AD-759 399

INVESTIGATION OF THE FEASIBILITY OF THE ELECTRON BEAM-EXCITED, HIGH-PRESSURE RECOMBINATION LASER

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Dallas, Texas

April 1973

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N00014-67-A-0310-0007
UTDP A003-1.1

RECOMBINATION LASER

Supplement NO. 1 to
Annual Report
by

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prepared for
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
APRIL 1973

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Security Classification

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) The University of Texas at Dallas P. O. Box 30365 Dallas, Texas 75230	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP	
3. REPORT TITLE INVESTIGATION OF THE FEASIBILITY OF THE ELECTRON BEAM-EXCITED, HIGH-PRESSURE RECOMBINATION LASER		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Supplement No. 1 to the - AD 756 681 First Annual Technical Report (period covered by this supplement 1/1/73 - 3/31/73)		
5. AUTHOR(S) (First name, middle initial, last name) Carl B. Collins Austin J. Cunningham Brian W. Johnson		
6. REPORT DATE 1 April 1973	7a. TOTAL NO. OF PAGES 27	7b. NO. OF REFS 2
8a. CONTRACT OR GRANT NO. N00014-67-A-0310-0007 b. PROJECT NO. ARPA Order No. 1807 c. Program Code 2E90 d.	9a. ORIGINATOR'S REPORT NUMBER(S) UTDP A003-1.1 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. DISTRIBUTION STATEMENT Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research	
13. ABSTRACT		

This report describes research applied toward the determination of the feasibility of developing a recombining, electron beam-excited plasma into a pulsed laser of exceptionally high peak power. The indication of small signal gain for optical amplification at 5875 Å is the principal subject of this suppelment.

DD FORM 1 NOV 65 1473

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
RECOMBINATION LASER						
LASER						

FIRST ANNUAL TECHNICAL REPORT

SUPPLEMENT NO. 1

Item A003.1

Short Title: RECOMBINATION LASER

ARPA Order Number 1807

Program Code Number 2E90

Contract Number N00014-67-A-0310-0007

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800 N. Quincy Street
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Effective Date of Contract: 21 March 1972

Expiration Date of Contract: 31 December 1973
Period Covered by this Report: 1 January, 1973 - 31 March, 1973
Amount of Basic Contract: $ 99,990
Amount of Modification #1: 91,400
Total Contract: $191,390

Sponsored by

Advanced Research Projects Agency

ARPA Order No. 1807

Form Approved Budget Bureau No. 22-R0293

CONTENTS

I. INTRODUCTION

The objective of the research described in the report to which this is supplementary, is to determine the feasibility of developing a recombining electron beam-excited plasma into a pulsed laser of exceptionally high peak power. Currently accepted theory supported by the results of this research indicates that this should be possible.

Although a wide variety of recombination processes are known to occur in gaseous plasmas, it is only the relatively complex and unfamiliar collisionally-stabilized one which appears to hold promise for a lasing medium. This process is optimized at high charge densities and relatively low energies, but is almost completely quenched in atomic and molecular systems which can participate in dissociative recombination. Theory predicts that in helium at charge densities of the order of $10^{16} cm^{-3}$ collisionally-stabilized recombination should produce large inverted population of the resulting neutrals which would tend to radiate in the 2.0μ to 0.3μ wavelength region, provided the temperature of the electron swarm is kept low. It is this requirement which suggests that unlike conventional visible and UV lasers excited by electron beams, lasing action from recombination would be optimized in the afterglow period following the termination of the beam. There is a considerable advantage in this from the viewpoint of fundamental collision cross-sections. In the conventional, directly-excited visible and UV systems over 95% of the beam energy is lost to the production of ionization not contributing to the laser output. In contrast to this, theory has predicted that the subsequent collisionally-stabilized recombination of the ions with electrons could provide a mechanism for recovering some of this ionization energy with a resulting orders of magnitude increase in the optical output.

Both the available output energy and pulse duration depend strongly on the electron density, high values of which only become available in large volume from e-beam excitation at high neutral gas pressures. In this requirement lies the basic uncertainty in the approach since previous investigations of this type of charge neutralization have centered on neutral gas densities some 200 times less than the 20 atmosphere values which theory requires for significant radiative output.

The research effort reported here has focused upon this recombination approach and the intent of the initial considerations were to first provide an additional test of theory in helium at intermediate pressures of one to seven atmospheres. From it could be directly determined the amount of light output, the lifetime of the recombination process, and whether or not population inversions were developed. While favorable indications of population inversion were reported as a result of the first year's activity, measurements in progress at the time of preparation of that document have provided substantially stronger evidence for optical gain, and consequently for the feasibility of a recombination laser. That evidence is the subject of this supplement.

II. TECHNIQUE

The evidence of gain reported in this supplement were obtained from measurements of the enhancement of the apparent brightness of the incoherently radiating plasma when contained in a resonant optical cavity. Two experimental arrangements were employed as shown in Figures 1(a) and 1(b). In each case the "back" mirror, farthest from the recording camera was a multilayer dielectric mirror, 15 mm in diameter and totally reflecting, r>99.5% over the 5800 Å - 6800 Å region. The "front" mirror was a wide band dielectric mirror reflecting ∿ 97% of the light over the 4400 Å - 7000 Å region. It was 25 mm in diameter and in the case of the arrangement shown in Figure 1(a) formed the limiting aperature of the recording system.

In such a configuration, the apparent axial brightness of an optically active plasma has been predicted[2] to depend upon experimental parameters as shown in Figure 2 for stable geometries lying between the confocal and the concentric.

Plotted are F values where

$$F=G(M-1) \quad , \qquad (1)$$

M is the ratio of apparent brightness of the plasma interposed between the point of observation and the "back" mirror to the brightness viewed from the same axial point in the absence of the back mirror, ie. purely incoherent radiation, and G is a scale factor depending only upon cavity geometry and difficult to compute precisely. Curves are shown as functions of loss coefficient per transit of the plasma and parameterically as functions of a_o, the passive optical transmissivity of the cavity and afterglow container per roundtrip. For the experiments reported here, the unloaded cavity had a transmissivity of $a_o \sim 0.85$, equivalent to a loss per roundtrip of 15% for the

Figures 1

Schematic representations of the two optical arrangements used in the enhanced brightness measurements referenced in Section III. In each case the "back" mirror was totally reflecting, r > 99.5% over the 5800 Å to 6800 Å region while the front mirror reflected ∿ 97% of the light in the 4400 Å to 7000 Å interval.

(a) The rear mirror and radiation from the interposed plasma was viewed and photographed along the low loss axis of the resonant cavity.

(b) The image formed at the film plane in (a) was magnified and projected onto the input photocathode of the image intensifier. Image intensity lost in the magnification was recovered by amplification in the image intensifier. The image on the output flourescent screen of the intensifier was then photographed.

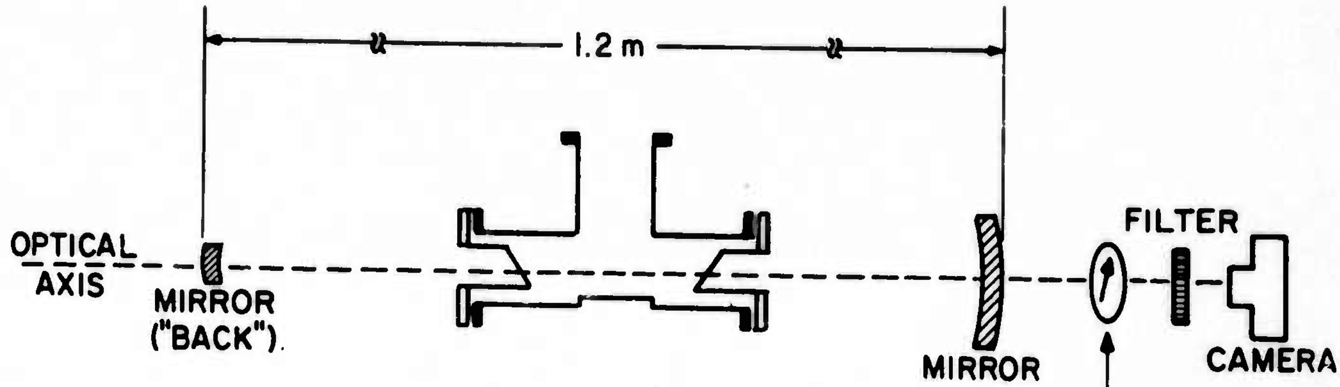

Figure 1(a)

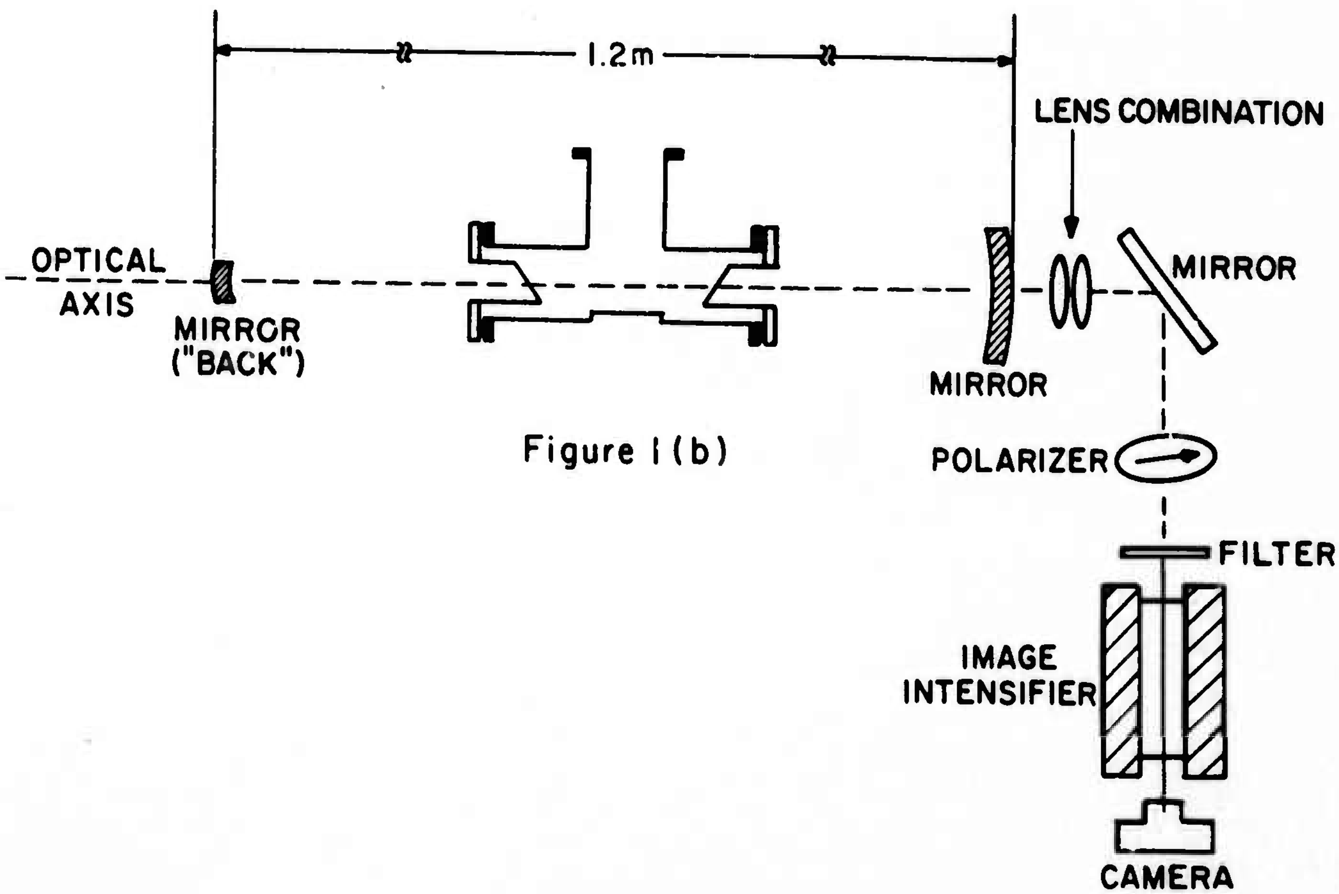

Figure 1(b)

Figure 2

Plot of the calculated F-factors for enhancement from equation (1) as a function of fractional loss (+) or gain (-) coefficient per transit of the plasma. Values of the passive optical transmissivity, a_o, for the cavity and afterglow container were varied parametrically as indicated.

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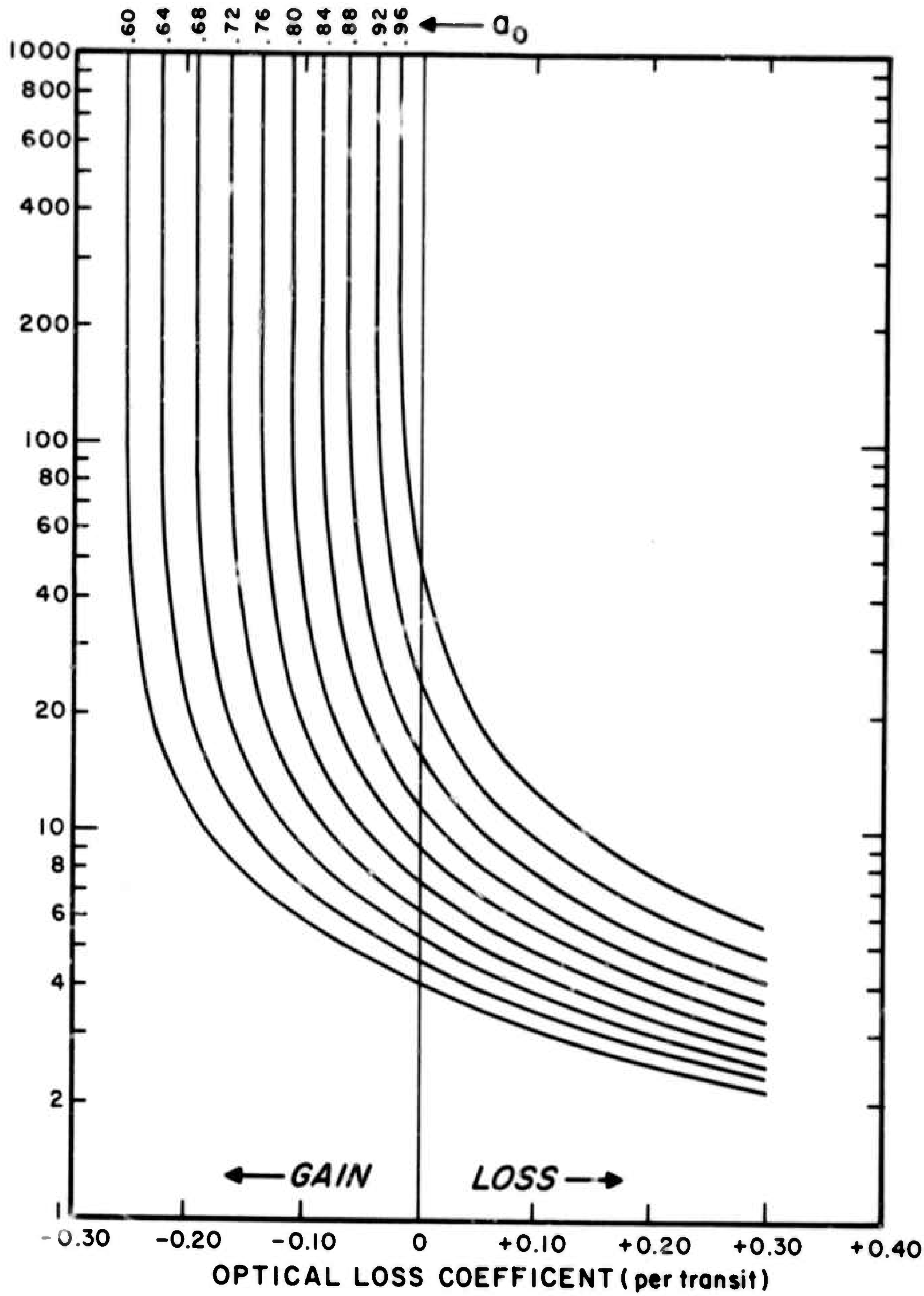

.60
.64
.68
.72
.76
.80
.84
.88
.92
.96
a_0
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
GAIN
LOSS
-0.30
-0.20
-0.10
0
+0.10
+0.20
+0.30
+0.40
OPTICAL LOSS COEFFICENT (per transit)

low-loss polarization corresponding to the Brewster angle. Since the emission sampled is principally incoherent, the intensity from the low-loss polarization cannot be selected uniquely by an external polarizer. A sum of that intensity, together with the projections of intensity components from the higher loss polarizations onto the low loss axis is obtained when the angle of the analyzing polarizer corresponds to that axis. In this sense the use of a single curve from Figure 2 can only be considered an approximation.

While this together with the uncertainties in the calibrating the geometric scale factor, G, make equivocal the quantitative interpretation of the data collected, from the viewpoint of this presentation, the most important feature of Figure 2 is simply the general form of the curves. As would be expected, near the threshold for lasing the decreasing enhancement of apparent brightness caused by the back mirror should be strongly and nonlinearly dependent upon loading of the cavity with successive increments of passive loss. This forms the basis of the measurements presented in the following section.

III. RESULTS

A simulation of the brightness measuremtns is found in Figure 3 to facilitate the interpretation of the subsequent figures. The experimental arrangement was as shown in Figure 1(a) with the exception that the resonant axis of the cavity was slightly displaced from the optical axis of observation. This was necessitated by a slight spurious inclination of the Brewster angle windows to the optical axis defined by the line perpendicular to the stops and apertures along the path. This is seen in Figure 3 as a displacement of the inner illuminated circle defining the position of the 15 mm "back" mirror relative to the center of the dark surrounding circle defining the bounds of the "front" mirror. No discharge of the plasma is recorded in the photograph. Illumination of the rear mirror was in this one case provided from behind with a short wavelength source to which the mirror was transparent.

Figures 4 show the enhanced brightness recorded by light unselected for polarization, but filtered to retain principally the 5875 Å component. Figure 4(a) shows the appearance of the rear mirror and interposed plasma and (b) shows only the plasma, the rear mirror having been covered with a mechanical shutter, As would be expected, higher contrast is obtained if an analyzing polarizer is used to select the intensity components projected along the axis corresponding to the lowest loss mode of the cavity as determined by the Brewster angle windows. Figures 5 show this effect with 5(a) corresponding to the image formed by components of light from that direction of polarization and 5(b) corresponding to the image formed from components rotated 90° to those of 5(a).

For calibration Figure 5(c) shows a gray calibrated scale from which the ratio of intensities can be estimated. Evidently a ratio of enhancement of at least about 5:1 is indicated. Of some interest is the appearance of a compact "spot" in the image from light from the lower loss modes which could be evidence

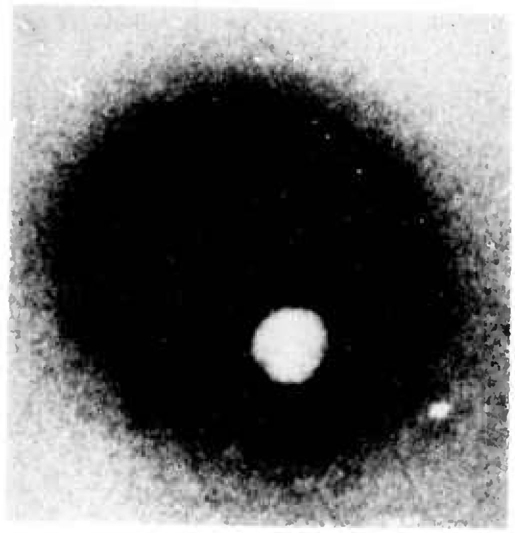


Figure 3

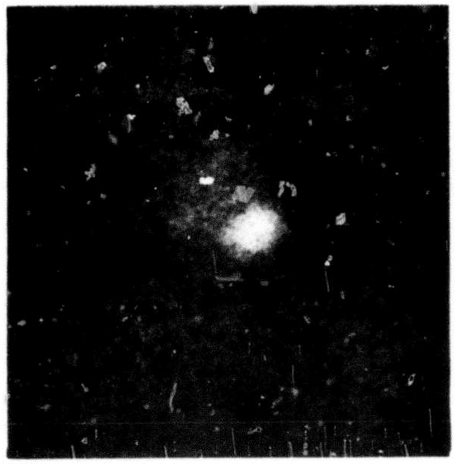
Photograph of the cavity illuminated from an external source for the purpose of identifying the various parts of the recorded image. No discharge of the plasma is included in this one case. The inner illuminated circle defines the position of "back" mirror as photographed, using experimental configuration shown in Figure 1(a). The dark surrounding circle defines the bounds of the front mirror. As discussed in Section III, the displacement of the resonant axis with respect to the optical axis of the cavity, results in the displacement which can be seen in the position of the "back" mirror with respect to the dark surroundings.

Figures 4

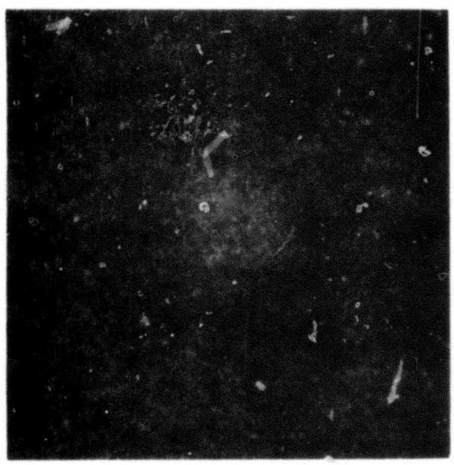
Photographs of the enhanced brightness of the afterglow light from the region of the plasma lying in the resonant cavity and observed along its axis with experimental configuration shown in Figure 1(a). The light was not selected with respect to polarization, but filtered to retain principally the 5875 Å component.

(a) Photograph showing the rear mirror and radiation from the interposed plasma

(b) Photograph showing the apparent brightness of the incoherent emission from the plasma viewed as in (a), but with the rear mirror covered.



4(a) All polarization modes sampled "Back" mirror uncovered.



4(b) All polarization modes sampled "Back" mirror covered.

Figures 5

Phototgraphs of the enhanced brightness in the resonant cavity of the afterglow light using the experimental configuration shown in 1(a). The light was filtered to pass principally the 5875 Å component and analyzed according to polarization to pass or reject the intensity components corresponding to the lowest loss mode of the cavity as determined by the Brewster angle windows.

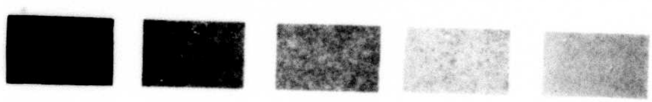
(a) Recorded image formed by afterglow radiation selected for polarization components corresponding to the low-loss cavity mode. The enhancement of apparant brightness of afterglow elements lying in the resonant cavity appears as a brighter compact spot within the boundaries of the rear mirror image.

(b) Recorded image formed by afterglow radiation selected for polarization components rotated 90° to those selected in (a).

(c) Logarithmically calibrated gray scale with which enhancement ratios can be determined from contrast ratios appearing in (a) and (b) above.

5(a) Low loss polarization mode **sampled.** "Back" mirror uncovered

5(b) Low loss polarization mode **sampled** "Back" mirror covered.



5(c) Gray scale logarithmically **calibrated** of the formation of a pre-lasing mode.[2]

With a geometric factor estimated to be of the order of 5, the gain indicated is sufficiently large to suggest proximity to the lasing threshold. As mentioned above, this implies a high sensitivity to cavity loading and provides the basis for a significant test of gain. By loading the cavity with successive increments of passive loss, a strongly non-linear dependence of decreasing enhancement should be observed. Figures 6 (a), (b), (c) and (d) present the enhancements observed for the low-loss polarizations for the cavity with, respectively, interposed 0, 8, 16 and 24%, increments of passive loss. It can be seen that it is the first increment which causes the most significant decrease in intensity with subsequent additions causing little or no visible changes. Calibration against a density wedge show the first increment to cause a reduction of enhancement by a factor of 2.5.

Entirely similar results were obtained for images filtered to select for the 6400 Å radiation with the exception that the "spot" appeared more compact and the brightness contrast higher in general agreement with the higher gain inferred for this transition and reported earlier[1]. Unfortunately, film sensitivity was inadequate to provide images suitable for calibration.

All of the data obtained with the arrangement shown in Figure 1(a) were recorded on Eastman 2485 film developed to an equivalent ASA of 8000. Resolution appeared limited by the grain size of the film as can be seen in the enlargements shown in Figures 3 through 6. Magnification was limited in practice by the decreasing brightness of the image and attempts to improve upon these fundamental limitations of optics required use of an active device such as an image intensifier to amplify brightness. Figure 1(b) shows schematically the implementation of this approach. In order to be assured of amplifying the same image previously recorded on film, the camera was replaced as shown in the figure with

Figures 6

Photographs supporting the investigation of the sensitivity of brightness enhancement ratios to loading of the resonant cavity. For these photographs the analyzing polarizer was oriented to pass intensity components corresponding to the lowest loss mode of the optical cavity and the light filtered to select principally the 5875 Å wavelength. The series shows the effect of loading the cavity with successive 8% increments of interposed passive loss.

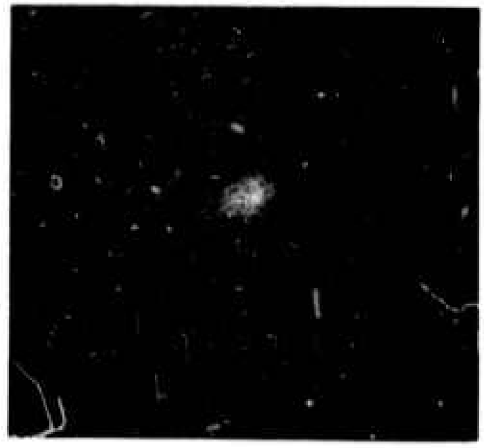
(a) 0% passive loss increment

(b) 8% passive loss increment

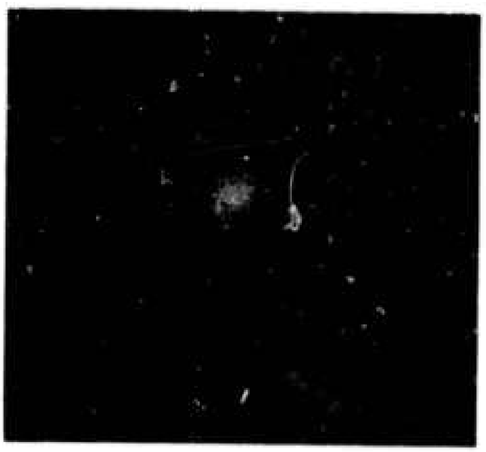
(c) 16% passive loss increment

(d) 24% passive loss increment

6(a) 0% passive loss increment.



6(b) 8% passive loss increment.



6(c) 16% passive loss increment.

6(d) 24% passive loss increment.

the first lens which was optically equivalent to the camera lens. The real image formed where the film plane had been was then enlarged with an identical lens shown in the second position, the final image being projected onto the photocathode of the image intensifier. In this arrangement the resulting amplification of brightness allowed for considerable magnification of the image as well as the recording of light from single discharges of the e-beam gun. Resolution was then limited not by the film but by the finite spot size of the fluorescence on the phosphor screen resulting from single photoelectrons emitted from the cathode. Resulting data is shown in the following figures. As in Figure 3, Figure 7 shows a calibrating photograph of the rear mirror illuminated from behind with a short wavelength source to which the mirror was transparent. No discharge of the plasma is recorded in the photograph, the objective being to determine the size of the image of the mirror.

Figure 8 compares with Figure 5 and shows the image recorded by 5875 Å light and analyzed according to the polarization state. Figure 8(a) shows the mirror as an unevenly illuminated disk with the bulk of the plasma lying to the side and below the optical path. In this figure the analyzing polarizer is set to maximize the components from low-loss modes corresponding to the Brewster angle of the windows. Figure 8(b) records the effect of covering the rear mirror. Figure 8(c) shows the image formed from rays polarized 90° to the low loss mode and 8(d) shows the image formed at the same polarization with the rear mirror covered. As in the prior data, a strong enhancement of the apparent brightness is produced by the rear mirror for light polarized along the axis corresponding to the lowest loss mode of the cavity.

Data for cavity loading is repeated in Figures 9(a) through (d), for 0, 8, 16 and 24% increments of passive loss of the cavity. Again the largest effect occurs for insertion of the first increment, particularly in the region where the compact spot is found. Clearly the magnified images confirm the indications

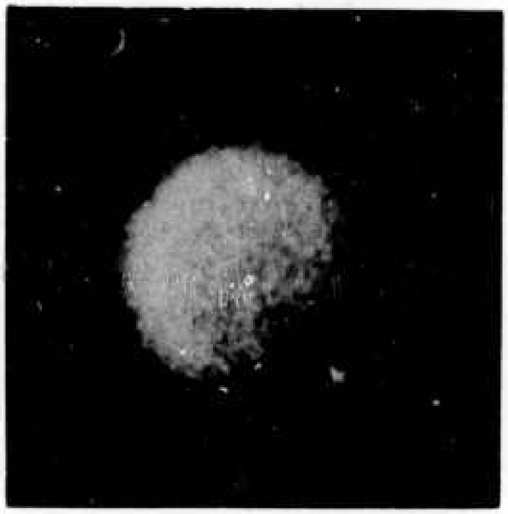


Figure 7

Photograph of the cavity illuminated from an external source for the purpose of identifying the size and position of the various parts of the recorded image. No discharge of the plasma is included in this one case. The illuminated disk is the image of the rear mirror as photographed along the axis of the resonant optical cavity using the experimental arrangement shown in Figure 1(b). This photograph is equivalent to the central portion of Figure 3 with the brightness amplified with the image intensifier system.

Figures 8

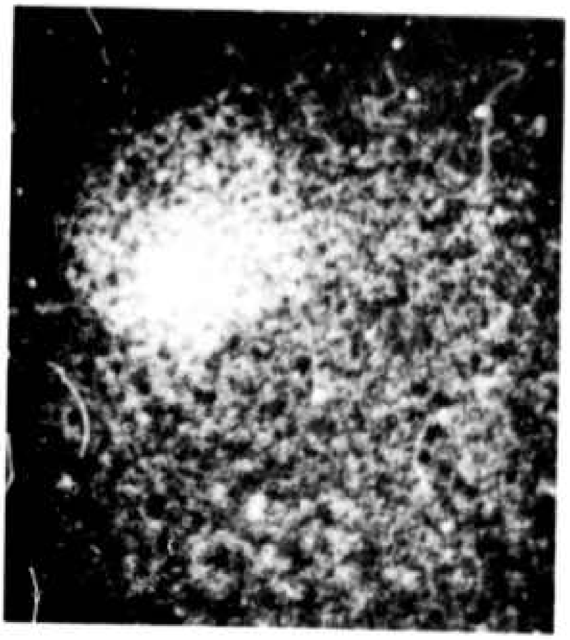
Photographs of the rear mirror and incoherent radiation from the interposed plasma are shown for different polarization states with the rear mirror covered and uncovered. The sampled radiation was filtered to pass principally the 5875 Å component and amplified with the image intensifier arranged as shown in Figure 1(b).

(a) Recorded image formed by afterglow radiation selected for polarization components corresponding to the low-loss cavity mode. The enhancement of apparant brightness of afterglow elements lying within the resonant cavity appears as a brighter compact spot within the boundaries of the rear mirror image.

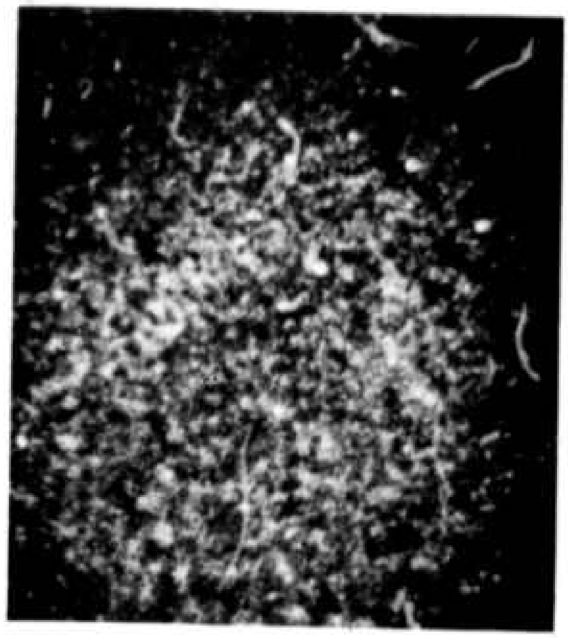
(b) Recorded image formed as in (a) but with the rear mirror covered.

(c) Recorded image formed as in (a) but selected for polarization rotated 90° with respect to the low-loss mode.

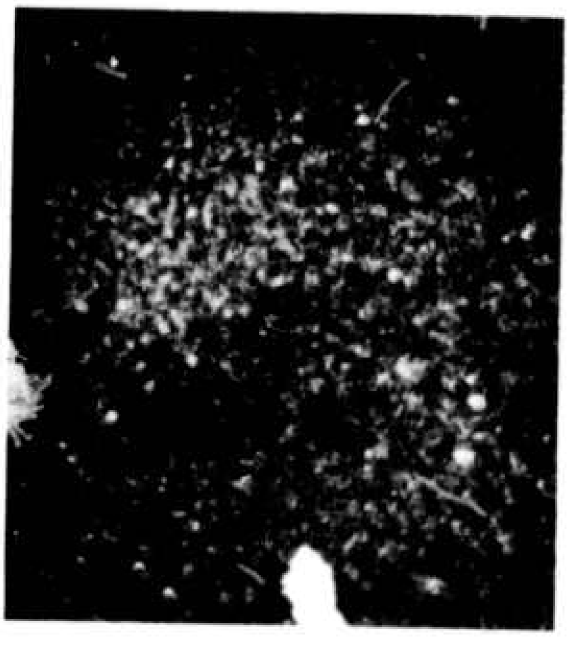
(d) Recorded image formed as in (c) but with the rear mirror covered.



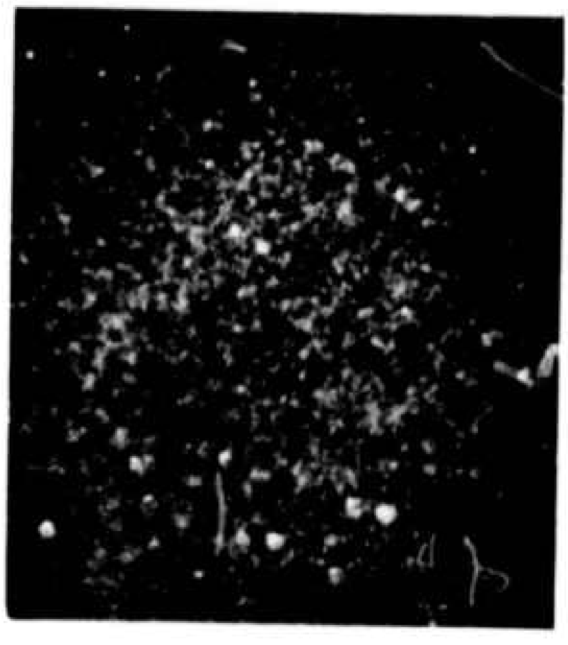
8(a) Low loss polarization mode sampled. "Back" mirror uncovered



8(b) Low loss polarization mode sampled. "Back" mirror covered



8(c) Low loss polarization mode rejected. "Back" mirror uncovered



8(d) Low loss polarization mode rejected. "Back" mirror covered.

Figures 9

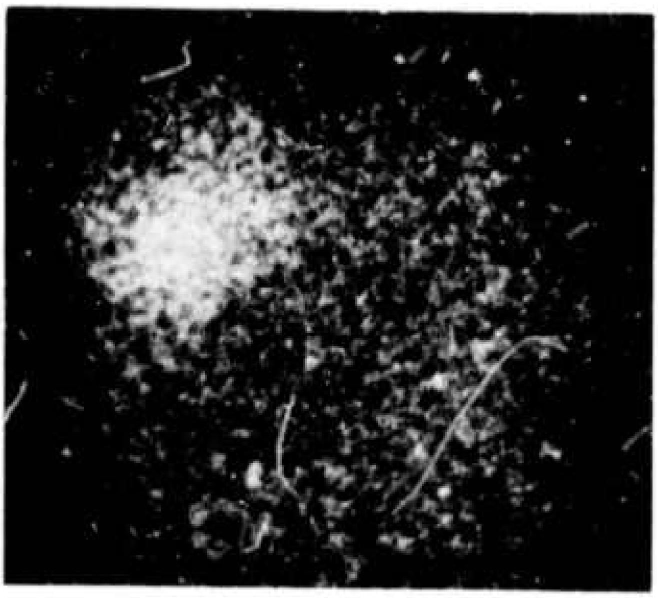
Photographs supporting the investigation of the sensitivity of brightness enhancement to loading of the resonant cavity. The analyzing polarizer was oriented to pass intensity components corresponding to the lowest loss mode of the optical cavity. Light was filtered to pass principally to 5875 Å radiation and the image intensity amplified in the arrangement shown in Figure 1(b). The series shows the effect of loading the cavity with successive 8% increments of interposed passive loss.

(a) 0% passive loss increment

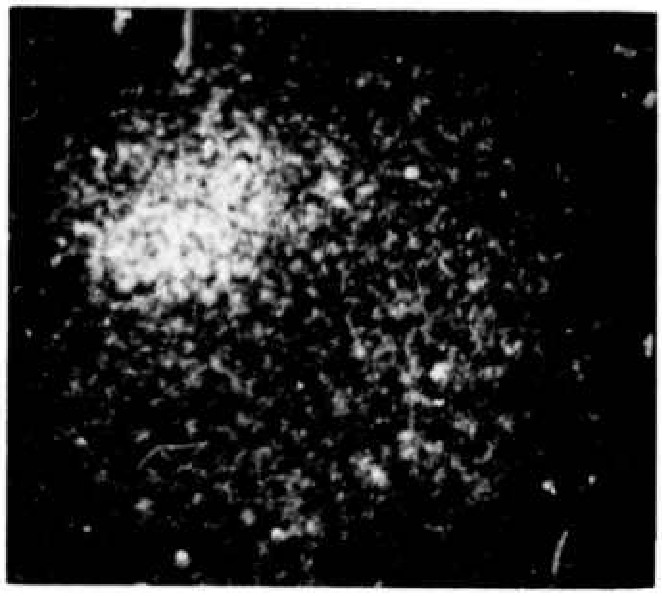
(b) 8% passive loss increment

(c) 16% passive loss increment

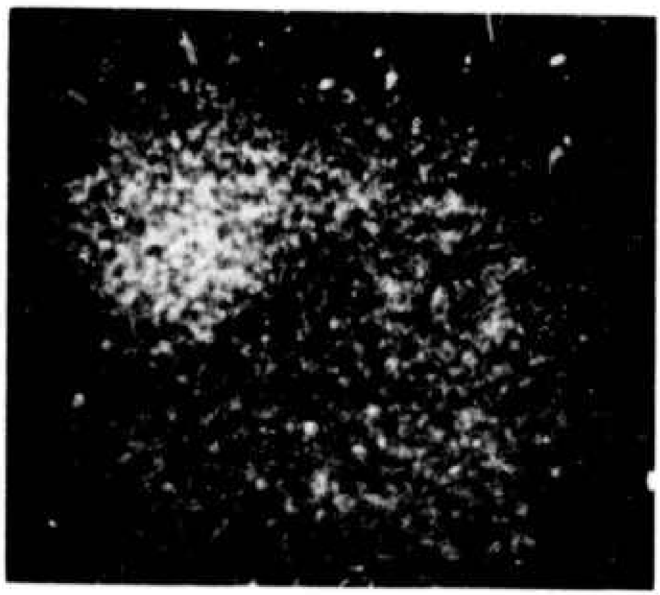
(d) 24% passive loss increment



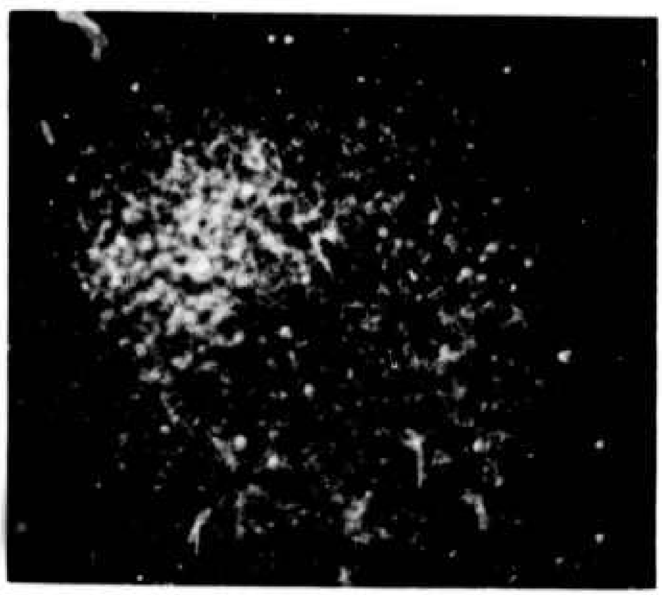
9(a) 0% passive loss increment.



9(b) 8% passive loss increment.



9(c) 16% passive loss increment.



9(d) 24% passive loss increment.

of the direct photographs, that there is a compact spot on the rear mirror, the apparent brightness of which is a strong function of polarization and cavity loading.

All indications remain that the afterglow shows gain and the proximity to threshold is indicated by these observations. This suggests gain approximately equal to the 7% passive loss per pass of the cavity. Furthermore, it is in general agreement with the quantitative estimates for the 5875 Å transition which were reported previously, but at that time dependent upon more precise knowledge of the geometric scale factor, G. Unfortunately, the greater limitations on film and photocathode sensitivities at the 6400 Å wavelength have to date prevented further quantitative estimates of the gain for that transition, but as mentioned above strong indications of gain was confirmed.

Experiments are continuing with emphasis on examination of the shorter wavelength transitions for similar evidence of gain. Priority is being placed upon the transitions at 5130 Å and 4400 Å as these have shown considerable intensity in survey spectra recently reported.[1] Nevertheless it can be expected that should gain be found in these transitions it is unlikely to exceed that characteristic of the 5875 Å feature discussed in the preceeding material. In this case it appears the realization of the recombination laser now indicated to be feasible will be contingent upon the production of a recombining afterglow of greater transverse length than can be obtained from the present Febetron 706 excitation system. From these indications it appears that excitation from a sheet beam source of the order of 1 x 10 cm in cross-section and $10 KAcm^{-2}$ current density will be needed. Further studies of the detailed requirements are in progress.

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