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METAL VAPOR EXCIMER LASER

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Period August 1, 1977 - October 31, 1977

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I. INTRODUCTION

The present report covers the three month period from August 1, 1977 through October 31, 1977 in which we investigated, by modeling and simplified calculations, some of the constraints on achieving a quasi-stable discharge. The fabrication and initial testing for much of the experimental equipment has been completed. These efforts are detailed in the two major sections of this report.

II. SECOND QUARTER EFFORTS

A. MODELING AND CALCULATION

Three topics relating to producing a quasi-stable longitudinally pumped e-beam preionized discharge have been briefly investigated in this quarter. To produce a reasonable stable discharge for 0.5 to 1 μ sec with a short duration (~ 30 ns) preionizing e-beam pulse requires uniform energy deposition along the discharge length and a carefully controlled initial ionization level and applied electric field. We have considered three aspects of this discharge problem and have made some preliminary estimates in the sections below. In the first of these we discuss the longitudinal e-beam deposition for various buffers and suggest a way to achieve a reasonably uniform initial axial electron distribution. The second considers the preionization level necessary to achieve a sufficiently long-lived quasi-stable discharge given a uniform axial electron distribution while the last section discusses various buffer gas options from the point of view of efficient Cd^* production.

1. Energy Deposition and Recombination

In view of the predicted higher Cd^* production efficiency with heavier buffer gases, (see Section 3) we have looked more closely at the electron beam energy deposition problem, specifically at its axial uniformity and the resulting initial electron density. A nonuniform axial distribution of initial electrons will compound the difficulties in achieving a quasi-stable discharge by increasing the power loading in the lower density region thereby leading to an unstable discharge. Clearly a very high energy electron beam would bypass this difficulty. Unfortunately, we are operating with a finite energy beam which will produce significant variations along the discharge path with higher Z buffer gases. We consider here recombination as a means of reducing the axial variation, i.e., after the initial nonuniform electron distribution is created, one allows recombination (a nonlinear process) to "smooth out" the axial electron density variations before applying the discharge electric field. With delay times in the 30 ns range, we should obtain significant reduction in the axial variation while leaving sufficient ionization to produce the quasi-stable discharge.

These estimates for the energy deposition assumed a one-dimensional model in which no energy diffuses laterally from the beam. Experimentally we are heading in this direction by applying an axial magnetic field to confine the electrons to the discharge region. A more detailed calculation, which considers energy diffusing from the beam is planned. For the moment this cruder model will suffice to demonstrate the effects of recombination on the electron distribution. The results of the energy deposition calculation

are given in Figure 1; energy deposition vs distance along the discharge tube is plotted for a 600 keV beam passing through various buffer gas and mercury mixtures under conditions suitable for pumping the CdHg*. The first 20 cm of the curve represents the region between the beryllium foil (vacuum-metal vapor interface) and the start of the discharge region. From the energy deposition data and the Febetron's current density ($\sim 150 - 200$ A/cm² max), we can compute the secondary production rate, namely,

$$S_{eb} = \left(\frac{dE}{dx} \right) \cdot j / E_f \quad (1)$$

where dE/dx is the stopping power (V/cm), j the current density (amp/cm²), and E_f is the energy required per ion-electron pair. These are $\sim 42, 36, 26$ and 23 eV for helium, neon, argon and mercury, respectively. (1) The electron density created by the end of a rectangular e-beam pulse will be

$$n_o = \sqrt{\frac{S_{eb}}{\alpha}} \quad (2)$$

where α is the recombination coefficient and we have assumed that we are in the recombination dominated regime. The recombination coefficient, α , relates to the dissociative recombination processes

for example. We have assumed, for the moment, that the molecular ion formation is far more rapid than the recombination process, although we will be modifying the codes shortly to include finite formation rates. The rates for the above processes are similar: $7 \times 10^{-7} (T_e/T_o)^{-1/2}$ and $5.5 \times 10^{-7} (T_e/T_o)^{-1/2}$ cm³/sec for the argon and mercury, respectively, with $T_o = 400^\circ\text{K}$. Hence, we will use $6 \times 10^{-7} (T_e/T_o)^{-1/2}$ and assume an electron temperature of 1 eV during the e-beam on time, giving

$$\alpha \sim 1.1 \times 10^{-7} \text{ cm}^3/\text{sec}$$

When the pump pulse is turned off, recombination will proceed, lowering the local electron density via

$$\frac{dn_e}{dt} = -\alpha n_e^2 \quad (4)$$

which has the solution

$$\frac{1}{n_e} = \frac{1}{n_o} + \alpha t \quad (5)$$

Figure 1 Energy Deposition vs Distance Along E-Beam Path for Several Buffer Gases

Clearly, the electron temperature will be falling during this time leading to increased recombination rates. Assuming that it falls instantaneously to the ambient temperature, one obtains the fastest recombination and minimum delay time to reach a prescribed ionization level. Under the 900°K assumption, the recombination rate is

$$\alpha \sim 4 \times 10^{-7} \text{ cm}^3/\text{sec} \quad (6)$$

In Figure 2, we have plotted the electron density along the discharge tube for several times after the termination of the e-beam pulse; this data is based on the argon data in Figure 1.

As Figure 2 shows, the axial variation is rapidly reduced as the electron density diminishes via recombination. As mentioned above, a more detailed model including molecular ion formation is needed and is being developed; we will report on the calculation in subsequent reports.

2. Stability of Preionized Discharges

From a stability analysis recently completed it is clear that a pre-ionized (cadmium/mercury) discharge will always be unstable. The stability criterion developed, however, does not predict the temporal variation of the discharge current and secondary electron density. It may be possible, for example, to obtain quasi-stable operation in a preionized discharge for the duration of 1 μ s. To investigate this possibility we have numerically analyzed the following three equations:

$$\frac{dn_e}{dt} = S_{eb} \delta(t) + \nu_i n_e - \alpha n_e^2 \quad (7)$$

$$\frac{dCd^*}{dt} = K^* n_e Cd - Ku^{**} n_e Cd^{**} + k_D^{**} n_e Cd^{**} \quad (8)$$

$$\frac{dCd^{**}}{dt} = Ku^{**} n_e Cd^* - k_D n_e Cd^{**} - \frac{Cd^{**}}{\tau} \quad (9)$$

where

$$\nu_i = k^+ Cd^{**} \quad (10)$$

H3328

Figure 2 Axial Variation of Electron Density at Several Times After E-Beam Shut-Off for Argon Case of Figure 4. Rapid molecular ion formation assumed.

where n_e is the secondary electron density, ν_i the ionization rate, α the recombination rate, Ku^* the rate constant for electron impact excitation of Cd^* , Ku^{**} the rate constant for electron impact excitation of Cd^* to Cd^{**} , k_D^{**} the electron superelastic rate constant for the de-excitation of Cd^{**} to Cd^* , τ the lifetime of the Cd^* and Cd^{**} and k^+ is the electron impact ionization rate constant of Cd^{**} .

Figure 3 shows the numerical predictions for three different preionization pulses. In the top curve the discharge current decays during the time of interest. When S_{eb} is increased by a factor of two, a small current growth sets in at the end of $1 \mu s$. Finally, if S_{eb} is increased by another 25%, the current grows rapidly and the equations predict a volumetric instability after about $0.6 \mu s$.

For a more meaningful analysis, a complete knowledge of the kinetics is necessary. The results presented in Figure 3, however, shows that quasi-stable operation is possible in a preionized discharge.

3. Effect of Various Buffer Cd^* Formation Efficiencies

A buffer gas is necessary in the cadmium mercury system to make the three body formation rate for $CdHg^*$ sufficiently rapid to effectively compete with such processes as Cd^* loss via electron impact. Presently little is known about the $CdHg^*$ formation rate in the presence of noble gas buffers. From the point of view of uniform e-beam energy deposition, it is preferable to use a low Z buffer, e.g., He (see Section A.1). However, preliminary Boltzmann code predictions show that efficient creation of Cd^* requires high Z buffers which take up little energy via elastic scattering. Figures 4 and 5 show calculations of fractional energy deposited in Cd^* , Hg^* and He translational energy for an assumed mixture containing $2 \times 10^{17} \text{ cm}^{-3}$ Cd, $2 \times 10^{18} \text{ cm}^{-3}$ Hg, and $1 \times 10^{19} \text{ cm}^{-3}$ He. To minimize the energy deposited into Hg^* , electric fields of $\sim 500 \text{ V/cm}$ are required. At this field, about 50% of the discharge energy goes into direct He heating whereas, if the He is replaced by argon, only 7% of the discharge power is deposited into translational energy of Ar while nearly 90% results in Cd^* formation. Clearly Ar is a better buffer if efficient Cd^* production is pre-eminent.

It should be kept in mind, however, that the present experiment has the limited goal of determining gain in $CdHg^*$, and because of experimental limitations relating to uniform e-beam deposition, it may be most advantageous to use helium.

B. EXPERIMENT

1. Initial Discharge Tube and Oven Heating Test

The oven consists of a covered stainless steel box lined with "Dura-board" (Carborundum Co.) insulation two inches thick. At the junction between box and cover provision is made for the ends of the discharge tube, electrodes etc. to pass through snug-fitting holes in the insulation. A tube is provided at one end of the box to allow introduction of a purge flow of unheated nitrogen. During the test this flow was maintained at about 8 SCFH without apparent effect on temperature uniformity within the oven.

Figure 3 Discharge Current vs Time for Several Preionization Pulses, Each 30 ns Wide

Figure 4 Percentage Discharge Energy Deposited into Cd*, Hg* and He vs Electric Field

Figure 5 Percentage Discharge Energy Deposited into Cd*, Hg* and Ar vs Electric Field

The floor of the oven is covered with a sheet of copper 0.06" thick to which are attached three 600 W rod-type heaters. These are secured to the plate by clips, at about three inch intervals, and smeared with a high temperature grease to improve conduction into the plate.

The discharge tube is therefore heated by convection currents rising from the plate. The prototype discharge tube is installed in the oven as shown in Figures 6 and 7. Temporary window housings are attached at each end and a sealed steel tube added to simulate the Febetron gun attachment. This tube, together with the window housings and discharge tube, are connected to a 10 CFM vacuum pump which maintained an internal pressure below 1 torr.

The oven and discharge tube were fitted with an array of thermocouples as shown in Figure 6 and described below. Thermocouples were fitted on the upper and lower surfaces of the tube at each end and in the middle. The upper center one was used as the feedback to the heater control and the temperature at this point was read at the control panel. All the other temperatures were recorded on a "Speedomax Type G" strip chart. Four thermocouples were mounted at 1", 3", 5" and 7" (#9 through #12, respectively) above the oven floor to probe the vertical temperature gradient.

Three thermocouples were used to check temperature uniformity in the heater plate. Two were attached adjacent to the heater rod, one adjacent to a clip fastening the heater to the plate, one midway between two clips, and the third to the edge of the plate adjacent to the oven wall. A stainless steel extension tube, representing the Febetron connecting tube, was fitted with a thermocouple at the attachment flange inside the oven and another at the outboard end. This tube was blanked off at the flange end and evacuated as would be the actual tube.

A thermocouple was located on the electrode at the point where it emerges from the quartz tube. This placed it in the oven insulation about 1" in from the outer wall. Another was placed at the outboard end of the electrode. A thermocouple was also placed on the mounting flange just outside of the oven to ascertain if any temperature problems might arise in this area.

a. Test Results

The discharge tube was evacuated and the heater controller set at 490°C. Temperatures as a function of time are shown in Table I. A discrepancy was noted between the strip-chart recordings and the control panel indication. Subsequent to the test the strip chart recorder was recalibrated and the figures in Table I have been adjusted to compensate for the discovered error. The discharge tube exhibited a difference of temperature from top to bottom of 8-10°C and from end to end of 5°C.

To probe the effects that thermally induced refractive index gradients would produce, we filled the tube with nitrogen and carbon dioxide and passed a helium neon laser beam along the discharge tube's axis. In actual running conditions, the refractive index of the mercury, buffer gas mixture near 5000 Å would be approximately

Figure 6 Schematic of Discharge Tube Layout and Thermocouple Location for Heating Tests

Figure 7 Discharge Tube Mounted in Oven, Top Cover Removed

TABLE I
RESULTS OF FIRST HEATING TEST OF
DISCHARGE TUBE AND OVEN

Thermo- couple	Time -hrs	0.75	1.75	2.25	3.75	6.25	6.75	7.25	
		(°C)							
1		335	455	475	475	485	545	550	
2		353	465	485	485	490	555	550	
Control		365	470	485	480	496	550	550	
4		380	475	495	485	495	560	562	Discharge Tube
5		345	465	480	480	485	550	550	
6		360	475	490	485	493	560	560	
9		305	485	500	500	500	570	570	
10		305	475	495	495	495	563	565	Vertical Reading
11		380	475	490	490	495	560	560	
12		380	475	490	490	495	560	560	
3		420	495	510	510	515	575	575	
16		440	500	510	515	540	580	580	Copper Plate
17		440	500	510	515	540	580	580	
8		285	455	470	470	473	545	550	Febetron tube attach
13		20	20	25	25	25	30	30	outboard end of tube
7		170	345	357	375	375	413	420	Electrode-Inboard
15		20	20	20	20	20	25	25	Electrode-Outboard
14		20	30	30	35	40	45	47	Window Flange

$$(n-1) \times 10^6 = \frac{2 \times 10^{18}}{2.7 \times 10^{19}} \times 1885 + \frac{10^{19}}{2.7 \times 10^{19}} \times 284 = 245 \quad (11)$$

where the first term represents the refractive index of Hg at 2×10^{18} density and second is that for argon at 1×10^{19} density.⁽⁴⁾ For N₂ or CO₂ at 1 atm pressure and 550°C, the density is 9×10^{18} which gives an $(n-1) \times 10^6$ of 98 and 148 at 6328 Å, respectively. We were therefore within a factor of two of the expected refractive index. No motion or distortion of the laser beam was noted at either 500 or 550°C. One could clearly look down through the CO₂ filled tube and read finely printed material, thereby indicating that temperature uniformity was more than adequate for good medium quality.

After 6-1/4 hours of the test the heater controller was reset to 550°C and it can be noted that equilibrium was reached at all points, internal to the oven, within 1/2 hour. After the readings of 7-1/4 hours the heat and the purge flow were turned off and the oven allowed to cool. In about 20 minutes the temperatures had dropped by 120°C when the discharge tube fractured between the left hand electrode and the Brewster window. The protruding parts of the discharge tube are a snug fit in the rigid oven insulation and it seems probable that thermal distortions of the steel box could therefore apply bending stresses to the discharge tube and cause such a fracture. In future a flexible insulation will be employed at these locations to avoid repetition.

b. Conclusions

The design of the oven is satisfactory and achieved the aim of providing essentially uniform heating throughout. The outside of the oven became hot to the touch, estimated at 75-80°C and for future designs the thickness of the insulation will be increased to reduce this temperature further. This will minimize thermal distortions which, in conjunction with soft insulation at the feed-through points, should eliminate a repetition of discharge tube breakage. The external connections (mirrors housing, Febetron interface) maintained a low temperature and no additional precautions will be necessary at these locations.

2. High Temperature Vapor Supply Test

The initial version of the vapor supply and its oven has been fabricated and heating tests without cadmium or mercury were performed. The supply consists of two sections, one housing the cadmium and buffer gas supply, the other containing the mercury. Both sections are enclosed in a stainless steel box lined with "Duraboard" (Carborundum Co.) insulation 2-inches thick.

There are three independently controlled heaters within the oven, one in each copper block housing the cadmium and mercury supply bottles and a third, consisting of high temperature heating tape which heats the

vacuum lines and valves. Since the portion of the valve assemblies must pass through the oven walls into room temperature air, we have fitted each valve with low conductivity, extension support rods and control stems (these connect with pneumatic actuators) which reduce heat loss and allow nearly all the valve assembly to be placed within the oven. Figure 8 shows the oven layout with the location of the heater and control thermocouples.

In this initial temperature uniformity test, we measured the temperature at the 15 points shown in Figure 8. We were striving for a 500°C temperature in the cadmium supply area while maintaining 300°C in the mercury zone. This test showed that the valve bodies (and also the bellows within) were running 60°C cooler and would therefore determine the cadmium density as it condensed in the bellows. We also noted that the mercury supply temperature did not respond to its controller since the heat loss from the cadmium portion into the mercury supply was setting the temperature. Better insulation for and a larger heat leak from the mercury supply zone are needed.

We have nearly completed an improved version of the vapor supply which incorporates a distillation section and improved heating capability. The heating tapes have been removed and a large, heated copper plate has been installed on the oven floor to provide a large area, uniform heating surface for the valve bodies and lines. This technique has proved very successful in the discharge tube oven (see discussion above). Furthermore, each of the valve bodies has been coiled with a metallicly sheathed heater to insure that the bellows assemblies remain above the controlling temperature in the oven.

The vapor supply has not yet been tested with mercury or cadmium. A key issue is to what extent the valves sealing capabilities will be diminished by any corrosion caused by cadmium or mercury. This will be the primary test upon this newer versions completion.

3. Temperature and Vacuum Control Circuitry

During this period the control circuitry was completed, tested and used in the high temperature vapor supply tests. The control system is now fully operational.

4. Magnet Test

We checked the high temperature resistance and the magnetic field of a single element of the multi-element magnet assembly. The magnet consists of 2" wide by 0.06" thick copper strap, insulated by glass tape, wound into a 16 turn coil with dimensions: 5" OD and 2.5" ID.

The resistance measurements were made at several temperatures using a 0-40 ampere dc power supply and a digital millivolt meter. Table II gives the measured resistance. We cycled the magnet between room temperature and 550°C several times with no ill effects; some cupric oxide

Figure 8 Layout of Vapor Supply Oven with Temperature Recorded During Heating Test

TABLE II
HIGH TEMPERATURE MAGNET COIL RESISTANCE TESTS

<u>Temperature (°C)</u>	<u>Measured R (mΩ)</u>
200	1.27 ± .13
300	1.94 ± .19
350	2.30 ± .23
555	3.15 ± .31

formed at the exposed terminals, although it did not affect our resistance measurements; the oxide was easily removed with light sanding.

The on-axis magnetic field was 1.7 G/A which will be higher when the full solenoid-like array is assembled. With the 80 V-1200 A capacity power supply, and the 3 m Ω resistance at 550°C, we will be able to produce magnetic fields greater than 2000 G.

The control circuitry for the large magnet supply is being fabricated; it will be ready to accommodate the supply delivery schedule which has been pushed back by the vendor to the second week in December.

III. SUMMARY

Achieving a quasi-stable discharge will probably require operating with initial electron densities in a narrow range near 10^{14} electrons/cm³. To obtain a uniform density of this magnitude along the full length of the discharge region, we propose allowing recombination to "smooth out" axial variations resulting from the nonuniform energy depositions of the e-beam. Using a low Z buffer will reduce this axial variation in energy deposition, at the cost of decreasing the efficiency for Cd* formation in the discharge. At the moment, since our prime interests are establishing the existence of gain, picking the low Z buffer and increasing the chances for achieving relatively stable discharge operation appears to be the most profitable path.

On the experimental side, a good deal of the equipment is fabricated and has survived preliminary temperature tests without cadmium or mercury present. The principal efforts in the next quarter will be checking the survival with both these corrosive materials present.

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