Automated Focusing of the ROSS Streak Tube Electron Optics

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I. Background

Many systems, including LLE's OMEGA, require fine temporal resolution of nanosecond-timescale events such as laser pulses and neutron bursts. In inertial confinement fusion (ICF), the time-varying intensity (shape) of the laser pulse that is directed at the target greatly affects the gain of the resulting fusion reaction[1]; because the ultimate goal of ICF is to increase gain and thereby produce net energy, the diagnosis of pulse shape is vital to the success of the program.

The function of measuring the pulse shape is performed by a streak camera, a device that can record intensity events from multiple channels at a temporal resolution of several picoseconds. This resolution cannot be achieved by purely optical means due to the difficulties of angularly deflecting an optical beam on such a short timescale. Instead, the streak camera uses a photocathode to convert the optical beam to an electron beam via the photoelectric effect; the electron beam is focused by electrostatic lenses (charged plates) and then swept across a phosphor screen by reversing the polarity of two deflection plates. As the electron beam sweeps across the screen, the temporal profile of the pulse is mapped onto the spatial axis in the direction of the sweep. The phosphor screen glows for several seconds, long enough for the image to be captured by a CCD array and read into a computer. In the final image, the pulse shape appears in the x-direction (the temporal direction), and the different channels appear in the y-direction (the spatial direction).

Streak cameras have been in use for several decades, and many of the individual devices still in use are that old. The Rochester Optical Streak System (ROSS) is an implementation of the basic streak camera architecture with the incorporation of modern electronic controls. The objective of this project was to create a computer program capable of autonomously focusing the ROSS's electrostatic lenses, thus allowing optimization of cameras that are operating in remote locations.

II. Methods

Two programs for automatic focusing were written: one for the P510 ROSS (with one electrostatic lens) and another for the P820 ROSS (with three electrostatic lenses). For each, the task of focusing was divided into two separate problems: evaluating images for focus quality, and adjusting lens voltages to optimize focus quality. A controlled light source illuminated the photocathode with a control pattern in order to make image evaluation easier and more consistent.

IIa. Experimental Setup

The control pattern, a vertical slit similar in appearance to a dashed line (with 5 lp/mm), was imaged onto the photocathode with an Offner triplet. In this setup, the light source was constant instead of pulsed, and the sweep plates were not used. The Offner triplet assembly was attached to the input of the streak camera. A ROSS optical module is currently being developed that would serve the same function as the experimental setup: providing a control signal to the camera for the purposes of focusing and calibration.

IIb. Image Evaluation

In the case of the P510 tube, image evaluation was relatively simple because the radially symmetric lens focused the electron beam equally in both the temporal and spatial directions. Therefore, the working assumption was that if the image was optimally focused in one direction, it was very close to optimally focused in the other direction. The image evaluation routine used the line-spread function (LSF) in the temporal direction as the measure for overall focus quality. Full width at half maximum (FWHM) was used to quantify focus quality, with a lesser FWHM indicating better focus. To determine FWHM, the evaluation routine found the maximum intensity of the line spread, stored all pixels with intensity greater than 25% of the maximum in a data set, and found the coefficients of a Gaussian fit to the data (Fig. 1). These coefficients yielded the FWHM.

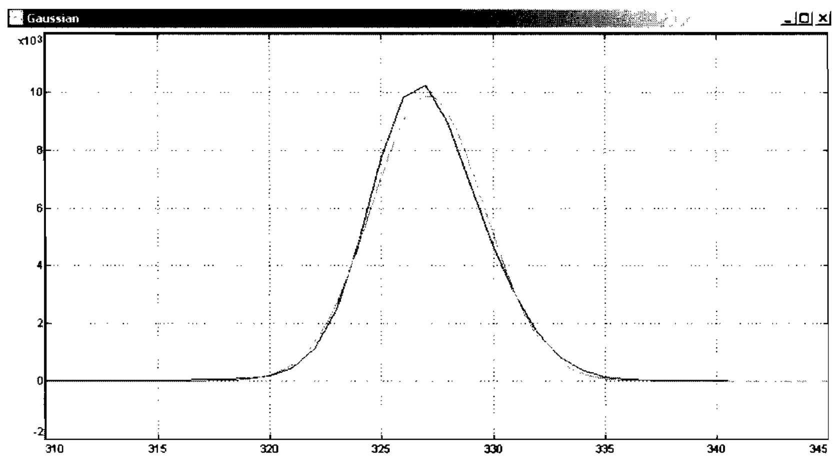

Fig. 1 The black (heavier) line is the LSF (image averaged over the spatial direction); the red (lighter) line is a Gaussian fit. The FWHM of the Gaussian was the measure of temporal focus quality.

In the case of the P820 tube, the image evaluation routine had to analyze temporal and spatial focus quality separately because each direction was focused by its own lens. The temporal focus quality, which is controlled by a cylindrical lens known as FB2, is measured in the same way as the P510: the program finds the FWHM of the line spread function. The spatial focus quality, which is controlled by a quadrupole lens, is quantified in terms of contrast: the program must compare the maxima and minima of the spatial profile (Fig. 2).

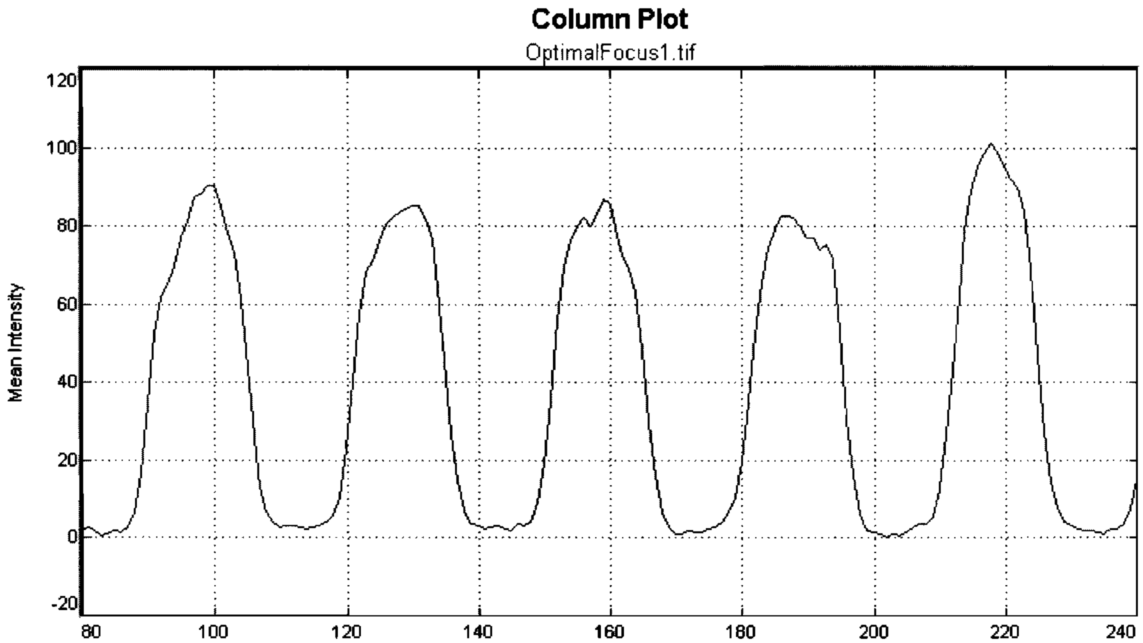

Fig. 2 The spatial profile of captured image. The x-scale is measured in pixels.

Contrast (**C**), a number between 0 and 1 that indicates the difference between maxima and minima, was computed for each peak and valley pair (Eq. 1).

Eq. 1 C = (Max - Min) / (Max + Min)

Then to reduce the effect of noise, all values of **C** that were greater than one standard deviation away from the mean were removed from the data set and the mean was recalculated. This final mean contrast ($\mathbf{C_f}$) was used as the measure of spatial focus quality; a contrast of 1.00 would indicate minima of zero intensity, while a contrast of 0.00 would indicate minima equal to maxima (no modulation).

IIc. Lens Voltage Optimization

In the case of the P510, the task of lens voltage optimization was, again, relatively simple: there was one input (a single lens voltage), one output (an LSF), and one goal (minimize FWHM). Essentially, optimization consisted of capturing images at different lens voltages, applying the evaluation routine to each to find the FWHM, and selecting the voltage that yielded the smallest FWHM. The solution space was likely to be a simple parabola, and experimentation showed this to be true.

In the case of the P820, the task of lens voltage optimization was considerably more complex: there were two inputs (both the FB2 and quadrupole voltages), two outputs (both FWHM and contrast), and two goals (to minimize FWHM and to maximize contrast). Because each image capture took about 10 s, testing all of the possible combinations of lens voltages would have taken too long (there is also a prospect of future streak tubes having even more lens voltages). In addition, the quadrupole is not completely independent of temporal focus; rather, FB2 and the quadrupole both affect the temporal focus. With only two lenses, the quadrupole could be optimized for spatial focus first, and FB2 could be optimized for temporal focus second. However, this would not necessarily yield the best temporal focus possible, and the problem would be exacerbated in future tubes with more than one quadrupole lens. Therefore, a previously untested approach was taken: the use of a genetic algorithm (GA) to evolve the best-focus solution. Given a problem in which the solutions can be rated in terms of their “fitness,” a number that indicates how successful they are, GAs utilize the biological evolutionary principles of genetic variation, natural selection, and inheritance to produce solutions that approach the maximum fitness with each successive generation.

III. Results

As expected, the solution space for the P510 turned out to be a parabola. To minimize the FWHM, the program captured several sample images (Fig. 3), found FWHM values via the image evaluation routine, plotted FWHM values versus lens voltages, calculated the parabolic fit, and selected the lens voltage at the minimum of the parabola (Fig. 4). Repeated testing showed that the program was indeed capable of consistently finding the lens voltage that minimized the FWHM.

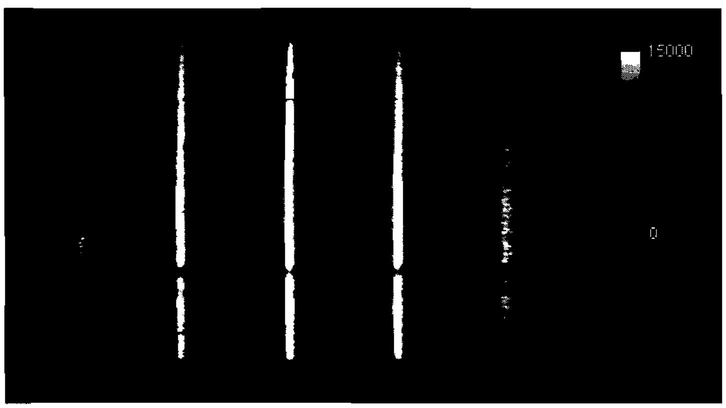

Fig. 3 Five images taken with the P510, with lens voltages ranging from −14300V to −14480V. The color scale on the right is in arbitrary units of intensity. The center image has the least FWHM, at about 6 pixels.

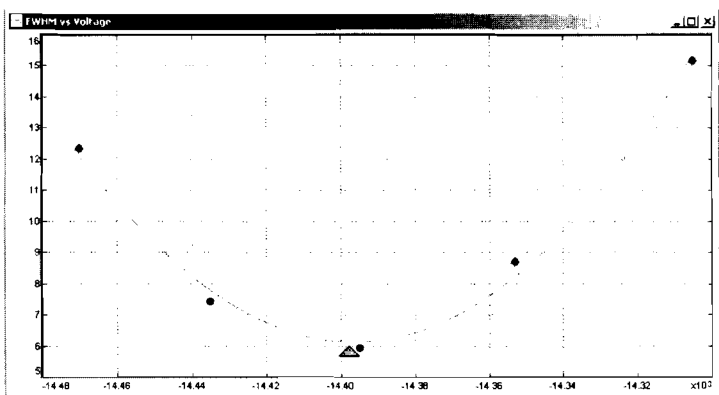

Fig. 4 FWHM (pixels) versus lens voltage (kV). This plots data from the images in Fig. 3. The green arrow indicates the predicted optimal voltage.

The solution space for the P820 was not as well-defined as the P510's parabola. Because the P820 had two input voltage (quadrupole and FB2), plotting its solution space required three dimensions. The total weighted fitness $\mathbf{F_w}$ (which measures overall quality of focus) was calculated using Eq. 2.

Eq. 2 $\mathbf{F_w} = 0.2*\mathbf{C_f} + -4*\ln(0.5)*\mathbf{FWHM}^{-2}$

The second term of Eq. 2 is –1 times the $\mathbf{x^2}$-coefficient of the LSF's best fit parabola (as **FWHM** increases, this term decreases and thereby lowers total fitness). The coefficient of the first term was selected so that the typical variation of both terms is approximately equal. This ensures that the contrast and line width of each image contribute about equally to that image's weighted fitness.

Fig. 5 shows the two input voltages mapped onto the two spatial directions and the weighted fitness mapped onto a color scale.

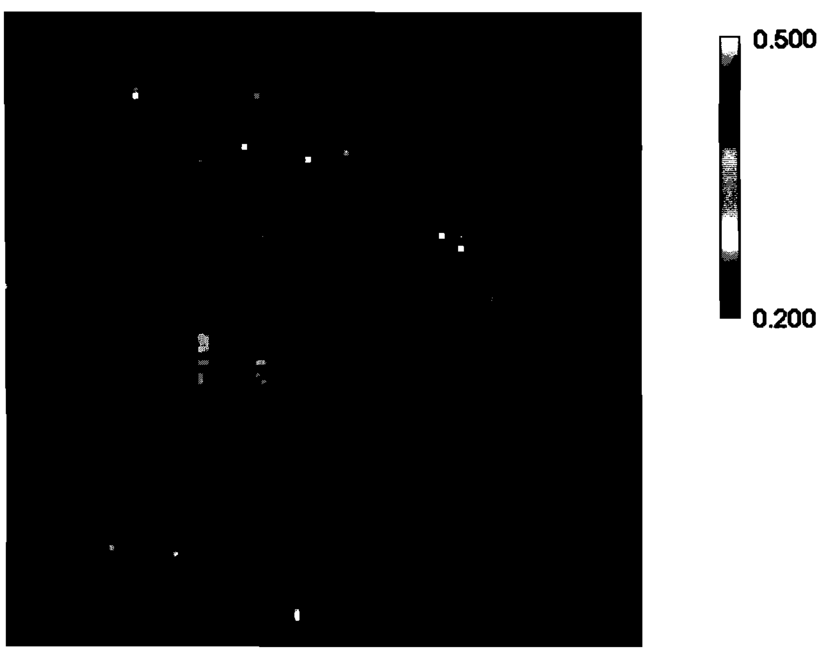

Fig. 5 A plot of the P820's solution space. The x-axis maps quadrupole voltage, and the y-axis maps FB2 voltage. The color of each point represents the weighted sum of the filtered contrast $\mathbf{C_f}$ and the squared inverse of **FWHM**, in arbitrary units.

Repeated trials suggested that focus quality is indeed dependent on the interactions of all lens voltages, as opposed to being influenced by each lens independently. This conclusion was reached because of the diagonal slant of the contours' major axes (Fig. 6); if the lenses had affected focus quality independently, the contours' major axes would have been orthogonal to the x- and y-axes of the graph.

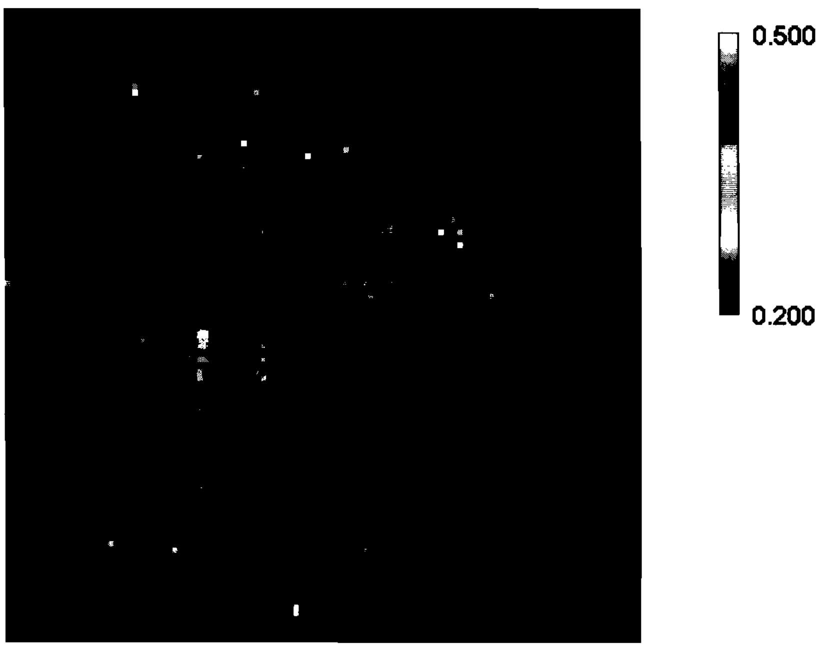

Fig. 6 Replica of Fig. 5, with contours of approximately equal fitness drawn for clarity.

IV. Conclusions

The programs written for this project should be further characterized for repeatability and effectiveness. There is a tradeoff between the speed of a focusing algorithm and its ability to find the true optimum; the programs written may not be achieving the most desirable balance between these two possibilities. Further analysis of the programs' performance could yield significant improvements. The GA developed for the focusing of the P820 should be tested against a non-GA. When applied to a streak tube like the P820, which has 2-3 lens voltages to adjust, a non-GA may prove faster and more effective; when applied to a streak tube like the PJX, which has multiple quadrupoles and many more lens voltages to adjust, the GA may prove superior than the non-GA. The reason the GA may perform better when used on a more complex system is that the GA adjusts all voltages simultaneously and is capable of searching the solution space for unforeseen interactions between lenses. The result could be faster search time and smaller FWHM.

This project was limited by time constraints, but it achieved the goal of creating a program for autonomous remote focusing of the ROSS. The project also demonstrated that a genetic algorithm is capable of reaching the optimal focus of an electron-optical system.

V. Acknowledgments

I would like to thank Bob Boni, Dr. Paul Jaanimagi, and Matt Millecchia for the large portion of time they spent helping me on my project this summer. I know the skills, techniques, and concepts that they taught me will be invaluable in whatever scientific field I eventually choose. I would also like to thank Dr. Steve Craxton for giving me the opportunity to participate in this program; I have learned a lot about what it would mean to be a professional research scientist.

VI. References

1. McCrory, R.L., *et al.*, *Nuclear Fusion* **41**:1413 (2001).

2. Lerche, R.A., McDonald, J.W., Jaanimagi, P.A., Boni, R., *et al.*, "Preliminary Performance Measurements for Streak Camera with Large-Format Direct-Coupled CCD Readout", *15th Topical Conference on High-Temperature Plasma Diagnostics* (San Diego, CA, April 19-22, 2004).

3. Obitko, Marek. "Introduction to Genetic Algorithms." <http://cs.felk.cvut.cz/~xobitko/ga/>