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Evaluation of Laser Stabilization and Imaging Systems for LCLS-II*

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By combining the top performing commercial laser beam stabilization system with the most ideal optical imaging configuration, the beamline for the Linear Accelerator Coherent Light Source II (LCLS-II) will deliver the highest quality and most stable beam to the cathode. To determine the optimal combination, LCLS-II beamline conditions were replicated and the systems tested with a He-Ne laser. The Guidestar-II and MRC active laser beam stabilization systems were evaluated for their ideal positioning and stability. Both a two and four lens optical imaging configuration was then evaluated for beam imaging quality, magnification properties, and natural stability. In their best performances when tested over fifteen hours, Guidestar-II kept the beam stable over approximately 70-110um while the MRC system kept it stable over approximately 90-100um. During short periods of time, Guidestar-II kept the beam stable between 10-20um, but was more susceptible to drift over time, while the MRC system maintained the beam between 30-50um with less overall drift. The best optical imaging configuration proved to be a four lens system that images to the iris located in the cathode room and from there, imaged to the cathode. The magnification from the iris to the cathode was 2:1, within an acceptable tolerance to the expected 2.1:1 magnification. The two lens configuration was slightly more stable in small periods of time (less than 10 minutes) without the assistance of a stability system, approximately 55um compared to approximately 70um, but the four lens configurations beam image had a significantly flatter intensity distribution compared to the two lens configuration which had a Gaussian distribution. A final test still needs to be run with both stability systems running at the same time through the four lens system. With this data, the optimal laser beam stabilization system can be determined for the beamline of LCLS-II.

I. INTRODUCTION

The laser injector lab of the Linear Accelerator Coherent Light Source (LCLS) is responsible for delivering a stable 253nm UV beam to the cathode gun at the beginning of the accelerator. The quality of this beam directly impacts the quality of the x-rays produced by the accelerator. These x-rays are used for experiments by researchers both internal and from around the world. In order for the beam to get from the laser injector lab to the cathode vault, it must travel through a beamline. In order for the highest quality beam to be delivered to the cathode, two factors must be considered in the beamline: stability and imaging.

SLAC has begun the development of LCLS-II, a superconductor linear accelerator capable of one million x-ray pulses per second. The beamline of LCLS-II will be approximately 26m compared to 10m in LCLS making stability that much more challenging. Currently, SLAC uses an internally developed stability system in LCLS. This system uses a VCC camera that reads the pointing stability of the beam. While this one camera system suffices for LCLS, it has some issues. First, there are concerns with backlash on the mirrors; the beam is not always corrected to the original position after a correction is made. Second, on occasion, the system will lose stability and have to be reset. Third, the system only uses one camera and a two-camera system is hypothesized to perform better. For these reasons, Guidestar-II and MRC active laser beam stabilization systems, both commercial systems with two sensors and piezo actuator mirrors, are being considered for LCLS-II.

The imaging system for LCLS-II will be responsible for de-magnification, a flat beam intensity distribution, and natural stability. The beam size at the cathode must be within 0.2-2mm. To achieve this, the optical configuration of the beamline must be able to de-magnify the beam to the proper size. Furthermore, the imaging system must make the beam intensity where is hits the cathode gun as flatly distributed as possible. This is crucial to minimize damage to the cathode and release the highest quality electron bunch to enter the accelerator. The ideal configuration will achieve this goal with the minimal amount of optics as this will increase natural stability, make the system more user friendly, and reduce the number of variables.

II. MATERIALS AND METHODS

A. Replicating the Beamline

The conditions of the beamline for LCLS-II were replicated using two optical breadboard tables separated by approximately 22m. Metal stands were used to hold the optics for the imaging systems in between these breadboard tables. A class 3R He-Ne laser was used for testing. In order to cover the large distance, extension cables for the piezo actuators were made locally at SLAC. A camera used in conjunction with Spiricon imaging software was used to record the centroid position and intensity

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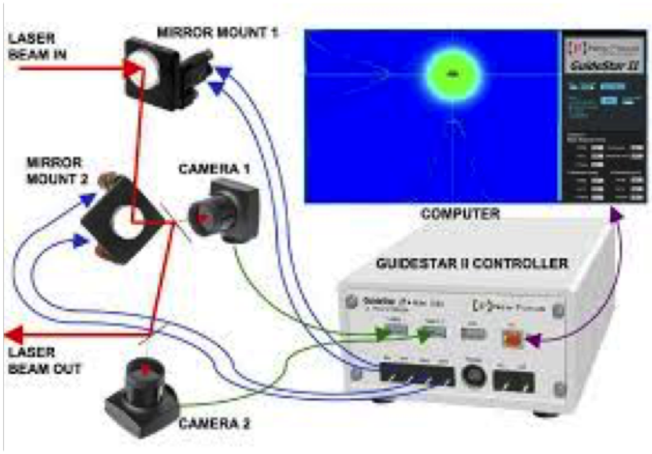

FIG. 1. Guidestar-II Active Laser Stabilization System

FIG. 2. MRC Active Laser Stabilization System

distribution of the beam. In addition, beam splitters were used to split the beam to the sensors, mirrors were used to both extend the distance the beam traveled and mimic the beamline, and lenses with short focal lengths were used to focus the beam on the cameras and sensors. The experiment took place in a warehouse under non-ideal conditions. There was no temperature, light, or vibration control. Additionally, wildlife was able to get into the building and was noted to interrupt the beam on occasion. In contrast, LCLS-II will use a high-powered laser and the system will be highly contained and controlled.

B. Guidestar-II Active Laser Stabilization System

The Guidestar-II is a camera-based stabilization system that is controlled by a graphical user interface (GUI). (FIG. 1) The GUI displays beam intensity, pointing stability, and plots the centroid location over time. For these reasons, the system is very user friendly. To start the system, the beam has to be in the range of the camera. It will then appear on the GUI and its centroid location displayed. The user then sets that point as the origin position to maintain the beam at. The issue with this system is that the cameras are made for 355nm-1200nm wavelengths and the beam for LCLS-II is 253nm. Therefore the cameras will have to be modified if this system is to be used in LCLS-II. This could be done either by working with Guidestar to develop special cameras, or possibly through the removal of filters.

C. MRC Active Laser Stabilization System

The MRC system is a quad-based system. (FIG. 2) On the back of the sensors are two sets of LEDs. The LEDs in the middle show where the beam is hitting the detector relative to the center. In order for the system to work, the beam must be perfectly centered on the quad. The easiest way to do this is by using a voltmeter. The X and Y outputs will read zero when the beam is centered on the quad. It is highly beneficial to use a lens to focus the beam on the quad detector, as the center range is quite small. The second set of LEDs is a vertical line with nine lights. These show the intensity level of the beam on the quad. The ideal range is between three and nine lights. The MRC system is highly dependent on the strength of the beam. In order to get three or more of the intensity LEDs to shine, both optical filters had to be removed from the sensors. This left the systems very sensitive to ambient light. To attempt to reduce the effect of the ambient light, shields were created with black construction paper around the sensors and beam blockers put in place in front of the sensors in a manner that did not affect the beam path.

D. Optimal Configuration of the Systems

Before the two commercial stabilization systems could be analyzed, it was first necessary to develop the optimal configuration of the piezo actuators and sensors. First, the location of the sensors relative to the actuators was tested. There were two possibilities: put a sensor directly after each actuator or put both sensors after both actuators. The idea behind putting a sensor directly after each actuator is that the system may be able to use one actuator to stabilize the beam at each sensor. Alternately, with both sensors after both actuators, the actuators could work together to stabilize the beam in both sensors simultaneously. Second, the location of the actuators was considered. The two options were to put them both after the 22m of transport, near the cathode, or to put one at the beginning of the 22m transport and one after. The theory behind putting the actuators near the cathode was to stabilize the beam right before it hits the

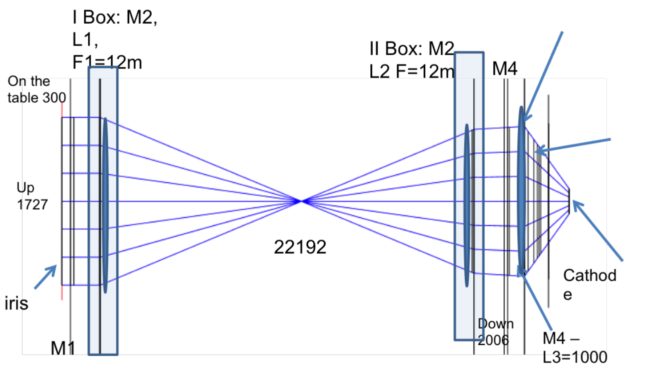

FIG. 3. Design of the two-box imaging configuration (contributed by Sasha Gilevich)

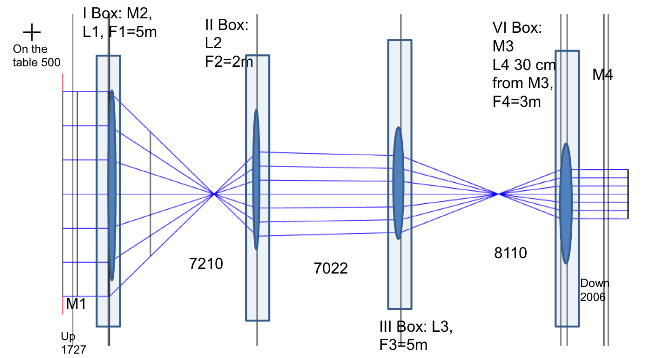

FIG. 4. Design of the four-box imaging configuration (contributed by Sasha Gilevich)

target. The thought behind putting them across the 22m of transport was to stabilize the beam over the longest distance possible.

E. Testing the Stabilization Systems

Once the optimal positioning of the systems was known, they could both be set up and compared. They were tested for long-term stability by allowing them to run for 15+ hours untouched. This test was always run overnight and changes in ambient light are noted to possibly affect the results. Due to a concern from previous use of the MRC system, a test of the systems ability to maintain stability through beam interference was desired. To test this, the beam was manually blocked repeatedly over a short period of time.

F. Imaging the Beam

The two optical configurations that were being considered were each set up and analyzed separately. Both systems began with a positive and negative lens used to collimate the beam over the distance of the experiment. Both two-box and four-box optical systems were evaluated. In LCLS-II a box is a vacuum-sealed container that holds the optics and will be hung from the ceiling. For the purpose of this experiment, the optics were not contained in a vacuum-sealed box.

G. Two-Box Imaging Configuration

In the two-box configuration (FIG. 3), the iris was located on the first optical breadboard, 300mm after the laser origin and 1727mm before the first optical box. Because this setup uses the minimum number of optical boxes, the focal length had to be particularly long (12m). In order to achieve this, a positive and negative lens was used in each box similarly to how they were used to collimate the beam at the beginning. The difference is by moving the lenses slightly further or closer than they are at the point of collimation, a specific focal length can be created. The distance between the two boxes was 22192mm. The lenses in the first box had focal length 103.0mm and the lenses in the second box had focal length 64.4mm. A third lens with a 3m focal length was located 3006mm after the second box. The final target is 863mm from this lens. In theory, this optical configuration should de-magnify the beam 6.7:1.

H. Four-Box Imaging Configuration

The first box of the four-box system (FIG. 4) contained a 5m focal length convex lens located 2227mm from the laser origin. The second optical box contained a 2m focal length convex lens 7210mm away followed by a 5m focal length convex lens in the third box 7022mm away. The final box used a 3m focal length convex lens placed 8110mm from the third box. The iris is located in the vault of the system, 2006mm from the fourth box. The beam is de-magnified 4.15:1 from the laser origin to the iris. There is a final convex lens with a focal length of 1.5m located 4816mm from the iris. From the iris to the cathode, the beam is de-magnified 2.1:1

I. Analyzing the Imaging Systems

A variety of data was collected in order to analyze the optical configurations. Images were taken of the beam size and intensity distribution of the beam at the target/cathode. In order to acquire the highest quality images, an air force target was used to properly image the beam. An air force target uses an array of three horizontal lines in vertical and horizontal configurations of varying sizes. (FIG. 5) The target is placed in front of the beam and the camera (represents the cathode) is adjusted slightly until the image is resolved. A resolved image will display the pattern of the air force target with

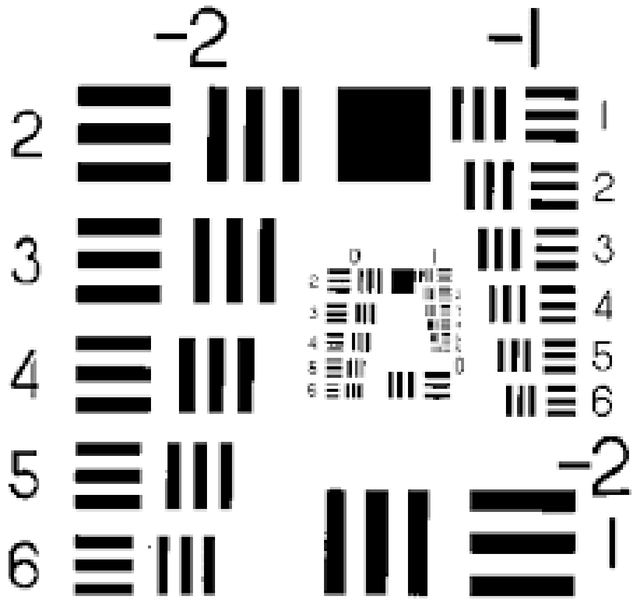

FIG. 5. Air Force Target

the highest quality. Once resolved, images were taken at a variety of iris sizes so that the de-magnification ratio could be confirmed and diffraction ring patterns could be analyzed. In the image, the Spiricon camera color-codes the beam intensity, allowing the intensity distribution to be analyzed. Short-term stability tests (less than 10min) were also run on each configuration with no active stabilization system so natural stability could be compared.

III. RESULTS

A. Optimal Configuration of Stabilization Systems

It was found that placing both sensors after both actuators gave significantly better results than placing a sensor after each actuator. The data showed that the system with a sensor after each actuator was unable to maintain a stable beam, had a huge range of tolerance before correcting the beam, and once correcting the beam, would overshoot the original position. (FIG. 6) This is most likely due to the systems being programmed to use both mirrors at the same time to correct the beam. The system could not adjust to control the image on sensor one by only moving actuator one and then proceeding to correct the image on sensor two with actuator two.

Once satisfied with the positioning of the sensors relative to the actuators, the position of the actuators was evaluated. The results concluded that placing an actuator at both ends of the 22m portion of the transport line allowed for the most stable beam compared to placing the actuators near the target, but only slightly.

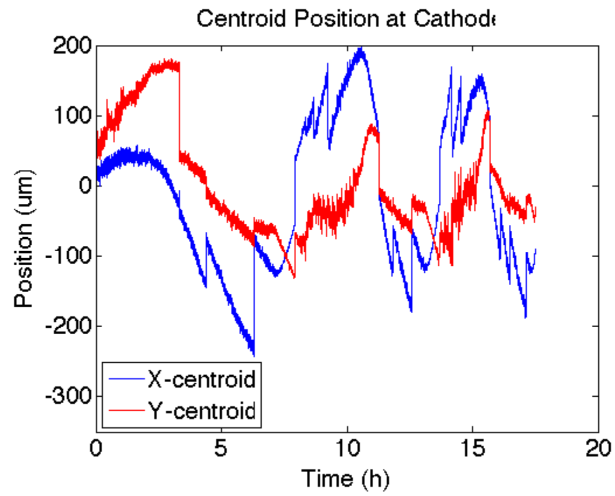

FIG. 6. X and Y centroid positions recorded over a period of 15+ hours with sensor one placed directly after actuator one and sensor two placed after actuator two.

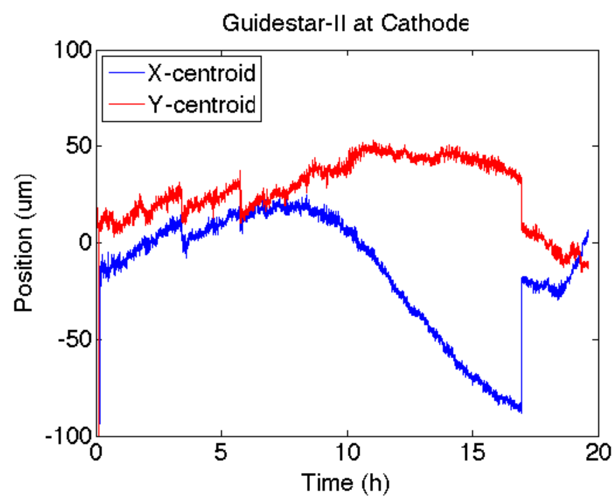

FIG. 7. Centroid position of the beam at the cathode stabilized by the Guidestar-II system for 15+ hours

B. Evaluation of Stabilization Systems

With the optimal configuration for the actuators and sensors known, the two systems could be compared side by side. In its best performance, when tested over fifteen hours, Guidestar-II kept the beam stable over approximately 70-110um. (FIG. 7) During short periods of time, Guidestar-II kept the beam stable between 10-20um, but was more susceptible to drift. Although the 10-20um short-term range is a very good range, the drift is very concerning, particularly the lack of an established tolerance range. In other words, sometimes the system will correct after the beam drifts 20um, but other times it will not correct until 80um or more. There does not appear to be any established limit where the Guidestar-II system will definitely correct the beam.

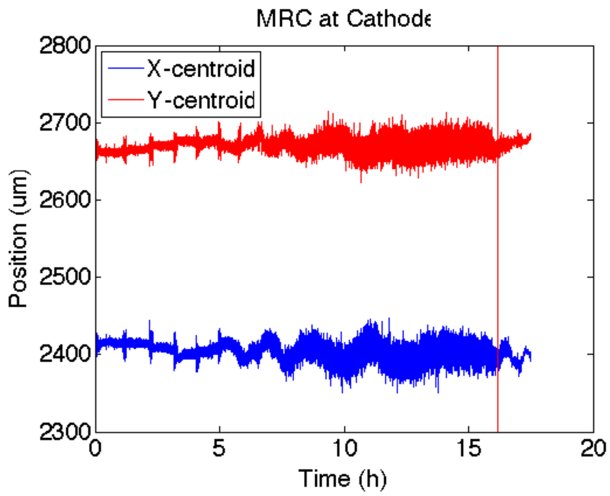

FIG. 8. Centroid position of the beam at the cathode stabilized by the MRC system for 15+ hours

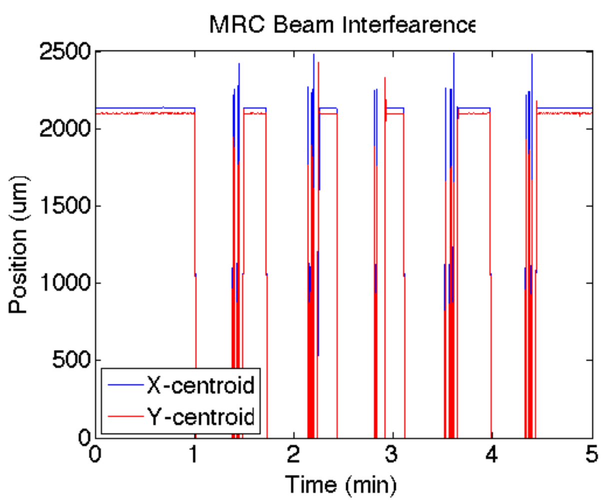

FIG. 9. Centroid position of the beam stabilized by the MRC system through beam interference

When tested over the same period of time, the MRC system had a range of approximately 90-100um. (FIG. 8) Unlike the Guidestar-II, the MRC system kept the beam stable over a larger range in the short-term, 30-50um, but was much less susceptible to drift. The concern with this is that although the beam is not drifting as much, the system appears to be constantly adjusting the beam over this 30-50um tolerance. This can be imagined as the beam vibrating within this range on the cathode and therefore never truly stabilizing the beam. The MRC system did prove to be able to stabilize the beam through interference, contrary to previous predictions. (FIG. 9)

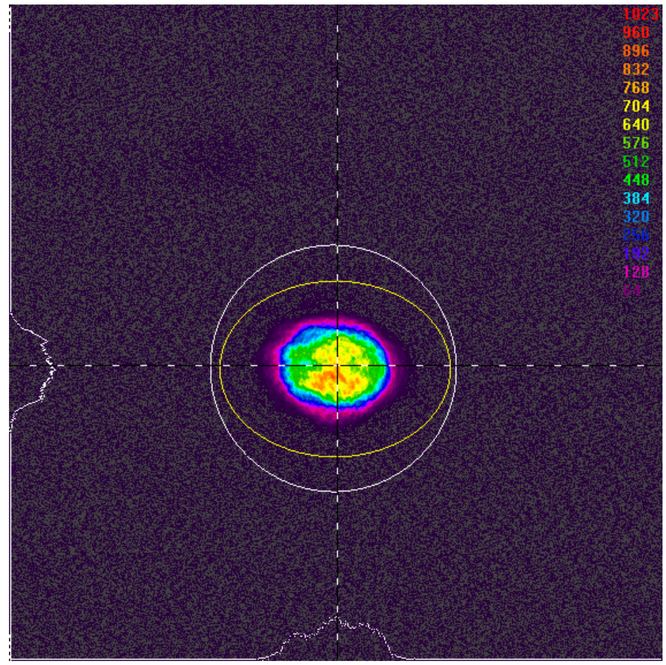

FIG. 10. Image of the beam size and intensity distribution at the cathode using the two-box configuration with a 5mm iris

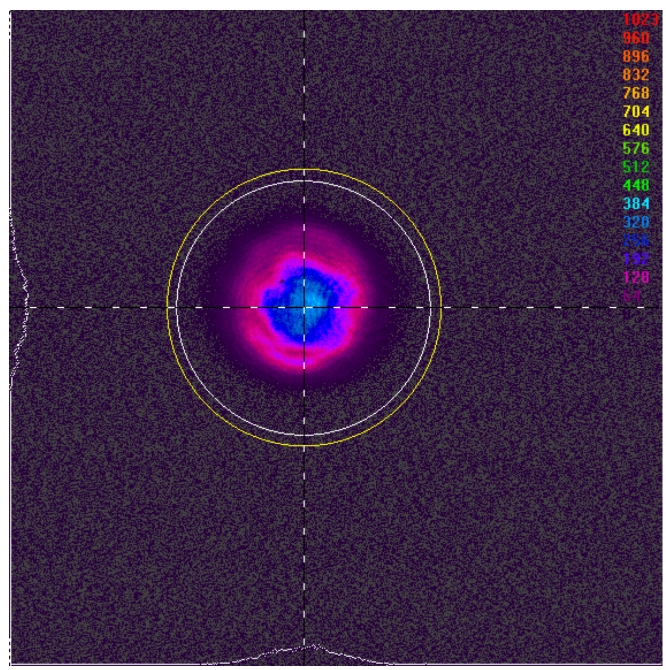

FIG. 11. Image of the beam size and intensity distribution at the cathode using the four-box configuration with a 2mm iris

C. Evaluation of Optical Configurations

Both optical configurations were within an acceptable tolerance of their expected magnification. The two-box system has an expected magnification of 6.7:1 and an actual magnification of 6.8:1. The four-box system has an expected magnification of 2.1:1 and an actual magnification of 2:1. The two-box system was slightly more stable than the four-box system; 55um range compared to 70um range. This is most likely due to the extra length (approximately 5000mm) the beam has to travel in the four-box system. Both images were also relatively well-defined and had minimal diffraction rings. What sets the two configurations apart is the intensity distribution. The two-box system had a Gaussian distribution (FIG. 10) while the four-box system had a significantly flatter intensity distribution. (FIG. 11)

IV. DISCUSSION AND CONCLUSION

The optimal configuration of the stability system was found to be both sensors after both the piezo actuators and to separate the piezo actuators by as much distance as possible. Both the Guidestar-II and MRC stabilization systems have similar stability ranges over extended periods of time. The Guidestar-II is able to keep the beam more stable than the MRC system in the short-term, but is more susceptible to drift. The concern with Guidestar-II is that there does not appear to be an established tolerance that the beam can drift before the system will correct itself. The concern with the MRC system is that the image is never truly stable because the beam is held in a higher range during the short-term.

A possible solution to these problems is to use both systems at the same time. If the MRC system is used to stabilize the beam over the 22m part of the beamline, it will stabilize the beam to the iris within the 30-50um ranges in the short-term. This will create a smaller range than that of the Guidestar-II systems long-term range, eliminating the issue of an undefined range before the system does a correction. The Guidestar-II would then stabilize the beam from the iris to the cathode in the 10-20um ranges, resolving the MRC systems issue of vibrating the beam within the 30-50um ranges. This idea is currently being set up and testing will follow.

The four-box optical configuration was found to be a better system than the two-box configuration. Although the two-box system was slightly more stable, the intensity distribution of the four-box system was significantly flatter than that of the two-box system. Because both systems fell within their magnification range, the intensity distribution was the deciding factor. Furthermore, the four-box option has the advantage of stabilizing the beam to the iris and possibly from the iris to the cathode if both systems are used together.

V. ACKNOWLEDGMENT

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VI. CITATIONS AND REFERENCES

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Guidestar-II QuickStart Manuel and System Specifications

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