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Mirror Langmuir probe: A technique for real-time measurement of magnetized plasma conditions using a single Langmuir electrode

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A new method for the real-time evaluation of the conditions in a magnetized plasma is described. The technique employs an electronic 'mirror Langmuir probe' (MLP), constructed from bipolar rf transistors and associated high-bandwidth electronics. Utilizing a three-state bias waveform and active feedback control, the mirror probe's *I*-*V* characteristic is continuously adjusted to be a scaled replica of the 'actual' Langmuir electrode immersed in a plasma. Real-time high-bandwidth measurements of the plasma's electron temperature, ion saturation current and floating potential can thereby be obtained using only a single electrode. Initial tests of a prototype MLP system are reported, proving the concept. Fast-switching MOSFET transistors produce the required three-state voltage bias waveform, completing a full cycle in under 1 μs. Real-time outputs of electron temperature, ion saturation current and floating potential are demonstrated, which accurately track an independent computation of these values from digitally stored *I*-*V* characteristics. The MLP technique represents a significant improvement over existing real-time methods, eliminating the need for multiple electrodes and sampling all three plasma parameters at a single spatial location.

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I. INTRODUCTION

Langmuir probes are commonly used to infer local electron temperatures, densities, and electric potentials in a wide range of plasmas [1-4]. These include low electron temperature plasmas (~0.05 to ~5 eV) characteristic of materials processing facilities and small-size laboratory plasmas to moderate temperature (~5 to ~100 eV), high electron density (~10^{20} m^{-3}) plasmas, characteristic of the edge region in plasma-fusion confinement devices. In many situations of interest, the electrons are sufficiently self-collisional that their velocity distribution follows a single-temperature Maxwellian. Therefore, when such plasmas exhibit fluctuations and turbulence, one can track the local 'fluid-like' evolution of the plasma's density (n) and electron temperature (T_e). These plasma parameters can be determined from a Langmuir probe's current-voltage (I-V) characteristic, i.e., the measurement of current passing through the electrode in response to an applied electrical bias. In fluid-like plasmas, the electron temperature is readily inferred; it is determined from the exponential increase of electron collection with applied voltage.

A variety of techniques can be used to record part or all of the I-V characteristic and to deduce plasma conditions based on the assumption of Maxwellian electrons: sweeping the bias voltage on a single electrode relative to a reference potential (single probe method), sweeping the bias on one electrode relative to another (double probe method), and applying a fixed differential bias to two electrodes while operating a third electrode in a 'floating' mode (triple-probe method). In most cases, the I-V characteristics are digitally recorded and the parameters of interest (electron temperature, density, floating potential) are determined by fitting the I-V data points with model functions. Direct measurement techniques, i.e., techniques that do not require the storage and post-processing of *I-V* data, have also been developed. These include the triple probe method [5] (directly yielding electron temperature, ion saturation current, and floating potential) and the harmonic detection technique [6], involving a voltage-swept single or double electrode (directly yielding electron temperature). Further information on the benefits and drawbacks of these and some other techniques is included in Appendix A.

Most plasmas exhibit large-amplitude broadband turbulence, a topic that is an important area of scientific investigation. However, for Langmuir probe systems that are too slow to follow the time evolution of turbulence, such plasma fluctuations appear as ‘noise’ on the *I-V* characteristic. Because the electrode-plasma sheath exhibits a non-linear response to temperature and voltage fluctuations, plasma conditions inferred from the fitting of such ‘noisy’ *I-V* characteristics may have substantial error. Thus, even in applications where only the time-averaged quantities are of interest, fast time-response measurements may in fact be required.

Unfortunately, high-bandwidth probe measurements can result in a significant data-storage and post-processing bottleneck. For example, in order to temporally resolve the plasma fluctuations that are typical of the edge of plasma-fusion confinement devices (e.g., [7]), ion currents, electron temperatures and floating potentials must be recorded at bandwidths approaching 1 MHz. Therefore, the brute-force method of generating very fast *I-V* characteristics will be adequate only if each sweep is completed in under ~1μs; digital sampling of these analog signals must be done at a sufficiently high rate to resolve the curvature of the *I-V* characteristic (> ~10MHz), since this feature encodes the plasma electron temperature. While hardware does indeed exist to store and post-process gigabyte-size data streams, a method that produces real-time signals of the desired quantities is clearly preferred.

The spatial structure of plasma turbulence can also affect the accuracy of Langmuir probe measurements. Double and triple probe methods assume that the plasma conditions are identical at all electrodes. However, in the presence of plasma turbulence, with its characteristic broadband *k* spectrum (e.g., [8]), local conditions are undoubtedly different at each electrode location.

In view of these considerations, an ideal Langmuir probe diagnostic should satisfy at least three basic requirements: (1) operate at a high enough bandwidth to resolve plasma turbulence (~1 MHz, for the edge of plasma fusion experiments), (2) output real-time signals of ion saturation current, electron temperature, and floating potential, and (3) employ only one Langmuir electrode. To this end, we have developed a new concept for a Langmuir probe diagnostic system, which is capable of meeting these requirements. A key element of the system is a 'mirror Langmuir probe' (MLP) – a high bandwidth device constructed from rf transistors and associated electronics, which mimics the *I-V* response of a magnetized plasma-electrode sheath. This paper describes the overall concept as it is developed for a specific problem – diagnosing plasma turbulence in the edge plasma of the Alcator C-Mod experimental fusion reactor [9]. Although the scheme presented here is designed around the characteristic time scales, plasma densities and temperatures found in this environment, the concept can be readily adapted to other plasma environments.

Section II outlines the overall scheme for a mirror Langmuir probe diagnostic, utilizing the MLP device, active feedback control and a three-state probe-bias waveform. Section III discusses the theory behind the construction of the MLP from rf transistors and high-speed operational amplifiers. An example of a working circuit segment from a prototype MLP system is described in section IV. This circuit is part of an electronics package that is currently being assembled for Langmuir probes in the Alcator C-Mod tokamak [10]. The focus of the present paper is restricted to the underlying concepts for a MLP-based diagnostic; detailed information on the hardware under development for Alcator C-Mod will be forthcoming in a future publication.

II. MIRROR LANGMUIR PROBE DIAGNOSTIC

The mirror Langmuir probe diagnostic is based on a unique arrangement of standard, high-bandwidth electronic components. The main feature of the system is that it generates periodically-updated analog signals corresponding to the inverse of the electron temperature ($1/T_e$), the ion saturation current (I_{sat}), and the floating potential (V_f) of a plasma in contact with a single electrode. Figure 1 illustrates the key concepts involved:

(1) A periodic Drive Voltage waveform (V_d) is connected through a Current Monitor to the Langmuir Probe of interest via a coaxial cable. In order to compensate for the effect of the cable and probe capacitances on the measurement of the current, a 'Dummy Probe" with identical coaxial cable may also be used; in this case, the Current Monitor reports the difference current between the two probes. Here, I_p represents a voltage signal corresponding to the current supplied to the Langmuir probe (shown immersed in a plasma with its vacuum vessel connected to ground). In a parallel leg, the probe voltage, V_p, is reduced by a scale factor (S_1), buffered, and sent to the Mirror Langmuir Probe (MLP). The MLP responds by driving a 'mirror current' to ground, a scaled replica of the probe current in the plasma (reduced by factor S_2). Via active feedback, the circuit continuously 'adjusts' three input parameters (discussed further below) such that the

MLP exhibits an electrical response that is identical to that of the actual Langmuir probe except that it operates with scaled voltages and currents.

(2) A Three-State Voltage Source Waveform is used to drive the probe/mirror circuit. The voltage source cycles through the following states. (For this example, the time to complete a three-state cycle is taken as 1 μs, a value that can be achieved using fast MOSFET components operating over a voltage range of ±200 volts.):

(a) Positive voltage, $V_S \sim +0.64W$. In this state, the probe/mirror becomes positively biased, collecting a net electron current on the Langmuir Probe. The value for W is set by a feedback loop, discussed below.

(b) Zero voltage, $V_S = 0$. In this state, a reduced current level flows through the probe/mirror circuits. The Langmuir probe is close to a 'floating' state.

(c) Negative voltage, $V_S \sim -2.4W$. In this state, the probe and mirror probe become negatively biased, with the Langmuir probe collecting a net ion current from the plasma.

The time durations of the three states are identical in this example. However, they may be optimized to yield the best performance of the error-minimization feedback network (described below). The relative amplitudes of the positive and negative biases ($+0.64W$ versus $-2.4W$) are chosen in conjunction with the magnitude of W and the time durations of the states to yield minimal current flow during state b (see discussion in next section). The choice of the positive and negative coefficients of W shown here is merely representative; they may be adjusted appropriately.

(3) The voltage source is capacitively coupled to the probe/mirror circuit. Therefore, apart from negligible leakage current through voltage-divider resistors, the time-averaged net current through the Langmuir Probe approaches zero for time scales larger than the voltage source waveform period. (The time scale is set by the capacitor value, C_i, and the impedance of Langmuir Probe, $\tau \sim T_e\ C_i/I_{sat}$.) This insures that the resultant I-V characteristics experienced by the Langmuir Probe will contain net electron-collection and net ion-collection regimes and that bias state b will roughly correspond to the time when the probe draws zero net current (a ‘floating’ state).

(4) A novel Mirror Langmuir Probe (MLP) circuit is used to mimic the electrical response of a magnetized Langmuir probe, up to frequencies in the range of ~50 MHz. A detailed description of this is device included in the next section of this paper.

(5) A feedback loop sets the appropriate input values to the MLP (labeled as $S_1/20T_e$, V_f/S_1, and V_i signals in Fig. 1). An error signal is constructed from the difference between the Probe Current (I_p) and the scaled Mirror Probe Current ($I_m \sim I_p/S_2$). An electronic switch, synchronized with the three states of the Voltage Source Waveform, routes the error signal to three integrators (conceptually shown as capacitors in Fig. 1). During state a (net electron collection), any mismatch in the currents is corrected by adjusting the

parameter, $S_1/20T_e$, which corresponds to the scale factor divided by 20 times the plasma electron temperature. Similarly, parameters V_f/S_1 and V_i (the definitions of these parameters are covered in detail in the next section) are adjusted during states *b* (reduced current level) and *c* (net ion collection), respectively. By successively updating each parameter, a 'best fit' to the *I-V* characteristic is dynamically obtained. The error-signal gain and integration times are set such that the three parameters respond within one voltage-source waveform period (~1 MHz).

(6) If the Probe Current, I_p, exceeds a preset range, the electronic switch disconnects from all integrators, effectively ignoring the error signal. (This feature is not included on the schematic in Fig. 1.) In this way, should a momentary unipolar arc develop from the probe to the plasma, its disruptive influence on the 'best fit' parameters stored in the integrators is minimized.

(7) The amplitude of the Voltage Source Waveform (scale factor, *W*) is adjusted over long time scales (typical value in this example is ~1 ms) by a feedback loop which attempts to keep the peak-to-peak amplitude of the Probe Voltage (V_p) in an optimum range. The time scale of this adjustment is chosen to be long compared to plasma turbulence time scales but short relative to the time scales for the mean plasma conditions to evolve. (In the case when the probe is being spatially scanned across a plasma region, the relevant time scale is a characteristic plasma gradient scale length divided by the probe's velocity.) Since the MLP circuit continuously updates the values of probe voltage divided by electron temperature, V_p/T_e (see next section), the feedback loop uses this information to

adjust the amplitude of the Voltage Source Waveform such that [max(V_p) - min(V_p)]/T_e ~ 3, averaged over the chosen time-scale. (Values other than ~3 may be chosen, resulting in a different amplitude of the Voltage Source Waveform, *W*. As noted previously, the relative amplitudes of the positive and negative biases, $+0.64W$ versus $-2.4W$, would be appropriately modified.)

(8) In order to minimize signal reflections in the Langmuir Probe and Dummy Probe coaxial lines, the Current Monitor has a 50Ω impedance in both legs, matching that of the cables. Therefore, in response to a stepped voltage change at V_d, the current and voltage at the Current Monitor 'updates' with a time delay that corresponds to the round-trip propagation time of the voltage pulse, $\tau_d = RC$, with $R = 50\Omega$ and C being the total capacitance of the coaxial cables. For example, a 10 meter cable (~100 pf per meter) would result in a time delay of 50 ns, or a total 'dead time' of 150 ns during the three-state bias cycle. Thus, it is important to avoid coaxial lines much longer than this, if a 1 μs bias cycle time is desired. In any case, these delays as well as the intrinsic delays and settling times for the electronic circuitry are easily accommodated by adjusting the timing of the electronic switch; 'error signals' are sent to the integrators only during times when the bias state has truly 'settled' and the Langmuir Probe has fully 'responded'.

(9) The output signals from the Mirror Langmuir Probe circuit are: the difference between the probe and mirror probe currents (the 'error signal'), the scaled inverse of the electron temperature ($S_1/20T_e$), ion saturation current (I_{sat}), and the scaled floating potential (V_f/S_1). The latter three signals, which have a frequencies of up to ~1 MHz in this

example, can be digitally sampled and stored. The quality of the 'fit' to the Langmuir *I-V* characteristics that is obtained by this 'analog computer' can be readily assessed; simply compare the RMS amplitude of the error signal to the ion saturation current level. In addition, a small subset of *I-V* characteristics can be periodically digitized at high bandwidth (~50 MHz) to verify that the analog 'fit' of the *I-V* characteristic is appropriate, using standard analysis tools.

III. ELECTRONIC LANGMUIR PROBE – THEORY OF OPERATION

The Mirror Langmuir Probe exploits the following key observation: With suitably scaled voltages and currents, the non-linear *I-V* response of a bipolar transistor can be made to simulate the non-linear *I-V* response of a Langmuir probe.

From planar Langmuir probe theory [1-4], the current collected by an electrode, I_p, at potential, V_p, immersed in a plasma with a Maxwellian electron energy distribution at temperature, T_e, is described by

$$I_p = I_{sat}\left(exp\left[\left(V_p - V_f\right)/T_e\right] - 1\right) \quad . \qquad (1)$$

Here, negative current corresponds to net ion current collected by the probe. The maximum ion current that can be collected corresponds to the 'ion saturation current', I_{sat}. When the probe voltage is equal to V_f, the probe 'floats', *i.e.*, draws no net current. In practice, Eq. (1) is found to apply for the range of probe biases, $V_p < V_{knee}$, where V_{knee} is set by the requirement that I_p not exceed a few times the ion saturation current.

It should be noted that planar probe theory is appropriate when: (a) the Debye shielding length is much smaller than the probe dimensions, and/or (b) the Langmuir probe is immersed in a magnetized plasma, i.e., a plasma where the cross-field ion orbit size is much smaller than the cross-field probe dimensions [1-4]. Both conditions apply for the application presently being considered. In order to handle the exceptional cases, one could replace the "-1" term in Eq. (1) with a term that is weak function of probe voltage, appropriate for the probe geometry. While MLP circuits may be constructed to mimic these specific cases, they are not treated here.

The current through the collector, I_C, of a bipolar transistor with base-emitter bias, V_{BE}, follows the Ebers-Moll equation [11],

$$I_c = I_s\{exp[\alpha V_{BE}] - 1\}, \tag{2}$$

where $\alpha = 1/T_{RT}$, T_{RT} is the temperature of the electrons in the transistor (at room temperature, T_{RT} is very close to 1/40 volts) and I_S is the saturation current of the transistor. The exponential term is always much larger than 1 in the present application, so the "-1" term in Eq. (2) can be dropped.

The simplified circuit segment in Fig. 2 shows how two bipolar transistors can be setup to simulate the Langmuir probe response of Eq. (1). A PNP transistor is used to source current to the input terminal while an NPN transistor is used to sink current. Any current into the device flows to ground via the power supplies. The parameters V_i, V_f, and $1/40T_e$ are constant, set by an external circuit, V_b is a constant voltage used to 'balance' the transistors for a specific value of ion saturation current (I_{sat0}), and V_p is the time-varying voltage of the electronically simulated Langmuir probe. Applying the indicated base-emitter biases to Eq. (2) results in the net current through the device,

$$\begin{aligned} I_p = I_s^{npn}\, exp\Big[\alpha^{npn}\big\{V_i + V_b + \left(V_p - V_f\right)/\left(40\,T_e\right)\big\}\Big] \\ - I_s^{pnp}\, exp\Big[\alpha^{pnp} V_i\Big] \end{aligned}, \tag{3}$$

accounting for different saturation currents and temperatures of the transistors. Eq. (3) reduces to an expression similar to Eq. (1),

$$I_p = I_{sat0}\left(I_{sat} / I_{sat0}\right)^{\left(\alpha^{npn} / \alpha^{pnp}\right)} exp\left[\alpha^{npn}\left\{\left(V_p - V_f\right) / \left(40\, T_e\right)\right\}\right] - I_{sat}, \qquad (4)$$

when

$$V_i = ln\left[I_{sat} / I_s^{pnp}\right] / \alpha^{pnp} \qquad (5)$$

and

$$V_b = \ln\left[I_{sat0} / I_s^{npn}\right] / \alpha^{npn} + \ln\left[I_s^{pnp} / I_{sat0}\right] / \alpha^{pnp}. \qquad (6)$$

Note that when the temperatures of the NPN and PNP transistors are such that $\alpha^{npn} = \alpha^{pnp} = 40$ volt^{-1} (~room temperature), Eq. (4) becomes identical to Eq. (1), the magnetized Langmuir probe response. The temperatures of the NPN and PNP transistors are assumed to have this value in the remaining discussion. Nevertheless, it is possible to ‘correct’ the outputted T_e values for other transistor temperatures; simply multiply the outputted T_e values by the ratio of the NPN transistor temperature divided by the temperature of 1/40 volts. If the temperature of the PNP transistor is not precisely equal to that of the NPN transistor, the factor in front of the exponential term in Eq. (4) will deviate from the desired I_{sat} value. However, this error is typically small and can be avoided altogether by placing these devices in good thermal contact; a temperature difference of 1^{o} C results in only a 1.6% deviation from the desired I_{sat} value under the extreme case of $I_{sat}/I_{sat0} = 100$.

Equations (4), (5), and (6), reveal the different roles that the four constants (V_i, V_b, V_f, and $1/40T_e$) have in determining the non-linear *I-V* response: V_i sets the ion saturation current level, I_{sat}, and dominates the *I-V* response for large negative probe biases. V_b adjusts for mismatches in the NPN and PNP transistors due to different transistor saturation currents and/or temperatures, i.e., V_b forces the I-V characteristic to cross zero when the probe voltage, V_p, is equal to the floating potential, V_f. The parameter, $1/40T_e$, scales V_p such that the I-V curve exhibits the desired exponential response. At large positive values of V_p, the probe current becomes most sensitive to this quantity. Since V_b depends only on transistor parameters, it can be determined off-line for a typical value of I_{sat} (i.e., I_{sat0}) and then held fixed while the other three input parameters are varied during operation of this 'electronic Langmuir probe'.

The goal of the external feedback loop shown in Fig. 1 is to adjust the three input parameters (V_i, V_f, and $1/40T_e$) such that the I-V characteristic of the MLP becomes a scaled replica of the real Langmuir probe; the strategy for this task is now apparent: adjust V_i during large negative voltage excursions, adjust $1/40T_e$ during large positive voltage excursions, and adjust V_f when the Langmuir probe is drawing minimal current (near 'floating' condition). Since there is some interaction among these parameters, the adjustments should be performed iteratively and over time scales during which the characteristic of the actual Langmuir probe is essentially unchanged.

An ideal voltage bias waveform for this task is one that cycles through the three desired bias states, with the feedback error signals switching in synchronization. In the example presented here, the choice for the voltage biases is: (a) $0.645T_e+V_f$, (b) V_f, and (c) $-2.355T_e+V_f$. From Eq. (1), the resultant currents are: (a) $+0.91I_{sat}$, (b) 0, and (c) $-0.91I_{sat}$. When states (a) and (c) have the same time duration, this bias waveform drives a zero time-averaged current through the plasma. Therefore, if the voltage source waveform is capacitively coupled to the Langmuir probe, the probe's time-averaged floating potential will appear across the capacitor. In this case, voltage source waveform biases with respect to laboratory ground are simply: (a) $0.645T_e$, (b) 0, and (c) $-2.355T_e$.

IV. ELECTRONIC LANGMUIR PROBE – EXAMPLE CIRCUIT

Figure 3 shows a more complete example of a MLP circuit that would interface with the conceptual circuit shown in Fig. 1. This circuit segment is part of a working prototype that is presently under development for Langmuir probe systems in the Alcator C-Mod experimental fusion reactor [10]. The probe voltage is reduced by the scale factor, S_1, such that the resultant signals lie in the ±2 volt range. This allows fast op-amps and fast, low power bipolar RF transistors to be used. (Electron temperatures in the range of 10 to 75 eV, ion saturation currents in the range of 0.01 to 2 amps, and floating potentials from -300 to +50 volts are encountered in the edge plasma of Alcator C-Mod. Therefore, a good choice for this application is $S_1 = 200$.) Key elements of the circuit are:

(1) Transistors Q1 and Q2 play the role of sourcing and sinking current to/from a 2kΩ resistor connected to ground. The net current through this resistor has the desired *I-V* response. The 2kΩ resistor (plus any further amplification in the circuitry) sets the current scale factor between the MLP current and actual Langmuir probe current, which is $S_2 = 2{,}000$ for the example shown here. It should be noted that real transistors have a finite resistance in series with their emitters (~1 Ω). Therefore, it is important to restrict the mirror currents to small values, thus avoiding an additional voltage term in Eq. (3) that would otherwise reduce the base-emitter bias in proportion to the emitter current. We have found that an overall mirror current scale factor of $S_2 = 8{,}000$ works quite well, restricting the maximum mirror current to the range of 0.3 mA for the present application.

The resultant ~0.3 mV of additional base-emitter bias yields a maximum 1.2% deviation from the ideal mirror current at the largest I_{sat} values that are encountered by the Langmuir probes in Alcator C-Mod.

(2) Q1 and Q2 are arranged so that U1 and U2 drive their emitters instead of bases; the bases of Q1 and Q2 are tied to +5V and -5V, respectively. This avoids the consequence of the 'Miller effect' [11], a coupling of collector voltage swing to the base terminal via the parasitic collector-base capacitance, which would otherwise limit the bandwidth. State-of-the-art rf transistors should be used for Q1-Q3. It should be noted that the value of the transistor's current gain (h_{fe}) is not critical in this application since, as seen in Eq. (2), the collector current does not depend on the base current, only the base-emitter bias. We have found the respective NPN and PNP bipolar rf transistors from NXP Semiconductors [12] to be excellent choices: BFR505 (h_{fe} ~ 100 $I_c \leq 18$ mA, $V_{ce} \leq 15$V, f ~ 9GHz) and BFT92 (h_{fe} ~ 50, $I_c \leq -25$ mA, $V_{ce} \geq -15$V, f ~ 5GHz).

(3) U1 and U2 apply emitter-base bias signals to Q1 and Q2 according to the scheme outlined in Fig. 2 (with sign reversals and different scale factors). U1 and U2 are high bandwidth op amps, such as the OPA656 from Texas Instruments [13] (unity gain stable, gain-bandwidth product ~ 200 MHz). Example resistor values from a working prototype circuit are shown in Fig. 3.

(4) Q3 plays to role of a 'current mirror' for Q1, sourcing an identical level of the Mirror Ion Saturation Current into its 2kΩ resistor. In this way, the ion saturation current level can be monitored by the external circuitry in real-time. Additional circuitry (not shown here) can be used to compensate for slight differences in the currents driven by Q1 and Q3 due

to manufacturing differences. In any case, the currents through Q1 and Q3 will be proportional at long as the temperatures of the transistors are the same.

(5) U3-U6 schematically represent components of a fast multiplier chip, such as the 4-quadrant multiplier, AD835 from Analog Devices [14] (250 MHz bandwidth). The scaled floating potential signal, V_f/S_1, is combined with the scaled probe voltage, V_p/S_1, and multiplied by the scaled inverse electron temperature, $S_1/20T_e$. This operation, combined with the gain of the inverting amplifier, U2, produces the desired bias signal for Q2, $(V_p\text{-}V_f)/40T_e$. As noted in the previous section, this output signal from U5 is used to control the amplitude of the Voltage Source Waveform via a long time-constant feedback loop. Additional circuitry (not shown here) can be used to monitor and remove DC offsets in the multiplier chip when the system is in an idle state (Voltage Source Waveform zero, V_i, V_f, and $1/T_e$ at 'initial guess' values with $V_f = 0$).

(6) As discussed above, the signal V_b plays the role of compensating for mismatches between Q1 and Q2 and insuring that the mirror current signal is zero when the probe bias is at the floating potential, $V_p = V_f$. This function is best accomplished by additional circuitry (not shown here) that adjusts V_b so that the Mirror Current Signal is zero when the system is in an idle state.

IV. FIRST RESULTS FROM PROTOTYPE CIRCUITRY

In order to test the principle and assess the potential performance of the mirror Langmuir probe scheme outlined above, we have performed some initial tests using prototype circuitry. Figure 4 shows a three-state voltage source waveform (top trace), generated by fast-switching MOSFET transistors (IXFH12N50F [15]) driven by fast gate drivers (MC4422A [16]), which are each optically coupled to separate local power supply ground planes (HCPL 9000 [17]). We find that these components can produced fast-changing output voltages ($\partial V/\partial t$ exceeding ~4000V/μs) and drive ~2 amps currents for short periods of time (i.e., wave-train duration of ~ 1s) – ideal for biasing a Langmuir electrode on one of Alcator C-Mod's fast-scanning probe systems. For the test shown in Fig. 4, the 'probe' was actually a 100 ohm resistor attached to 3.2 meters of 50 ohm coaxial cable. The TTL waveforms also shown in Fig. 4 are generated using an erasable complex programmable logic device (CPLD – ATF750C [18]). Waveforms (c), (d) and (e) are used to trigger the MOSFET/GATE devices while waveforms (f), (g) and (h) select among the three feedback loops that control the mirror Langmuir probe (see Fig.1). These tests demonstrate that a three-state bias cycle can be completed in less than 1 μs, thus satisfying one of our stated design goals for an ideal Langmuir probe diagnostic. The waveforms also exhibit sufficiently long 'data sampling' time periods where the switching transients have settled. With further refinement, even faster switching waveforms may be possible.

Figures 5-7 show results from some first tests of a prototype mirror Langmuir probe (MLP) circuit. In this case, the 'probe' was actually a separate 'electronic Langmuir probe' (ELP) constructed to operate at the voltages and currents of a real Langmuir probe. This ELP consisted of banks of 12 NPN and PNP rf transistors operated in parallel (for increased current handling). The bias configuration is based on the concepts shown in Fig. 2. This allows us to independently control the 'electron temperature', 'floating potential' and 'ion saturation current' of the 'probe' and to explore the performance of the MLP circuit under a variety of conditions. Unfortunately, the present version of the ELP circuit is not capable of operating at the full bandwidth of the MOSFET/MLP circuitry. (It also exhibits some erratic jumps and drifts in its I-V characteristic, which actually makes for a good test of the MLP circuit!) Given these limitations, these initial tests were performed at reduced switching frequency, approximately 1/5th the nominal rate. Nevertheless, Figs. 5-7 clearly illustrate the principle of operation. The blue, green and red curves are the respective values of ion saturation current, floating potential and inverse electron temperature (which is shown non-inverted for clarity) outputted by the MLP circuit. The gray curves are the same values computed directly from the voltage and current data. This post-processing numerical algorithm does the same 'computation' that the MLP circuit does in real-time; it cyclically updates the values of ion saturation current (I_{sat}), floating potential (V_f) and inverse electron temperature ($1/T_e$,) so that Eq. (1) matches the observed current and voltage for each state. The agreement between the two signals is found to be very good. As outlined in section II, the amplitude of the voltage source waveform can be controlled by the real-time outputs so as to maintain the optimum bias. This feature has been implemented in the prototype circuitry and accounts for the modulation in the peak-to-peak voltage amplitude seen in trace (a) of Fig. 5.

Figure 7 illustrates the operation of the active feedback in more detail. Each time the 'data sample' is taken of a given bias state, the error signal is driven towards zero by adjustment of the corresponding MLP control parameter: I_{sat}, V_f, and $1/T_e$. We have found the prototype error-integrator/feedback scheme to be stable down to short integration times. For example, factor-of-two step changes in I_{sat} and $1/T_e$ are completed in under 100 ns. Thus the present system should work well with the three-state voltage bias waveforms shown in Fig. 4. and is ready for testing with the real Langmuir probes that exist on Alcator C-Mod – the topic of a future investigation.

V. SUMMARY

A new concept for a Langmuir probe diagnostic is described. This diagnostic utilizes a novel, high-bandwidth ‘electronic probe’ to ‘mirror’ the *I-V* characteristic of a real Langmuir probe that is immersed in a magnetized plasma. Active feedback control and a three-state voltage bias system is used. The resultant ‘analog computer’ is capable of reporting the plasma’s ion saturation current, floating potential, and inverse electron temperature in real time with a bandwidth of ~1 MHz. The theory of operation for such an electronic ‘mirror Langmuir probe’ (MLP) is described and an example circuit segment from a working prototype is discussed. Initial test results demonstrate the feasibility of implementing the concept using standard electronic devices. Based on this conceptual framework, an optimized MLP package is presently being assembled for electric probes on the Alcator C-Mod tokamak. The results from this hardware development and an assessment of its performance will be reported in detail in a future publication [10].

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APPENDIX A – HIGH-BANDWIDTH LANGMUIR PROBE METHODS

A number of techniques can be used to measure plasma conditions at high bandwidth with Langmuir probes, each having advantages and disadvantages. (Note: all these techniques rely on the electron velocity distribution being well described by a single-temperature Maxwellian). While not meant to be an exhaustive list, the following techniques are noteworthy. For comparison, we have added the 'mirror Langmuir probe' technique to the end of this list.

(a) Triple probe technique [5]

- Three probes are operated simultaneously: a double probe with fixed differential bias and a single floating probe.
- Electron temperature is directly outputted, deduced from difference in floating probe and double probe potentials; ion saturation current and floating potential are also directly outputted.
- Advantage: direct readout of three plasma parameters.
- Disadvantage: plasma conditions must be identical at all three electrodes, even during turbulent fluctuations - a condition rarely satisfied.

(b) Admittance probe [19]

- A single frequency voltage drive is applied to a Langmuir electrode and a "dummy" electrode through a capacitor bridge.
- Change in probe admittance induced by the plasma is deduced, which is proportional to ion saturation current divided by electron temperature.
- Advantage: direct readout of ion saturation current divided by electron temperature.
- Disadvantage: need additional probe to measure ion saturation current; again, plasma conditions must be identical at both electrodes.

(c) Time-domain triple probe [20]

- A double probe is operated with voltage bias switched between positive, negative and floating states.
- Resultant *I-V* characteristics are digitized at high sampling rate and stored.
- Electron temperature, ion saturation current and floating potential are unfolded in way similar to the "triple probe technique" from the different bias states, assuming that electron temperature is unchanged during the "floating" state.
- Advantage: requires two electrodes - an improvement over triple the probe method.
- Disadvantage: need to digitize, store, and post process large data stream; again, plasma fluctuations must be identical at both electrodes.

(d) Fast-swept single Langmuir probe (e.g., [21])

- A fast voltage sweep is applied to a single Langmuir electrode, using a "dummy" electrode to null a balanced current-sensing bridge in the absence of plasma.
- Resultant *I-V* characteristics are digitized at high sampling rate and stored.
- *I-V* characteristics are fit numerically with a model function, yielding electron temperature, ion saturation current, and floating potential.
- Advantage: requires only one electrode.
- Disadvantage: need to digitize, store, and post-process a large data stream.

(e) Harmonic probe current detection technique (e.g., [22])

- A pure frequency voltage drive is applied to a single Langmuir probe, using a "dummy" Langmuir probe to null a balanced current-sensing bridge in absence of plasma.
- Ratio of first and second harmonic current signal is monitored with analog circuitry.
- An analog signal proportional to plasma electron temperature is outputted directly.

- Advantage: direct readout of plasma electron temperature using only one probe; real-time feedback control of voltage bias waveform can be performed.
- Disadvantage: Additional probes needed for ion saturation current and floating potential measurements; again, plasma fluctuations must be identical at all electrodes.

(f) Mirror Langmuir Probe technique [this paper]

- A fast-switching power supply is used to cyclically bias a single electrode into ion collection, electron collection, and near-floating bias states; an electronic device that mimics the *I-V* response of a magnetized plasma-electrode sheath, a 'mirror Langmuir probe', is also biased with the same waveform.
- Via active feedback control, the mirror probe's *I-V* characteristic is continuously adjusted to be a scaled replica of the 'actual' Langmuir electrode immersed in a plasma.
- Electron temperature, ion saturation current, and floating potential are directly outputted in real time from the mirror probe.
- Advantage: requires only one electrode; directly outputs three plasma parameters measured at the same spatial location; real-time feedback control of voltage bias waveform can be performed.
- Disadvantage: requires use of state-of-the-art electronics – fast-switching power supply and 'mirror Langmuir probe' device.

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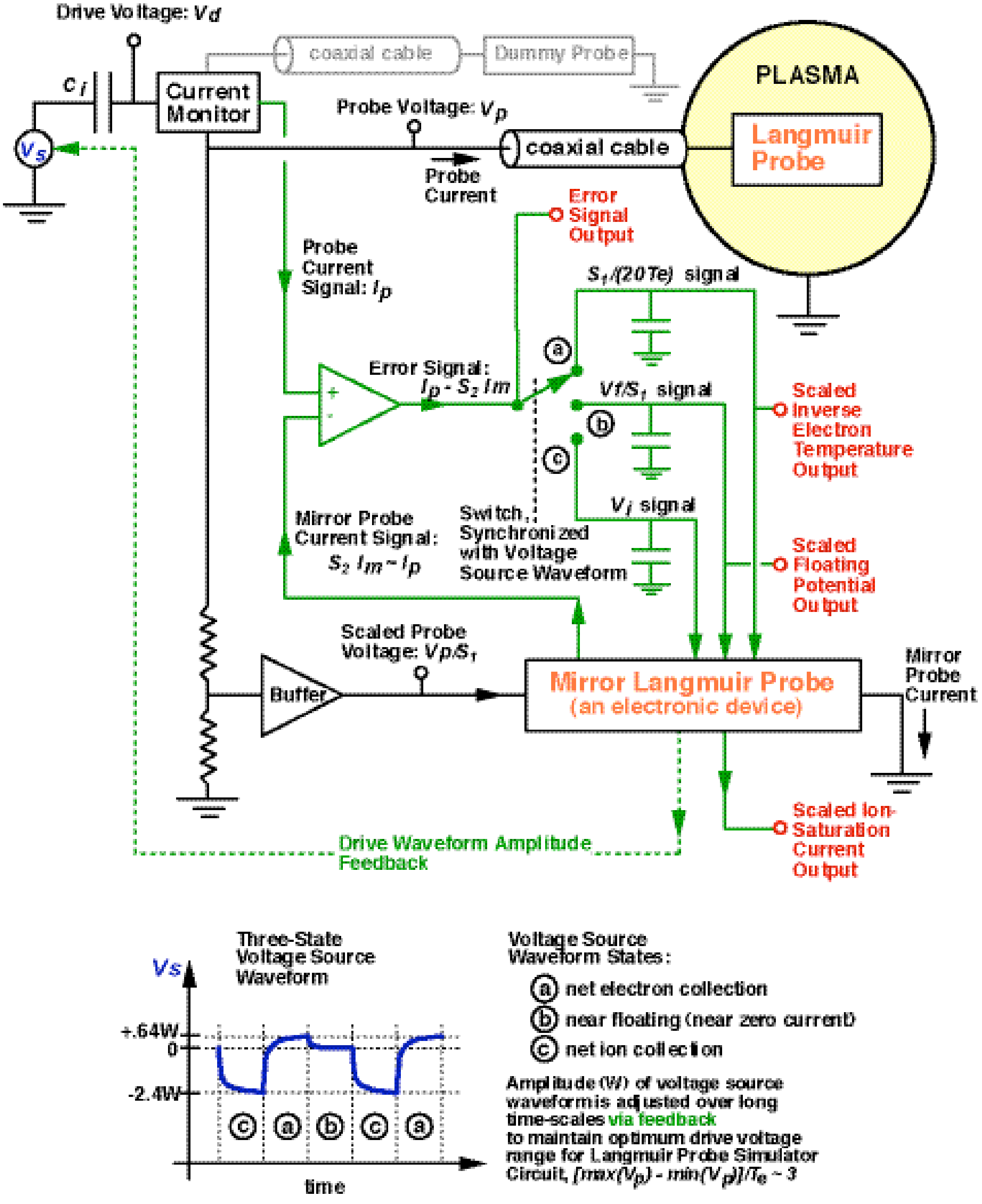

Fig. 1 - Mirror Langmuir Probe diagnostic concept.

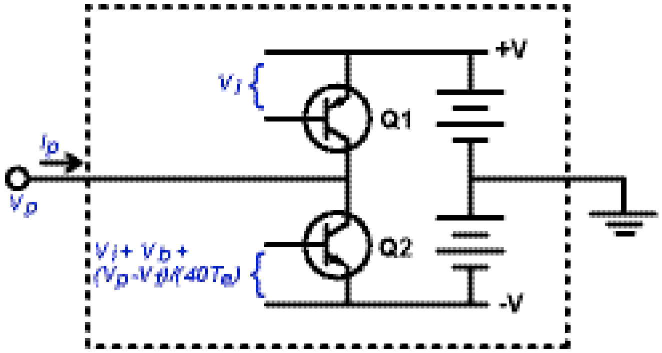

Fig. 2 - Bipolar transistors biased to mimic Langmuir probe response.

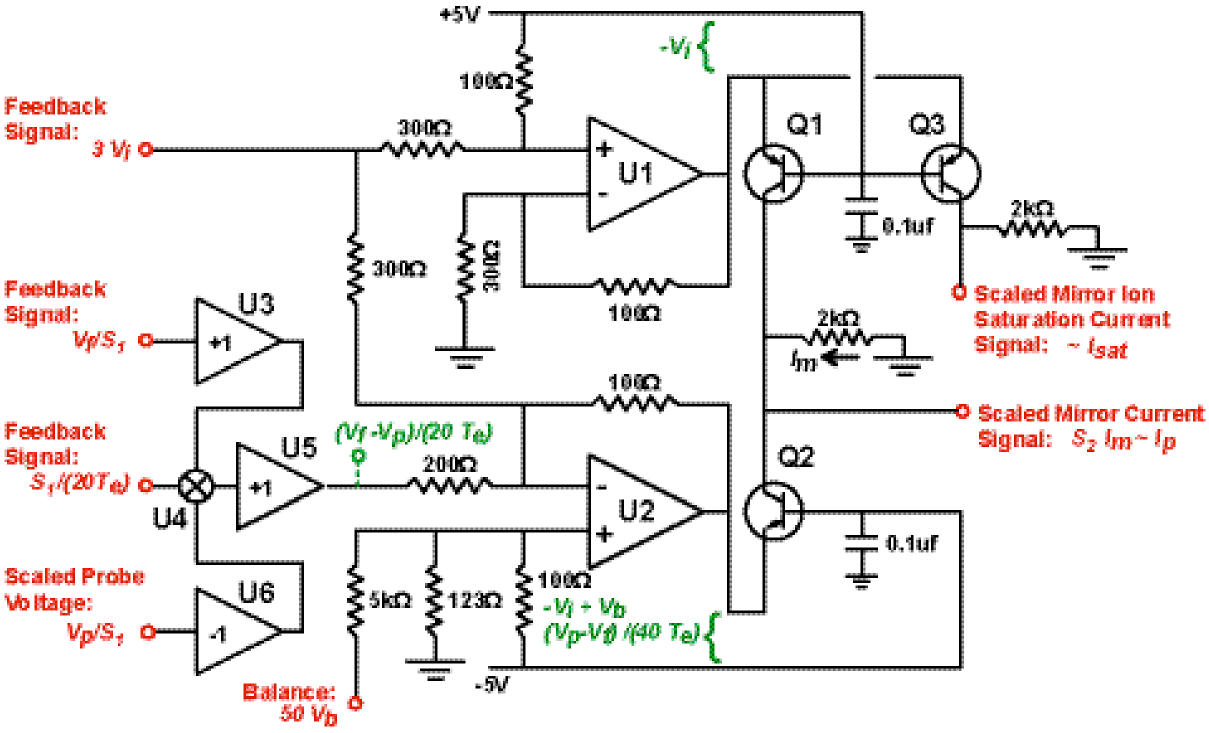

Fig. 3 - Example Langmuir probe simulator circuit.

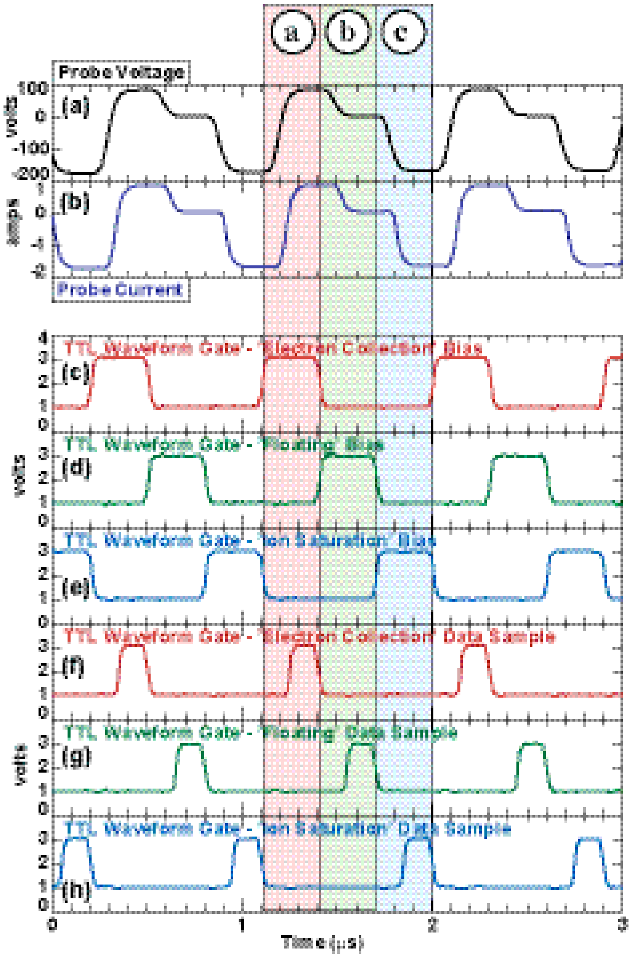

Fig. 4 – Example of a three-state voltage bias waveforms generated by a prototype switching circuit. Trace (a) is a probe voltage-bias waveform with asymmetric positive and negative amplitudes, as discussed in section II. In this case the 'probe' is actually a 100 ohm resistor, producing the measured current signal, (b). TTL logic signals (c), (d) and (e) trigger the switching MOSFETs while logic signals (f), (g) and (h) are used to switch among the three feedback loop signals in the mirror Langmuir probe.

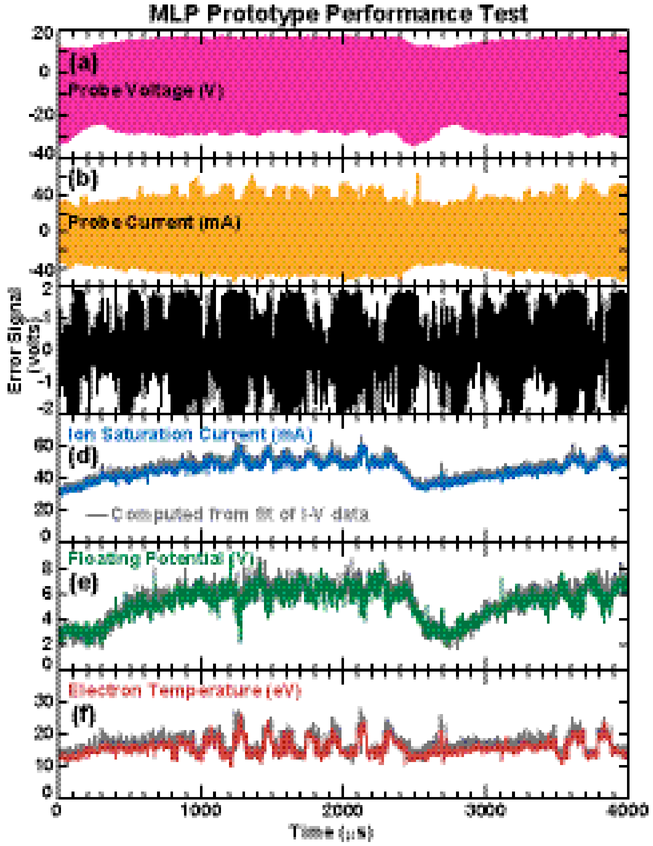

Fig. 5 – Signals from prototype circuitry, demonstrating the principle of an electronic 'mirror Langmuir probe' with active feedback control. Traces (a) and (b) are the voltage and current signals of a Langmiur probe (for this test, a separate electronic circuit is use as the 'Langmuir probe'). Solid traces (d), (e) and (f) correspond to the respective analog outputs of ion saturation current, floating potential and inverse electron temperature (shown non-inverted for clarity). The MLP circuit determines these values in real time by minimizing the 'error signal' during each bias state. The gray curves in (d), (e) and (f) are values computed independently by a post-processing algorithm using the measured currents (a) and voltages (b).

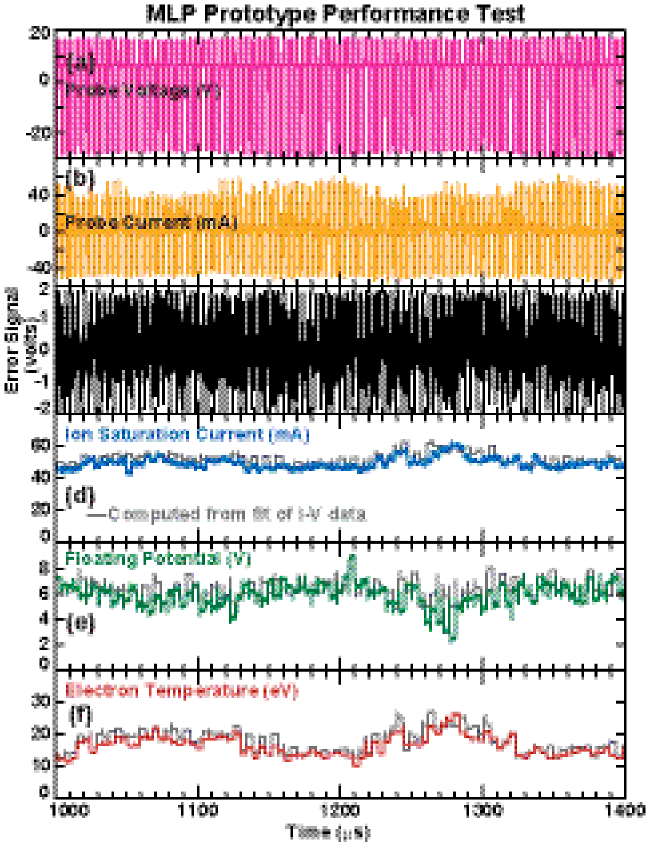

Fig. 6 – Time-expanded view (x10) of the signals shown in Fig. 5.

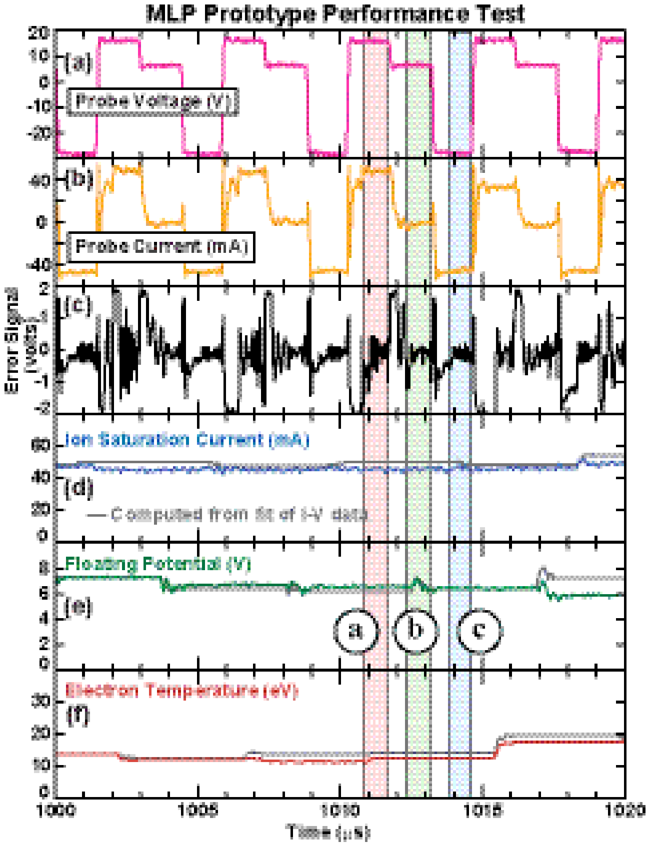

Fig. 7 – Time-expanded view of the signals shown in Fig. 6. Active feedback drives the ‘error signal’ to zero during the data-sampling times of the three bias states (highlighted bars). In this way, the three control parameters for the mirror Langmuir probe are dynamically adjusted and outputted: electron temperature, floating potential and ion saturation current.