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AUTOMATIC RF AND ELECTRON GUN FILAMENT CONDITIONING SYSTEMS FOR 6 MeV LINAC

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Abstract

RF conditioning of vacuum windows and RF cavities is a necessary task for eliminating poor vacuum caused by outgassing and contamination. Also, startup and shutdown process of linear accelerator requires gradual increase and decrease of electron gun filament voltage to avoid damage to the filament. This paper presents an EPICS based multi-loop automatic RF conditioning system and Electron Gun filament conditioning system for Klystron based 6 MeV Linear Accelerator.

INTRODUCTION

Particle accelerators are a crucial instrument for scientific innovations and knowledge in all fields of research and engineering. As accelerators grow more complex, so do the demands placed on their control systems. The complexity of the control system hardware and software reflects the complexity of the machine. At the very same time, the machine must have simple access and operation, as well as a greater level of stability and adaptability.

Radio Frequency (RF) charged particle accelerators use accelerating RF cavities to accelerate electrons or ions to energies up to hundred mega electron volts. A particle source produces ions or electrons, which inject into the cavity with some minimum initial energy. A significant amount of RF power must be coupled into the accelerating cavity structure to transfer energy to the charged particles. High power klystron amplifiers are commonly employed as a RF power generation source for accelerators. In addition, waveguides and couplers are utilized to transmit RF power from the klystrons to the cavities. Injected RF power resonates with incoming particles, accelerating them to produce a higher energy, faster moving charged particle beam.

Several auxiliary systems, such as a water load and cooling system, vacuum maintenance system, control system and safety interlocks support the entire process. Maintaining a good quality vacuum in the LINAC cavity and connected components is critical for uninterrupted beam transport and smooth operation. When RF power is fed into the cavity during start-up and operation of the accelerator, the vacuum level degrades owing to poor manufacturing of the cavity's internal structures, RF breakdowns, outgassing, and arching. To cope with this issue, an auxiliary vacuum system is employed which consists of one or more series-connected pumps that continually generate a low-pressure zone inside the cavities. Radio frequency (RF) breakdown is a typical problem in accelerating structures and has been widely researched [1, 2, 3]. It is vital to avoid severe RF breakdown since it can harm accelerating structures and microwave devices irreparably. Breakdowns and multipacing restrict the power that the cavity can absorb during the conditioning process [4]. This phenomenon limits the RF structure from working in high-power mode and from producing full-energy beams. The frequency of breakdown is highly linked with the vacuum state and RF power intensity. Outgassing and sparking impact vacuum performance and restrict the RF field level that can be consistently attained.

Therefore, for safe operation, RF power is gradually injected into the cavity, ramping up in multiple stages from the lowest to the highest level while constantly monitoring the LINAC characteristic parameters such as vacuum level, temperature profile, arching, and other system interlocks [5]. The process of gradually "warming up" the LINAC cavity is known as RF conditioning. The amount of time required for conditioning, varies on the nature of cavity and might range from a few days to months.

This paper presents the design and development of a system for automated RF conditioning of electron linear accelerator cavities at the LINAC project PINSTECH. RF power conditioning scheme, hardware setup, logic design and software development techniques have been thoroughly addressed. The suggested structure is implemented with the Experimental Physics and Industrial Control System (EPICS), which is a collection of software components and tools used by developers to create distributed control systems for particle accelerators, big experiments, and massive telescopes [6]. In the last section, test setup developed for automated conditioning of electron gun filament has been discussed.

CONDITIONING STRATEGY

Numerous conditioning strategies have been employed at different accelerator facilities [7, 8, 9]. Linear accelerator prototypes (Medical and Industrial) at the LINAC project PINSTECH comprises of standing wave cavities structure, produces 06 MeV electron beam and runs at 2.5MW input RF power at resonance mode when the cavity is fully tuned. Electrons are injected by a 30keV electron gun and RF power is applied by a klystron that generates an oscillating RF signal of 50Hz frequency, 2.5 MW peak power and 5usec pulse width. The average power effectively delivered into the cavity is determined by three factors: peak amplitude, pulse width, and frequency.

$$P_{inj} = P_{peak} \cdot T_{on} \cdot f$$

Where P_{inj}, P_{peak}, T_{on}, f represent injected power, peak power, pulse width and frequency, respectively. These three parameters can be changed to enhance or reduce injected power.

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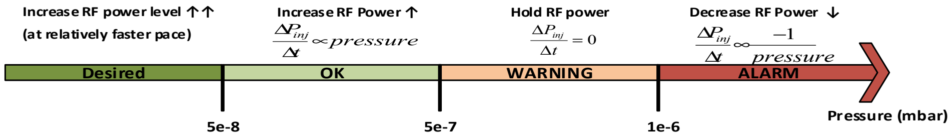


Figure 1: RF power conditioning strategy w.r.t vacuum dynamics of accelerator cavity.

At the beginning of the conditioning process, the lowest possible RF power is injected and its strength is increased gradually while constantly monitoring the vacuum quality. Magnitude and direction of power gradient $\frac{\Delta P_{inj}}{\Delta t}$ is adjusted based on vacuum dynamics. Pressure level data is a solid indication of breakdowns and outgassing phenomenon occurring inside the cavity. The desired operating range of pressure for power ramp up is 5×10^{-8} mbar or below. If the pressure rises up to 5.0×10^{-7} mbar, a high-pressure warning signal is generated and the RF power ramp-up process is halted. Consequently, pressure tends to settle down and vacuum quality improves. However, if the vacuum quality deteriorates further and pressure level exceeds 1×10^{-6} mbar, a vacuum interlock is triggered and RF power is ramped down instead, with a relatively greater step size. Figure 1 illustrates the relationship between RF power gradient with pressure level of cavity.

Power ramp-up scheme consists of three nested loops that correspond to the RF pulse parameters P_{peak} , T_{on} and f. These parameters act as main incrementing variables of respective loops. They are initialized at lower values and increased by a step size with each iteration of loop. Basic flow of the program is described in following steps:

1. Set Peak power, rep rate and pulse width of RF pulses to an initial value of 20kW, 0.7usec and 5Hz, respectively.

Innermost Loop (Increase RF Pulse peak power)

2. Increase RF pulse amplitude gradually while constantly monitoring the vacuum level. As power level rises, breakdowns begin to occur and vacuum level shows frequent surges. Depending on vacuum gradients and trends, adjust the step size and delay between two successive levels of RF power.
3. Condition to the maximum power that can be obtained without frequently activating the vacuum interlock.
4. After the pressure and breakdown rate have been reduced, increase the RF power to a higher level. Repeat this procedure until peak power reaches 800kW.

Middle Loop (Increase RF Pulse width)

5. Increase pulse width gradually up to 5 usec with step-size, $\Delta T_{on} = 0.2\, usec$. For each increased level of pulse width, repeat steps 2-4 until 1.6MW peak power has been achieved.

Outermost Loop (Increase RF Pulse rep rate)

6. Increase pulse rep rate gradually up to 50Hz with a step-size $\Delta f = 5Hz$. For each increased level of frequency, repeat steps 2-5 until RF pulse peak power has reached up to 2.5MW with 50Hz rep rate and 5usec pulse width.

HARDWARE DESIGN AND INSTRUMENTATION

The suggested RF conditioning methodology employs a variety of cutting-edge devices and instruments from diverse vendors. The following are the primary components employed in the conditioning setup: vacuum gauge controller, programmable logic controller (PLC), Inverted magnetron gauges, signal generator, peak power meter, oscilloscope, arc detector, delay generator, high speed RF interlock switch, temperature sensors, relays, safety interlocks, klystron and water-cooling system. The overall block diagram of the RF conditioning system is shown in Fig. 2.

RF signal is produced by signal generator, and passed to the klystron through an RF interlock switch. This switch is triggered by a gating sequence generated by the delay generator. As a result, the incoming RF pulse is transmitted only for a specific duration of time, obtaining the desired pulse width. This pulsed RF power is amplified by klystron and transferred to the cavity through waveguides.

During the RF conditioning process of high-power vacuum components such as cavities, couplers, windows, etc., it is necessary to monitor the vacuum quality, arcing, and forward and reflected RF-power levels. To monitor forward and reflected power, two directional couplers are connected to the wave-guide. Signals from directional couplers are measured with a high-speed oscilloscope that is interfaced with control software EPICS through TCP/IP. A pumping station consisting of a rotary and turbo pump linked in series maintains the vacuum level inside the cavity. These pumps operate continuously in order to attain the specified set point. Pumping speed is estimated based on pressure level feedback from vacuum gauges. Two IMG gauges are used to measure the pressure within the cavity at two different locations. A vacuum gauge controller is used to read gauge data and deliver it to the PLC through its analogue output.

Siemens S7-300 PLC system has been employed, as a field controller, to collect pressure readings and monitor auxiliary systems such as water load, temperature control, and arc detection. The PLC controller communicates withf Sensors/actuators and exchanges data with the primary control software built in EPICS. PLC is connected with arc detector, pressure switches, temperature sensors, and flow meter. In case of a malfunction or an abnormal circumstance, the PLC generates an interlock signal, which disables the RF switch.

LOGIC DESIGN AND SOFTWARE DEVELOPMENT

Control system architecture is developed in the EPICS environment that also serves as an integration tool for all software components. EPICS StreamDevice support module is configured and installed to communicate with field instruments via TCP/IP or RS232/485 protocol. StreamDevice is a generic EPICS device support for devices with a "byte stream" based communication interface. For each device that needs to be interfaced with control software, a soft IOC (input-output controller) is developed in EPICS. These IOCs act as servers, collecting data from the attached instrument and broadcasting it to many clients through the channel access networking protocol.

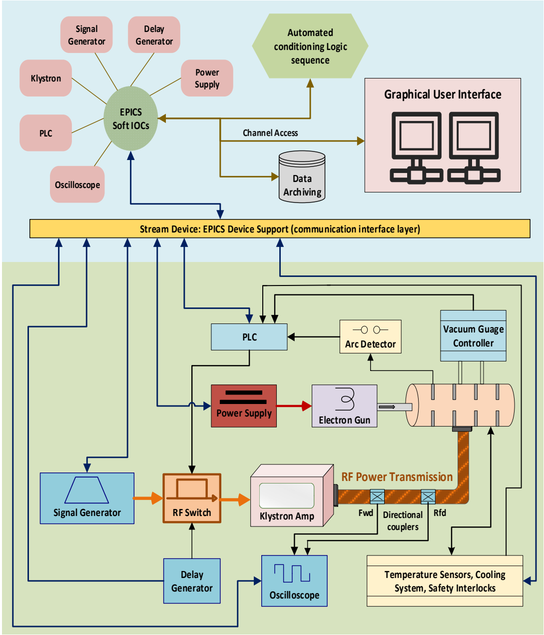


Figure 2: Hardware setup and instrumentation.

For conditioning tasks, soft IOCs have been developed and configured that interface with their respective equipment. Examples include klystron, signal generator, e-gun power supply, delay generator and PLC, allowing their complete remote access. Each IOC has a dedicated database that stores information in the form of records or process variables (PVs). PVs are configured and linked with the real-system field parameters. IOCs can communicate with other IOCs, as well as with databases and front-end applications. All process variables are accessible anywhere on the network via channel access protocol.

The EPICS sequencer module is used to program the algorithm for the automated conditioning system in state notation language (SNL). This application operates in the background and exchanges data with the relevant IOCS and databases. It reads the most recent values of process variables and makes decisions according to control logic. Front-end application often known as Graphical User Interface (GUI) is developed in Control System Studio-Phoebus. An interactive graphical user interface has been created, allowing the user to modify and monitor associated process variables and their trends. Operators can connect and communicate with any instrument from any remote location using the front-end application. To perform RF conditioning, operator can send start/stop requests and set values of related parameters such as initial power, final power, step size and time delay etc.

These values are sent to the sequencer program that evaluates the next decision and updates relevant PVs in the database. IOCs serve as a link between database and field instruments for updated information exchange. The sequencer program is written in the form of states, and its flow chart is depicted in Fig. 3. It has five states: ***Start, Vacuum Monitor, Increment Decrement*** and ***Fault.***

program begins with the *'Start'* state, at the request of operator's start command, initializing all variables: Initial and final RF pulse frequency, rep rate, amplitude and the step sizes denoted by f_0, f-max, T_0, T_{on}-max, P_0, P-max, Δf, ΔT_{on} and ΔP, respectively. If all the interlocks are cleared and system is in ready mode, program advances to the next state, *Vacuum Monitor.*

In the *Vacuum Monitor* state, program waits for a set period Δt (default: 2 min) and monitors pressure data with 1 Hz frequency, making the next decision based on the vacuum quality. This decision can be further divided into three segments: a) If pressure level remains in normal range for the entire two minutes, it advances to *Increment* state. b) If pressure increases to the warning level, program returns to the same *Vacuum monitor* state and waits for the pressure to settle down. c) If pressure continues to rise and crosses the alarm limit, program immediately switches to the *Decrement* state.

In the *Increment* state, program steps up the RF power level in three nested incrementing loops. It achieves this, by iteratively increasing pulse peak amplitude, pulse width or frequency based on the preceding level in the loop and step size. After stepping up RF power, it returns to *Vacuum Monitor* state.

In the *Decrement* state, program steps down the power by decreasing RF pulse amplitude. After reducing the RF power level, it pauses for a defined period before returning to the *Vacuum Monitor* state.

Meanwhile, if system interlock occurs, program enters

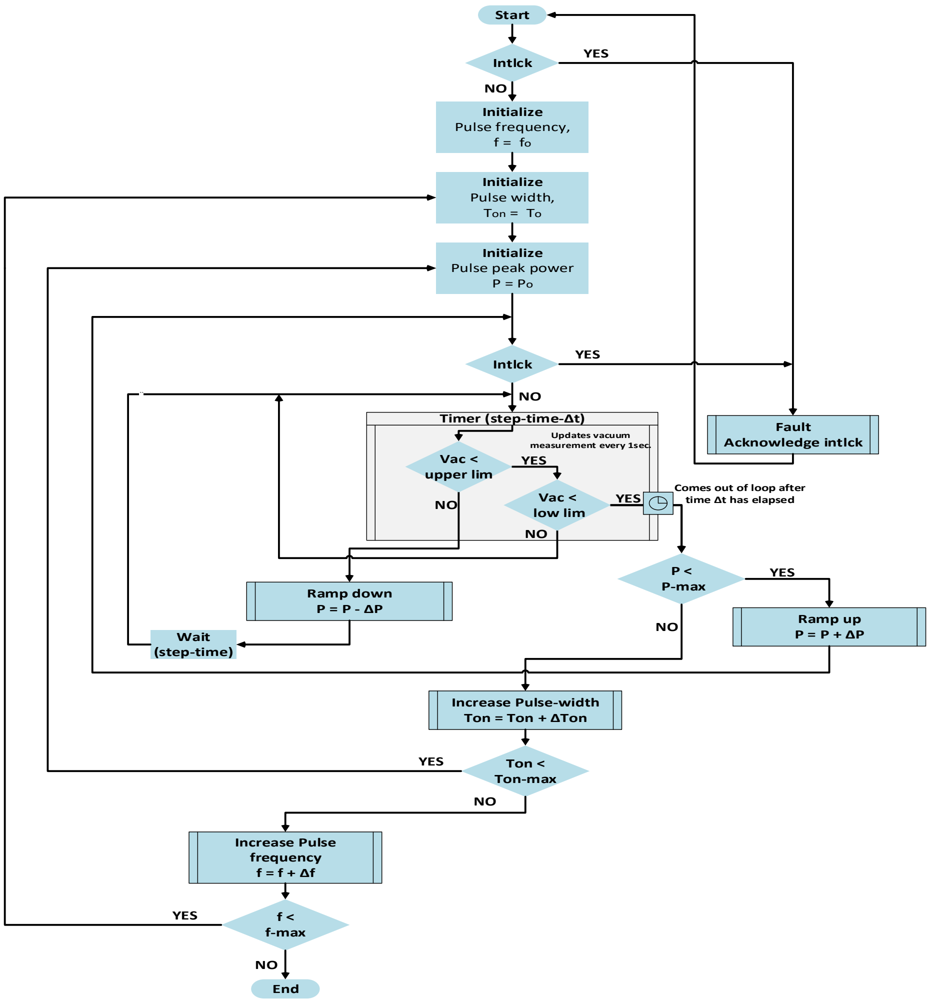


Figure 3: Flow chart of conditioning algorithm.

the *Fault* state and turns off RF power. Once the fault has been recovered and acknowledged, the conditioning process can be restarted only if the operator sends the start instruction. When the maximum required level of RF power is attained, the conditioning process is terminated, and the program transmits a complete signal to the database and GUI. The program can be paused at any time during operation through GUI. Furthermore, all associated parameters such as power gradient, step sizes, time delays, and limitations may be adjusted at any moment for a more flexible operation and conditioning procedure.

ELECTRON GUN LOW VOLTAGE CONDITIONING

A high voltage DC electron gun generates the electron beam that is injected into LINAC. The gun filament is composed of tungsten and is housed in a chamber filled with barium oxide. A tungsten disc is positioned at the end of the chamber and is primarily responsible for electron emission. A low voltage and high current (12V, 2.5Amp) is supplied to the filament that heats the tungsten disc indirectly. As a result, when the disc attains a breakdown temperature of 1200°C, it begins releasing electrons with a few electron volts of energy. These electrons are then excited by a 30 KV pulsed power supply and kicked into the accelerating cavities for further gain in energy and speed.

During the low voltage (LV) excitation of electron gun filament, a sudden rise in temperature might cause thermal breakdowns and damage the electrodes. Therefore, for the safe beam on operation, low voltage applied to the gun filament should be increased gradually from 0 to 10V to maintain a minimum temperature gradient. This is referred to as LV conditioning of electron gun filament. The conditioning process eliminates contaminants on the insulating ceramic and the electrode surface, avoids poisoning of electrodes and improves breakdown threshold. During LV conditioning a vacuum level of 1×10^{-8} mbar is maintained to transport electron beam smoothly and avoid electric discharges. Voltage ramp up strategy must be in accordance with the vacuum quality.

A test setup has been developed for automatic LV conditioning and ramp up of electron gun filament voltage. Gun filament is powered up by DC power supply, which is serially interfaced with EPICS soft IOC. A serial to optical converter has been used as an intermediate link to provide isolation from power supply. All parameters of power supply: set voltage, actual voltage and actual current are linked with IOC. Their values are also accessible from database and GUI. A sequencer program is developed for automatically ramping up the power supply voltage with respect to the vacuum level. A single loop program increases, holds or decreases gun voltage according to pressure level of cavity. Vacuum warning and alarm limits are adjustable from the GUI. Program continuously monitors interlocks and pauses the ramp-up process in case of any alarm or fault. This is to prevent excessive discharges during the conditioning.

RESULTS

Automatic RF conditioning system has been developed, installed and tested at LINAC Project, PINSTECH. Numerous experiments have been conducted using the developed software and performance is satisfactory. This setup facilitates users for safe and reliable conditioning of accelerator cavities with minimum human intervention.

Figure 4 depicts a specimen of data during one of the RF Power conditioning trials. It shows 150-minute span of the process where injected power and pressure measurements are represented by red and green curves, respectively. RF power was systematically increased by the control software. Discontinuities in graph (around: 11.30 and 12:00) reflect the RF power cut-down events due to vacuum spikes and system fault. In the beginning [11.00-11:30], RF power was increased with larger step, but for the remaining period power gradient was decreased due to small margin in pressure level and warning limit.

Figure 5 illustrates a snapshot from electron gun LV conditioning process that was being controlled by the developed software. Electron gun filament voltage and cavity pressure are plotted by red and blue colors, respectively. Their relative trend in graph can be divided into three categories: First segment [12:36-12:50] represents 'Increment' state where vacuum quality is good and filament voltage is increased smoothly with constant rate, Second segment [12:50-13:05] shows 'Hold' state where vacuum is in warning range, and program holds the filament voltage. Third and the last segment shows voltage 'Decrement' state, where pressure crosses alarm limit at 13:07 and voltage is decreased quickly.

Figure 6 displays Operator Interfaces (OPI) for RF conditioning and e-gun conditioning systems. GUIs are user-friendly and facilitate operator with the provision of adjusting variables (limits/step sizes), acknowledging alarms as well as initiating, monitoring or ceasing the conditioning process.

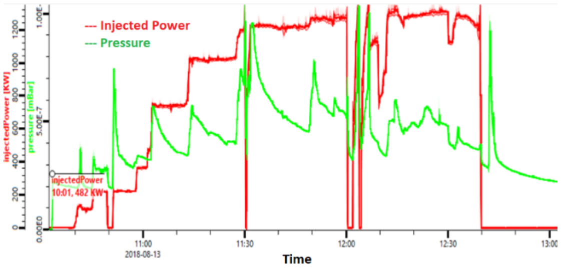


Figure 4: RF Power conditioning Process.

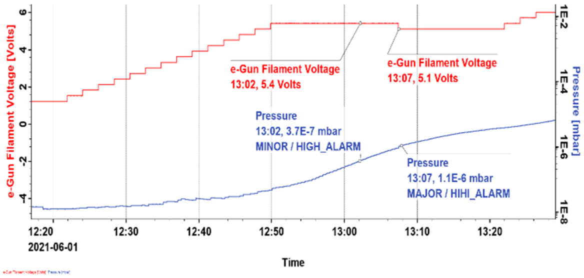
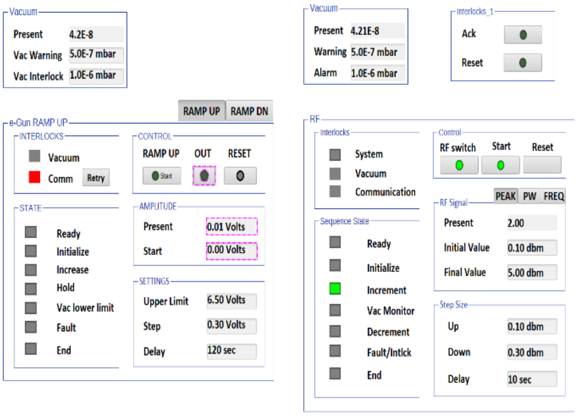


Figure 5: e-Gun LV conditioning.



Present 4.2E-8
Vac Warning 5.0E-7 mbar
Vac Interlock 1.0E-6 mbar
Present 0.01 Volts
Start 0.00 Volts
Upper Limit 6.50 Volts
Step 0.30 Volts
Delay 120 sec

Present 4.21E-8
Warning 5.0E-7 mbar
Alarm 1.0E-6 mbar
Present 2.00
Initial Value 0.10 dbm
Final Value 5.00 dbm
Up 0.10 dbm
Down 0.30 dbm
Delay 10 sec

Figure 6: OPIs for RF & e-gun conditioning.

CONCLUSION

An optimal scheme for RF power conditioning of standing wave linear accelerators is proposed and discussed. Aim of this work was to develop an automated system to perform recommended conditioning strategy in a reliable and efficient manner with minimum surveillance. The proposed system has been successfully implemented in EPICS platform and PLC has been used as main controller for interfacing of hardware electronics. Both software and hardware design strategies have been discussed. All components and instruments used for this project are easily available commercially. System's parameters are accessible and reconfigurable based on the requirement of end-user. A similar setup for LV conditioning of electron gun filament has also been developed. This system has been tested and installed at LINAC Project, PINSTECH. It has been effectively used during several experimental runs and its performance is well in-line with the desired requirements.

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