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Design of Instrumentation and Control System Integration for the DECY-13 Cyclotrons Commissioning

Frida Iswinning Diah[1], Fajar Sidik Permana[2], Emy Mulyani[3]

[1,2,3] Research Center for Accelerator Technology – Research Organization for Nuclear Energy – National Research and Innovation Agency, Jl. Babarsari kotak pos 6101 ykbb, Yogyakarta 55281 INDONESIA (tlp. (0274) 488435, 464436; email: [1]frid002@brin.go.id, [2] faja018@brin.go.id, [3]emy.mulyani@brin.go.id)

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Corresponding Author: Frida Iswinning Diah

ABSTRACT — A cyclotron is a particle beam accelerator used for various applications, one of which is to produce medical radioisotopes. Research Center for Accelerator Technology, Research Organization for Nuclear Energy - National Research and Innovation Agency (Pusat Riset Teknologi Akselerator, Organisasi Riset Tenaga Nuklir - Badan Riset dan Inovasi Nasional, PRTA ORTN-BRIN) is conducting research and development (R&D) for the DECY-13 cyclotron that has reached the stage of testing its primary components. The primary components of the DECY-13 cyclotron consist of seven systems. In commissioning, it is necessary to prepare an integrated instrumentation and control system (ICS) design that unites the operation of all DECY-13 cyclotron's primary components to produce a particle beam as desired. The integration process was carried out in two stages: determining operating procedures during commissioning and identifying operating parameters; and designing the ICS integration. The process of identifying parameters and determining operating procedures was carried out by studying test data and operating standards for each component to obtain important parameters in operation. Next, the ICS architecture was developed by integrating the operating system on the primary components using the distributed control system (DCS) method. The DCS configuration consisted of three layers, namely the operator, the main control, and the device layers. Communication between the device and the main control layers was carried out using the RS-232 serial communication, while the communication between the main control and the operator layers used the Ethernet. The RS-232 communication between the device and main control layers was used to manage data acquisition, data logging, and operation control. At the operator layer, there was a host-PC that functioned as a data viewer and data logging. This design is expected to be a guide in the implementation of ICS improvements, and realizing ease during commissioning.

KEYWORDS — Control System, Integration, Cyclotron, Commissioning.

I. INTRODUCTION

A cyclotron is a type of particle beam accelerator still being developed for wide applications, including for the health sector, where it is used to produce medical radioisotopes useful in cancer diagnosis and treatment. The Accelerator Technology Research Center, Nuclear Energy Research Organization - National Research and Innovation Agency (Pusat Riset Teknologi Akselerator, Organisasi Riset Tenaga Nuklir - Badan Riset dan Inovasi Nasional, PRTA ORTN-BRIN) is developing the prototype of the 13 MeV cyclotron, called DECY-13, in which some of its primary components have been tested. The primary components of a cyclotron consist of seven systems, namely a magnetic system, a radio frequency (RF) generator system, an ion source system, an accelerator system, a cooling system, a vacuum system, and a beam detection system [1], [2]–[6]. Each of these components has been tested; therefore, the commissioning process is required in order to reach the final step of the design process for the DECY-13 cyclotron. This stage is also commonly referred to as beam commissioning since its main purpose is for the full cyclotron operation to produce beams following the design [7].

During the commissioning process, one stage that must be completed is a comprehensive cyclotron operation, meaning that all the primary components of the cyclotron will be operated consecutively as per the general cyclotron operating standard. At this time, the operation of the DECY-13 cyclotron cannot be conducted effectively and efficiently since the primary components are distant from each other, and the control system has yet to be integrated.

In addition, the complexity of the operating parameters in the cyclotron makes it difficult for the operator to conduct careful observations and documentation, like what has been done when testing the ion source system using the direct current (DC) voltage [3], [8]. In the test, more than three people were required to conduct observations and recordings since the ion source system consisted of several separate subcomponents. It also occurred when testing the RF generator and the acceleration systems [9]–[11].

The evaluation of some of these components indicates that it is necessary to increase or develop an integrated operating system to facilitate operators in the operation, observation, and documentation of events during the operation [12]. Therefore, planning the operating system's integration, whose main focus of ensuring a smooth commissioning process, is essential. Finally, the system's characteristics are expected to be obtained appropriately, preventing operating errors and guaranteeing the safety of tools and personnel.

To achieve the goal, namely the design of the instrumentation and control system (ICS) for the commissioning of the DECY-13 cyclotron, the writing of this paper is divided into six sections with the following details. Section I is the introduction containing the background, problem, goal, and systematic writing. Section II presents the design method used. Furthermore, Section III covers the details of the primary components of the DECY-13 cyclotron. Section IV explains the design process that is carried out and is further discussed in section V. Finally, Section VI is the conclusion of this paper's writing.

II. DESIGN METHODS

The accelerator is a system with complex attributes. In simple terms, an accelerator device comprises four parts: a particle or ion source, an accelerator system, a beam extraction system, and a beam transport system [13]. The preparation of the control system concept will mirror the development of control technology made in its time. In accelerator technology, programmable logic controllers (PLCs) technology, as well as LabView and EPICS software, are tools that are still widely utilized today to construct a system control in accelerators [14]–[17].

For special needs, the design of cyclotron control systems for research purposes differs from those of commercial cyclotrons used in hospitals. At the beginning of the design process, several cyclotrons for radioisotope production used the distributed control system (DCS) method, including KIRAMS Korea and CIAE China [18], [19]. Meanwhile, the accelerator control system technology for research in developed countries is currently more focused on the system upgrade process, as the components and software are no longer compatible with current technological advancements [14], [16].

The primary components of the control system on the cyclotron have nonuniform specifications. Some components have been equipped with RS-232 serial communication, but some remain using analog input and output. As a result, the process of identifying the control system for each primary component was carried out early during the design process based on the current conditions of the DECY-13 cyclotron and references to the accelerator control system, both old and recent. Prior references (before 2018) were examined for comprehending the fundamental concept of developing a cyclotron control system. Recent references (2018-present) were taken into account to ensure that the system design created could be easily upgraded and optimized in response to current technological advancements.

Since the beginning of research and development (R&D), the design of the DECY-13 cyclotron in 2010 has been based on the development of medical cyclotrons in Korea, particularly the ICS design, which also refers to the design of KIRAMS Korea. In general, the devices used for the control system are PLCs, LabVIEW software, and modules from National Instruments [20], [21]. In the process of designing an ICS, three elements are needed, namely human resources, software, and hardware. Software is required for data analysis, communication protocols, simulation, automation, data storage, and control configuration. Meanwhile, data acquisition systems, devices for websites and networks, timing devices, protection devices, PLCs, actuators, and sensors are a few examples of the employed hardware elements [12].

For the early stages of the DECY-13's ICS design, activities were focused on designs that had flexibility and robustness, the local plant control that must be integrated with the main plant, the created programming system that must be programmer-friendly, the ease of access to local control, the stability of file flow, and the easy user interface (UI) and system maintenance [20]. Taking into account various aforementioned references and considerations, the design flow can be established and presented in Figure 1. The first step was to study the literature on the development of ICS on accelerators, especially medical cyclotrons, the components of the DECY-13 cyclotron, and the operating system for commercial medical cyclotrons. Next, the control devices and parameters of the primary components were identified, and the operation flowchart was constructed. From all these processes, the ICS architecture and the to-be-used components could be developed, which might then serve as a guide for future research design.

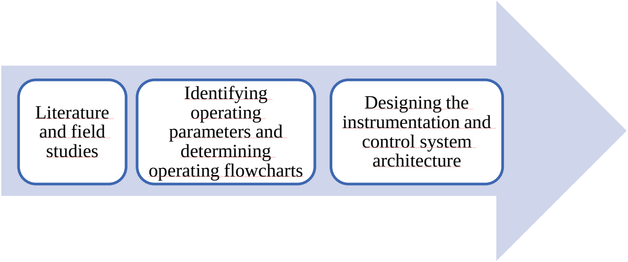

Figure 1. Flow of the ICS design method of the DECY-13 cyclotron.

III. OVERVIEW OF THE DECY-13 CYCLOTRON

The DECY-13 cyclotron R&D process, which has been carried out since 2009, is designed to produce particles with an energy of 13 MeV and a current of 50 μA for the production of ^{18}F [22]. The commissioning preparation procedures that had been carried out were testing the quality of the beam current in the central area, magnetic testing by mapping and shimming, testing the RF generator with a dummy load, and measuring the impedance of the RF-dee system with a network analyzer [3], [11], [23]–[25]. Through these tests, essential specifications and parameters for the primary components that affect the performance of the individual or integrated components in the DECY-13 cyclotron system can be determined. A simple illustration in the form of a block diagram of the DECY-13 cyclotron is depicted in Figure 2.

A. ION SOURCE SYSTEM

Experiments to test the performance of the ion source were carried out several times using a DC voltage of 2,000 kV to extract the particle beam out of the ion source head. The best results for the beam current emanating from the measured ion source were 126 μA and 170 μA in the central region area, while the expected minimum current extracted from the ion source was 200 μA. During this testing process, several parameters were constantly monitored and manually controlled; these parameters were the vacuum value, the rate of hydrogen gas, the value of the voltage and current of the power supply (PS) for the ion source cathode, and the magnetic coil current [3], [10]. The 2,000 kV DC voltage, also known as the puller voltage, was a substitute for the RF voltage in the accelerator system. The objective of testing the ion source system is to generate a beam current in the central region area stably before cyclically accelerating up to 13 MeV energy.

B. MAGNET SYSTEM

There are two primary components in the DECY-13 cyclotron magnet system, namely the magnetic power supply (MPS) and the electromagnet system. MPS is responsible for supplying power to the coils of the electromagnet system to produce stable current. All essential parameters of the MPS components that affect cyclotron operation are the value of current and internal interlock systems indicator [26]. The operation of this magnetic system must be stable in providing a certain magnetic field value so that the particle beam accelerated through the accelerator system moves along its path and is successfully accelerated up to 13 MeV energy [5].

C. RF GENERATOR SYSTEM

The RF generator in the cyclotron functions as a voltage source for the particle accelerator system to reach a certain

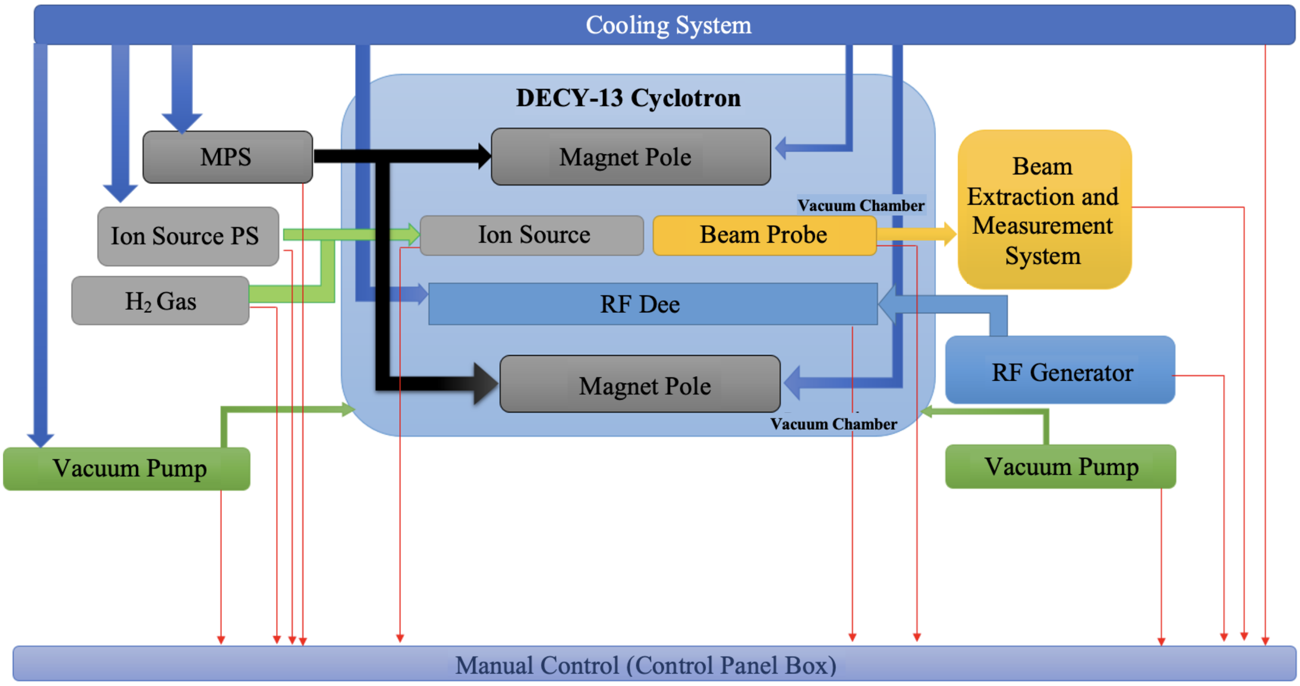

Figure 2. Illustration of the block diagram of the components in the DECY-13 cyclotron.

energy which is comprised of three modules, namely the RF signal generator module with direct digital synthesizer (DDS) technique, the driver amplifier module, and the final amplifier module. In the last test, the power generated reached 6.8 kW using a dummy load [11]. The generated power is the main parameter in the operation of the RF generator. In contrast, the parameters that affect the power generation process include frequency, voltage, power feed, feedback, module temperature, phase, forward power, and reflected power [4].

D. ACCELERATION SYSTEM (RF-DEE, LINER, AND CAVITY)

The RF-dee system on the DECY-13 is designed to have a frequency of 77.76 Hz to accelerate particles up to 13 MeV energy. Measurements with a network analyzer showed a frequency of 77.75 MHz with a fine tuner position of 11 mm and an impedance value of 32.6 W + j29.0 W [9], [25]. Optimization of the shape of the coupler and the final amplifier module circuit was carried out so that the appropriate frequency value was acquired, and impedance matching could occur.

E. BEAM DETECTION SYSTEM

The beam measurement process was carried out using a beam probe which is a probe tip connected to a conductor wire and installed in the probe rod and electrically isolated from the probe rod and other devices. Tests were performed using ion source experiments with a puller voltage as a particle attractor. The measured important parameter in this experiment was the current of particles caught on the probe tip in the central region [3]. The particle beam catcher was designed using a 0.25 mm thick copper sheet [27]. Under these conditions, in addition to the beam current, the position of the beam probe also determines the validity of the position as a function of the accelerated particle energy.

F. VACUUM SYSTEM

The DECY-13 cyclotron vacuum system consists of multiple components, namely a rotary pump for low vacuum processing, a diffusion pump for high vacuum processing, and several valves whose open/close are arranged in such a way to obtain the expected vacuum value [28]. In cyclotron operation, the vacuum system is vital because it affects the value of the resulting beam current. During normal cyclotron operation, the value is maintained at 10^{-6} torr so that the accelerated particle beam current value remains stable at an optimum value.

IV. PROCESS OF SYSTEM DESIGN

A. OPERATIONAL FLOWCHART DESIGN AND OPERATIONAL PARAMETERS IDENTIFICATION

Cyclotron operation, in general, can be learned from a number of commercial cyclotron operation manuals and by directly asking the cyclotron operator at the hospital [10]. For cyclotrons that are used specifically used for research, some literature from Reutger can be used as a guide [29]. Information can also be gained from the experts directly; one of them is Prof. Jong Seo Chai from Sungkyunkwan University, Korea, during a workshop at PRTA. Apart from that, experiments on several main components of the DECY-13 cyclotron that have been carried out also serve as indispensable references for the preparation of operational steps.

Based on these studies, the operational steps for the DECY-13 cyclotron can be arranged as shown in the flowchart in Figure 3. The operating procedures here were required for the next steps, namely when designing the UI and integrating operation panels so that they were easy to operate by the operator. The operation of the DECY-13 cyclotron commenced with a checklist of all prerequisite components, including the readiness of the power supply system for each primary component, the cooling system, the interlock system for each component, and the personnel and equipment safety system during operation. If the checklist was complete, the following steps included turning on the primary computer system, main box panel, and components.

The subsequent step was to turn on the cooling water system, consisting of a chiller and a demineralizer. Then, wait until the operating conditions for cooling water in all the primary components was met. The following step was to activate the vacuum system until it reached 10^{-6} torr to optimize

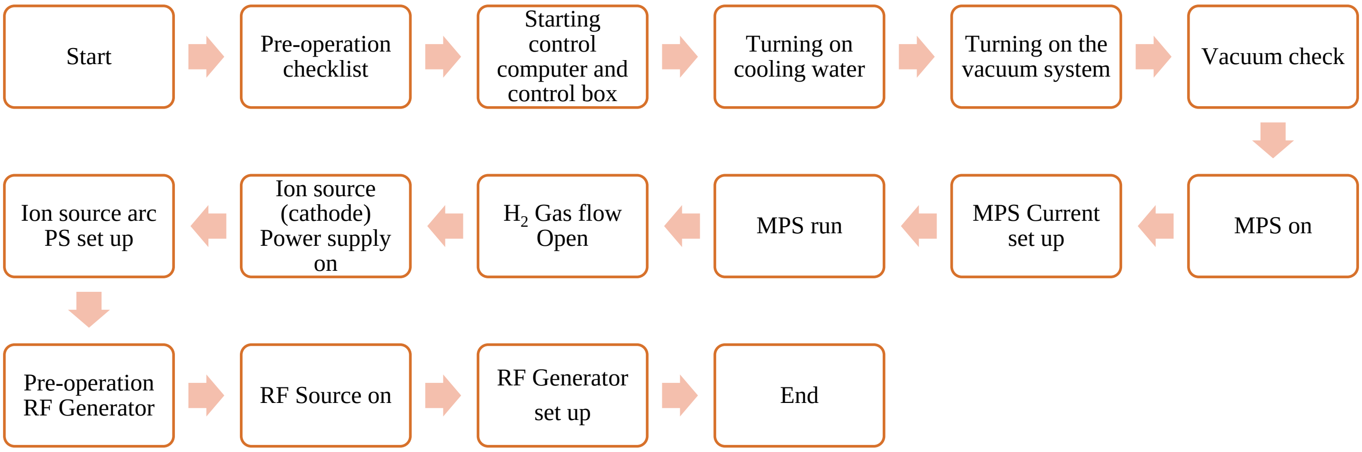

Figure 3. DECY-13 cyclotron operation flowchart during commissioning.

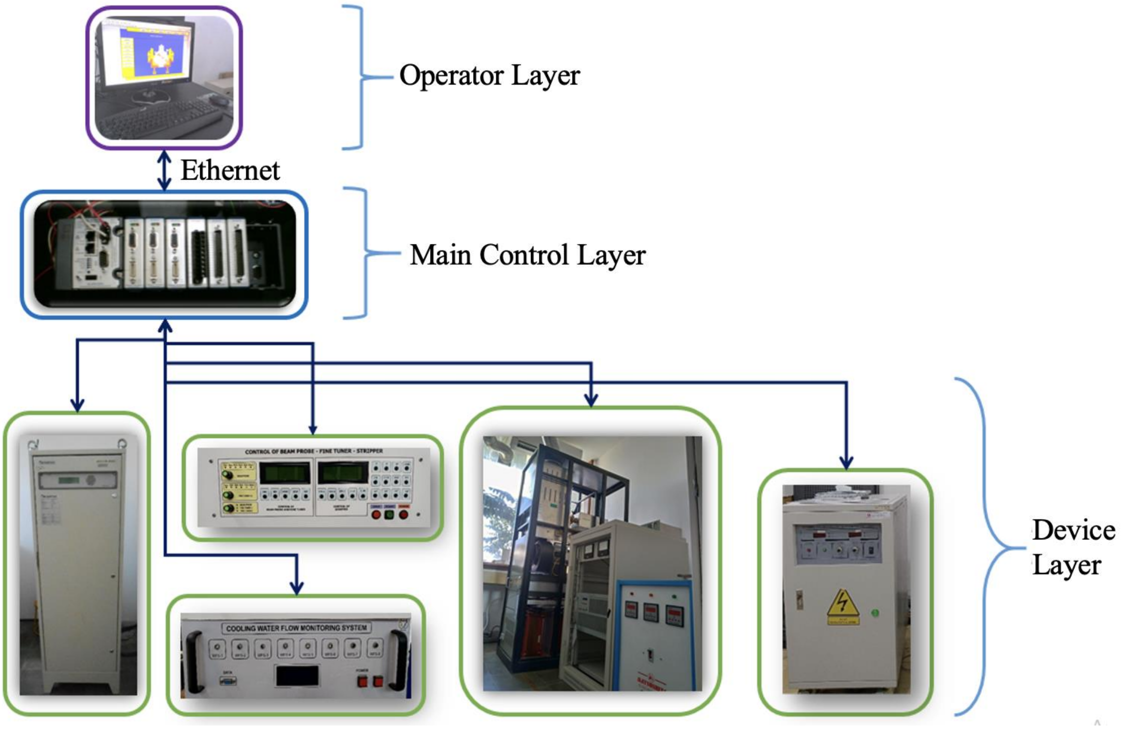

Figure 4. DECY-13 cyclotron control system schematic.

the accelerated beam current and reduce the occurrence of discharges in the components in the vacuum chamber since they could damage these components.

After the vacuum reached a value of 10^{-6} torr, the MPS was turned on with a maximum current setting of 200 A and a voltage of 100 V. For magnetic field stability, the MPS was operated for approximately 30 minutes prior to the activation of the ion source cathode power supply. Before the power supply was turned on, roughly 5-6 sccm of hydrogen gas was delivered into the vacuum chamber. The cathode current and voltage were regulated and increased slowly to avoid discharges and to generate a stable current. After the cathode current was fulfilled, it was stabilized for 30 minutes before the RF generator was activated. The RF generator was operated to transfer 10 kW of power with a frequency of 77.76 MHz into the accelerator system [11]. As the power was completely transferred to the accelerator system, the particles in the ion source head were extracted and moved circularly. After that, they were accelerated to a certain energy level until they hit the extractor, which was then forwarded to the target system and processed for radioisotope production.

B. DESIGN OF CONTROL SYSTEM ARCHITECTURE

The main focus in the design of the DECY-13 operating system integration is a simple and user-friendly system, allowing the operator to easily operate the cyclotron during commissioning. Therefore, the architecture used DCS, which consisted of three layers, namely the device, main control, and operator layers, as shown in Figure 4. This method was also used by KIRAMS for the design of GIS on the early generation of the 13 MeV cyclotron due to its simple configuration, flexibility, and ease of maintenance [18]. The device layer consisted of the primary components of DECY-13 and their local control system installed in the control panel box. The main control layer was the main controller for cyclotron operations, which utilized high-performance embedded controllers and modules that facilitated communication between the device and the main control layers.

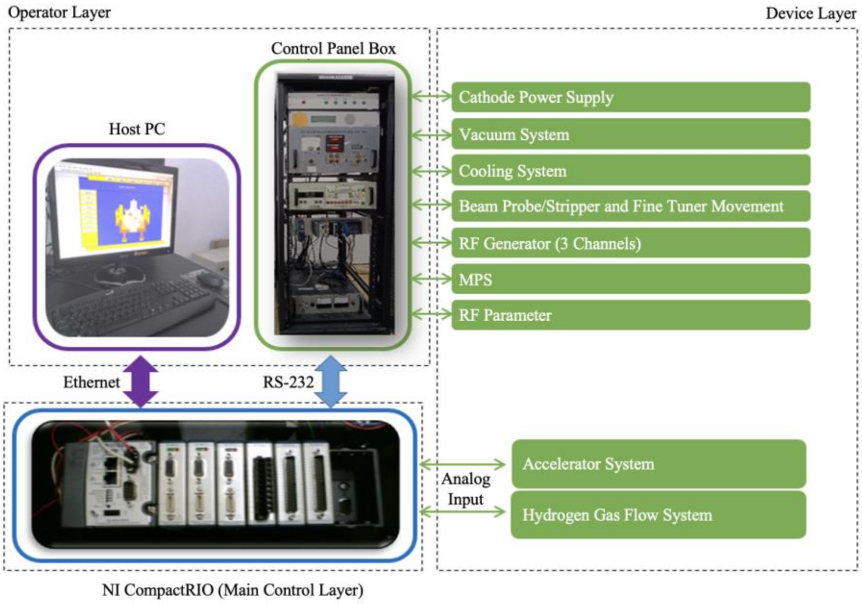

Figure 5. Configuration of DECY-13 cyclotron's ICS.

In commissioning the DECY-13 cyclotron, the operator controlled the cyclotron's operation through a UI in the form of a control panel box integrated with the host PC. Aside from being a UI, the host-PC was also used for data logging and displaying infographics of essential parameters during the operation.

V. DISCUSSION

For the current conditions, at the device layer, there are the main components of a cyclotron with local control that use a controller in the form of a TRiLOGI PLC product or an ATMega microcontroller which functions as a local component controller during the system testing process. In addition, in its operation, several primary components of the cyclotron have a control panel box as a UI.

The primary components that are equipped with a PLC are the vacuum system, fine tuner drive system, beam probe, and stripper. Meanwhile, the three subcomponents of the RF generator use a microcontroller. An RS-232 communication line has been provided for these components to facilitate the connection with the main control layer. It differs from other primary components, such as ion source, cooling, magnetic, accelerator, and beam detection systems, whose components still need to be fully integrated. Under these conditions, additional components and modifications still need to be made in order for them to be integrated with the main control layer.

During the test, the operator manually controlled and separated the ion source system consisting of a cathode power supply and a hydrogen gas flow system. Therefore, to be integrated with the main control layer, it was necessary to add local control and an RS-232 communication line for each component. Meanwhile, in the cooling system, the PLC was used for monitoring purposes, with the LCD serving as a parameter display on the control panel box. An RS-232 cable was added from the PLC to the main control layer for the integration process. Aside from being a data logging and infographic display, the cooling system controller through the device control layer could also provide interlock signals to several primary components using the cooling system, such as diffusion pumps in vacuum systems, MPS, ion sources, electromagnets, and RF accelerator systems (dee-cavity-coupler). This way can protect the device on the DECY-13 cyclotron from any damage.

For a magnetic system consisting of an MPS and an electromagnet system, a local controller was available on the internal MPS, which had also been equipped with an RS-232 communication line. On the other hand, the accelerator and beam detection systems for the integration, main control was connected to the analog input module with the dee voltage as the main parameter and measured particle beam current on the beam probe.

An illustration of the ICS of the cyclotron's primary components that have been integrated with the DCS method is presented in Figure 5, with the position of the host PC and control box panels close together. In addition to identifying the control parameters described above, the operating parameters of each primary component are identified and presented in Table I of the appendix. The identification of these parameters can serve as a basis for future research in compiling programs for UI on host PCs and data logging.

VI. CONCLUSION

In the ICS design process for commissioning the DECY-13 cyclotron, a design that eases operators to carry out operations and observations during the commissioning process has been obtained. In addition, in the short term, a simple design will facilitate implementation, while in the long term, it will facilitate system upgrades, routine maintenance, or troubleshooting when problems occur in the system.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest during the writing of this paper.

AUTHOR CONTRIBUTION

Conceptualization, Frida Iswinning Diah, Fajar Sidik Permana, and Emy Mulyani; accelerator control system concept, Frida Iswinning Diah and Fajar Sidik Permana; DECY-13 cyclotron overview, Frida Iswinning Diah and Fajar Sidik Permana; control system development of DECY-13 cyclotron, Frida Iswinning Diah and Fajar Sidik Permana; discussion, Frida Iswinning Diah, Fajar Sidik Permana, and

Emy Mulyani; writing—framework and flow, Emy Mulyani; writing—review, Emy Mulyani.

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APPENDIX

TABLE I
ICS CONFIGURATION OF THE OPERATING PARAMETERS OF THE DECY-13 CYCLOTRON COMPONENTS

No.	Subsystem	Parameter	Description
1	**Cooling system**	Water level	Level of water torn (make up water)
		Water temperature	Temperature of water-cooling tower (CT)
		Water flow rate	Water flow from the CT to the chiller I
		Water conductivity	Temperature of water that is in/out of the chiller
2	**Vacuum**	Vacuum value	Low and high vacuum values
		Heater temperature	Temperature of diffusion pump heating oil
		Valve position (on/off)	Position of valve in the vacuum system
3	**Magnet system**	Cooling water temperature	MPS and magnetic coil
		Cooling water flow rate	MPS and magnetic coil
		In/out temperature of cooling water	MPS and magnetic coil
		Interlock status	MPS
		Ready status	MPS
		In/out current and voltage	MPS
4	**Ion source system**	Cathode voltage	Reads on the Ion Source Power Supply
		Cathode current	Ion Source Power Supply
		Gas rate	Rate of H_2 from the tube to the cyclotron vacuum chamber
		Ion source position	The movement of the ion source is towards/away from the central region and upwards and downwards.
		Gas valve opening	The opening position of the ion source gas rate control valve
5	**RF system**		
	DDS exciter	V_{DC}	DC voltage output
		I_{DC}	DC current output
		Reflected	Reflected RF power
		Forward	Transmitted RF power
		Temperature	Temperature DDS when operating
	Driver amplifier	V_{DC}	DC voltage output
		I_{DC}	DC current output
		Reflected	Reflected RF power
		Temperature	Transmitted RF power
	Final amplifier	Plate Voltage	Anode plate voltage
		Plate Current	Current in the anode plate
		Filament Voltage	Triode tube filament voltage
		Reflected	RF power returns while transmitting
		Forward	RF power is transmitted
6	**Accelerator system** (dee, cavity, coupler, liner)	Cooling water temperature	Temperature of dee water cooling
		Frequency, phase, amplitude	Dee system
		Fine tuner position	Dee system
7	**Beam detection system**	Beam flow	Extracted particle beam from ion source head
		Beam probe position	The distance of beam probe towards central region