First results of the Ultra-Fast Biasing Langmuir Probe in a pulsed low temperature magnetron plasma

C. J. Hickling[1,2], S. Hall[2], R. Seath[2], J. R. Harrison[2], R. Sharples[3], J. W. Bradley[1]

[1] *Department of Electrical Engineering and Electronics, University of Liverpool, Brownlow Hill, Liverpool, L69 3GJ, UK*

[2] *UK Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK*

[3] *Department of Physics, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK*

E-mail: c.hickling@liverpool.ac.uk

By utilising Field Programmable Gate Arrays (FPGA), in a configuration similar to that of the Mirror Langmuir Probe[1] (MLP), it is possible to bias a single probe at 3 precise voltages in sequence. These voltages can be dynamically adjusted in real-time based on the measured electron temperature to ensure the transition region is always sampled. By employing this method, real-time outputs of electron temperature, ion saturation current, and floating potential have been achieved on a low temperature pulsed magnetron at 150 kHz. This probe is designed with the intention to be implemented onto MAST-U at 1 MHz to aid in the study of exhaust physics and enable further investigation into filamentary behaviour.

The benefits offered by probes are extensive, as they provide important information about plasma they are in contact with while also being low cost and simple to operate. Single tip sweeping bias (conventional) Langmuir probes are powerful diagnostics for measuring electron temperature, ion saturation current, and floating potential. One of the simplest ways to obtain this information is by utilising the following planar probe equation [2, p. 86].

$$I(V_B) = I_{sat}\left(\exp\left[\frac{e(V_B - V_f)}{k_B T_e}\right] - 1\right) \tag{1}$$

Probes are widely used to diagnose the Scrape-Off Layer (SOL) and divertor of magnetic confinement fusion devices. Plasma in these regions is known to contain fast moving filamentary structures that require highly resolved measurements in order to fully characterise (typically order of 100 kHz in time and 1cm in space). The temporal or spatial limitations of current probes prevent fast events such as filaments being observed. A triple probe provides real-time voltage dependent currents at the cost of sampling different regions of plasma. Since the triple probe samples at 3 constant voltage levels, it does not account for any change in temperature in the system. Conversely a single probe provides high spatial resolution at the cost of the time required to sweep the power supply, which also induces currents in the cables, limiting the temporal resolution, typically to the order of 10 kHz.

By sampling far enough into the ion or electron region of an I-V characteristic, information about only the ions or electrons can be obtained. By re-arranging equation 1, for each of the 3 parameters of interest and solving them at electron temperature scaled biases, it is possible to operate the device as a time multiplexed triple probe. Previous work explains this method in detail [3] and has found the FPGA to be a sufficient tool for solving equation 1 with sufficient speeds to trace a slow moving 10 Hz change in the magnetic field in a low temperature linear device [4].

Experimental Setup

The plasma system

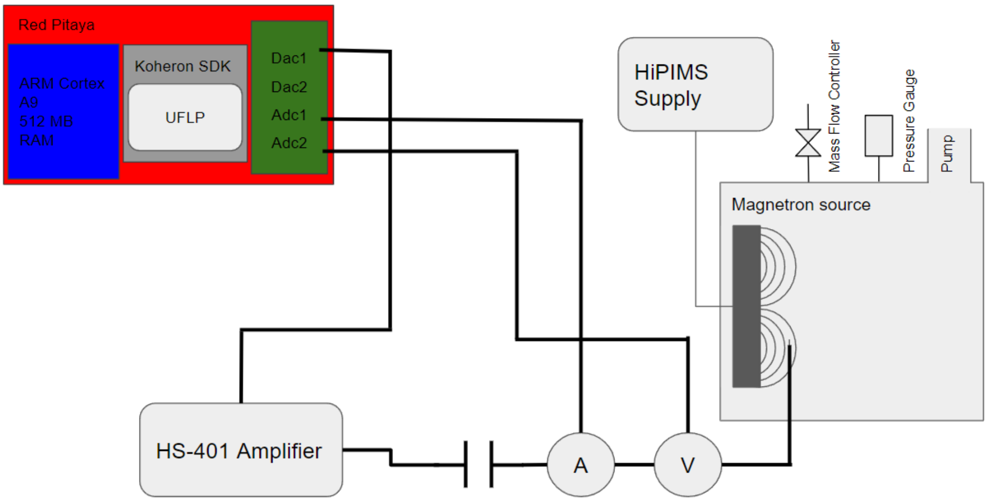

Figure 1: A schematic of the experimental setup of a HiPIMS plasma system operating with an Argon plasma at 12 mTorr of gas pressure. HiPIMS settings at 50 Hz repetition rate with 250μs on time

The plasma source used in this study is a planar magnetron used for the deposition of engineering quality thin films. It consists of an electrically conductive target plate, that is often water cooled, behind which sits a permanent magnet. Above the target are a number of closed magnetic field lines, which form what is known as a “magnetic trap”. Densities up to $10^{19} m^{-3}$ can be achieved within the magnetic trap with typical electron temperatures, T_e, of 2-5 eV. The confined plasma has a broad spectrum of plasma waves and instabilities in the frequency range kHz - MHz [5]. By operating a magnetron with a high-power impulse magnetron sputtering (HiPIMS) power supply, the resulting plasma has a well defined profile [5, 6] with a short pulse length that has similar plasma parameters to the divertor or scrape off layer of a tokamak.

Data acquisition system

The drive signal is generated by a Red Pitaya, which has a capability to output a 125 MHz signal in the voltage range of ±1 V. Immediately following a reset state, the device initialises some guesses of the requested parameters. The initial temperature guess is used to generate the very first bias output. The equations will then sequentially solve in order to obtain the desired results. The electron temperature will then be used to set a new bias range. In order to sample low temperature plasmas, a HS-401 Bipolar amplifier has been used to supply a 26 dB gain to the original signal. The voltage is measured directly via a voltage probe into the Analogue to Digital Converter (ADC) (±20V) on the Red Pitaya. The current needs to first be isolated from the main path via the use of a 1:1 isolation transformer before measuring the voltage both sides of a sense resistor. In the case of a HiPIMS measurement this voltage needs to be stepped down to be within the rail voltage of the instrumentation amplifier used to calculate the current. A gain resistor is used to set the input as 1V = 7 mA.

Results

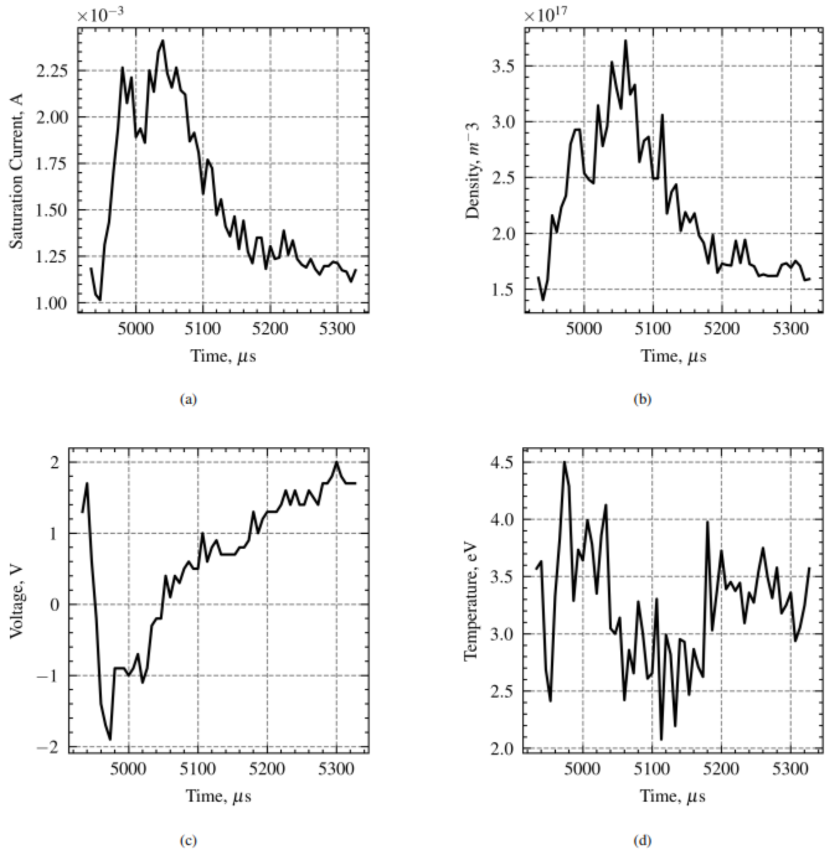

Figure 2: ion flux (a), plasma density (b), floating potential (c) and electron temperature (d) gathered at 150 kHz using a single probe multiplexed at dynamic bias at values $V_{+,-,0}$ = 0.64Te V, -3.325Te V and 0 V. Trends show good agreement with previously collected data [6]

High speed plasma fluctuations have been measured in a low temperature HiPIMS plasma device at 150 kHz using this technique, as shown in figure 2. The solving of an electron temperature with a changing bias includes a positive feedback loop. If a small electron temperature change occurs, the bias range is changed and electron temperature is again calculated to a different value which is seen as noise in the measured electron temperature data. The implementation of a low-pass filter to electron temperature measurements smooths out this acquisition and damps the feedback loop allowing the device to successfully track changing electron temperatures in the plasma. A large amount of noise can be observed in the electron temperature data, shown in Figure 2(d), which there is strong evidence that it is cause by stray capacitance in the cabling producing noise in the measured current at the probe tip.

Conclusions

Plasma parameters have been collected and dynamic adjustment of the bias range has been implemented. The acquisition speed was limited to 150 kHz due to bandwidth limitations in the current measurement, but simulations suggest 947 kHz is achievable. A redesign of measurement electronics is required to achieve a higher temporal resolution along with noise reduction, through the implementation of an identical probe that is not exposed to the plasma to cancel cable capacitance effects (a dummy probe [1]). These preliminary tests prove the efficacy of this diagnostic to enable the study of fast filamentary structures.

Acknowledgements

The authors would like to thank Dr William McCarthy and Dr Theodore Golfinopoulos at the MIT Plasma Science and Fusion Center as well as Dr Charlie Vincent and Dr Jack Lovell at UKAEA for their invaluable insight and assistance to this work. This work has been funded by the RCUK Energy Programme [grant number EP/T012250/1] and is supported by the Engineering and Physical Sciences Research Council [EP/L01663X/1].

References

[1] Lambombard, B., & Lyons, L. (2007). Mirror Langmuir probe: A technique for real-time measurement of magnetized plasma conditions using a single Langmuir electrode. Review of Scientific Instruments, 78(7), 9.

[2] Stangeby, P. C. (2000). The plasma boundary of magnetic fusion devices. Institute of Physics Publishing, Philadelphia, Vol. 224.

[3] Vincent, C., Mccarthy, W., Golfinopoulos, T., Labombard, B., Sharples, R., Lovell, J., Kuang, A. Q. (2019). The Digital Mirror Langmuir Probe : Field Programmable Gate Array Implementation of Real-Time Langmuir Probe Biasing. Review of Scientific Instruments, 90(8), 1–7.

[4] McCarthy, W., Golfinopoulos, T., Woller, K. B., Vincent, C., Kuang, A., & Labombard, B. (2021). First application of a digital mirror Langmuir probe for real-time plasma diagnosis. Review of Scientific Instruments, 92(10), 6.

[5] Lockwood Estrin, F., Karkari, S. K., & Bradley, J. W. (2017). Triple probe interrogation of spokes in a HiPIMS discharge. Journal of Physics D: Applied Physics, 50(29), 295201.

[6] Poolcharuansin, P., & Bradley, J. W. (2010). Short- and long-term plasma phenomena in a HiPIMS discharge. Plasma Sources Science and Technology, 19(2), 25010.