

## VII. GASEOUS ELECTRONICS\*

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#### A. ELECTRON DENSITY MEASUREMENTS IN CONTINUOUS ARGON ION LASERS

We are continuing our studies of the electron density in argon ion laser discharges. Several improvements have been made in our diagnostic equipment since our last report.<sup>1</sup> We present some preliminary results of measurements performed on continuous argon discharges.

##### 1. Steady-State Discharge Measurements

Figure VII-1 is a block diagram of the experimental apparatus used for determining the electron densities of steady-state plasma discharges. The measurements are termed steady-state to distinguish them from the investigation of transient behavior discussed below. The microwave signal input to the cavity was obtained by mixing the

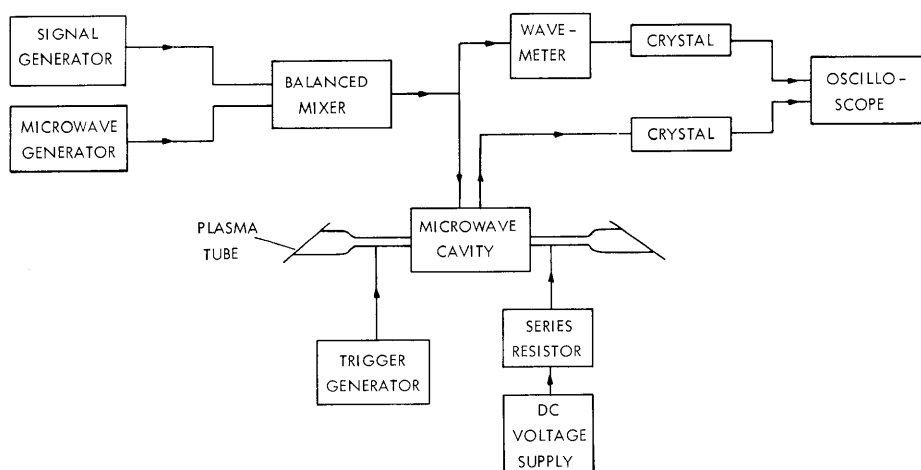


Fig. VII-1. Continuous-discharge experimental equipment.

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output of the microwave generator with that of a frequency adjustable signal generator (General Radio Type No. 1001-A). The microwave-generator output was held fixed, at a frequency of 5450.0 MHz. The signal-generator output was continuously tunable in the range 15-50 MHz. The sum and difference frequencies of these two sources appeared at the output of the balanced mixer, with only a very small (2%) amount of power at the microwave-generator frequency. Thus the sum frequency, having a tunable range of 5465-5500 MHz, was used as the input to the microwave cavity. The cavity output power was converted to a DC voltage by the crystal and displayed on an oscilloscope. The signal-generator frequency was adjusted to minimize the cavity output and, thus, the cavity resonance was found for a given plasma in the discharge bore. The resonant frequency was read from the signal-generator control dial within 0.2 MHz. The frequency measurement was calibrated by then adjusting the signal-generator frequency to the resonance of a reference cavity wavemeter and comparing the readings. The wavemeter was set at a fixed resonance of 5470.0 MHz and had an accuracy of 0.1 MHz.

The discharge current was varied by means of electrical resistors in series with the tube, at each of 5 pressures: 0.28, 0.56, 1.17, 2.5, and 4.7 Torr. Each density measurement was performed several seconds after incrementing the discharge current; hence, all transient discharge phenomena had subsided.

The measured data of the steady-state discharge is shown in Fig. VII-2. There, the electron density of the plasma is shown as a function of the discharge current, for several room-temperature filling pressures. The density was calculated from the measured cavity resonance shifts, under the assumption that the radial electron distribution was ambipolar diffusion-dominated.

As seen from Fig. VII-2, the three low-pressure curves show evidence of what is generally referred to as the discharge discontinuity.<sup>2</sup> This is a value of current, varying with tube radius and filling pressure, over which a discontinuity appears in the V-I characteristic and the intensity of spectral emission of the discharge. The present measurements indicate a similar break in the electron density-current relationship at the discontinuity. Stable operation in the regions marked by dashed lines was not possible, because of voltage limitations of the power supply. As the discharge current was increased, the discharge conductivity was found to discontinuously increase. While the exact nature of the discontinuity is not known, the data of Fig. VII-4 suggest that the instability involves primarily a change in the electron mobility rather than in electron density.

We feel that the curvature in the plot of density against current in Fig. VII-2, at 2.5 and 4.7 Torr pressures is the result of the reduction of the neutral density, because of gas heating. As the discharge current is increased, the temperature of the gas is raised, thereby producing the condition by which pressure balance with the anode and cathode

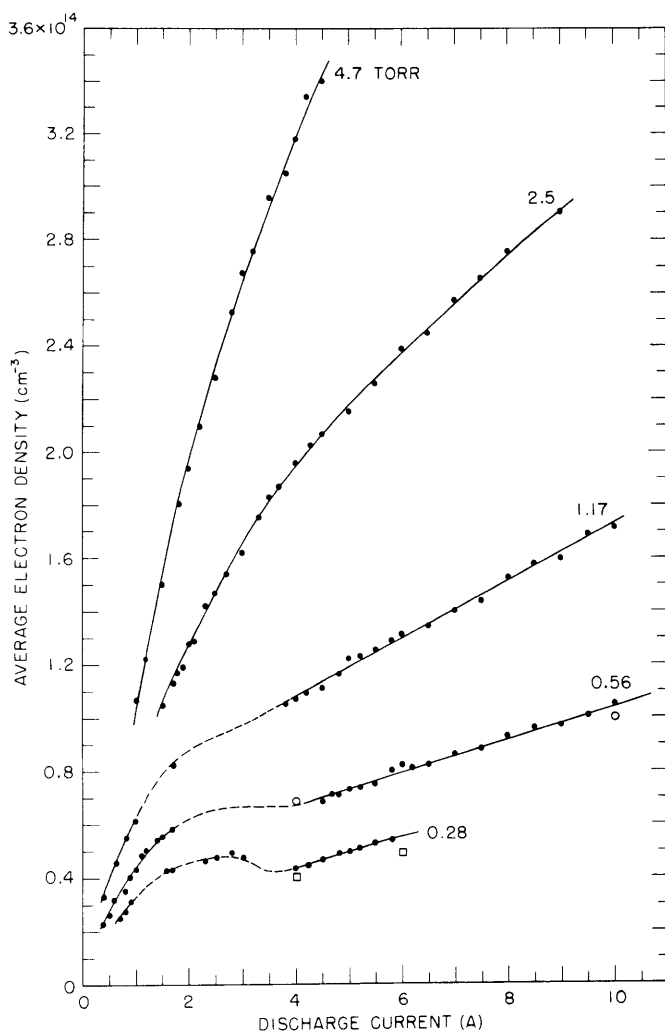


Fig. VII-2. Measured electron density vs cw discharge current.

regions drives gas out of the active plasma region.

The temperature of the coolant fluid was monitored during the course of the measurements and was found to rise from 60 to 110°F, as the current was increased over the measurement range. This temperature rise was not large enough to produce a significant change in the rate of electron recombination at the tube wall. The coolant temperature has a significant effect upon the dielectric properties of the coolant, however. We found that the "empty" cavity resonance, i.e., the resonance with no plasma generated, varied linearly with temperature and  $\Delta f_0/\Delta T = 0.02$  MHz/°F, over the temperature range stated above. The maximum shift was 1.0 MHz at 110°F. The data of Fig. VII-4 were corrected for this effect by compensating each plasma-cavity measurement at the temperature at which it was performed by the amount that the empty cavity resonance changed, at that temperature, from its room-temperature

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resonant frequency. In the correction we assumed that the relative shift in resonance from the empty cavity to the infinite plasma-cavity case, i. e.,  $f_m - f_o$ , is independent of the small change attributable to temperature in the coolant dielectric constant.

### 2. Time-Dependence Measurements

We investigated the initial transient behavior of electron density during the turn-on of the continuous argon plasma discharge. For this, the same experimental arrangement was used as in the steady-state measurements (Fig. VII-1), except that the trigger generator was also used here to trigger the oscilloscope trace as well as the discharge. The signal generator was pre-set to a given frequency value. With the turn-on of the discharge, the varying electron density produced a cavity-plasma resonance at the pre-set frequency. The density value corresponding to this frequency was calculated and, from the oscilloscope trace, the time at which the resonance minimum occurred was recorded. Figure VII-3 is an oscilloscope trace of the cavity output for the turn-on of

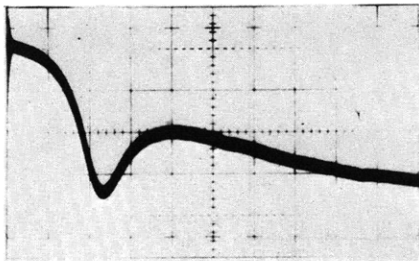


Fig. VII-3.

Oscilloscope trace of cavity output during cw discharge turn-on. Time scale: 5 ms/div.

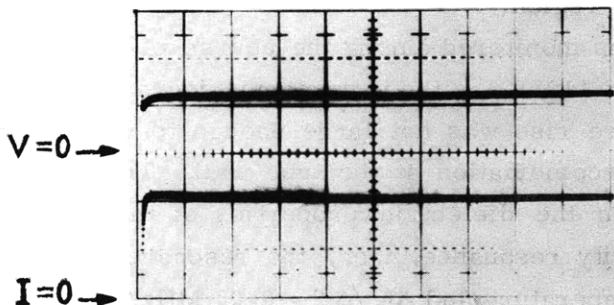


Fig. VII-4.

Oscilloscope trace of current and voltage of cw discharge turn-on. Upper trace: voltage, 200 V/div. Lower trace: current, 2 A/div. Time scale: 5 ms/div. Discharge pressure, 0.3 Torr.

a typical continuous discharge. Figure VII-4 shows the corresponding oscilloscope trace of the current and voltage of the discharge.

The measurements were limited to those discharge pressure and current

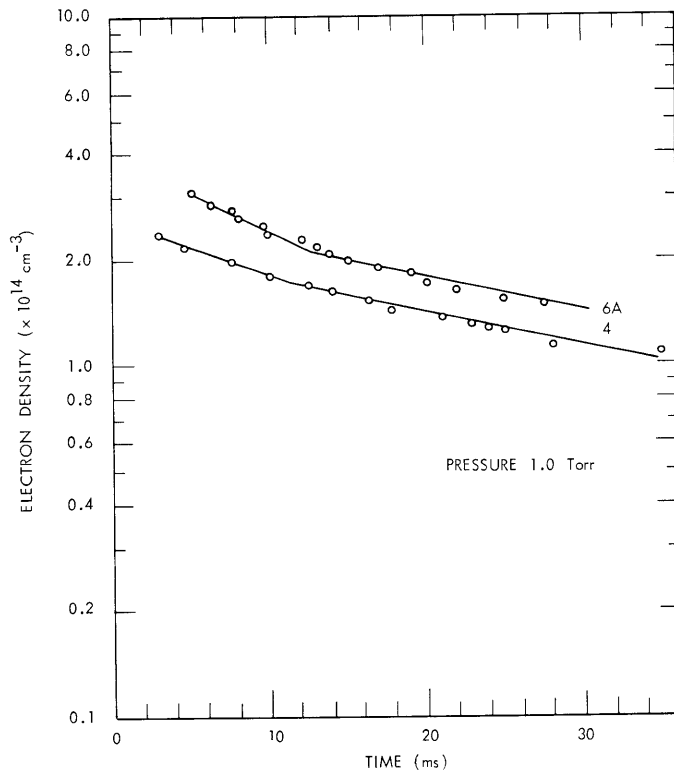


Fig. VII-5. Measured electron density vs time, for cw discharge at 1.0 Torr pressure.

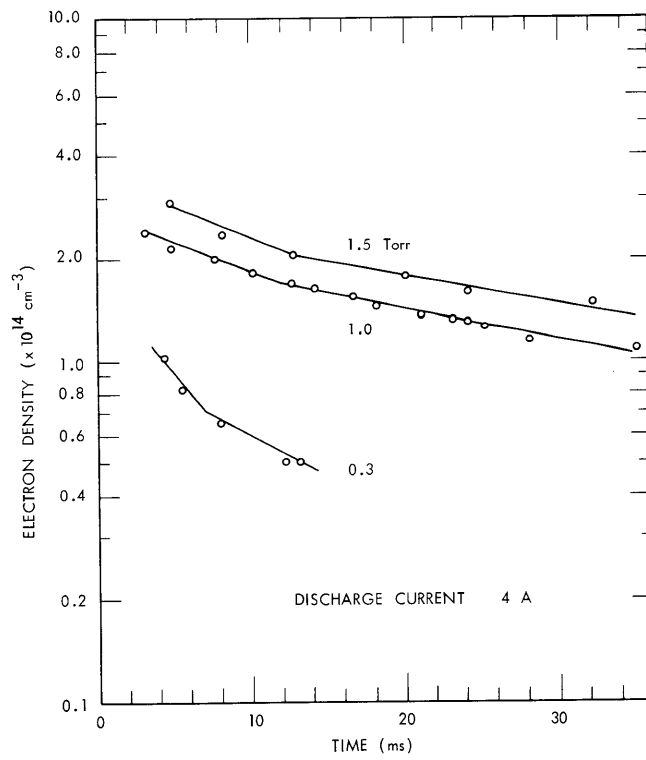


Fig. VII-6. Measured electron density vs time, for cw discharge at 4 A current.

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combinations that were found to give a monotonic rise in discharge current up to the steady-state value, without overshoot. This limit was imposed in order to observe the transient behavior of the electron density when the controllable discharge parameters were held constant. Reference is made to Fig. VII-4 which illustrates the type of initial current and voltage characteristics of the discharges upon which the density measurements were performed. The maximum variation in the steady discharge current was less than 5%.

Figure VII-5 shows the measured data of electron density as a function of time for two values, 4 A and 6 A, of the steady-state discharge current, at a pressure of 1.0 Torr. Figure VII-6 similarly shows the measured data for a discharge current of 4 A at 0.3, 1.0, and 1.5 Torr pressures.

The ringing of the circuit which was used to trigger the discharge did not allow the measurements to be performed at times less than  $\sim 3$  ms. As is seen from Figs. VII-5 and VII-6, the maximum number of plasma electrons were produced in the time  $0 \leq t \lesssim 3$  ms. At the time when the initial measurement could be made, the density had reached a value considerably greater than its ultimate steady-state value. The measurements show the temporal decrease in electron density from a peak value that occurred at some time,  $t \lesssim 3$  ms.

There appear to be at least two distinct decay periods of the electron density, characterized by different rates. From the data of Fig. VII-5, for  $p = 1.0$  Torr,  $I = 6$  A, the time dependence of electron density may be expressed as  $e^{-t/\tau}$ , where  $\tau \approx 33.9$  ms for approximately  $5 \leq t \lesssim 12$  ms, and  $\tau \approx 45.4$  ms for  $12 \lesssim t < 30$  ms. The steady-state value of density for this discharge was  $n_e = 1.23 \times 10^{14} \text{ cm}^{-3}$ , whereas the highest density measured (at 5 ms) was  $n_e = 3.25 \times 10^{14} \text{ cm}^{-3}$ . For  $I = 4$  A, the steady-state density was found to be  $0.95 \times 10^{14} \text{ cm}^{-3}$ , and the peak value (at 3 ms) was  $2.38 \times 10^{14} \text{ cm}^{-3}$ . The values of the two decay times for the 4 A discharge were:  $\tau \approx 26.2$  ms and  $\tau \approx 46.7$  ms for the intervals  $3 < t \lesssim 12$  ms and  $12 \lesssim t < 35$  ms, respectively.

At times greater than  $\sim 30$  ms the electron density reached a value within a few per cent of the steady-state value, and thus the resonance peak displayed on the oscilloscope screen (see Fig. VII-3) became broad and its time determination was difficult to measure.

G. J. Raff

### References

1. G. J. Raff and E. V. George, "Electron Density Measurements in Pulsed Argon Ion Lasers," Quarterly Progress Report No. 100, Research Laboratory of Electronics, M. I. T., January 15, 1971, pp. 122-125.
2. A. N. Chester, Phys. Rev. 169, 184 (1968).