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

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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.

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] and subsequently demonstrated Au ion cooling in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in 2019 [2]. In the process, the LEReC project needed to overcome many engineering challenges, including the necessary transverse stability of the electron beam along the full 100 m of beam transport.

Although many factors contribute to the transverse stability of the electron beam, it was understood during the design phase that the laser beam illuminating the photocathode also needed to be adequately stable transversely in order for the resultant electron beam to behave efficaciously. As such, a limit of 10 μm rms position variation was placed on the center-of-mass (CoM) of the laser beam spot on the photocathode. For LEReC, the laser beam is generated by a high-power fiber laser located outside the accelerator tunnel for reasons of accessibility during operations [3,4]. The shaped laser beam is then steered over a total distance of 34 m down to the photocathode, and this optical path involves three independent laser tables. Initial laser and transport design focused on the passive stabilization of the transverse movement of the beam, known as its pointing stability, via structural methods [4]. However, the LEReC commissioning process demonstrated the need for active stabilization, as the cited passive stabilization methods proved to be insufficient for achieving the required pointing stability of 10 μm rms.

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DESIGN MOTIVATIONS

Data logged as part of the diagnostics system that monitors the LEReC laser transport tracks the beam's center-of-mass as it would appear on the photocathode [4]. 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 [4]. Figure 1 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.

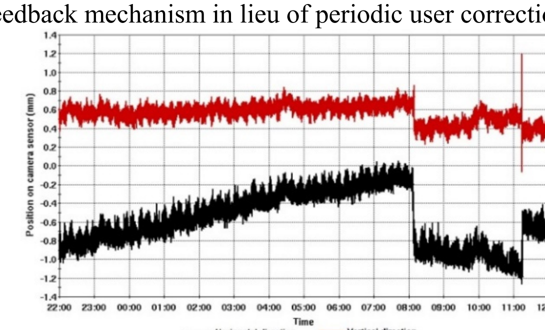

Figure 1: Example data of CoM laser position (horizontal position in black, vertical position in red) during operations without active pointing stabilization, showing fast fluctuations, slow drifting, and user corrections.

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In addition to significantly reducing these targeted instabilities, any potential design was evaluated against operational needs and conditions, the most important of which are: dynamic range (i.e., pulsed-to-CW response for both pulsed and CW electron beam generation [1]), exception handling, beam profile sensitivity, integration, and diagnostic capabilities.

APPROACH

As a first step, it was recognized that 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

Using a stock active laser beam stabilization system available from MRC Systems GmbH, a stabilization section was inserted just before the laser transport, consisting of two serial detector-piezo mirror pairs. The detector and actuated piezo mirror in each pair are separated by 1 m of free-space propagation and connected through a closed-loop controller. The controller continuously adjusts the trajectory of the laser beam through the system to produce an output beam with fixed position and angle. The output beam is then injected into the transport. This feedback system offers up to 100 kHz of bandwidth and removes any fast fluctuations present in the incoming laser beam.

Since the quadrant diodes operate on leakage light with a limited dynamic range, the installed setup can only provide stabilization while the laser is in CW mode. Otherwise, insufficient light is incident on the sensors. 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

While an in-house system for counteracting the slow drifting could have also been designed around quadrant diodes, it was no longer necessary to sacrifice dynamic range and programming flexibility for speed in this regime. Moreover, 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. Consequently, 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.

Based on this design premise and the fact that feedback response times on the order of seconds are acceptable for the correction of slow drifting, 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.

CAMERA-BASED STABILIZATION AND SLOW-FEEDBACK ALGORITHM

Since no new steering mirrors were required for the slow stabilization system, new hardware installation in the tunnel was limited to two new cameras and flip filters along the transport. As with the fast stabilization system, the use of two detectors fixes both position and angle.

The cameras are connected to a computer located outside the tunnel, forming a local network. Triggering and camera settings are therefore divorced from those used in the controls system and by the operational cameras. This isolation enables programmatic camera control (the so-called "dynamic camera loop", discussed in more detail below) for exception handling and ensuring image quality. The use of flip filters expands the dynamic range of the cameras and is controlled by the timing status of the laser. Failsafe mode for the flip filters is set to "in" so that stabilization in CW mode remains possible in the event of device failure.

Although connected to the same computer, the system stabilizing the laser beam trajectory to the second laser table (the "relay table system") and the system stabilizing the trajectory to the third laser table (the "gun table system") run independently of one another, with the exception that the gun table system must be active for the relay table system to become active. This communication is performed over the computer's hard drive.

To eliminate the possibility of large, sudden corrections that would trip the electron beam in high-current conditions, each adjustment of the piezo mirror voltage made by the slow feedback is limited to 5 mV, which is the minimum voltage change of the controlling electronics crate communicating with the piezo actuated steering mirrors. 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 (3 sec versus 1.5 sec). The two systems also differ in the values used in their dynamic camera loops and decision-making statements. These values constitute the calibration of a script.

The core of the slow stabilization system script, which is written in MATLAB, employs connected component analysis in grayscale and the determination of aligned reference frames. Simple center-of-mass movement and edge detection were also explored but ruled out due to limitations in handling both the large, diffuse beam on the relay table and the highly structured beam on the gun table. After an image clears the dynamic camera loop, a Gaussian filter is applied to the image to remove noise, and the centroid locations of a set number of connected components are calculated. These centroid locations are then compared between frames and their differences averaged to yield a single relative pixel displacement value

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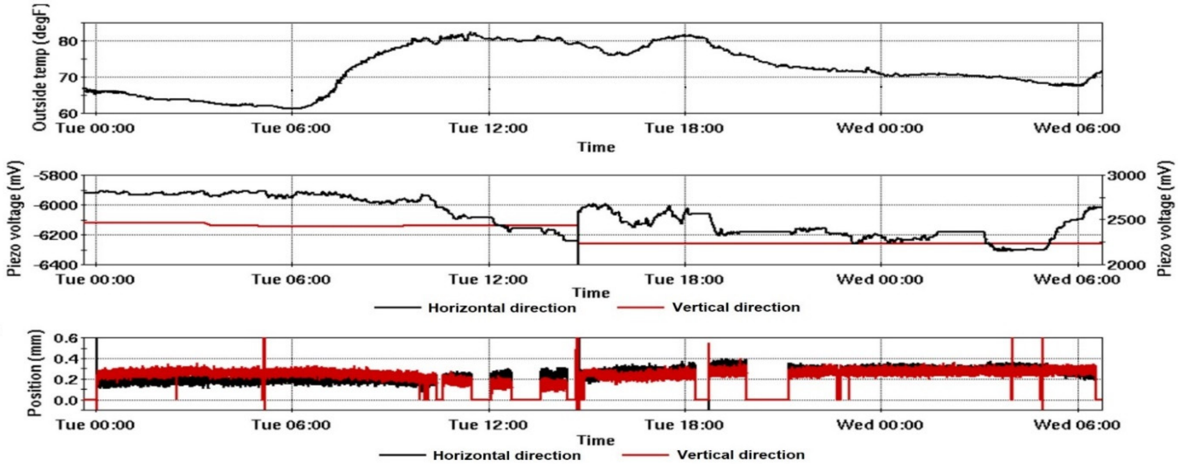

Figure 2: Example of pulsed operations during the 2019 Run with slow stabilization active. Top plot - outside temperature. Middle plot - piezo commands sent to steering mirrors (includes user commands). Bottom plot - beam position on camera sensor, which is logged as zero when there is no beam (e.g. closed shutter).

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 frame, rather than to the preceding 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.

If a user actively changes the alignment through the transport, the difference calculation will exceed an exception threshold twice consecutively, triggering a 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. If these values do not agree (as would be the case if a user had sent a new command), the script exits the stabilization loop and enters user alignment mode, wherein it awaits a new steady-state condition.

The dynamic camera loop can prevent images from proceeding to the stabilization loop by determining whether an image is underexposed or overexposed. The "no beam" exception is thrown only after the 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.

Procedures for rebooting cameras and handling network communication issues are also included in the script. Owing to these various procedures and loops, the slow stabilization scripts run continuously.

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. Figure 2 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, 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 (Fig. 3). However, values between 15 and 20 µm were more typical.

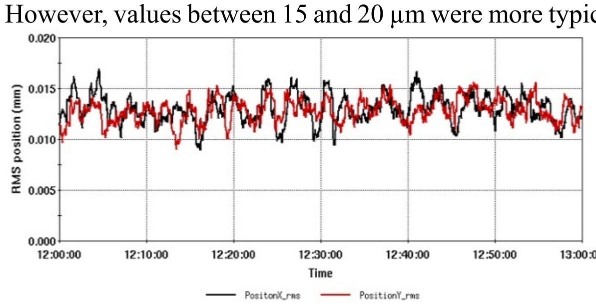

Figure 3: RMS CoM position with fast stabilization active.

SUMMARY AND NEXT STEPS

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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