ACTIVE POINTING STABILIZATION TECHNIQUES APPLIED TO THE LOW ENERGY RHIC ELECTRON COOLING LASER TRANSPORT AT BNL*

L.K. Nguyen†, A. Curcio, W. Eisele, A.V. Fedotov, A. Fernando, W. Fischer, P. Inacker, J. Jamilkowski, D. Kayran, K. Kulmatycski, D. Lehn, T. Miller, M. Minty, A. Sukhanov, Brookhaven National Laboratory, Upton, NY, USA

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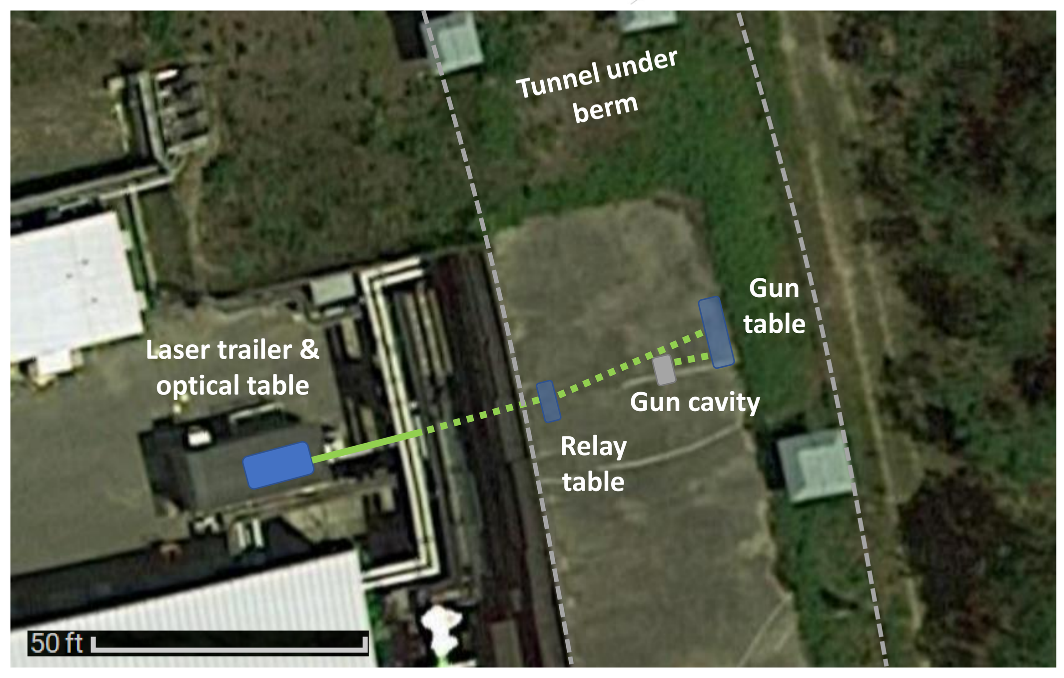
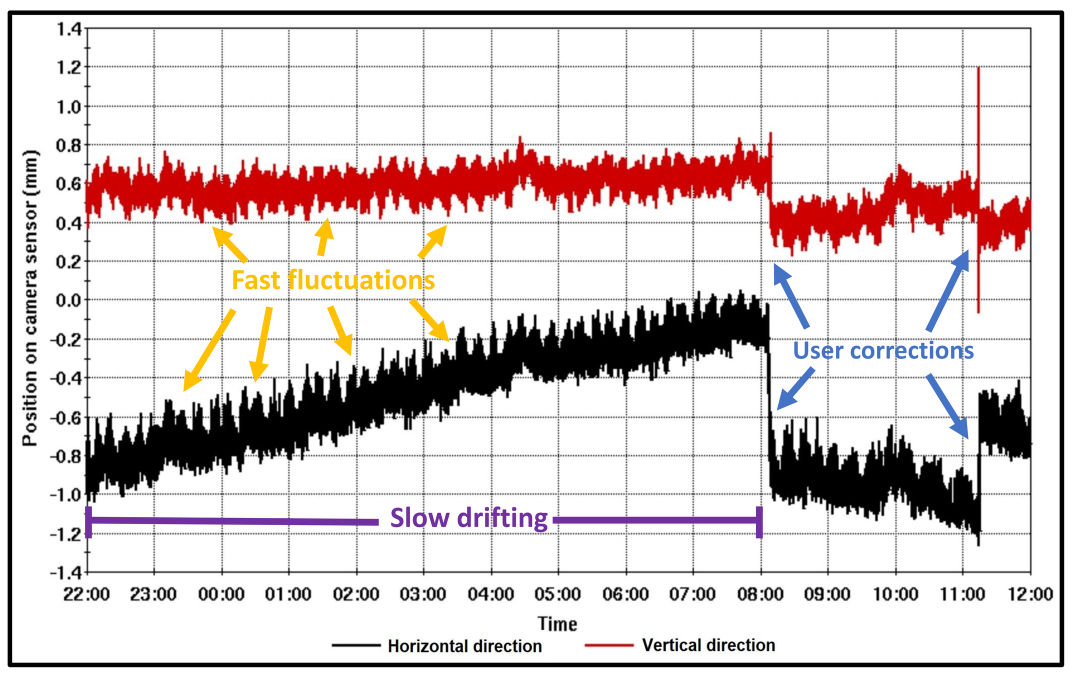
ABSTRACT

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. The pointing stability of the electron beam, which is crucial given its long transport, is highly dependent on the center-of-mass (CoM) stability of the laser spot on the photocathode. For reasons of accessibility during operations, the laser is located outside the accelerator tunnel, and the laser beam is propagated over a total distance of 34 m via three laser tables to the photocathode. The challenges to achieving the required CoM stability of 10 µm RMS on the photocathode include mitigation of the effects of vibrations along the transport and of weather- and season-related environmental effects, while preserving accessibility and diagnostic capabilities. Due to the insufficiency of infrastructure alone in overcoming these challenges, two active laser transport stabilization systems aimed at addressing specific types of position instability were installed during the 2018 Shutdown. After successful commissioning of the full transport in 2018/19, we report on our solutions to these design challenges.



Approximate layout of laser tables and transport



Without active stabilization

DESIGN MOTIVATIONS

In the absence of any active stabilization, the data from the 2018 Run consistently showed the presence of two types of unwanted CoM movement. The first type, herein referred to as "fast fluctuations", consists of shot-to-shot variations superimposed on a second type, herein referred to as "slow drifting", occurring over the course of hours. Investigations into the nature of these position variations determined that the fast fluctuations originate in the drive laser components and are compounded by the presence of air currents prior to the beam's injection into the transport, whereas the slow drifting arises from the weather- and season-related relative movement of the three laser tables composing the transport. The above left figure shows the approximate layout of the laser tables, with the one housed in the laser trailer clearly outside the tunnel and subject to a different environment. The above right figure shows data collected towards the end of the 2018 Run as an example. Fast and slow mechanisms of pointing instability are clearly visible in the plot, as are two instances of user corrections. Such user corrections can cause excursions in the electron beam orbit that trip the machine protection system in high-current conditions, underlining the need for a continuous feedback mechanism in lieu of periodic user corrections.

APPROACH

Existing commercially available systems employing quadrant photodiode position detectors do not have the flexibility to provide the necessary exception handling for stabilizing the beam through the entire transport but can be used to address the fast fluctuations present in the laser before the beam transport. In order to address the slow drifting of the laser beam through the transport, an in-house solution was developed around the unique needs and infrastructure of LEReC and the RHIC complex.

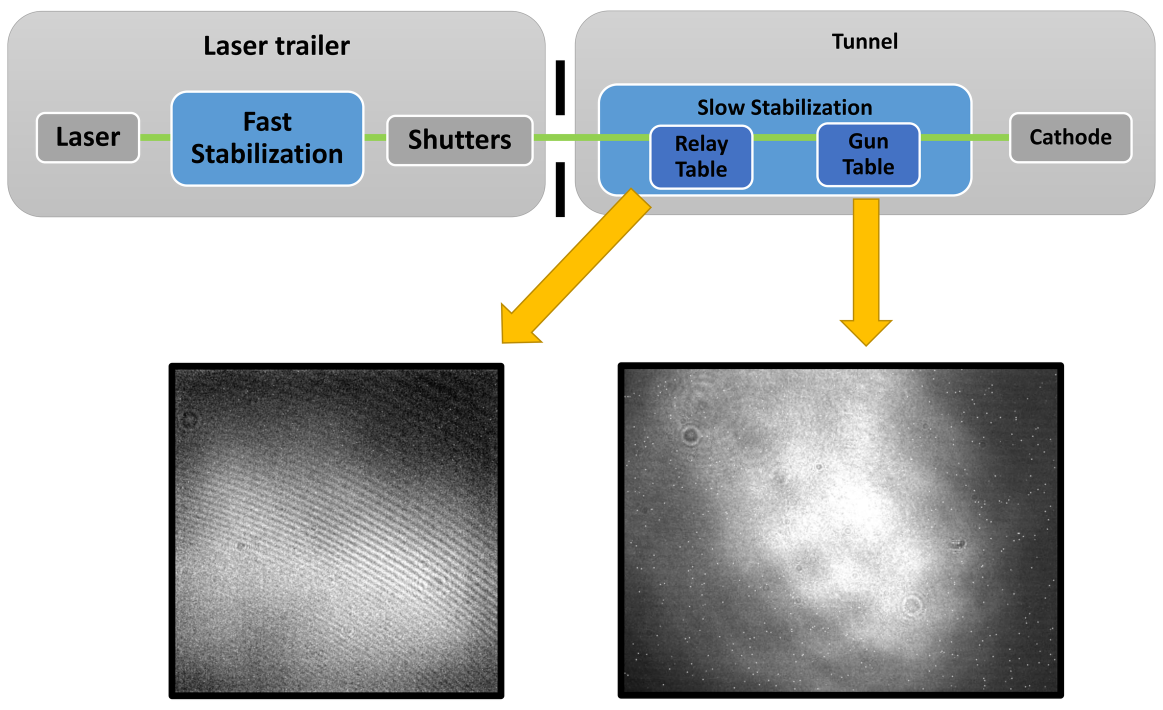
FAST STABILIZATION

- Uses a stock active laser beam stabilization system available from MRC Systems GmbH
- Stabilization section was inserted just before the laser transport, consisting of two serial detector-piezo mirror pairs
- Detector and actuated piezo mirror in each pair are separated by 1 m of free-space propagation and connected through a closed-loop controller
- Controller continuously adjusts the trajectory of the laser beam through the system to produce an output beam with fixed position and direction
- Offers up to 100 kHz of bandwidth and removes any fast fluctuations present in the incoming laser beam
- Use of leakage light with a limited dynamic range means setup can only provide stabilization while the laser is in CW mode
- Functionality in the manufacturer's controller enables the remote activation and de-activation of the system, allowing pulsed mode to be programmatically avoided

SLOW STABILIZATION

- No longer necessary to sacrifice dynamic range and programming flexibility for speed in this regime
- A separate set of actuated mirrors that could not respond to user commands in the event of mis-steering would have introduced exceptional risk when placed in the accelerator tunnel, so a system in which slow stabilization could be performed using the same steering mirrors as those used by operators to control the laser trajectory was sought
- Feedback response times on the order of seconds are also acceptable for the correction of slow drifting
- Thus, a slow, camera-based stabilization system using the idea of aligned reference frames was developed
- By automatically adjusting camera settings and using flip filters, the system can achieve a dynamic range that allows the feedback to be active across all operating modes without user input

Conceptual layout of active stabilization techniques for LEReC



Example of laser beam profile on the relay table (left) and gun table (right) for the same beam through the transport in pulsed mode. The slow stabilization system was designed to handle both the relay table's large, diffuse beam and the gun table's highly structured beam with pulsed-to-CW dynamic range.

CAMERA-BASED STABILIZATION AND SLOW-FEEDBACK ALGORITHM

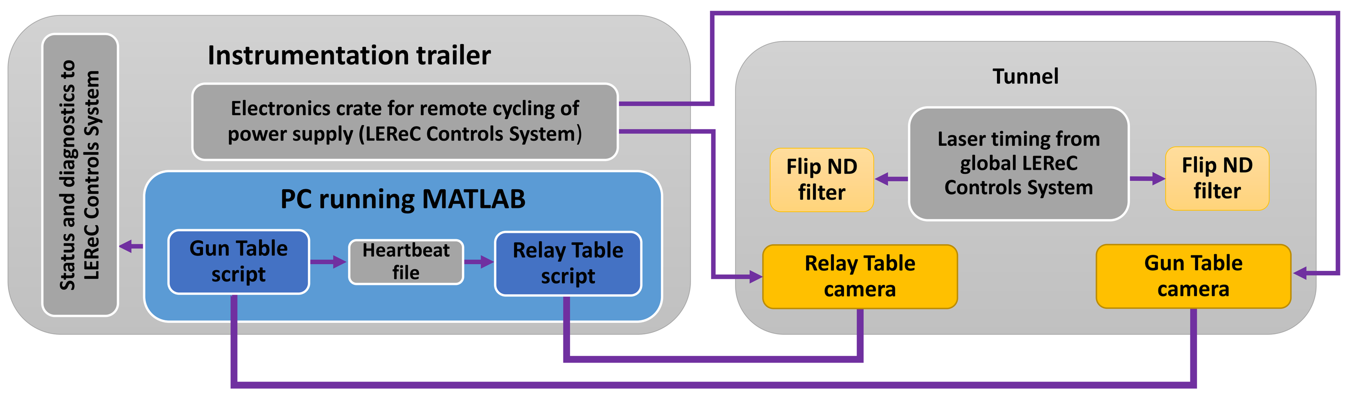
New hardware installation in the tunnel was limited to two new cameras and flip filters along the transport, fixing both position and angle. See the lower right figure for the main connections and lines of communication. Triggering and camera settings are divorced from those used in the controls system (and hence by the operational cameras), enabling programmatic camera control (the so-called "dynamic camera loop") for exception handling and ensuring image quality. The use of flip filters expands the dynamic range of the cameras. Failsafe mode for the flip filters is set to "in" so that stabilization in CW mode remains possible in the event of device failure.

Two nearly identical MATLAB scripts run in parallel. Exception handling loops and procedures mean the scripts run continuously without user input. The relay table stabilization system differs from the gun table stabilization system in its calibration values and the use of a heartbeat READ in place of the gun table's heartbeat WRITE. Gun table stabilization must be active for relay table stabilization to become active. Other than this communication, the two systems run independently. A simplified flow diagram for the gun table stabilization system is shown below.

The core of the slow feedback algorithm relies on connected component analysis in grayscale and the determination of aligned reference frames. Connected component centroids are compared and their displacements averaged to yield a single relative pixel displacement value in the horizontal and vertical directions, which are treated independently. A frame is tagged as the aligned frame when the frame-to-frame variation remains below a certain threshold for an acceptable number of consecutive frames (the system's steady-state condition). Once an aligned frame is established, subsequent frames are compared to the aligned reference frame. When the difference exceeds a threshold for correction twice consecutively (to mitigate false corrections), an adjustment is sent to the appropriate axis by either adding or subtracting 5 mV from the current piezo voltage setpoint. A fixed pause is also included in every iteration of the stabilization loop, representing a minimum delay. In order to give the gun table stabilization system enough time to react to a correction made upstream by the relay table stabilization system, the latter has a longer delay.

If a user actively changes the alignment through the transport, the difference calculation will trigger the release of the aligned frame. As an additional measure for giving precedence to user control, before sending a new command, the stabilization loop compares the current piezo voltage setpoint to the last correction sent by the feedback in the current alignment and enters user alignment mode if the values do not agree. The feedback then awaits a new steady-state condition.

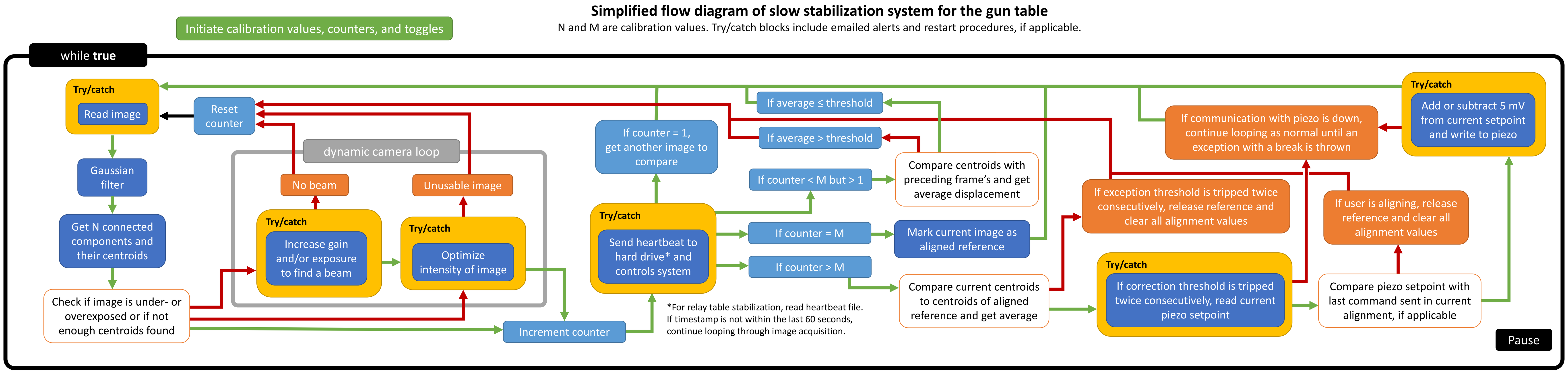
The "no beam" exception is thrown only after the dynamic camera loop has been given a chance to increase the camera's gain and exposure time to set maximum limits, lest changes in power level or laser mode rendered the current camera settings obsolete. While in the dynamic camera loop, no commands are sent, which immediately halts stabilization after a shutter closes.



Conceptual layout of the slow stabilization system communication. Cameras are on a local network, with one-way communication to the network Controls System for diagnostics data.

Simplified flow diagram of slow stabilization system for the gun table

N and M are calibration values. Try/catch blocks include emailed alerts and restart procedures, if applicable.

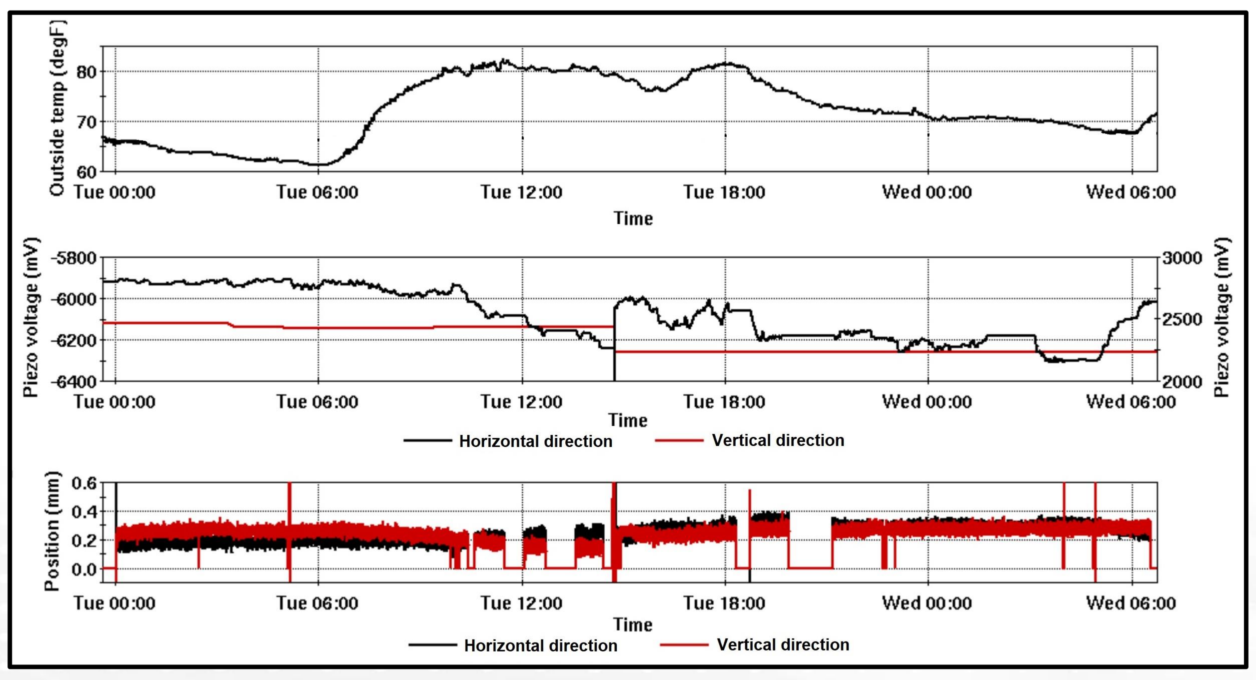


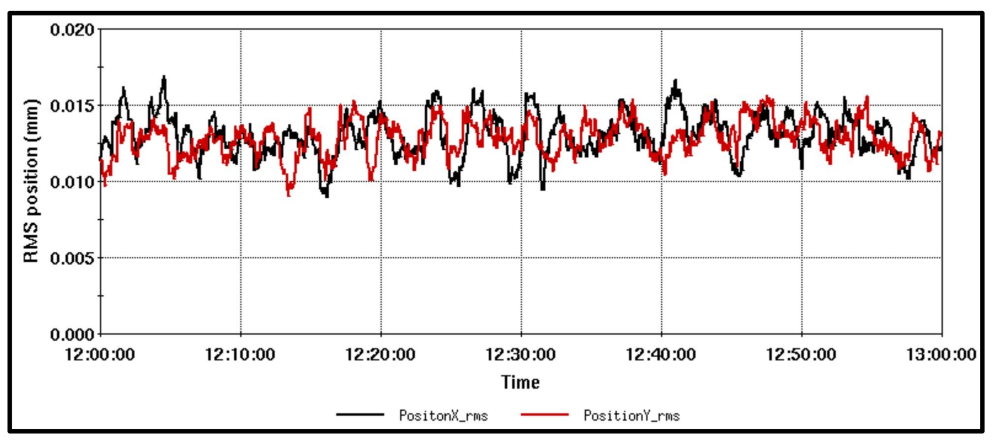
Results from proof-of-concept testing with an alignment laser using a 70-meter long transport, when scaled to the LEReC laser transport (which was unavailable at the time), predicted theoretical stabilization down to 50 µm peak-to-peak.

RESULTS FROM OPERATIONS

As anticipated, the slow active stabilization system was available in all laser modes during the 2019 Run. The figure to the right shows a 30-hour period near the end of the run, in which LEReC was operating the laser in pulsed mode. As in the figure nearest right, the theoretical limit of 50-micron peak-to-peak position variation for the slow stabilization system was occasionally achieved, but standard performance is considered 100 µm peak-to-peak due to the increased sensitivity to structural changes in the laser beam profile.

When available in CW mode, the activation of the fast stabilization system succeeded in providing rms position stability near 10 µm with optimized alignment. However, values between 15 and 20 µm were more typical.





After being implemented during the 2019 Run, the active pointing stabilization techniques outlined in this paper largely yielded the expected results and contributed to the LEReC project's success in achieving bunched beam cooling. Future efforts will focus on achieving consistency in both fast and slow stabilization systems as LEReC moves forward into sustained operations for RHIC Physics.

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