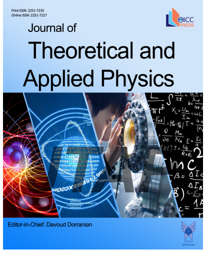

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# Design and implementation of control system for IPM e-LINAC

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**Original Research**

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**Abstract:**

The construction of a LINAC facility to provide hands-on experience has been under way at Institute for Research in Fundamental Sciences (IPM). The LINAC, which accelerates an electron beam of 1 mA current to 4.5 MeV energy, is mostly regarded as a facility for research and development and educational purposes in the field of beam physics and accelerator engineering. A unified control system is required to supervise all subsystems and make LINAC parameters controllable for the user. As the purpose of the facility is for beam studies, the control system was designed to make all key operational parameters and beam characteristic available in a user-friendly presentation. This paper describes the requirements of the control system and presents the design of a LabVIEW-PLC-based control system of the IPM LINAC.

**Keywords:** Linac; Electron beam; LabVIEW-PLC-based control system; Beam Physics

## 1. Introduction

A research linear accelerator is developed at Institute for Research in Fundamental Sciences (IPM) in order to provide hands-on experience in accelerator science and technology. In spite of the widespread applications of such an accelerator in industry or medicine, the LINAC is mostly regarded as a facility for research and development and educational purposes in the field of beam physics and accelerator engineering. Therefore, efforts have been made to make the machine parameters as flexible as possible in order to study the effect of each, on the output electron beam. This is not possible unless a reliable beam diagnostic system and a comprehensive and user-friendly control system is provided. The machine parameters are presented in Table 1.

At this stage, the first accelerating tube of the LINAC is operational, which accelerates an electron beam of 1 mA current to 4.5 MeV energy. Identified as Iran first linear accelerator project, all main components of the accelerator, such as accelerating tube, klystron, modulator, RF assembly, electron gun and diagnostic box are designed and constructed [1, 2]. The LINAC consists of a thermionic electron gun followed by a prebuncher cavity, a travelling wave buncher and a constant impedance traveling wave accelerating tube and a diagnostics bench at the end [3]. The electron gun provides a beam with an energy up to 50 keV. The buncher and the accelerating tube are connected together and fed with 2MW RF power. The operating frequency of the LINAC is 2997.9 MHz. The maximum pulse duration and the pulse repetition rate are 7 $\mu$s and 250 Hz, respectively. The accelerating part of the accelerator are shown in Figure 1.

A 2.5 MW klystron serves as the power source. The main characteristic of this laboratory is the possession of measur-

**Table 1.** Operational parameters of IPM e-LINAC.

| Parameter | Value |
|---|---|
| Beam energy | 4.5 MeV |
| Beam current | 1 mA |
| RF power | 2 MW |
| Frequency | 2997.9 MHz |
| Pulse | 250 Hz |
| Pulse width | <7 $\mu$s |

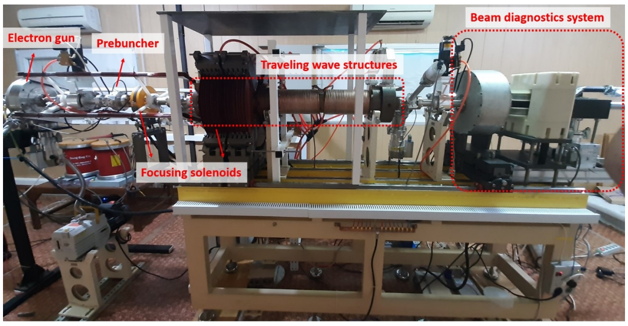


**Figure 1.** Accelerating room of the IPM e-LINAC.

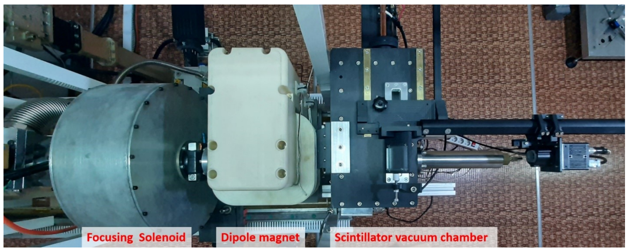


**Figure 3.** Elements of the diagnostics bench.

able and controllable electron beam. Figure 2 represents the RF source room of the machine.

The diagnostic bench is composed of a movable scintillator-based beam profile monitor with a dipole magnet and a focusing solenoid up-stream. With the dipole magnet off, the profile monitor and the up-stream solenoid constitute a complete tool for the measurement of the beam transverse parameters like size, position, emittance and divergence [4, 5]. Then, the dipole can be turned on in order to measure the momentum spectrum [6]. In this process the motorized scintillator moves and measures the beam profile after bending. The movable scintillator view screen allows to choose the bending angle in order to achieve the best resolution in the momentum spectroscopy. The configuration of the diagnostics bench illustrated in Figure 3.

A research LINAC, in comparison to industrial accelerator, control system is responsible for supervisory of a significant number of parameters, therefore demands a more accurate and complex implemented control system. Ultimately, more than 30 parameters need to be either controlled or supervised. In the following, field variables of accelerator subsystems are introduced, then the control system architecture is presented and finally, the system implementation is described.

## 2. Field variables of control and supervisory system

Regarding the goal of maximum LINAC performance, one of main guidelines for choosing hardware, software and architecture for control system is ease of maintenance, upgrade and troubleshooting. Field tier is the lowest level of control system. This level, which includes sensors and actuators, is in direct contact with field variables. Therefor an exact knowledge of the devices workflow is essential for design and implementation of the control system. The following is a brief overview of the areas which supervisory and control plays role.

### 2.1 Vacuum

Inadequate vacuum level can cause a significant reduction in electron gun cathode lifetime and increase the probability of RF induced electrical breakdown, reflection of RF power to klystron, and cause permanent damage to components. Friability of the diagnostic box glass windows is another reason to supervise vacuum value to prevent damage to vacuum turbomolecular pumps.

### 2.2 Electron gun

Control and supervisory of the anode-cathode high voltage and filament current is vital for safety of the high voltage power supply and cathode [8].

### 2.3 RF source

As in commissioning phase adjusting injected RF power controls electron beam energy and causes heating, frequency mismatch and vacuum decrease, RF power and frequency are measured through a directional coupler and a spectrum analyzer.

### 2.4 Beam diagnostic box

In IPM e-LINAC, beam current, energy spectrum and cross-sectional beam profile are measured using the beam diagnostic system shown in Figure 4. The accelerator diagnostic box includes a dipole magnet, a solenoid, a scintillator, and an optical system including a CCD camera and adjustable optical lens.

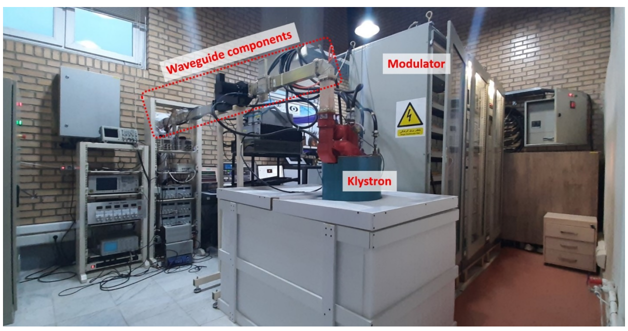


**Figure 2.** RF power source room of the e-LINAC (down).

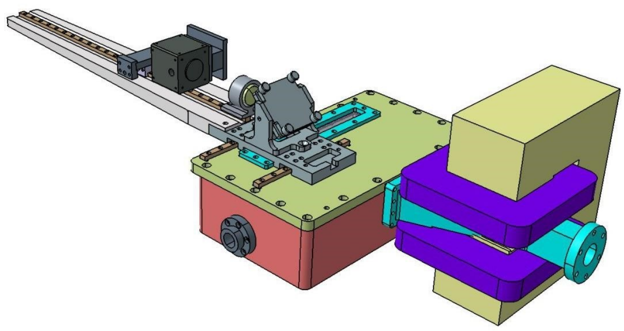

**Figure 4.** Beam diagnostic box of IPM e-LINAC [7].

**Table 2.** IPM e-LINAC control System Interlocks.

| Interlock trigger | Causes | Action or description |
|---|---|---|
| Vacuum value<br><br>unexpected increase | • High-voltage breakdown in gun<br>• Breakdown on surface of tube (in conditioning phase)<br>• Breakdown of glass vacuum window (on the diagnostic box) | • Decreasing HV to zero<br>• Isolating vacuum chambers by closing vacuum valves<br>• Input RF power cut off<br>• Shutting down diagnostic box vacuum pumps |
| Gun high-voltage<br><br>unexpected increase | • User command<br><br>• Instability of the HV power supply due to a breakdown | • Making sure the increment is slow enough to avoid breakdown in gun<br>• Decreasing HV to zero |
| Temperature increase | • Failure of the cooling system<br>• Frequency mismatch | • Decreasing HV to zero<br>• Input RF power cut off |
| Accelerator cabin door opened | • Personnel inside the accelerator cabin | • Decreasing HV to zero<br>• Input RF power cut off |
| PLC-LabVIEW<br><br>disconnection | • PLC power source failure<br>• PC failure<br>• Network connection problem | • Decreasing HV to zero<br>• Isolating vacuum chambers by closing vacuum valves<br>• Input RF power cut off<br>• Shutting down diagnostic box's vacuum pumps |
| Modulator safety | • Overvoltage<br>• Overcurrent | • Power off the unit |
| Missing vacuum value | • Faulty vacuum measurement unit<br>• Faulty network connection<br>• Faulty gauge to measurement unit connection | • Preventing increase of gun HV<br>• Preventing injection of RF power<br>• Preventing vacuum valve opening |
| Emergency stop button | • User discretion | • Decreasing HV to zero<br>• Isolating vacuum chambers by closing vacuum valves<br>• Input RF power cut off<br>• Shutting down in-danger vacuum pumps |

## 3. Control system architecture

The IPM e-LINAC control system employs a three-tier architecture model as illustrated in Figure 5. The Process and Presentation tier (1) mainly includes user interfaces and soft interlock processes. National Instruments LabVIEW is used for processing parameters and graphical user interface (GUI). The Equipment tier (2) includes devices which are in contact to both user interface (Presentation tier) and field-level devices, which comprises PLCs, spectrum analyzer, CCD camera, Serial server, vacuum units and Trigger Distributer Unit. Field Tier (3) includes instrument and devices which are directly measuring or applying operational parameters.
The configuration offers reliability, flexibility and simplicity of maintenance which are essential features for beam research project.

## 4. Hardware implementation

A LabVIEW workstation in combination of a Siemens S7-300 PLC station constitute hardware core of the control system. An industrial Moxa Ethernet ** switch and a Moxa NPort 5650 Serial server facilitate network connections of the control system. Figure 6 presents a schematic view of control system configuration and Figure 7 shows hardware implementation of the control system panel.
Electron gun subsystem includes high-voltage, filament and grid power supplies. Grid power supply, which controls electron injection, is synchronized with RF power injection

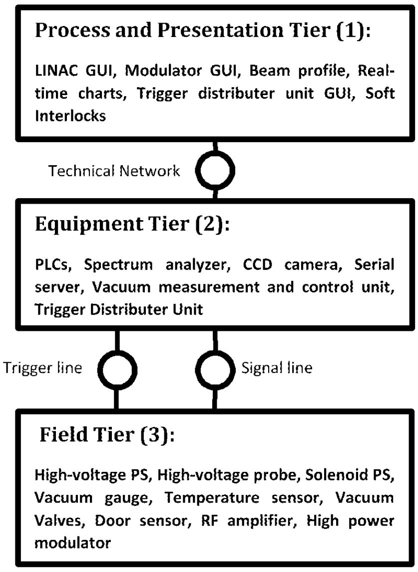


**Figure 5.** Accelerator control system components at three individual tiers.

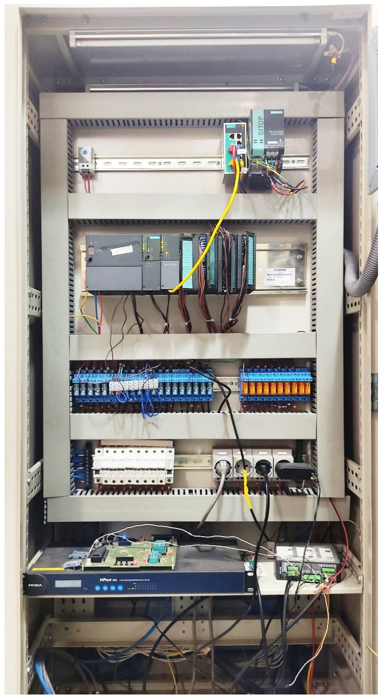

**Figure 7.** Hardware implementation of the control system.

by trigger distributer unit. Gun filament current and high voltage are monitored using a current transmitter and a PINTEK HVP-40 probe.

The machine is separated into three sections with two vacuum gate valves; (1) electron gun, (2) accelerating section, (3) diagnostic box. The state of VAT vacuum pneumatic gate valve kf63 is controlled and monitored through S7-300 PLC. Vacuum value in each section is measured by Pfeiffer PKR 250 vacuum gauges and is sent to central workstation by a Pfeiffer TPG 256 vacuum gauge controller over RS232. The diagnostic section consists of a dipole, a focusing solenoid, a vacuum chamber, a movable scintillator plate and a CCD camera [3]. The position of the scintillator plate is adjusted using linear guide employing Autonics A16K-M569 stepper motor. As accurate focusing solenoid and dipole magnetic are essential for beam characteristic measurement, an accurate MeanWell RSP-3000-12 power supplies has been employed. Beam profile image is captured by Jai BM-141GE CCD camera captures and transferred to NI Vision through GigE protocol.

Forward and reflecting RF power is measurement through two directional couplers using an Agilent N900A spectrum analyzer which communicate with LabVIEW. Low level RF generator is controlled by a feedback from spectrum analyzer and vacuum values.

The high power modulator unit is controlled using a specific internal trigger and the trigger distributer unit (TDU) uses modulator signal as its reference for synchronization of LINAC components.

• Trigger Distributer Unit (TDU)

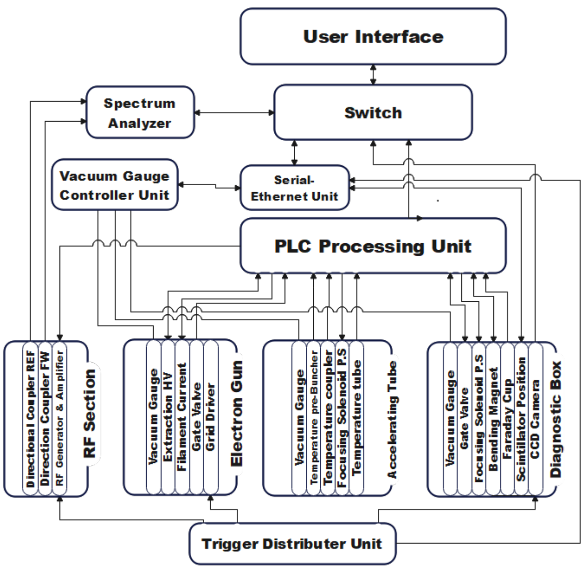


**Figure 6.** Schematic of IPM e-LINAC control system configuration.

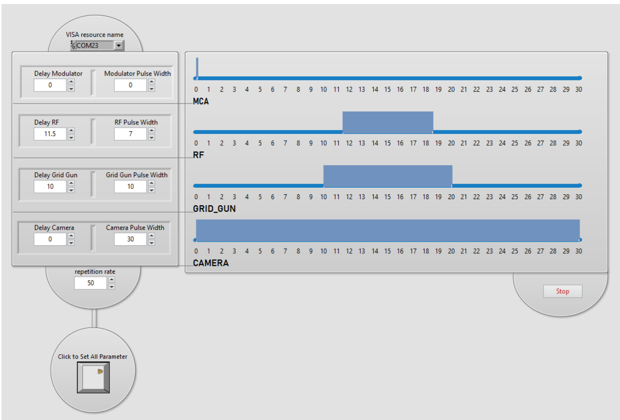


**Figure 8.** User interface showing controlable parameters of the trigger distributer unit (TDU).


**Figure 9.** Graphical User interface of IPM LINAC (in operation).

As the purpose of the project is education and beam physics studies, beam parameters are adjustable. In order to adjust trigger signal of RF amplifier, electron gun grid, CCD camera and the modulator, a custom FPGA trigger distributer unit (TDU) was designed and constructed. Optical isolation has been implemented to reduce noise effect.

The developed trigger distributer unit which employs Xilinx Sparatan-6 FPGA processor, generates adjustable trigger signals for each component with reference to modulator trigger signal. Electron gun grid power supply and RF amplifier trigger signal are important in adjustments of klystron performance and beam characteristics. Figure 8 shows controllable parameters of the trigger distributer unit in the control system GUI.

## 5. Safety interlocks

PLC-based and software interlocks was implemented to ensure safety and stable operation of the machine. In case of any danger to the machine and personnel, safety interlocks initiate shutdown process. Interlocks are implemented by an entangled LabVIEW-PLC cooperation, so any failure in LabVIEW-PLC connection initiate shutdown process

Table 2 lists implemented interlocks and their descriptions. In conditioning phase, the injected RF power is gradually increased to prepare accelerating tube surface for higher powers. Vacuum monitoring can also be helpful to prevent multiplacting and discharge effects in conditioning phase.

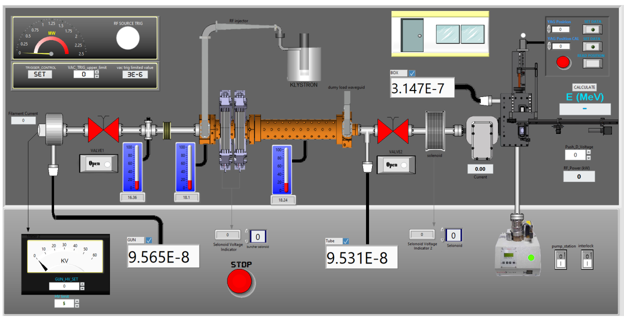


**Figure 10.** Main panel of the IPM LINAC GUI.

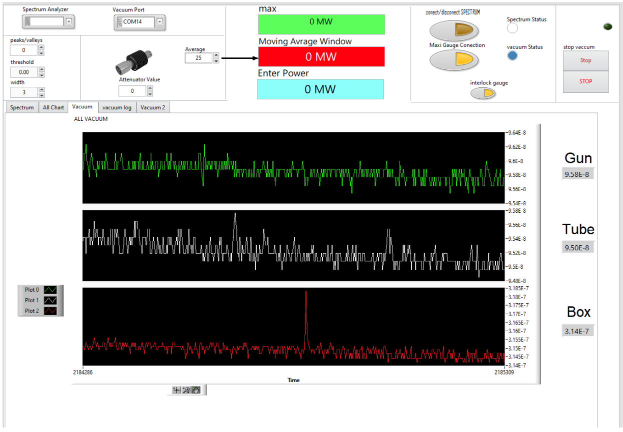


**Figure 11.** Graphical chart of vacuum values, details and settings of input RF power.

IPM LINAC accelerator tube, which is constructed by regular copper, requires more conditioning time in comparison to OHFC (oxygen-free high thermal conductivity) tubes, hence IPM LINAC control system requires more reliability and special interlocks for conditioning phase.

Breakdown of diagnostic box's glass window also will cause sudden failure in vacuum value. Thus, an interlock was implemented to terminate RF power and close vacuum gate valves in case of any unexpected change in vacuum.

Inadequate vacuum value causes a reduction in electron gun filament lifetime, electrical breakdown in electron gun and tubes, damage to cavities and RF window due to increase in multipacting rate, and RF power reflection as a result of consecutive electrical breakdown, so an interlock ensures a minimum value before vacuum for electron gun filament power supply activation.

## 6. User interface

Further improvements, high-level programming language, availability of toolkits, and wide range of available functions led the project to use LabVIEW as GUI framework. The user interface of the system which includes three separate panels is shown in Figure 9.

The main panel of the GUI focuses on overall status and warnings of different components. It shows a schematic view of the accelerator and related variables on each com-

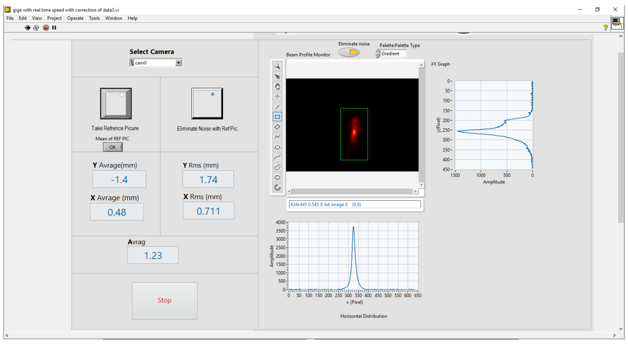


**Figure 12.** Graphical interface and real-time parameters of the output beam.

ponent. The basis of this design is that the user can easily observe parameters and status of the LINAC.
Figure 10 shows the main panel the IPM LINAC GUI. Vacuum, RF power panel and beam diagnostic panel are also shown in Figure 11 and Figure 12.
The beam diagnostic panel includes a real-time picture of electron trajectory on the final scintillator, and graphical analysis charts of transverse beam profile. The program calculates real-time transverse beam properties such as horizontal and vertical beam sizes (RMS), average beam positions and distributions.
To accurately measure beam parameters, the noise before beam injection was recorded and compared with the image after injection of the beam. Figure 12 shows the in-operation beam characteristics of IPM LINAC.
NI Vision LabVIEW module handles image processing, applying filters and real-time calculation of beam parameters. The beam diagnostic panel of the control system is presented in Figure 12.
A beam of 4.5 MeV with a 0.5 MeV$\pm$10% [6] energy spread and 25 mm-mrad emittance was extracted and measured by the control system and the beam diagnostics box. The control system in now operational for beam physic research purposes at IPM.

## 7. Conclusion

The successful implementation of the control system of the IPM LINAC was presented in this paper. The requirements for safe and reliable operation of IPM research LINAC was described and the accelerator control system architecture was presented in three individual tiers. The design of the control system enables adjustments of the beam parameters for beam physics and accelerator engineering studies. PLC S7-300 was used for field-side tire communications and a LabVIEW software workstation was exclusively developed for accelerator parameter control and beam diagnostics. A beam of 4.5 MeV was extracted and detected from the accelerator using the implemented control system and the beam diagnostics box. The control system in now operational for beam physic research purposes at IPM.

**Ethical approval**
This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

**Authors Contributions**
All authors contributed equally in design the main sample, measure all the processes and also prepare the text.

**Availability of data and materials**
Data in this manuscript are available by request from the corresponding author.

**Conflict of Interests**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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