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A compact, smart Langmuir Probe control module for MAST-Upgrade

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Abstract: A new control module for the MAST-Upgrade Langmuir Probe system has been developed. It is based on a Xilinx Zynq FPGA, which allows for excellent configurability and ease of retrieving data. The module is capable of arbitrary bias voltage waveform generation, and digitises current and voltage readings from 16 probes. The probes are biased and measured one at a time in a time multiplexed fashion, with the multiplexing sequence completely configurable. In addition, simultaneous digitisation of the floating potential of all unbiased probes is possible. A suite of these modules, each coupled with a high voltage amplifier, enables biasing and digitisation of 640 Langmuir Probes in the MAST-Upgrade Super-X divertor. The system has been successfully tested on the York Linear Plasma Device and on the COMPASS tokamak. It will be installed on MAST-Upgrade ready for operations in 2018.

Keywords: Plasma diagnostics — probes

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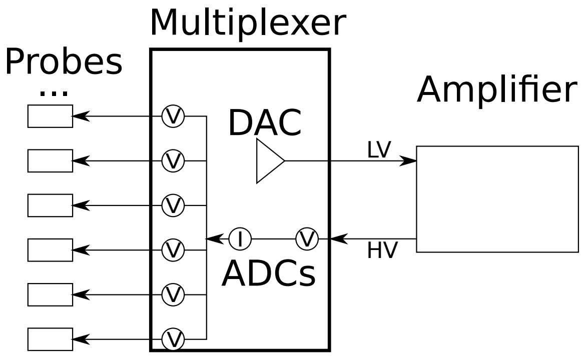

Figure 1. Schematic of one probe module. The FPGA-based multiplexer contains the DAC, ADCs and switches. Only 6 of the 16 probes are shown, for clarity.

1 Introduction

Langmuir probes are a widely used plasma diagnostic. They consist of a conductor inserted into the plasma, which is biased with a voltage relative to the wall. The net current drawn by the probe as a function of the bias voltage can be used to infer the plasma electron temperature and density [1].

MAST-Upgrade will feature over 800 Langmuir probes, with 640 measured in any one discharge. These will provide extensive coverage of the first wall in two toroidal locations, separated by 180 degrees. The large number of probes will be essential for diagnosing MAST-Upgrade's novel Super-X divertor [2], but the cost and space requirements for operating so many probes simultaneously require bespoke electronics.

2 System Design

The probe diagnostic system is made up of 40 electronics modules, each responsible for up to 16 probes. Each module consists of a power supply, an amplifier and a multiplexer. Figure 1 shows a schematic of the system, illustrating the relationship between the amplifier and multiplexer. Multiplexing the probes greatly reduces the cost, space and power requirements per probe, enabling the operation of the large number of probes installed in MAST-Upgrade.

The multiplexer can be programmed with an arbitrary waveform for the bias voltage, which is generated by a digital-to-analogue converter (DAC) and fed into the amplifier. The amplified voltage, which has a range of ±250V and is capable of driving up to 3.5A, is fed back into the multiplexer, where the voltage and current are digitised by analogue-to-digital converters (ADCs) with 16-bit resolution. The signal is then multiplexed to one of the 16 probes connected to the multiplexer, by a set of programmable switches. The switching sequence, like the waveform, is completely configurable and programmed before each shot. Each probe in the switching sequence is swept with one full waveform, before the system moves to the next probe.

A 12-bit ADC on the output of each switch enables measurement of the probe voltage even when the switch is opened and the probe disconnected from the amplifier. Since in this case the floating potential of the probe is measured, this enables simultaneous floating potential measurements for all 640 probes measured in each shot, in addition to the multiplexed swept voltage and current. All ADCs sample at 1MSPS, giving a time resolution of 1μs. The DAC also outputs at 1MSPS,

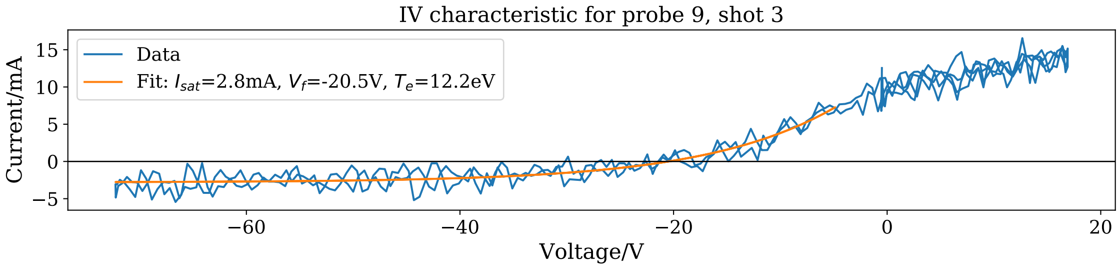

Figure 2. An IV characteristic for one of the probes inserted into the York Linear Plasma Device.

though the amplifier limits the available bandwidth for the high-voltage waveform to about 60kHz. The maximum length of each bias voltage sweep is 65ms, but sweeps of 65μs are expected to be used for MAST-Upgrade. Fast voltage bias sweeps are needed in order to provide acceptable time resolution for each individual probe: sweeping 16 probes with a 65μs sweep means each probe is swept once every 1.04ms.

The waveform generation, ADC sampling and switch operation are handled by a Xilinx Zynq FPGA, containing both FPGA programmable logic and a dual core ARM CPU, on an Avnet MicroZed board. The ARM CPU runs a Linux operating system with a web server, allowing simple configuration and readback using standard hardware and software tools: Ethernet networking and the HTTP protocol. The FPGA fabric provides deterministic timing, which is required for the correct sampling of the DAC and ADCs, and for ensuring the switches are set at the correct times. Using the FPGA results in a design which is lower cost and more compact than a corresponding analogue solution.

The system represents a significant upgrade to MAST's previous Langmuir probe diagnostic. The addition of the FPGA allows us to incorporate complex logic in a compact design, and provides a digital record of exactly which probe is active at any one time, compared with the analogue time trace used previously. We are now able to bias probes in an arbitrary sequence, providing the opportunity to prioritise certain probes over others in different discharges. The amplifier bandwidth has been improved by approximately a factor of 2, which will enable faster voltage sweeping for improved time resolution per probe. Furthermore, the system is now able to simultaneously measure the floating potential of all un-swept probes, which allows for high time resolution measurements of this parameter whilst still biasing other probes in the same discharge.

3 Tests on the York Linear Plasma Device

A prototype power supply, amplifier and multiplexer were installed on the York Linear Plasma Device (YLPD) [3], connected to 12 probes, in order to test the operation and suitability of the system. Since lower currents were expected on the YLPD than on MAST-Upgrade, the multiplexer's current sense resistor was temporarily changed from 0.2Ω to 2Ω, to enable measuring smaller currents.

An example of the current measured as a function of voltage (an "IV characteristic") is shown in Figure 2. This data comes from a probe near the centre of the plasma column, in a high field (100mT), high power (1.2kW applied) discharge. The data is averaged over 30 500μs bias voltage sweeps, each of which consists of a down sweep followed by an up sweep, in order to measure steady state plasma parameters. The fit is a 3 parameter fit, assuming the current is of the form:

$$I = I_{sat}\left(1 - \exp\left(\frac{e(V - V_f)}{T_e}\right)\right) \tag{3.1}$$

Here, I_{sat} is the ion saturation current, e the ion charge, V_f the floating potential and T_e the electron temperature, in electron-volts.

The probes have a surface area of 2.5mm^2, and are cylindrical in shape, with the circular face aligned with the magnetic field. We calculate the density, assuming the ions and electrons are at a similar temperature, to be $4 \times 10^{17}\text{m}^{-3}$. The density and temperature are in line with the expected parameters for this type of discharge on the YLPD.

It should be noted that there are more sophisticated models for the IV characteristic, such as the first-derivative technique [4] and a 4-parameter fit which accounts for sheath expansion [5]. However, the purpose of these tests was to ensure that the electronics would produce suitable data for more advanced analysis, not to perform that analysis itself. A more accurate determination of the plasma parameters using these more advanced analysis methods is left as future work.

As previously mentioned, the IV characteristic shown in Figure 2 consists of an up sweep and a down sweep. Whilst these could in principle be averaged to produce a signal with lower apparent noise, one of the goals of this test was to establish whether parasitic current induced by capacitance and other electronics effects could be effectively removed. This has traditionally been done by assuming that all parasitic current has been induced due to the system's (constant) capacitance, and is therefore proportional to $\mathrm{d}V/\mathrm{d}t$. Averaging an up and a down sweep with equal and opposite $\mathrm{d}V/\mathrm{d}t$ should therefore remove all parasitic current, and leave only the current drawn from the plasma. However, it was found that this was insufficient in the complex electronics of the new system, which has additional sources of induced current.

The induced current is however highly reproducible for a given waveform. Therefore, a number of sweeps with the programmed waveform were performed in the absence of plasma, and the current at each point in time during the sweep was averaged across all these sweeps. This current was then subtracted from the measured current drawn by the probe in plasma. The overlap of the up and down sweep in Figure 2 demonstrates that this method is effective at removing parasitic current.

4 Tests on the COMPASS tokamak

The system has also been tested on the COMPASS tokamak. COMPASS is a compact tokamak ($R = 0.56$m, $a = 0.2$m), which uses an ELMy H-mode divertor plasma as its baseline scenario [6]. It provided the opportunity to test the probe electronics in environments not possible to achieve in the YLPD, with strong transients (ELMs) and higher currents.

We present two example results from a week of shots when the system was connected to a poloidal array of dome-shaped probes embedded in the divertor target places (see [4] for details). Figure 3 shows the simultaneous floating potential measurements for 8 divertor probes, around the L-H transition. The outer strike point is located just below the bottom of the figure. A series of short lived fluctuations can be clearly seen, moving radially outwards. Due to the short time duration of these fluctuations, it would not be possible to measure them using traditional voltage sweeps.

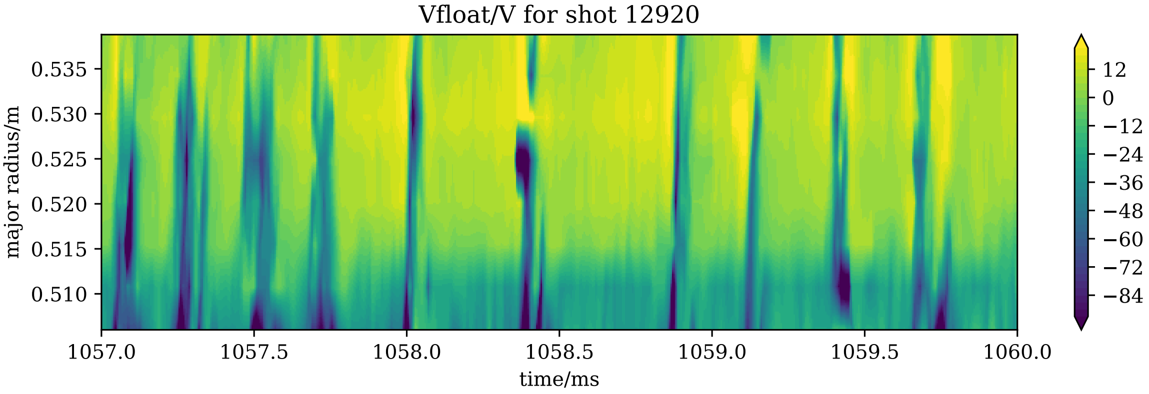

Figure 3. Floating potential measured around the L-H transition in the COMPASS divertor.

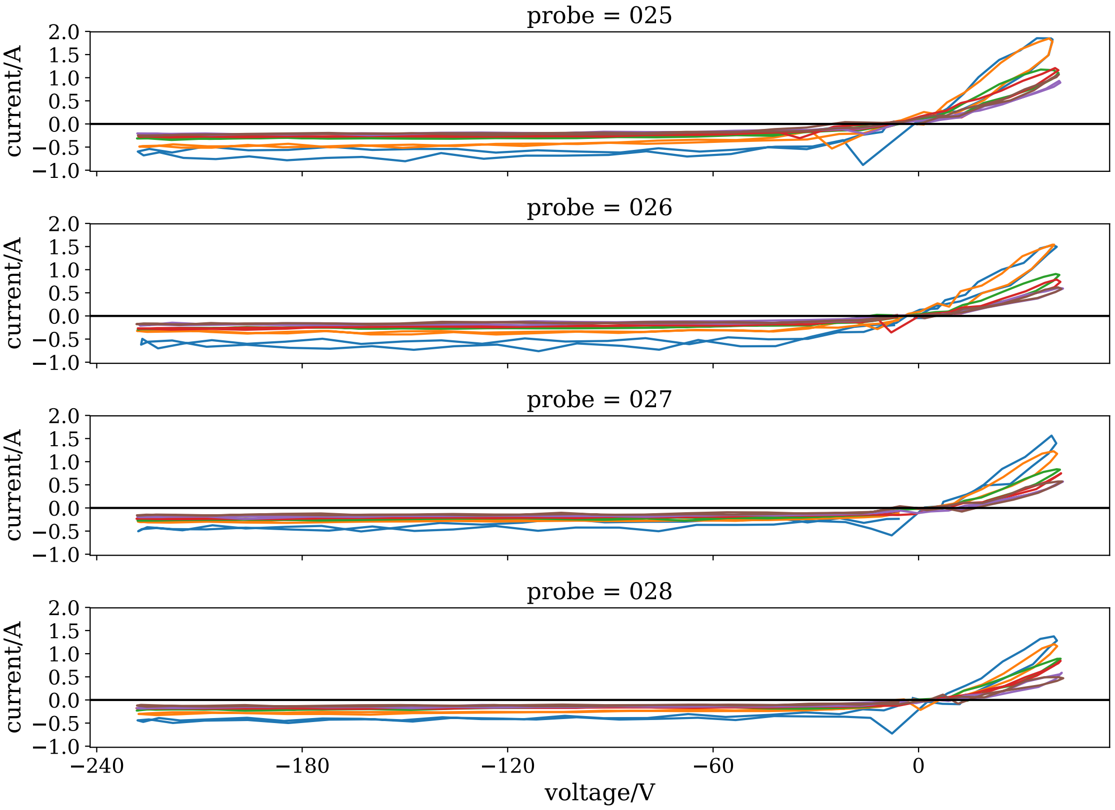

Figure 4. IV characteristics for COMPASS shot 12920, for 4 probes near the outer strike point, during a single inter-ELM period.

Only the high speed simultaneous floating potential measurements allow us to resolve these sorts of phenomena.

Figure 4 shows a number of successive sweeps for 4 probes between two ELMs. The times of each sweep are shown in Figure 5, which shows the D-alpha signal for context. Each line represents the start time of the sweep of the first probe in the multiplexer sequence. Sweeps were 65μs long,

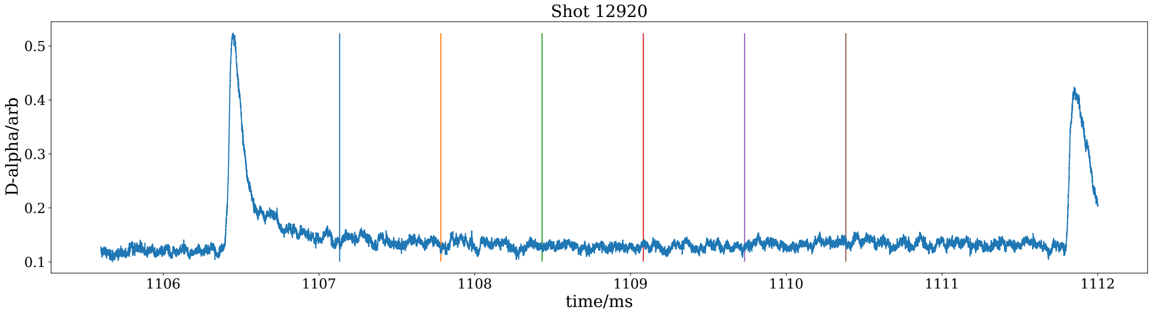

Figure 5. D-alpha signal during the sweeps of Figure 4.

and only a subset of the swept probes are shown here, for clarity.

The decay in both ion and electron currents with time can clearly be seen, as can the radial decay, from probe 25 nearest the strike point to probe 28 furthest away. However, the plots also show an interesting hysteresis-like effect in the electron current region, where the up and down sweeps do not match. The induced current has already been removed, and the success of this removal is shown in the ion current region, where the two sweeps match very well. The hysteresis effect persists over multiple sweeps, so it is unlikely to be related to some short lived plasma phenomenon which occurs within the time of one sweep.

We explain this effect by considering the finite bandwidth of the amplifier. As mentioned in Section 2, the amplifier bandwidth is limited to approximately 60kHz to help stabilise the high voltage output, and has a limited slew rate. It can be seen from Figure 4 that there is a very large positive current (up to 1.8A), and the increase from zero up to maximum current and back again occurs in a very short time: only 20μs in a 65μs sweep. The rate of change of current was as high as 200kAs^{-1} in some of the sweeps near the strike point, shortly after the ELM crash. The large rate of change of current pushes the amplifier towards its bandwidth limit, and the current lags behind the voltage in time. This means that during the up sweep, the measured current is actually lower than it should be for a given voltage (the current measured is that of a slightly earlier, and hence lower, voltage), and during the down sweep the measured current is higher, since it corresponds to an earlier and hence higher voltage. The effect is smaller at later times, and for probes further from the strike point, when the maximum current (and hence the rate of change of current) is smaller.

It would be possible to reduce or even eliminate this effect by sweeping the electron region more slowly than the ion region, and this knowledge can be used in designing optimum voltage sweep waveforms for operation on MAST-U. However, the compact nature of COMPASS, and the size, shape and location of its probes compared with those in MAST-Upgrade, may in fact be exacerbating the problem. It is possible that much lower currents will be observed in the MAST-Upgrade Super-X divertor, and the rate of change would easily be accommodated with the sweep waveforms used in these tests. Nevertheless, it is useful to push the electronics to the limit to learn about these effects in advance of the first MAST-Upgrade plasmas, and to know that we have the flexibility to deal with such complications.

5 Conclusion

The installation of over 800 Langmuir Probes on MAST-Upgrade requires a novel suite of electronics to operate and measure. The chosen solution is modular, with 40 modules consisting of a power supply, high voltage amplifier and multiplexer, with each module responsible for 16 probes. This allows 640 of the probes to be measured in each MAST-Upgrade shot.

The multiplexer exploits the power and flexibility of FPGA technology to enable the system to produce arbitrary probe bias voltage waveforms, which can be optimised for expected plasma conditions, and arbitrary probe multiplexing sequences. By programming an FPGA with the required logic, the design is kept compact compared to an analogue solution. An ARM processor running a web server and Linux allows each module to be easily configured, and data read back using standard hardware and software interfaces.

A single module of the system has been installed on the York Linear Plasma Device. It has demonstrated functional correctness, and produced data which appears to match the expected measurements, which suggests the diagnostic is reliable. The module has also been installed on the COMPASS tokamak, where it made measurements of the divertor plasma with an array of dome-shaped probes. Using high speed simultaneous floating potential measurements, a feature not present in the old MAST probe electronics, a series of short lived fluctuations were detected, along with information about their radial velocity. The swept data revealed inter-ELM dynamics, and also highlighted some interesting electronics effects which will need careful consideration to ensure accurate measurements when the final system is installed on MAST-Upgrade.

Acknowledgments

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