LIGHT PATH CONSTRUCTION FOR AN OPTICAL STOCHASTIC COOLING STABILITY TEST AT THE CORNELL ELECTRON STORAGE RING

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Abstract

An experiment at the Cornell Electron Storage Ring (CESR) to test the optical path-length stability of a bypass suitable for Optical Stochastic Cooling (OSC) is being pursued. The approximately 80 m light path for this experiment has been assembled, and synchrotron light has been successfully propagated from both sources. A feedback system based on an Electro-Optic Modulator (EOM) to correct the path-error accumulated in both the light and particle path has been table-top tested. We present on the design and construction of the light optics for the OSC stability experiment at CESR.

INTRODUCTION

Optical Stochastic Cooling (OSC) [1] is a beam cooling technique. Based on the same principles as microwave stochastic cooling, OSC operates in the optical wavelength regime in order to take advantage of the large bandwidth, of the order of 100 THz, that an optical system can support. In the Cornell Electron Storage Ring (CESR) at Cornell University, an experimental program aimed at developing high gain OSC using an arc-bypass approach is under development [2–4]. As a stepping stone towards high gain OSC, Cornell is pursuing a path-length stabilization experiment based on the interference of synchrotron radiation produced by two dipoles at the start and end of the arc-bypass. The motivation, status and design of the beam optics are detailed in [5]. This paper focuses on the construction and initial commissioning of the light path to be used in the experiment.

LIGHT PATH DESIGN

The interference takes place between bend magnets B44W and the downstream B46E which are separated 71 meters along the nominal beam path. From each bend magnet, a portion of the synchrotron radiation is picked off from a 12.5 × 12.5 mm water-cooled beryllium (Be) mirror located 5.44 m from the source point. The mirrors are angled so that the bend radiation is directed perpendicularly through a viewport into an optics station. Interference is to be performed at the east station just downstream from B46E. The west station was designed with the purpose of aligning B44W's bend radiation along the light-path axis and collimating the radiation for the long transport to the east side.

To obtain an initial alignment of the light path, a HeNe laser was used. A pellicle beam splitter is used to join the HeNe path to B44W's. This same beam splitter also serves to direct a portion of the light to a substation used for co-aligning the HeNe light and radiation from B44W. This substation consists of two cameras separated by 0.5 m and another beam splitter so that radiation is incident on both cameras simultaneously. Two remotely controlled mirrors in the bend radiation path, prior to where it joins the HeNe path, are used so that the bend radiation can be made to spatially overlap the HeNe on both cameras.

A lens doublet is used for collimation. At the doublet, the radiation size is largely determined by the source divergence. Therefore, if the focusing is chosen so that $M_{22} = 0$, which occurs when $F_{\text{doublet}} = -L_{\text{source}}$ where F_{doublet} is the effective focal length of the lens doublet and L_{source} is the distance from the radiation source to the first lens of the doublet, we would expect a constant radiation size after the doublet. Taking into account the commercially available lens sizes and space constraints of the optics module, we selected $F_1 = -F_2 = 500$ mm. For $M_{22} = 0$, the doublet spacing, $l_d = 5.1$ cm. To account for the lenses having an error in the focal length on the order of 1%, the second lens in the doublet was placed on a controllable stage to make an adjustment of the effective focal length. The above argument is based on geometric optics and neglects diffraction. As a check, we used Synchrotron Radiation Workshop (SRW) [6] and confirmed the radiation becomes collimated to an approximately 6 mm RMS size without significant growth after the doublet.

After exiting the west station, the light path for B44W's transport is parallel to the beam trajectory before cutting across a chord along CESR's northern arc. This cut results in the optics path being approximately 20 cm shorter than the beam path. During OSC, part of this extra distance can be used to accommodate the use of a high gain amplifier. In addition to the storage ring, the CESR tunnel houses the synchrotron used for boosting the beam to the operational energy, nominally 6 GeV for CHESS but set to 3 GeV for this experiment. Two periscopes are used to raise and lower the light path over the synchrotron. The upper mirror of each periscope is on a remotely controlled, vertically oriented stage that can be used for rough adjustment of the light path-length. The light path is enclosed in 4" PVC pipe to protect against air drafts inside the tunnel.

Once on the east side, another substation holds the Electro-Optic Modulator (EOM) used for the path stabilization. A lens doublet chosen to behave as a reverse beam expander with 250 mm and 25.4 mm focal length lens are used to reduce the radiation to the 1 mm diameter aperture of the EOM.

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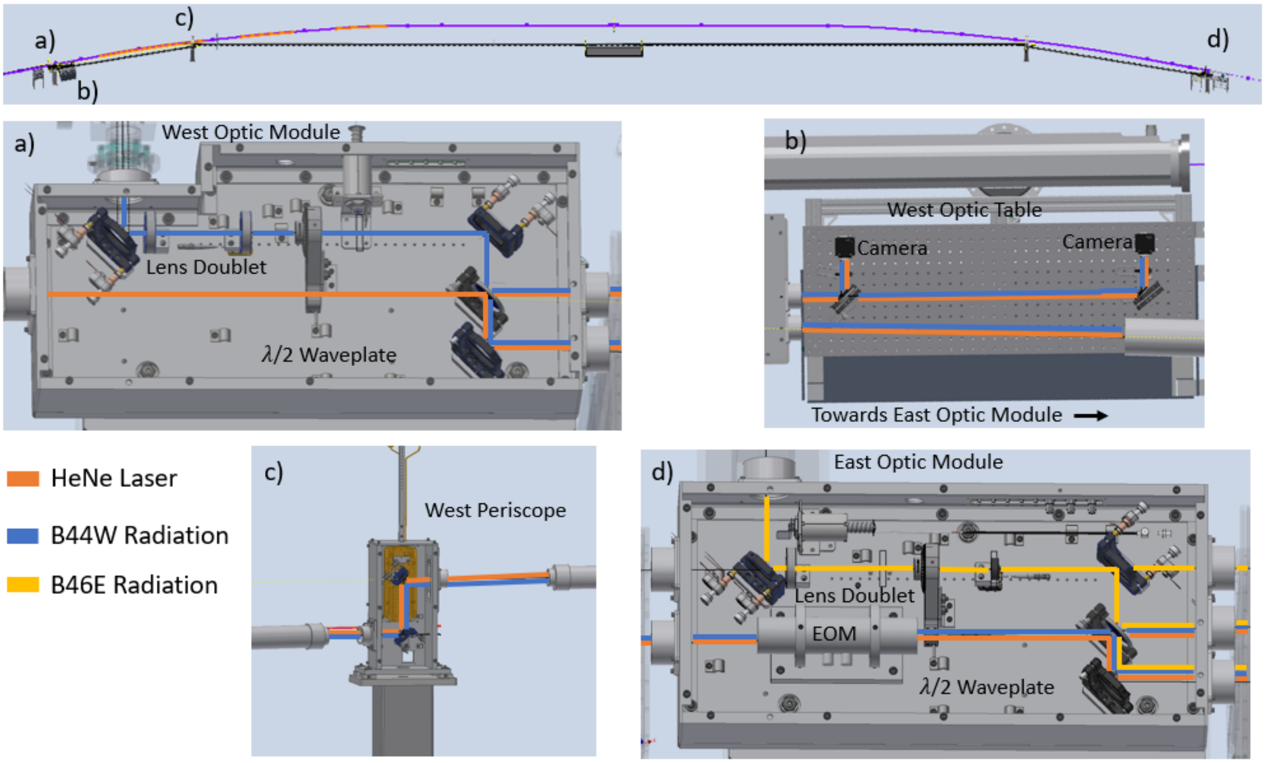

Figure 1: Drawings of the experimental setup. *Top)* The northern arc of CESR is shown (purple), along with the light path (black). The locations of drawings a-d are shown in the top image. *a)* Inside the west optic module. Radiation from B44W enters through the port in the top left, and traverses the first controllable mirror, lens doublet, waveplate and second controllable mirror. The beam splitter combines the HeNe laser path with that of the synchrotron light. *b)* The alignment table after the west optic module. Half the light is viewed on two cameras for alignment, the other half is sent across the ring. *c)* One of the two periscopes used to bring the light up and over the synchrotron. The top mirror height is remotely adjustable. *d)* Inside the east optic module. B44W's radiation enters the module on the bottom left port and goes into the EOM. Light from B46E enters in the top left port and is collimated and reduced with a lens doublet. Both wave packets are combined in the beam splitter on the right.

The light-path for radiation emitted from B46E is similar to the initial part of the light-path for B44W. Two remotely controlled mirrors are used to steer the radiation and a lens doublet is used to produce a beam that is the same size as its counterpart from the west. Here the two lenses were chosen to have focal lengths of 250 mm and 25.4 mm, but with a separating distance of 28.8 cm. Once again, the second lens was placed on a remote-control stand to account for focusing errors. A pellicle beam-splitter is used to join the east and west paths. Similar to before, a portion of the light is sent to a substation consisting of two cameras and a beam-splitter. In this station, the goal is to spatially overlap the light from B44W and B46E on both cameras so that their paths are colinear. The other portion of the combined radiation goes onto a photodiode to detect the interference during the experiment. Figure 1 illustrates the light path design.

Construction and Alignment

The construction of the light path and installation of the optics stations started during the CHESS 2020 winter down and was completed in early 2021. After the construction, during the weekly 6-hour access for routine machine maintenance, a HeNe laser was used to get an initial alignment of the entire light path. The electronics to communicate with the mirrors, stages and cameras are housed under the west and east stations and were surrounded by 2" × 3" × 6" lead bricks to avoid radiation damage.

During the spring 2021 machine studies week, the Be mirror for B44W was inserted for the first time and an initial attempt at aligning the synchrotron light was performed. Light was successfully propagated to the west alignment substation. During a machine studies week, the lattice is frequently reconfigured making beam loss more common resulting in increased radiation inside the CESR tunnel. We believe this caused one of our cameras to malfunction. To remedy this, we first placed dosimeters at various heights near the alignment substation and, based on readings gathered over a week of nominal CHESS conditions, decided to lower the table 40 cm below the plane of CESR. We also added additional lead shielding and the ability to remotely power on the cameras to ensure a longer lifetime. After re-configuring and re-installing the west substation, during the

CHESS spring 2021 run the Be mirror was inserted with nominal CHESS conditions (6 GeV with 100 mA average current). There was no observed impact on the beam and so it was deemed safe to leave in, allowing us to continue the alignment parasitically during CHESS running. In January of 2022, light from B44W was successfully propagated to the east module as shown in Fig. 2.

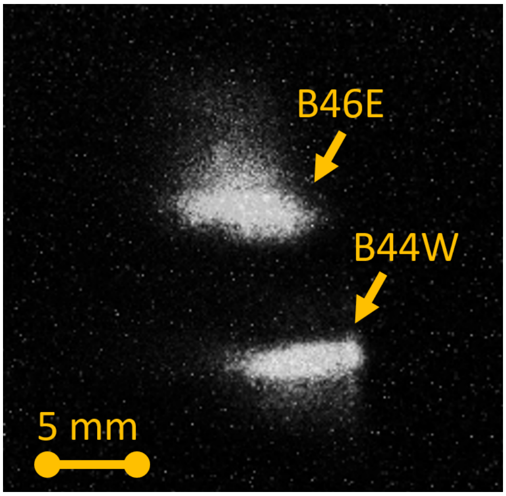

Figure 2: The radiation from the two sources after propagation through the entire system, read with a camera behind the east optics table.

FEEDBACK SYSTEM FOR STABILIZATION

The path stabilization will be done with an EOM, *ConOptics* model *360-80-02* [7]. The EOM uses an 80 mm long $LiTaO_3$ crystal that provides a half-wave voltage of 120 V at 830 nm. To drive the EOM, we procured a *Trek 609E-6* 4 kV bipolar amplifier [8], resulting in up to ±13 µm of path adjustment. Our correction speed is limited by the amplifier bandwidth of 13 kHz. Prior to the light path construction, accelerometer measurements were performed at various points in the CESR tunnel and on the vacuum chamber at frequencies up to 450 Hz. The integrated noise spectrum was on the order 1 µm which is well within EOM's path-adjustment range.

Table-Top Test of Feedback System

In order to test the feedback system before operation, a table-top test with a Michelson Interferometer was conducted [9] with the EOM placed in one of the arms. An 800 nm laser was used during the test. When the light from both arms was recombined, it was split such that half was seen by a camera (to aid in transverse alignment) and half was seen by the photodiode to start the feedback loop. Due to noise in the environment, prior to turning on the feedback we observed a standard deviation path-length fluctuation between the two arms of 70 nm. High frequency diode noise was removed with a 100 kHz low-pass filter before sending the interference signal to a PID controller (as shown in Fig. 3). The optimal settings were tuned by hand and found to be be 0.4, 10^4, and 0, respectively for the proportional, integral and derivative terms.

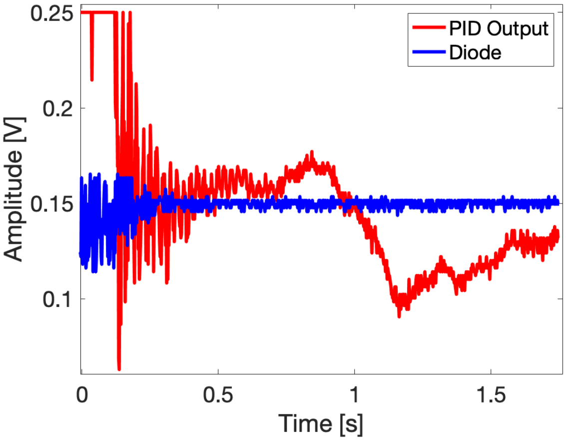

Figure 3: A plot of the stabilized interference. The noise on the left side of the plot was produced by manually shaking the optics table. The diode is reading the noise in the interference pattern and the PID is producing a signal to compensate for it. As seen, the noise is significantly reduced by the feedback system around 0.2 s.

By comparing the interference visibility from the noise in the hall both with and without the feedback system, it was determined that path length errors were corrected to a standard deviation of 8 nm which would be acceptably small for OSC.

CONCLUSION

An optical system has been developed and constructed for an experiment to test the optical path-length stability of a bypass suitable for OSC at CESR. Synchrotron light has been successfully propagated from both sources and made to spatially overlap. A table-top test of the planned EOM-based feedback system has been completed, demonstrating a capability for correcting the path-length errors within the requirements for a full OSC experiment at CESR.

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