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# EURO-LABS

EUROpean Laboratories for Accelerator Based Science  
HORIZON-INFRA-2021-SERV-01-07 Project EURO-LABS

## MILESTONE REPORT

# Design of the XY table and purchase of materials and equipment for the device

## MILESTONE: MS31

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### Abstract:

A two-dimensional scanning table has been developed, installed, and tested at the 60 MeV proton irradiation line of the AIC-144 cyclotron at the Institute of Nuclear Physics of the Polish Academy of Sciences. The table allows to uniformly irradiate an area of 385 mm x 405 mm. The system is ready to be used for irradiation of electronics and testing of detectors where a broad radiation field is required. The system be used for the incoming. The experiments using Transnational Access within WP4 of EURO-LABS will greatly benefit from this apparatus.

EURO-LABS Consortium, 2024

For more information on EURO-LABS, its partners and contributors please see <https://web.infn.it/EURO-LABS/>

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## Executive summary

*A 2D scanning table has been installed, tested, and put in operation at the irradiation line of the AIC-144 cyclotron at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków. The device was fully designed and assembled at the Department of Radiation Research and Proton Radiotherapy IFJ PAN. The 2D scanning table enables precise positioning of detectors for beam scanning and irradiation of samples attached to the scanning surface. The table allows to irradiate the area of 385 mm x 405 mm. The system is controlled by the dedicated software tool XY Scanner written in the Phyton framework. It was demonstrated that the table allows for sample positioning with the precision better than 1 mm. The system is ready for supporting irradiation of electronics and testing of detectors when broad homogenous radiation fields are required. The system will be used for the incoming Transnational Access experiments within WP4 of EURO LABS.*

## 1. INTRODUCTION

The proton irradiation station located at the Experimental Hall of the AIC-144 cyclotron at the Institute of Nuclear Physics of the Polish Academy of Sciences, is used for performing scientific experiments and for tests of detectors and electronics with accelerated proton beams. The beam diameter depends on the beam production method and ranges from about 10 mm to about 120 mm. Moving the target with respect to the stable beam position allows to increase the size and the uniformity of the irradiation field. Finally, a quick and reproducible method to measure beam profiles is needed in order to precisely adjust the position of irradiated targets before and during the irradiation.

The goal of this work was to develop a 2D scanner to enable precise positioning of detectors for beam scanning and irradiation of samples attached to the scanning surface. The design, construction and testing of the device was performed at the Department of Radiation Research and Proton Radiotherapy in the Institute of Nuclear Physics of the Polish Academy of Sciences.

## 2. THE DEVICE AND ITS PARAMETERS

The scanning table contains two linear drives (one for horizontal – X axis, one for vertical – Y axis) attached to each other and a frame to which irradiated samples and probes can be attached, either directly or by additional holders. The device is mounted on the irradiation bench rail – like for the other equipment (e.g. collimators and ionisation chambers) its position along the beam axis (Z) can be adjusted. Depending on the Z position, the sample can either hang over the bench or over the floor behind the bench's end. In the latter case it is possible to irradiate larger samples, i.e. the beam axis

can reach not only the bottom, but also the middle or top points of the sample. Using commands sent via Ethernet from a PC in the control room, the sample can be positioned to static coordinates or automatically scanned along a programmed trajectory with selected speed and optional pause times at specified points. The scanner's control programme can also simultaneously acquire data from two Unidos electrometers, which enable the measurement of beam profiles.

The main device parameters are listed below:



*Fig. 1 The XY table at the irradiation station at the AIC-144 at IFJ PAN. An electronic circuit mounted on the scanning surface for irradiation.*

- External dimensions:  
length: 200 mm  
width: 960 mm  
height: 780 mm
- Frame dimensions:  
Axis X = 500 mm  
Axis Y = 320 mm
- Movement ranges:

Axis X = 385 mm

Axis Y = 405 mm

- Maximum torque: 2.40 Nm
- No. steps for revolution: 200
- Translation per one motor step: 0.04 mm
  - One step:  $1.8^\circ$
  - Screw translation: 8 mm / 1 revolution

### **3. DESIGN AND CONSTRUCTION**

#### **3.1. MECHANICAL CONSTRUCTION**

The scanner includes two rails, each one with a carriage. The first rail is mounted horizontally to the irradiation bench. The second one, vertical, is mounted on the horizontal carriage. Finally, a frame to which samples and probes can be attached, is mounted on the vertical carriage. Each carriage is moved by a lead screw, placed inside the rail. The screw goes through a plastic anti-backlash nut block, mounted below the carriage. To prevent the backlash, which would reduce the positioning precision, the block consists of two separate threaded parts joined by a flexure. A small screw goes through a thread in one part and presses the second one, prying apart the two threaded sections. To minimize friction between the carriages and rails, each carriage has four plastic rollers mounted on the corners.

#### **3.2. DRIVES**

Scanner's lead screws are rotated by two stepper motors. This kind of motor is suitable for the application because they can move with high precision and provide a high torque without the need to use a transmission. To provide reliable operation, elastic couplings made of aluminium are used to connect motors with lead screws. They compensate any small nonlinearities between the motors and screw axes while transmitting the torque.

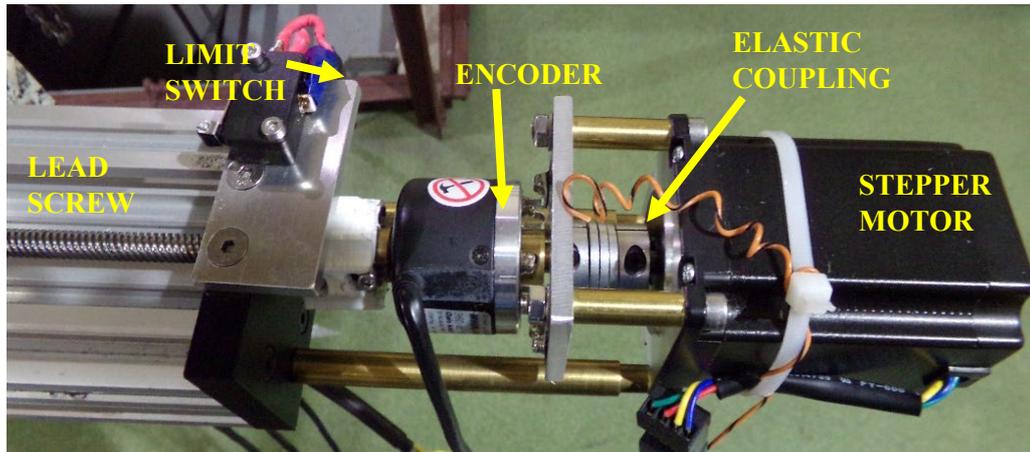


Fig. 2 Drive of the X axis (step motor, encoder elastic coupling, limit switch, lead screw).

### 3.3. POWER SUPPLY

The scanner is powered by one-phase 230 V 50 Hz voltage. To provide lower voltages necessary for its component's operation and user safety, two DC power supplies are used:

- DIN100W24 – 24 V, max 100 W (4.15 A), powers the stepper motor drivers and devices connected to them: motors and encoders.

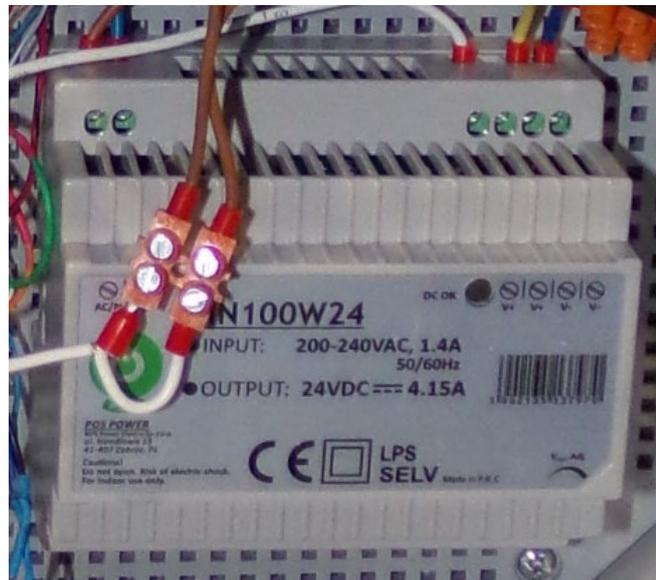


Fig. 3 DIN100W24 power supply for HBS86H steering drivers.

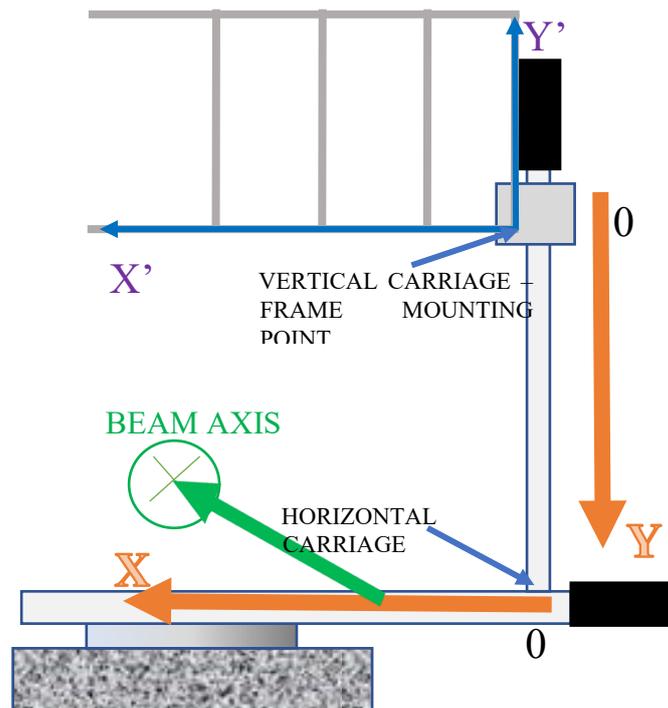
- 12V/2.9A – powers the control system – this power supply is connected to one Arduino® Uno (Arduion® Uno - controller board based on the ATmega328P microchip) board containing a voltage regulator, which further reduces the voltage to 5V. This voltage powers this Arduino board, the second one connected to it and also a Waveshare UART (Universal Asynchronous Receiver-Transmitter) to Ethernet converter. Two separate power supplies are used, because otherwise the circuit with motors could cause interference in the control system by introducing

voltage changes (i.e. high, changing power consumption by motors, voltages induced in their coils).

### 3.4. DESCRIPTION OF XY TABLE COORDINATE SYSTEM.

The scanner position can be described by two coordinates: X and Y. X is the position of the horizontal carriage on its rail, Y – the vertical carriage position.

- X is zero when the horizontal carriage is near it's left end (when we look towards the ion guide – similar to a patient undergoing an eye radiotherapy). When the scanner moves right, X increases.
- Y is zero when the vertical carriage is near its top end. When the scanner moves down, Y increases.



*Fig. 5 Coordinate system of the scanner. For the origin ( $X=0$ ,  $Y=0$ ) the scanner stays in its reference (zero) point. When the frame moves downwards, Y increases. When it moves left, X increases. The second coordinate system,  $X'Y'$ , provides the position in the frame – it can be used to describe where samples are mounted.*

There is also the second coordinate system:  $X'$  and  $Y'$ . It's associated with the scanner's frame – if an element is tightly attached to the frame, it has certain  $X'$  and  $Y'$  coordinates which don't change during

the scanner movement. If we mount a sample in the  $[X', Y']$  point of the frame, we can find the  $[X, Y]$  scanner position in which the sample will pass the beam axis using the following equations:

$$X = X' + A$$

$$Y = Y' + B$$

A and B are values which have to be measured after each disassembly or other reconfiguration of the scanner.

## 4. SOFTWARE DESCRIPTION

### 4.1. SYSTEM REQUIREMENTS

The *XY Scanner* software tool controls the scanner operation. It can be run it on a PC after meeting the following requirements:

- processor: Intel CITM) i5 CPU 650 @ 3.20GHz 3.19 GHz
- RAM: 2.0 GB (available 1.8 GB)
- system: Windows 10 Pro 64bit, version: 22H2
- Python 3.9.7 (necessary to run the program)
- at least one Ethernet card (necessary to connect to the scanner)

### 4.2. MAIN CONTROL PANEL

The *XY Scanner* software has been written in the Python language. The graphical user interface (GUI) of the software is presented in Fig. 6.

The *XY Scanner* package has been shared on: <https://github.com/SebastianKusykIFJ/ProtonScanner>.

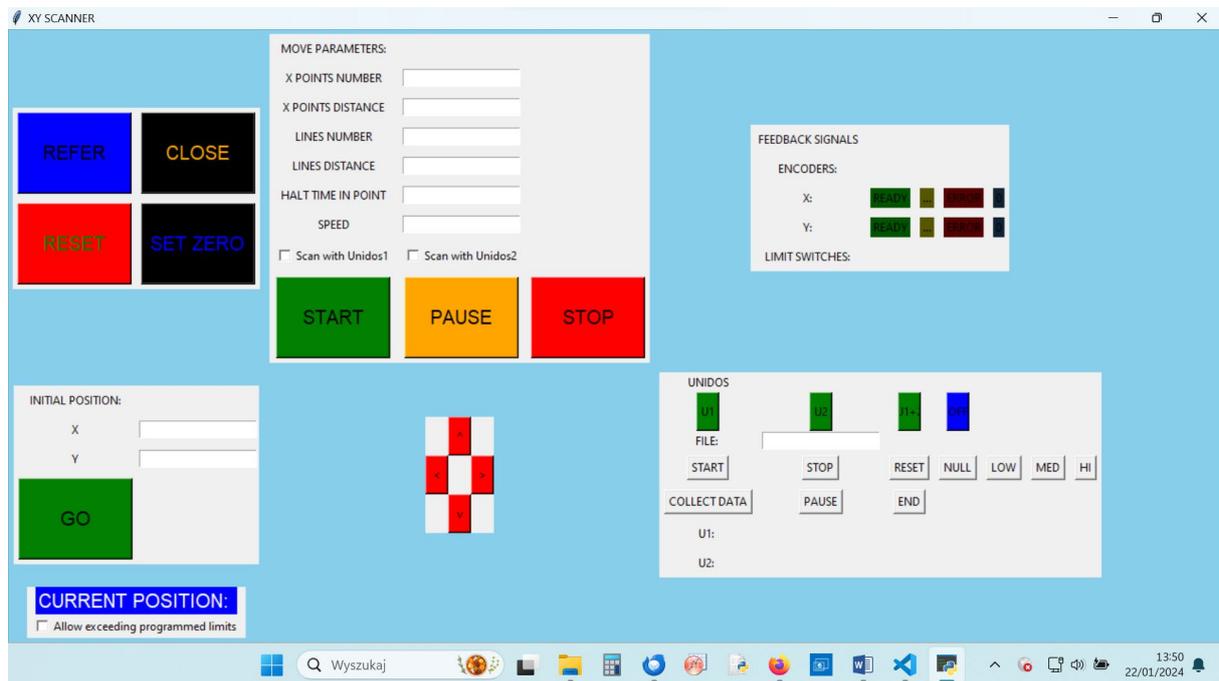


Fig. 6 Graphical user interface to control the use of the XY scanner

The general functionality of the GUI is described below:

- General controls:
  1. RESET button – performs a soft reset of GRBL (*GRBL - an open-source software that enables precise control of Computerized Numerical Control machines*). It offers superior motion control, accuracy, speed, and cost-effectiveness when used with Arduino boards (The acronym for the name GRGL comes from the name of the gerbil rodent also known as the desert rat/) by sending an appropriate command to the scanner.
  2. REFER button – performs homing of the scanner. First, a standard GRBL homing procedure is executed: scanner moves in both axes until limit switches are pressed, retracts until they are released and repeats this cycle for the second time. However, to find a more accurate zero point, both axes are then moved away from limit switches to the nearest zero points detected by encoders. Prior to that, Arduino2 is directed to start forwarding encoders' zero signals to GRBL limit switches input. After precise homing finishes, Arduino2 is directed to stop forwarding that signal and the displayed current position is set to zero.
  3. SET ZERO – defines the current position as zero in both axes. This button can be pressed for test or if user is unsure about the current position.

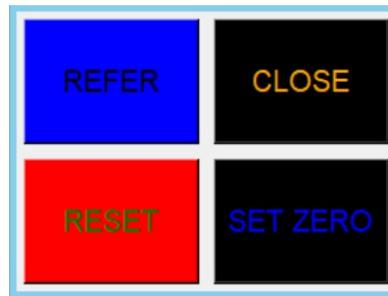


Fig. 7 General controls frame.

- Initial position – moves the scanner to a given point (coordinates in mm). User enters the coordinates in X and Y fields and presses GO button to start moving.

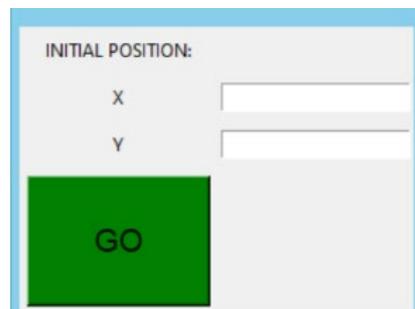


Fig. 8 Initial position frame. By typing 0 in X and Y fields and clicking GO, one can command the scanner to move to its initial coordinates.

- Current position – displays the current position according to the PC program. If homing hasn't been completed and user hasn't pressed the SET ZERO button, the field remains empty, because the coordinates are unknown. "Allow exceeding programmed limits" checkbox controls whether the program can send commands which would make the scanner move beyond the programmed limits. This box is unchecked by default. It can be checked for test purposes or if the user is sure about the scanner coordinates and doesn't want to run unnecessary homing (i.e. one knows that the scanner has been at [100, 100] coordinates when the program was started and wants to move to [-100, -100] coordinates and redefine them as [0, 0] by pressing SET ZERO).



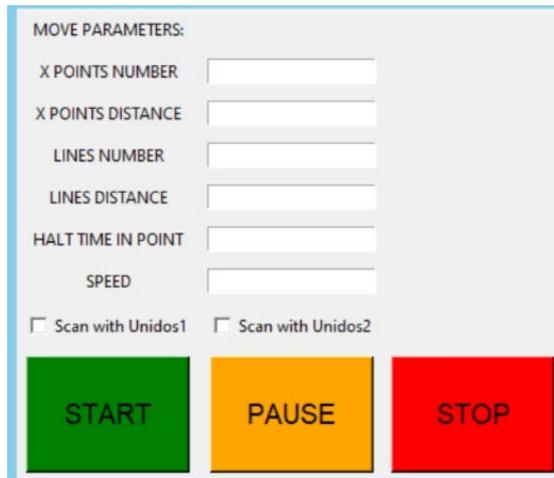
Fig. 9 Current position frame. Before homing, it displays no coordinates, because they are unknown. After homing, it displays the coordinates where the scanner should be placed according to its latest queued command.

- Move parameters – enables automatic scanning. During this process, scanner moves along a trajectory composed of horizontal lines. For a number typed in LINES NUMBER it repeats the following cycle:
  1. Moves in X direction, increasing X, for X POINTS DISTANCE – it is repeated X POINTS NUMBER times.
  2. Moves in Y direction, increasing Y, for LINES DISTANCE.
  3. Moves in X direction, decreasing X, for X POINTS DISTANCE – it is repeated X POINTS NUMBER times.
  4. Moves in Y direction, increasing Y, for LINES DISTANCE.

All movements are performed with speed set in the SPEED field. Scanning can be performed in two modes:

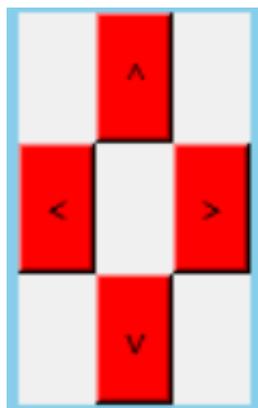
1. Commands are queued in GRBL memory, PC sends a new command when GRBL accepts it (has sufficient memory for its storage). In this mode the scanner doesn't stop at the defined points. This mode is active when HALT TIME IN POINT is empty or zero and none of "Scan with Unidos..." are checked.
2. GRBL gets a new command after it has finished the previous one (PC asks GRBL each 0.5 s about the operation status). In this mode the scanner halts at each defined point for a short time, waiting for the next command. In this mode in each point two optional operations can be realized:
  - a. additional waiting time, typed in HALT TIME IN POINT – time measurement is realized by the PC clock.
  - b. Unidos electrometer measurements: depending on which checkboxes are checked, the program will ask the selected electrometer(s) about the measured value and wait for their response. The received values are saved in a log file with the coordinates received from GRBL.

This mode is active when HALT TIME IN POINT is greater than zero or at least one of the "Scan with Unidos..." checkboxes is checked.



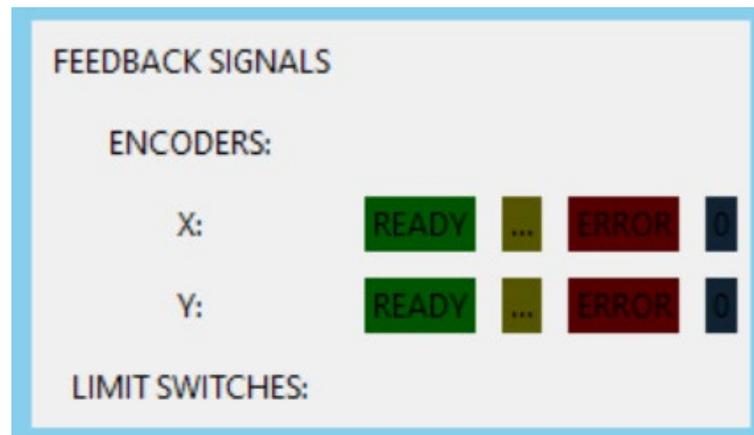
*Fig.10 Move parameters frame.*

- Jog buttons– pressing these buttons allows for short movements of the scanner.



*Fig. 11 Jog buttons frame.*

- Feedback signals – displays the feedback signals received from stepper motor drivers and from encoders. The appropriate fields light up depending on the drivers' status or when encoders are crossing their zero points.



*Fig. 22 Feedback signals frame.*

### 4.3. ARDUINO SOFTWARE DESCRIPTION

Scanner contains two Arduino microcontroller boards. One of them (Arduino1) runs GRBL firmware, available on <https://github.com/gnea/grbl/> (GNU General Public License). It communicates with PC through UART port and controls the stepper motor drivers and limit switches. GRBL can also control tools such as spindles or laser engravers, which opens the possibility to control the beam shutter if the necessary safety requirements are fulfilled.

The second Arduino (Arduino2) contains a custom written program. It is used for auxiliary functions, which GRBL does not support:

- Detection of the zero signals from encoders for precise homing. Arduino2 pins are connected to Arduino1 GRBL end stops input in such a way that Arduino2 can set logic states which override those generated by end stops. Enabling and disabling this override is controlled by commands sent from PC.
- Checking operation status of motor drivers. HBS86H motor drivers have feedback outputs which send the information about operation status: whether set and measured positions are the same or not, or if an error happened and drivers stopped working. Arduino2 reads the logic states of these outputs and sends them to PC.
- Scanner movement with push buttons. The device can be controlled not only from the control room, but also in the Experimental Hall with a small control panel.

## 5. ACCEPTANCE TESTS

The acceptance tests of the XY table were split into the tests without beam (tests of the drive systems) and the tests during proton irradiation.

## 5.1. TESTS OF THE DRIVE SYSTEMS

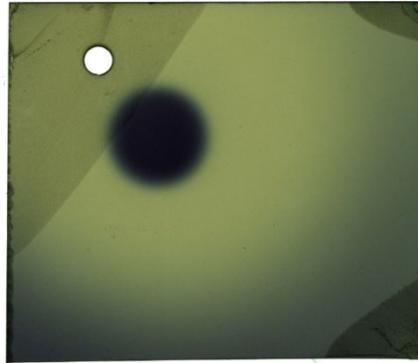


*Fig. 13 Scanner trajectory registered with pen and paper for the following parameters:  
 X points number: 2; X points distance: 40; lines number: 100; lines distance: 1mm; halt time in point: 0, speed: 1000.*

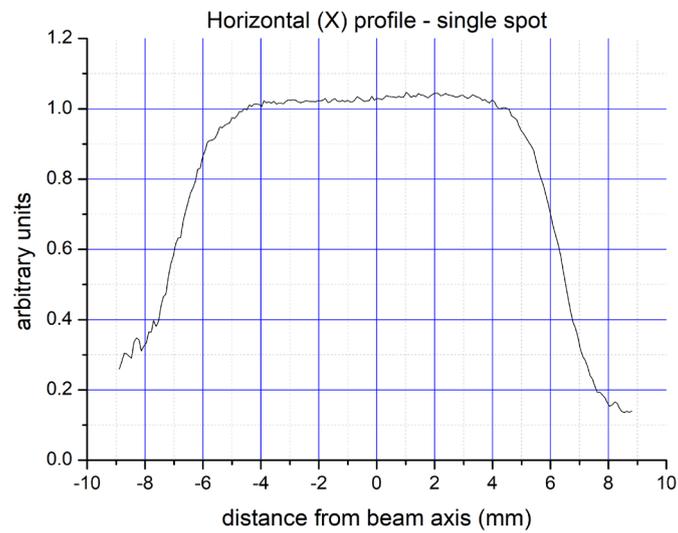
Several scanner tests were performed without the proton beam. In Fig. 13 an example of such a test is presented. A pen attached to the scanner frame drew trajectories on a piece of paper attached to a vertical surface. In this way, the accuracy of horizontal and vertical movement was checked. The line distance was set to 1 mm. This was one of the tests which demonstrated that the XY table is capable of positioning with an accuracy much better than 1 mm.

## 5.2. IRRADIATION TESTS

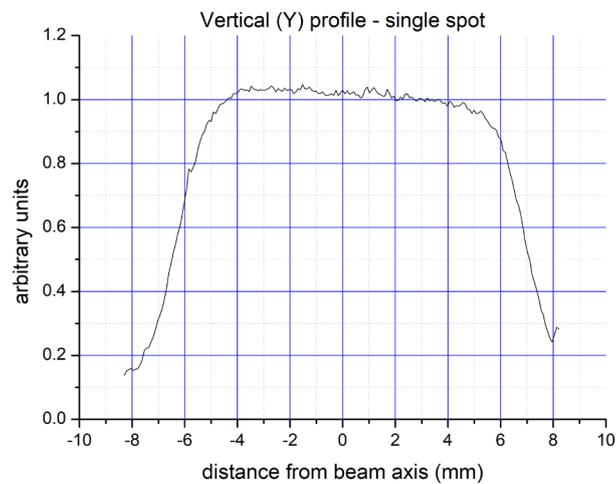
The performance of the XY table during proton irradiation was tested using Gafchromic EBT-3 films (self-developing dosimetry film). In Fig. 14 the Gafchromic film was irradiated with a 60 MeV proton beam collimated by a 10 mm diameter collimator. In Figs. 15 and 16 the beam profiles obtained by scanning the optical density of the irradiated film are presented.



*Fig. 14 Gafchromic film 1 - after irradiation in static position.*



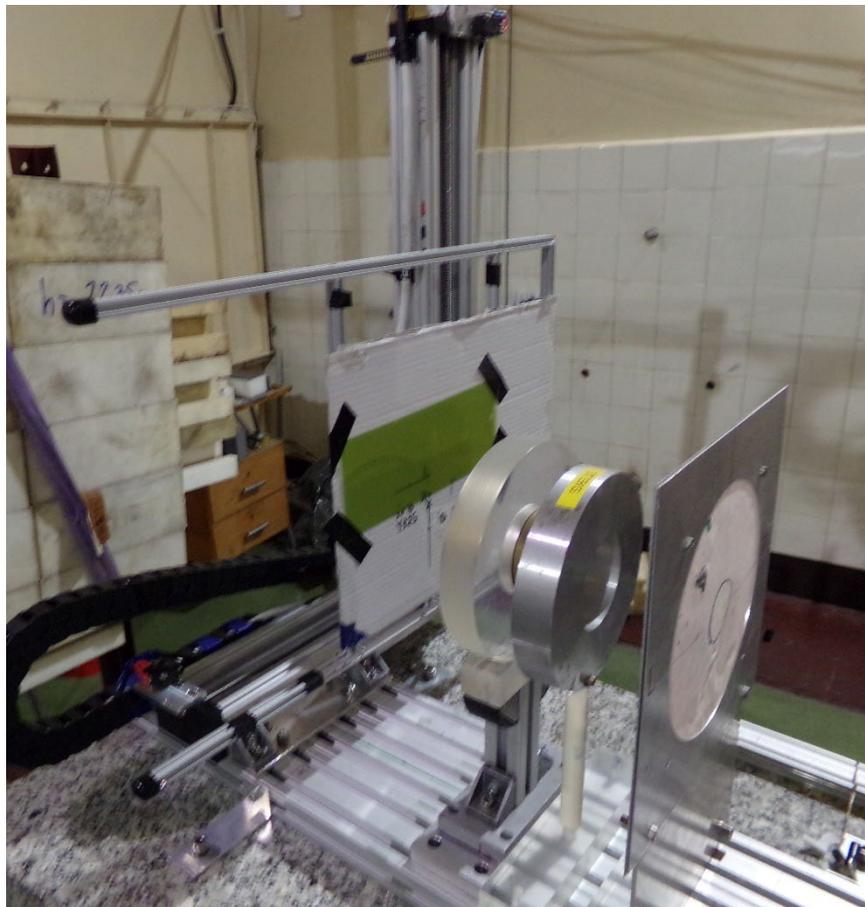
*Fig. 35 Horizontal beam profile for a single irradiation position.*



*Fig. 16 Vertical beam profile for a single irradiation position.*

The second film was placed in such position that every point on it could be reached by the beam centre. The point [ $X'=215\text{mm}$ ,  $Y'=325\text{mm}$ ] was now the centre of the bottom edge of the film. The following parameters have been set:

- Initial X: 100
- Initial Y: 314
- X points number: 15
- X points distance: 13
- Lines number: 6
- Lines distance: 13



*Fig. 17 Irradiation setup for film 2 and 3.*

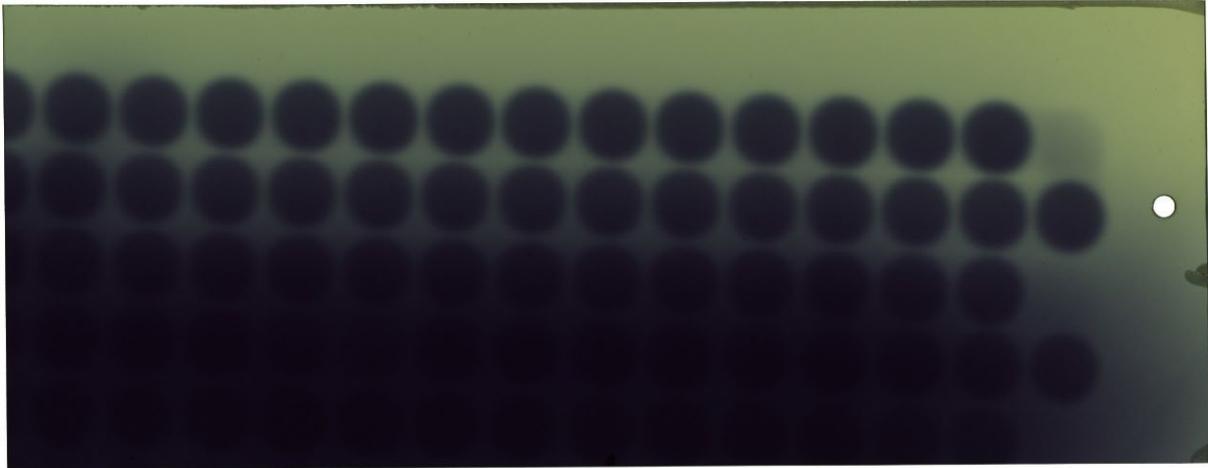


Fig. 18 Results of irradiation of Gafromic film with collimated 60 MeV proton beam in step-shoot mode.

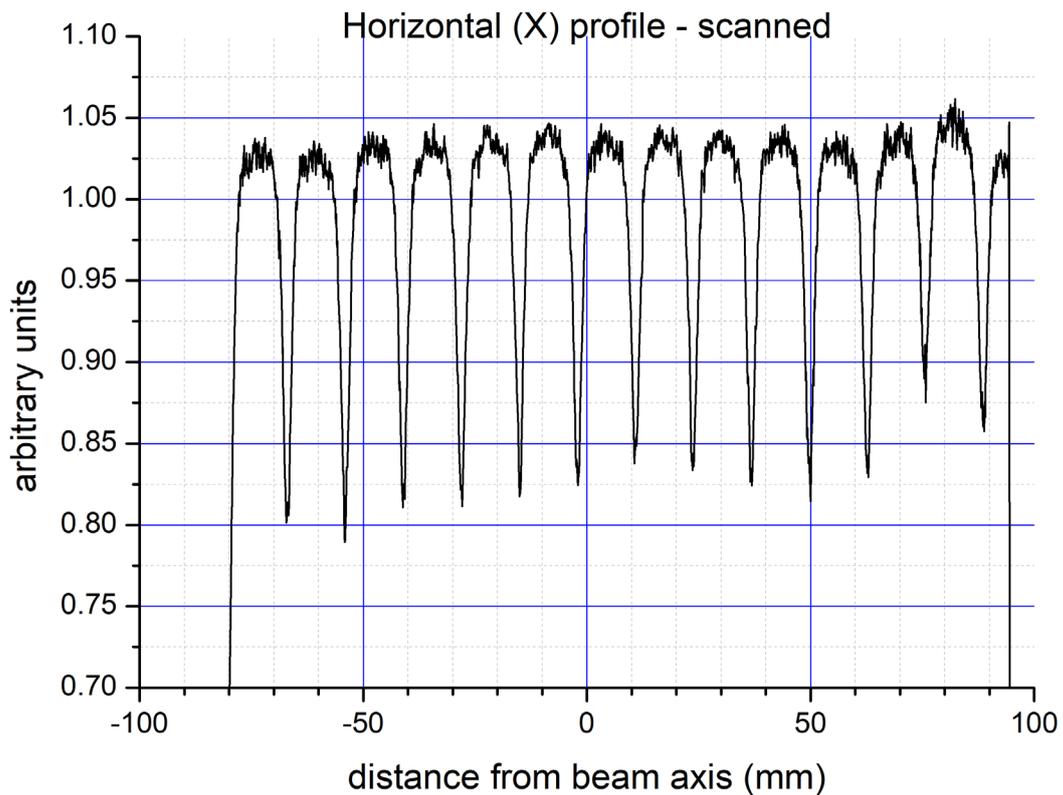
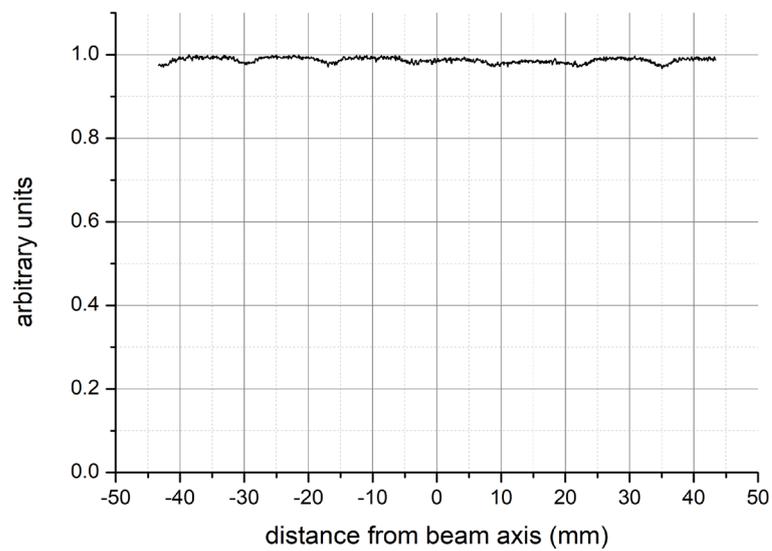


Fig. 19 Horizontal profile of the top line on film 2, measured approximately through centre points of irradiated spots (see Fig.18).

The third picture (Fig.20) shows a uniformly irradiated field measuring 87.5 mm by 40.3 mm.



*Fig.20 Result of uniform irradiation of Gafromic film with a collimated proton beam of 60 MeV energy.*



*Fig. 21 Horizontal irradiation profile of film 3 (from Fig. 20), dose uniformity +/- 1.5%.*

## 6. SUMMARY

A 2D scanning table has been installed, tested, and put in operation at the irradiation line of the AIC-144 cyclotron at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków. The device was fully designed and assembled at the Department of Radiation Research and Proton Radiotherapy IFJ PAN. The 2D scanning table enables precise positioning of detectors for beam scanning and irradiation of samples attached to the scanning surface. The table allows to irradiate the area of 385 mm x 405 mm. The system is controlled by the dedicated software tool *XY Scanner* written in the Python framework. It was demonstrated that the table allows for sample positioning with the precision better than 1 mm. The system is ready for supporting irradiation of electronics and testing of detectors when broad homogenous radiation fields are required. The system will be used for the incoming Transnational Access experiments within WP4 of EURO LABS.

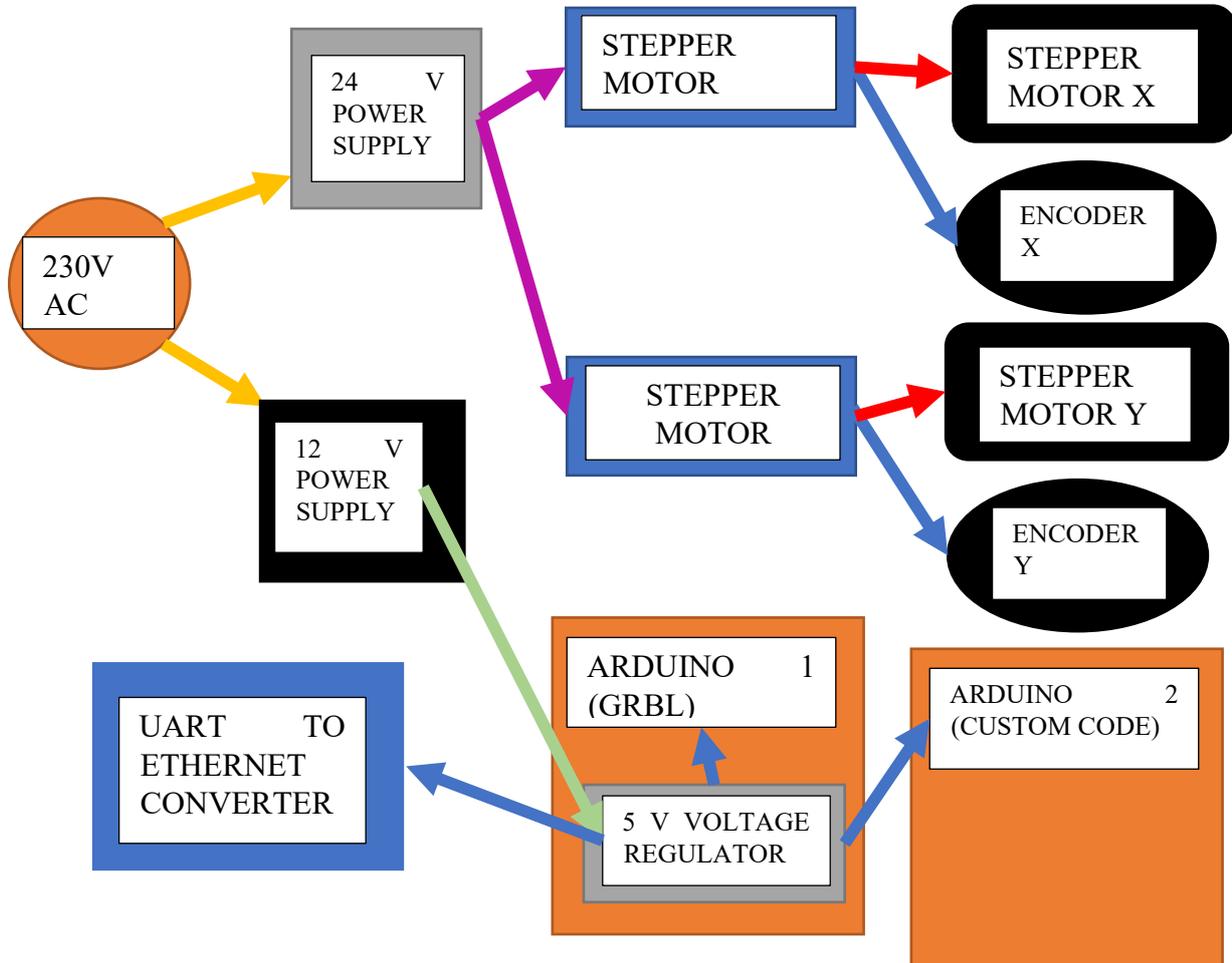
## 7. APPENDIX 1

List of parts used to assemble the 2D scanning table:

1. 2x C-Beam Linear Actuator Bundle, 500 mm, with Nema 23 stepper motor, 1.8 deg/step, 340 oz-in
2. 4x limit switch
3. 2x optical encoder MHK40 8/360/5/BZ/N
4. 1x 24V power supply DIN100W24
5. 1x 12V power supply
6. 1x safety switch
7. 2x stepper motor driver Leadshine Easy Servo HBS86H
8. 2x Arduino Uno
9. 1x Waveshare 2-channel UART to Ethernet converter

## 8. APPENDIX 2

Block diagram of the electric system.



*Fig.22 Power distribution block diagram.*

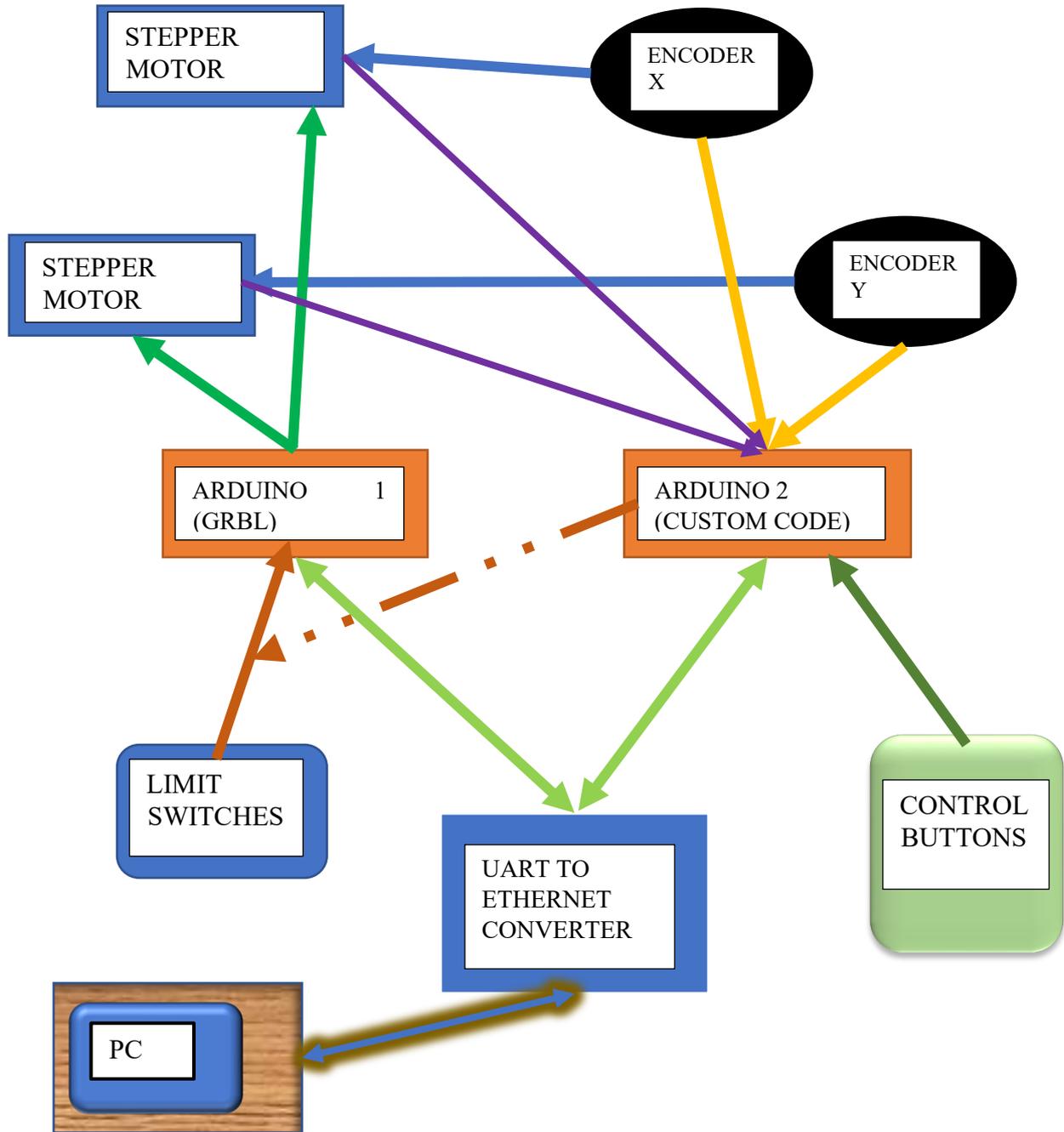


Fig.23 Signal distribution block diagram.

## 9. APPENDIX 3

Configuration of open source GRBL firmware for Arduino.

code	meaning	value
\$0	Step pulse, microseconds	10
\$1	Step idle delay, milliseconds	25
\$2	Step port invert, mask	0
\$3	Direction port invert, mask	0
\$4	Step enable invert, boolean	0
\$5	Limit pins invert, boolean	1
\$6	Probe pin invert, boolean	0
\$10	Status report, mask	1
\$11	Junction deviation, mm	0.01
\$12	Arc tolerance, mm	0.002
\$13	Report inches, boolean	0
\$20	Soft limits, boolean	0
\$21	Hard limits, boolean	1
\$22	Homing cycle, boolean	1
\$23	Homing dir invert, mask	0
\$24	Homing feed, mm/min	25
\$25	Homing seek, mm/min	500
\$26	Homing debounce, milliseconds	250
\$27	Homing pull-off, mm	1
\$30	Max spindle speed, RPM	1000
\$31	Min spindle speed, RPM	0
\$32	Laser mode, boolean	0
<b>\$100</b>	<b>X steps/mm</b>	<b>100</b>
<b>\$101</b>	<b>Y steps/mm</b>	<b>100</b>
\$102	Z steps/mm	100
\$110	X Max rate, mm/min	5000
\$111	Y Max rate, mm/min	5000
\$112	Z Max rate, mm/min	5000
\$120	X Acceleration, mm/sec <sup>2</sup>	100
\$121	Y Acceleration, mm/sec <sup>2</sup>	100
\$122	Z Acceleration, mm/sec <sup>2</sup>	100
\$130	X Max travel, mm	1000
\$131	Y Max travel, mm	1000
\$132	Z Max travel, mm	1000