CERN-EN-2019-001

Motorized linear stages for the UA9 experiment

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Abstract

In this paper, we describe the mechanical structure of the motorized linear stages that are used for plastic scintillator detector placement in a high-energy particle beam during the dedicated UA9 collaboration measurements at CERN, including a detailed overview of the software. The stages show adequate operational performance, such as a step resolution of about 4 μm and a positioning repeatability of about 10 μm. Meanwhile, the graphical interface that we have developed gives us the possibility of easily manipulating the system remotely. The linear stages were successfully used during the last two years (2017–2018) of test-beams at the SPS North Area beamline.

Keywords: Crystal, Translation Stage, Stepper Motor, Arduino, MATLAB.

1. Introduction

Interest in the use of bent crystals for high-energy particle beam collimation and extraction by means of the channelling effect between crystalline plane has recently increased. [1–4]. A significant contribution to the technological progress of the development and installation of these crystals in accelerators was made by the UA9 collaboration [5, 6]. However, to use any bent crystal for charged particles steering, it first has to be characterized by the determination of its main properties, including deflection angle, channelling efficiency, and so on. We have conducted these measurements at the H8 SPS extraction beamline [7].

A charged particle that crosses a crystal which is few millimeters long can inelastically interact along the path with the nuclear of the lattice, producing a shower of secondary particles. Therefore, measurement of the probability of the inelastic nuclear interaction (INI) and its dependence on the crystal planes orientation with respect to the beam direction [8, 9] is one of the most important goals of the experiment. We have used an installed dedicated tracker [10] to reconstruct the particle tracks before and after the crystal (Fig. 1a). The tracker consists of five position-sensitive micro-strip planes. The angular resolution of each arm (upstream arm: Plane 1 and Plane 2; downstream arm: Plane 3, Plane 4 and Plane 5) of the tracker is about 2.8 μrad for a 400 GeV/c proton beam. Due to the multiple Coulomb scattering, the cumulative angular resolution is about 5.2 μrad.

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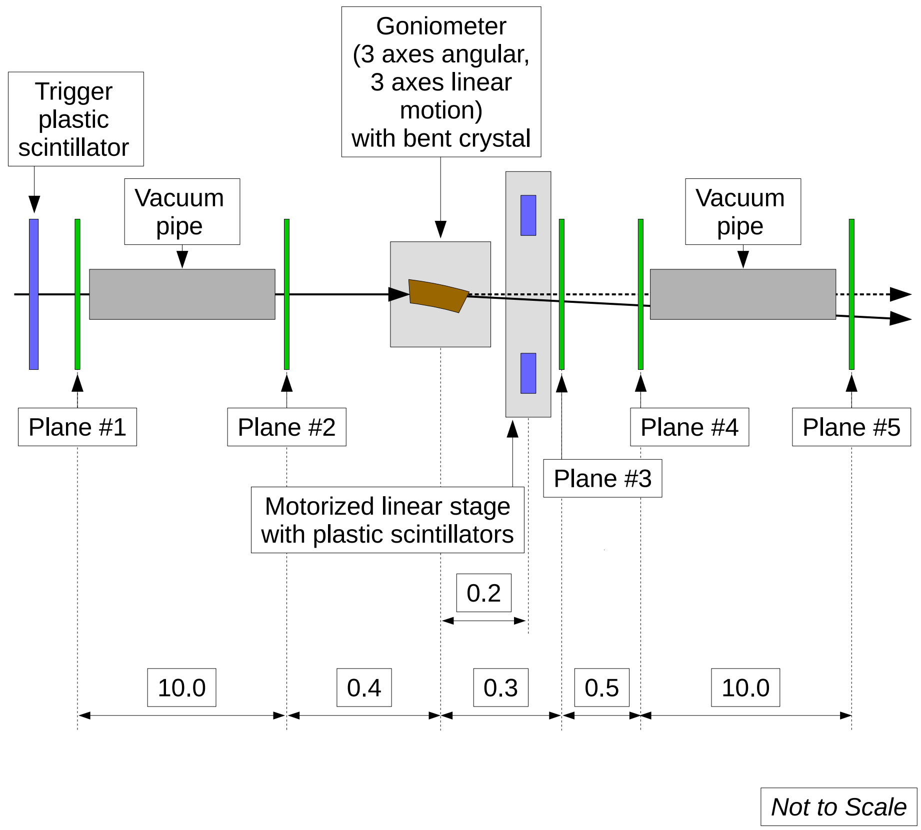
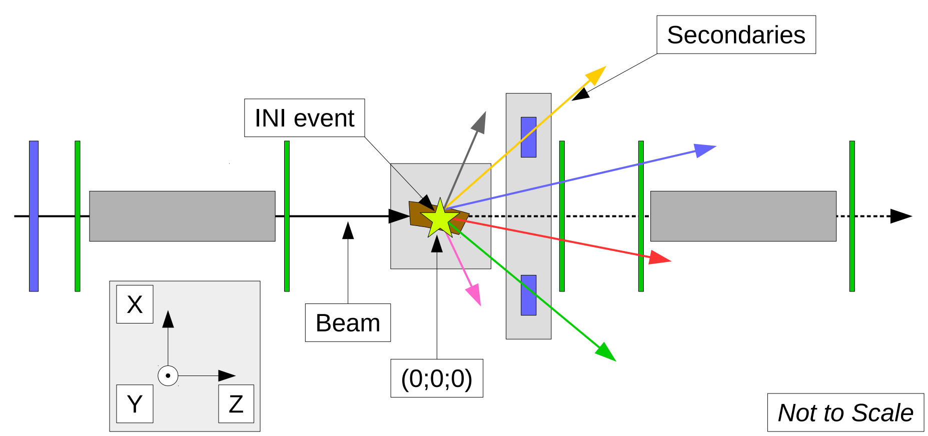


(a) Experimental setup. The rough distances are given in meters.



(b) Illustration of the INI event.

Figure 1: H8 apparatus of the UA9 experiment.

To measure the INI that happens in the crystal (Fig. 1b) a pair of plastic scintillators [11] ($10 \times 25 \times 5$ mm^3) is used in coincidences mode. For more effective INI events registration, the position of the detectors should be accurate and symmetrical (with precision of about 0.1 mm) with respect to the center of the beam.

Until 2017, plastic scintillators were usually manually installed on the beamline, each time interrupting the operation of the experimental line. This procedure of the work was laborious and cost a lot of experimental time. Thus, it was decided to create motorized linear platforms to move the plastic scintillators with the possibility of remote control. It was also possible to remotely carry out calibration and alignment of the detectors with respect to the beam direction.

In this paper, we indicate the structure of the platforms and the software that we used for their remote control. We will also describe some of the results of the beam profile scanning using the linear stages and plastic scintillators.

2. Hardware description

2.1. Stages

Using SOLIDWORKS® 3D CAD [12] software, we have developed 3D models of double (Fig. 2) and single (Fig. 3) translation stages. Some aluminum components (1–4 on Figure 2) for the linear stages are produced by the CERN workshop, the plastic holders (5 on Figure 2) for the scintillators and boxes for the DB9 connectors (14 on Figure 2) are 3D printed. The most important components (6–14, 17 on Figure 2) of the stages are available from [13]. The single translation stage is just a copy of the double stage half.

To satisfy all of the experimental requirements, two new single translation stages, which were already assembled (Fig. 4), were the same as single stage to reproduce the double stage. The stroke of all of the stages is about 200 mm, with a thrust of more than 10 kg, repeatability better than 10 μm and maximum speed 10 mm/sec with a resolution (16 microstepping) of 1.25 μm.

Let define the translation stages in the following way: a double stage done at CERN is defined as TS-2C (TS – Translation Stage, 2 – double, C – CERN); a single stage at CERN is TS-1C (TS – Translation Stage, 1 – single, C – CERN); and a double stage done by the external company is TS-2Z (TS – Translation Stage, 2 – double, Z – Zapp).

The connector layout of the translation stages is shown in Figure 5 for double linear stages (TS-2C and TS-2Z) and in Figure 6 for the single stage (TS-1C). From the pinout point of view, all stages have the same wiring.

The source files of the stages 3D model can be found in the CERN UA9 Collaboration DFS storage [14] and through the CERN Engineering and Equipment Data Management Service (EDMS) [15].

2.2. Controller

To control the motors in the stages, we have created controller boxes that consist of motor drivers, a microcontroller for the communication between user and linear stages, a power supply and a fan for cooling. An Arduino UNO [16] (Atmel Atmega 328 MCU) board was chosen to use as a microcontroller, together with

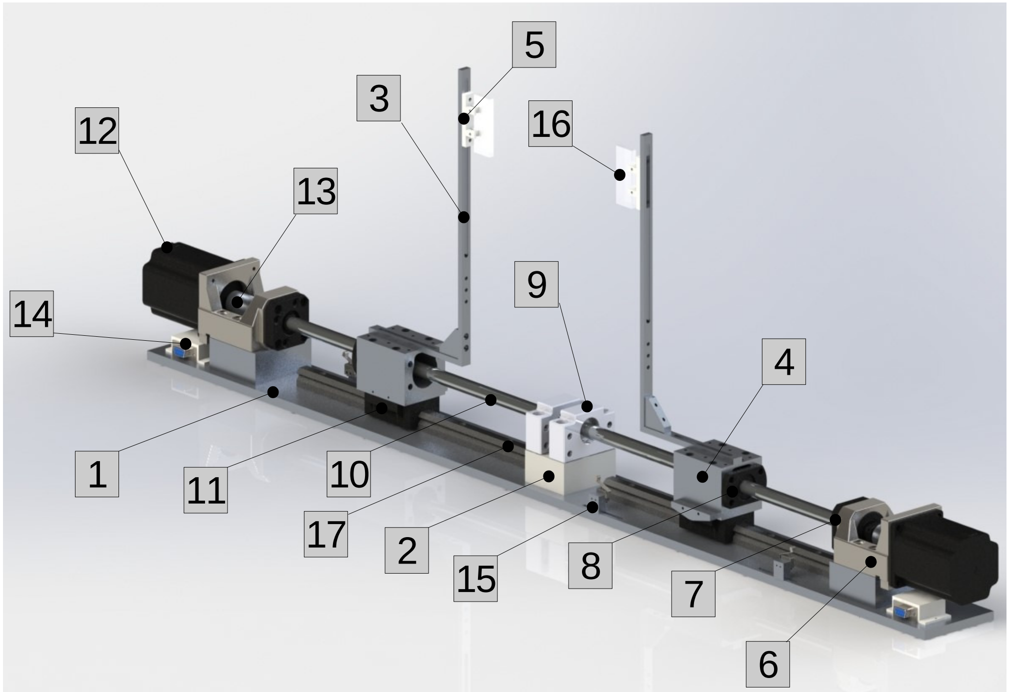


Figure 2: A 3D drawing of the double linear stage with mounted plastic scintillators. 1 – base plate, 2 – block for support, 3 – holder for the scintillator, 4 – ballnut bracket, 5 – plastic holder for the scintillator, 6 – motor mounts (MBA 10-C), 7 – ballscrew support (FK10-C7, with mounting method B), 8 – ballnut (R1204T3-FSKD), 9 – ballscrew support (BF10-C7), 10 – ball-screw (R1204-C7, length 400 mm), 11 – bearing block (BGX-H-15-FN-ZF), 12 – stepper motor (SY57STH76-4004A NEMA23), 13 – flexible coupling (BF-D25L34), 14 – DB9 connector, 15 – microswitch (HONEYWELL 1SX1-T), 16 – plastic scintillator, 17 – normal grade profile rail (BGR-15-LN, length 294 mm).

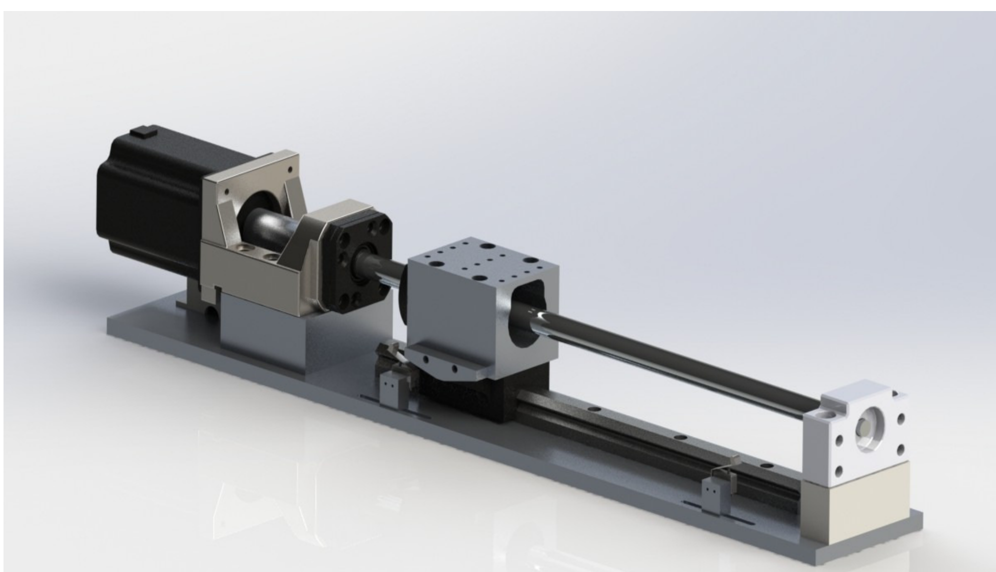


Figure 3: A 3D drawing of the single linear stage (see Fig. 2 for description).

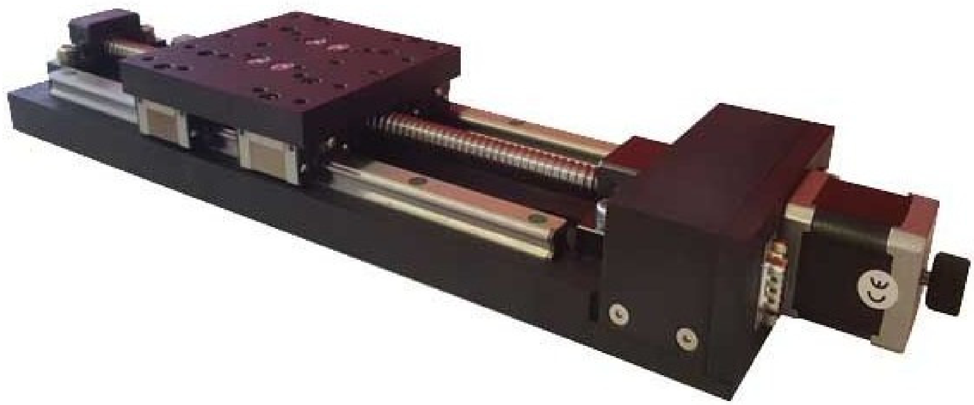


Figure 4: A photo of the single linear stage (ZXT200MA06).

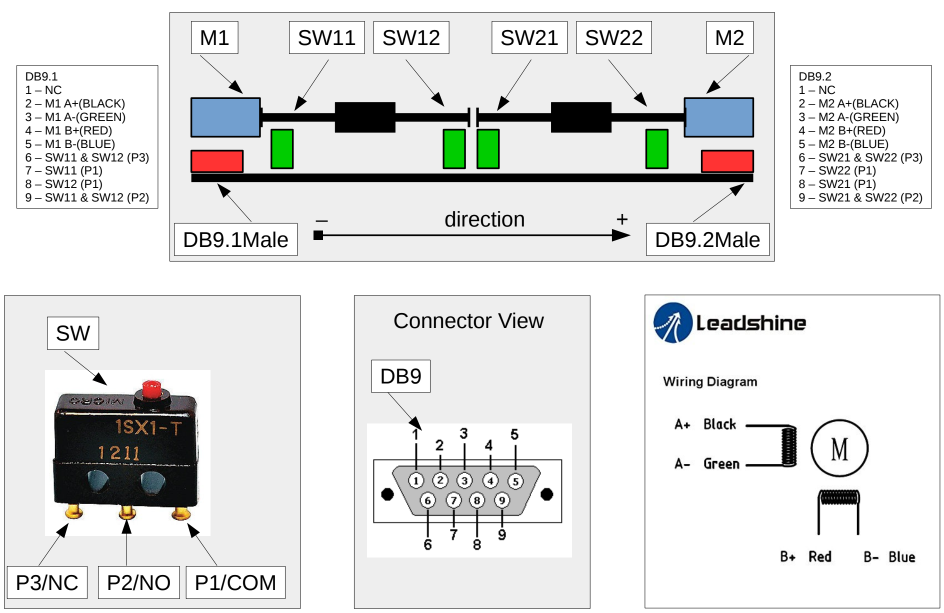


Figure 5: Pinout scheme of the double translation stage.

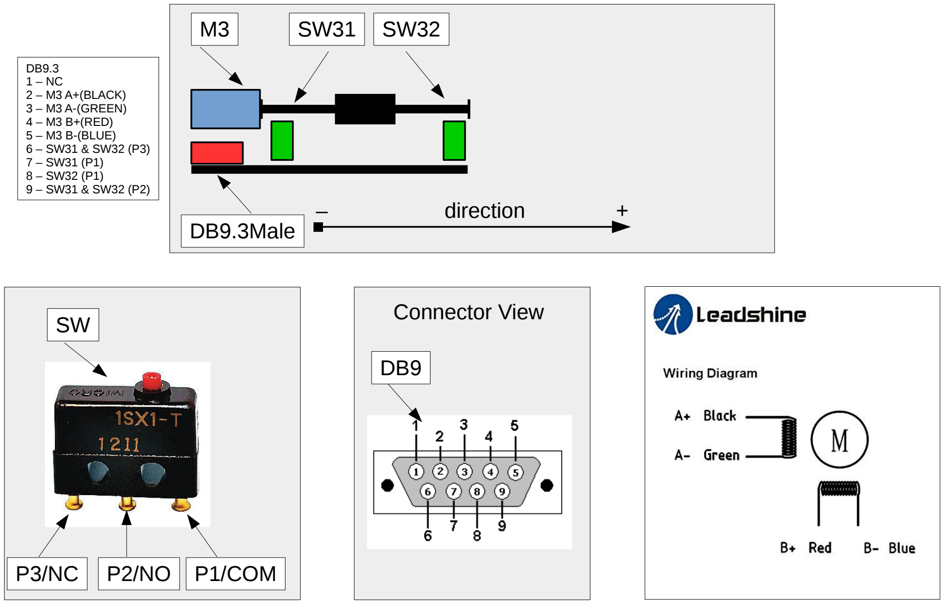


Figure 6: Pinout scheme of the single translation stage.

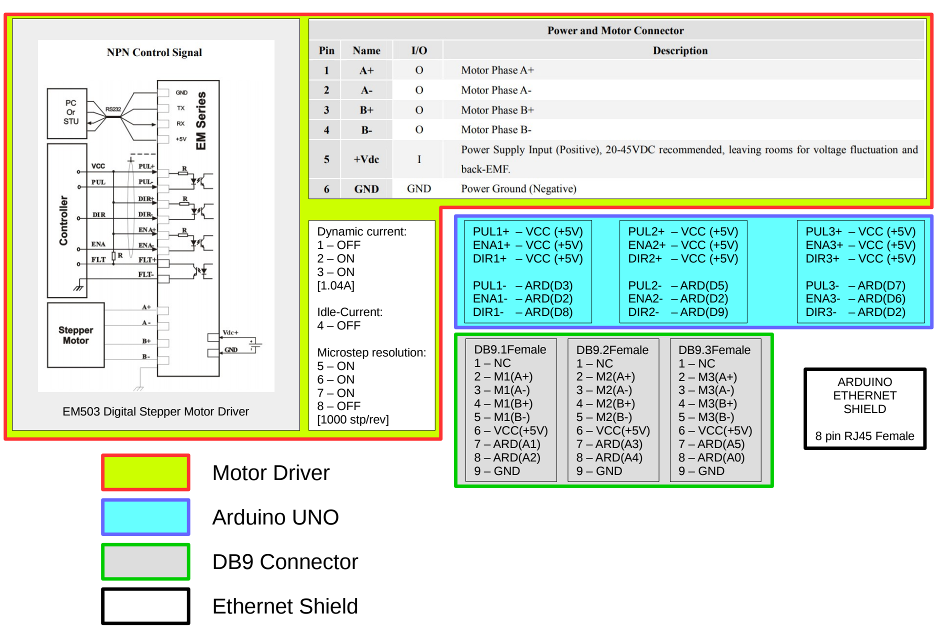


Figure 7: Pinout scheme of the controller box.

an Ethernet shield (Arduino Ethernet shield 2 without POE) that provides Ethernet communication with the user's PC. Figure 7 shows a detailed description of the Motor Controller Box (MCB) pinout. There is a MCB-1 for TS-2C (connected as Motor1 (M1) and Motor2 (M2)) and TS-1C (connected as Motor3 (M3)), another MCB-2 is for TS-2Z (connected as M1 and M2). Each MCB was developed to fit four motor drivers per box.

We decided to use a Leadshine EM503 2-phase digital stepper driver [17] for the motor drive. This unit's multi-stepping allows a low resolution input to produce a higher microstep output for smoother system performance. Each driver has eight jumpers for its adjustment.

To apply a current to the motor up to 1.5 A (peak current), one can change the status of the switchers 1,2,3: SW1 – OFF, SW2 – ON, SW3 – ON. SW4 determines whether the idle current is reduced automatically or remains the same as the dynamic current setting:

- SW4 – ON: the motor idle current reduces automatically when there is no pulse applied to the driver.
- SW4 – OFF: the motor idle current is the same as the dynamic current, when there is no pulse applied to the driver.
- SW4 – OFF-ON-OFF or ON-OFF-ON: to get the optimized performance (auto-configuration). The motor parameters are identified and the EM driver's current loop parameters are calculated automatically.

For our measurements, we decided to put 1000 steps/revolution of the microstep resolution, which corresponds to: SW5 – ON, SW6 – ON, SW7 – ON, SW8 – OFF, with SW4 – OFF. The full revolution of the axes corresponds to 4 mm of the linear displacement (the ball-screw granularity) and leads to the stage movement resolution of 4 [mm/revolution]/1000 [steps/revolution] = 0.004 [mm/step].

To provide 1.5 A per motor for each MCB, we decided to use a power supply unit TRIO-PS/1AC/24DC/5-2866310 [18].

3. Firmware description

This section will described the firmware that we used, which is uploaded on the Arduino board to control the motion stages. The source code can be found in [14], [15]. The program consists of three main blocks. The first block (Setup) is to setup the system: configuration of the board pins, Ethernet connection setting and initializing of the timer interruptions. The second block is called the Loop, which works continuously waiting for the commands from the user. The last part of the system is Interruption itself, where each 100 microseconds the program is interrupted to execute the command received from the user.

Each Arduino board is registered in the CERN network [19] with its MAC-address. This enabled each board to be specified to a fixed network IP-address connected on the dedicated outlet. The MAC-addresses are as follows: MCB-1 (90:A2:DA:10:76:FE), MCB-2 (90:A2:DA:0F:8B:0E).

4. Software description

The software installation file ("TS_GUI_AppInstaller") can be found in [14], [15]. A different version of the software is available for different operating systems. Following the installation procedure, the user will be asked to choose the installation folder. Because the Graphical User Interface (GUI) is written in MATLAB® [20], the installer will automatically download the MATLAB® Runtime [21], which is a standalone set of dynamic libraries that can be used to run compiled MATLAB® applications or components on computers that do not have a MATLAB® installation.

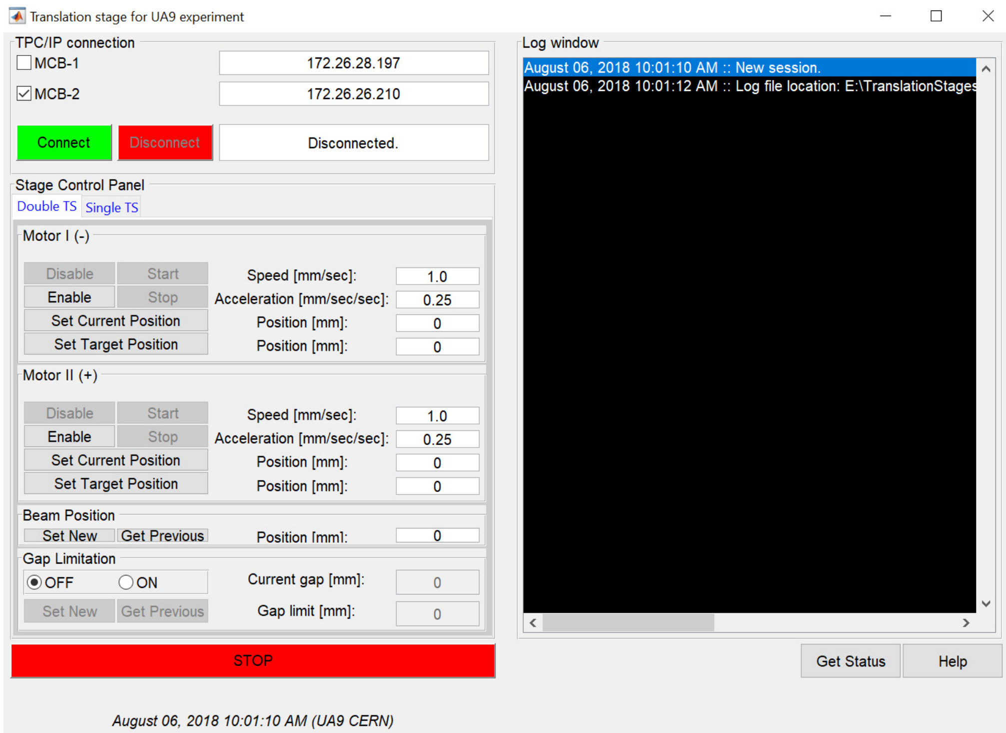
After installation is completed, the user can run an execution file of the program. This will open a GUI window and automatically create a log file in the same directory. Figure 8 gives a sample of the GUI window. The window is split into three main parts (panels): TCP/IP connection, Stage Control Panel and Log window.

The TCP/IP connection panel is used to make an Ethernet connection between the user's PC and one of the controller boxes. The panel has two fields: (1) MCB-1 and (2) MCB-2, which correspond to controller boxes with the fixed IP-addresses. By clicking the related checkbox, one can switch from one MCB to another. To connect to the chosen MCB, it is necessary to press the "Connect" button, and to disconnect the user presses the "Disconnect" button. The present status of the connection is indicated in the window next to the buttons. For the connection, the user's PC has to be on the same network (e.g. CERN network) as the MCBs.

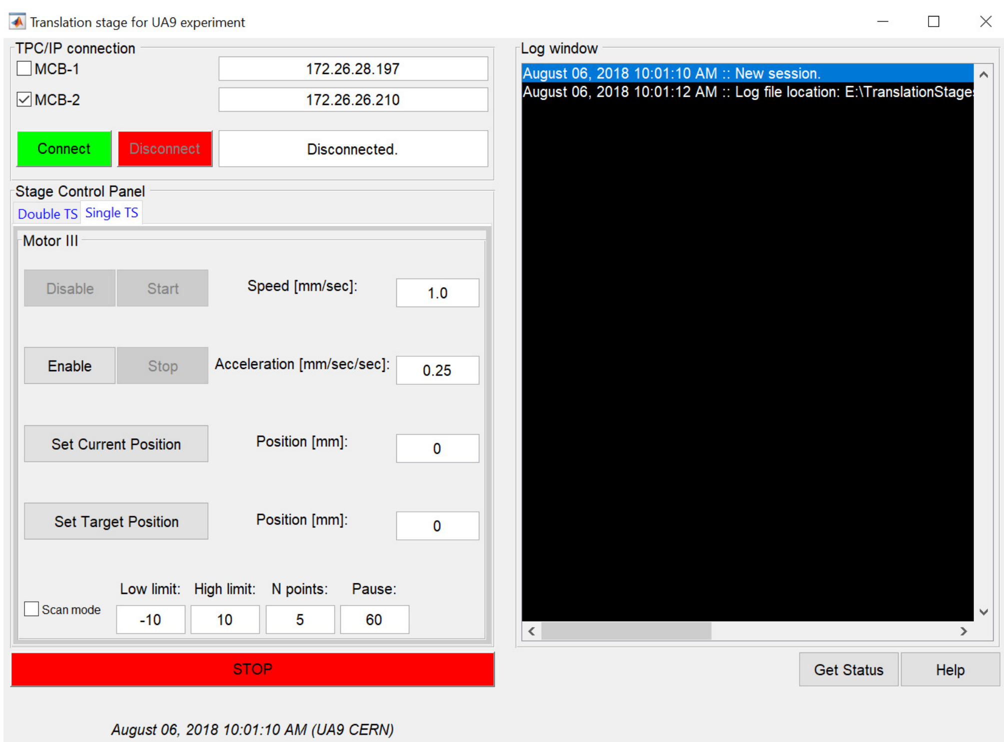
The Stage Control Panel consists of one tab for MCB-1 (Double TS) and two tabs for MCB-2 (Double TS ans Single TS). Each tab has motor control subpanels to move the motors. The Double TS is used to control the double translation stage (TS-2C or TS-2Z) and the Single TS tab for a single linear stage (TS-1C). The coordinate systems of the stages are shown in Fig. 5 and Fig. 6.

Motor subpanel description. "Enable"/"Disable" – to switch on/off the motor, this signal is used to send the current to the motor and while it is not moving to maintain the stop position of the motor. "Set Current Position" – to set the position of the motor with respect to the reference zero position. "Set Target Position" – to set the absolute final position of the movement. "Start"/"Stop" – to start and stop the movement of the motor. After the pressing "Start", the system takes the speed and acceleration values from the corresponding windows and sends them to the controller with the command to start the movement. Figure 8b shows the Single TS tab with some additional fields. "Scan mode" checkbox switches on the scanning mode for the single linear stage (M3). After pressing the button "Start" the motor will move from the "Low limit" to the "High limit" positions with "N points" stops waiting for "Pause" seconds during each stop. To avoid a failure of the system, it is forbidden to press the button "Start" for the same MCB when one of its motors is moving.

Beam position subpanel description. An additional panel for the beam position logging in the reference frame. "Set New" – to set the new value of the beam position. "Get Previous" – to find the previous position of the beam in the log file.



(a) Double TS tab.



(b) Single TS tab.

Figure 8: Graphic user interface for the linear stages controlling

Gap limitation subpanel description. An additional panel to limit the distance between two positions of the motors for the double linear stage. When the distance between two motors is reached, the program will stop all of the motors. OFF/ON fields are used to switch OFF/ON the gap limitation. After pressing "ON", the actual gap value between two motors is taken as a limitation. "Set New" – to set the new value of the gap limitation. "Get Previous" – to get the previous gap limitation value from the log file.

The global red button "Stop" is used to stop all of the motors on the same MCB in case of emergency. After pressing the button "Get Status", the program will send a request to the microcontroller. The received answer will then be printed in the Log window and the motors' positions will be corrected. For more details, the user can use the "Help" button. The history of the present session is written in the Log window.

There are two limit switchers (endpoints) per motor to stop the motor's movement in case it reaches the limit of the motion range. Knowing the position of each switcher in the reference frame, one can define the position of each motor.

5. Test beam operation

This section will demonstrate how to use the double translation stage during the H8 test-beam session.

The TS-2C stage is connected to the MCB-2 with mounted scintillators, as illustrated in Fig. 2, which are placed on the SPS extracted beamline. The task is to align the pair of the plastic scintillators symmetrically with respect to the beam center, applying a gap of 10 mm between the detector's edges (Fig. 9).

I. Position calibration procedure:

1. Switch on the MCB-2.
2. Check the Ethernet connection.
3. On the user's PC, launch the program executable file.
4. When the GUI window is opened, choose the MCB-2 controller box on the TCP/IP connection panel and check the IP-address.
5. Press the button "Connect". A system is connected message is written in a window next to this button.
6. Choose the Double TS tab in the Stage Control Panel.
7. Press the button "Enable" in the Motor I (-) subpanel. This will enable all of the motors connected to the MCB. The button "Start" and "Stop" will be activated.
8. If the current position of the motor is unknown, put 0 in the related window and press the button "Set Current Position". In the opened pop-up window, the user will be asked to choose how to set the current position of the motor: manually or from the log file. If the last correct position of the motor is in the log file, then the "From the Log file" button has to be chosen. The program will then search in this file for the last written position for the current motor and put it in the related window. If the last position is not written in the log file or a new coordinate should be defined, then the "Manually" button has to be chosen.
9. Set -1000 mm (or 1000 mm for the Motor II (+)) in the target position window.

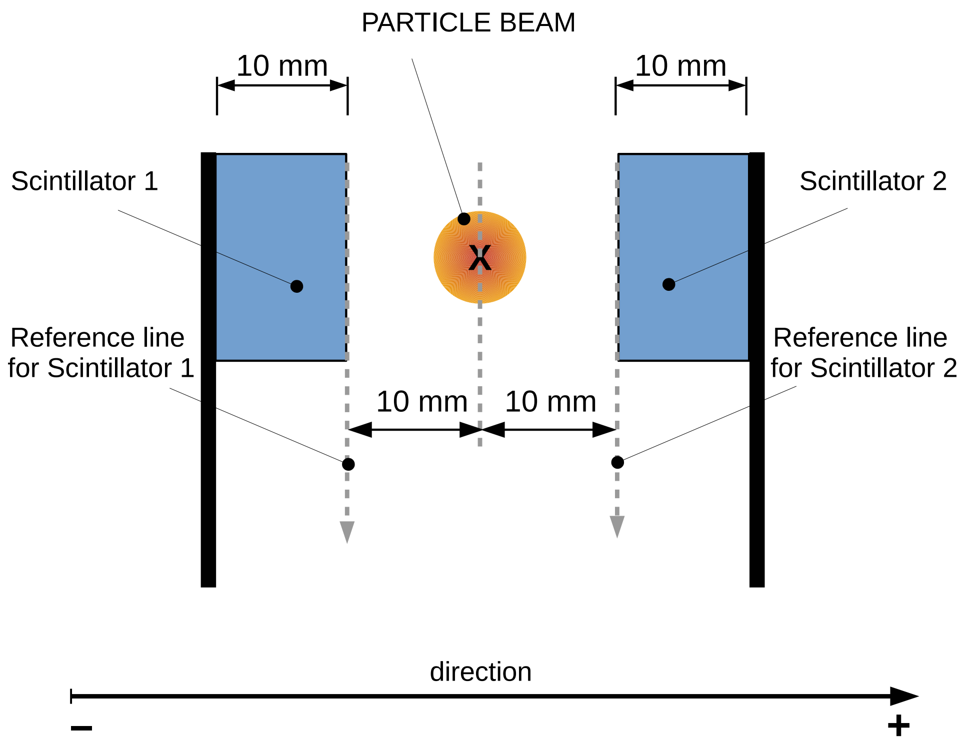


Figure 9: Geometrical configuration for the plastic scintillators with respect to the particle beam axis.

10. Press the button "Set Target Position" to set the position to which the motor has to move.
11. Press the "Start" button. If the motor has to be stopped, then the "Stop" button can be used.
12. After pressing "Start", the motor will start to move from the current position to the target position. When it reaches the target position, the motor will stop. However, in the calibration case ($-1000/1000$ mm), the motor will touch the limit switcher and stop.
13. The maximum distance between detectors in the present configuration is 378 mm. Therefore, in two extreme positions of the motors, when they touch the limit switcher, the coordinates are -189 mm and 189 mm for the Motor I(+) and Motor II(+), respectively. If another experimental assembling of the detectors is used, then the movement range should be remeasured.

After the calibration procedure, the program knows the actual positions of the motors, which allows us to align the scintillators with respect to the beam axis. The next step is to make a linear scan with scintillators to find the beam position in the coordinate system of the linear stage.

II. Beam profile measurements:

1. Following the previous procedure, a linear scan per each scintillator has to be done to define the position of the beam center, separately measuring their signal counts (Fig. 10).
2. Knowing the position of the beam center in the coordinate system of the stage, the scintillators can be placed at the symmetrical position with respect to the particle beam axis.

The "Disable" button must be used at the end of the measurements, which will switch off the motors. The "Disconnect" button will be disconnected the MCB from the user's PC.

6. Conclusions

During the last two years, the use of the motorized linear stages with remote control has enabled us to align the plastic scintillator detectors for the INI measurement with respect to the particle beam axis. It has also decreased beam interruption time, which was previously required for manual manipulation or calibration of the detectors. A position resolution of 4 μm with a repeatability of about 10 μm satisfies all expectations for the UA9 measurements at the H8 beamline. In the coming years, all of the stages will be actively used by the UA9 collaboration for the bent crystal characterization measurements, not only at the CERN accelerator facilities.

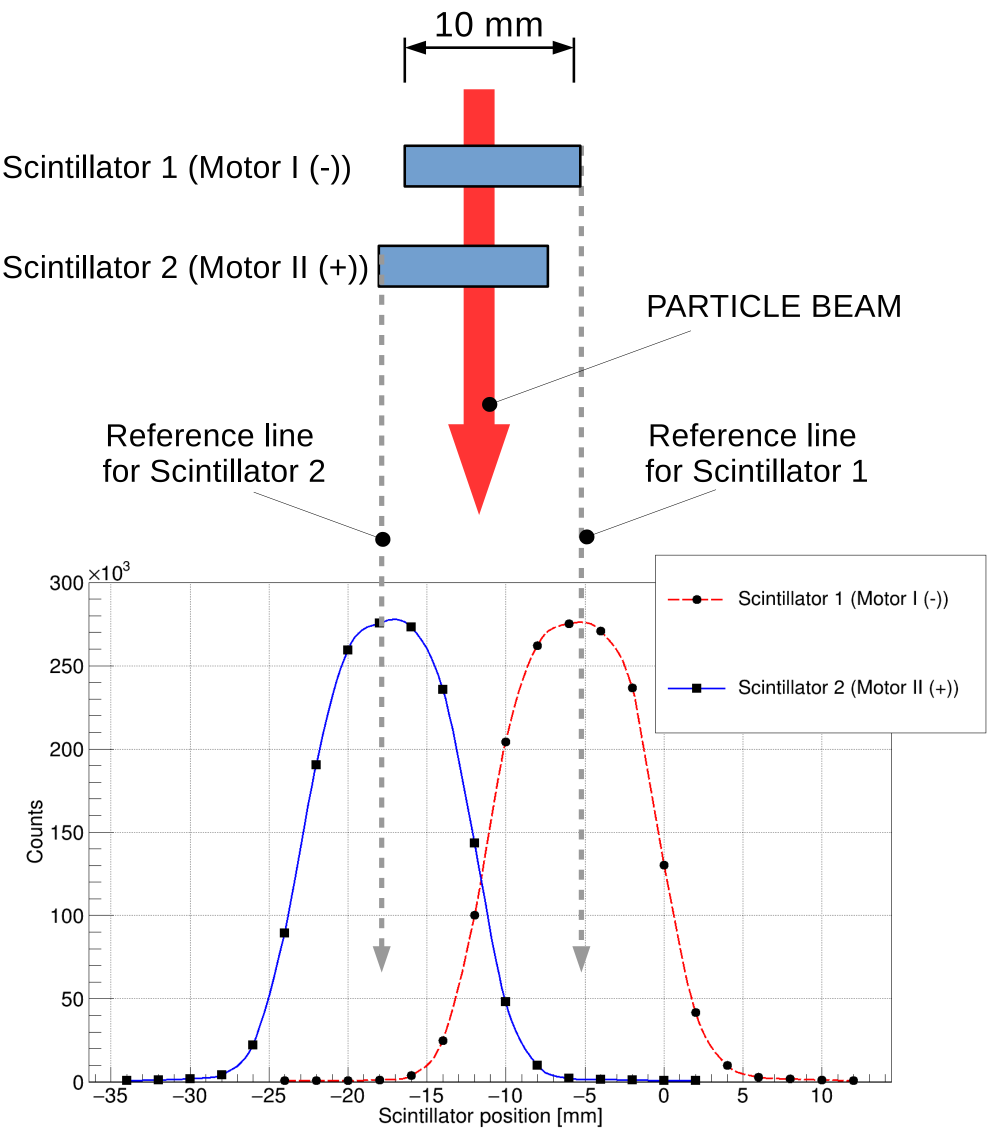


Figure 10: Beam profile measured by two plastic scintillators.

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