METAL VAPOR EXCIMER LASER

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I. INTRODUCTION AND SUMMARY

In the period covered by this report, we have reached the final construction stages of the Cd:Hg experiment. The major accomplishments were in the experimental areas where we have completed the vapor supply oven, tested the guide magnet assembly, and have begun tests on the electron beam energy deposition with the Febetron 736.

In terms of discharge/kinetic modeling, we have further investigated the matter of recombination "smoothing" discussed in the last Quarterly. We have found that the degree of axial electron density "smoothing" arising from recombination depends on both the electron-ion recombination and molecular ion formation rates: the slower the molecular ion formation rate relative to the electron-ion recombination rate, the lesser the degree of smoothing. We have found, with a simple model, that recombination "smoothing" can still be significant in the Cd:Hg experiment, although a precise estimate is difficult to achieve since the effect depends strongly on the rates (and their temperature dependence) which are not well known.

II. THIRD QUARTER EFFORTS

A. EXPERIMENT

1. Vapor Supply Test with Cadmium and Mercury

We have made an initial test of the vapor supply at temperature with cadmium and mercury present and found only negligible corrosion on some of the O-rings used in the vacuum couplings. The present vapor supply is the improved version discussed in the last quarterly report; it incorporates controllable heaters on the valve bodies and a large copper base plate to achieve uniform heating throughout the oven. In addition, this supply has the capability to distill either the mercury or cadmium from a "raw" supply bottle to a "clean" source bottle for experiments. Figure 1 shows a drawing of this new arrangement.

Before we made the vapor tests, we had two problems with the oven. The stainless steel, pneumatically actuated valves would occasionally stick in either an open or closed position. This problem was not related to metal vapor attack since the problem appeared before cadmium or mercury were added to the system. In cutting one of the valves in half, we noted scoring of the interior surface against which the valve plunger slid. The scoring was not the fault of metal chips entering the valve during our assembly, but seemed to be related to internal problems with the valve, perhaps poor quality control. We have had to change three of the four valves on the system; the problem has disappeared for the present time.

The second problem that caused additional delays was the burning out of the metal sheathed heater used on the valve bodies and copper base plate.

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Figure 1 Drawing of Vapor Supply Oven

Each heater is rated at 600 W and is 0.09" in diameter and 36" long. These heaters are attached to the valve bodies and copper base plate by brazing along their entire length. We found that the heater burnout always occurred at a point where the brazing had a gap or near the heater end near the electrical connections where we did not braze for fear of destroying the insulation on the electrical connections. At these points where heat transfer was not good, the heaters glowed red and eventually burned out. We have solved the problem by more careful brazing to the object being heated. With the heater and valve problems eliminated, we were able to maintain the system at $575 \pm 10^{\circ}\text{C}$ and sufficiently low pressure ($\sim 30 \mu$) to conduct the vapor tests.

Each of the supply bottles was filled with a small quantity of cadmium or mercury and the cadmium and helium supply portion of the oven heated to 575°C while the mercury supply was maintained at 300°C . In this test the system was exposed to either cadmium and mercury, but not both simultaneously. The valves in both compartments were opened and closed several times to insure that all interior surfaces of the bellows valves were exposed to the metal vapors. No leaks or vacuum failure developed at any point in the system after running for eight hours at densities of $6 \times 10^{17}/\text{cm}^3$ and $4 \times 10^{18}/\text{cm}^3$ for cadmium and mercury, respectively. After the system cooled, several of the metal O-ring sealed connections were broken to check for corrosion. The stainless steel O-rings showed only minor etching of their surfaces after exposure to cadmium at 575°C ; this indicates that maintaining the vacuum system integrity should be less of a problem than initially assumed.

2. Magnetic Field Tests

In order to reduce losses of the preionizing e-beam due to scattering into the discharge tube walls, an axial magnetic field will be used. This same field will guide the e-beam through a 45° angle to permit measuring optical gain along a longitudinal path (see Figure 2). The field strength should be sufficiently large to produce a Larmor radius small compared to the discharge tube radius which in the present tube design is 14 mm. Figure 3 displays the distribution of Larmor radius resulting from 500 keV electron scattered from the 3 mil titanium foil of the Febetron.

To produce the guide field, we are using the arrangement of magnet shown in Figure 2. In addition, there are magnets not shown which extend from the discharge tube to the Febetron along the 45° side area.

Each of the magnets in the straight section consists of 16 turns of 2" x 0.06" glass tape insulated, copper strap wound into an annular shape with 2.5 and 5.0" interior and exterior diameters, respectively. These coils are mounted coaxially and spaced by one inch. The two magnets in the 45° bend section also have 16 turns of the same strap, but are wound in an oval fashion to provide clearance for the section containing the Brewster window. The magnets are connected in series with a power supply capable of delivering 2000 amps at 90 V for several seconds. For the 40 cm discharge configuration, 12 magnets are required; 10 of these magnets have $3.1 \text{ m}\Omega$ resistance at 550°C while the two larger magnets used in the 45° section have a total resistance of $10 \text{ m}\Omega$ for a total resistance of $41 \text{ m}\Omega$. At 2000 amps, therefore, the voltage required will be 82 V which is within the capabilities of our supply. At these high current conditions, the magnet temperatures will rise at $20^\circ\text{C}/\text{sec}$.

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Figure 2 Magnet Assembly for Hg:Cd Experiment

Figure 3 Larmor Radius as a Function of Angle for 500 keV Electrons and Angular Distribution of Electron Scattered from Febetron Titanium Foil

We have measured the magnetic field over a 39 cm length and 2 sq cm area in the straight section of the magnet assembly. These measurements were made at 250 amps at room temperature to keep the magnet heating low. Figure 4 shows the axial variation of the magnetic field; except near the ends of the six magnet test section the field varies by $< \pm 6\%$. In Figure 5, one can see the transverse variation for two planes perpendicular to the magnet axis: the first plane passes through the mid plane of a coil while the second represents the field behavior midway between two coils. Once again the variations are quite small and would lead to negligible variations in the Larmor radius.

We have calculated the magnetic field pattern in the 45° bend section using a 3 dimensional code. Figure 6 shows the magnetic field lines in a plane passing through the center of all magnet coils when the coils are carrying 1000 amps. In the bend section, the field will be smaller than the maximum field by $\sim 25\%$, i. e., 1750 gauss compared to 2400 at 1000 amps. The Larmor radius will also increase to by 25%, but fortunately, the larger Larmor radius occurs where the discharge tube has the largest dimension and losses due to the reduced field should be small. We are beginning e-beam guiding experiments to substantiate these calculations.

3. E-Beam Energy Deposition Tests

After checking out the recently installed Febetron 736 e-beam (see Table I for characteristics) we made several measurements of the e-beam penetration in helium and argon with and without a guide magnetic field. These tests were made with the configuration shown in Figure 7.

Figure 4 Axial Variation in Magnetic Field for Straight Magnet Assembly

ALL FIELD VALUES IN GAUSS
MAGNET CURRENT = 250 AMPS

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Figure 5 Transverse Variation in Magnetic Field for Straight Magnet Assembly. Measurements made in two planes shown.

Figure 6 Magnetic Field Distribution in Bending Section. All fields are measured in gauss.

TABLE I
FEBETRON 736 E-BEAM CHARACTERISTICS

Maximum electron energy:	500 keV
Maximum electron penetration in water:	1.8 mm
Peak output current:	1000 A
Beam energy per pulse:	12 J
Maximum energy density:	2 J/cm ²
Pulse duration, half peak power:	16 ns
Maximum dose per pulse:	10 ⁶ rads
Maximum peak dose rate:	3 x 10 ¹³ rads/sec
Dose per pulse 12" from window:	3 x 10 ⁴ rads
Pulse-to-pulse reproducibility of maximum dose:	± 3% rms

Figure 7 Schematic of Calorimeter and Straight Magnet Assembly for E-Beam Energy Deposition Tests

The energy remaining in the e-beam after it traversed a given length was measured by a pair of aluminum calorimeters mounted on the face of a plastic piston which moved within a long, vacuum-tight plastic cylinder; this cylinder was positioned coaxially within the eight magnet assembly (see Figure 7) which could produce fields up to 5000 G. Each of the calorimeters was made of 1 mm thick aluminum to insure stopping the e-beam (see Figure 8) while reflecting a small fraction of the incident beam (reflection coefficient $\sim 16\%$). One of the calorimeters, a 3 mm disk mounted on the cylinder axis, measures the axial energy density while the larger, annular calorimeter (ID = 4 mm, OD = 22 mm) intercepts nearly the full beam to yield total energy remaining in the beam. Both calorimeters were fitted with chromel-alumel thermocouples whose leads ran through a brass tube which was used to position the calorimeter. The output from each calorimeter was recorded by a pair of Keithley microvoltmeters coupled to a fast chart recorder. Table II gives the relationship between voltage levels and energy stopped in each calorimeter.

At small distances between the foil and piston, signals were very large and easy to interpret (see Figure 9a). At larger distances (and correspondingly lower signals), spurious signals arising from a combination of magnet heating and transient, magnetic field induced voltages became significant (see Figure 9b). The high currents required to produce sufficient magnetic fields lead to rapid magnet heating ($\sim 20^\circ\text{C}/\text{sec}$) and subsequent heating of the buffer gas in contact with the calorimeter. In addition, there is electrical pickup produced by small loops in the thermocouple leads. In spite of these noise sources reasonably good data over nearly 2 orders of magnitude was still possible.

Figure 8 Range of Electrons in Aluminum vs Energy

TABLE II
RELATIONSHIP OF ENERGY STOPPED IN CALORIMETER AND
SIGNAL OUTPUT

Q = Total energy in e-beam (joules)

A = Calorimeter area

t = Calorimeter thickness (0.1 cm)

ρ = Aluminum density (2.7 gm/cm³)

C_p = Aluminum specific heat (0.91 J/gm)

B_A = Aluminum backscatter correction factor (1.16)

K = Thermocouple sensitivity (0.025°C/μV for chromel-alumel)

V = Thermocouple voltage (μV)

$$Q = V \times K \rho t A C_p \cdot B_A$$

$$Q = 7.4 \times 10^{-2} V(\mu V) \cdot t \cdot A \text{ joule}$$

$$\frac{Q}{A} = 7.4 \times 10^{-2} V(\mu V) \cdot t \text{ joule/cm}^2$$

Figure 9a High Level Calorimeter Signal Including Transient Magnetic Field Induced Noise

Figure 9b Low Level Calorimeter Signal. Both transient magnetic field induced noise and magnet heating signal apparent.

The data in Figures 10 and 11 represent the energy stopped in the two calorimeters after a 450 keV e-beam has passed through the given length of argon gas at 1 atm. The calorimeters were contained within a pyrex tube with a 3 cm internal diameter. It is clear that the magnetic field (~ 4500 G) significantly reduced the energy loss -- both in terms of the on-axis energy density (central calorimeter) and the total energy (annular calorimeter). The energy density at $Z = 0$ corresponds to 0.5 J/cm^2 and falls to 0.05 J/cm^2 at 50 cm. The oscillation, more pronounced in the central calorimeter, is quite repeatable and has the periodicity of the magnet assembly. The magnitude of the oscillation is larger than one would expect based on the axial variation measured and discussed above. We will investigate this further in the next quarter along with the effect of varying tube diameters on the rate of e-beam energy loss.

Plotted on Figure 11 is a one-dimensional calculations for the energy remaining in the e-beam after traveling a given distance in 1 atm of argon. The calculation was scaled by a single multiplicative factor to adjust for total beam energy. This model assumes no walls and, therefore, no wall losses. The good agreement suggests that the Larmor radii must be sufficiently small to minimize losses at the walls.

4. Discharge Circuitry

Our initial design called for producing a 1 kV/cm discharge over a 40 cm length. We now have all the components, i.e., capacitors, spark gap and power supply to produce 50 kV pulses. We also have an extra capacitor and spark gap, but would require a higher voltage supply to boost the pulse capability to 100 kV if the need arises. We will trigger the discharge with a fast, high voltage pulse from an Ion Physics Mini-Marx which can

Figure 10 Axial Calorimeter Signal as a Function of Distance From Foil for a 450 keV E-Beam Passing Through 1 atm Argon. Tube internal diameter = 3 cm.

Figure 11 Annular Calorimeter Signal as a Function of Distance From Foil for a 450 keV E-Beam Passing Through 1 atm Argon. Tube internal diameter = 3 cm.

produce up to 100 kV pulses with a 3 ns risetime. Assembly of the discharge circuitry awaits final installation of the discharge tube oven.

5. Dye Laser Probe

We will use a tunable dye laser pumped with a pulsed nitrogen laser as the probe in the gain experiment. This system is an Avco Dial-a-Line unit which can operate in the 4500-5000 Å range producing 3 ns wide, kilowatt pulses with linewidths of several angstroms. This unit is operating; the beam directing optics are in-house but not yet assembled.

B. MODELING AND CALCULATIONS

In the last report, we discussed the possibility that recombination could reduce axial variations in the e⁺ beam produced electron density and thereby reduce the likelihood of producing an unstable discharge. That conclusion was based on the assumption that molecular ion formation was rapid compared to recombination. In this section we extend the calculations to include the effects of a finite molecular formation rate.

Assume a four component system: electrons, atomic ions, molecular ions, and neutral atoms which can serve as a buffer. An e-beam produces electrons with a constant source function S_{eb} for a period τ_p and then shuts off. Recombination is assumed to occur only through a dissociative-recombination step (rate constant α) while the molecular ion formation is controlled by a three-body rate constant, K_F . The resulting equations are

$$\begin{aligned} n_e &= S_{eb} (\theta(t) - \theta(t - \tau_p)) - \alpha n_e n_m \\ n_I &= S_{eb} (\theta(t) - \theta(t - \tau_p)) - K_F n_I N^2 \\ n_m &= K_F n_I N^2 - \alpha n_e n_m \end{aligned}$$

where n_e , n_I , n_m , and N are the electron, atomic ion, molecular ion and neutral densities, respectively. The recombination rate α is assumed constant for $t < \tau_p$, but for $\tau_p < t$, α is allowed to vary since the electron temperature is falling as described below. With the e-beam on, an electron temperature of 1 eV is assumed; with the e-beam off, the temperature is assumed to drop as $\exp - (\nu_e 2m_e/M t)$ where ν_e is the elastic collision rate between electrons and neutrals and m_e/M is the ratio of electron to neutral masses. In a mixture typical for this experiment, i.e., 1×10^{19} argon/cm³ and 2.0×10^{18} mercury/cm³, electron cooling will be dominated

by electron-mercury collisions largely due to the Ramsauer minimum in the electron-argon cross section. Near 1 eV the cross section for e-Hg collisions is $\sim 3 \times 10^{-14} \text{ cm}^2$ (1) which yields a ν_e of

$$\nu_e = n_{\text{Hg}} \sigma \nu_e \approx 4 \times 10^{12}$$

and an electron temperature decay rate of

$$\gamma_{\text{tme}} = \frac{2m_e}{M_{\text{Hg}}} \nu_e = 2.1 \times 10^7 \text{ sec}^{-1}$$

A major uncertainty in this model is the recombination coefficient's dependence on electron temperature. We have scaled the Hg_2^+ recombination rate by two methods:

$$\alpha_1 = \alpha^0 \left(\frac{T_e^0}{T_e} \right)^{1/2}$$

and

$$\alpha_2 = \alpha^0 \left(\frac{T_e^0}{T_e} \right)^{.7} \left(\frac{T_g^0}{T_g} \right)$$

where the first is the simple theoretical scaling taking only the electron temperature into account and the second assumes the strongest dependence based on both theoretical and empirical grounds. (2) From Biondi's 1953 paper, (3) $\alpha = 5.5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ for Hg_2^+ at $T_e^0 = T_g^0 = 400^\circ\text{K}$, which would yield

$$\alpha_1 = 1 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$$

and

$$\alpha_2 = 2.4 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$$

at $T_e = 11,000^\circ\text{K}$ (1 eV) and $T_g = 900^\circ\text{K}$. The following calculations will use these two different temperature scaling approaches.

The three body formation rate, K_F , was taken as either $1.2 \times 10^{-31} \text{ cm}^6/\text{sec}$ or $2.5 \times 10^{-31} \text{ cm}^6/\text{sec}$ and a density of $1 \times 10^{19} \text{ atm/cm}$ was assumed.

Since we are modeling the multi-component system by a single atomic species, we chose a range of formation rates, typical of Hg_2^+ ,⁽⁵⁾ to check the sensitivity of the "smoothing" to 3-body formation rate. The results of these calculations are shown in Figures 12 and 13.

The curves represent the time variation of the electron density produced by a 25 ns wide, rectangular e-beam pulse yielding a source function of 2, 8, and 32×10^{22} electrons/cm³-sec. This range approximates the maximum difference in pumping that one might obtain in a 1 meter path length in a typical Cd:Hg:Argon mixtures at a total density of 2×10^{19} /cm³. Figure 12, in which the recombination rate is scaled as $T^{-1/2}$, demonstrates that a finite molecular ion formation rate reduces the smoothing effects, and moreover, the extent of the smoothing depends significantly on the magnitude of K_F . For the "worst" case in which S_{eb} varies by a factor of 16, recombination with $K_F = 2.5 \times 10^{-31}$ cm⁶/sec yields an electron density ratio of 5.8:1 at 140 ns. (This time was chosen since the lowest electron density we believe to be usable is approximately 6×10^{13} electrons/cm³), while the $K_F = 1.2 \times 10^{-31}$ cm⁶/sec case leads to a larger ratio, 13:1 at 200 ns. Clearly we are in a range where precise information about these rates is critical in determining the effectiveness of recombination smoothing.

The smoothing's dependence on K_F is even stronger in Figure 12 where the temperature scaling of the recombination coefficient is $T_e^{-0.7} T_g^{-1}$. Here, for a factor of 16 difference in S_{eb} , $K_F = 2.5 \times 10^{-31}$ cm⁶/sec yields an electron density ratio of 3.5:1 at $t = 180$ ns while $K_F = 1.2 \times 10^{-31}$ cm⁶/sec produces a ratio of 13:1 at 200 ns. Once again a minimum electron density of 6×10^{13} /cm³ was assumed.

Figure 12 Electron Density vs Time Produced by a Rectangular E-Beam Pulse ($\tau_p = 25$ nsec) for Several Pump Rates and Molecular Ion Formation Rates. Recombination coefficient α scales as $T_e^{-1/2}$.

Figure 13 Electron Density vs Time Produced by a Rectangular E-Beam Pulse ($\tau_p = 25$ nsec) for Several Pump Rates and Molecular Ion Formation Rates. Recombination coefficient α scales as $T_e^{-0.7} T_g^{-1}$.

These calculations demonstrate that we are operating in a regime where significant improvement in axial electron density uniformity can be achieved by recombination, although the specific extent of this improvement is difficult to gauge because of the large uncertainties in the relevant rates and their specific temperature dependences.

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