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THE POINTING STABILIZATION ALGORITHM FOR THE COHERENT ELECTRON COOLING LASER TRANSPORT AT RHIC*

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Abstract

Coherent electron cooling (CeC) is a novel cooling technique being studied in the Relativistic Heavy Ion Collider (RHIC) as a candidate for strong hadron cooling in the Electron-Ion Collider (EIC). The electron beam used for cooling is generated by laser light illuminating a photocathode after that light has traveled approximately 40 m from the laser output. This propagation is facilitated by three independent optical tables that move relative to one another in response to changes in time of day, weather, and season. The alignment drifts induced by these environmental changes, if left uncorrected, eventually render the electron beam useless for cooling. They are therefore mitigated by an active "slow" pointing stabilization system found along the length of the transport, copied from the system that transversely stabilized the Low Energy RHIC electron Cooling (LEReC) laser beam during the 2020 and 2021 RHIC runs. However, the system-specific optical configuration and laser operating conditions of the CeC experiment required an adapted algorithm to address inadequate beam position data and achieve greater dynamic range. The resulting algorithm was successfully demonstrated during the 2022 run of the CeC experiment and will continue to stabilize the laser transport for the upcoming run. A summary of the algorithm is provided.

INTRODUCTION

The luminosity demands of future colliders and the prospect of more productive runs for existing ones have made investigations into novel cooling techniques increasingly important. At Brookhaven National Laboratory (BNL), site of the future Electron-Ion Collider (EIC), coherent electron cooling (CeC) is being experimentally studied in the Relativistic Heavy Ion Collider (RHIC) for strong hadron cooling in the EIC. Although CeC employs many proven technologies and processes, its successful implementation still involves the overcoming of many challenges [1]. As a result, the CeC experiment is accompanied by several novel systems.

Among these is the CeC laser beam trajectory stabilization system, also known as the pointing stabilization system or the (transverse) position stabilization system, found along the laser transport. This system was developed and installed to help meet the demanding requirements regarding alignment between the electron beam and the ion beam, as the electron beam is generated by laser light striking a photocathode [1]. Like the system monitoring and stabilizing the laser beam along the laser transport of the Low Energy RHIC electron Cooler (LEReC) [2, 3], the CeC version of the system is a "slow" feedback system controlled by two MATLAB scripts. However, several key differences with the LEReC scripts exist to address CeC's unique setup and laser operating conditions. Chief among these are the need for even greater dynamic range than the LEReC system, and the lack of adequate laser beam position data from the controls system for the purposes of the stabilization system.

ENVIRONMENT AND SETUP

In the description that follows, an "Operations camera" is a camera that is part of the Controls System used by operators of CeC; these cameras were installed during the construction/commissioning of the cooler itself and are on a common timing system with CeC instrumentation. "Stabilization camera", on the other hand, refers to a camera (there are two in all) that is on a local network with the computer running the pointing stabilization scripts. In terms of reliability, this means that Controls System downtime does not affect the monitoring capability of the slow position stabilization system. However, a network connection is needed to make changes to the voltages of the piezo steering mirrors.

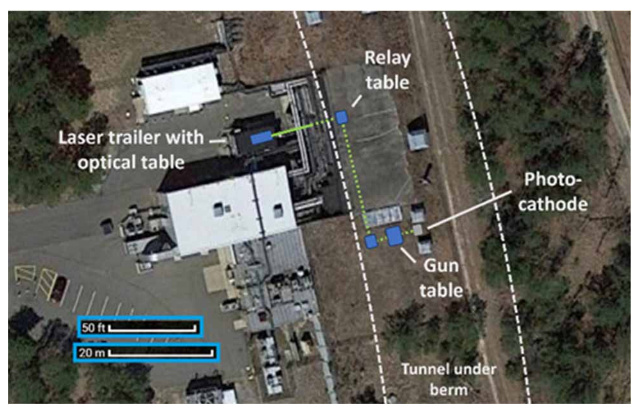

Figure 1: Aerial view of Interaction Region 2 (IR2) at RHIC, showing the approximate layout of the CeC laser transport.

Figure 1 shows an aerial view of the CeC laser transport. The laser beam is generated in the laser trailer, outside the RHIC tunnel. The first piezo steering mirror, controllable remotely in the Controls System, is located on an optical table here in the trailer. From the trailer, the laser beam travels through an evacuated pipe to reach the so-called relay table, just inside the tunnel. The first Operations camera and, slightly past it, the first stabilization camera is located here. Downstream of the cameras but still on the relay table is the second piezo steering mirror, also remotely controllable in the Controls System. After reflecting off this relay piezo mirror, the laser beam travels down another

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evacuated pipe to reach the gun table. The second operations camera and second stabilization camera are located here.

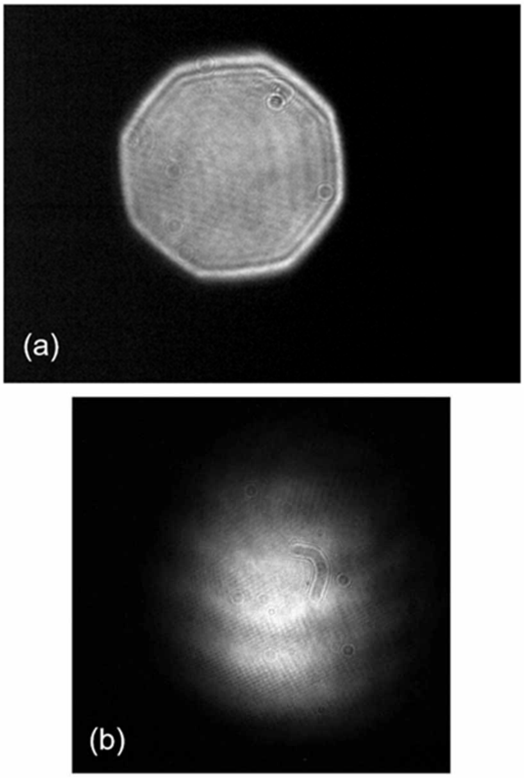

Figure 2: Laser beam as viewed by different cameras on the gun table. (a) Operations camera, which views the beam after expansion and spatial filtering by a variable aperture (iris). (b) Stabilization camera, which views the beam before expansion for better tracking information.

The beam then proceeds to the photocathode, at which point, it will have traveled approximately 40 m. Note that this is about 6 more meters of propagation distance than what the LEReC laser beam experiences [2], so the effect of the relative movement of the three optical tables (trailer, relay, gun) with changing temperature, humidity, and other environmental factors is generally more pronounced in the CeC system.

Although the beam profile at the relay table looks essentially identical on both the Operations camera and the stabilization camera, this is not the case at the gun table. Because a uniform intensity distribution is sought in the laser light illuminating the photocathode, the laser beam is greatly expanded and then passed through a variable aperture (iris) at the gun table, and the gun table Operations camera sees the laser beam as it would appear on the surface of the photocathode. See Fig. 2(a) for an example. This uniformity masks the movement of the beam behind the aperture, as the aperture fixes the center of mass (CoM) in this case. It is not until the beam has become significantly misaligned that the calculated CoM begins to reflect movement of the beam itself, at which point, it is already unacceptably out of specification. Even at the relay table where the beam is smaller and CoM data from the Operations camera would be valid, lack of dynamic range still necessitates reliance on the stabilization camera. Thus, unlike the LEReC scripts [3], the CeC scripts do not query CoM data generated by the Operations cameras for use in the feedback. Instead, they perform their own CoM calculation on the images captured by the stabilization cameras for tracking. Importantly, the gun table stabilization camera samples the laser beam prior to enlargement for this purpose. Figure 2(b) is the image that appears on the gun table stabilization camera when the image on the gun table Operations camera is 2(a).

Unlike the Operations cameras, the stabilization cameras are both accompanied by a flip mount that can insert or retract an attenuating neutral-density filter. The position is controlled by the scripts based on laser operating conditions (i.e., low power versus high power). This is one of the methods by which the stabilization cameras have much greater dynamic range than the Operations cameras. The other method is their ability to dynamically change trigger sources and expose images for much longer than 1 second, which is the limit of the Operations cameras owing to the 1-Hertz Controls System timing trigger. More details about this flexibility are provided in the next section.

The controls system architecture largely follows that of the LEReC slow position stabilization system, which was installed and commissioned first [2]. The LEReC scripts also served as the template for the CeC scripts, and Ref. [3] should be consulted regarding the shared design motivations and automation paradigm.

SCRIPT

As in Ref. [3], the scripts are written in MATLAB. One script creates a feedback loop between the trailer piezo mirror and the relay table stabilization camera (together called the relay, or upstream, system); another creates a feedback loop between the relay table piezo mirror and the gun table stabilization camera (together called the gun, or downstream, system). The systems operate independently but on different bandwidths so as not to interfere with each other. The essential aspect to this is that the gun system is configured to be at least twice as fast as the relay system. Moreover, the gun system, which is closest to the photocathode, is given precedence, such that the relay system is suppressed if the gun system is not actively stabilizing.

Figure 3 shows the programming flow for both scripts; differences between the relay system script and the gun table system script are related to the establishment of precedence as described above.

Starting in the upper left, an image is read in, with exception handling encapsulating any camera errors. The words “mod() write” at various locations in the loop indicate that only certain iterations perform the stated action. Among these is the writing of the captured image to the so-called dash. The dash is an internet-based viewer for the stabilization system cameras, which are on a local network and therefore not otherwise viewable unless the images are published to another application. The dash confirms the performance of the stabilization systems to the outside world and acts as backup diagnostics in the event that the

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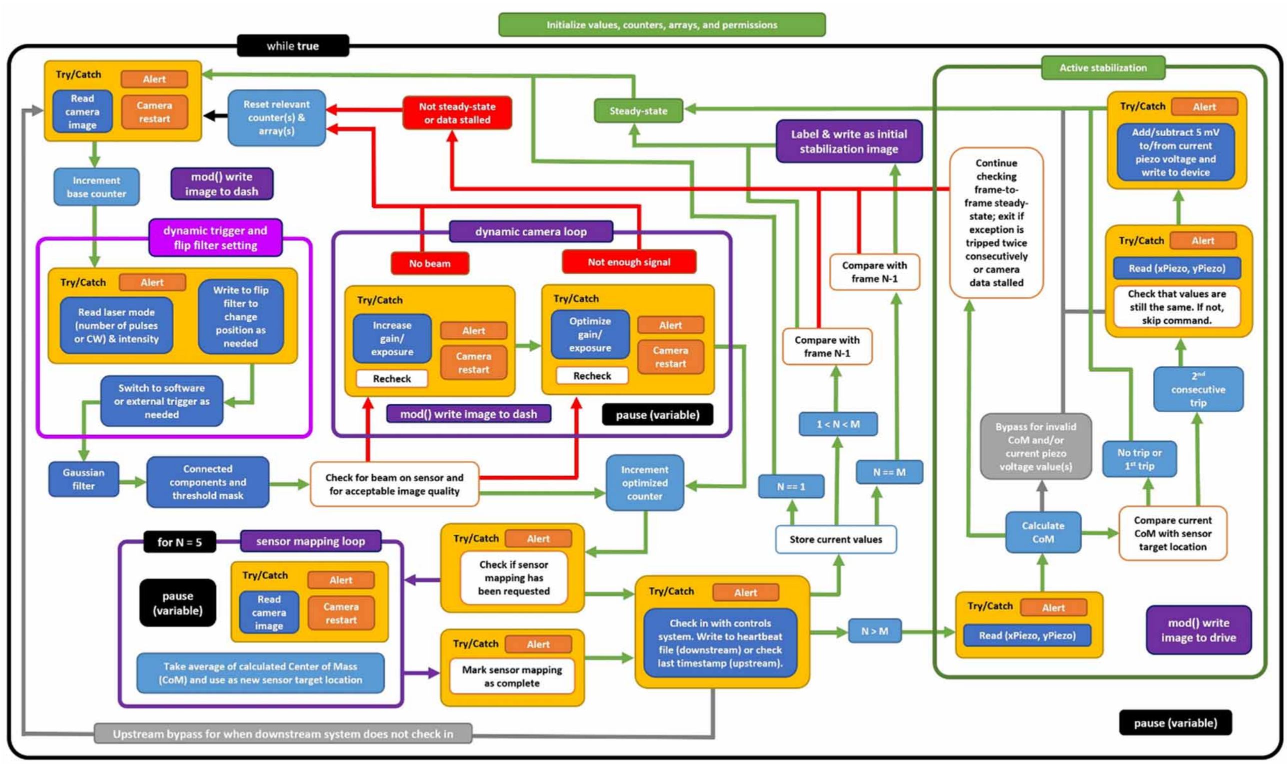

Figure 3: Flowchart for relay and gun system scripts (differences noted where appropriate).

operations cameras are down. In fact, there have been times when CeC has been able to operate despite losing its main laser transport diagnostics because the stabilization cameras and scripts continued to operate locally.

After an image is successfully captured, the script enters the dynamic trigger and flip filter block, wherein the script reads the current power setting and timing mode of the laser and determines which trigger source to use (external or software) and which position the flip filter should be in. This block constitutes an upgrade over the LEReC scripts, which are restricted to using software trigger and have their flip filter position controlled by the timing system in a completely binary fashion (i.e. filters inserted for continuous-wave mode, filters out for pulsed mode). However, LEReC's system was implemented for Operations, where continuous-wave mode was normal, and such flexibility was not required.

In general, external trigger is used when the exposure time is optimized at 1 s or less, and it can achieve the minimum camera exposure time of about 50 µs. Software trigger, meanwhile, allows the exposure time to exceed 1 s (maximum exposure time is set to 5 s in the scripts) and is employed for low-power pulsed mode. The strength of the neutral-density filter is approximately 1.5OD. Changes to the laser will typically require a recalibration of this block.

From here, the script performs some image processing to control for noise and enters the dynamic camera loop, which forms the core of the automation and exception handling capability of the slow position stabilization system paradigm [2, 3]. Specifically, the loop is responsible for detecting whether or not there is a beam on the sensor. If there is, the loop optimizes the image quality, preferring to optimize exposure time over gain due to the detrimental noise characteristics of high gain. If there is no beam, the loop prevents the script from proceeding to active stabilization.

Towards the end of the run, an upgrade to the CeC scripts was made such that, at this point, if a beam was detected, sensor mapping could be performed if requested. The purpose of this functionality was to ensure proper cross-alignment between the Operations cameras and the stabilization cameras since, as stated above, CeC's CoM data used for stabilization are based on the stabilization camera images. When an operator centers the beam on the Operations cameras and requests a sensor mapping, a new "center" is recorded for the stabilization camera images, based on the average of five images. However, a premature end to the RHIC (and hence CeC) run meant that this upgrade was not released in time for full use.

Once camera image quality and steady-state conditions are met, the script automatically enters the active stabilization engine. Using MATLAB's weighted centroid function (Image Processing Toolbox) and comparing the calculated CoM with the recorded target position, the system adds or subtracts 5 mV to/from the current voltage on the appropriate piezo mirror and mirror axis if the difference threshold is tripped twice consecutively. Stabilization automatically disengages when exception thresholds are tripped twice consecutively. Except for the source of the target position, this steady-state and stabilization automation is identical to LEReC's systems, and Refs. [2, 3] should be consulted for more information.

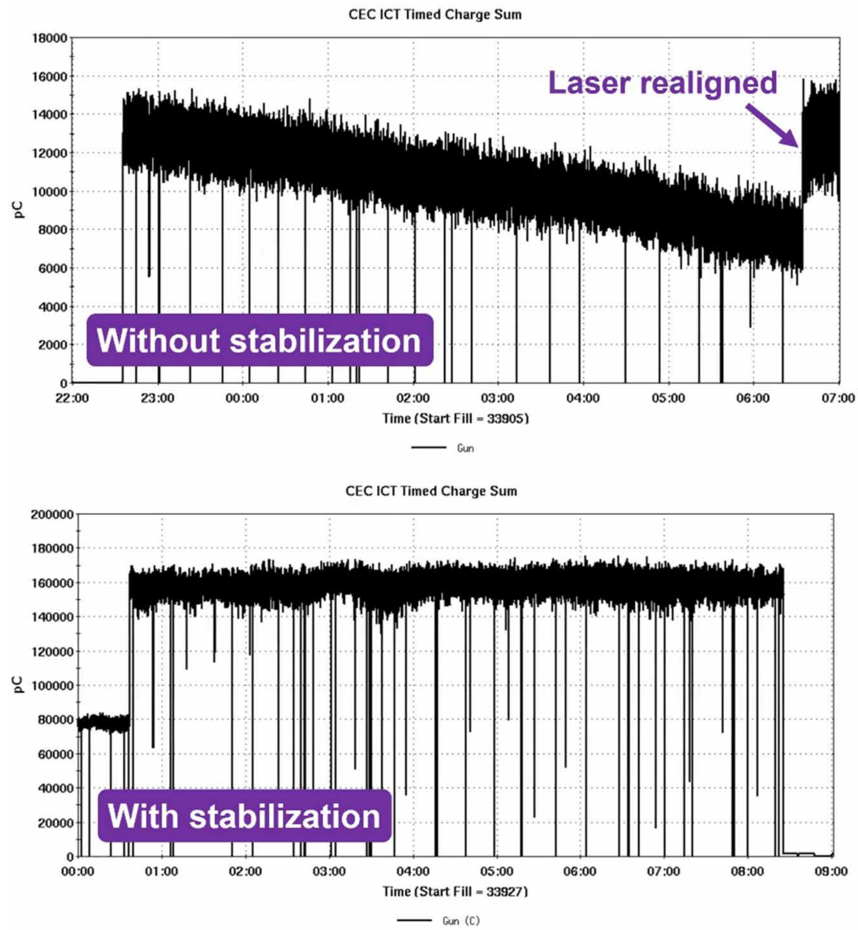

Figure 4: Effect of laser pointing stabilization systems on long-term electron beam charge stability.

Lastly, like with LEReC's scripts, each iteration of the CeC scripts is controlled by a variable pause length, driven largely by the exposure time of the image. However, even for minimal exposure times, the pause length is not allowed to drop below 1.5 s for the gun system. This constraint forces the bandwidth of the overall system (by the principle mentioned above, the relay system can subsequently iterate no faster than once every 3 s), and the system thus only responds to slow drifts in the laser trajectory.

RESULTS

Since center of mass information from the Operations cameras does not reflect laser beam movement well, electron beam charge stability is the main metric used for laser beam position stability on the photocathode. Figure 4 shows the summed electron beam charge with and without the slow laser position stabilization systems. In the top plot, the systems are not active, and there is a 60 % drop in summed charge over the course of 8 hours. The restoration of charge with the laser realignment at around 06:30 confirmed that this loss was laser-driven, rather than cathode-driven. When the systems were made to be active a following night (bottom plot), charge stability was maintained to within ±10 % over the same length of time. However, since measured charge depends on many factors, such as quantum efficiency and lattice variations, this only puts an upper bound on the laser position instability during that time. These data were collected during the most recent run.

CONCLUSION

The CeC pointing stabilization algorithm has successfully stabilized the laser trajectory for two runs. Its success has confirmed not only the algorithm itself but also the flexibility and rapid deployment capability of the original design paradigm.

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