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# POINTING STABILIZATION ALGORITHMS EXPLORED AND IMPLEMENTED WITH THE LOW ENERGY RHIC ELECTRON COOLING LASER*

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*Abstract*

The electron beam for the Low Energy RHIC electron Cooler (LEReC) at Brookhaven National Laboratory (BNL) is generated by a high-power fiber laser illuminating a photocathode, with a total propagation distance of 34 m separating the laser output and the photocathode. This propagation is facilitated by three independent laser tables that have varying responses to changes in time of day, weather, and season. Alignment drifts induced by these environmental changes are mitigated by an active "slow" pointing stabilization system found along the length of the transport, and this in-house system was commissioned as part of the full laser transport in 2019, as previously reported. In 2020, the system became fully operational alongside LEReC, the world's first electron cooler in a collider, and helped establish the transverse stability of the electron beam required for cooling. A summary of the different slow stabilization algorithms, which were continually refined during the run in order to achieve long-term center-of-mass stability of the laser spot on the photocathode to within 10 µm RMS, is provided.


## INTRODUCTION

The Low Energy RHIC electron Cooler (LEReC) is the first electron cooler using RF-accelerated bunched electron beams. It was successfully commissioned in 2018 [1], first demonstrated Au ion cooling in the Relativistic Heavy Ion Collider (RHIC) in 2019 [2, 3], and subsequently became part of RHIC Operations in 2020 [4, 5] and 2021 [5], facilitating the completion of RHIC's Beam Energy Scan II program at low energies.

In achieving stable cooling operations, LEReC overcame many engineering challenges. Some of these challenges were addressed with active feedbacks [5]. Among these feedbacks were the active pointing stabilization systems of the laser beam illuminating the photocathode and thus generating the electron beam. The physical arrangement, performance specifications, design motivations, and controls system architecture of the so-called "slow" active pointing stabilization system are described in Ref. [6] and incorporated herein. The purpose of this paper is to elaborate on the scripts controlling this slow feedback system, as the scripts continued to evolve over the course of 2020 Operations without modifications to the installation or infrastructure.

## SCRIPT COMPONENTS AND DESIGN CONSIDERATIONS

As stated in Ref. [6], LEReC's slow laser trajectory stabilization system was created in-house, with automation and stabilization being performed by a MATLAB script. This flexible approach meant that the system could be adapted at the script level, without the need to disrupt operations to gain access to the RHIC tunnel. In general, all versions of the script controlling the system had the following components in common:

1. Iteration delay. This delay ensured that the system's bandwidth addressed only slow drift behavior, allowing high-frequency fluctuations to pass through. Its duration ranged from 1.5 secs to 5 secs and depended on camera settings, location of control (see no. 6 below), and the programming block that was being executed.
2. Exception handling. This facilitated continuous monitoring by the system, with no need for operator input in activating/deactivating the stabilization engine. Examples included closed-shutter conditions (no-beam exception), unusual fast behavior (typically associated with operator alignment, but may indicate laser issues or mechanical slippage in the transport), device communication errors, and stale data. The result was seamless 24/7 operations.
3. Dynamic camera setting. This was required for some exceptional handling capabilities (e.g., the no-beam exception) and was also used for image quality control in the stabilization analysis. It was paired with variable neutral-density filters in front of the cameras in order to extend dynamic range.
4. Stabilization analysis. This encompassed any process that was used to generate numeric data to which trip thresholds could be compared for stabilization decision-making. Most modifications to LEReC's scripts during 2020 Operations involved this component, and these are described in more detail in the next section.
5. Corrective action. To mitigate false corrections, a maximum position deviation (trip) threshold needed to be exceeded twice consecutively before the system adjusted the alignment. Trip thresholds sometimes differed between the axes, and the axes in general were treated independently. In all versions of the script, a simple difference calculation sufficed for comparing current position values and trip thresholds. The threshold values were determined experimentally. Once the conditions for a correction had been met, the script would send a single 5-mV adjustment to the appropriate piezo actuator by either adding or subtracting 5 mV from the current piezo voltage setpoint. PID-type control was not used in order to eliminate the possibility of moving the laser beam by more than a tolerated amount on the photocathode during each iteration, as explained in Ref. [6]. Exception handling also existed to ensure that this amount was not accidentally exceeded as a result of device read errors.

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6. Serial but independent correction. Physically, the system comprised an upstream (farthest from the photocathode) piezo-actuated mirror and a downstream (closest to the photocathode) piezo-actuated mirror for both angle and position stabilization of the laser beam on the photocathode. Each steering mirror was controlled by a script running independently of the other script, with one exception: the upstream script could only engage its stabilization engine if the downstream script had confirmed, via a heartbeat timestamp, that it was active. Interference was eliminated by ensuring that the scripts ran on different bandwidths. Specifically, the downstream script ran at least twice as fast (via a shorter iteration delay) than the upstream script, ensuring that it would have time to react to any upstream adjustment.

Figure 1 shows a schematic representation of these script components in terms of scope. For example, exception handling for full automation was needed at all levels of analysis and device communication, whereas corrective action was only taken in the deepest parts of script—after all outer checks had been cleared. Hence, the exception handling loop is shown encompassing more elements than the corrective action loop.

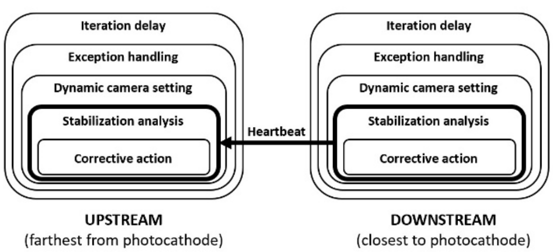


Figure 1: Schematic representation of script components in terms of scope, showing downstream-upstream precedence. The two scripts were otherwise independent and could differ in their details.

## STABILIZATION ANALYSES

The following subsections outline the development of the stabilization analysis component of LEReC's slow feedback script. "Local" refers to analysis performed on images taken by the slow stabilization system's dedicated camera network, whereas "external" refers to any analysis performed outside the system's scope.

### *Local Connected Component Analysis Using Steady-State Stabilization*

Due to the highly structured laser beam intensity profile at the time, the original slow feedback script used connected component analysis and aligned reference frames [6]. A Gaussian filter was first applied to the image in order to remove noise, and then the centroid locations of a set number of connected components were calculated. For the latter step, the binary 8-connected component analysis available in MATLAB's image processing library was extended to grayscale by binning image pixel values to produce an array of binary masks that were then averaged.

The centroid locations were compared frame by frame and their differences averaged to yield a single relative pixel displacement value in the horizontal and vertical directions. A frame was tagged as the aligned frame when the frame-to-frame variation remained below a certain threshold for an acceptable number of consecutive frames (the system's steady-state condition). Once an aligned frame was established, subsequent frames were compared to the aligned frame, and trip threshold monitoring began. The script could then enter the corrective action code block as needed.

Although this algorithm showed good results initially [6] and was thus used for the first few weeks of 2020 Operations, excessive structural changes in the laser beam intensity profile began degrading the system's stabilization performance by resetting the aligned reference image too frequently. The reference image was therefore fixed in the next version of the script.

### *Local Connected Component Analysis Using Stored Aligned Images*

This version of the script replaced the steady-state aligned image with a stored aligned image intended to mitigate issues with the drifting reference. The switch to a supplied reference also allowed the possibility of self-alignment by the system for the first time. However, before this functionality could be fully realized, the structural changes in the laser beam intensity profile worsened to the point of warranting a thorough investigation of the laser. The problem was eventually traced to multimode operation in the main amplifier, and the main amplifier was consequently realigned.

### *Local Center-of-Mass*

Following the realignment of the main amplifier, the laser beam intensity profile became more stable and Gaussian in shape. A center-of-mass (CoM) position analysis therefore became appropriate. Furthermore, a target CoM position could be supplied for stabilization. However, as the script development progressed, an issue regarding position mapping became apparent. Namely, the slow stabilization camera imaged the laser beam before the aperture that performed final spatial filtering, whereas the Operations camera imaged the laser beam after the aperture. Since the alignment onto these two sensors could drift and differ, regular recalibration would be required for the position target to remain valid. While this process could be automated, it was disruptive and conflicted with the general design principle of seamless operation.

Since normal operations involved stable CW laser beam conditions, the decision was made to use CoM data generated by the Operations cameras for the feedback mechanism, thereby circumventing the need to perform position mapping or reinstall the slow stabilization camera in a post-aperture location. Laser conditions outside this regime (e.g., pulsed) would require user intervention to reestablish acceptable feedback signals, but this was rare.

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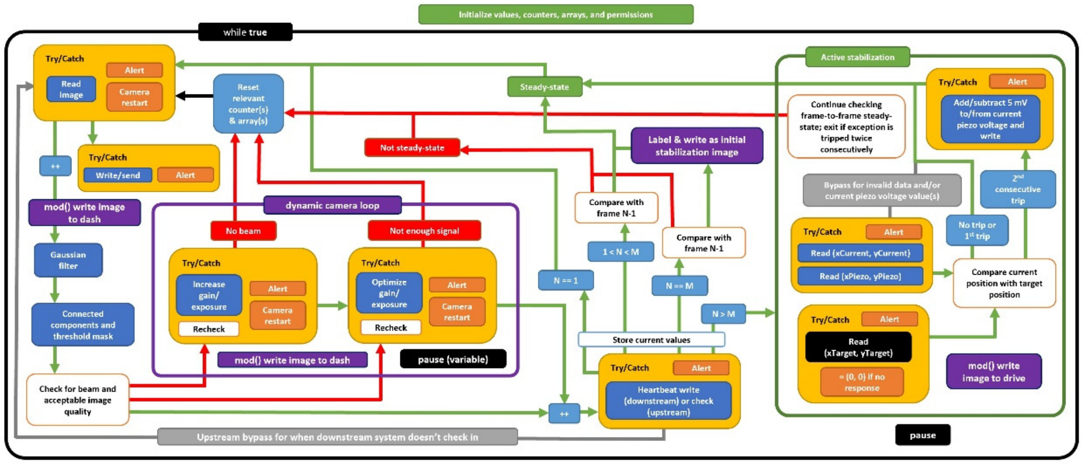


Figure 2: Flow diagram of final script, showing main components.

### *Arbitrary External Closed-Loop Feedback*

At this stage, the slow feedback algorithm was modified to accept as input CoM position values generated by the application responsible for logging LEReC's laser beam position on the photocathode. In other words, it was implemented in standard closed-loop form. Such external CoM data therefore represents any numeric data, regardless of calculation method, with which a closed loop can be formed using calibrated trip thresholds. Hence, this version of the script is called arbitrary external closed-loop feedback. Note that this generalization also means that the script can be extended to any set of metrics (i.e., arrayed data).

A target position was also accepted as input by the script in order to perform self-alignment. This final, closed-loop, self-aligning slow laser trajectory stabilization system was released to LEReC Operations on March 4, 2020, and was used for the remainder of the 2020 Run, as well as for the entire 2021 Run.

## FINAL SCRIPT AND SAMPLE DATA

Figure 2 shows a flow diagram of the final script. Local connected component analysis was retained for steady-state determination and other diagnostic information due to its greater sensitivity. However, as stated, the active stabilization engine was generalized to closed-loop form and for user target input. Remaining nodes are dedicated to programming flow, exception handling, and device/data communication.

The plots in Fig. 3 show the results that can be achieved when this slow stabilization system is implemented and properly calibrated.

## CONCLUSION

This paper summarized the algorithm development of LEReC's very successful slow laser trajectory stabilization system. However, it also detailed a flexible stabilization approach wherein components may be customized or omitted accordingly for rapid deployment. For example, a second system has already been implemented in the Coherent electron Cooler laser transport at BNL, accommodating much different laser and instrumentation characteristics, with similar results.

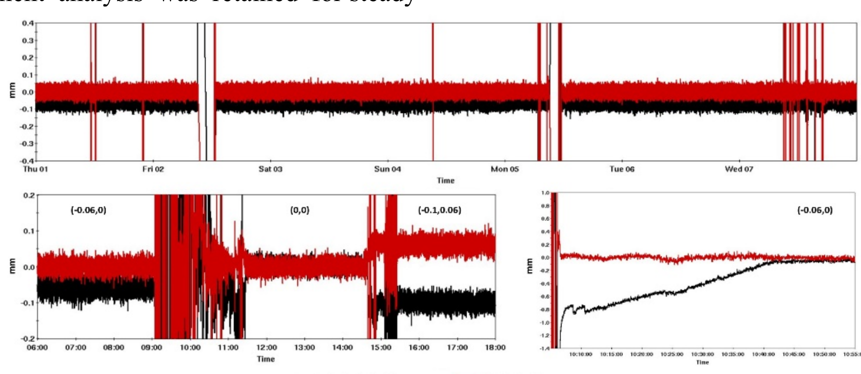


Figure 3: Performance of the final slow stabilization script. The top plot shows a one-week period of Operations (out-of-range data represents a closed laser shutter). The bottom left plot shows the system's response to different target positions; the bottom right plot shows the system's self-alignment in greater detail. Fundamental to the system's functionality was its ability to provide long-term stabilization despite persistent fast fluctuations and to immediately cope with no-beam conditions via self-activation and self-deactivation.

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