Genetic Algorithm Optimization of X-ray Emission from Laser-Cluster Interactions

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Introduction

Clustered gases are a very interesting target in laser-plasma physics due to their ability to very efficiently absorb short pulse laser energy; this can be as high as 95% [1]. This makes clustered gases excellent x-ray sources, as large amounts of energy absorbed produces a high temperature plasma leading to bright x-ray emission [2]. This report will describe a recent experiment in Gemini TA2 in which the effect of the temporal shape of a laser pulse on x-ray emission from a clustered gas target was explored, and the optimum pulse shape that yielded the highest x-ray emission was found. A genetic algorithm was used to find this optimum pulse shape, a technique enabled by operation of the beam line at 5Hz, allowing for rapid averaging of large data sets. Genetic algorithms are a useful tool for exploring large and multidimensional parameter spaces. The optimization of a result based on the variation of a single parameter is achievable with a simple parameter scan. However, scanning a multidimensional parameter space would require taking a large data set and be very time consuming. A genetic algorithm averts this problem as it does not require every possible point in the parameter space to be tested. In this experiment a three-dimensional parameter space was explored, these were the second, third and fourth order spectral phase terms of the laser. Changing these properties of the laser pulse allows the direct manipulation of the pulse shape in time.

Method

The optimization routine was performed using the front end of the Gemini laser at the Central Laser Facility. The laser delivered pulses of 150mJ to an argon gas target that was allowed to cluster as it expanded from the gas jet into the vacuum chamber. The gas jet was backed with a pressure of 30bar. Using the Hagena parameter [3] the average cluster size was estimated to be 14nm containing ~10^5 atoms with an internal cluster density ~10^{22} atoms cm^{-3}. The laser is capable of operating at 5Hz, therefore it can quickly gather large volumes of data for averaging. This was very important for the optimization as variation between shots can be very large in laser plasma interactions. The laser's pulse shape was manipulated using the *Dazzler*, which is an acousto-optic dispersion filter, that could be directly controlled by the genetic algorithm code. The x-ray yield was measured using silicon PIN diodes, sensitive to x-rays with energy in the range 2 – 20 keV.

Genetic Algorithm

Genetic algorithms attempt to optimize a single number called the *fitness function* by altering a certain number of experimental parameters. It does this using a technique that has been influenced by the process of natural selection. The algorithm looped over 9 generations, each generation consisted of 15 individuals. Each individual represents a trial solution and was given a value for each of the 3 experimental parameters being varied. These parameters were the second, third and fourth order dispersion of the laser's spectral phase. Individuals were initialized randomly for the first generation then with each successive generation new individuals were created by assessing the performance of the individuals from the previous generation. The individual's fitness was the x-ray PIN diode signal averaged over 50 shots. After a generation was completed the fitness of each individual was assessed. The two fittest individuals went through to the next generation unchanged, whilst the remaining 13 were created by crossing over spectral phase values of two 'parent' individuals, taken from the previous generation. Random mutations were also applied to the values of these new individuals. The fittest 4 individuals of a generation were chosen to be the parents for the next generation. As the generations progressed the fitness of the fittest individual was found to increase up to an eventual plateau, by which point the optimum pulse shape was found.

Temporal Control of Laser Pulse

The *Dazzler* [4] controls the temporal shape of the laser pulse using an acoustic wave launched into a birefringent material. As the laser propagates though the birefringent material its polarization is rotated from the ordinary axis to the extraordinary axis (where its group velocity is slower). The frequency of light whose polarization rotated is determined by the frequency of the acoustic wave in the material. Therefore, tailoring the acoustic wave allows one to control when specific frequencies move to the extraordinary axis and hence move slower than the remaining frequencies in the ordinary axis, therefore direct control of the dispersion is possible.

X-ray Detection

The task of x-ray detection was performed by a Quantrad 025-PIN-125 silicon PIN diode. This diode had a cross sectional area of 0.25cm^2, an intrinsic region thickness of 125μm and was reverse biased with a potential difference of 100V. It was filtered with a layered filter consisting of 0.1μm ruthenium, 0.1μm aluminum and 3.5μm mylar. This filter significantly attenuated any x-rays bellow 1 keV and shielded the diode from any light emitted by the plasma. The sensitivity curve of the diode is shown in Fig. 1. The diagnostic was time integrated as the response time of the diode was much larger than the x-ray pulse duration emitted by the plasma. X-rays incident on the diode will create a charge by generating electron-hole pairs, these are swept away from the intrinsic region by the bias voltage and a current is generated. This current was measured by an oscilloscope recording the potential difference across a 50Ω resistor. The amount of charge generated is related to the x-ray pulse energy by $Q = 0.282E$ [5] which is derived from the band gap of silicon.

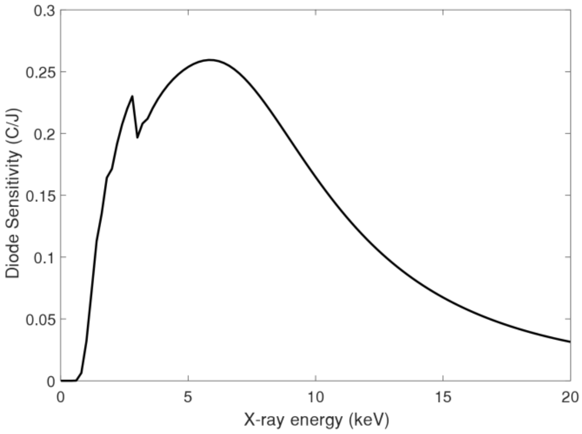

Figure 1: Sensitivity curve of the x-ray PIN diode, the transmission of its layered filter was also included in the calculation of this curve.

Results

Figure 2 shows how x-ray yield changes with the second and third order dispersion of the laser pulse. The range of values the algorithm could set on the fourth order dispersion were too small to have a significant effect, so it has been ignored from this graph. The most compressed pulse was certainly not the optimum (the point with 0 second and third order spectral phases). From this scatter graph it can be seen that x-ray yield is highly sensitive to second order dispersion with a clear optimum at $500fs^2$, whereas the most compressed pulse would have $0fs^2$. Introducing second order dispersion has the effect of chirping the pulse, hence increasing its duration and decreasing its maximum intensity. There is also a preference towards negative third order dispersion. This has the effect of giving the pulse a slow rise as shown in Fig. 3, which is the shape of the optimum pulse, in terms of the x-ray signal.

Discussion

The result of the genetic algorithm has shown that a higher x-ray yield is not achieved simply by irradiating the clusters with a more intense pulse. The physical processes involved in laser cluster interactions are very complex and as such it is difficult to provide a concise explanation as to why the pulse shape evolved into the pulse seen in Fig. 3. One interpretation is that electrons are outer ionized from the cluster and form an electron cloud during the initial slow ramp of intensity. Then these electrons are heated through a collisionless process such as described in Ref. [6]. Here the electron cloud can be thought of as a driven harmonic oscillator that is resonant when the oscillation frequency about the center of the cluster matches the laser frequency. The positive chirp seen in the optimum pulse may have evolved to keep this resonance as the electron cloud energy increased.

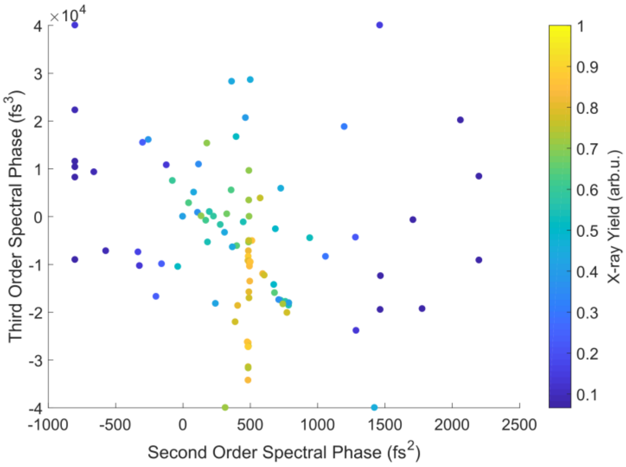

Figure 2: Every trial solution attempted by the genetic algorithm across all generations, with the colour representing the x-ray yield of each trial solution.

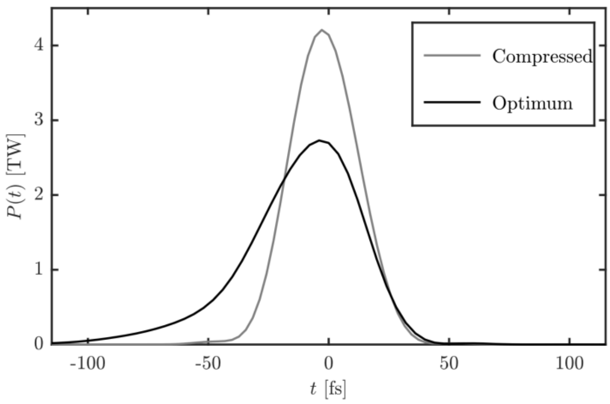

Figure 3: Temporal shape of the optimum pulse (found by the genetic algorithm) and the most compressed pulse.

Conclusion

In conclusion, the genetic algorithm used in this experiment was a success. It found the temporal shape of the laser pulse that led to the highest yield of x-rays in the energy range 1 – 20 keV when irradiated onto a gas of argon clusters. Due to the complex physics involved in laser cluster interactions it would have been very difficult to determine this pulse shape by theory alone. The knowledge gained by performing this optimization can benefit the development of clustered gas targets for use as x-ray back-lighters. It has also given insight into the complex processes involved in laser-cluster interactions.

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