I. INTRODUCTION

During the past 15 years or so, the development of computer-based tools, the growth of physics education research, and concomitant changes in undergraduate instruction have helped improve physics learning. These changes, particularly in laboratory-based instruction, can facilitate the development of useful skills such as data acquisition, modeling, communication, and working as part of a team. Such skills can help students prepare for undergraduate research, which can in turn strongly enhance the educational experience and may produce more physical science students. 

We expect that students will develop fundamental skills in the introductory labs, and consequently that students are sufficiently prepared for upper-level laboratory courses and undergraduate research. However, previous studies of traditional introductory labs indicate that such skill development does not take place in a meaningful, lasting way for the majority of students. Consequently, a significant gap can develop between the skills used for solving traditional textbook problems and navigating the traditional introductory laboratory, and the skills needed to practice physics.

This gap may be bridged by engaging introductory students in projects that allow concrete observations and require the development and use of several skills. We suggest using projects that allow concrete observations because past work has shown that the majority of introductory students are either in the Piagetian concrete operational stage or are making a transition to formal reasoning operations. Nonetheless, introductory students have a tremendous advantage: They often have great enthusiasm for starting research. Consequently, while their cognitive development and conceptual understanding catch up to their enthusiasm, they may benefit significantly by undertaking projects that develop research skills. Such projects also may be especially helpful for strengthening skills just learned, such as mathematics, programming, and experimental skills, by using these skills to perform a real task.

In this paper, we describe a project that uses the beam chopping process to develop several research skills in introductory physics students. For this project, a student devises a simple model of a complete chopping cycle, implements this model numerically, sets up the corresponding experiment, acquires data, and compares the results of the model to the experimental data. In the following, we describe these components of the project and discuss the potential value of this project for introductory physics students.

II. A SIMPLE MODEL OF THE BEAM CHOPPING CYCLE

For our purposes, a beam chopper is a device that is used to periodically modulate beams of visible light, typically in experiments in which small signals must be extracted from significant background noise. A mechanical beam chopper usually consists of a DC motor and a thin metal blade that has N slits cut into it at regular angular intervals, as shown in Fig. 1. By increasing the blade’s angular speed, $\omega$, the frequency $f = N\omega/2\pi$ with which the beam is blocked and then not blocked is increased. We assume that the beam has uniform irradiance (power per unit area) $I$ across its entire circular cross section of radius $r$. The total power transmitted by the beam is then $P_{\text{tot}} = I\pi r^2 = I A_{\text{null}}$

We show a sequence of sketches that illustrate one complete cycle of the chopping process in Fig. 2. For simplicity, we assume that the angle $\theta_{\text{beam}}$ subtended by the beam is less than the angle $\theta_{\text{blade}} = 2\pi/2N$ subtended by each blocking (or transmitting) region of the blade. We also assume that the chopping process starts at time $t = t_0 = 0$ with half of the beam blocked. Therefore, at time $t = t_0$, the transmitted power $P$ is half of its maximum value, that is, $P(t = t_0) = P_{\text{tot}}/2$. At time $t = t_1$, the beam is entirely blocked by the blade and the transmitted power falls to zero. At time $t = t_2$, the trailing edge of the blocking region of the blade begins to move out of the path of the beam; at time $t = t_3$, half of the beam is again transmitted; and at time $t = t_4$, the entire beam is transmitted. At time $t = t_5$, the next blocking region of the blade begins to block the beam; and finally, at time $t = t_6$, half the beam is again blocked and one chopping cycle has been completed. From Fig. 2, it is clear that for $t_1 < t < t_2$, $P = 0$, and that for $t_4 < t < t_5$, $P = P_{\text{tot}}$

An essential part of this project involves figuring out the functional form of $P(t)$ during the other portions of the chopping cycle. The power transmitted by the blade at time $t$ is equal to the product of the irradiance and the cross sectional area of the portion of the beam that is transmitted at time $t$, that is, $P(t) = I A(t)$. Because we have assumed that $I$ is constant, the time dependence of $P(t)$ is the same as that of $A(t)$. From $t = t_0$ to $t = t_1$, $A(t) = A_{01}(t)$, where

$$A_{01}(t) = \frac{1}{2} A_{\text{null}}$$
As shown in Fig. 3, $x_1$ and $x_2$ are obtained by determining the appropriate roots of

$$x \tan \omega t = \left[ r^2 - (x - x_0)^2 \right]^{1/2}.$$  

We derived Eq. (1) by first calculating the area under the upper boundary of the beam between $x_1$ and $x_2$, and then subtracting from it the area under the leading edge of the blocking region of the chopper blade between $x_1$ and $x_2$:

$$A_{01}(t) = \int_{x_1}^{x_2} \left[ r^2 - (x - x_0)^2 \right]^{1/2} dx - \int_{x_1}^{x_2} x \tan \omega t dx.$$  

We give the explicit time dependence of $A(t)$ in terms of $A_{01}(t)$ for an entire chopping cycle in Table I.

We have written a program that computes $A(t)$, and show the predicted variation of $A(t)$ during one complete chopping cycle in Fig. 4 for beam radii of $r = 1.0$ mm and $r = 1.5$ mm.

Because of the assumption of constant irradiance, the maximum transmitted power increases when the beam radius increases. Consequently, $A(t)$ achieves a larger maximum value for $r = 1.5$ mm than for $r = 1.0$ mm. In Fig. 4, we also see that the $A(t)$ versus $t$ curve makes the transition between 0 and $A_{tot}$ over a longer time interval (that is, $t_4 - t_2$ increases) when the beam radius increases. These results are consistent with intuition: The bigger the beam, the more power is transmitted and the longer it takes to unblock the beam. This consistency is helpful for students who are be-

Table I. The time dependence of the cross sectional area of the transmitted portion of the beam, $A(t)$, in terms of $A_{01}(t)$ given by Eq. (1).

<table>
<thead>
<tr>
<th>Time interval</th>
<th>$A(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_0 \leq t \leq t_1$</td>
<td>$A_{01}(t)$</td>
</tr>
<tr>
<td>$t_1 \leq t \leq t_2$</td>
<td>0</td>
</tr>
<tr>
<td>$t_2 \leq t \leq t_3$</td>
<td>$A_{01}(t) - (t-t_2)$</td>
</tr>
<tr>
<td>$t_3 \leq t \leq t_4$</td>
<td>$A_{tot} - A_{01}(t-t_3)$</td>
</tr>
<tr>
<td>$t_4 \leq t \leq t_5$</td>
<td>$A_{tot}$</td>
</tr>
<tr>
<td>$t_5 \leq t \leq t_6$</td>
<td>$A_{tot} - A_{01}(t-t_5)$</td>
</tr>
</tbody>
</table>
beginning to make the connections between their physical intuition and the output of the experimental apparatus discussed in Sec. III.

III. EXPERIMENT

A schematic diagram of the beam chopping experiment is shown in Fig. 5. Light from a light emitting diode (LED) is collimated by a pair of variable apertures to form a beam that is chopped and subsequently propagates through another pair of variable apertures before being detected by a photodiode. The photodiode output is displayed on a digital oscilloscope and can be recorded using a computer with LabVIEW software and a GPIB interface card.13

The apertures adjacent to the LED can be used to manipulate the cross section of the light beam to explore different limits (for example, $\theta_{\text{beam}} < \theta_{\text{blade}}$ versus $\theta_{\text{beam}} > \theta_{\text{blade}}$). The apertures closest to the photodiode are used to limit the amount of stray light that impinges on the photodiode, and can also be used to define the angular acceptance of the detector. One should be aware of the dimensions of the photodiode to ensure that the cross sectional area of the light beam is smaller than the effective area of the photodiode.

For our experiment, we used a variable DC power supply to light the LED and a digital multimeter to monitor the voltage across the LED. We experimented with different beam intensities to produce the cleanest waveform, and found it useful to take an average of several oscilloscope traces to improve the signal-to-noise ratio.

After acquiring an averaged oscilloscope trace of the photodiode output during one chopping cycle, we normalized the data to enable a comparison with the results of the simple model. In particular, we subtracted the background signal (obtained by extinguishing the LED) from all data and then divided each datum by the resulting maximum signal. The resulting normalized output signal $S(t)$ has a maximum value equal to unity and is graphically compared to $P(t)/P_{\text{tot}} = A(t)/A_{\text{tot}}$ in Fig. 6.

Although the implementation of the beam project that we have described here is relatively expensive, it need not be. For example, a beam chopper can be fabricated from a DC motor and a cardboard blade; fixed diameter apertures can be used instead of variable apertures; and photos of the oscilloscope trace can be used to perform qualitative comparisons to theoretical predictions. Consequently, cost need not be a significant barrier to the completion of this project.

IV. RESULTS AND DISCUSSION

As shown in Fig. 6, there is a close correspondence between the signal predicted by the model and the observed signal. The predicted signal differs from the experimental data by no more than 0.08 at times when the beam is almost completely blocked or almost completely transmitted. In particular, the predicted signal is more “abrupt” than the observed signal near these times. The reasons for the differences between the model and the experimental data can be pursued as an extension to the project, and lead one to explore the validity of the assumption of uniform irradiance across the cross section, and to learn more about the angular divergence of the source and the angular acceptance of the detector. Although typical LEDs emit quite uniformly over the central part of their cross section, they also emit strongly over a wide range of angles ($\pm 30^\circ$).14 Consequently, one expects some “rounding” in the experimental curves near the times that the nondivergent model beam is about to be completely blocked or transmitted. By checking the validity
of assumptions and understanding the properties of detectors, students can further develop their research habits.

Because advanced physics knowledge is not required, this project has the advantages of being accessible and comprehensible. Nonetheless, completing this project requires the development and demonstration of skills in modeling, computation, experiment, and analysis. Furthermore, this project can be used to strengthen physics understanding because the results raise questions about initial assumptions and the performance of detectors. Finally, the use of beam modulation in several types of spectroscopy (for example, photoluminescence, molecular and atomic, and time-of-flight spectroscopies) and in the lock-in amplification technique makes this project relevant to many different fields of physics.

The student author (J.A.B.) found this project to be especially interesting, and more beneficial than any other experience in his undergraduate career, because it emulated a complete research project, from conception to presentation. This completeness contrasts with even upper division laboratories, which are often limited in scope because of time. By completing this project, he obtained an understanding of the beam chopping process and how the process produces a waveform; how to apply mathematics to model this physical process; a working knowledge of C programming; the ability to use all the instruments and programs used in the experiment; analytical skills; the ability to design and produce a formal poster presentation; and a feel for how scientific research is conducted. These achievements demonstrate significant development of several research skills and a strengthening of habits of inquiry, all in the context of a process—beam chopping—that is useful in several fields and accessible to the introductory student.

ACKNOWLEDGMENTS

We thank Dr. Jim Carroll, Dr. David Reid, Dr. Natthi Sharma, and Dr. Marshall Thomsen for their helpful comments on the original version of this manuscript. This project was supported by NSF Grant No. 9803189.

Electronic address: ebehringe@emich.edu

Electronic address: josephbrincat@hotmail.com


11Beams of particles also can be chopped. Neutral particle beams can be modulated using a mechanical chopper, and charged particle beams can be chopped by electrostatic deflection (for example, deflecting a beam using an electric field so that the beam no longer passes through an aperture).

12The source code for the C language programs that computes A(t) for different cases, that is, \( \theta_{\text{beam}} < \theta_{\text{blade}} \) and \( \theta_{\text{beam}} > \theta_{\text{blade}} \), can be downloaded from (http://www.physics.emich.edu/molab/beamchop/index.html).

13We used a Hewlett Packard Model 54603B Oscilloscope with the Model 54650A HP-IB Interface Module together with LABVIEW software and the Model PCI-GPIB Interface Card from National Instruments to acquire the averaged oscilloscope trace shown in Fig. 6.


15See, for example, P. Horowitz and W. Hill, The Art of Electronics, 2nd ed. (Cambridge U.P., New York, 1990), p. 1051.
