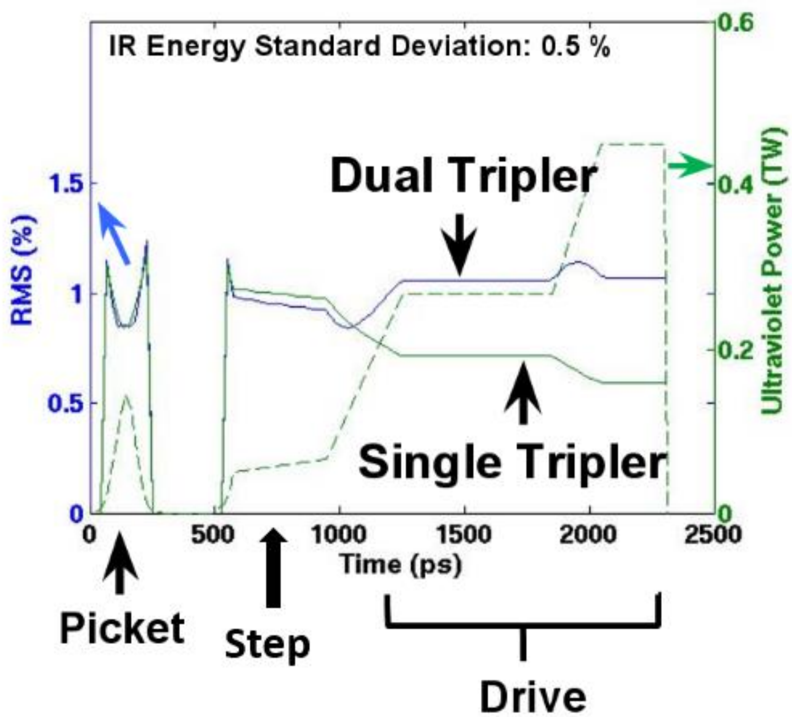

Figure 6: Predicted RMS power imbalance (left vertical axis) throughout the 80-Gbar pulse for dual-tripler (blue) and single-tripler (green) designs with current 12.2-mm FCCs on OMEGA. The right vertical axis plots the desired UV power in TW, shown dashed in green. UV power throughout the pulse is directly proportional to the desired UV intensities in Figure 4.

V. Crystal Length Optimization

Since the current FCCs were designed for higher IR input intensities than required for the 80-Gbar pulse, it was suspected that they would be of suboptimal length for the single-tripler design modeled in Figure 6. Figure 7 shows that lengthening the FCCs in the single-tripler design decreases sensitivity to changes in IR energy. However, in the nonlinear frequency conversion process, the reconversion of UV light back to IR and green light limits the achievable UV power in long-crystal, single-tripler designs, as shown in Figure 8. The longest crystal length that was able to achieve the peak power in the 80-Gbar UV pulse was 15 mm. Therefore, the optimal FCC design for the 80-Gbar pulse used in this study is a single-tripler design with 15-mm crystals. This design achieves lower RMS UV pulse error than both dual- and single-tripler designs that use the current 12.2-mm length FCCs.

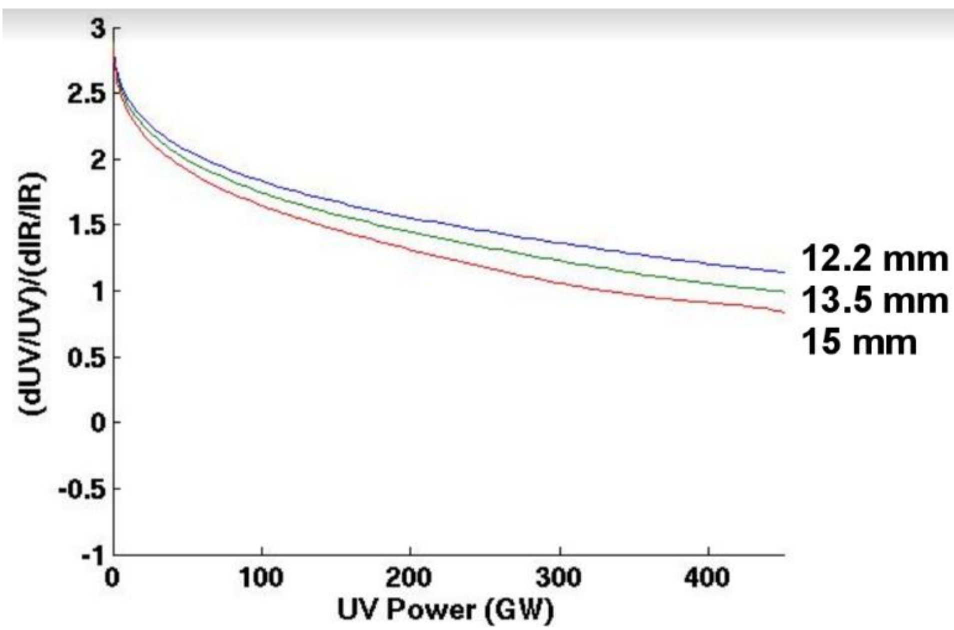

Figure 7: Sensitivity of UV power to changes in IR power is plotted on the vertical axis v. UV pulse power (horizontal axis) for single-tripler designs with crystal lengths of 12.2 mm, 13.5 mm, and 15 mm. The vertical axis is the numerical derivative of UV power with respect to IR power normalized by the ratio of IR and UV powers. The percent error in IR power multiplied by the vertical axis value gives the UV error in percent. The single-tripler design with longer FCCs has lower vertical axis values for all UV powers, implying that longer crystal designs provide less UV error, and thus greater power balance, for the range of UV intensities in the 80 Gbar pulse (0-450 GW).

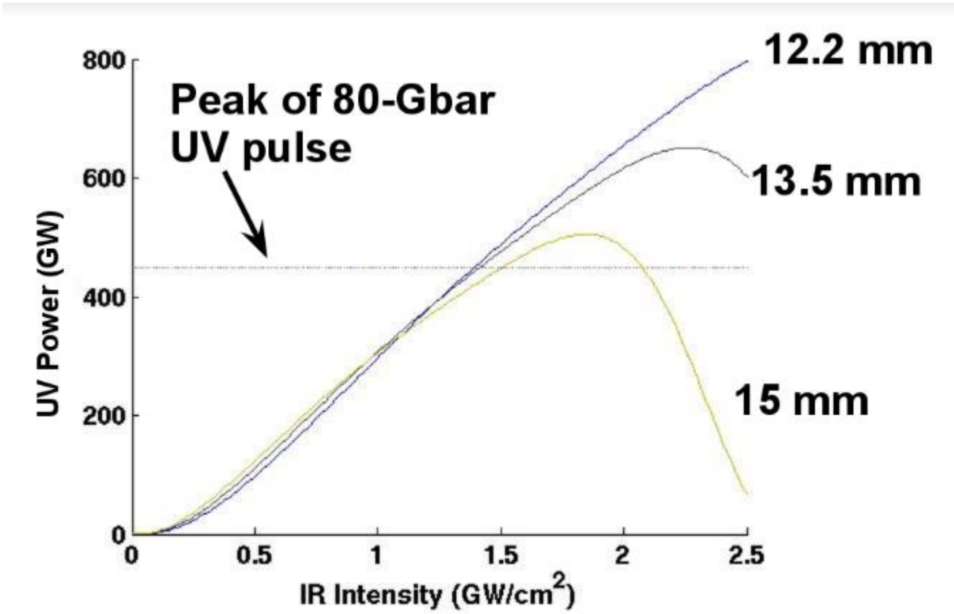

Figure 8: UV power v. IR intensity for single-tripler designs with different FCC lengths. Reconversion, in which UV converts back to IR and green light, happens at lower IR intensities for longer FCC single-tripler designs. This lowers the limit on achievable UV power. A single-tripler FCC design with 15-mm length crystals can achieve the 450 GW peak UV power in the 80-Gbar pulse, but cannot generate more than 500 GW of UV power.

VI. Conclusion

Using a Monte-Carlo-based approach, the statistical performance of different FCC designs was compared and two optimized designs for LLE's 60-beam OMEGA laser were found. It is anticipated that these designs will provide enhanced UV power balance over the current FCC configuration for LLE's 100-Gbar implosion goal. The single-tripler design with the current FCC crystal thickness of 12.2 mm is being implemented on OMEGA by removing the second tripler. An improved single-tripler design for OMEGA consists of a 15-mm doubler crystal and a 15-mm tripler crystal, although this design would make OMEGA incapable of generating more the 500 GW of UV power per beam. With the Monte-Carlo merit function, LLE can now predict approximately how much error there will be in the UV pulse for given errors in the IR energy, doubler tuning, and tripler tuning, thus providing a tool to perform an error budget analysis, and to compare and optimize different FCC configurations. Future work may include enhancing the Monte-Carlo method by adding other sources of UV pulse error, such as beam-to-beam differences in IR wavefront and beam-to-beam variations in crystal temperature.

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