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Comparative Analysis and practical Feasibility of Plasma Position Control

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ABSTRACT

Fusion reactors are the technology for energy generation of the future. Plasma position control is main element for the effective performance of the fusion reactors. Field-Programmable Gate Array (FPGA) is an integrated circuit that proves to be an effective method for position control in comparison with the traditional PLC based control. This paper aims to have comparison of both methods in terms of working and time response characteristics. The paper helps to establish an reliable working and justifies the lesser time response by the use of FPGA techniques. Practical considerations and comparison of feedforward and feedback control for maintaining plasma stability and alignment are also discussed in this paper. Thus, the paper aims to have a detailed study and validation in terms of results for selecting an effective plasma position control system.

Keywords: Plasma Position Control, Field-Programmable Gate Array (FPGA), Tokamak, Response time, Feedback control.

1. INTRODUCTION

Fusion reactors are a key area of research in energy generation, aiming to replicate the process that powers the sun. Fusion involves the merging of light atomic nuclei (like hydrogen isotopes) to form heavier nuclei, releasing vast amounts of energy. Plasma position control is a critical aspect of managing plasma in fusion reactors, where maintaining stability and the desired configuration is essential for efficient fusion reactions [1]. This involves using advanced feedback control systems that monitor plasma parameters through various sensors, such as magnetic probes. Overall, effective plasma position control not only enhances reactor performance but also minimizes the risk of disruptions, paving the way for the successful development of fusion energy as a sustainable power source. Thus, Plasma position control is a major concern in fusion reactors [2].

In a magnetically confined tokamaks, the plasma current and shape controller is the component of plasma magnetic control that determines the DC voltages applied to the poloidal field coils, to control the coil currents and the plasma parameters viz. plasma shape, current, and position. Plasma position control is essential for obtaining repeatable high temperature, high-density discharges of longer duration in tokamaks [3]. Radial position and plasma current are the input parameters that affect the plasma stabilization current which in turn affects the plasma position. As the relationship between the input and output parameters are nonlinear in nature, intelligent controllers are to be developed.

A tokamak is a device designed to confine plasma using powerful magnetic fields, playing a pivotal role in the pursuit of nuclear fusion as a viable energy source. Shaped like a doughnut, the tokamak employs a combination of toroidal and poloidal magnetic fields to stabilize and control the hot plasma, which can reach temperatures of millions of degrees Celsius. The primary goal of a tokamak is to sustain the conditions necessary for fusion reactions, where isotopes of hydrogen, such as deuterium and tritium, combine to release vast amounts of energy. This design allows for continuous operation and has been extensively studied in various research projects which aims to demonstrate the feasibility of fusion power on a large scale. By effectively controlling plasma stability and position, tokamaks

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represent one of the most promising approaches to achieving controlled nuclear fusion, potentially providing a clean and abundant energy source for the future [3].

2. Design of FPGA based plasma position controller

A Field-Programmable Gate Array (FPGA) is an integrated circuit that can be configured by the user after manufacturing, allowing for a high degree of flexibility in digital circuit design [4]. Unlike traditional microprocessors, which run predefined instructions, FPGAs can be programmed to perform specific functions tailored to a wide range of applications, from signal processing to complex control systems. Their architecture consists of an array of programmable logic blocks and interconnections, enabling the creation of custom hardware configurations that can execute parallel operations efficiently. This makes FPGAs particularly advantageous in scenarios requiring real-time processing and rapid responsiveness, such as telecommunications, automotive systems, and industrial automation. The ability to reprogram FPGAs also facilitates rapid prototyping and iterative development, making them a valuable tool in both research and commercial applications.

FPGA-based position control systems are increasingly utilized in applications requiring high-speed processing and real-time responsiveness, such as in plasma position control within fusion reactors. FPGAs (Field-Programmable Gate Arrays) offer the flexibility to implement complex control algorithms directly in hardware, allowing for rapid data acquisition and processing from various sensors that monitor plasma parameters. By leveraging parallel processing capabilities, FPGAs can execute control tasks more efficiently than traditional microcontrollers, enabling precise adjustments to magnetic fields and plasma currents to maintain stability and desired positioning. This adaptability is particularly advantageous in dynamic environments like fusion reactors, where conditions can change rapidly. Overall, FPGA-based systems enhance the reliability and performance of position control, contributing to the successful operation of advanced technologies in fusion energy research.

An FPGA SoC (System on Chip) based plasma position controller integrates the reconfigurable capabilities of FPGA technology with the processing power of a traditional microcontroller or processor on a single chip. This hybrid architecture is particularly advantageous for applications in fusion reactors, where precise and rapid adjustments to plasma position and stability are crucial. By combining real-time data acquisition from sensors with sophisticated control algorithms implemented in the FPGA fabric, the system can quickly respond to dynamic changes in plasma conditions. The SoC design allows for efficient use of resources, minimizing latency and enhancing performance through parallel processing capabilities. This enables the implementation of complex control strategies, such as adaptive feedback loops, which are essential for maintaining optimal plasma confinement. Overall, FPGA SoC-based plasma position controllers represent a cutting-edge solution, significantly advancing the reliability and effectiveness of fusion energy research.

In this paper, FPGA SOC based plasma position controller is implemented. Xilinx Zynq ZC702 evaluation board has been used to simulate and implement the logics. Fiber-optic trans-receiver isolates the power supply with other subsystems.

3. Parameters for Tokamak configuration

The word tokamak is a translation of the Russian word токамак, an acronym of toroidal chamber with magnetic coils".

The tokamak configuration is a revolutionary design for plasma confinement in nuclear fusion research, characterized by its doughnut-shaped (toroidal) structure. This design employs a combination of toroidal and poloidal magnetic fields generated by external coils to stabilize and control the plasma, which must reach extremely high temperatures—millions of degrees Celsius—to enable fusion reactions. The toroidal magnetic field, created by coils encircling the torus, serves as the primary confinement mechanism, while the poloidal magnetic field, produced by additional coils, helps maintain plasma shape and stability. A significant plasma current, induced within the plasma itself, adds to the overall magnetic confinement. Essential components like the divertor manage heat and particle exhaust, ensuring the integrity of the reactor materials.

For nuclear fusion to occur, several necessary conditions must be met, typically represented by the fourth state of matter known as plasma. These conditions include:

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- **Temperature**

Fusion reactions require extremely high temperatures—typically in the range of millions of degrees Celsius. At these temperatures, the kinetic energy of the particles is sufficient to overcome the electrostatic repulsion between positively charged atomic nuclei, allowing them to collide and fuse.

- **Density**

A sufficiently high density of plasma is crucial to increase the likelihood of collisions between fusion nuclei. The greater the number of particles in a given volume, the higher the probability of fusion reactions occurring. This density must be carefully controlled to maintain a balance between achieving enough collisions and avoiding instabilities.

- **Confinement**

Effective confinement of the hot plasma is essential to sustain the conditions necessary for fusion. This is achieved through magnetic fields in devices like tokamaks or inertial confinement methods. Confinement must keep the plasma stable and prevent it from coming into contact with the reactor walls, which could cool it down and quench the fusion reactions.

- **Plasma**

These simultaneous conditions—high temperature, adequate density, and effective confinement—create the plasma state of matter. In this state, electrons are separated from nuclei, allowing for the high-energy interactions necessary for fusion. Achieving and maintaining plasma is central to harnessing fusion energy as a viable and sustainable power source.

In a tokamak, plasma is confined by magnetic fields generated through a combination of external coils and the currents flowing within the plasma itself as shown in Figure1. The external coils create a toroidal magnetic field that forms the primary confinement structure, effectively keeping the plasma stable and away from the reactor walls. Additionally, as a significant current is induced in the plasma—typically through transformer action—this generates a poloidal magnetic field that complements the toroidal field. Together, these magnetic fields create a helical configuration that stabilizes the plasma, allowing it to maintain the high temperatures and densities necessary for nuclear fusion. This intricate interplay of magnetic forces is essential for achieving sustained fusion reactions, making the tokamak a leading design in fusion research.

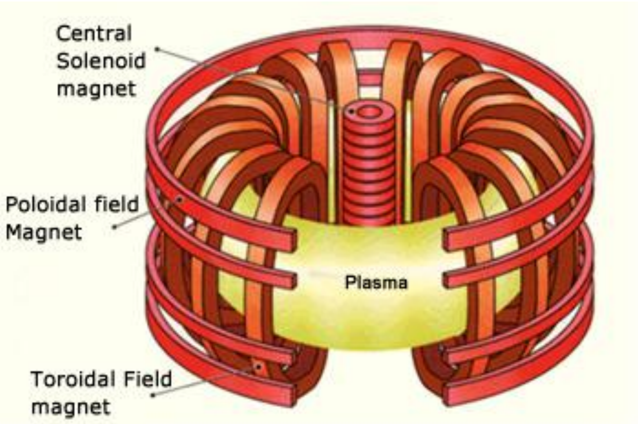

Figure 1: Arrangement of Coils

4. Design considerations

In fusion devices like tokamaks, the Toroidal Field (TF), Poloidal Field (PF), and Divertor Coils (DC) work together to confine and control plasma effectively. Hot plasma created in the tokamak needs to be confined and controlled in order for sustained fusion to occur as shown in Figure 2. The solenoid, which is positioned around the plasma, induces a powerful electric current in the plasma, thus heating the plasma up (much as a wire is heated when a current is

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passed through it). The TF coils generate a strong magnetic field that wraps around the toroidal shape of the plasma, providing the primary confinement necessary to keep it stable. Meanwhile, the PF coils create a vertical magnetic field that adjusts the plasma's shape and stability, allowing for fine-tuning of its configuration to prevent instabilities. The divertor coils play a critical role in managing the outflow of particles and heat by directing plasma towards the divertor, which is designed to handle impurities and excess thermal load. Together, these components are essential for achieving the conditions required for sustained nuclear fusion and ensuring the overall efficiency and safety of the reactor.

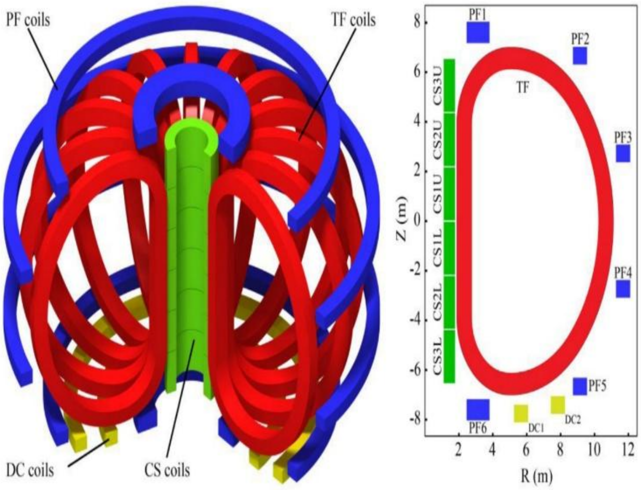

Figure 2: Arrangement of Coils

TF coils generate the primary magnetic field that traps plasma particles within the vessel, creating a strong confinement necessary for fusion reactions. Meanwhile, PF and divertor coils shape the plasma and ensure its stability both radially and vertically. The PF coils adjust the plasma's configuration, helping to maintain equilibrium and prevent instabilities, while the divertor coils manage the flow of particles and heat, directing them towards the divertor to remove impurities and excess energy. Together, these coils work synergistically to maintain a stable plasma environment, essential for effective nuclear fusion.

5. Practical consideration to design Plasma Position Controller

When designing a Plasma Position Controller for fusion devices, practical considerations around feedforward and feedback control are essential for maintaining plasma stability and alignment

5.1. Feedforward Control

Feedforward control relies on predictive modelling to anticipate plasma behavior based on operating conditions. Accurate models help calculate the necessary coil currents to maintain the desired plasma position before deviations occur. This proactive approach requires fast-response algorithms that can quickly adapt to changes, utilizing real-time data from position sensors to inform adjustments. Additionally, the system should be capable of dynamic adaptation, responding to variations in plasma conditions, such as changes in plasma current or external disturbances, enhancing overall robustness. The block diagram is as shown in *Figure 3*.

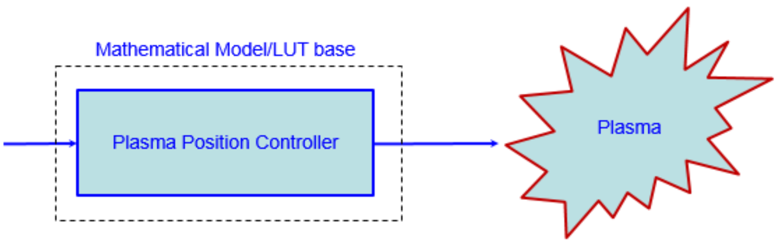

Figure 3 : Feedforward control for Plasma position control

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5.2. Feedback Control

Feedback control involves continuous monitoring of the plasma position through advanced diagnostics, allowing for real-time adjustments. A feedback loop calculates the deviation of the plasma from its desired position, applying corrective actions through control coils to minimize this error. Tuning the controller parameters is crucial for optimizing response time and stability, ensuring minimal oscillations and overshoot. Thorough stability analysis is also necessary to understand how feedback adjustments impact plasma behaviour, ensuring that the control system can effectively handle perturbations. The block diagram is as shown in *Figure 4*.

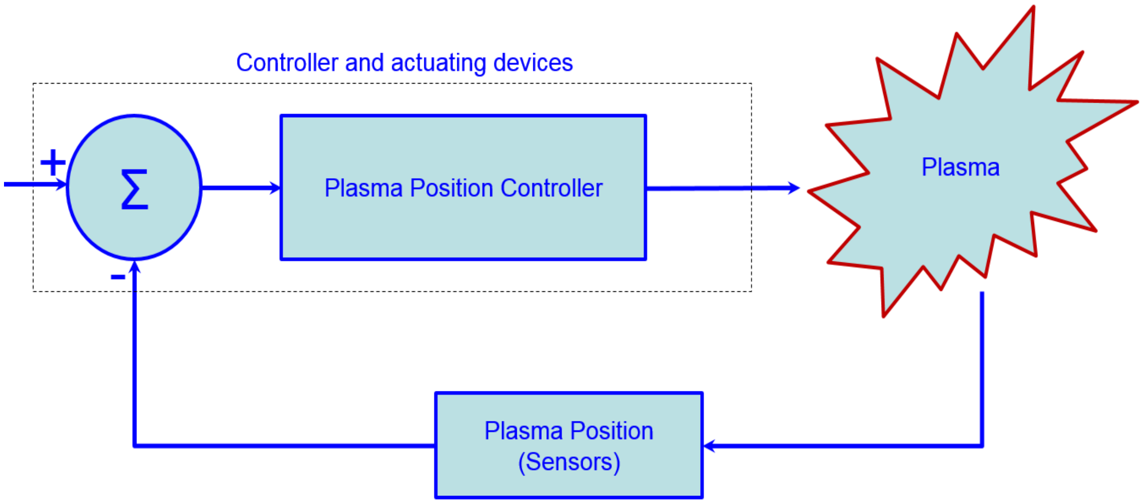

Figure 4: Feedback control for Plasma position control

5.3. Response time for Plasma position control

When designing a Plasma Position Controller, response time is a critical practical consideration that directly impacts the system's effectiveness in maintaining plasma stability. A fast response time ensures that the controller can quickly react to changes in plasma position and dynamics, which is essential for preventing instabilities that could disrupt the fusion process.

5.4. Importance of Fast Response Time

The dynamics of plasma can change rapidly due to various factors, such as variations in plasma current, external disturbances, or operational adjustments. Therefore, the controller must be able to compute necessary adjustments almost instantaneously. This requires high-performance algorithms capable of processing data from position sensors and calculating corrective actions in real time. A swift response time not only enhances the stability of the plasma but also reduces the likelihood of reaching threshold points that could lead to major disruptions. A detailed comparison for PLC based control and Fast control in terms of the response time is as shown in Table 01 [5].

Table 1: Different response time strategies

Slow control (PLC)	**Fast control (DSP/FPGA base)**
Slow Control (PLC) for Plasma Position Control refers to the use of Programmable Logic Controllers (PLCs) to manage and regulate plasma position in fusion devices over longer time scales.	Fast Control using DSP and FPGA for Plasma Position Control refers to the implementation of Digital Signal Processors (DSPs) and Field-Programmable Gate Arrays (FPGAs) in managing the rapid adjustments required for maintaining plasma stability in fusion devices

6. Block Diagram for Plasma Position Controller

The detailed block diagram for Plasma Position controller is as shown in Figure 05. At the core is the Position and velocity sensor block, which measures real-time plasma position and parameters, providing essential data. This data is processed in the Position Controlling block, where filtering and normalization occur. The processed information is then fed into the Control Algorithm Block, which applies control strategies (e.g., PID control) to generate necessary control signals. These signals are rapidly executed by the Fast Control System Block, utilizing FPGA technology to ensure immediate adjustments using the current loop. The system features a Feedback Loop that continuously returns data from the sensors to the processing block, enabling ongoing adjustments. This allows operators to monitor and interact with the system, ensuring effective oversight and management of plasma positioning. This integrated approach ensures optimal plasma stability and performance in fusion devices.

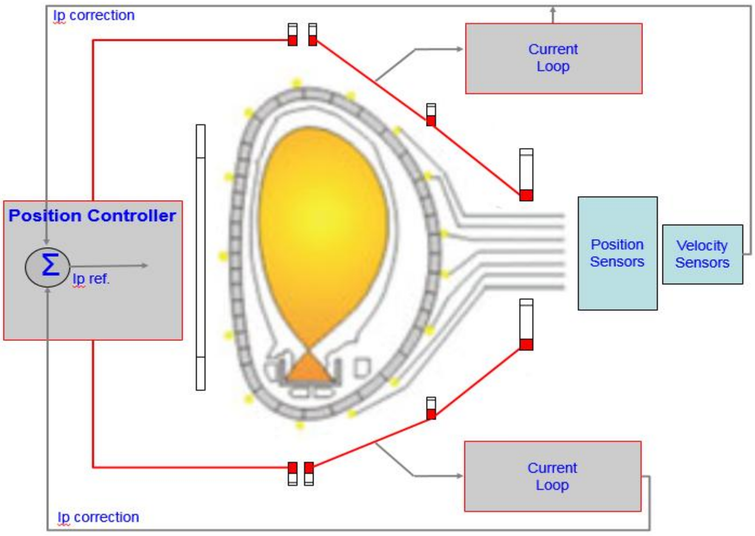

Figure 5: Block diagram for Plasma Position controller

The actual implementation in the plasma model is as shown in *Figure 6*. The Position controller generates the signal to the Power supply model with the variable rate of change of current which than controls the actual Plasma model. The plasma model is simulated using MATLAB and the feedback of the 6 position coils is than given as feedback.

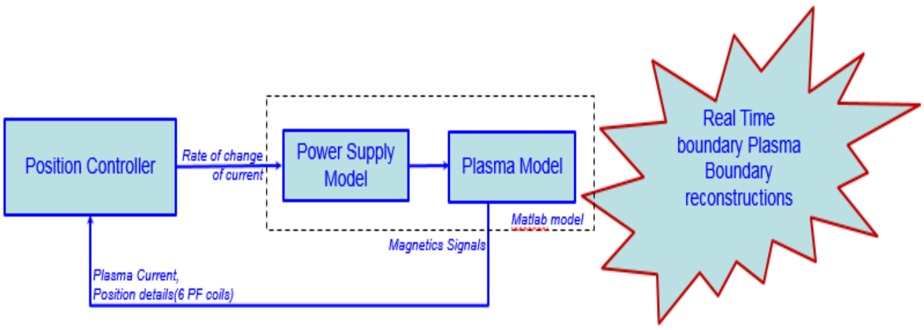

Figure 6: Implementation of Plasma Position Controller

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7. Controller architecture, test set-up and results

The Controller architecture with heart, FPGA controller XC7Z030 is as shown in Figure 7 [6].

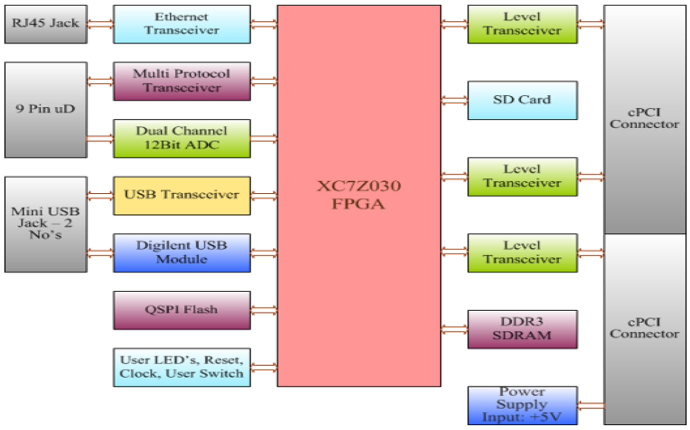

Figure 7: FPGA architecture

The controller architecture for plasma position control, integrating a central processing unit (referred to as the "heart") with the Xilinx XC7Z030 FPGA, provides a robust and efficient solution for managing plasma stability in fusion devices. This architecture is designed to leverage the strengths of both components to ensure rapid response and precise control. The FPGA, specifically the Xilinx XC7Z030, serves as the high-speed processing unit dedicated to executing real-time control algorithms. Its ability to perform parallel processing enables it to handle multiple tasks simultaneously, making it ideal for managing the complex dynamics of plasma control. With low latency, the FPGA processes data from plasma sensors in real time, implementing control algorithms such as PID control to determine the necessary adjustments for magnetic fields. The output signals generated by the FPGA directly drive the actuator interface, which translates these commands into specific current adjustments for the magnetic coils. An integral part of the architecture is the data acquisition system, which continuously collects real-time data from plasma sensors. This data is fed into the FPGA for immediate processing and into the CPU for longer-term analysis. The feedback loop established between the FPGA and the sensors allows for continuous monitoring and rapid adjustments, creating a closed-loop system that enhances plasma stability. The actual card is as shown in Figure 8.

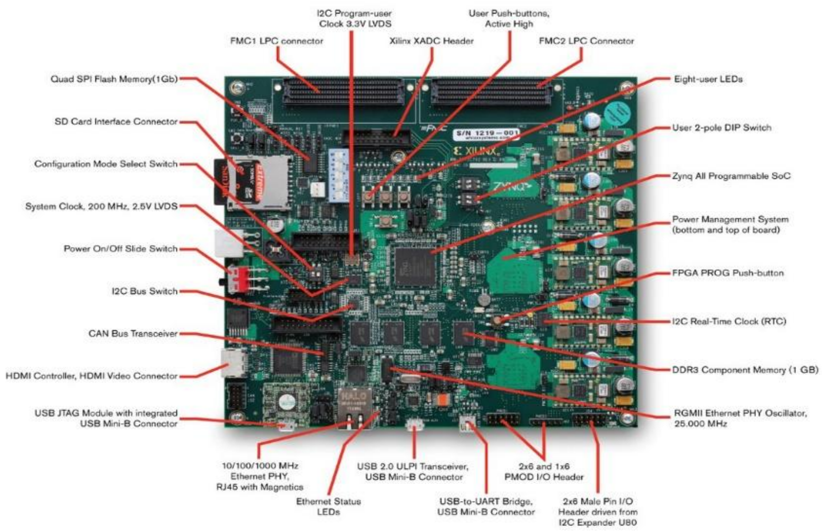

Figure 8: Xilinx hardware

The test setup for plasma position control using an FPGA, integrates various hardware and software components to evaluate the system's performance effectively as shown in Figure 9. Central to the setup is the FPGA development board, which processes real-time data from plasma sensors, such as magnetic field sensors and temperature probes.

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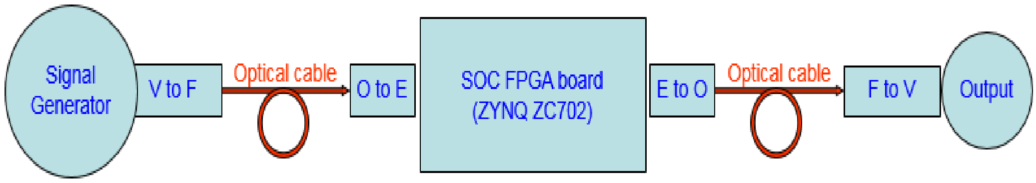

Figure 9: Test setup-01 with fast controller

The test setup for a plasma position control system utilizing a slow controller, typically based on a Programmable Logic Controller (PLC), is designed to evaluate the effectiveness of long-term stability management in fusion devices as shown in Figure 10. This setup integrates the PLC with various sensors that monitor plasma parameters, such as position, temperature, and pressure, providing critical data for decision-making.

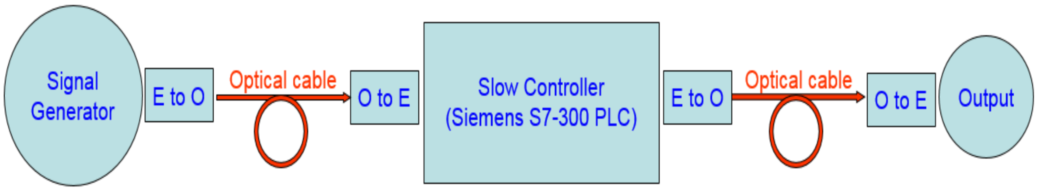

Figure 10: Test setup-02 with slow controller

The result comparison of both the test setup in terms of voltages and their response time is detailed in Table 2.

Table 2: Test validation results

Input voltage for Test set up 01	**Output voltage (Fast Controller)**	**Input voltage for Test set up 02**	**Output voltage (Slow controller)**	**Results**
0.5 V	2.0037 V	0.5 V	2.523 V	Response time is reduced considerably
1.0 V	2.0101 V	1.0 V	2.591 V	
1.5 V	2.0450 V	1.5 V	2.412 V	
2.0 V	2.0510 V	2.0 V	2.505 V	
2.5 V	2.0012 V	2.5 V	2.492 V	
3.0 V	2.0340 V	8.0 V	2.580 V	
	Response Time : ~10s of µs.		Response Time : ~10s of ms.	

8. CONCLUSION

Reducing response time in plasma position control using FPGA involves leveraging the parallel processing capabilities of FPGAs to handle multiple control loops simultaneously. This paper aims to the control strategy implementation in hardware for Plasma Position controller. When designing a Plasma Position Controller, response time is a critical consideration that directly impacts the system's effectiveness in maintaining plasma stability. A fast response time enables the controller to swiftly react to changes in plasma position and dynamics, which is essential for preventing instabilities that could disrupt the fusion process. Utilizing FPGA technology enhances this responsiveness through parallel processing capabilities, allowing for real-time data acquisition and control. In this paper, the model verifies that there is considerable reduction in response time which can make the system efficient.

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