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Abstract

For the first time, a digital Mirror Langmuir probe (MLP) has successfully sampled plasma temperature, ion saturation current, and floating potential together on a single probe tip in real time in a radio-frequency driven helicon linear plasma device. This is accomplished by feedback control of the bias sweep to ensure a good fit to I-V characteristics with a high frequency, high power digital amplifier and field-programmable gate array (FPGA) controller. Measurements taken by the MLP were validated by a low speed I-V characteristic manually collected during static plasma conditions. Plasma fluctuations, induced by varying the axial magnetic field ($f = 10$ Hz), were also successfully monitored with the MLP. Further refinement of the digital MLP pushes it towards a turn-key system that minimizes the time to deployment and lessens the learning curve, positioning the digital MLP as a capable diagnostic for the study of low radio-frequency plasma physics. These demonstrations bolster confidence in fielding such digital MLP diagnostics in magnetic confinement experiments with high spatial and adequate temporal resolution such as edge plasma, scrape-off layer, and divertor probes.

1. Introduction

The Langmuir probe is a workhorse diagnostic for studying the edge of fusion plasma devices such as tokamaks and stellarators. The digital MLP is continuing to be developed by a joint collaboration between the University of Liverpool UK, the United Kingdom Atomic Energy Authority (UKAEA), and the MIT Plasma Science and Fusion Center for deployment on MAST-U with the goal of researching turbulent transport. However, much of the important physics happens at time scales faster than traditional Langmuir probe biasing techniques can capture. This limitation is due to the need to sweep the voltage at which the probe is biased in order to construct the full I-V characteristic used to determine the electron temperature (T_e), density (n_e), and floating potential (V_f) [1]. Triple probes have been used to collect Langmuir probe measurements with high time resolution, but at the cost of spatial resolution. However, if one knows the expected T_e then it is possible to optimize three bias voltage states on a single probe tip and still extract accurate measurements of the plasma parameters. For such a bias scheme to be possible, it is necessary to determine the plasma temperature in real time and adapt the bias states accordingly. This is the approach of the Mirror Langmuir Probe (MLP) biasing system, and has been successfully implemented with analog electronics on Alcator C-Mod with a high time resolution (1.1 MHz) [2].

More recently, work has been done to implement the real time calculation and bias control in digital Field Programmable Gate Array (FPGA) based electronics. The first implementation of such a digital MLP

controller, as reported by Vincent, et al. [3], was not tested using a real probe in plasma, but only against a second digital FPGA system that simulated the response of a probe in plasma.

This paper reports on the first successful adaptation of the FPGA MLP controller for diagnosing a real laboratory plasma. Specifically, the probe was tested in both stable and fluctuating plasma conditions with approximate time averaged values of $\langle T_e \rangle \sim 8eV$, $\langle n_e \rangle \sim 2.3 \cdot 10^{17} m^{-3}$, $\langle V_f \rangle \sim -4.5V$. The probe measurements in stable plasma conditions were compared to time-averaged measurements which were determined using a full I-V characteristic collected manually with a variable voltage supply and multimeter.

The paper is organized as follows: section 2 discusses the MLP algorithm implemented in the FPGA logic. Section 3 discusses the system used to drive the probe in the plasma and the linear plasma source DIONISOS. Section 4 reports on the results of the first set of real plasma tests of the probe.

2. The MLP Algorithm

The MLP algorithm starts by picking three bias states that are optimized to the plasma conditions assumed for some initial guess based on either expected electron temperature or a prior measurement of temperature. This optimization ensures a good fit to the Langmuir probe equation [4]

$$I_{LP} = I_{sat} \left(e^{\frac{(V_{pr}-V_f)}{T_e}} - 1 \right) \quad (1)$$

where I_{sat} is the ion saturation current at large negative biases, V_{pr} is the applied bias to the probe, V_f is the floating potential, and T_e is the electron temperature, for the lower part of the bias sweep before the rollover of the I-V characteristic occurs.

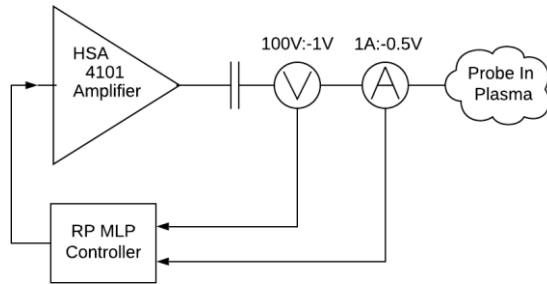


Figure 1 – Schematic of the Langmuir probe system used to drive the voltage and measure probe bias and current. A 100 V bias across the voltmeter produces a signal of -1 V. Also, a 1 A current through the ammeter produces a signal of -0.5 V at the MLP.

Ideally, the three applied bias states draw currents through the probe for $-I_{sat}$, zero current, and $+I_{sat}$, similar to triple probe operation. Applying the optimal bias states is simplified by capacitive coupling, shown in Figure 1, between the probe and the voltage driver. When the V_{pr} is not optimal, such that the time averaged current is not zero, the capacitor charges up to near (or ideally at) V_f by the differential current draw. The probe bias can then be expressed as the sum of the capacitor voltage, V_c , and the externally applied biases:

$$V_{pr} = V_{\mp,0} + V_c \quad (2)$$

where $V_{\mp,0}$ corresponds to the three bias states. Solving the Langmuir probe equation simultaneously around $I_{LP} = 0.964I_{sat}$, and $-0.964I_{sat}$ finds that the necessary applied biases for these optimal states are [3]:

$$V_- = -3.325T_e \quad (3a)$$

$$V_+ = 0.675T_e \quad (3b)$$

$$V_0 = 0 \quad (3c)$$

The chosen values of current are less than I_{sat} in order to reduce the magnitude of V_- necessary to achieve it. A new value of one of the plasma parameters is calculated at each of the three bias states using a rearranged Langmuir probe equation:

$$I_{sat} = \frac{I_{LP}}{\left(\exp\left(\frac{V_{pr} - V_F}{T_e}\right) - 1\right)} : V_{pr} = V_- + V_C \quad (4a)$$

$$T_e = \frac{(V_{pr} - V_F)}{\ln\left(\frac{I_{LP}}{I_{sat}} + 1\right)} : V_{pr} = V_+ + V_C \quad (4b)$$

$$V_F = V_{pr} - T_e \ln\left(\frac{I_{LP}}{I_{sat}} + 1\right) : V_{pr} = V_C \quad (4c)$$

Here, V_{pr} is the total voltage on the probe and is a directly measured experimental quantity (this may

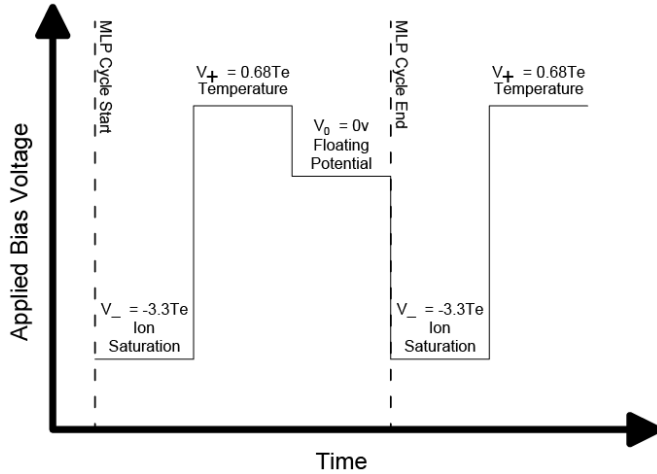


Figure 2 – The Bias states of the MLP algorithm. At each of the three bias states, a different plasma parameter is updated to a new value.

slightly differ from the imposed V_{pr} due to cable capacitance, pickup voltages, etc., and I_{LP} is the measured current drawn by the probe. The ordering of the bias states and calculations is shown in Figure 2. Note that while the optimization was based around the assumption of capacitor voltage equal to the floating potential, the algorithm does not require this to be true in order to calculate a temperature accurately, as the calculation uses the real voltage-current pair at the probe tip. As such the capacitor is only necessary for ease of driving the bias, not for the real-time calculation.

A full description of the algorithm implemented in FPGA-based electronics can be found in Vincent *et al.* [3], while a

treatment of the analog approach is found in LaBombard *et al.* [5].

3. Experimental Set Up

3a. Langmuir probe drive and control system

The MLP controllers were implemented on StemLabs Red Pitaya; however, other off-the-shelf FPGA boards could be used. The Red Pitaya integrates a Xilinx Zynq 7010 FPGA with two 125MHz 14-bit ADCs, two 125MHz 14-bit DACs, and a Dual-Core ARM Cortex-A9 MPCore microprocessor. The ADCs were used to monitor probe current and voltage, and one DAC was used to send the requested voltage to a NF Corp HSA 4101 RF amplifier, which has a peak-to-peak voltage range of 142V and slew rate of $5000\text{V}/\mu\text{s}$. The Langmuir probe was capacitively coupled to the amplifier using a variable capacitor, and measurements of the current and voltage on the probe took place on the “plasma side” of the coupling capacitor. A schematic of the circuit is shown in Figure 1. The Langmuir probe electrode was a 25 mm diameter tungsten plate placed at one end of the 40 mm diameter plasma column, shown in Figure 3.

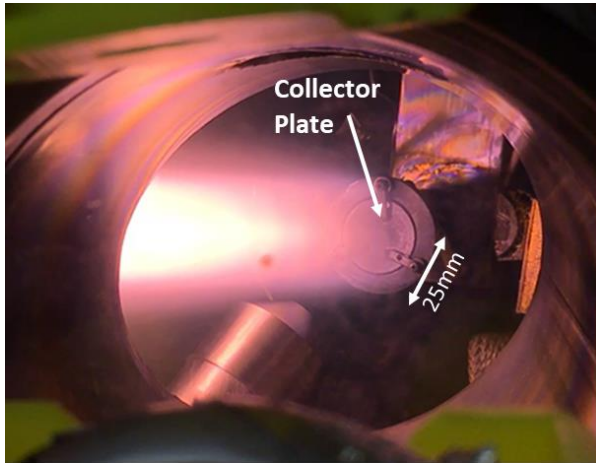


Figure 3 –The collector disk at the end of the plasma column that was used as the Langmuir probe electrode.

Real time calculation and bias selection is carried out on the FPGA chip. The hardware description language used to configure the FPGA for these calculations is available at: <https://github.com/Rondin119/MIT-mirror-langmuir-probe-Dionisos>.

The FPGA hardware and configuration employed in this implementation limits the best achievable time resolution of measurements to ~ 800 kHz, mostly due to the time needed to calculate the division in the MLP equations. However, the frequency was intentionally limited to ~ 140 kHz during these tests to account for uncertainties in the stability of the calculation and the time response of the drive system. The MLP cycle time is readily reconfigured by changing the number

of clock cycles allocated to each bias state in the high-level software configuration of the device, with an approximate theoretical minimum of ~ 55 clock cycles needed per level to complete the calculations. The FPGA logic has not been optimized with respect to clock cycles, so this lower limit could be pushed down in such an optimization.

At the conclusion of each bias level, the voltage-current pair at the probe tip is saved into memory on the FPGA board and transferred via a First In First Out (FIFO) FPGA buffer to the Red Pitaya RAM (see Appendix A). As such the Red Pitaya serves as both the controller and digitizer in this experiment. An I-V characteristic is then fit to these saved voltage-current pairs in post processing to extract the plasma parameters. The real-time values of plasma parameters calculated in the FPGA, used for the adaptive control, are likewise saved at the conclusion of the three bias state sweep. This allows for direct comparison between the real-time values and values extracted via a more traditional Langmuir probe analysis.

3b. DIONISOS

DIONISOS is a linear plasma device coupled to a 1.7 MV tandem ion accelerator used to study plasma-material interactions (PMI) [6] (Figure 3). The helicon plasma source is driven by a 13.56 MHz RF power

supply coupled to the plasma with a Nagoya type III antenna and immersed in a magnetic field of up to 0.1 T with a set of Helmholtz coils. The plasma column is confined to approximately 40 mm diameter from the plasma source tube. Normal plasma temperatures and ion fluxes are 2-6 eV and $10^{21} m^{-2}s^{-1}$, respectively. For PMI tests, materials under study are electrically isolated for variable biasing and sit at the intersection of the ion beam and plasma column. For the MLP tests, the ion beam was not used.

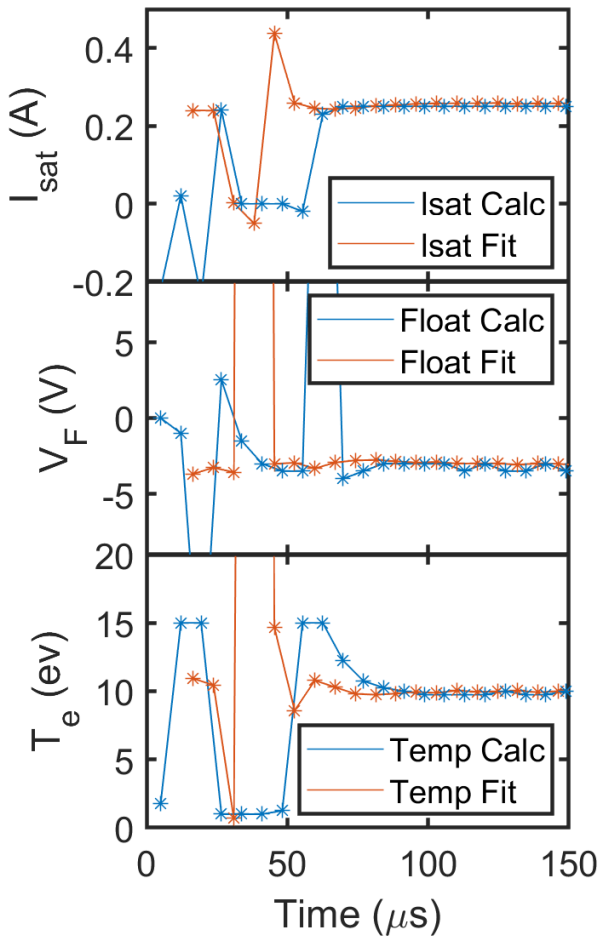


Figure 4 – Plasma conditions were held constant while MLP triggered. “Isat/Float/Temp Calc” are the results of the calculation done on the FPGA, while “Isat/Float/Temp Fit” is the post-processing fit of the I-V characteristic of the saved current and bias state. All three signals lock onto stable values within 90 microseconds. The algorithm takes several cycles to lock on. The ion saturation current locks onto ~0.25A, floating potential locks onto ~-3V, and temperature locks onto ~10 eV. Post-processing fit produces nearly identical results to the real-time calculation.

Two tests of the MLP were performed. First, the plasma control parameters of RF power, magnet current, and gas flow were held constant while the MLP controller swept the bias on the probe. For comparison, measurements were taken using a manually adjustable voltage supply and a multimeter in place of the MLP with the same probe electrode, converting the electrode into a standard swept Langmuir probe. The second test of the MLP was performed by programming a time-varying magnetic coil current which caused time-varying plasma parameters at the same frequency. The fluctuation was limited to 10Hz due to the magnet power supply and coil inductance, but the implemented MLP time resolution was much higher, ~140kHz (7 μs) for a full three bias cycle (Figure 2).

4. Real Plasma Experiments

Two tests of the MLP were performed. First, the plasma control parameters of RF power, magnet current, and gas flow were held constant while the MLP controller swept the bias on the probe. For comparison, measurements were taken using a manually adjustable voltage supply and a multimeter in place of the MLP with the same probe electrode, converting the electrode into a standard swept Langmuir probe. The second test of the MLP was performed by programming a time-varying magnetic coil current which caused time-varying plasma parameters at the same frequency. The fluctuation was limited to 10Hz due to the magnet power supply and coil inductance, but the implemented MLP time resolution was much higher, ~140kHz (7 μs) for a full three bias cycle (Figure 2).

4a. Stable Plasma Tests

For the first test of the MLP, the results are shown in Figure 4. The real-time algorithm required ~90 microseconds to lock onto a stable value. The real-time floating potential converged first, preceding the electron temperature and ion saturation current by ~40 microseconds. Real-time and post-processing values overlay perfectly after the real-time algorithm converged. The converged floating potential value was -3V, the I_{sat} was 0.25A, and the electron temperature was 10eV.

The manually collected I-V characteristic fit with Eq. 1 is shown in Figure 5. The characteristic shows

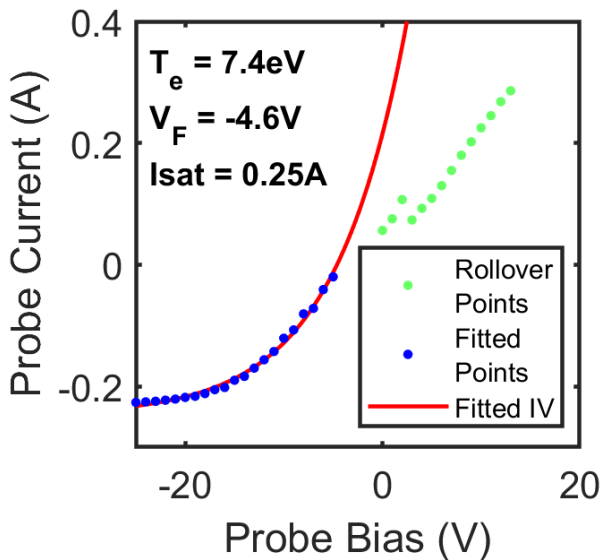


Figure 5 – Manually constructed I-V characteristic taken using a multimeter and variable voltage source. The I-V characteristic shows signs of rolling over into the electron saturation regime before the inverse of the ion saturation current is reached. In order to make a comparison to real-time MLP results, a fit is applied only to points at a lower probe bias, marked in blue, while points at higher probe bias, marked in green, are excluded. The fit so-obtained, as well as the results of the real-time MLP algorithm, will over predict plasma temperature, due to the mismatch of the real I-V characteristic with Eq. 1.

clear evidence of I-V rollover before negative ion saturation current is achieved [7]. Restricting the fit to the lower portion of the I-V characteristic gives an estimate of floating potential as -4.6V, I_{sat} 0.25A, and temperature as 7.4eV. The early I-V rollover means the current is no longer accurately predicted by the Langmuir probe equation used in the derivation of the algorithm and used for fitting during post-processing of the MLP data for the entire range of optimized biases. As a result, the MLP will overestimate plasma temperature in this experiment, explaining the discrepancy between the MLP temperature and manual temperature. Even so, since the I-V rollover is weak in this case, the MLP can still accurately track changes in temperature despite the absolute magnitude being overestimated. This problem could be alleviated in future tests by solving equation 1 around lower probe currents, reducing the required bias range to try and avoid rollover. However, it is not known what effect this would have on the stability of the real time calculation. Additionally, if the bias range is reduced too far, the three bias-current pairs become very close in bias-current space, which will degrade the quality of the fit and increase the fit sensitivity to noise in the measurements.

4b. Fluctuating Plasma Tests

In the second test, two frequencies were used to program the current output of the magnetic coil current: 10Hz (Figure 6) and 20 Hz (Figure 7). In both cases, the MLP clearly tracks the oscillation in plasma parameters at the drive frequency. The programmed current amplitude used in both cases was the same. However, the amplitude of the fluctuation in the plasma parameters decreased when the frequency increased. This may indicate that the magnet power supply is insufficient to fully overcome the magnetic coil inductance, setting an upper limit on the fluctuation frequency.

The MLP real-time calculations are systematically lower and have less precision than the fit values due to the manner in which the real-time calculations are saved. The details of how the real-time data is

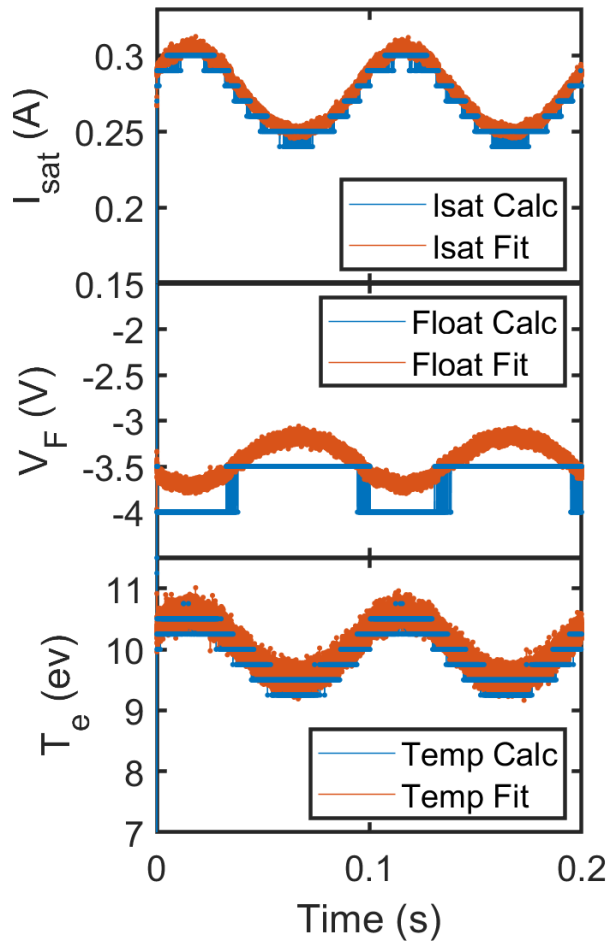


Figure 6 – MLP was triggered simultaneously with a 10Hz fluctuation in DIONISOS magnetic field strength. “Isat/Float/Temp Calc” are the results of the calculation done on the FPGA, while “Isat/Float/Temp Fit” is the post-processing fit of the I-V characteristic of the saved current and bias state. Clear variations are seen in all three plasma parameters tracked well by both real time calculations and post processing fits. The large quantization steps for the real time calculation are caused by a divide-by-32 on V_f and I_{sat} and a divide-by-16 on T_e during saving. All real time values are rounded down during saving, resulting in the real-time values being systematically lower than the post-process results.

saved by the Red Pitaya (see Appendix A)

necessitated that a divide-by-32 be applied in the real time FPGA bit value of floating potential and ion saturation current and a divide-by-16 be applied to the real time bit values for temperature prior to saving in RAM. These values are rounded down, causing the perceived downshift in values. Within the FPGA implementation of the algorithm, full precision is used and thus it is expected that those values match the post-processed ones much more closely. It is unclear what part of the large scatter present in

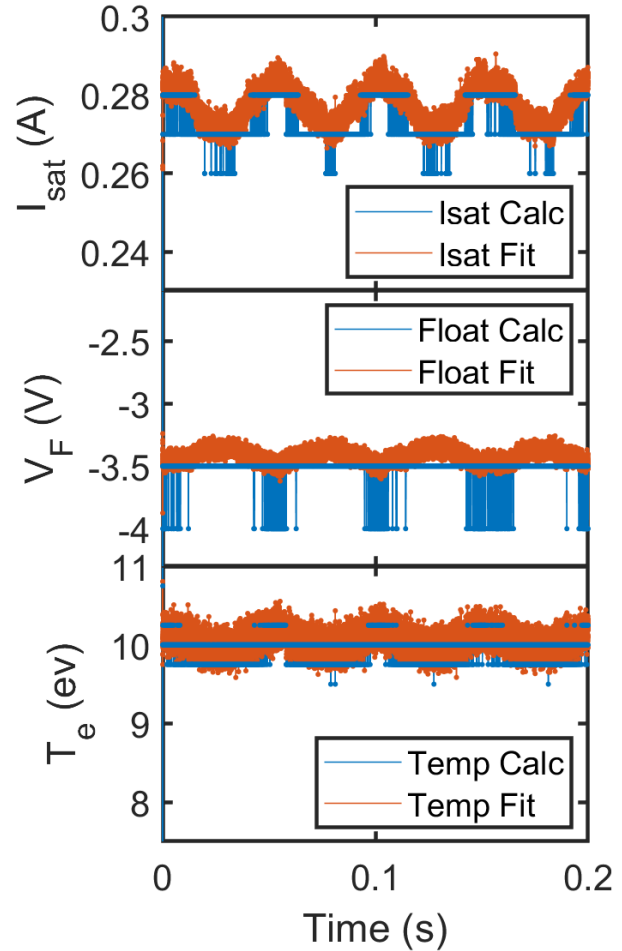


Figure 7 – MLP was triggered simultaneously with a 20Hz fluctuation in magnetic field strength. “MLP Isat/Float/Temp Calc” are the results of the calculation done on the FPGA, while “MLP Isat/Float/Temp Fit” is the post-processing fit of the I-V characteristic of the saved current and bias state. Programed fluctuation amplitude was held constant from 10Hz test, but plasma fluctuation was a much smaller amplitude. This is evidence that the magnet power supply and inductance is insufficient to perform the full magnetic field fluctuation programmed. Post-process and real-time calculations agree well.

both the fitted values and real-time values is due to real plasma fluctuations versus due to error in the quantization and fitting.

As noted previously, DIONISOS is driven by a 13.56 MHz RF source, and thus we expect interesting dynamics on this time scale. While this is well above the theoretical maximum time resolution for the digitization of data, it is a factor of 10 slower than the ADC conversion rate of the Red Pitaya and maximum clock speed of the FPGA. Therefore, it is possible, in principle, to phase lock the measurements of the plasma parameters to the RF signal and learn about the dynamics of the plasma at that frequency. Additional work is planned along these lines.

5. Conclusion

A digital mirror Langmuir probe drive controller was implemented on a commercial FPGA board and tested on the DIONISOS linear device for real plasma parameter measurements. Two tests were conducted to determine functionality: first, the MLP results were compared with a manually collected I-V characteristic using the same probe tip in steady plasma conditions; second, an artificial fluctuation was induced at a known frequency in the plasma and the MLP was used to track it.

When the plasma conditions were held fixed, the MLP estimates for the plasma parameters showed good agreement with the estimates obtained via the manually collected I-V characteristic except for a discrepancy that can be explained by an early roll-over in the IV characteristic. The real time MLP calculations and the post processing fits done on MLP data showed near perfect agreement.

When a low-frequency fluctuation was induced in the plasma, the MLP was able to track it with high fidelity. The fluctuation frequency was limited by the inductance of the magnet and the magnet power supply.

The digital FPGA mirror Langmuir probe controller was able to replicate the functionality of the original analog mirror Langmuir probe, albeit at a reduced frequency, in a real plasma environment. It is capable of calculating the plasma temperature, floating potential, and ion saturation current in real time and adjusting the bias states of the three-point probe sweep. The use of primarily off-the-shelf components allowed for rapid setup and deployment. This demonstrates that the digital mirror Langmuir probe can be a powerful diagnostic for studying plasma turbulence in the low RF range. The digital MLP is continuing to be developed by a joint collaboration between the University of Liverpool UK, the United Kingdom Atomic Energy Authority (UKAEA), and the MIT Plasma Science and Fusion Center for deployment on MAST-U, with the goal of researching turbulent transport, and on DIONISOS for researching turbulence on the scale of the RF power source.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request

Appendix A

The FPGA FIFO (First In First Out buffer) takes and transfers 32-bit data. The first bit is used to denote whether the data is a current-voltage pair or the real-time plasma parameters and the next five bits are used for a time stamp, leaving 26 bits for data. Within the FPGA logic the current and voltage are both represented as 14-bit signed numbers, therefore a divide-by-2 is required on both to fit into the FIFO. Within the FPGA logic each of the plasma parameters are represented with a 20-bit signed number where one bit equates to 0.0156 eV, 0.0156 V, 0.0003 A for T_e , V_f , I_{sat} respectively. Thus, in order to fit T_e , V_f , I_{sat} into the 26 available bits, it is necessary to throw out bits.

It is known that the calculated temperature will be positive and below 60 eV due to limitations placed on the calculation algorithm, thus the first 8 bits (the sign bit and the 7 most significant bits) can be safely discarded converting it to a 12-bit unsigned number. Due to the 14-bit ADC used to digitize the signal, it is safe to assume that V_f , I_{sat} will not have significant information in the first 6 bits and thus can be represented by a 14-bit signed number.

Finally, it is necessary to remove the last 5 bits (equivalent to a divide-by-32) of floating potential and ion saturation current and the last 4 bits (equivalent to a divide-by-16) of Temperature prior to being sent to the FIFO. The resulting values are rounded down, causing the perceived downshift in values observed in Figures 6 and 7.

A possible solution to this problem that does not involve a loss of precision in saved data would be to give each of the temperature, the potential, the ion saturation current, the collected current, and bias their own 32-bit number with the first 3 bits used as a flag to differentiate them. This was not done as it would significantly reduce the duration of data acquisition due to more quickly filling the RAM and it would cause the current-voltage pair to be asynchronous in time.

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