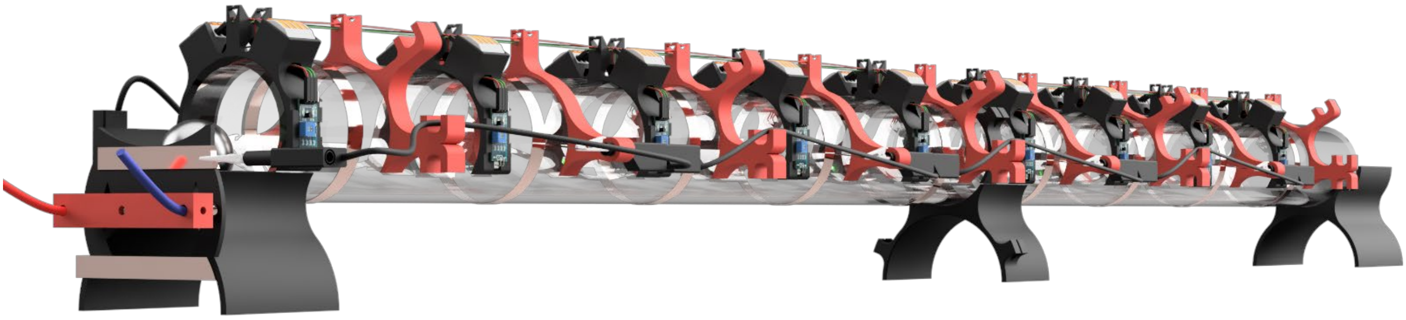

3D PRINTED LINAC

Assembly Instructions

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Contents

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Version 1

More ideas for the classroom:

https://cern.ch/scoollab/classroom-activities

0) Introduction

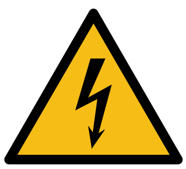
Linear particle accelerators (LINACs) are fundamental to modern particle physics. At CERN, linear accelerators are at the very core of the accelerator chain and serve as the main source for ion beams (LINAC 3) and proton beams (LINAC 4), respectively. Despite their importance for experimental particle physics, very few teaching aids have been available to demonstrate the underlying principles in a hands-on fashion to high school students. This is why the 3D printed LINAC has been developed.

At its core, the 3D printed LINAC is a **fully functional model** to **demonstrate how charged particles can be accelerated in oscillating electric fields**. In the model, a graphite coated ping pong ball is accelerated through a plexiglass tube using a custom-built High Voltage switch.

Minimal equipment is needed: A 3D-printer for the main components, an Arduino for controlling the accelerator, some standard electronic components, and a plexiglass tube. A list of the required materials is provided in this manual. Note, however, that setting up the LINAC model can be challenging, and the model itself is still work-in-progress.

This manual is built on the **premise that you are either an engineer, physicist or a physics teacher** and that you are hence **familiar with all precautions necessary to safely handle High Voltages** generated by a Wimshurst machine. **Do not build this accelerator if those conditions do not apply to you. Do not use any other source of High Voltage!**

Health and Safety Warnings

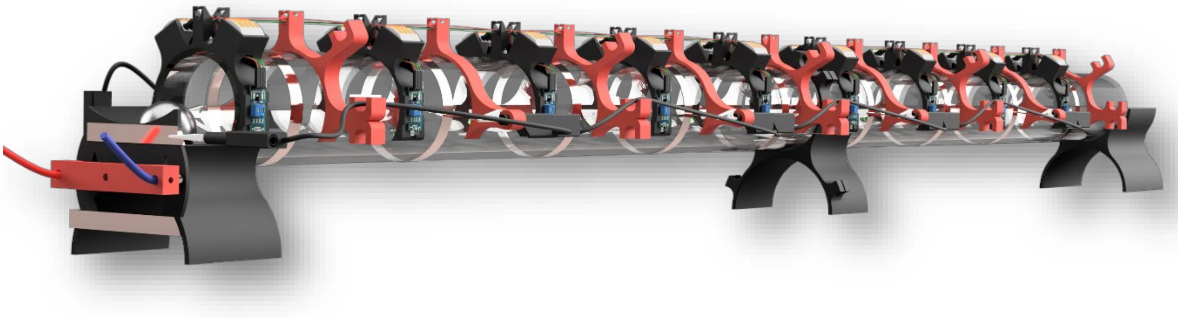


Attention High Voltage!

The experiments described in this manual make use of a Wimshurst machine commonly used in high schools for teaching purposes.
Do not use any other High Voltage source!
Serious risk of electric shock and resulting injuries!

All safety restrictions set forth in the manual of the Wimshurst machine **and all governmental safety regulations apply.**

1) 3D printed LINAC: Overview



1.1) Physics Background

The 3D-printed LINAC uses electrostatic fields generated by a Wimshurst machine to accelerate a graphite coated ping-pong ball in a plexiglass tube. In contrast to the well known salad bowl accelerator, the 3D-printed LINAC does not rely on repeatedly **reversing the charge of the ping pong** ball. Instead, the **polarisation of the accelerating field is reversed** by means of a custom build Arduino-controlled High Voltage switch. This minimizes the risk of building up student misconceptions and mirrors more closely the fundamental principle of actual linear accelerators.

1.2) Main components and variants of the experiment

The 3D-printed LINAC consists of the following main components:

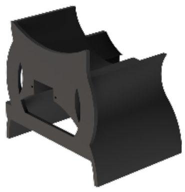
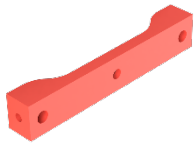
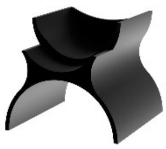
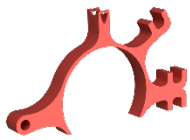
a) **High Voltage Source:** Standard Wimshurst machine
b) **Accelerated particle:** graphite coated ping-pong ball
c) **Beam pipe:** 150cm plexiglass tube (transparent PMMA)
d) **Drift tubes:** Copper foil tape
e) **High voltage switch:** Small servo motor which alternates between two positions
f) **Accelerator control:** Arduino microcontroller and several electronic components

The accelerator comes in two different variants: It can either be controlled manually via a pushbutton or by using light barriers. Control via light barriers is an add-on, i.e., it can be added optionally to the experiment after the manual control has been implemented.

2) 3D printed LINAC: Manual control via pushbutton

The simpler version of the LINAC uses a pushbutton to control the state of the high voltage switch. Pushing the button manually reverses the polarisation of the drift tubes each time the ping pong ball passes one of the copper tape loops.

2.1) Required Materials & 3D printed parts

A) 3D printed parts		
Track start & HV switch	**HV switch bar**	**Center support**
		
1x	1x	1x
End support	**High Voltage Pylon**	
		
1x	9x	

B) Required materials

Wimshurst Machine	Plexiglass Tube	Ping pong ball
		
1x	1x	1x
Standard Wimshurst Machine as used for classroom demonstrations	Rec. size: 150 cm Diameter (outside): 80 mm Diameter (inside): 70 mm	Either already graphite coated or standard ping pong ball
Knurled Screw	**Electronic components**	**Other Components**
 2x M4	1x Arduino Uno 1x Servo MG90S 1x resistor 10kΩ, 1kΩ, 100Ω 2x Zener Diode, 5,1V 1x pushbutton 1x potentiometer 1x breadboard Jumper Wires	1x Graphite spray if ping pong ball not already coated 1x Self adhesive copper foil tape, width app. 10 mm 11x Laboratory HV cables (banana plug) 11x Alligator clip for 4mm banana plug

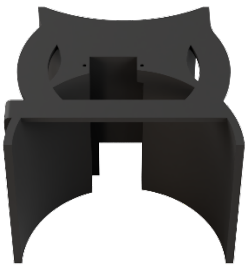
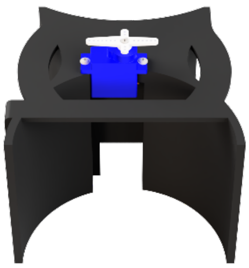
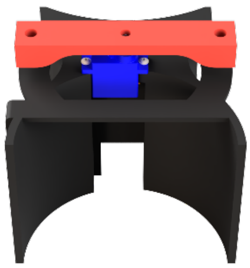
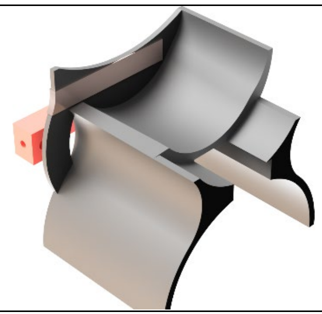
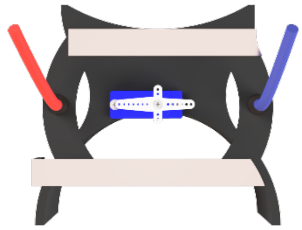
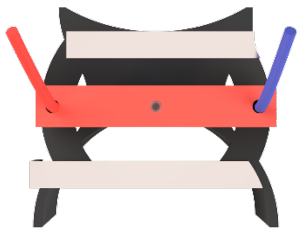
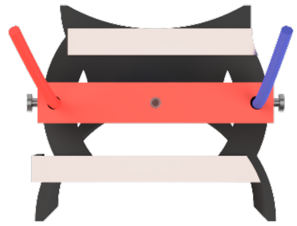
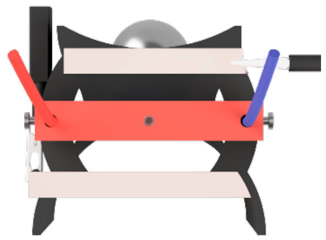
2.2) Assembly

The assembly of the LINAC model requires the following steps:

1) First, the HV switch, which also serves as tube support and the starting point of the acceleration track has to be assembled.
2) After that, the plexiglass tube will be placed onto the support structure. The copper tape, which serves as "drift tubes," needs to be wrapped in loops around the plexiglass tube.
3) In the next step, the HV pylons have to be clipped onto the plexiglass tube.
4) The High Voltage cables have to be connected to the Wimshurst machine and the High Voltage switch. Furthermore, the copper loops have to be connected.
5) The control circuit has to be build, and the Arduino needs to be set up and the provided sketch needs to be uploaded.

Each step will now be explained in greater detail.

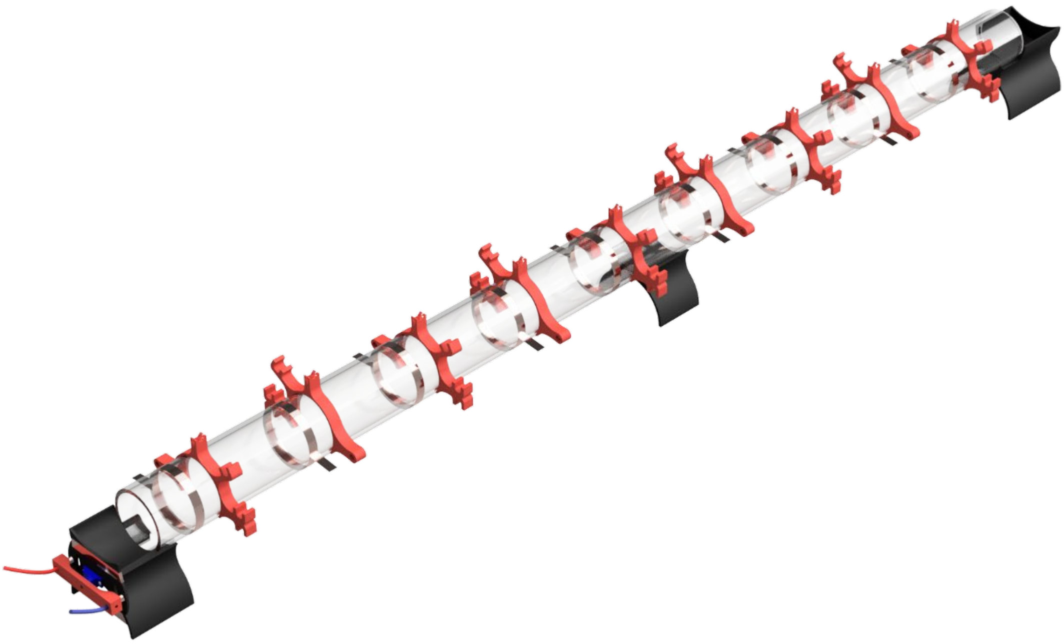
2.2.1. Assembly of HV switch/track start

		
The 3D-printed part should look like this.	*Mount the servo (MG90S) in the recess provided.*	*Glue the HV switch bar to the servo. The orientation is clearly defined by the shape of the recess in the HV switch bar.*
		
Stick the copper tape in two strips on the bracket as shown in the picture.	*The copper tape should be taped around the bracket so that the ping pong ball touches the tape on the other side.*	*Ultimately the servo will change the positions of the connections to the Wimshurst machine (red and blue) in such a way that the polarisation of the copper tape is reversed each time the switch is tripped.*
		
Insert the two HV lab cables to the Wimshurst machine through the openings in the HV switch bar. The HV lab cables must be stripped prior to this, so that good contact is made with the copper tape.	*Fasten the HV lab cables with the locking screws. The pressure must not be too strong (otherwise, the HV switch bar will not move) or too weak (no reliable contact).*	*Clip the HV lab cables to the copper tape using the alligator clips. These cables will lead to the "drift tubes," that is, the copper tape loops around the plexiglass tube.*

2.2.2. Preparation of the "drift tubes"

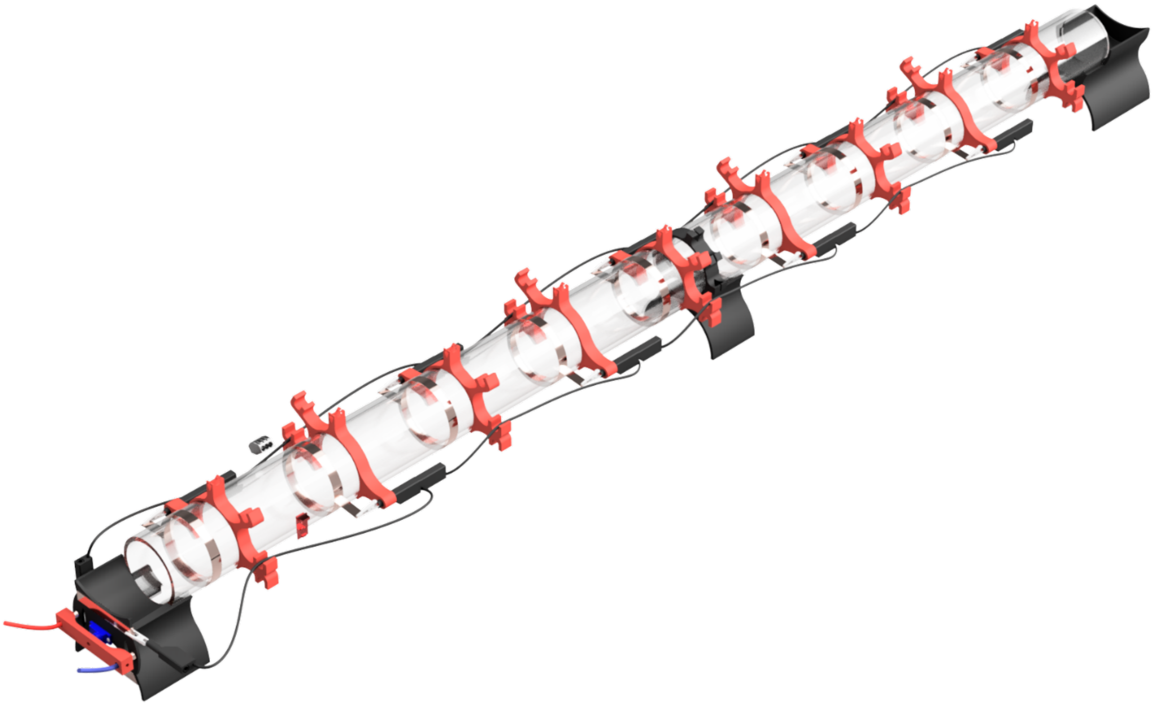
Place the plexiglass tube on the support structure, cut pieces of tape of suitable length, and place them in loops around the plexiglass tube as shown in the picture. The spacing of the loops will depend on the voltage you can achieve with the Wimshurst machine – the greater the voltage, the further the loops can be place apart. Try 15cm spacing as a starting value and adjust the spacing accordingly to obtain the maximum acceleration.

2.2.3. HV pylons



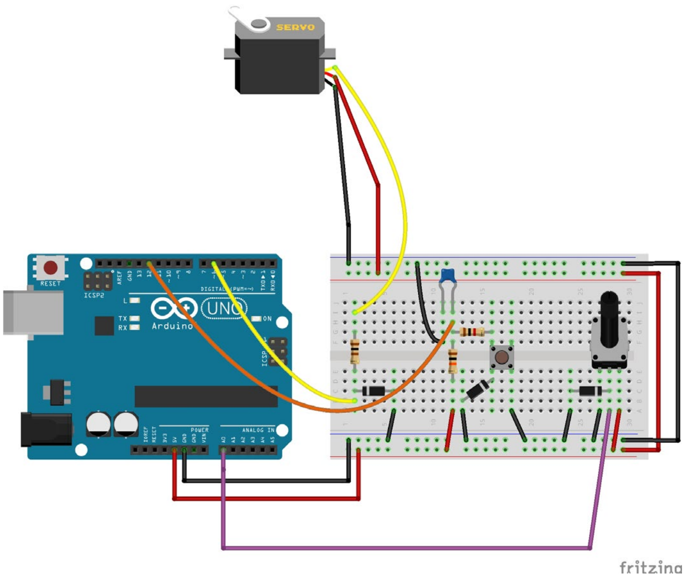
Clip the HV pylons onto the plexiglass tube with alternating orientation. Leave a bit of space between the HV pylon and the copper loops since the alligator clips have a certain length.

2.2.4. Connect Wimshurst machine and copper tape loops ("drift tubes")



Connect the HV lab cables of the switch to the Wimshurst machine, if not already done. Connect the HV lab cables clipped onto the copper tape of the HV switch to the drift tubes in an alternating fashion (see picture above). The HV cables should not touch the ground or conductive surfaces at any point since that will greatly reduce the voltage that can be constantly generated with the Wimshurst machine. You can use the metal spheres of the Wimshurst machine to determine the voltage that is achieved once the HV lab cables have been connected (1cm spark gap ~ 10kV). Usually, a significant voltage drop will be observed once the HV lab cables have been connected. This cannot be completely prevented; however, the voltage drop should be as small as possible.

2.2.5. Control circuit



The control circuit for the linear accelerator is depicted above. A sketch for the Arduino Uno is provided on the S'CoolLAB website.

Build the circuit according to the schematics and upload he provided sketch to the Arduino. Once powered up, two different positions of the HV switch will be stored in memory, which correspond to the positions between which the switch will alternate. Use the potentiometer to move the switch to the first position and press the pushbutton to store it into memory. After that, set the second position with the potentiometer and store it using the pushbutton.

Once stored, pressing the pushbutton again will result in the switch cycling between those previously-stored positons.

A word of explanation on the Zener diodes: The diodes serve as overvoltage protection for the Arduino input since the Wimshurst machine tends to induce considerable voltage peaks in the Arduino jumper wires. Additionally, software debouncing has been implemented. Several readings of the input for the pushbutton will be compared, and a change of state will only be accepted if these readouts match.

2.3) Operating the accelerator

Operating the accelerator model is straightforward. If not already done, spray the ping pong ball with the graphite spray to create a conductive coating. Do so several times and let it dry.

Place the coated ping pong ball on the track start. It needs to touch the copper tape; the track is slightly inclined to facilitate this contact. Make sure the Wimshurst machine is properly connected, and contact to the copper tape is made through the stripped HV cables. Usually, the ping ball should start moving by itself once the Wimshurst machine is charging up. If it does not, try to move the first "drift tube" (=copper tape loop) closer to the track start. Sometimes the ping pong ball has to be gently kicked off.

Once the ping pong ball starts moving down the tube, press the pushbutton each time, the ping pong ball passes through one of the loops. This will reverse the polarisation of the drift tubes and make the ball accelerate over time. As you will find, it can be quite challenging to time it just right. This can be used as a motivation to move on to the more sophisticated light barrier controlled LINAC model.

3) 3D printed LINAC: Automatic control via light barriers

The more sophisticated version of the LINAC uses light barriers to automatically detect if the ping pong ball approaches one of the drift tubes (=copper tape loops). Technically, it is an add-on to the simpler pushbutton LINAC. Only additionally required materials are therefore listed below.

2.4) Additional Materials & 3D printed parts required

A) Additional 3D printed parts
Light Barrier Mount  9x

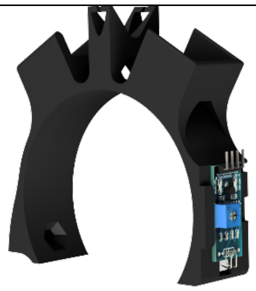
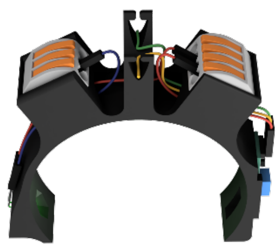
B) Additional materials required
Electronic components 9x Light-dependent resistor module for Arduino 9x lever-nuts with 4 connectors 9x lever-nut with 3 connectors 2x Zener Diode, 5,1V 2x resistor 100Ω 9x LED (green, 6000mcd, 20°) (Lots of) Jumper Wires, m-m, m-f, and f-f in different lengths

2.5) Assembly

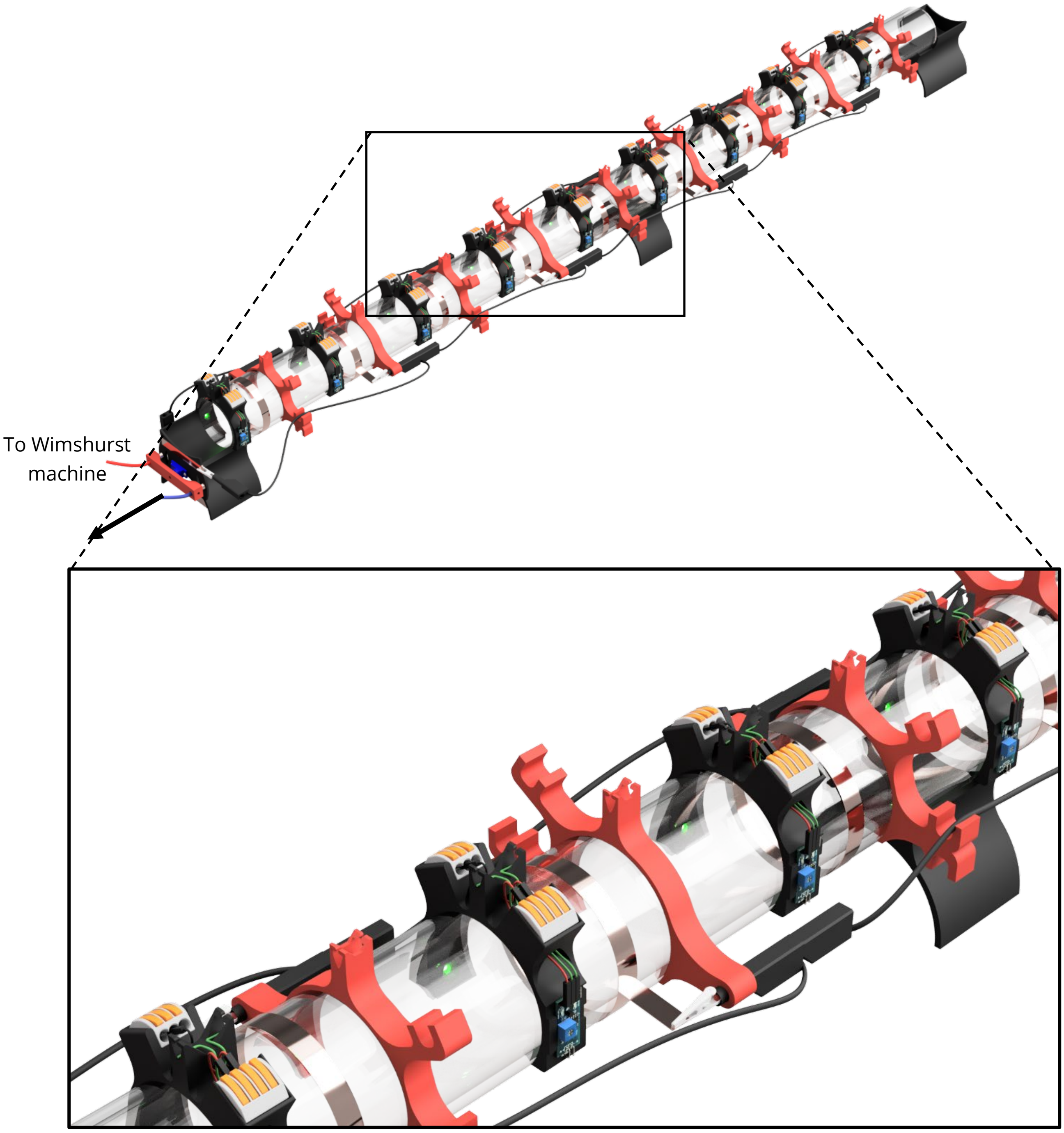
To install the light barriers in the linear accelerator, follow these steps

1) For each Light Barrier Mount:
   a. Attach the LEDs to the mount.
   b. Attach a Light-dependent resistor module to the mount.
   c. Insert the lever-nuts into the recesses of the Light barrier mounts.
   d. Connect the LED and the Light-dependent resistor module to the lever-nuts according to the schematic.
2) Clip the Light Barrier Mounts onto the plexiglass tube at the appropriate positions.
3) Modify the control circuit according to the provided schematic.
4) Wire the Light Barriers to each other and to the control circuit.
5) Upload the provided sketch to the Arduino.
6) Test and explore!

2.2.6. Assembly of Light Barrier Mount

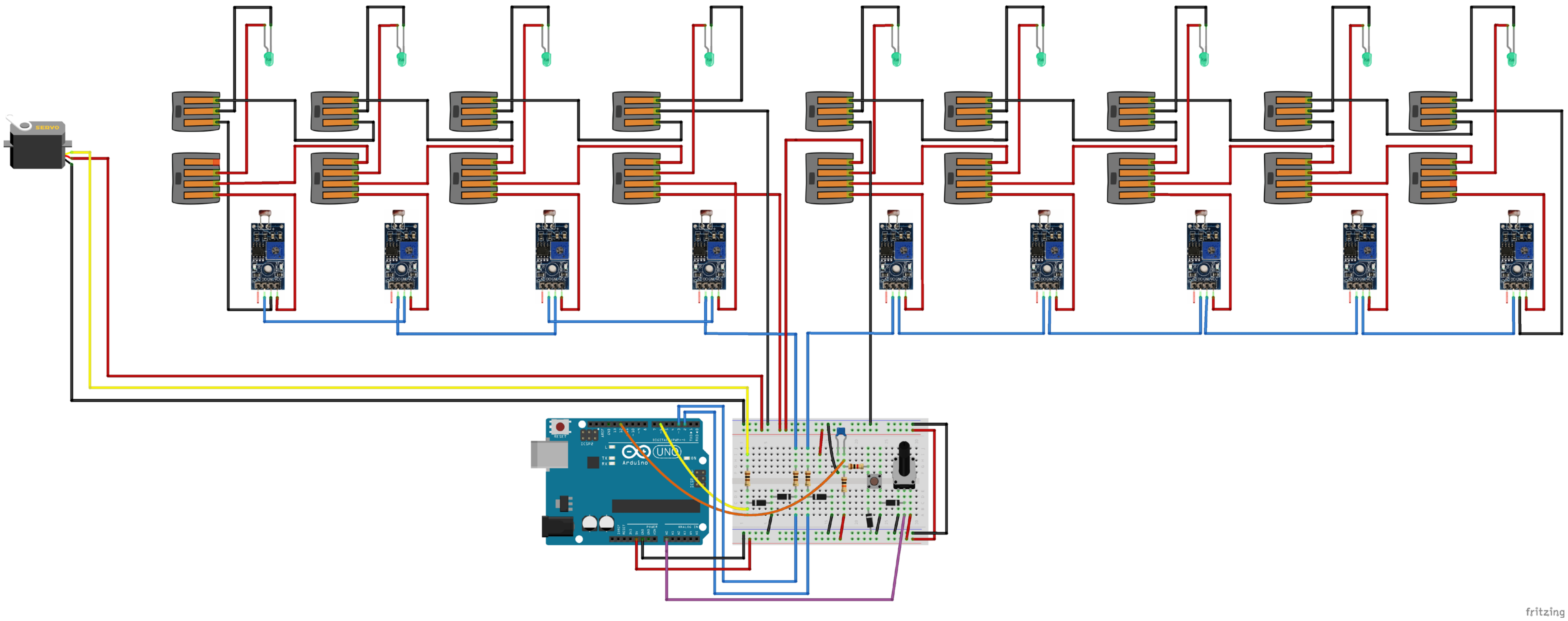
		
The 3D-printed part should look like this.	*Insert the LED into the recess from the inside. Guide the legs of the LED through the two openings provided for this purpose.*	*Carefully bend the legs of the LEDs.*
		
Press the photoresistor module onto the holder. Carefully bend the Photodiode so that it sits opposite the LED.	*Insert the lever-nuts onto the mount.*	*Wire LED and the photoresistor module according to the wiring scheme. Also, insert the jumper wires for the connection of the photoresistor modules to the neighboring Light Barrier Mounts.*

2.2.7. Attach the Light barrier mounts



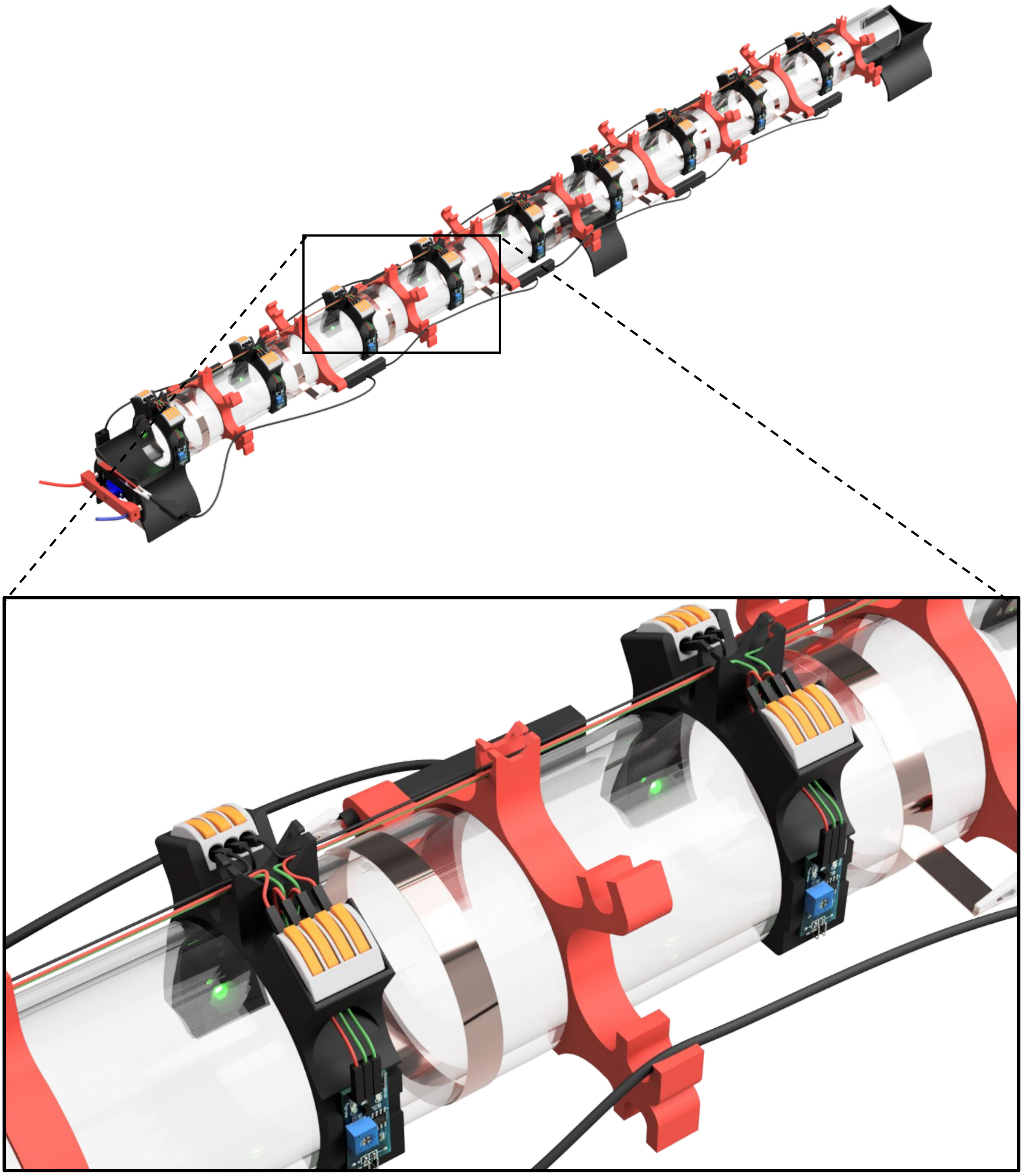
Clip the Light barrier mounts onto the plexiglass tube. The mounts should be placed on the opposite side of the copper tape relative to the HV connectors. Once the ball passes one of the light barriers, it will shade the photoresistor from the LED and thus trigger the HV switch. This will reverse the polarisation at the drift tubes and result in further acceleration of the ping pong ball.
LEDs have been chosen over laser diodes for safety reasons. Note, however, that laser diodes would generally produce a more reliable signal independent from external lighting conditions.

2.2.8. Modify the control circuit



Modify the control circuit to match the depicted schematic.

2.2.9. Wire the Light Barriers



Wire the light barriers according to the schematic. Set the threshold of the Light-dependent resistor modules using the adjustment screw in such a way that the HV switch will be triggered by the Arduino when the photoresistor is shaded from the LED by the ping pong ball.

*Note that the wiring of the Light-dependent resistor is somewhat unusual, a so-called daisy-chain (with output D0 being connected to the ground input of the next module). This is necessary to implement an inverted AND-logic; that is, the HV switch will be triggered if **any** of the modules changes its state from* *false (unobstructed light) to true (light blocked). Simply combining the (digital) outputs of all the light barrier modules would result in an OR-logic because only the light barrier which is blocked by the ball sets its output to 5 V representing logical 'true'. In this case the switch would only be triggered if **all** of the modules changed their state at the same time. This is obviously not what is needed here. This wiring comes at the price that only a certain number of modules can be connected in a row. If a module is triggered, all of the subsequent modules will be turned off (since ground will be on VCC level and therefore there won't be any potential difference anymore). This will result in the switch being triggered.*

2.2.10. Upload the Arduino sketch, set the photoresistor threshold, test

Operation of the LINAC is very simple once all of the thresholds of the light-dependent resistor modules have been set correctly. Place the ball on the track, start, and turn the crank of the Wimshurst machine. The ping ball will start moving through the plexiglass tube, and the HV switch should automatically be triggered each time the ping pong ball passes the light barrier. As a consequence, the ping pong ball should be accelerated throughout the tube.

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Reference Images