A GIANT PULSE RUBY LASER
CONSTRUCTION AND TECHNIQUES
OF OPERATION
by
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B.Sc., University of British Columbia, 1967

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department
of
PHYSICS

We accept this thesis as conforming to the
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THE UNIVERSITY OF BRITISH COLUMBIA
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Department of PHYSICS

The University of British Columbia
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Date SEPTEMBER 15, 1969.
SIDE VIEW OF LASER CAVITY INCLUDING MIRRORS AND DYE CELL

VIEW OF OPTICAL PUMPING CAVITY (UPPER HALF REMOVED) EXPOSING FLASH TUBES AND RUBY WATER JACKET
A giant pulse ruby laser was constructed using a 6" long by \frac{3}{8}" diameter ruby crystal. Techniques are discussed for controlling the temporal and spectral distribution of the laser output. A "Q" spoiling dye cell (cryptocyanine in methanol) was used to produce output pulses of 150 megawatts. "Mode locking" modulation of the output was also observed using the above dye cell. Using multiple surface front mirrors and apertures (3 to 5 mm. in diameter) the spectral line width of the output was reduced to .05 A.
ACKNOWLEDGEMENTS

I would like to sincerely thank Dr. R. A. Nodwell for his guidance and encouragement throughout this work. I would also like to thank Dr. J. Meyer for his encouragement and helpful suggestions during the preparation of this thesis.

I would also acknowledge the assistance of Mr. P. Haas in the construction of the apparatus.
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INTRODUCTION

The technology of giant pulse ruby lasers is of interest to plasma physicists because of potential applications for plasma diagnostics. It has become possible recently to make use of scattered laser light from high density plasmas \( n_e = 10^{16} \text{ CM}^{-3} \) as a diagnostic tool. Several experiments have been done to measure the ion temperature as well as the electron density and temperature. Velocity distribution departures from thermal equilibrium have also been measured using the laser scattering technique. These experiments all use a giant pulse ruby laser as a high power coherent light source. The high power is necessary because the intensity of the scattered light is about \( 10^{-12} \) the intensity of the incident light. Pulsed ruby lasers have also been employed in double exposure holography to record shock wave positions and standing wave vibrational modes. In the mode locked configuration, lasers have been used for multi-exposure Schlieren photographs.

The most useful of these diagnostic techniques is laser scattering. In dense plasmas \( n_e = 10^{17}, T_e = 1.5 \text{ eV} \) the electromagnetic fields between the electrons and ions set up characteristic oscillations. If the scattering vector, \( \Delta k \), is much longer than the Debye length for the plasma, the interaction of the laser's electromagnetic field and these plasma oscillations produces satellites.
These occur approximately at the beat frequency of the two fields. For the oscillations associated with the electron acoustic wave distinct and well resolved satellites occur typically at ± 30 Å from the laser wavelength. The information associated with the ion acoustic wave is contained in the central peak. This peak for the above plasma has a half width of .2 Å. In order to accurately determine the shape of the central peak it is necessary to use a laser emitting a spectral line with a half width of much less than .2 Å. Most commercial lasers cannot produce this narrow a spectral line. Those that can are prohibitively expensive.

This work was initiated after an attempt was made with a T.R.G.-10Å laser to observe the scattered signal in a jet plasma due to the ion density fluctuations. The lack of reproducibility of the spectral distribution of the laser made it impossible to obtain any information about the ions.

It is the purpose of this work to develop a technology in ruby laser design and construction which will allow the investigation of the ion temperature and density. Such technology would also be useful in holography, Schlieren, and other interferometric techniques of plasma investigation.
The physical principles behind lasing action are quite simple. In general, some medium (solid, liquid, or gas) is optically pumped to produce a population inversion between two states that are optically connected. A resonant optical cavity is then set up so that a photon spontaneously emitted by the medium is amplified to produce a standing wave pattern within the optical cavity. Some portion of the energy in the standing wave escapes through a partial mirror as the emitted laser beam. For amplification to occur, the population inversion must be great enough so that the gain per passage through the cavity exceeds the losses at the ends and sides of the cavity. It is not difficult to see that the greater the population inversion the higher the gain.

To obtain higher population inversions, the technique of "Q" spoiling is used. This means that the efficiency or "Q" of the cavity is, by some suitable method, held at a small enough value so that depletion of the upper state by stimulated emission is small, and the population of the upper level is limited only by the pumping rate and the losses. When the population inversion has reached the desired level, the Q of the cavity is quickly increased. This produces a laser pulse of higher intensity than could be achieved without Q spoiling. The two most commonly used methods of Q spoiling
are rotating mirrors and saturable dyes.

We can form an analogy between laser cavities and microwave cavities. In microwave cavities certain modes or standing wave patterns will be set up if the proper driver frequency is applied. In a laser cavity very many modes of approximately the same frequency are possible due to the large size of the cavity compared to the wavelength of light. Which mode the lasing action is initiated in is determined by the Q of the cavity for that mode and on the occurrence of a photon spontaneously emitted in that mode. The latter event is entirely random. We can see then that if the Q of the cavities for two modes is about the same, it is impossible to tell which will lase first.

The process of mode selection entails reducing the Q of all but a few, or ideally, a single mode to a level which will not produce laser action. If we can sufficiently reduce the Q of all but one mode, the emitted spectral line will be very narrow. Its half width will depend on the length and the Q of the cavity. The higher the Q, the narrower the line. More complete discussions on modes are given in books by Levine and by Lengyel. Experimental consideration on mode selection will be given in Chapter V.

The theory of modes and mode selection is not completely in agreement with experiment. The problem, in part, is due to the difficulties in applying boundary conditions to the electromagnetic theory. Experimentally, problems arise because of the inhomogenieties in the lasing medium.
CHAPTER III

DESIGN AND CONSTRUCTION OF LASER

The lasing medium used for this work is "pink" ruby crystal. In ruby crystal each unit cell contains two $\text{Al}_2\text{O}_3$ molecules. In "pink" ruby crystal about .05% of the $\text{Al}^{3+}$ is replaced with $\text{Cr}^{3+}$. The crystal axis or "C" axis for ruby can be oriented in any direction with respect to the lasing axis. If the "C" axis and lasing axis are parallel, the laser light is unpolarized. If the rod is cut so that the crystal axis is $60^\circ$ or $90^\circ$ to the laser axis the light is linearly polarized. The plane of polarization in the latter case is perpendicular to the plane of the "C" axis and the laser axis. In this work a $60^\circ$ crystal was used.

![Diagram of laser axis and "C" axis](image)
In designing the optical pumping system it is important to know the absorption spectrum of the ruby. This has been investigated by Maiman et al. The results of their work are shown in Fig. 2.

We can see there are two main absorption bands, one at 4000 Å and one at 5500 Å, each about 1000 Å wide. To optically pump these bands we use a xenon filled flash tube. Xenon is used because it produces an almost black body spectrum, with a maximum near the pumping bands.

The laser head

The laser head consists of a ruby rod, flash tubes and the optical pumping reflector or cavity that couples the
energy from the flash tubes to the ruby rod. There are many configurations for laser heads. The most common are:

the tri axial system of ruby rod, helical flash tube and cylindrical reflector;

FIG. 3

the close coupled system of linear flash tubes close to the ruby in a small cavity;

FIG. 4

the elliptical cylinder with the flash tube at one focus and the ruby at the other.

FIG. 5
The efficiency of these configurations has been studied by Congleton et al. and the results are given in FIG. 6.

In spite of the above, the choice of cavity configuration is more likely to be made from a point of view of convenience in construction and maintenance. For example, the helical flash tubes are the most efficient and capable of high energy dissipation, but they are also the most difficult to mount and maintain. Mounting problems occur because the thermal shocks produce spring like movements which crack the flash tubes. Consequently, the configuration used in this work is a modification of the single elliptical cylinder. Two elliptical
cylinders were machined in a solid aluminium block. The two cylinders have a common focal line and all the focal lines lie in the same plane. The aluminium block was cut along the plane of the three foci to form two half shells. The ruby was placed at the common focus and the flash tubes were placed one at each remaining focus.

It was found in work with a TRG 104 laser that air cooling has two disadvantages. First, the cooling of the ruby rod is inefficient. A recycle time of more than one shot per minute results in power loss. The second, and probably more serious is that air taken from the room contains sundry vapours and dust particles. As the air is blown over the surface of the rod and mirrors, the vapours and dust particles form deposits. This not only reduces transmission of light but also forms centers for absorption. This usually results in permanent damage to the dielectric coatings, or in extreme cases, to the ruby or mirror substrate. What appears to be a very small pit on the surface in the laser path usually produces very high diffraction losses. This can result in a gain of less than one and thus no lasing action.

To improve this situation the rod and flash tubes were water cooled. The air around the ruby ends and mirrors then is relatively stagnant. Also the duty cycle is limited mainly by
DOUBLE ELLIPTICAL ALUMINIUM CAVITY (ONE HALFSHELL)
the power supply (~30 sec. recharge time).

The flash tube and water jacket assembly used was the E.G. & G. - FX - 65 - B6 xenon filled. Each tube is capable of 2000 Joules energy dissipation, giving 4000 Joules maximum pumping energy. The ruby rod was a "pink" ruby, 60° cut, 6 inches long by $\frac{3}{4}$ inch diameter. The ends of the rod were cut at the Brewster angle to reduce losses at the surface. The rod was enclosed in a pyrex tube whose surface was sandblasted to defocus the incident light. Rubber "0" rings in brass fittings were used to seal the ruby to the pyrex water jacket. (See FIG. 8)

The cavity was cut by tilting a 2½" milling head at 61° and cutting one half-shell at a time. This gives an eccentricity of 0.56.

The reflecting surface of the pumping cavity was formed by polishing the surface of the aluminium block. Aluminium, under these conditions, reflects about 80% of the incident light in the absorption band region of the ruby.

The whole assembly is mounted in a lucite base and box to protect against high voltage breakdowns. The laser head is mounted at 30° to the optical bench to compensate for the Brewster ends. The cooling water is run in series, going first to the ruby and then to each flash tube. To allow the air bubbles in the cooling water to escape, the water output was always placed at the highest point in the water jacket.
The capacitor bank for the laser power supply must be designed in conjunction with a suitable flashtube. The R.C. time of the bank and flashtube should be less than one millisec. for efficient pumping. Care must also be taken that the initial current surge is low enough so that the maximum power rating of the tube is not exceeded.

The initial surge of current in the flashtube can be reduced with the aid of suitable inductances. In a delay line configuration and with the correct termination this can produce a square pulse output. This square wave can be made to end just about the same time laser action starts. The main advantage of this technique is that it increases useful flash-tube life.

The bank used in this work was split into two equal sides (one for each tube) of about 800 uF each. To increase flashtube life three inductances were placed in the circuit to help shape the pulse. (See FIG. 9)
CURRENT PULSES

The current pulse is shown in the oscilloscope trace before and after the inductances were added. This technique increased flash tube life by a factor of two or three.

There are two commonly used trigger circuits in laser flash tube discharges. The most common is the external trigger pin. Here a high voltage spike is applied to a wire in close proximity to the flash tube. This produces enough initial ionization to start the discharge. The second method is series injection triggering. Here a low inductance transformer is placed with its secondary in series with the bank and flash tube. This produces a high voltage spike across the flash tube electrodes in excess of the tube’s breakdown voltage. The secondary of the transformer must carry the full bank current. We can see the self inductance of the secondary must be low enough not to slow the main discharge significantly. The series injection removes the difficulty of high voltage breakdowns between the trigger pin and the cavity or other metallic parts. The series injection method is especially useful if the cavity and flash tube are in the same water bath.
In the latter case tap water can be circulated to cool the ruby without fear of high voltage breakdowns. In this work series injection triggering was used. Two E.G. & G. 179 trigger transformers were set up in series with the bank and the flash tubes. A circuit diagram (in block form) is shown in FIG. 11.
DIAGNOSTIC TECHNIQUES

In laser diagnostics we are usually concerned with the output beam energy, its temporal distribution, and its spectral distribution. This chapter will discuss methods used to monitor these.

The energy output of a pulse laser is usually measured with calorimetric methods. The beam is absorbed by some medium and the temperature change of the medium is monitored. In this work a commercial (T.R.G. 109) thermopile pair was used. The unit employs two identical carbon cones and two thermopiles to monitor the temperature of the cones. One cone is used as a reference and one cone is used as the energy absorber. These are connected in a bridge network and the temperature difference between them is calibrated directly in Joules. To ensure an accurate energy reading it is necessary to construct the cones in such a way as to maximize the percentage of light absorbed. The absorbing surface is the inside of a highly polished narrow cone. (See FIG. 12)
Thus all reflections are focused to the apex of the cone and the majority eventually absorbed.

Monitoring the temporal development of the laser pulse requires very fast electronics. The rise time of the Q-spoiled laser pulse can be of the order of one nanosecond. A Tektronix Model 519 oscilloscope was used to record the laser light output. It has a rise time of 0.3 nanoseconds. The 519 has only one vertical sensitivity which is of the order of 10 volts per centimeter.

To detect a fast signal of this size a Hewlett-Packard Lp 4203 photo diode was used. The rise time of this diode is quoted as less than one nanosecond. To obtain a signal of the order of 10 volts across a 125 ohm cable terminator, a 100 volt power supply was used. It consisted of a 100 volt battery and two 0.1 uF ceramic capacitors. (FIG. 13)
The capacitors are the effective power supply for short pulses (fast rise) due to the inductance of the battery. To obtain a light signal from the laser beam a clear glass plate is usually placed in the laser path approximately at the Brewster angle. Because the laser light is polarized and because the glass is placed at the Brewster angle, very little light is reflected by the glass plate. A very small part of the beam can be extracted this way.

In this work the laser back mirror was a 99.9% reflecting dielectric mirror. Some portion of the remaining 0.1% was transmitted. The photo diode was placed behind the back mirror in the 0.1% beam with suitable neutral density filters. This allowed a constant monitoring of the light output. It is possible, after calibration with the thermopile energy meter, to associate an energy with a given area under the curve and
thus to calculate power output. To do this we must be sure that the diode has a reasonably linear response to light input over the range used (\( \approx 10 \) volts). The following graph gives the voltage output compared with light input.

![Graph showing voltage output compared with light input.](FIG. 15)
To investigate the spectral distribution a Fabry-Perot interferometer was used. Photographs were taken of the fringe patterns on Tri-X-Pan (KODAK) film. The negatives were studied on a densitometer and chart recorder assembly. (Jarell Ash) The diagram below gives the schematic of the Fabry-Perot technique.

A narrow spike filter was used to eliminate all light except $6943 \pm 4 \text{ A}$. Lens "A" was used to flood the Fabry-Perot with the laser light dispersed by the ground glass screen. A PENTAX Reflex camera with a 200 mm. lens was used to photograph the fringe pattern. The camera was used at the bulb setting of the shutter which was manually held open during laser firing.
To obtain the actual intensity distribution of the fringe pattern, a calibration curve was made of film density vs. integrated light input. The film density is defined by:

\[ D = \log_{10}(\frac{i_0}{i}) \]

where \( i_0 \) is the intensity of light transmitted through unexposed and developed film.

and \( i \) is the intensity of light transmitted through exposed and developed film.

The integrated light input, or the exposure, \( E \), is defined by:

\[ E = I t \]

where \( I \) is the intensity and \( t \) is the time.

The expression for \( E \) shows that if we halve the intensity \( I \), and double the exposure time, \( t \), we obtain the same \( E \). This is not true in general. The failure of the film to follow this expression for \( E \) is called reciprocity failure. To avoid this problem all film, including the calibrations, were exposed with the laser with about 20 nsec. duration. The calibration curves were calculated from exposures with a neutral density step filter; (Hilger & Watts). This controls the exposure in convenient steps. The exposure through the \( i^{th} \) step of the wedge is given by:

\[ E_i = I t T_i \]

where \( T_i \) is the transmission of the \( i^{th} \) step.
The calibration graph was then drawn with $D$ vs. $\log E$. 

![Graph showing the relationship between $D$ and $\log E$.]
RESULTS

Chapter III was devoted to the methods used in the optical pumping of ruby rods. In this chapter we will discuss the various laser cavities used to produce laser action. Experimental results will be given for each configuration used. Before doing this the laser cavity components other than the ruby will be discussed.

In working with giant pulse ruby lasers it is difficult to avoid damage to optical surfaces. The damage results from the absorption of energy from the laser beam itself. To avoid the problem of absorption with highly reflecting back mirrors two techniques are commonly used. The simplest is the use of dielectric back mirrors. These can be made to withstand powers of the order of several hundred megawatts per square centimeter.

Such mirrors are commercially available from several optical companies. The other technique is to use total internal reflecting 90° roof prisms. Here a right triangular prism is used to reflect the light back parallel to its incident axis.

FIG. 18
The major problem with these prisms is the difficulty in polishing a 90° corner. Imperfections in the corner not only produce diffraction losses but also form centers for absorption and eventual irreparable damage. The other problem with roof prisms is the reflection from the front surface. To avoid this problem dielectric antireflection coatings can be applied or a Brewster angle can be cut on the front surface (See FIG. 18).

Front mirrors for high power lasers are usually dielectric coated to produce the desired reflection for feedback. In some cases where a low feedback is required, a parallel faced sapphire or dense glass flat can be used as a front mirror. These reflect about 8% to 10% per surface, depending on the refractive index. These flats are much less susceptible to pitting. The "Q" cell which contains methanol and cryptocyanine also has anti-reflection coatings on the outside surface. (See FIG. 19)

![Anti-reflection coated surface](image1)

![Brewster angle](image2)

FIG. 19
The alternative to using anti-reflection coatings is mounting the optical windows at the Brewster angle. The disadvantages of the Brewster angle mount is the loss of the light at the methanol-glass interface. This, however, is small.

The alignment of the various surfaces of the laser is critical. The mirror surfaces must be parallel to each other and perpendicular to the effective laser axis. The method most commonly used to align the surfaces employs an He-Ne gas laser as an auto-colimator. The laser beam is directed through a pinhole and all surfaces are aligned such that the reflections from the mirrors fall concentrically on the pinhole. The various components can also be centered on the beam of the He-Ne laser. This is especially useful if the ruby or other components are mounted to compensate for Brewster angle surfaces. The refractive index of ruby and glass does not vary significantly from 6943 Å (ruby laser wavelength) to 6328 Å (He-Ne laser wavelength). Thus these surfaces can be centered on the Ne-He beam. It is not difficult to adjust the reflected beam to within a few millimeters over 3 or 4 meters. This means we can align the surfaces parallel to each other within $10^{-4}$ radians.

An auto-colimating telescope is another method used to align laser mirrors. The image of a set of cross hairs at the focal point of the telescope main lens is centered on the cross hairs. This is repeated for each surface. This method is not useful for centering the various components on a common axis.
NORMAL MODE

A  100 nSEC/CM
B  0.1 mSEC/CM

FABREY-PEROT  1.0 A  INTERORDER SEPARATION

FIG. 20

**Laser Configurations**

The most basic configuration for laser operation is referred to as "normal mode." In this configuration the cavity in which laser action occurs is formed by two mirrors. The Q of the cavity is constant and laser action starts as soon as the population inversion is high enough to sustain it. The back mirror is usually as close to totally reflecting as possible and the front mirror is partially transmitting. The percent
transmission of the front mirror for optimum laser action is a function of ruby length and quality. In this work a 20% reflecting uncoated sapphire flat was used. The back mirror was a 99.9% reflecting dielectric coated glass flat. In this cavity threshold for laser action varied between 1800 and 2200 Joules input. The variation in threshold energy is a function of flash-tube condition, pumping cavity condition, and the cleanliness of mirrors and ruby surfaces. The actual laser output consisted of short spikes typically 50 to 100 nsec. in duration. These occur randomly at a rate of about one every 3 uSEC. The duration of this process is of the same order of time as the flashtube pulse; in this case, 5 millisec. (See FIG. 20)

The spectral distribution of the light was recorded with the Fabry-Perot. The exposure of the ring pattern was the sum of all the normal mode spikes. The spectral distribution was quite broad, typically .5 A full width half intensity (FWHI). (See FIG. 20)

The energy output of the laser was typically 3 Joules at 2 K.V. (= 3000 Joules input) to a maximum of 10 Joules at 2.25 K.V. (4000 Joules). This gives an efficiency of .25%.

"Q"-Spoiling

As was discussed earlier (see Page 3), "Q"-Spoiling is the process in which the Q of the laser cavity varies temporally. The "Q" of the cavity is held at a low value until high population
inversion is achieved. It is then rapidly changed to a high value and the high gain system produces a short duration high energy pulse.

In this work cryptocyanine was dissolved in methanol. Cryptocyanine in methanol has an absorption band centered at about 7040 Å which is 370 Å wide.3 (FWHM) (See FIG. 21)

The process of "Q-switching" with cryptocyanine involves the optical pumping of the dye's absorption band. The initial absorption is controlled by the concentration of the dye and the length of the dye cell. When the population inversion in the ruby is high enough to start laser action in spite of the dye cell losses, the dye cell is quickly pumped to transparency.
This increases the Q of the cavity. The combination of high population inversion and high Q then produces a "giant pulse."

Throughout this work an antireflection coated dye cell 10 mm. long (internal length) was used. It was positioned between the ruby and the 99.9% reflecting dielectric back mirror. The concentrations used were typically from $0.2 \times 10^{-6}$ Molar to $6.0 \times 10^{-6}$ Molar.

"Q" spoiling characteristics with dye cells

Weak Solutions

Weak solutions are solutions with a concentration of between $0.2 \times 10^{-6}$ and $2 \times 10^{-6}$ molar. The most interesting characteristic about lasing action in this region is "mode locking." Mode locking is the modulation of the output light at a frequency which corresponds to the time required for light to travel twice the length of the cavity. In this work the cavity was of the order of 0.5 metres long and the period between mode locked maxima was of the order of $1M \times 3$ nsec./$M = 3$ nsec. The temporal width of the mode locked pulse varied between about 1.0 and 3 nsec. The duration of the mode locking sequence of pulses was about 50 to 100 nsec. Fig. 22 A shows a typical pulse with a dye cell concentration of $0.67 \times 10^{-6}$ M. The time base is 50 nsec./cm. Fig. 22 E shows a similar trace with a time base of 10 nsec./cm. The above results were obtained with a sapphire front reflector, and a 99.9% reflecting dielectric back mirror.
MODE LOCKING

DYE CELL CONCENTRATION
= \(0.6 \times 10^{-6}\) M.

FIG. 22

If the pumping energy is increased in this configuration double pulsing occurs. Because of this, the energy in any one pulse is limited. The spectral distribution of the mode locked pulse is fairly broad. Fabrey-Perot measurements give line widths of the order of .3 to .4 A.
It is interesting to notice the secondary modulation of some of the mode locked pulses. In FIG. 22 E, for example, the modulation suggests a beating of two frequencies approximately 8% apart. This could be explained if a secondary cavity 4% shorter existed. No such cavity exists. Similar traces are shown in FIG. 22B, C, D, F. It is clear from traces like FIG. 22B and 22D that the beating effect is inconsistent from shot to shot. We can see from traces in FIG. 22C and 22D that the beating effect is not amplitude modulation. Here the pulses are much more spike shaped and the out-of-phase components can be resolved. The origin of these different frequencies is not known.

In a mode locked spike the energy output is typically .05 Joules. The temporal half width of each spike is of the order of 2 nsec. This gives an average power per spike of .05 J/2 nsec. = 25 M watts.

In some cases mode locking does not occur. Then a 50 nsec. duration pulse with about 1 Joule of energy is typical. The spectral distribution is effectively the same as for mode locking. If a pulse of this nature is required consistently it can be obtained by placing a second front mirror in the laser cavity. In this work a sapphire flat was added to the system at a distance of about 10 inches from the front mirror (also sapphire). It was positioned by trial and error until mode locking was suppressed. Then an output pulse of .5 Joules in 40 nsec. was
typical. This is for 2.2 KV input. The dye cell concentration was $1 \times 10^{-6}$ Molar.

**Intermediate Solutions**

Intermediate solutions are those with a molarity between $2.0 \times 10^{-6}$ and $2.5 \times 10^{-6}$ molar. In this region mode locking occurs infrequently. About one in twenty shots will have regular modulation with the characteristic periodicity. Even in these cases the percent modulation is low compared with weak solution work. In general the pulses are non-uniform and non reproducible. This is attributed to the random starting time of the various modes that form the laser output. The pulse length for weak solutions was of the order of 50 to 100 nsec. The pulse length for intermediate solutions was between 25 and 50 nsec. The total energy output for weak and strong solutions was about equal for the same pumping energy. We can see then that the power output, not the energy output, is a function of the dye cell concentration.

The spectral distribution is still quite broad. The line typically has a half width of $0.25$ A. FIG. 23 shows the spectral and temporal distribution of an intermediate concentration laser pulse.

As with weak solutions, if the pumping energy is increased the laser gives double or triple pulse output. It was
noticed, in the Fabrey-Perot pictures of double pulses that a doublet structure appeared. This indicates that if the laser pulses twice it does so at different wavelengths. The wavelength difference is of the order of 0.2 Å (FIG. 24). The wavelength shift is possibly due to the heating of the ruby red by the flash tubes. This would change the effective cavity length and consequently the modes selected by the cavity. If we assume that the rate of change of the temperature of the rod is constant over the time between pulses, we can calculate the
expected spectral broadening of each line due to heating. The time between pulses in double pulsing is of the order of 300 nsec. The duration of each pulse is typically 50 nsec. Therefore, the wavelength shift during a pulse is \( \frac{0.05 \text{ usec.}}{300 \text{ nsec.}} \times 0.2 \text{ A} = 3 \times 10^{-5} \text{ A} \). This shift is clearly negligible compared to the 0.2 A half width of the line.
Strong Solutions

Strong solutions are those with a molarity between $2.5 \times 10^{-6}$ M and $6 \times 10^{-6}$ M. Above concentration of $6 \times 10^{-6}$ M, laser action did not occur.

The strong solution region is the most commonly used in dye Q spoiled ruby lasers. Strong solutions produce the shortest pulses and the highest power output. Pulse lengths as short as 10 nsec. were recorded. FIG. 25 was obtained with a cell concentration of $3.0 \times 10^{-6}$ M. The energy contained in
this pulse was 1.5 Joules. This gives a power output of 150 MW. In 13 shots taken at this concentration there was no double pulsing recorded. Also in the Fabrey-Perot pictures of these 13 pulses, no doublet structure was evident. FIG. 25 shows a typical Fabrey-Perot picture of strong solution laser spectrum. The half width of the line is of the order of .2 A. It was noticed in the work with strong solutions that the temporal development of two different pulses was quite similar. (See FIG. 25A, B, C). This reproducability indicates that fewer modes are producing laser action and that possibly the modes are lasing in the same order each time.

In all the dye cell work to this point a 99.9% reflecting dielectric back mirror and a sapphire (uncoated) front mirror were used. The dye cell was placed between the ruby and back mirror. In mode lock suppression an extra sapphire front mirror was added.
Cavity Configurations

We discussed earlier in this chapter the effect of the dye cell concentration on laser action. In this part we wish to discuss some of the different cavity configurations and their effect on laser action. We are specifically interested in spectral line width.

The spectral line width is determined by the modes that propagate within the cavity. We usually speak of two classifications of modes, transverse and longitudinal. Longitudinal modes occur because standing wave patterns with a different number of wavelengths can occur along the same axis in the same length of cavity. Transverse modes occur because standing waves can produce different phase patterns across the laser cavity. These are exactly analogous to microwave transverse modes.

The ruby emission band is several Angstroms wide at room temperature. For a one meter long cavity this would result in several hundred longitudinal modes, all of high Q. To select longitudinal modes we must reduce the Q of the cavity for those modes we wish to eliminate. This is done by adding reflecting surfaces to the front mirror. The transmission through this combination is the same as for a Fabry-Perot. As a result, the only modes that propagate are those modes whose wavelengths are common to all the resonant cavities in the system.
These modes must satisfy \( n_i \lambda = 2 d_i N_i \cos \theta \)

where

- \( n_i \) = number of wavelengths in cavity of length \( d_i \)
- \( \lambda \) = wavelength of light
- \( d_i \) = length of cavity
- \( N_i \) = refractive index in cavity
- \( \theta \) = angle of deviation from the normal of the mirror.

The modes must also lie in the emission band of the ruby.

An uncoated sapphire flat was used as a front mirror. This gave two surfaces to select longitudinal modes. In a few cases a third surface, a dielectric 30% mirror was added to the front mirror.

The single sapphire flat was not successful in reducing the spectral line width, even at low powers. It was expected that firing the laser close to threshold should reduce the line width by reducing the number of modes with a high enough population inversion to lase. The failure of this technique was attributed to inhomogeneities in the ruby rod.

To overcome this, small diameter apertures were added to the cavity near the surfaces of the ruby. Using only a small part of the ruby for lasing and working near threshold we obtained a relatively narrow line. Line widths between 0.15 and 0.08 Å were recorded with apertures between 0.5 cm. and 0.2 cm. in diameter. It is also possible that these apertures had some effect in reducing the number of transverse modes. The main drawback to this method
is the low power output. Energies of .05 Joules in 20 nsec.
were typical. This gives a power of only 2.5 megawatts.

FIG. 26 shows a typical Fabrey-Perot picture for low
power aperture work. In an attempt to improve this result a 30%
dielectric mirror was added to the sapphire front reflector system.
It was positioned about 5 mm. from the sapphire flat. FIG. 27
shows the Fabrey-Perot trace for this configuration (with strong
dye cell solution). Three distinct wavelengths are evident.
The laser didn't double pulse during these shots so we attribute
these spectral lines to the same laser pulse. Densitometer traces
TRIPLE FRONT REFLECTOR NO APERTURE
20 nSEC/CM 3.2 X 10^-6 M.
FIG. 27

3 m.m. APERTURE 3.2 X 10^-6 M.
20 nSEC/CM
FIG. 28
EXTENDED CAVITY (1.0 Meter)
TRIPLE FRONT REFLECTOR
3.2 X 10^{-6} M 10 nSEC/CM

FIG. 29

gave the half width of the most intense line to be .11 A ± .01 A. The uncertainty in measurement is due to the grain of the film producing inconsistent half width measurements. The other lines were both measured to be .10 A ± .01 A. At this point a small aperture (D = 4 mm.) was added between the ruby and front mirror. Working near threshold with this aperture the following two Fabrey-Perot pictures were typical. (FIG 28 A and B)

These two pictures were taken with the aperture in different transverse positions. Densitometer traces of FIG. 28A
gave a half width of \( 0.11 \pm 0.01 \text{ A} \) and of FIG. 28B gave a half width of \( 0.06 \text{ A} \pm 0.01 \text{ A} \). The power output was typically \( 0.1 \) Joules in 20 nsec. or 5 megawatts.

It is possible the aperture to some degree controlled the transverse modes.

In an attempt to reduce the Q of some of the transverse modes, the main cavity was extended to about 1 metre long from 0.6 metres. The same techniques as above produced a spectral half width of \( 0.04 \text{ A} \pm 0.01 \text{ A} \). The power was of the order of 5 megawatts. (See FIG. 29)
CONCLUSIONS AND FUTURE IMPROVEMENTS

This work has presented techniques useful in producing high power laser pulses as well as narrow spectral lines. However, the basic incompatibility of these two objectives has also been demonstrated. One hundred megawatt powers can be obtained if line widths of the order of .3 A are tolerable. With slight modifications to the system, line widths of .05 A are possible if powers of 5 megawatts are usable. With this latter setup it would be possible to determine the ion temperature and density in a plasma jet with the technique of laser scattering.

Further improvement on the spectral line width with the laser rod presently employed would be very difficult owing to the inhomogeneities of the ruby. If a better rod were available, more sophisticated techniques of mode control could be used. In particular, spherical mirrors in a confocal configuration have been used to produce single mode laser action. The big advantage to confocal mirror configurations is the degeneracy in the wavelengths of the transverse modes. This would make narrow spectral lines possible at relatively high powers. For this system to be useful a ruby rod of higher optical quality than was used here is necessary.
BIBLIOGRAPHY


