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A Closed Loop Controller for Electron-Beam Evaporators

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Abstract

A simple instrument for automatically controlling the deposition rate of an electron-beam evaporator is described. The design incorporates a commercially available, microprocessor based, Proportional-Integral-Differential (PID) process controller which provides loop control and automatic determination of optimal proportional, integral and differential loop constants. A logarithmic amplifier is used to linearize the overall loop response. The controller is used in conjunction with a compact electron-beam heated evaporator.

I. INTRODUCTION

The growth and properties of ultra-thin metallic films in the 0-10 nm range is a very active area of research. This is particularly true for magnetic films due to the promise of new low cost and small sized data storage products [1]. The production of high quality films requires evaporators capable of controlling film thickness to submonolayer accuracy and limiting contamination from unwanted sources. Recently, compact evaporator designs have been developed which produce a clean, low flux of atoms of a high melting point material [2,3]. These designs use a filament to electron-beam (e-beam) heat a source rod of material held at a high potential, usually incorporated in a water or cryogenically cooled chamber. This type of compact e-beam evaporator has been improved to include integral flux monitoring of the atomic beam by collecting and measuring a portion of the atomic beam flux that is ionized by the heated filament, as described by Jones *et al*. [3]. The ion current provides a measurement of the atomic beam flux and thereby allows control by a feedback mechanism. The ion flux monitor also allows flux measurements at very low deposition rates, i.e. at 0.01 nm min^{-1}, which is below the useful detection limit of standard quartz crystal flux monitors.

The ability to monitor the atomic beam flux in the evaporator allows the addition of closed loop control and avoids the problem of the uncertainty and drift of the atomic beam flux with heating power of the evaporator. This paper describes a simple, low cost circuit designed to allow closed loop control of compact e-beam evaporators. In addition, we describe a custom compact e-beam evaporator which can be built from mostly off-the-shelf components. The controller design includes a commercial PID process controller, which provides loop control and automatic determination of optimal loop constants, and a logarithmic amplifier to linearize the overall loop response. Figure 1 shows a photograph of the e-beam evaporator and controller.

II. EVAPORATOR DESIGN

The evaporator design is similar to that described by Jones *et al*. [3], which incorporates an integral flux monitoring aperture. The evaporator, shown in figure 2, is mainly built from commercial components, with the exception of the apertures and some connecting parts for the shutter mechanism, allowing for the economical construction of a high quality evaporator. The commercial parts consist of: 1) a water cooled evaporation chamber on a double sided NW35CF flange with two integral electrical feedthroughs for the filament [4], 2) a port multiplexer containing five NW16CF ports on a rotatable NW35CF flange [5], 3) a linear motion thimble with a linear travel of 31 mm [6], 4) a rotary motion feedthrough [7], 5) a standard BNC electrical feedthrough [8], and 6) a high voltage electrical feedthrough [9]. The port multiplexer allows the attachment of the various electrical, rotary, and linear feedthrough devices. The linear motion thimble allows the source rod, which is attached to the high voltage feedthrough, to be positioned relative to the filament loop. The position of the source rod is adjusted according to the procedure outlined by Jones *et al*. [3], to yield an ion flux measured at a collecting aperture which is relatively insensitive to the position of the source rod. Adjustments to the source rod position are made after large amounts of material have been used.

The excellent linearity of the ion current with Iron deposition rate for this type of compact e-beam evaporator is shown in Fig. 3. The calibration constant of this unit for an

Iron source is obtained from the slope in Fig. 3 and is 5.6 nA/(nm min^{-1}) for a sample positioned at 13 mm from the end of the evaporator. While the ion current is a very good measure of the evaporator flux it requires the operator to constantly adjust the filament current to keep the ion flux constant as the evaporator temperature changes. This can be tedious as the ion flux is a strong function of filament current, as shown in Fig. 4. The ion current is found to be exponential with filament current over the useful range of the evaporator and can be fit to an exponential function, $I_{ion}(I_{filament})=\exp(-128.1+20.7\,I_{filament})$, where $I_{filamnet}$ and I_{ion} are in amperes, as shown by the solid line in Fig. 4. The strong dependence of the ion current on filament current results from the exponential relationship of the filament emission current with filament temperature in the thermionic emission process [10]. The solution that we chose to this control problem is the addition of a closed loop controller to keep the ion flux constant while linearizing the exponential dependence of the ion current on filament current, as described in the following section.

III. CONTROLLER DESIGN

The material evaporation rate is determined by the temperature of the evaporant source rod. The source rod temperature may be controlled by varying either the accelerating potential or the filament current (the latter varies the electron emission current bombarding the source rod). At first glance controlling the accelerating potential seems to be the easier solution, as the heating power of the source rod should be roughly linear in this variable. However, the calibration constant of the flux monitor inside the evaporator would change when varying the accelerating potential, due to changes in the evaporant ionization efficiencies and changes in the focusing properties of the e-beam on the source rod. Thus there would not be a linear relation between ion current and deposition rate, as observed in Fig. 2, if the acceleration voltage was varied to control the source rod temperature. Therefore we chose to servo the filament current while keeping the accelerating voltage constant. This was achieved with the addition of a closed loop controller to keep the ion flux constant while linearizing the exponential dependence of the ion current on filament current. Linearization of the ion current is accomplished by the minor addition of a logarithmic amplifier.

Figure 5 shows a simplified schematic of the controller and its attachment to the evaporator. The overall control scheme requires that the operator manually set the filament current to a level (up to 5 A, using the front panel mounted Filament Current Adjust Knob) that is slightly lower than that needed to achieve the correct ion current. The PID controller then takes over and adds to this a smaller filament current (up to 1 A) which is varied automatically to maintain the ion current at the setpoint. The small range of regulated filament current required is due to the narrow range where useful operation of the evaporator occurs, as shown in Fig. 4.

The first element in the loop is a current-to-voltage (I-V) converter which converts the ion current to a voltage with a gain of 1 V per 10 nA (a gain of 1V per 1 nA can also be used for lower flux rates by replacing the 100 MΩ resistor with a 1 GΩ resistor). The I-V converter also provides the necessary collector bias (about −25 V) to collect the ions. Here a high voltage op-amp [11] is used operating on a single −45 V power supply. This device has low input bias current FET inputs and a 90 V total power supply voltage rating. The next stage is a level shifter which converts the collector bias referenced I-V signal to a ground referenced, 0-10V signal required by the PID controller. A specialized difference amplifier

[12] is used in this case because of its large common mode input range of ±200 V. The PID controller [13] with setpoint programming is a front panel mounted instrument. While often used for automatic temperature control with a thermocouple input, these devices can be configured to accept an analog input voltage, which might represent a variety of process variables. The unit used is set for a 0-10 V input signal, representing the range of ion current, and provides a current output of 4 mA to 20 mA, which after suitable conditioning, controls the filament current. The PID controller converts the input to a digital value and updates the output level at an 8 Hz rate. The input resolution exceeds 15 bits and the output resolution is in the 13-14 bit range. It has a very powerful and reliable autotuning algorithm which determines the PID values on command. These factors make it extremely simple to introduce the controller into a slowly responding system to provide fully automatic closed loop operation. The 4-20 mA differential output current of the PID controller is converted to a 2-10 V signal using a 5k ohm resistor and a conventional instrumentation amplifier [14]. The next stage is the logarithmic amplifier that is used to linearize the control loop. Since the ion current varies exponentially with filament current, loop response linearization will occur by placing the logarithmic element anywhere within the loop. The decision to put the log amplifier after the PID controller is motivated by two factors, first the output resolution of the controller is less than half that of the input, and second, the ease of creating a zero offset (a necessary condition since Log(0) is undefined) by using the 4-20 mA controller output range instead of the alternately available 0-20 mA range. The logarithmic amplifier [15] converts the 2-10 V control signal to a 0-10 V signal which varies in accordance with the expression Vout=14.3Log[Vin/2 V]. The output of the Log amp is scaled and summed with

the front panel controlled filament current adjust signal to create the total filament current control signal. This signal drives the input of a transconductance or voltage-to-current amplifier which delivers the filament current. The transconductance amplifier is comprised of a high gain error amplifier [16], and a power operational amplifier [17]. The floating filament made it rather easy to insert a 0.1 ohm current sensing resistor in the return path and apply the developed signal to the inverting input of the error amplifier for feedback. This resistor sets the gain of the transconductance amplifier at 1 A/100 mV and should be connected using the four wire "Kelvin" technique to avoid extraneous voltage drops. This is easily done using special four lead current sensing resistor [18] with the sensing leads connected to a difference amplifier. Although the power op-amp requires bipolar power it is only necessary to have a high current positive power supply (12 V, 8 A) because the filament is driven with positive current. The negative power supply need only sink the device bias current which is about 100 mA. The power op-amp is mounted on a heat sink and a small fan provides forced air cooling. A high voltage power supply integral to the unit is adjustable from 0-2000 V from the front panel. Front panel mounted meters display the filament current, filament emission current, and source high voltage, as shown in Fig. 1.

IV. PERFORMANCE

The addition of the closed loop controller allows easy use and control of the e-beam evaporator. Operation requires setting the desired ion current on the PID controller unit and turning up the filament current to a value sufficient for the controller to yield the desired ion current. This is achieved by setting the filament current to give an emission current (monitored on the front panel meter) that is sufficient to heat the source. The duty-cycle of the PID controller is monitored by a push button on its front panel. Tuning the PID controller for the correct PID control values is done by putting the unit in auto-tune. With the addition of the log amp to linearize the control loop we find that the PID control values work well over the entire useful range of the evaporator, as shown in Fig. 3. Without the log amp we found that the PID control values needed to be adjusted depending on the filament current, which is expected given the exponential dependence observed in Fig. 4.

The regulation of the ion current by the PID controller is demonstrated in the following measurement. As shown in Fig. 6, the setpoint is initially set for 1 nA ion current and at ~5 s the setpoint was changed to 5 nA. The traces in Fig. 6 shows the ion current reading as the PID controller ramps up the filament current to reach the new ion current setpoint. Initially, a slight overshoot of the setpoint can be observed depending on the PID settings. Once regulation of the setpoint is achieved the ion current is observed to be extremely constant and stable. Deviations from the regulated value are about 0.05 nA p-p, and correspond to a flux stability of 1% over long time periods.

In summary, we have built a compact e-beam evaporator and designed a versatile closed flux loop controller that allow us to carry out studies of thin film Fe growth [19]. The e-beam evaporator and controller offer a wide range of fluxes, clean and easy operation, and can be built easily with commercially available components.

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identified in this paper is to specify experimental procedures. In no case does this identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

References

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5. Part number PM-50 port multiplexer from Kimball Physics Inc., Kimball Hill Road, Wilton, NH 03086.

6. Part number VZLM925 linear motion thimble from Kurt J. Lesker Co., 1515 Worthington Ave., Clairton, PA 15025.

7. Part number 670004 rotary motion feedthrough from MDC Vacuum Products, *op cit*.

8. Part number 7593-01-CF BNC electrical feedthrough on a 1.33 inch OD flange from Ceramaseal, PO Box 260, Route 20, Lebanon, NY 12125.

9. Part number 954-5143 12kV electrical feedthrough from Varian Vacuum Products, 121 Hartwell Avenue, Lexington, MA 02173.

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14. Part number AD620BN, Analog Devices, PO Box 9106, Norwood, MA 02062-9106.

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17. Part number LM12CLK, National Semiconductor, PO Box 58090, Santa Clara, CA 95052-8090.

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Figure Captions

1. Picture of compact UHV e-beam evaporator and closed loop controller.

2. Schematic diagram of the UHV e-beam evaporator.

3. Ion current measured at the collecting aperture of the e-beam evaporator versus deposition rate for an Fe source. The deposition rate was measured by a quartz crystal monitor positioned 13 mm from the end of the evaporator. The evaporator was operated by setting the setpoint of the closed loop controller for a given ion current for each point in the figure. The current-to-voltage convertor gain was 1 V per 10 nA, and the accelerating voltage was 2000 V. The solid line is a linear best fit to the data points yielding a slope of 5.6 nA/(nm min^{-1}).

4. Ion current measured at the collecting aperture of the e-beam evaporator versus filament current. The current-to-voltage convertor gain was 1 V per 10 nA, and the accelerating voltage was 2000 V. The solid line is a best fit to the log of the ion current vs filament current.

5. Schematic diagram of the closed loop controller and its connection to the e-beam evaporator.

6. Time dependence of the ion current after initially setting the setpoint of the controller to 1 nA and then changing the setpoint to 5 nA at ~5 s, for two settings of the current-to-voltage convertor gain; (solid line) 1 V per 10 nA and (dashed line) 1 V per 1 nA. The accelerating voltage was 2000 V.


FLUX CONTROL
POWER
EUROTHERM
R
M
OP1
OP2
A/M
PAR
BIAS
ADJUST
COLLECTOR
EMISSION CURRENT [mA]
FILAMENT CURRENT [A]
HIGH VOLTAGE [V]
FILAMENT CURRENT
ADJUST
HV ADJUST
NIST
E–BEAM EVAPORATOR
CONTROLLER

Figure 1

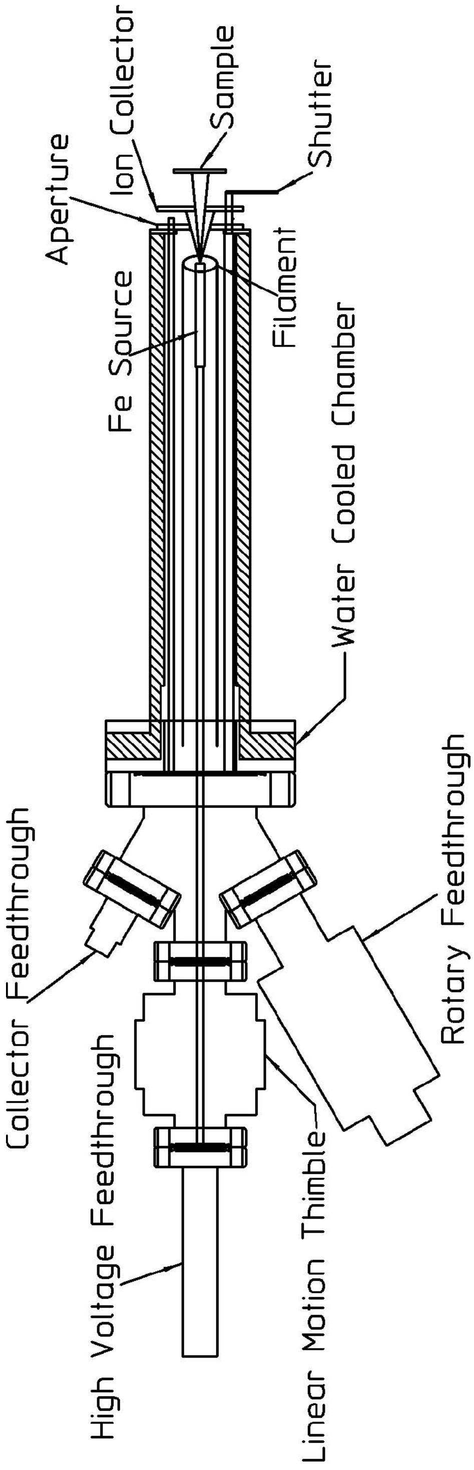
Aperture
Ion Collector
Sample
Shutter
Fe Source
Filament
Water Cooled Chamber
Collector Feedthrough
Rotary Feedthrough
High Voltage Feedthrough
Linear Motion Thimble

Figure 2

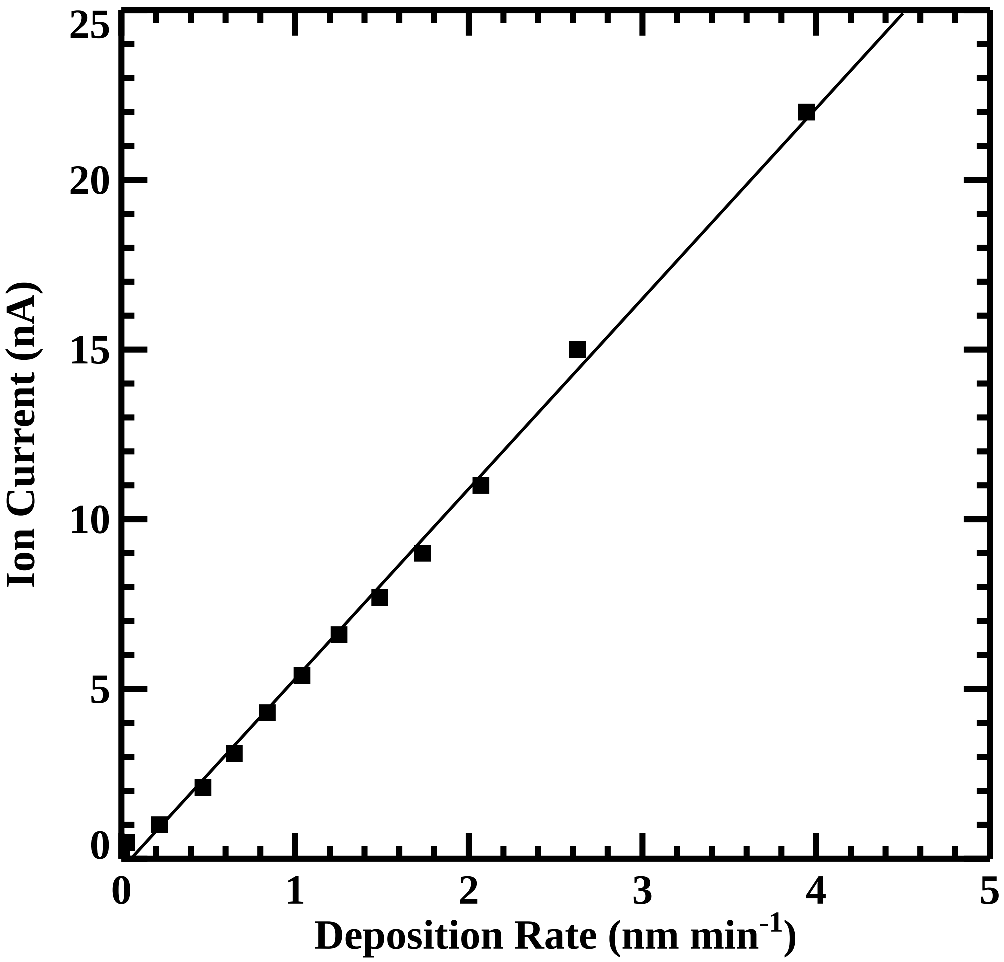

Figure 3

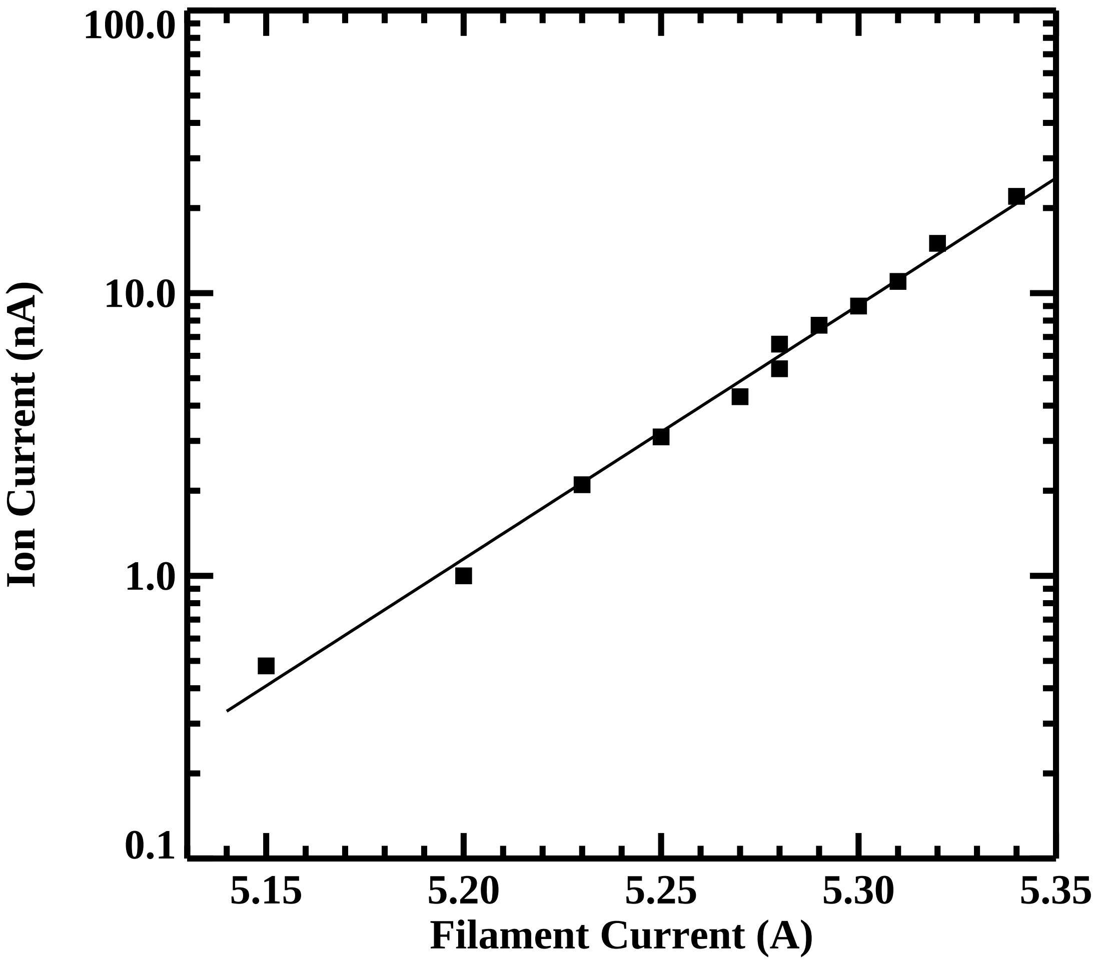
100.0
10.0
1.0
0.1
Ion Current (nA)
5.15
5.20
5.25
5.30
5.35
Filament Current (A)

Figure 4

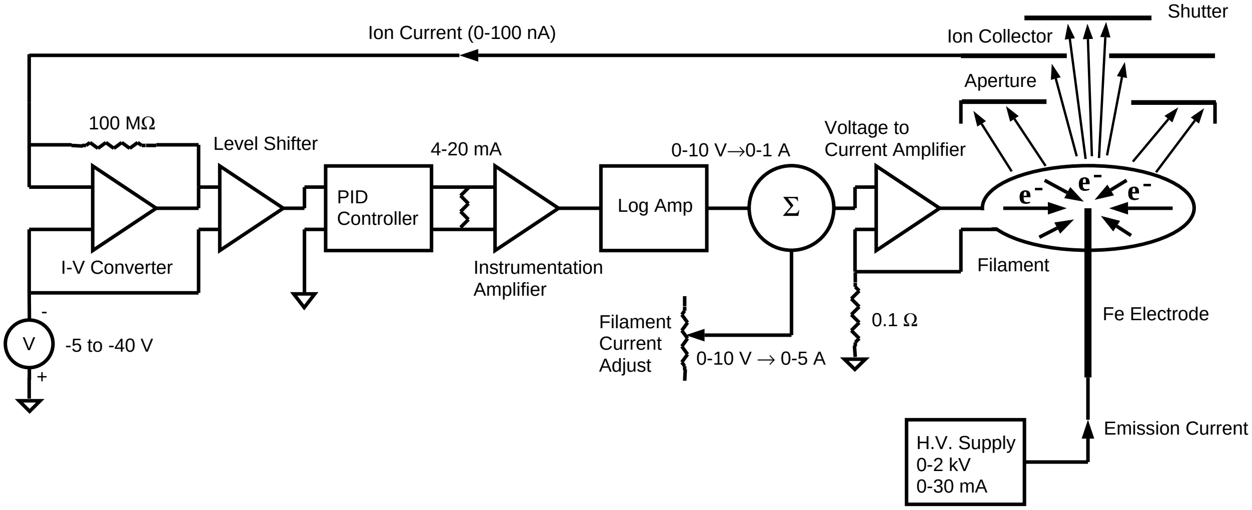
Shutter
Ion Collector
Ion Current (0-100 nA)
Aperture
100 MΩ
Level Shifter
4-20 mA
0-10 V→0-1 A
Voltage to
Current Amplifier
PID
Controller
Log Amp
Σ
e⁻
e⁻
e⁻
I-V Converter
Instrumentation
Amplifier
Filament
-
V
-5 to -40 V
+
Filament
Current
Adjust
0-10 V → 0-5 A
0.1 Ω
Fe Electrode
Emission Current
H.V. Supply
0-2 kV
0-30 mA

Figure 5

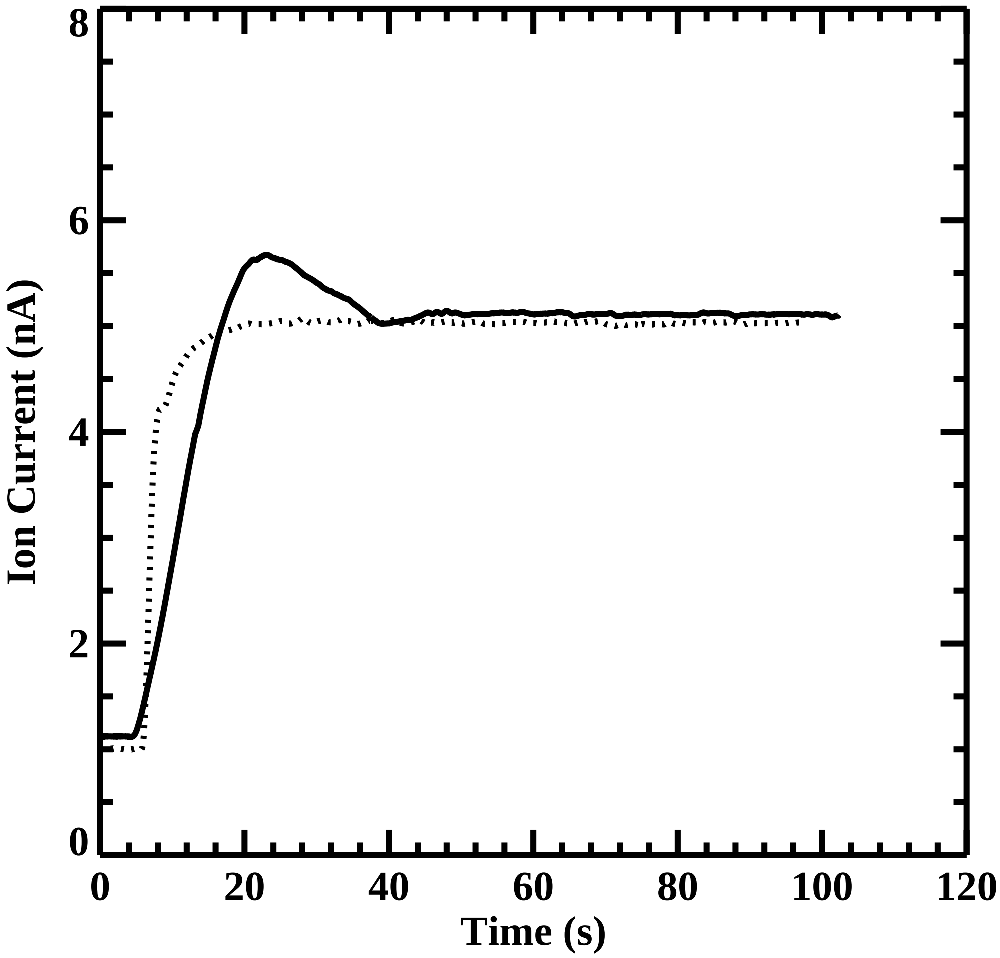

Figure 6