PID-Regulated Heating System for PIP-II Reference Line

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Abstract

The Proton Improvement Project-2 centers on building a new superconducting linear particle accelerator (Linac) at Fermilab. At the heart of the accelerator is the reference line, a critical system that defines the ideal path for the particle beam as it passes through magnets, RF cavities, and other beamline elements. Temperature stability is crucial for the reliable operation of RF components, such as mixers and filters. Fluctuations affect key performance parameters like conversion loss, isolation, and linearity. To mitigate any drift caused by ambient temperature changes, a heating plate assembly is utilized to maintain key components at a controlled temperature of 40°C. The system utilizes an aluminum 36”x36”x0.5” heat plate powered by a MOSFET-based control circuit, delivering approximately 460 W of thermal energy through a resistor array. Real-time temperature feedback is provided by a PT100 Resistance Temperature Detector (RTD), which interfaces with a Proportional–Integral–Derivative (PID) control algorithm to maintain closed-loop temperature regulation. The control signal actively modulates the gate voltage of an N-channel MOSFET, dynamically adjusting power delivery in response to deviations from the temperature setpoint. Simulations and LTspice models validate the functionality and responsiveness of the circuit under varying conditions. The prototype has successfully demonstrated stable thermal control, paving the way for integration into the PIP-II infrastructure. The final design will feature an expanded resistor array, as well as communication with a PLC for continuous data acquisition and diagnostics. This work directly supports Fermilab’s broader mission by contributing to the stability and reliability of core accelerator systems, enhancing the precision of particle beam delivery for future physics experiments.

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A. Introduction

The Proton Improvement Project-2 centers on building a new superconducting linear particle accelerator (Linac), allowing for boosted discovery potential of neutrino behavior, and strengthening Fermilab's global research status. The reference line of an accelerator is akin to its heartbeat. It is used to design the path for the beam, accounting for the ideal positions through magnets, RF cavities, and beamline elements. Precise temperature control is critical for both operational stability and experimental accuracy inside of particle accelerators.

B. Progress

1. Thermal Energy and Power Requirements

To design a heating system that can bring the aluminum plate to the desired operating temperature, it is first necessary to estimate the amount of thermal energy required. This is calculated using the fundamental heat transfer equation:

$$\mathrm{Q} = \mathrm{mc}\Delta\mathrm{T}$$

Where Q is the thermal energy (joules), m is the mass of the plate (kilograms), c is the specific heat capacity of the material (in J/kg·°C), and ΔT is the desired temperature change. Using the specific heat capacity of standard aluminum (approximately 900 J/kg·°C), and assuming the heat plate has a mass of approximately 29 kg, and needs to be heated from 25 °C to 40 °C (ΔT=15 °C), this is the estimate of the energy required:

$$Q = (29\,kg)\left(900\,\frac{J}{kg}°C\right)(15\,°C)$$

$$\mathrm{Q} = 391{,}500\ \mathrm{J}$$

Given the heating time of 850 seconds, the corresponding power requirement is then calculated:

$$\mathrm{P} = \frac{\mathrm{Q}}{\mathrm{t}}$$

$$= \frac{(391{,}500\ \mathrm{J})}{(500\mathrm{s})}$$

$$\mathrm{P} \approx 460.6\ \mathrm{W}$$

This estimation provides a baseline for the electrical power needed to elevate the heat plate from ambient temperature to its target operating setpoint. This ensures stable and uniform heating, and is essential for maintaining consistent thermal performance across the system's components.

In real-world conditions, heat loss to the environment must also be accounted for. Heat dissipates from the plate surface to the ambient air through conduction. Assuming a surface area of 1.722 m^2 and a conductive heat loss coefficient h = 5 W/(m^2·°C), the maximum heat loss at a 15°C temperature differential is:

$$Q_{loss} = (h)(A_{total})(\Delta T)$$

$$= \frac{(5W)}{(m^2 °C)}(1.77m^2)(15°C)$$

The effective net heating power delivered to the plate must exceed both the required power to raise temperature and the ongoing heat loss to the ambient environment [5].

2. Temperature Sensing Using Resistance-based Feedback

The circuit utilizes an array of four 1Ω resistors, connected in series to a high voltage (48V), moderate-current (20A) Meanwell Switching Power Supply. By wiring the resistors in series, each one drops part of the voltage supplied, each respectively seeing 12V across, further allowing for even spread of thermal conduction across the plate. As seen in Figure 1, the circuit schematic for the prototype [1]:

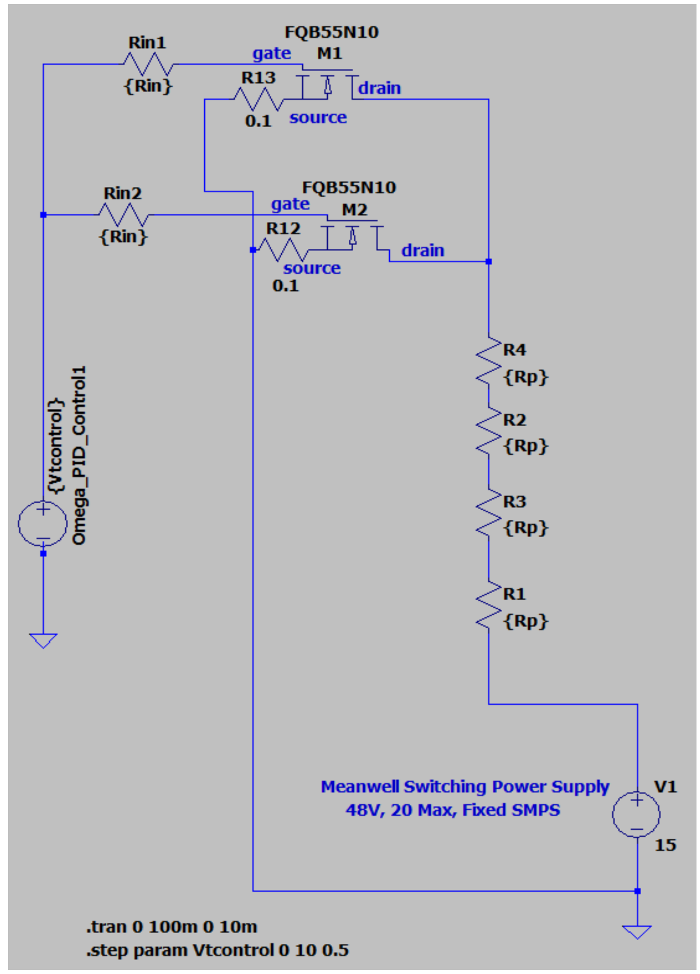

Figure 1. Control Circuit Diagram of Prototype

The heating system is embedded within a feedback control loop using a PT100 Resistance Temperature Detector (RTD). RTDs operate based on the principle that electrical resistance varies predictably with temperature. The relationship between resistance R and temperature T is approximately linear for PT100 sensors, and is modeled as [2]:

$$R(T) = R_0\,[1 + \alpha(T - T_0)]$$

Where α is the temperature coefficient of resistance, and R0 is the resistance at a reference temperature T0 (0 °C for PT100 sensors). This enables accurate real-time monitoring of the plate's temperature. The resulting resistance is converted to temperature and fed into the PID (Proportional-Integral-Derivative) controller.

3. PID Control Strategy for Temperature Regulation

The PID controller calculates an error signal, defined as the difference between the measured temperature, and the target setpoint, using the equation:

$$\text{PID output} = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

Where e(t) is the instantaneous error. In this setup, initial values include Kp=10 W/°C, Ki = .02W/°C*s, and Kd = 0. The controller's output signal modulates the gate of an N-channel MOSFET to regulate heating power. The system operates as a closed-loop feedback mechanism, dynamically adjusting heat delivery based on continuous sensor input. This ensures that the plate temperature remains precise, even in the presence of external disturbances or thermal losses. A simplified form of the heater control logic can also be shown as[5]:

$$\text{Heater Power (\%)} = K_p e(t) + K_i \int e(t)dt$$

The sensor exhibits a time lag in response, approximately using:

$$\alpha\text{sensorlag} = \frac{dt}{sensor\ lag + dt}$$

Where the time constant sensor lag (e.g., ~60 s) corresponds to ~0.016 Hz (1/RC).

Figure 2a. shows how these time-domain responses evolve throughout operation. It plots the actual plate temperature, sensor-measured temperature, setpoint, and the corresponding heater power percentage, illustrating system dynamics including overshoot, stabilization, and lag behavior:

Figure 2a. Sensor Behavior approaching setpoint.

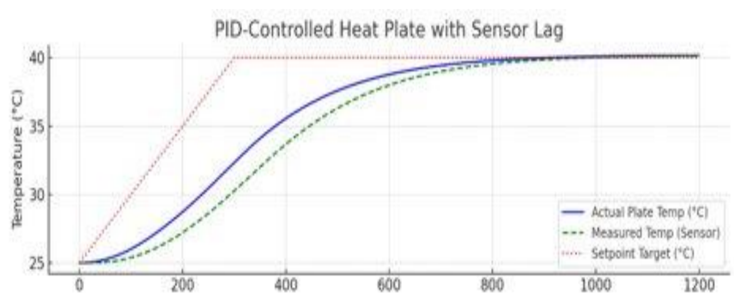

Figure 2b. The system's thermal response was observed to be uniform, and the PID

loop successfully mitigated overshoot and stabilized the temperature near the setpoint:

Figure 2b. Heater Power (%) vs Time(s)

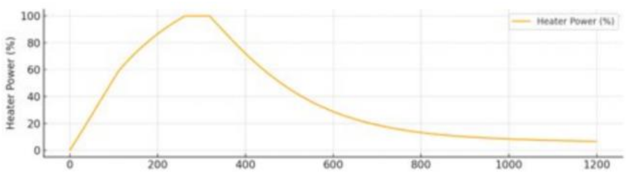

Figure 3 demonstrates varying gate control voltages observed throughout operation, showing how the controller utilizes the PID loop feedback for temperature regulation [1] [3]:

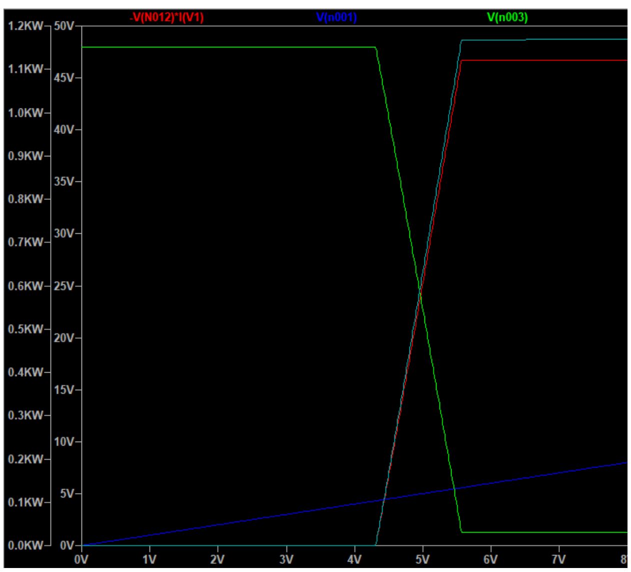

Figure 3. LTspice Simulated DC Control Voltages

Further investigation was conducted through LTspice simulations to verify the behavior of the circuit under varying thermal load conditions. These simulations confirmed that the MOSFET gate voltage modulation responded as intended to changes in temperature. Thermal spreading across the plate was observed to be relatively uniform, due to the series configuration of the resistor array. Future variants may evaluate temperature readings using additional RTDs, and embedded thermocouples. Furthermore, these optimizations would further align the system with the strict stability and precision requirements demanded by the RF components in accelerator environments.

C. Conclusion

1. Future Work

With the successful completion and demonstration of the prototype, the next step is to begin production of final design. The final design uses an eight resistor array, and is going to be installed inside an enclosure with RF components mounted on one side. The temperature controller will be connected to a PLC for live data acquisition and logging. Figure 4 shows the final design footprint, including the eight-resistor array [1]:

Figure 4. Final Design Footprint

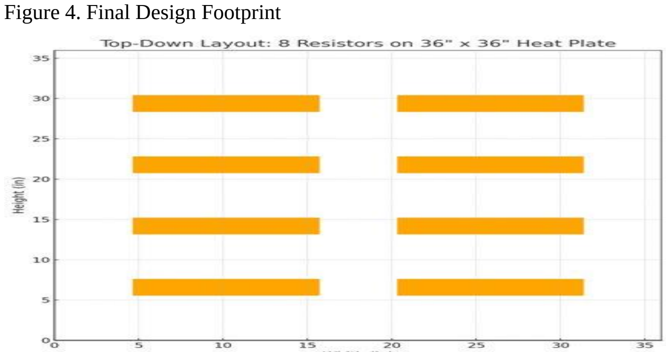

Figure 4. Digital Schematic Footprint of Final Design

2. Impact on Laboratory or National Missions

Fermilab's mission involves developing and operating world-class particle accelerators for physics research. Many subsystems, especially those in RF cavities, cryomodules, and beam diagnostics are highly sensitive to temperature fluctuations. The heat plate plays a key role in supporting the infrastructure that makes experiments possible, stabilizing RF components to ensure proper function.

References

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Appendix

Participants

- *Ahmed Syed, Fermi National Accelerator Laboratory, RF Staff Engineer -*
  - Project/Internship Supervisor - provided initial purpose of project, technical documents, and technical support throughout the design process.

- *Dave Peterson, Fermi National Accelerator Laboratory, Principal Engineer –*
    - Provided technical support, documentation, and general advising throughout the design process.

- *Clara Bruno, University of Illinois Chicago, Electrical Engineering Undergrad –*
    - Peer review of documentation, proofreading, software assistance.

Scientific Facilities

- Fermi National Accelerator Laboratory, Batavia IL 60510-5011.

Notable Outcomes

- Applied learning and exposure to core electrical engineering concepts, experience in navigating professional work environments, contributing to subsystems that support laboratory missions.