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Vulcan: A Versatile High Power Glass Laser User Facility

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ABSTRACT

This paper describes the design criteria which have led to the present configuration of the VULCAN glass laser system. The laser provides facilities for university users for research in a number of different areas. This broad user base has led to a facility which is extremely versatile and the demands placed on it have led to a relatively high repitition rate.

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I. Introduction

The Central Laser Facility at the SERC Rutherford Appleton Laboratory has operated a high-power neodymium glass laser, Vulcan [1], for over ten years. During this time the output energy has risen from 20 J in two beams to the current level of 2.8 kJ in eight beams.

The user community, mainly comprising of groups from British universities, has been active in research areas such as X-ray laser studies [2], laser compression [3] and laser matter interactions [4]. Their requirements have varied in terms of total power and energy, range of pulsewidths, spatial and temporal quality of beams and the repetition rate of firing full power shots. This has resulted in the development of a laser system where the above requirements may be accomodated in a versatile and flexible way to meet user demands.

We report here the current status of the Vulcan laser following an upgrade carried out in two stages in February-May 1988 and April-June 1989. In the first of these, all laser components except the master oscillators and preamplifier systems were replaced and restaged. All new components, including rod amplifiers, vacuum spatial filters and disc amplifiers were designed and tested at RAL. The restaging has given improvements in the beam quality, allowed higher total energies to be delivered on target (both at 1053nm and 0.527nm) and provided better image relaying towards the target plane. In the second stage of the upgrade two 150mm diameter disc amplifiers were added to provide high energy backlighting beams. In addition, image relaying of the output of the laser to the furthest of the three main experimental halls has been installed to permit operation in this area at the highest powers available from the laser.

II. Design Considerations

The Vulcan laser is designed to support a user community with wide interests in plasma physics; ICF issues including thermal transport and hydro instabilities, x-ray laser research, the simulation of astro-physical plasmas, and biological uses of x-rays. To enable several different research programmes to run concurrently the laser is scheduled to provide some twenty runs a year, each lasting for four to six weeks and with two target areas operating on alternate laser shots. The requirements on the laser vary between the different experiments in terms of number of beams, pulsewidths, energies etc. Consequently in redesigning the laser system, flexibility and adaptibility was of primary importance.

This requirement for versatility and cost effectiveness dictated the following points in the design: the availability of different pulsewidths along a number of beamlines and the need to be able to switch these from shot to shot meant that full image relaying [5] could not be employed; the premium on experimental time available to each user group meant a high full-power shot rate was required. This led to the development of a cooling system for disc amplifiers to permit shots every twenty minutes.

The output stage of the VULCAN laser is based upon 108 mm clear aperture disc amplifiers. Space and cost considerations prohibited the installation of additional larger aperture amplifiers to boost the output energy. Instead, improved energy extraction has been achieved by increasing the fill factor to approximately 0.8 by propagating a flat-topped apodised beam.

These points, together with others relating to ease of alignment, servicing of the various components and more efficient operation of the laser in general, were incorporated into the new system.

III. System Description

(i) General Layout.

A schematic of the Vulcan laser system is shown in Figure 1. The "standard" layout of Vulcan consists of two synchronised Nd:YLF oscillators operating at a wavelength of 1053nm and feeding chains of phosphate glass rod and disc amplifiers. The oscillators are described in Section IV(i).

The pulses from each oscillator are amplified in independent but identical short and long pulse rod amplifier chains, with amplifiers of sizes 9mm, 16mm, 25mm and 45mm in diameter. Under normal operating conditions, these amplifiers give gains of 40, 25, 15 and 10 respectively. In each chain, an air spatial filter, positioned beteween the 9mm and the 16mm amplifiers, is operated close to diffraction limit to provide a smooth input beam to the rod amplifier chains. Following the 16mm amplifier, the beams are collimated by a vacuum spatial filter (VSF) and remain so through out the rest of the laser system. Further VSFs are used between each subsequent stage of amplification to limit the nonlinear growth of intensity perturbations. The characteristic measure of this phenomenon, the B-integral, has a maximum total value of 3 for each rod amplifier chain while its value for any one stage does not exceed 1.3 for short pulse operation. A Faraday isolator and 50mm-diameter Pockels cell are also present in each chain to isolate the system from backward reflections and to prevent amplification of spontaneous emission. The Pockels cells have a gate of 25ns which is synchronised to the laser pulses.

The beams are apodised following the 16mm amplifiers using the soft-aperture technique developed at the Lawrence Livermore National Laboratory (LLNL)

[7]. These apodisers modify the spatial profile of the beams to a quasi flat-top one. A typical near-field output of the rod amplifier chain is shown in Figure 2. At the output of the rod amplifier chains, the beams are approximately 40mm in diameter. About 15J of energy is available in a 1ns pulse and about 3J in a 100ps pulse. Due to the efficient cooling regime of these amplifiers, these energies can be delivered every two minutes. These shots prove useful in timing of the various beams of the laser and in tuning of the harmonic crystals.

Following the rod amplifier chains, either of the pulses can be injected into the six-beam system or the two-beam "backlighting" system. This is achieved by using remotely controlled mirrors on kinematic mounts and 50% splitters as appropriate. This configuration can be changed on a shot to shot basis and in this way, any combination of pulsewidths in the main beams and backlighting beams can be delivered.

The six-beam system consists of a VSF which increases the beam size to 100mm followed by a two-way splitting of the beam. These beams are then double-passed in 108mm diameter box disc amplifiers using Faraday rotator/polariser combinations. These two beams are then split into three and these six beams are then amplified by a single-pass through 108mm diameter box disc amplifiers. The backlighting beams are identical to the main beams as far as the double-pass stage. Following this, the beams are expanded to a size of 150mm and then amplified in further box disc amplifiers. As in the rod amplifier chains, the beams are spatially filtered following each stage of amplification.

Throughout the entire system, the VSFs range from f/16.2 in the early part of the rod chain to f/40 at the output of the laser. Pinhole sizes are chosen to effectively filter the beam but are kept large enough to avoid pinhole closure, during the pulse, due to plasma blow-off [8]. This leads to pinhole sizes which are 5-20 times diffraction limited, depending on the pulse duration being used.

Each of the six beams is capable of delivering a maximum of 300J of energy in a 1ns pulse (limited by damage to components at the output of the system) or about 80J in a 100ps pulse (limited by the onset of small scale self focussing). The backlighting beams can each produce 500J in a 1ns pulse. Full power shots can be fired every twenty minutes, this time being determined by the cooling requirements of the disc amplifiers (see Section III(iii)).

(ii) Rod Amplifiers

During the upgrade, existing 16mm, 25mm, 32mm 45mm and 76mm rod amplifiers, originally supplied by Quantel of France, were replaced by RAL designed and tested units of 16mm, 25mm and 45mm size. These Quantel amplifiers had been in service for ten years and a variety of improvements which could be made to ease servicing and eliminate potential problems had become obvious. These included: the insertion and orientation of the rod inside the amplifier; ease of diagnosis and repair of faults inside the housing; water leaks and subsequent electrical problems at the termination of the flashlamps and the entire amplifier being able to be removed and replaced without realignment.

A 45mm amplifier of the new design is shown in Figure 3. With the installation of these new amplifiers, the down-time of the laser has been greatly reduced. A faulty amplifier can easily be replaced by a new, properly-orientated one by use of kinematic bases. Faults arising from the build-up of air pockets have also been eliminated by modifications to the housing. The deionised water/glycol mixture used to cool the flashlamps has also been centralised in a single reservoir instead of being in separate units for each amplifier.

(iii) Disc Amplifiers

(a) Cooling Enhancement

Prior to the upgrade, the disc amplifiers used on Vulcan had been based on the design developed at LLNL. Originally, the recommended maximum repetition rate for firing of these amplifiers was one shot per hour but even at this rate, some residual thermal effects degraded the beam quality over a period of time. Due to the need to fire more regularly while still maintaining the beam quality, a study was undertaken to improve the cooling regime of these amplifiers.

These tests were performed using a 108mm amplifier in double-pass configuration followed by a VSF as shown in Figure 4. The far-field image of the transmission of the pinhole was obtained using a 10m focal length lens. Initially, without firing the amplifier,the normal transmission of the pinhole was determined. The amplifier was then fired seven times on a twenty minute cycle. The transmission of the pinhole was then measured, using low energy rod shots, during the period the disc amplifier thermally stabalised. The results of these can be seen in Figure 5 (curve A).

These tests showed the serious degradation in the pinhole transmission with this rapid rate of firing. Measurements of the cooling rates of various parts of the amplifier assembly showed that the flashlamps, the flashlamp reflectors and the disc shield retained most of the heat following a shot. The cooling system was consequently redesigned to try to extract thermal energy from these components more effectively. The new cooling scheme is shown in Figure 6.

The new scheme feeds nitrogen gas into the disc cavity through two manifolds running the length of the amplifier. Jets of gas are introduced into the dead spaces between the discs which had previously retained heat. The jets create turbulence in these spaces and carry heat away to the ends of the amplifier where the gas exits. Additionally, a high efficiency fan was fitted to blow air into the lamp assembly. This air is drawn from the laser clean-room via a 99.997% HEPA filter. The two separate lamp assemblies are coupled together at one end and the air is freely discharged from the other end of the assembly. Nitrogen is fed into the coupled ends to achieve efficient oxygen purging. In operating this system, the nitrogen supply is stopped one minute before a shot is fired, to prevent turbulance within the amplifier. Immediately following a shot, all air and nitrogen supplies are turned on. The air is turned off five minutes before a shot to allow all the oxygen to be purged by the nitrogen.

Following these modifications, the amplifier was replaced in the arrangement shown in Figure 4 and the experiment repeated (Figure 5, curves B-E). The differences between Curves A and B can only be due to static mechanical alterations. A comparison of the far-fields of the VSF pinhole transmission with and without cooling is shown in Figure 7. These results were obtained following a series of seven disc shots fired on a twenty minute cycle. These results showed that cooling of the disc cavity and lamp assemblies permits a twenty minute shot cycle to be maintained without any serious beam distortions.

(b) "Box" Amplifier Design

Since the upgrade required doubling the energy and power of a single beam, an amplifier of roughly twice the active area of a 108mm amplifier was needed. One of the reasons for choosing the 150mm size was that LLNL use this size of amplifier so the acquisition of the discs would be easier than with a totally new size. From LLNL measurements [9] on different types of disc amplifiers, a "box" design was selected to maximise the input energy requirements while using fewer flashlamps.

The main feature of the box design is that unlike the old cylindrical amplifiers, all the flashlamps "see" the face of the discs so that the coupling efficiency is much higher. However, with fewer flashlamps, the expected gain is less for fixed energy input. The gain can be improved, though, by increasing the bore size of the flashlamps and by increasing the doping of the discs from 2% to 3%. A prototype 150mm box disc amplifier was built and is shown in Figure 8. This amplifier contained four 30mm thick discs of phosphate glass with 3% Nd doping and was pumped by twelve 20mm bore flashlamps with 190kJ storage.

The entire assembly was rigorously tested to assess its performance under active conditions. Cooling and beam distortion tests similar to ones already described were conducted and the results are shown in Figure 9. The pinhole used in these transmission studies was 2 x diffraction limit (about 30urad) and so it was sensitive to small changes in beam quality. The amplifiers were tested in double-pass configuration although they would only be used on Vulcan in single-pass mode. Hence, real performance of the amplifiers would be significantly better than shown. Despite this, however, the results show that beam deterioration is modest with more than 60% of the energy within 25μrad. This represents a large improvement on the 108mm cylindrical disc cooling already described.

Gain measurements also showed a small-signal single-pass gain of 4.3 at 190kJ energy storage by the flashlamps. Other beam propagation tests indicated that at even at shot rates as high as four per hour, near diffraction-limited optical quality was possible with this design.

Following this successful testing of this box design, all 108mm cylindrical disc amplifiers were replaced with 108mm box amplifiers during the 1988 upgrade. These amplifiers contained six 30mm-thick discs and were pumped by eight 25mm-bore flashlamps.

After one year of operation only one amplifier had to be removed from the system to be serviced. The performance of these amplifiers has been excellent in terms of gain and in their ability to fire every twenty minutes without beam distortions. The 150mm box amplifiers have now also been installed on Vulcan and their performance in the system is currently being analysed.

(iv) Capacitors

During the first upgrade period, the capacitor banks for the disc amplifiers were moved to a new building adjacent to the laser bays. All the capacitors required were installed during the 1988 shutdown. Due to the box design for the disc amplifiers, the energy requirements for the 108mm amplifiers had been reduced from 200kJ to 180kJ per amplifier. The 150mm amplifiers required 200kJ each. One major change in the capacitor bank circuits was the installation of one ignitron switch per amplifier. This allowed individual timing of each amplifier in relation to the laser pulse and hence gave control of the balance in the output energies of the laser.

IV. Oscillators

A variety of different oscillators are used on Vulcan and these are briefly described here:

(i) the "standard" oscillators in the system are an actively modelocked and Q-switched oscillator [10] sychronised to a single longitudinal mode Q-switched oscillator. The outputs of these two oscillators are typically 80ps and 0.4 - 6 ns respectively;

(ii) two synchronised oscillators, similar to the actively modelocked one in (i), but with one operating at 1053nm and another at 1064nm. These two oscillators, provide 200ps pulses, for "Beat-Wave" studies [11];

(iii) a Nd:YLF active/passive modelocked [12] oscillator using saturable absorbers to provide 20 - 30 ps pulses for X-ray laser experiments [13];

(iv) a broadband oscillator employing phosphate glass as the active medium [14] to produce 0.6 - 6 ns pulses with a bandwidth of about 1.2 nm for ISI studies [15]-[18]. This oscillator can be sychronised to the standard oscillators in (i);

(v) development work is in progress to generate sub-picosecond pulses on Vulcan using fibre/grating pulse compression [19].

V. Data Acquisition

Computer control of the operations of Vulcan has been achieved over the past twelve years using a GEC 4080 system. Modifications to the operating program over this time had led to the fragmentation of the code and frequent program changes had become necessary. This, together with the lack of programming power compared to modern computers and high maintenance costs, has led us to replace the 4080 with two IBM PC clones, namely Tandon PCs. These two are linked by a simple network which allows archiving of the data acquired by the experimenters and gives access to all the information gathered on every shot. This information can include the energies of each beam at ω and 2ω, streak camera analysis of the pulsewidths, determination of the level of pre-pulse present and a framestore image of each of the beams at the output of the laser to ascertain the beam profiles.

VI. Summary

The present state of the Vulcan glass laser has been reported and a summary of the capabilities of the laser is given in Table 1. The reasons behind the development of such a laser system for multi-user experiments have been highlighted and the design modifications needed to achieve this, in particular the increase in the firing rate of the disc amplifiers, have been described.

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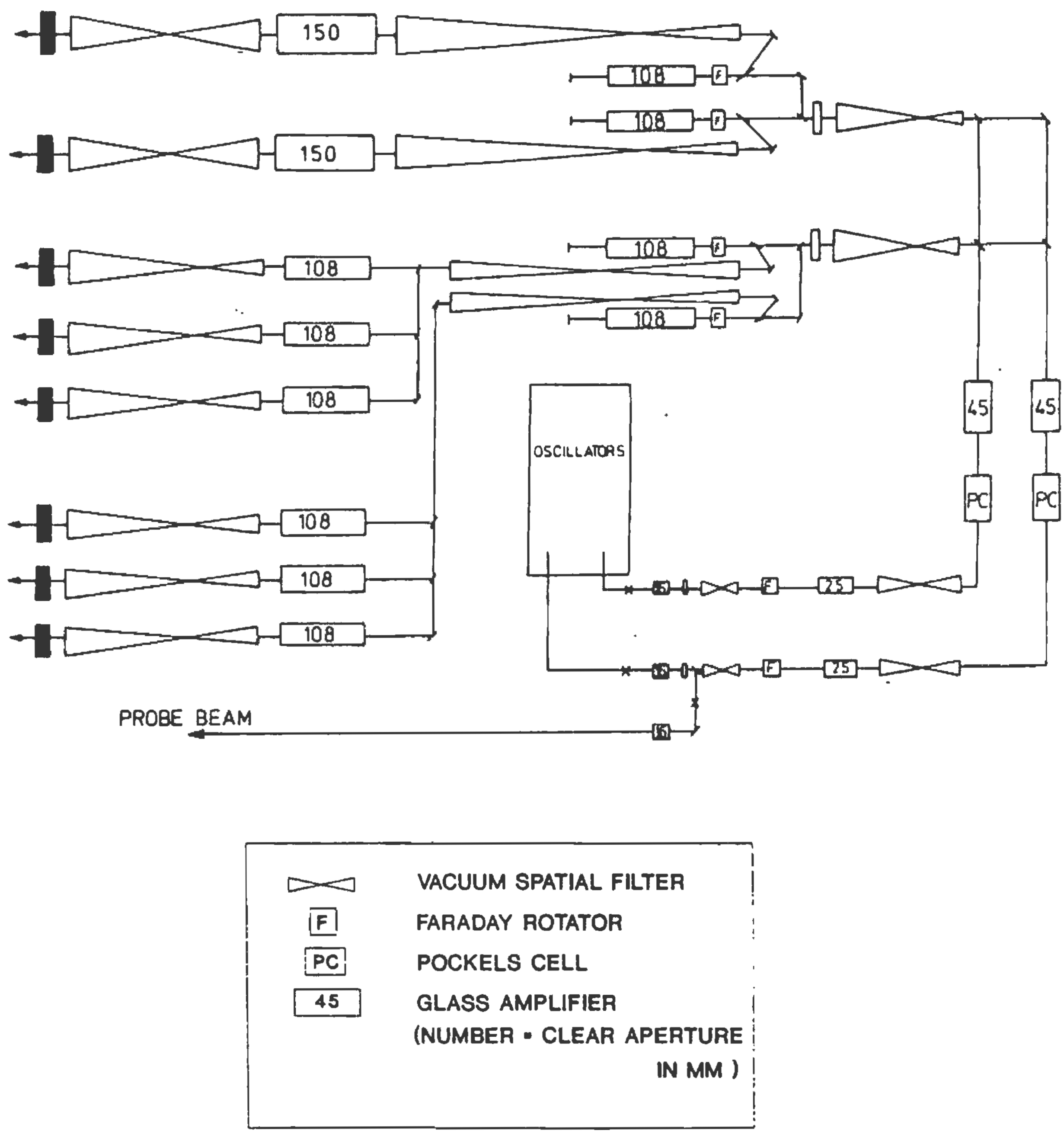
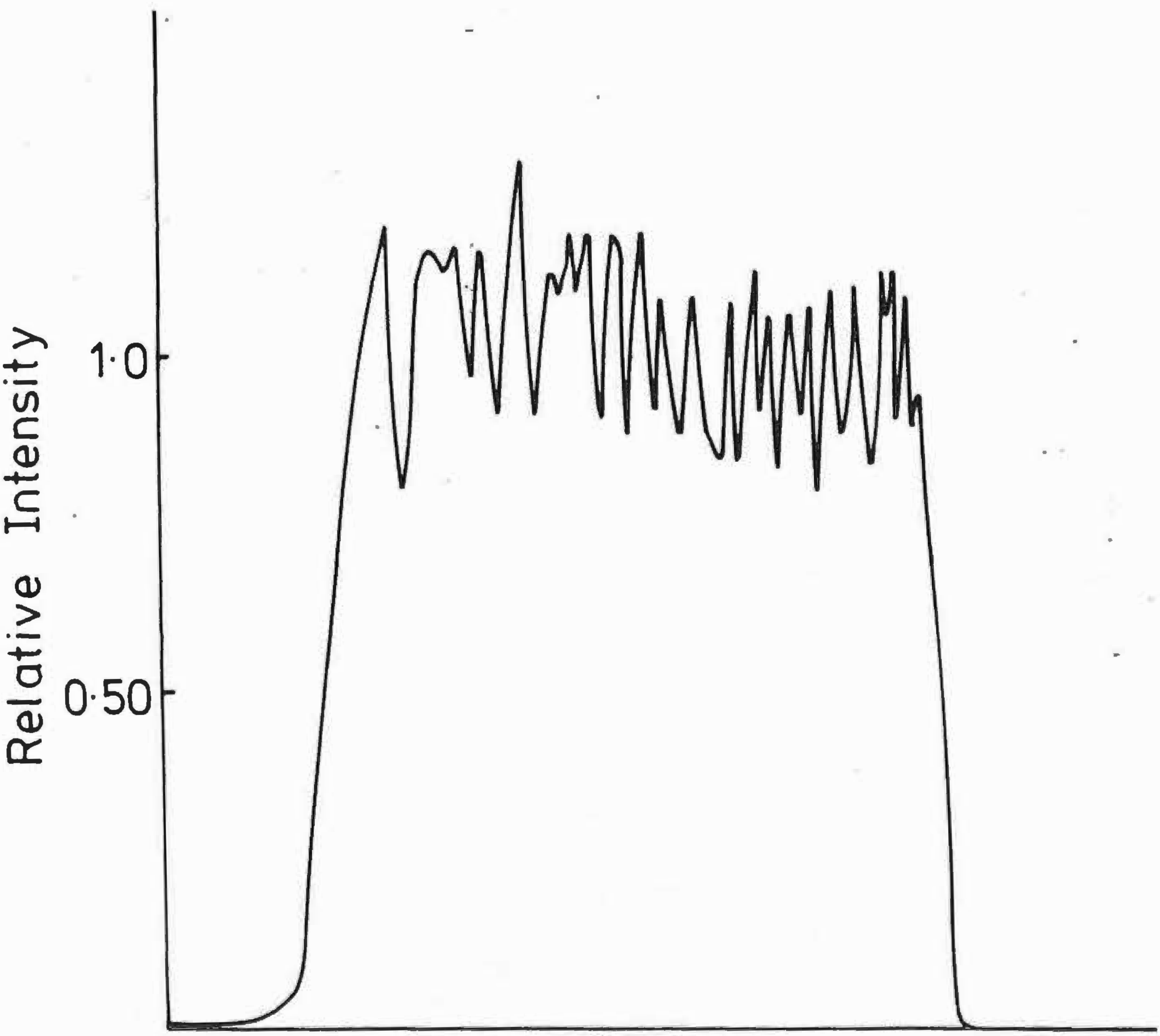


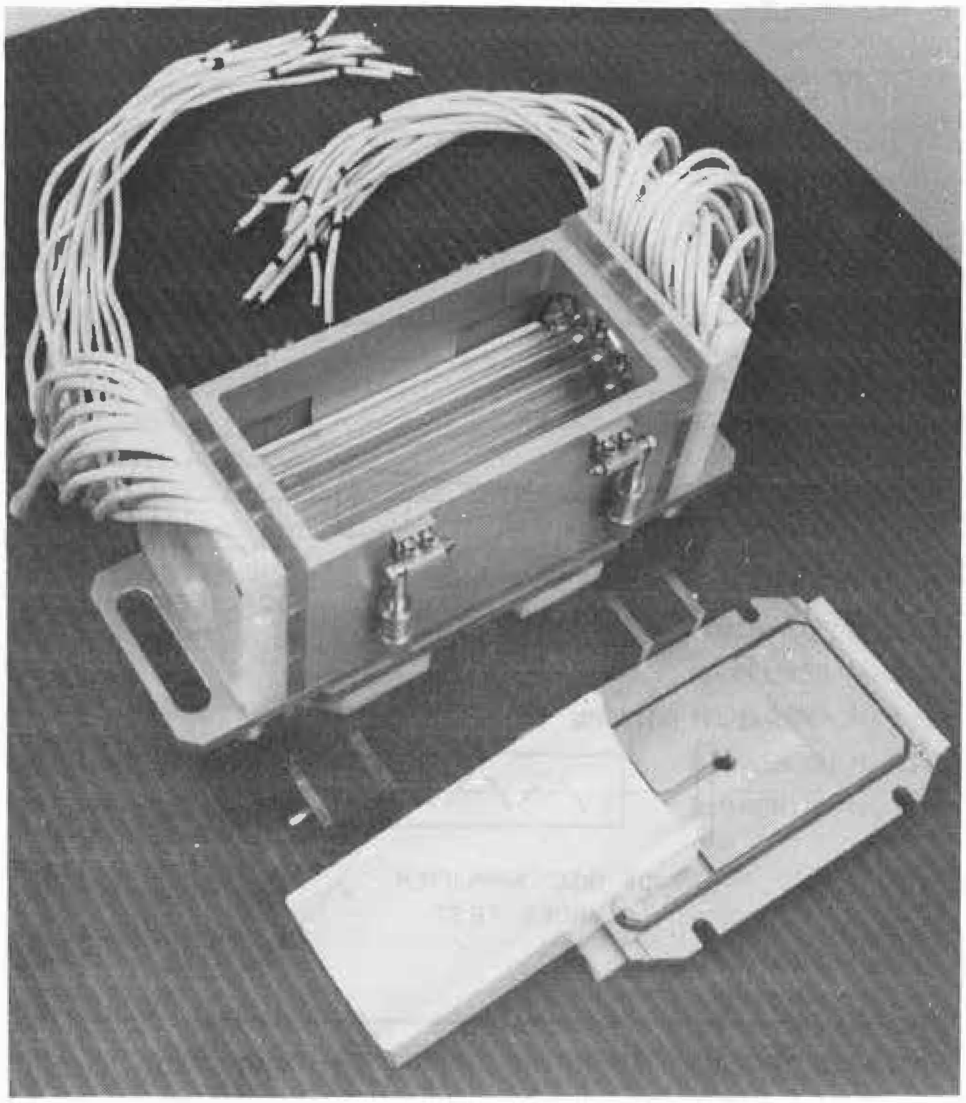
Schematic Layout of the VULCAN Glass Laser System

Figure 1



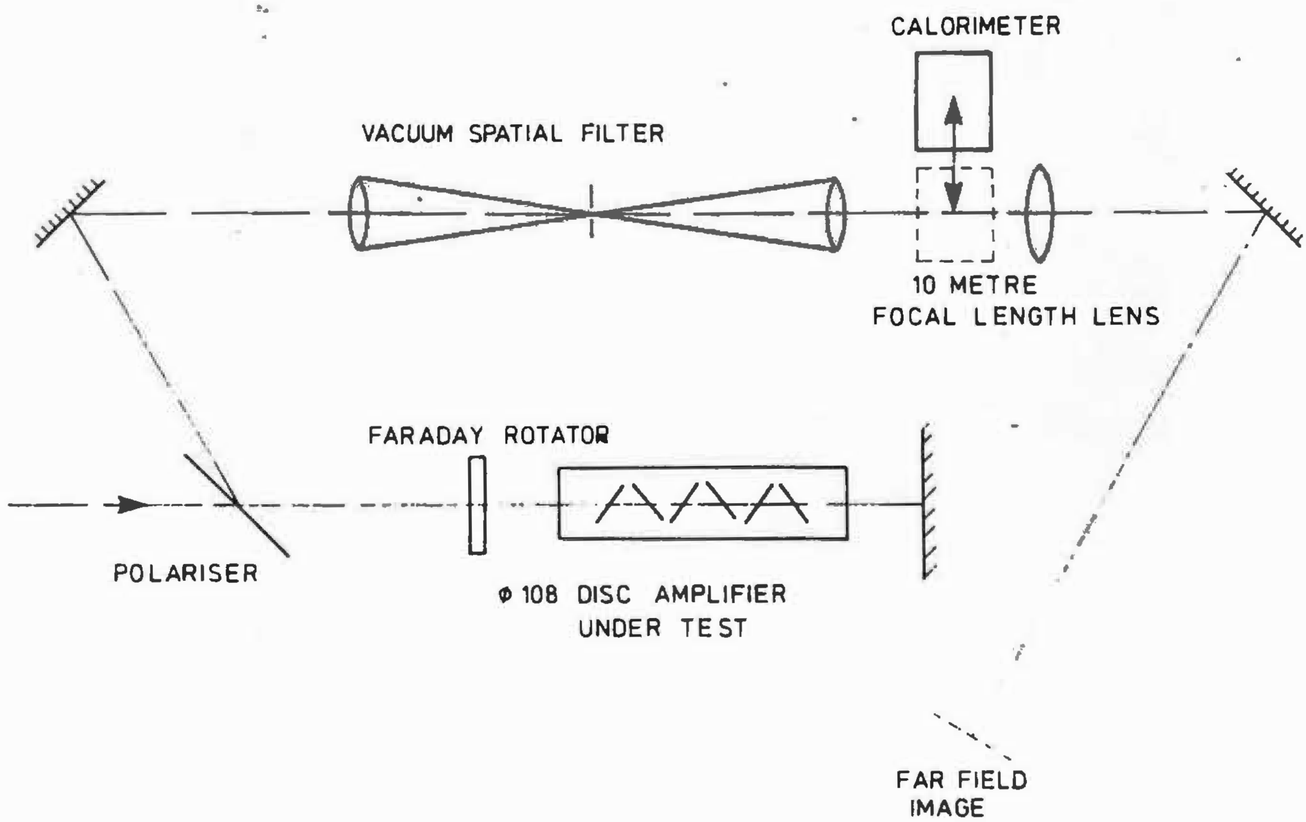
Near-field Profile at the Rod Chain Output

Figure 2



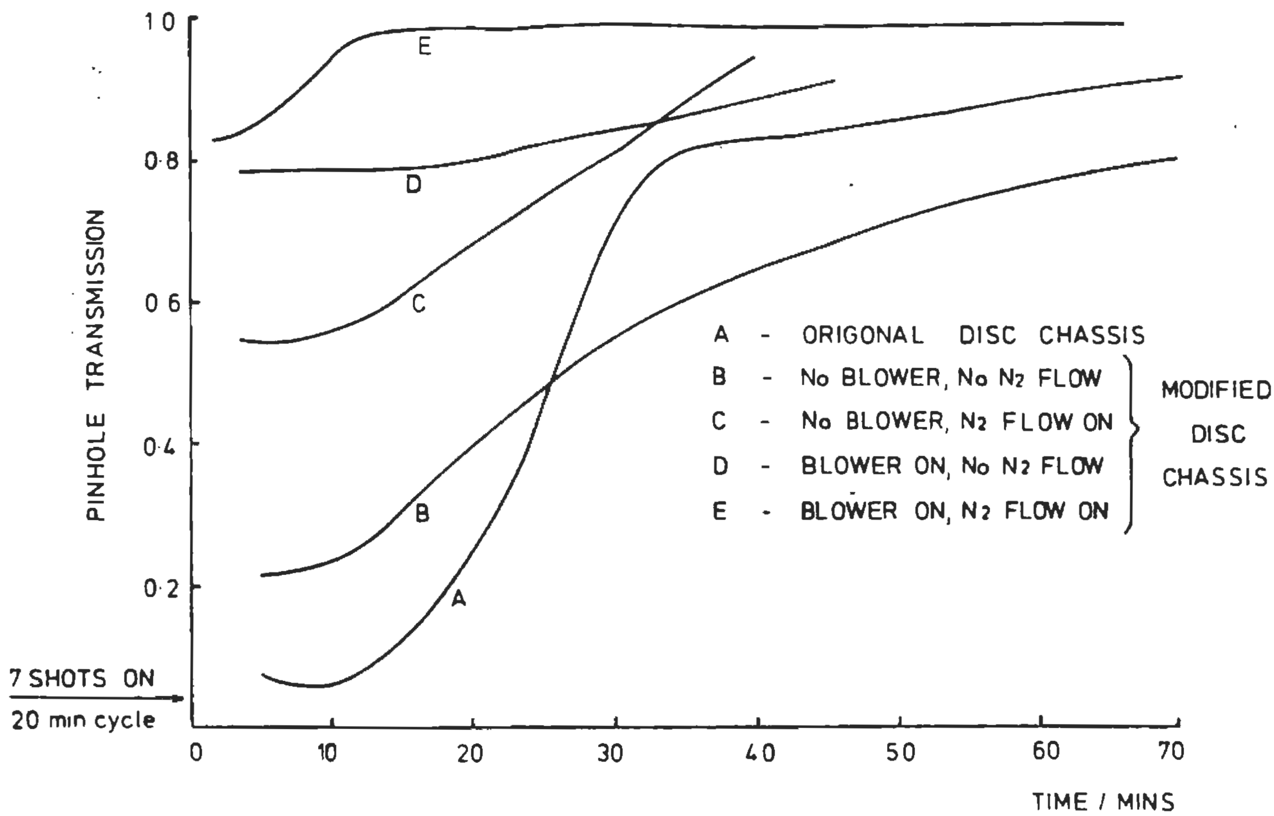
45 mm Diameter Rod Amplifier Assembly

Figure 3



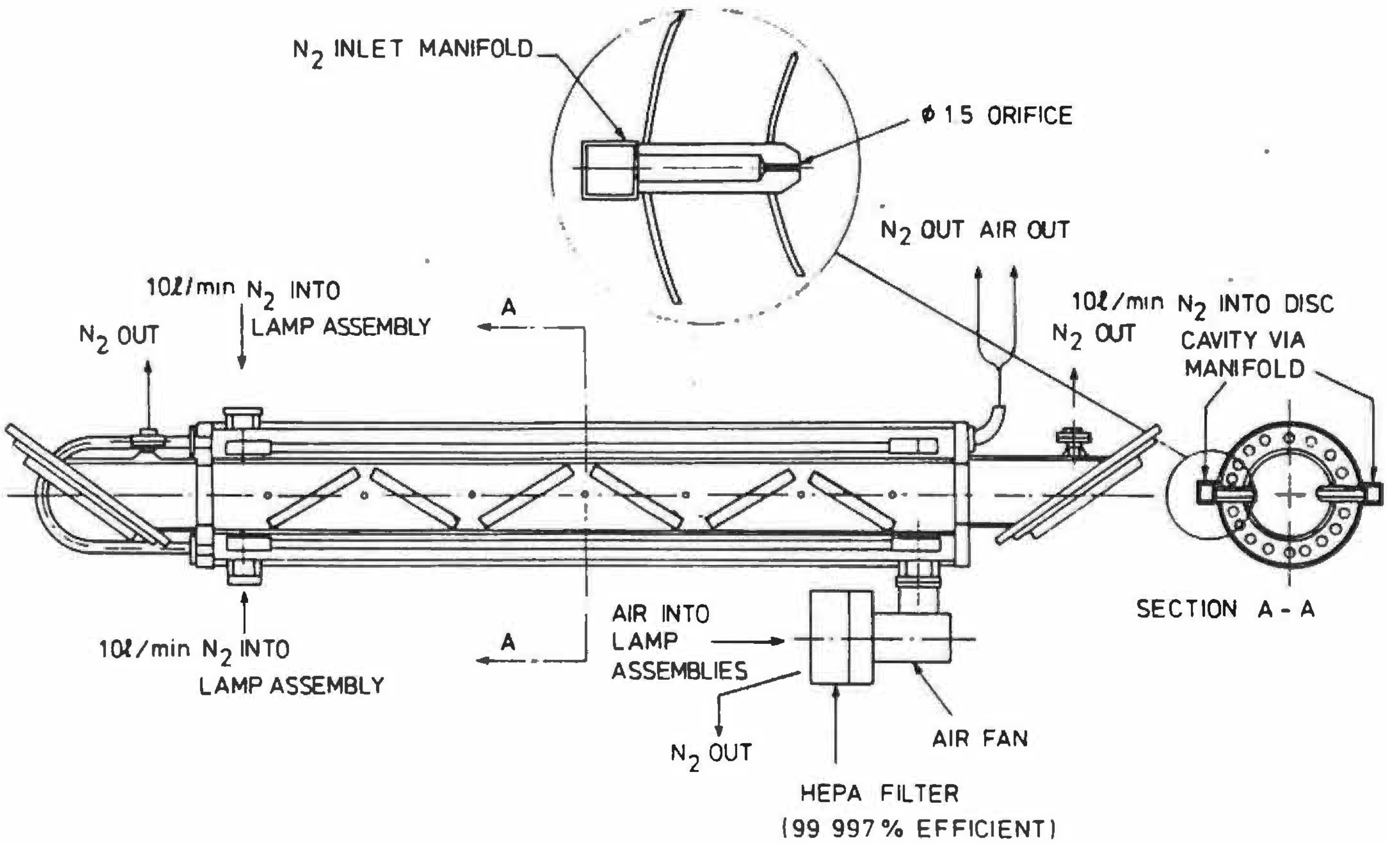
Experimental Layout for Disc Amplifier Testing

Figure 4



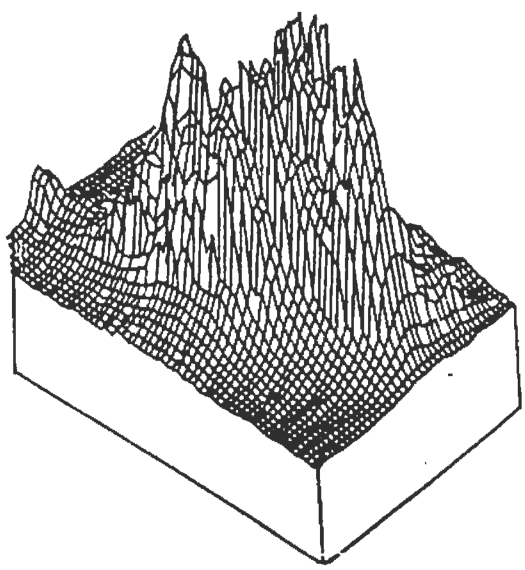
Results of Disc Amplifier Testing

Figure 5

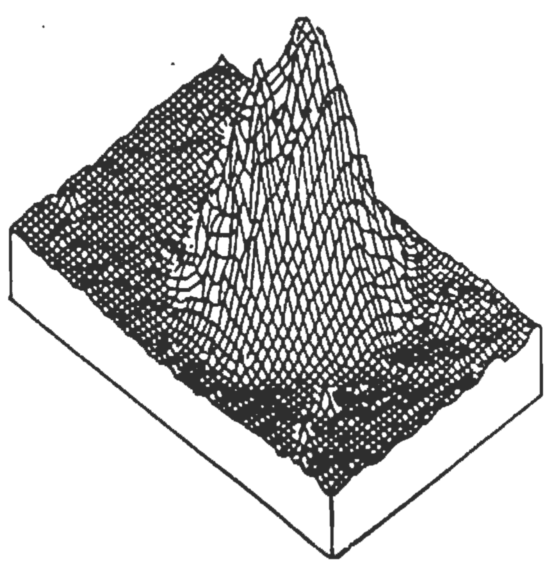


Cooling Scheme For Disc Amplifiers

Figure 6



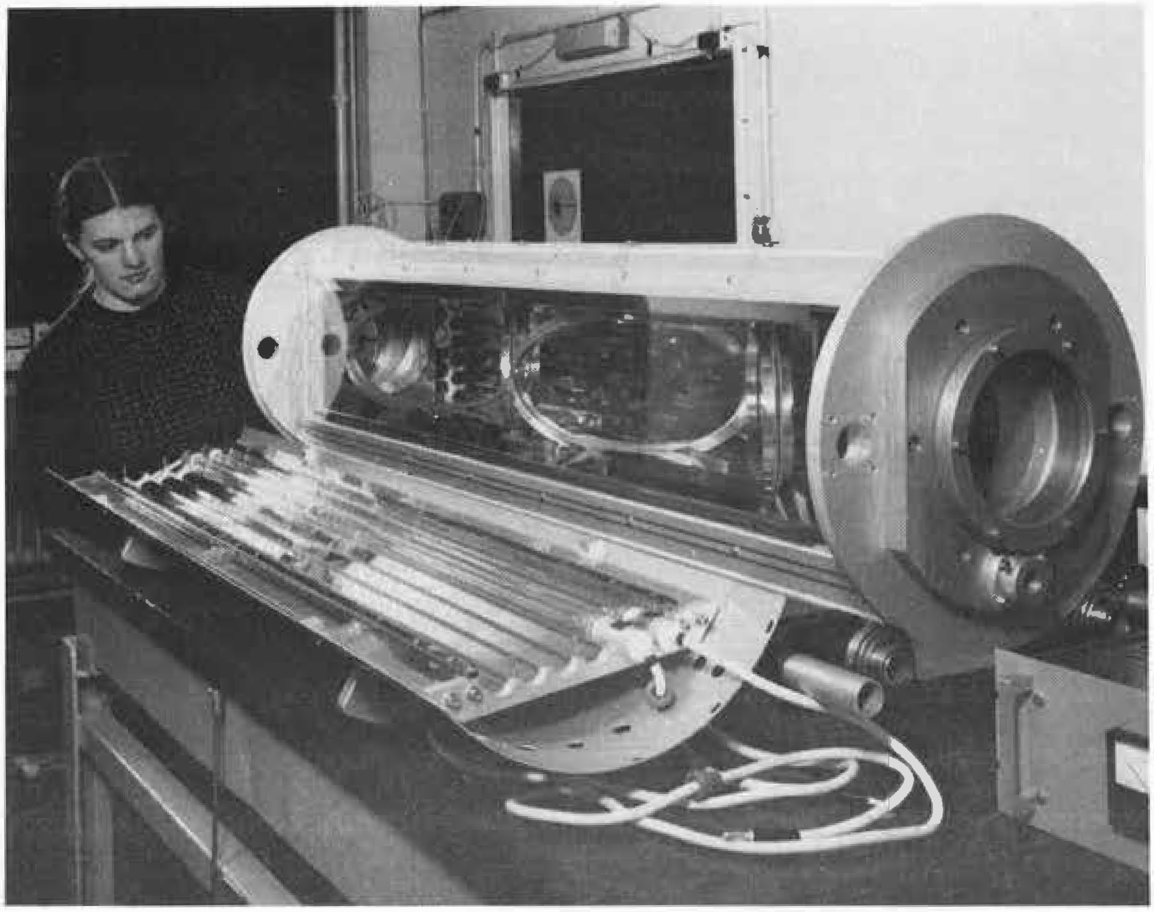
Focal Spot Profile of Beam Passing Through Uncooled Disc Amplifier



Focal Spot Profile of Beam Passing Through Cooled Disc Amplifier

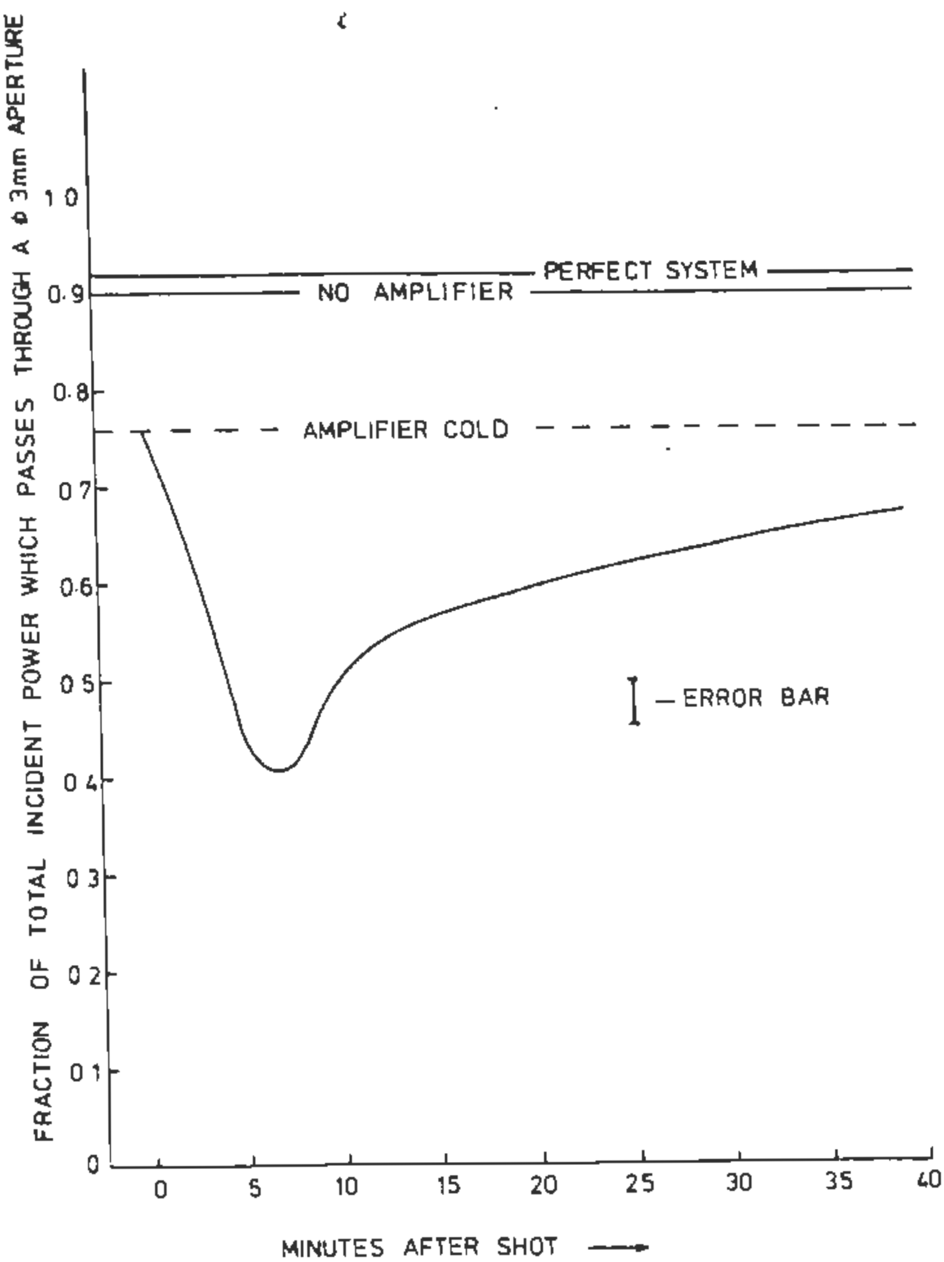
Comparison of Focal Spot Profiles

Figure 7



150 mm Diameter Box Amplifier

Figure 8



Results of Cooling Tests on the 150 mm Box Amplifier

Figure 9

TABLE 1.
SUMMARY OF OUTPUT CAPABILITIES OF VULCAN GLASS LASER SYSTEM

LASER OUTPUT PARAMETERS		SPECIAL CONFIGURATIONS
Six Beams	1.8kJ/1ns 500J/100ps	SHORT PULSE LENGTHS 20 ps 15J/Beam
Two Beams	1kJ/1ns 300J/100ps	BEAT WAVE 1053 nm 100J/200 ps and 1064 nm 100J/200 ps synchronisation better than 20ps
Pulse Lengths	70-500 ps + 0.7-25 ns synchronisation better than 20ps	
Wavelengths	1053 nm 527 nm at 50% energy 315 nm at 50% energy, single beam	BROAD BAND OSCILLATOR For I.S.I. Experiments
Repetition Rate	20 minutes	