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E-BEAM HCl LASER

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E-BEAM HCl LASER

I. SUMMARY

Of the infrared transmission windows existing in the sea-level atmosphere which are of interest for Navy and DoD applications, only the 3.5 - 4.0μ band lacks a corresponding efficient electric-discharge laser source. The research program described herein attempts to determine if the gaseous hydrogen chloride medium, under suitable electronic excitation conditions, can provide stimulated emission in this wavelength region. The reported study seeks to determine the feasibility of such an HCl laser source by means of combined theoretical and experimental investigation. The results of the theoretical study have been previously reported.

Briefly, on the basis of theoretical interpretation of available electron-HCl collision data, a comprehensive numerical analysis of electron-HCl excitation processes has been conducted. These studies have resulted in the determination of a self-consistent set of electron-HCl cross sections for elastic, rotational, vibrational, and electronic processes. The cross sections for vibrational excitation are found to be particularly large, over a relatively broad range of discharge conditions, a condition compatible with very efficient ($>50\%$) electron excitation of the vibrational energy mode of HCl. The theoretical analysis also indicates a substantial electron dissociative attachment rate in the electronegative gaseous HCl medium. Substantial electron number densities may be required for significant vibrational excitation, requiring high electron beam current densities.

During the present reporting period an indirectly heated cathode electron gun, capable of delivering a 2A/cm^2 beam for 10 microseconds, has been developed for the experimental program. Initial electrical tests on this gun and the associated pulsing network were conducted. The output from this electron gun stresses the foil window to near its structural limit, and considerable effort was necessitated to achieve the desired high current operating conditions. As a consequence, no discharge tests with hydrogen chloride were conducted during this reporting period.

Thus far, on the basis of theoretical results, the prospects for a pulsed electric discharge hydrogen chloride laser appear encouraging. However these results only indicate the existence of large electron pumping rates. The possibility of obtaining population inversions in the presence of many competing reactions can only be determined experimentally, as in the type of experiment which is still in progress.

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13. ABSTRACT

The feasibility of producing stimulated in the 3-5 wavelength band by exciting hydrogen chloride vibrational levels by electron impact is being investigated theoretically and experimentally. Theoretical interpretation of available transport data predicts large vibrational excitation rates. A high current density electron gun capable of sustaining a high electron density discharge has been developed and is described. The pulsed hydrogen chloride laser experiments in progress are also described.

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II. INTRODUCTION

Requirement for HCl Electric Discharge Laser

Several important applications for high-power, infrared, coherent radiation have been identified by the Navy and DoD. These applications require either continuous or repetively-pulsed laser emission at wavelengths which can be transmitted through the atmosphere with minimum absorption, scattering losses. The 3 to 5μ atmospheric window has received considerable attention recently. However, the only known efficient laser sources in this window are chemical lasers operating on the vibrational-rotational transitions of DF and HCl and the chemical and electrical CO laser. Some of the most important Navy and DoD applications for the laser would benefit substantially from utilization of electric-discharge excitation for the laser medium. Reliance upon alternative chemical excitation generally necessitates storage of hazardous and reactive chemicals which could present unnecessarily aggravated damage conditions in a combat situation. Further, the chemical reagents required for the laser would require periodic resupply, thereby possibly creating serious ligistic problems for the operating Fleet. The fully developed HCl or DF electrically-pumped laser could be envisioned to operate in a closed cycle, thereby obviating the storage and supply problems. In this mode of operation, an initial charge of laser gases would be pumped continuously through a closed loop, provided with the necessary discharge and cooling sections. Such closed-cycle operation has been demonstrated successfully in other laser media such as CO_2/N_2 and CO. The CO electric discharge laser, although very efficient overall, has not yet been shown to operate efficiently on vibrational transitions which yield wavelengths lying solely within the 3 - 5μ band.

Present Contract Research

Since mid-April 1972 the United Aircraft Research Laboratories (UARL) have been engaged in a research program sponsored by ONR/ARPA, under Navy Contract N00014-72-C-0450 (Ref. 1) to explore the possibility of generating stimulated emission pulses from the vibrational-rotational transitions of hydrogen chloride excited by controlled electric discharge. Theoretical studies conducted prior to the Contract award had indicated the possibility of laser action in hydrogen chloride pumped by electron impact; however, these calculations also indicated that careful control of experimental parameters would be necessary for a successful demonstration. For these reasons, an experimental investigation of HCl excited by a pulsed discharge, sustained by a pulsed electron beam, has been pursued in the subject research program.

III. TECHNICAL RESULTS

Theoretical Analysis of Electron Collision Processes in HCl

A theoretical analysis of electron-vibrational excitation in hydrogen chloride has been presented in Ref. 1. This analysis is based on the early electron-HCl transport data of Bailey and Duncanson (Ref. 2). These data indicate the onset of large electron energy losses in HCl for characteristic electron energy values below 1.0 eV. Using the effective electron drift velocity and characteristic energy as a function of electric field strength/neutral gas density ratio from these transport data, a self consistent set of rotational vibrational and electronic excitation cross sections have been deduced by solving the Boltzmann equation for the electrons in the presence of the imposed electric field. The deduced vibrational cross sections are quite large indicative of temporary negative ion formation.

Recent Electron Cross-Section Measurements at Yale University

Since the previous technical report under this contract no additional experimental data pertaining to electron transport in HCl has been reported. The electron transmission experiments undertaken with Professor George Schulz's laboratory at Yale University have been renewed. The slope of the vibrational excitation cross-section near threshold is being measured, and although the magnitude of the peak of the vibrational excitation cross-section has not been measured, indications are that it is quite large (Ref. 3), in agreement with Ref. 1.

Observation of Vibrational Excitation in HCl at Avco Everett Research Laboratories

In preliminary experiments undertaken by R. E. Center, et al., at AVCO Everett Research Laboratories (AERL) spontaneous emission from an HCl e-beam sustained discharge (Ref. 4) has been observed. To date stimulated emission has not been seen. By adding carbon monoxide to the mixture and monitoring relative spontaneous emission signals, AERL estimated that the vibrational excitation cross-section for HCl is comparable to CO. Thus, efficient vibrational excitation in HCl can be anticipated. Efficient vibrational excitation in HCl was predicted previously in the UARL theoretical study (Ref. 1).

Electric Discharge Laser Demonstration in HF and DF at Mathematical Sciences Northwest

Stimulated emission from low-lying vibrational transitions of HF and DF have been observed by S. R. Byron, et al., at Mathematical Sciences Northwest (MSNW) in preliminary, low energy output (~ millijoule) experiments (Ref. 5). These results were obtained with an experimental configuration consisting of five electron guns ($J_b \approx 50$ mA/cm^2) firing transversely into a sustainer electric field. The active optical path length provided was 50 cm. Laser Emission on the vibrational transitions v=3→2, 2→1, and 1→0 have been observed in both HF and DF (multiple P-branch lines on certain transitions in DF). Laser Action in HF has been seen both with and without H_2 present as an additive at approximately ten times the HF partial pressure. Argon and nitrogen buffers at 100 times the HF concentration have been effective. The total mixture static pressure was 190 torr and the discharge was at room temperature. Laser action in DF has been observed with Ar/DF mixtures at 99:1 molar ratios thus far. MSNW noted that the addition of hydrogen to the HF discharge produced better results. Whether this improvement is a result of additional vibrational energy transfer from H_2, or a shift in the chemical equilibrium of the mixture resulting in lower HF decomposition, is not known. A marked sensitivity of the output to the mixture electric field to neutral number density ratio was observed in accordance with previous UARL theoretical predictions, (Ref. 1).

The experiments at AERL and MSNW both serve to confirm somewhat the behavior predicted by the UARL theoretical model reported previously (Ref. 6). The AERL experiment demonstrates that a substantial vibrational excitation rate can be obtained in an e-beam ionized, HCl electric discharge. The electron vibrational excitation cross section that they would derive from their data is approximately two to five times smaller than that predicted from early electron drift data (Ref. 1). The experiments at MSNW, although performed with HF (and DF), more or less confirm the UARL model predictions. Reference 6 suggested the addition of D_2 to the discharge to utilize vibrational energy transfer from electron pumped deuterium vibrational states. The MSNW experiments demonstrated high gain on low-lying vibrational transition with low partial pressures of active species as predicted. Furthermore these preliminary experiments illustrate the necessity for careful E/N control to operate in a regime of high vibration excitation with minimal rotational and electronic excitational losses. Lastly the requirement for large electron densities in these pulsed discharge lasers is confirmed. In summary, these other preliminary experiments illustrate that hydrogen chloride can be excited effectively in a pulsed, externally ionized discharge, and should be capable of lasing, given the proper conditions.

Experimental Design

It was estimated in Ref. 1, that in order to promote a reasonable number of HCl molecules into the upper vibrational levels, it is required that

$$N_e \Delta\tau \geq \alpha \left(\frac{\nu_v}{N} \right)^{-1} \qquad (1)$$

where $\Delta\tau$ is the pulse duration, α is the fraction of HCl molecules promoted to vibrational states, and ν_v/N is the vibrational excitation rate (see Fig. 4, Ref. 1). Assuming reasonable values for these quantities, it is required that

$$N_e \Delta\tau \geq 2 \times 10^{13} \ \mathrm{cm}^{-3} \mu\mathrm{sec}. \qquad (2)$$

Now an estimate can be made of the electron beam current density level required to sustain this plasma density against recombination (at the pressures of interest diffusion is negligible). If HCl is the dominant positive ion in the Ar/HCl discharge, then dissocivtive attachment in HCl will be the primary recombination mechanism. The dissociative attachment rate has been estimated from the measured cross-section using the solution for the electron distribution from Ref. 1. The approximate value is z x 10^{-10} cm^3 sec^{-1}. The electron production rate, S, can be estimated (Ref. 7) from an average electron energy of 100kV, to be

$$S = 6.3 \times 10^{17} \; p_A J_b \quad cm^{-3} sec^{-1} torr^{-1} A^{-1} cm^2 \tag{3}$$

where p_A is the argon reduced partial pressure, and J_b is the post-foil electron beam current density. The steady state electron number density is found by equating the production to the loss rate and is given by

$$N_{e_o} = 8.9 \times 10^{10} \; \frac{p_A}{p_{HCl}} \; J_b \quad cm^{-3} - \frac{cm^2}{A} \tag{4}$$

In the present experiments the gas mixture is envisioned to be a low partial pressure of hydrogen chloride (~ 0.5 torr) in an excess of argon (~ 50 torr) to provide stopping power for the electron beam. Then a requirement for the electron beam gun current density can be derived by combining Eqs. (2) and (4):

$$J_b \Delta \tau \geq 2.25 \; A/cm^2 \; \mu sec$$

The upper limit for the pulse duration is given by the vibrational-translational relaxation time. This has not been measured at the cryogenic temperature desirable for development of partial population inversions. A reasonable approximation is 100 μsec. The range of pulse duration chosen for these preliminary experiments is 5-20 μsec.

The relatively high current discharge required for this application is confirmed by the experiments at MSNW. They estimated their electron number density to be 3 x $10^{13}$$cm^{-3}$ with a pulse duration of 30 μsec. The higher electron densities for a given electron beam current is thought to be a result of a lower electron attachment rate in HF. Of course the relationship presented above are only valid to an order of magnitude, and experimental measurements of the actual discharge characteristics are necessary.

e-Beam Ionizer

The ionizer for the present small scale HCl discharge laser experiment is a modified version of operational UARL cw diode e-guns. An end-view of one of the guns is shown in Fig. 1. The modification consisted of substituting a dispenser cathode for the coated cathode normally employed. This substitution lowered the average work function of the 2.5 cm diameter emitter from approximately 3 eV to 2 eV.

During this reporting period, several problems had to be overcome in achieving stable activation of the dispenser cathodes. However, solutions to the problems were found and the gun now operates with emission current densities that easily exceed 10A/cm^2.

The goal for post foil e-beam current density in the present discharge experiments has been 2 A/cm^2. This performance has been achieved without foil failure on a nonrepetitive basis. However, it has been observed frequently that as the prefoil current density is increased the ratio of post-foil to prefoil current density decreases. The expected ratio is about one-third, when the combined effects of foil and foil holder losses and collector efficiciency are considered. The measured electron current transmission ratio is about one-fourth at low e-beam current levels and drops to about one-tenth at the highest levels. One example of the performance under the latter condition is shown inf Fig. 2. In this case the upper curve represents the current density incident on the foil. The amplitude at the leading edge of the incident pulse is 70 A, or 14A/cm^2 and the pulse duration is 16 microseconds. However, the amplitude of the resulting post-foil e-beam pulse (lower curve) is only 7.5 A or 1.5 A/cm^2 with a pulse duration of 5 microseconds. The foil did not fail when subjected to the pulse shown in Fig. 2. In fact the foil and e-gun were subsequently used at a current level one-fourth that shown in Fig. 2 for 7200 pulses at 1-pps. However, a thermal analysis of the Fig. 2 pulse suggests that the foil did approach the melting point at the end of the pulse. This failure via melting appears to be attributable to the characteristics of the power supply as described below.

The power supply used to operate the e-gun is a basic Marc generator with an output impednace of approximately 500 ohms. The pulse shown in Fig. 2 was the result of the generator voltage pulse shown in Fig. 3. The waveform shown in Fig. 3 represents the open circuit voltage of the generator. According to the voltage measurement, the leading edge of the waveform is 125 kV. As a consequence of the generator output impedance, the 70 ampere gun pulse lowered the gun voltage to approximately 90 kV. For this condition the transmission and average residual energy of 0.8 mil aluminum foil are only 0.68 and 58 KeV, respectively. Thus, over half of the incident power was absorbed by the foil at the leading edge of the pulse. Shown in Fig. 4 are the power densities incident on and adsorbed by the foil during the pulse (Figs. 2 and 3). Evident in Fig. 4 is the point in time (six microseconds) at which the decreasing e-beam range in aluminum becomes equivalent to the thickness of the foil. thereafter cutting off transmission. The integral of the electron energy absorption curve, divided by the product of the enthalpy of aluminum and the foil thickness, yields the final temperature of the foil. For this example, the foil approached or exceeded its melting point (660°C). This result, although apparently pessimistic since the foil did not fail, is, nevertheless, consistent with the general appearance of foils that have been subjected to such high incident power levels. In each case in which the 500 ohm generator has been used, the foils appeared bubbled or blistered. In some cases, the foils apparently had melted and subsequently refrozen on a time scale that was too short to result in failure. (The pressure differential across the foil is 50 torr).

The feasibility of achieving acceptably high post-foil e-beam current density-pulse width products, assuming the use of a low output impedance, square-pulse generator, can be determined based on the above results. For example, if it is assumed that the applied gun voltage is 160 KV, the foil is 0.8 mil. aluminum, the pulse rise and fall times are each less than one microsecond, and that the final foil temperature is limited to one-half the melting point (330°C), it is easily shown that 20 microcoulombs/cm^2 can be delivered post-foil with the modified UARL e-gun. This level is equivalent to 2 A/cm^2 for 10 microseconds, which is the design goal for this present application.

Future Experiments

From the previous discussion, it is evident that the present UARL hot cathode electron gun is capable of attaining the current density - pulse duration product necessary for reasonable vibrational state excitation in HCl medium. Discharge tests are required to verify the levels of ionization attainable. Two additional solenoid magnets are being added to the discharge tube as can be seen from Figure 5. These new magnets are shown surrounding the electron gun and the foil holder region. These additional solenoids will continue the magnetic field through the foil to the cathode to avoid adverse scattering at the foil. This procedure has been found necessary in other cw electron beam sustained laser devices in operation at UARL (Ref. 8).

Also shown in Figure 5 is a laser oscillator configuration utilizing internal mirrors to provide a long (approximately 56 cm of active path volume) optical path. Resonator stability is provided by linking the paired mirror structures with low thermal expansion rods.

A high voltage pulse generator (Marx bank with crowbar) is being assembled in order to provide the desired square voltage pulses to the electron gun. This unit should provide for operation at higher ionization levels. In the interim, discharge tests are continuing with the present power supply. The laser configuration modifications are scheduled for completion prior to delivery of the pulser, so that preliminary sidelight emission and laser tests will proceed before the new square wave, high voltage pulser is installed.

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3. G. J. Schulz, Yale University, private communication; May, 1973.

4. R. E. Center, AVCO Everett Research Laboratories, private communication: April, 1973.

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6. Office of Naval Research, Department of the Navy, Arlington, Virginia; Contract No. N00014-72-C-0450; Advanced Research Projects Agency, Department of Defense, Order No. 1877. "E-Beam HCl Laser." Period of Performance: April 24, 1972 to December 31, 1972. As proposed under UARL Report No. P-L16, "Proposed Investigation of an HCl Medium Excited by Controlled Pulsed Electric Discharge", January, 1972.

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8. R. H. Bullis, UARL, private communications; April, 1973.

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COAXIAL ELECTRON BEAM GUN
(FOIL SUPPORT REMOVED)

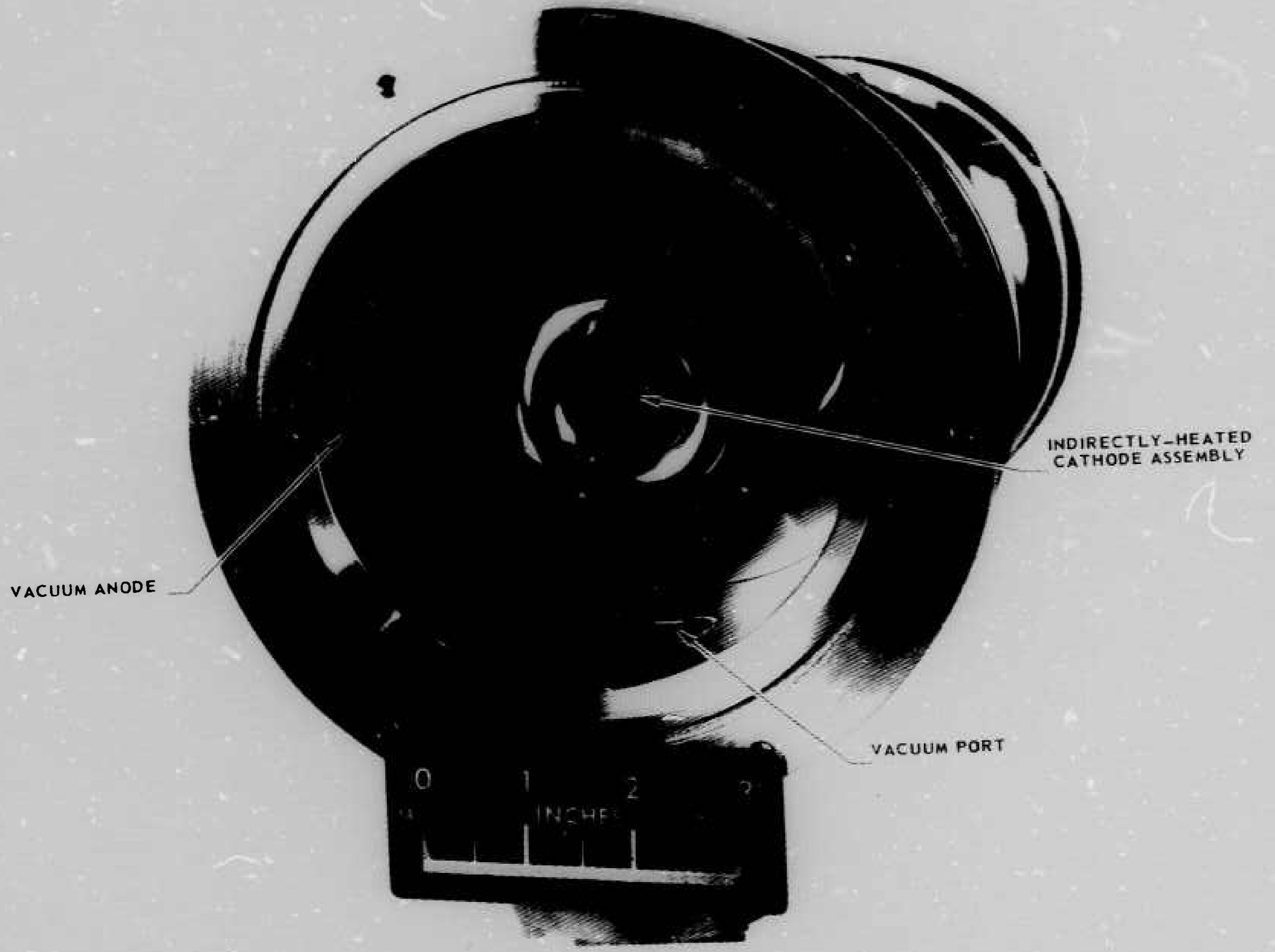


FIG. 1

FIG. 2

PREFOIL AND POSTFOIL e–BEAM CURRENT

(5 cm^2 DIODE GUN; 0.8 mil Al FOIL)

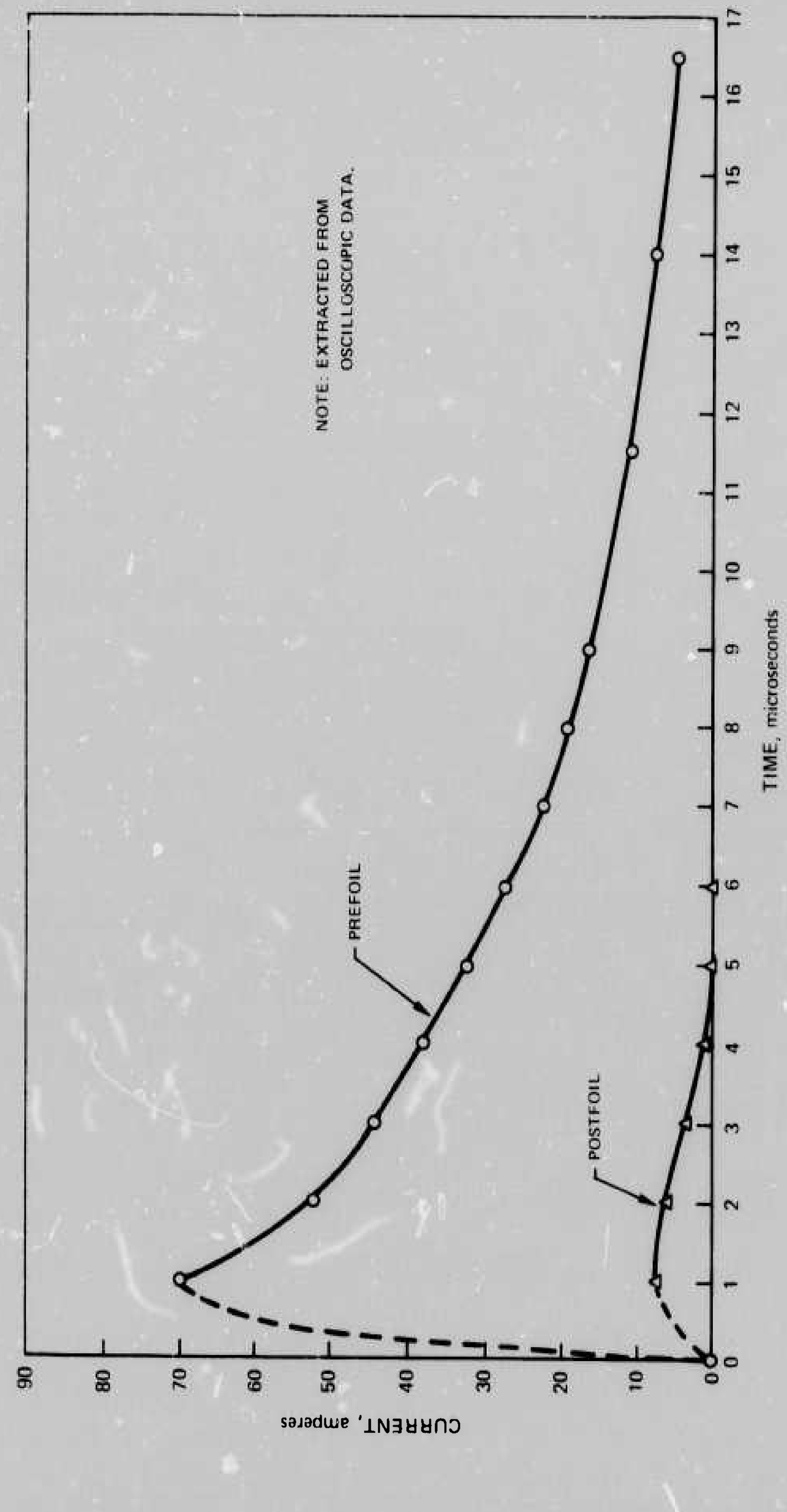


FIG. 3

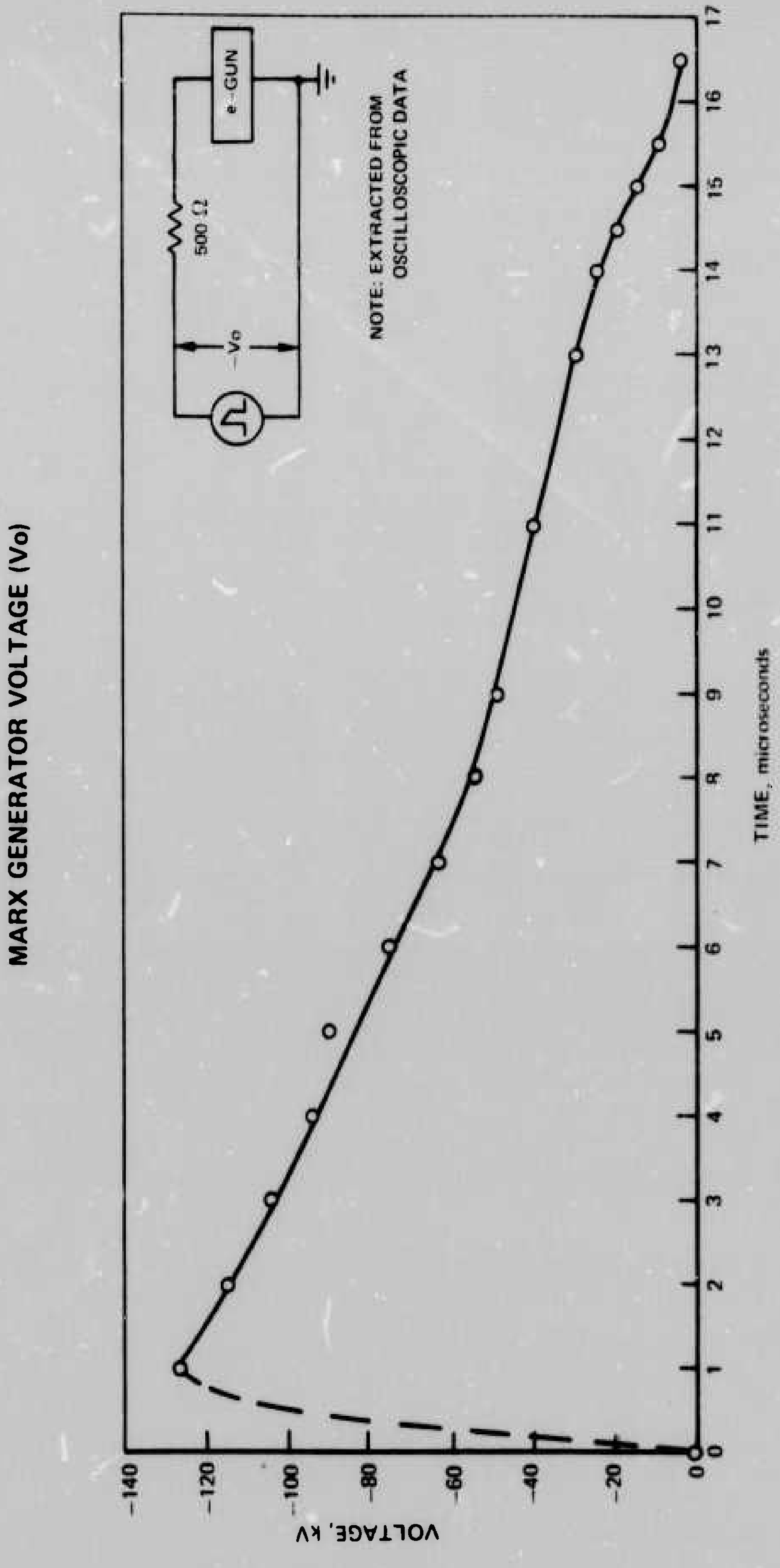
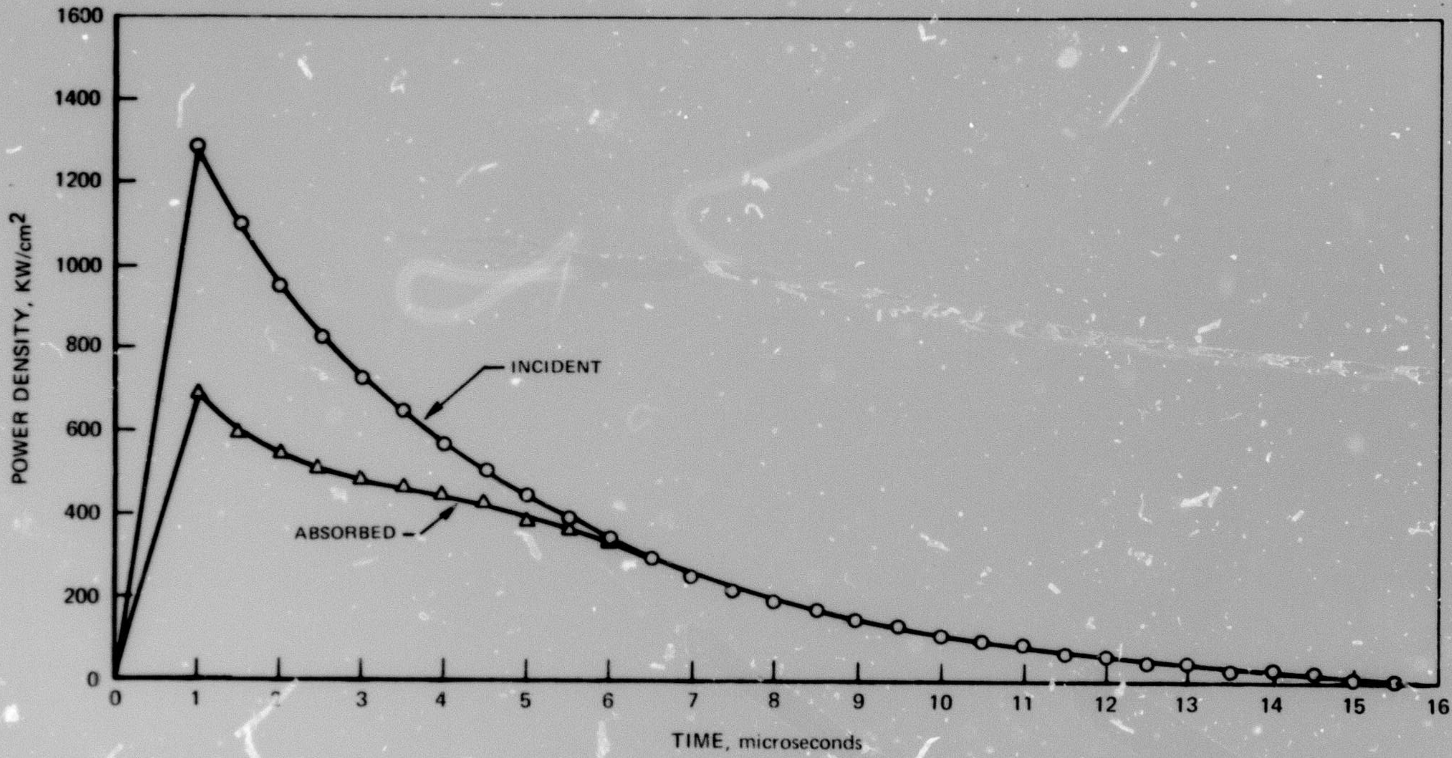

MARX GENERATOR VOLTAGE (Vo)
NOTE: EXTRACTED FROM
OSCILLOSCOPIC DATA
500 Ω
e-GUN
-Vo
VOLTAGE, kV
-140
-120
-100
-80
-60
-40
-20
0
TIME, microseconds
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

FIG. 4

INSTANTENEOUS POWER DENSITY DUE TO e–BEAM PULSE



PULSED DISCHARGE LASER CONFIGURATION

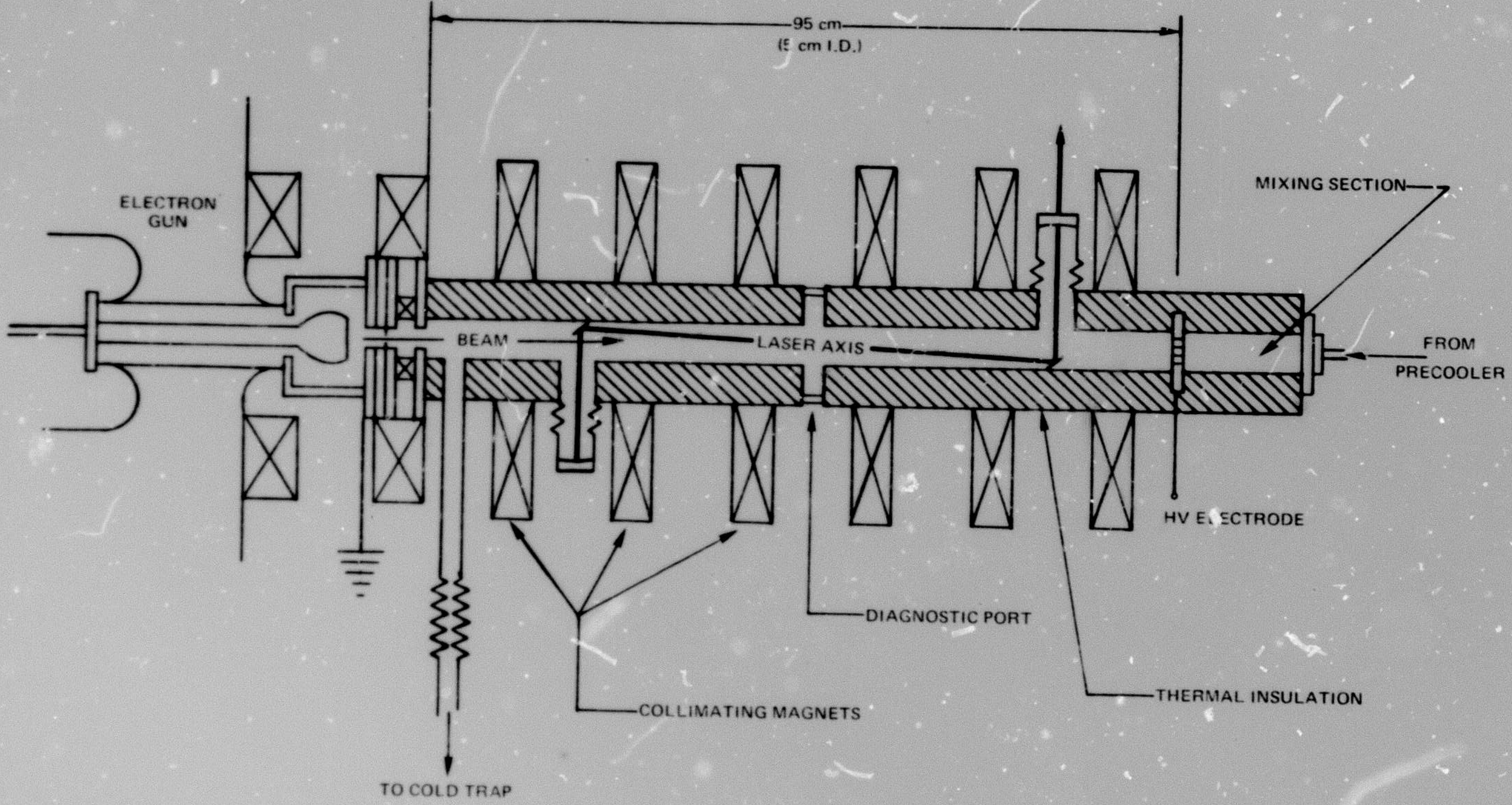


FIG. 5