MEASURING PLANCK'S CONSTANT BY COMPUTER
– Applying myDAQ and LabVIEW in Teaching of Modern Physics

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Many physics teacher put special emphasis on high-sounding terms, such as research-based education, development of the problem-solving ability of students, active work with students etc. Although everybody knows that whilst 30-35 students attend a maximum of two physics lessons a week, whilst there is a shortage of necessary equipment for even the basic demonstrations in most of the schools, whilst the teacher has no time to prepare for the demonstrations or measurement-tasks due to the high number of compulsory lessons, the catchwords mentioned above will not come true in high-school physics teaching. What remain are face-to-face teaching, analysing textbook graphs and watching projected pictures and videos.

The educational products of National Instruments are a huge help for physics teachers, namely the myDAQ and the LabVIEW programming environment. Quantitative demonstrations of experiments driven and evaluated by so-called virtual instruments written in the LabVIEW graphical programming language can be conducted in the lessons easily and quickly, and they capture the students' attention. At Miklós Radnóti Experimental High School in Szeged we are open to new methods if they indeed give a hand to the teachers' work and help students understand the topics better, and therefore, we have joined the enlarging group of myDAQ users. For the time being, however, just as an extracurricular activity.

The article was translated from Hungarian by Kornél Kovács.

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Measuring Planck's Constant Using LEDs

Students are familiarised with famous historic experiments while being taught modern physics, but very few of those can be carried out in the lessons due to the lack of necessary equipment and enough time.

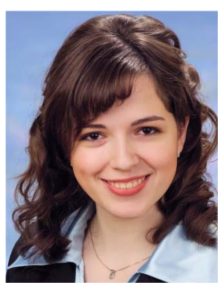
Planck's constant can be measured in many different ways as it appears in lots of physical phenomena that are taught in high school (like the photoelectric effect or electron diffraction). We have chosen a modern physical measuring method, which is relatively known, but not so widespread in high-school textbooks: we measure the value of h by analysing the electrical and optical properties of LEDs.

We have decided to use this way of measuring because on the one hand, it can be successfully carried out even with our amateur knowledge of myDAQ and LabVIEW, and on the other hand, it requires only a few cheap additional ingredients, so the method can easily fill a gap in the teaching of modern physics.

LED is an abbreviation for Light Emitting Diode. In the absence of external voltage in the p-n junction electrons can jump from the n side to the p side, which results in the aspect of moving holes from p to n. This diffusion of electrons lasts until the electric field (a potential barrier) that is building up grows strong enough to stop it. We say that the LED is forward-biassed if we connect the negative pole of the power supply to the n side and the positive pole to the p side, creating an electric field which has a direction opposite that in the p-n junction. Over a forward threshold voltage V_0 the potential barrier gets overcome and the flow of charges starts. During the recombination of electrons, in the p side $V_0 e$ energy gets released in the form of a photon. This energy can be expressed by the following equation:

$$\varepsilon_{\text{photon}} = hf = V_0 e,$$

where h is Planck's constant, f is the frequency of the photon, V_0 is the forward threshold voltage and e is the



Anikó Somogyi, mathematics and physics teacher. Graduated at University of Szeged in 2016. Has been teaching at Miklós Radnóti Experimental High School in Szeged since 2015 as a trainee then as a teacher. Aims to help "discovery-based learning" with widespread usage of ICT devices. The three-member-team won the myDAQ competition in 2017 announced by the Roland Eötvös Physical Society and National Instruments Co.

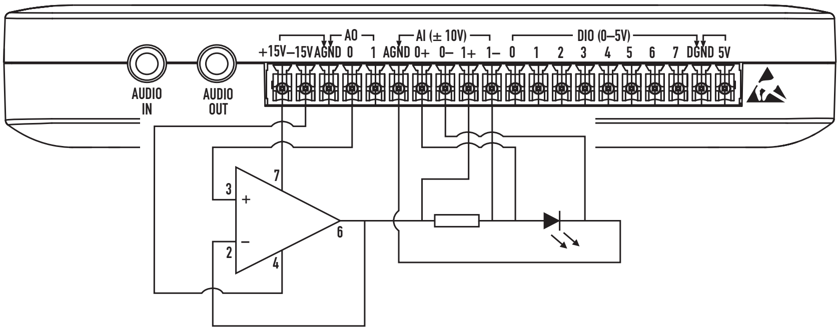


Figure 1. Wiring diagram for measuring the LEDs current-voltage characteristic (needed: OP37 operational amplifier, 10-ohm resistor)

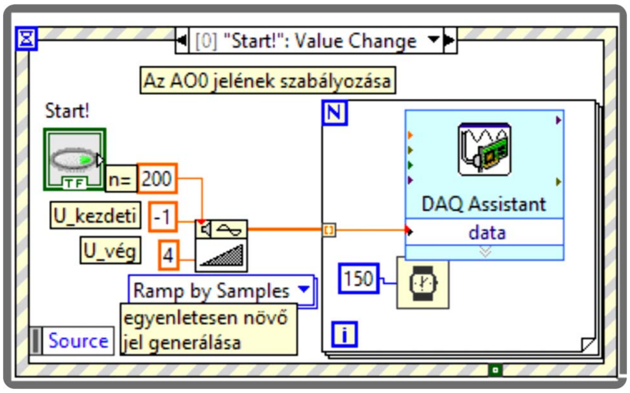


Figure 2. Modulating the myDAQ's output (AO0) voltage on the virtual instrument's block diagram

elementary charge. After measuring the LED's opening voltage and wavelength (frequency), Planck's constant can be calculated using the equation above [1, 2].

We used HB5-436HOR-C (red), HB5-434HY-C (yellow), HB5-433EAGD-C (green), HB5-438ABD-C (blue), highly luminous LEDs for our measurements [3].

Measuring the Forward Threshold Voltage

Our first aim was to record the current-voltage characteristic of the LEDs. As a result of increased voltage applied in the opening direction between the anode and the cathode of the LED, the current starts to increase first exponentially, then the rate of increase gets linear. The zero crossing of this linear section is the V_0 forward threshold voltage. This voltage is different for LEDs that are made from different semiconductor substances, so this value is a characteristic electrical property of the LED given.

For recording the characteristic we attached the accessories that can be found in the NI Starter Accessory Kit to the myDAQ [4].

Figure 1. shows the circuit we built, in which we use an OP37 operational amplifier for voltage tracking. The role of the amplifier is to make the voltage of the power supply chargeable [5]. (Because of negative feedback, the value of input and output voltage are the same.)

As we referred to it earlier, the myDAQ has output and input channels as well. Thus both controlling and measuring can be carried out by computer. We applied linearly increasing voltage from –1 to 4 V to the circuit through one of the device's analogue output channels, the AO0 plug. We increased the voltage in 200 steps, allowing 150 ms to pass between each. *Figure 2.* shows the module that carries out this modulation in LabVIEW.

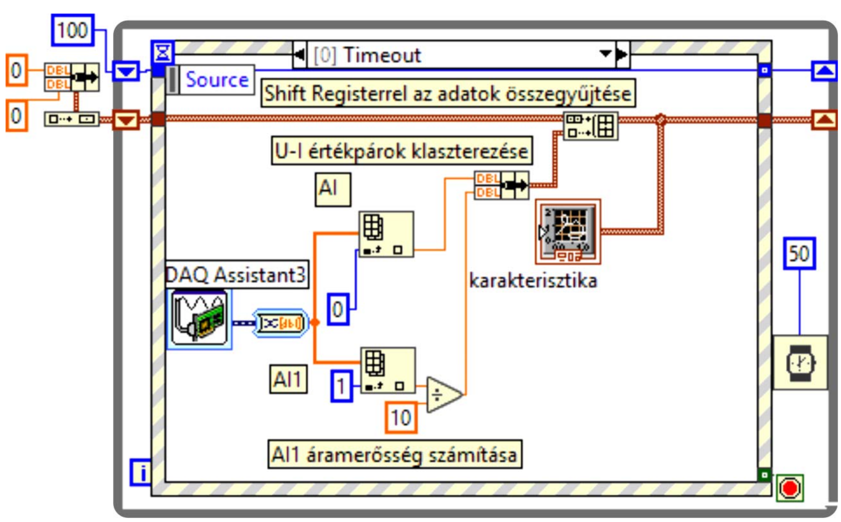
In another cycle of the same virtual instrument, we measure a point of the LEDs' current-voltage characteristic every 50 ms. The myDAQ's two input channels are used to measure the voltage between the two outputs of the LED (AI0 channel) and the voltage on the resistor that is in series with the LED (AI1 channel); this voltage was then converted to the current through the LED using Ohm's law (*Figure 3.* and *4.*).

Measuring the Wavelength

In the second part of our measurement, we studied the optical properties of the LEDs. While the LED is operating, approximately 1% of the recombinations result in light emission. The wavelength of the LED's light, which can be considered monochromatic, also depends on the semiconductor substance.

We built a spectroscope using a diffraction grating and a cylindrical box which was covered with black cardboard on the inside [7]. The setup was connected to the myDAQ [6]. The 1000-lines/mm grating [8] was fixed to the bottom of the box so that its midline overlapped the box's axis of rotation. The path of the light was designed in such a way that a slit made from

Figure 3. Simultaneous measuring of current (AI1) and voltage (AI0) in virtual instrument



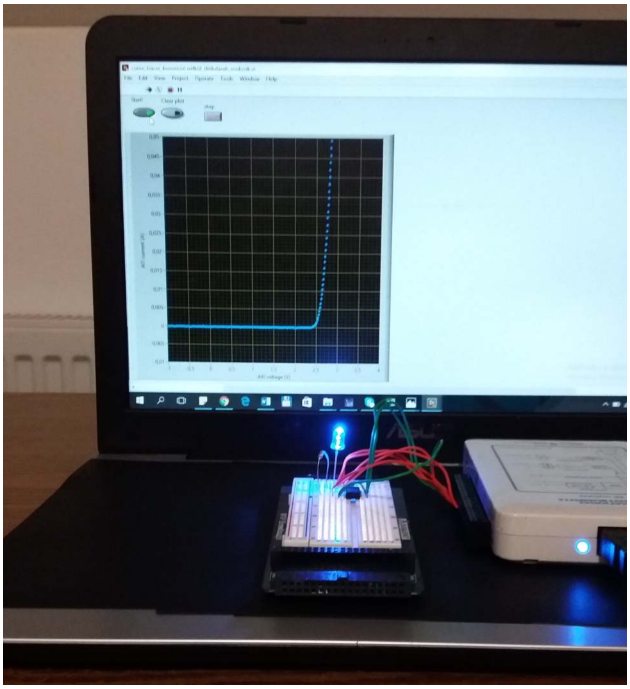


Figure 4. Recording current-voltage characteristic with the myDAQ

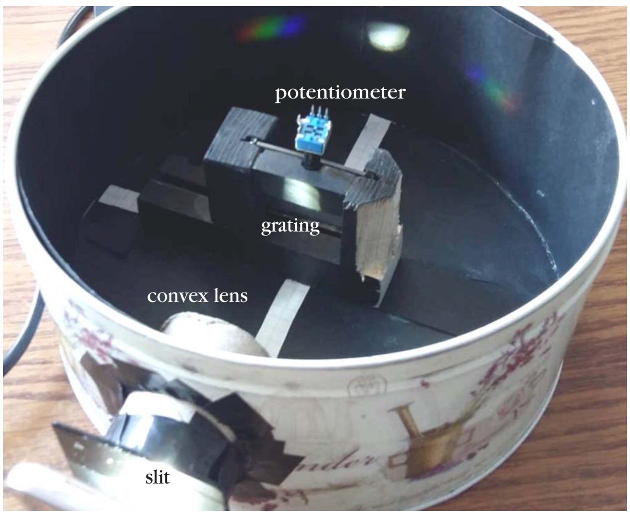
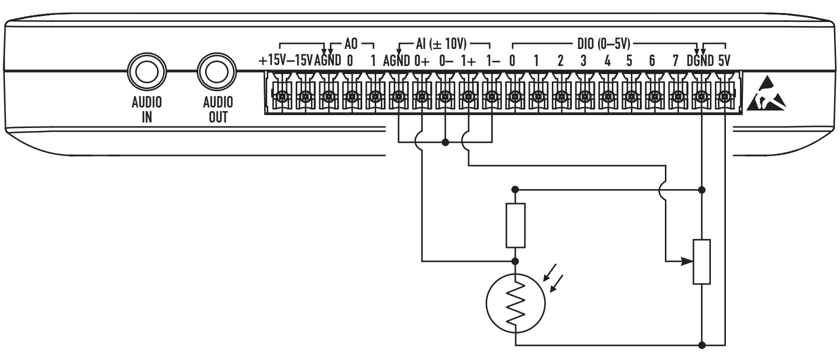


Figure 5. Light's path in the spectroscope

blades was lit by the LED, and then the beams entering the spectroscope were collimated by a convex lens of 45 mm focal length and 37 mm diameter [9].

Figure 6. Wiring diagram for measuring the LED's wavelength (ingredients: potentiometer, photoresistor)



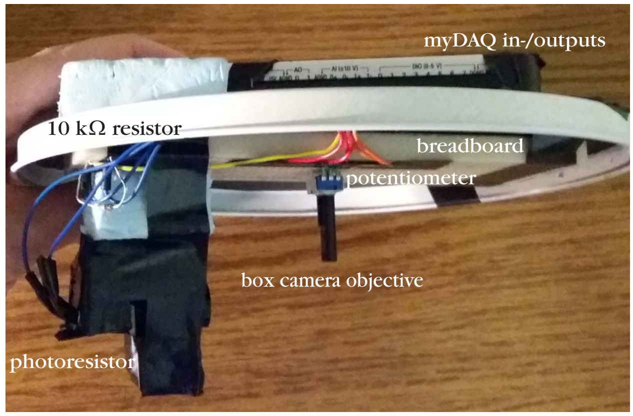


Figure 7. Connecting the potentiometer and the detector to the myDAQ and fixing them to the box

As a result of this setup, parallel light beams reached the diffraction grating at an incident angle of 0° through a hole 4 cm in diameter cut into the side of the box (*Figure 5.*).

Our detector was made using a 16-mm focal length box camera objective [10] and an FW 150 photoresistor [11] placed at the focal plane of the objective glass. The detector was fixed to the edge of the inner side of the box cover so it could be turned to the path of the beam.

A photoresistor is a sensor for detecting light: a passive semiconductor without a barrier layer, whose resistance depends on the intensity of the light incident on it. Photons increase the number of delocalised charges, which results in the decrease of resistance. The myDAQ's +5 V output voltage was connected to one output of the photoresistor, then a 10 kΩ resistor was connected to it in series, which was grounded through the DGND input. The photoresistor's value is 560 kΩ if no light reaches it, so the voltage on the 10 kΩ resistor was nearly zero. As the intensity of light grows, the resistance of the photoresistor decreases, so the voltage on the 10 kΩ resistor increases. This voltage was measured through the myDAQ's AI0 channel (*Figure 6.*).

We used an R-0904N-type potentiometer from NI Starter Kit to measure the rotational angle. The breadboard, the potentiometer and the detector were glued to the inside of the box cover. The myDAQ was fixed to the outer side of the cover (*Figure 7.*).

To bring the rotational axis of the potentiometer and the box together, we used a wooden support, in which we drilled a proper-sized semicircle hole. When closing the box the potentiometer's rotating part was fixed in the hole. With the help of this mechanical system, the potentiometer and the detector can rotate together around a common axis when the cover is turned.

The potentiometer was connected to the myDAQ as a voltage divider, the voltage, which was changing

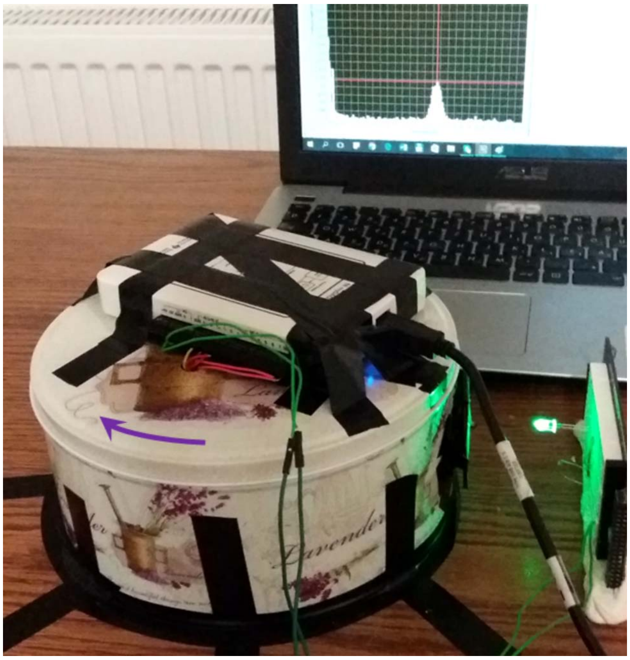


Figure 8. The spectroscope, the myDAQ attached to it and the controlling computer in use

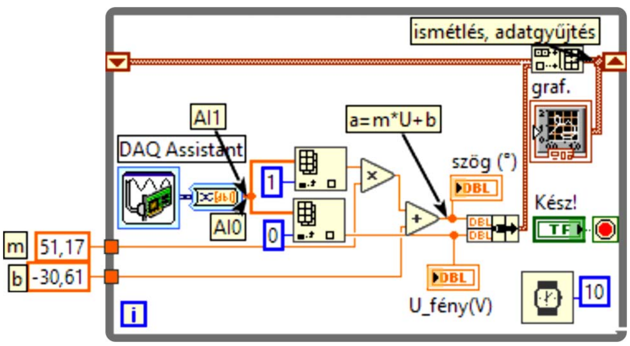


Figure 9. Block diagram of virtual instrument required for measuring the angle related to the LED's first order of diffraction

between 0 and 5 Volts, was measured on channel AI1 (*Figure 6.*).

To be able to measure the angle of rotation with the potentiometer, we had to perform calibration, so we determined the properties of the linear function connecting the angle of rotation α to the voltage measured V ($\alpha = aV+b$). Let V_1 and V_2 denote the voltages that belong to 180° and 0°. With these, the parameters of the function are

$$a = \frac{180°}{V_1 - V_2} \quad \text{and} \quad b = -\frac{180°}{V_1 - V_2}\, V_2 .$$

After calibrating our bevel, we detected the diffraction of LED light.

The box was fixed to the table, then the cover was rotated slowly by approximately 50° while the voltage related to the light intensity was measured as a function of the rotational angle (*Figure 8.*).

By plotting these data pairs we got the intensity diagram of the LEDs' light diffracted in first order.

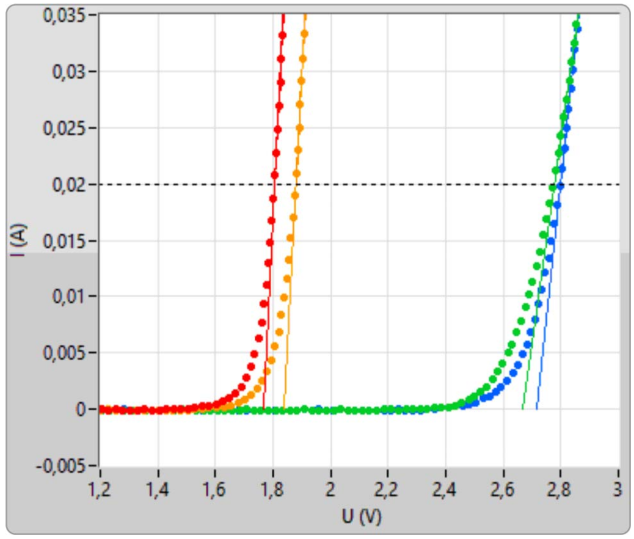


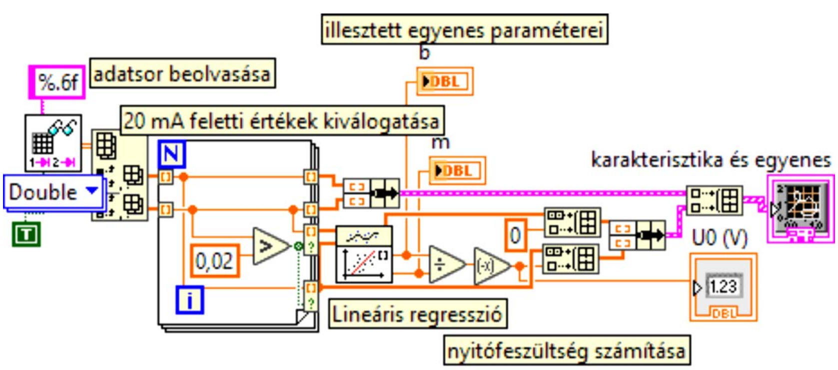
Figure 11. Current-voltage characteristics of LEDs of different colour (red, yellow, green, blue)

Evaluating the Results

Evaluation was also carried out using LabVIEW. First of all, we determined the LEDs' forward threshold voltage. Since above 20 mA LED characteristics can be approximated as linear, we separated these pairs of data and applied linear regression.

Using the resulting line's parameters (slope and intercept) we could calculate its zero crossing, which is the forward threshold voltage (*Figure 10.*).

Figure 10. Evaluation of the LEDs' current-voltage characteristic (linear regression and opening voltage calculation) in block diagram of virtual instrument



In *Figure 11,* we plotted 4 different LEDs' current-voltage characteristic along with the lines fitted to the linear sections.

The second step was to evaluate the measurements done with the spectroscope. We determined the diffraction pattern's maximum first (*Figure 12.*). We would like to note that with the help of the cursors provided by LabVIEW's graphs, finding the maxima manually is also possible. If we restrict our data to

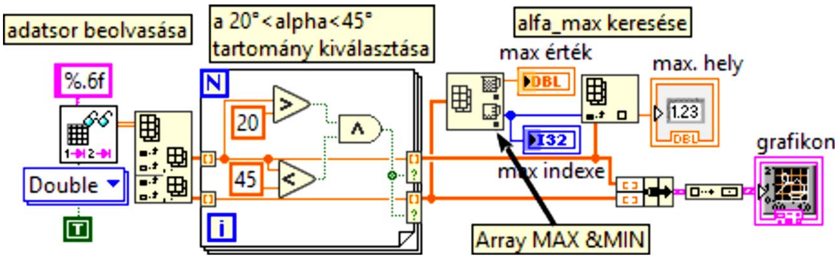


Figure 12. Searching the angle related to the maximum light intensity

the first order's angle interval (about 20–45°), then a more elegant way is using the LabVIEW's Array max & min extreme value searcher.

In *Figure 13,* we plotted the intensity diagram of diffraction of the LEDs of 4 different colour; the voltages, which are proportional to the light intensity, are functions of the angle of diffraction. We would like to draw the attention to the fact that if retrieving the real spectra of the LEDs' is needed, it is necessary to take the photoresistor's relative spectral sensitivity into consideration. To determine the wavelength, we used the grating equation $d\sin\alpha = n\lambda$, where $d = 10^{-6}$ m. From the angle α that belongs to maximum light intensity, measured at the first order of diffraction, we determined the wavelength and the frequency of the different LEDs. The results of the two steps of measurement are summarised in *Table 1*. (Elementary charge and speed of light in vacuum were taken as known.)

In case of each LED the calculated value for Planck's constant differs by no more than 10% from the $h = 6.626 \cdot 10^{-34}$ Js official value.

The value calculated for every LED has the correct order of magnitude and is very close to the official value, so demonstration measurements using LEDs would be appropriate for estimating the constant (for instance, as part of a lesson). (The measurement can be conducted in 5 minutes if the preparations are not considered and if two myDAQs are available – to avoid the problems with modifications.)

If the photon energy derived from the opening voltage is plotted as a function of light frequency, the four measured points fit a line crossing the origin, and this basically proves Planck's hypothesis. The slope of the regression line crossing the origin is the value of Planck's constant. The measured value of $6.54 \cdot 10^{-34}$ Js differs from the official value by 1.33% (*Figure 14.*).

Figure 13. Intensity graph of different coloured (red, yellow, green, blue) LEDs

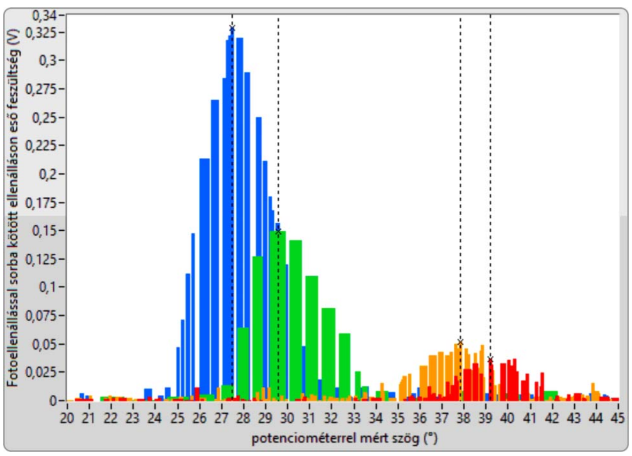
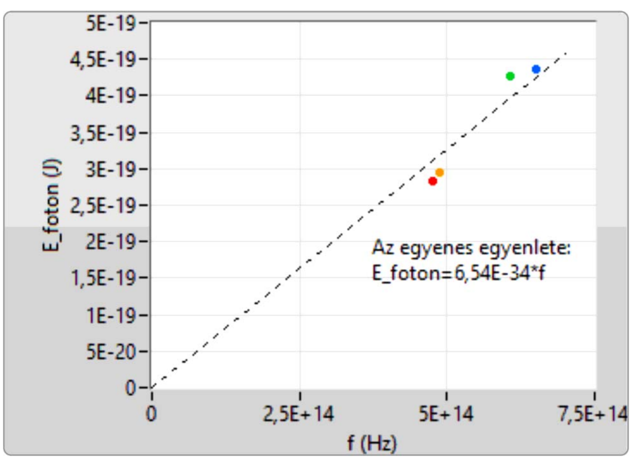


Figure 14. Current-voltage characteristics of different coloured (red, yellow, green, blue) LEDs



About Using myDAQ and LabVIEW

Our setup, method and presentation of the results had one purpose: to show that using myDAQ and LabVIEW with some simple additions can open up new horizons in high-school measurements and their evaluation.

We know that purchasing such equipment might not be feasible in the majority of schools, but it is also possible to apply for grants that provide schools with these devices. This is much more than nothing at all, as the teacher can learn the basics of how to use the device and the software. Many virtual instruments can be found on the internet that are free to download and can help learning and conducting successful measurements. For possible applications of different sensors we recommend the NI myRIO Project Essen-

Table 1.

Results of measurements conducted with 4 different coloured LEDs

colour	red	yellow	green	blue
α (°)	39.2	37.9	29.6	27.5
λ (nm)	632	614	494	461
f (Hz)	$4.75 \cdot 10^{14}$	$4.89 \cdot 10^{14}$	$6.07 \cdot 10^{14}$	$6.50 \cdot 10^{14}$
V_0 (V)	1.77	1.84	2.67	2.72
$V_0 e$ (J)	$2.83 \cdot 10^{-19}$	$2.94 \cdot 10^{-19}$	$4.27 \cdot 10^{-19}$	$4.35 \cdot 10^{-19}$
h_{calc} (Js)	$5.96 \cdot 10^{-34}$	$6.02 \cdot 10^{-34}$	$7.04 \cdot 10^{-34}$	$6.70 \cdot 10^{-34}$
δ_{rel} (%)	–10.0	–9.2	6.2	1.1

tials Guide [13], in which references to measurement experiments can be found as well as descriptions.

Obviously, it is worth involving students who are interested in physics in the very first attempts as well. There are many situations in which the role of the expert and the layman can readily interchange. We can learn much from the students and also about the students.

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