MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
GARCHING BEI MÜNCHEN

PULSED HIGH POWER IODINE LASER AT IPP

G. Brederlow, K. Hohla, K. J. Witte

IPP IV/74 June 1974

Reprint of the Paper presented at the 7th European Conference on Plasma Production by High Power Lasers
22 - 26 April 1974, Garching, F.R.G.

IPP IV/74

G. Brederlow
K. Hohla
K. J. Witte

Pulsed High Power Iodine Laser at IPP

June 1974 (in English)

Abstract

The basic features of the iodine laser as a high power laser are reported. The scaling laws for the dimensions of iodine laser amplifier are given. The two laser systems Asterix II (100 J/1 nsec) already existing and Asterix III (1 kJ/1 nsec) being under construction are described in detail.

I. Introduction

The iodine laser was already discovered in 1964 by Kaspar and Pimentel, but laser-physical and technical interest in the development of this laser was rather late in coming. Systematic study of the high power potential of this laser did not start till 1970, when Hohla and Kompa recognized its suitability as a pulsed high power laser.

The basic characteristics of this laser are as follows: The iodine laser is a photochemical dissociation laser. Excited iodine atoms are used as the active material. The pumping of this gas laser is accomplished by the photodissociation of certain organic iodides such as C_3F_7J. The primary pumping scheme is as follows:

$$C_3F_7J + h\nu_{UV} \text{ (photolysis)} \longrightarrow C_3F_7 + I\ (5^2\ P_{1/2})$$

$$I\ (5^2P_{1/2}) \longrightarrow I\ (5^2P_{3/2}) + h\nu \quad \text{(laser)}$$

The concentration of excited iodine atoms will, however, be influenced by a variety of secondary chemical processes during and after the flash. But it has been shown that conditions can be found where there are no chemical limitations to the accumulation and storage of significant excited iodine densities.

The iodine laser will be pumped in the wavelength region of 280 nm. The emission wavelength is 1.315 μ.

2. The basic features of the iodine laser

At Max-Planck-Institut für Plasmaphysik a series of basic investigations have already been conducted with the iodine laser. In particular, the effectiveness of the pumping mechanism, the dependence of the stimulated emission cross-section on various parameters and other important aspects have been investigated. Furthermore, a high-power laser system has been built and tested.

The information yielded by these studies about the basic features of the iodine laser are briefly summarized in the following:

1. The iodine laser can be operated as a pulsed high-power laser (kJ range).
2. In principle, it should be possible to achieve a bandwidth limited pulse length in the range of 100 psec.
3. It should be possible to achieve diffraction limited divergence of the laser beam.

4. From the present state of our knowledge we can expect a total efficiency of the laser in the range up to 0.5%. The principal factor limiting the efficiency depends mainly on the spectral width of the UV absorption of the parent alkyl iodides and on the energy output of the flashlamps in the absorption region.

5. The inversion rate α, $\alpha = \Delta n/n$, is in the range $0.1 \leq \alpha \leq 0.2$. To give a sufficiently high density of the stored energy, in the high-power laser amplifiers, α should exceed 0.1.

6. In principle, the energy stored in the amplifier cannot be completely extracted. As a consequence of the degeneracy of the upper and lower levels and owing to the homogeneous pressure broadening extending over all the hyperfine components a maximum of 66% of the stored energy can still be extracted. Calculations show that normally it should be possible to get an amplifier extraction efficiency $\eta^* = 50\%$ with rather small input energies.

7. To ensure that the pump energy delivered is stored and not directly converted into radiation, the small signal amplification V

$$V = e^{\sigma \Delta n l} \tag{1}$$

(σ stimulated emission cross-section, l - length of the light path) has to be adjusted in such a way that $V < V_{TH}$ when V_{TH} is the threshold amplification for parasitic oscillations and given by the Schawlow-Towns relation:

$$V_{TH}^2 R_1 R_2 T^2 = 1 \tag{2}$$

($R_1 R_2$ - reflection coefficients
T - transmission)

The design of the amplifier and the entire laser system should be such that the actual values of the reflectivities R_1 and R_2 are as low as possible. The adjustment of V can be done by varying the stimulated emission cross-section. In an iodine laser this can easily be accomplished by means of pressure broadening by adding a foreign gas to the laser medium. The species of the foreign gas should be chosen such that at a given pressure the pressure broadening is as high as possible and the deactivation rate by collisional processes as low as possible. The maximum storable energy per cm^2 e_{ST} is then given by

$$e_{ST} = \frac{h\nu}{\sigma} \ln V_{TH} \quad \left[J/cm^2 \right] \tag{3}$$

8. The amount of energy that can be stored can be diminished by collisional deactivation processes. The time constant for this process caused by the molecular iodine and by impurities is of the order of msec, depending on the type and partial pressure of the impurities.

For oxygen at a partial pressure of

$$P_{O_2} = 10^{-2}\ [\text{torr}] \text{ the time constant } \tau \text{ is}$$

$$\tau = 3.5\ [\text{msec}]\ .$$

Therefore, the storage times should be much shorter than msec, if the amplifier has been evacuated down to a pressure range of 10^{-2} torr before filling with the laser medium.

9. Another reason for using short storage times is that the light pulses of the flashlamps evaporate impurities from the walls of the laser vessel. These impurities cause shock waves travelling from the walls towards the center and disturbing the optical homogeneity of the laser medium. To ensure diffraction limited beam divergence, the laser beam has to pass the amplifier before the shock waves have entered the active region. This means that the amplifier has to be pumped and released in a few μsec.

3. Scaling laws for iodine laser amplifiers.

The results and considerations reported here can be formulated to yield scaling laws for the dimensions of iodine laser amplifiers. Here will be discussed the scaling laws for an amplifier with a cylindrical volume with external flashlamp illumination. If the desired output energy E_o, the output energy density/cm^2 e_o which should not exceed the damage threshold value, the amplifier extraction efficiency η^x, the tolerable threshold amplification V_{TH} and the inversion rate α are specified, the remaining amplifier parameters such as the diameter d of the amplifier cylinder, the pressure p of the alkyl iodide, the length l of the cylinder, the maximum tolerable stimulated emission cross-section σ, the pressure p^x of the foreign gas and the input energy e_i to the amplifier can be calculated in a first approximation:

The diameter of the amplifier is found from the ratio E_o/e_o to be

$$\boxed{d = \frac{4}{\pi} \sqrt{\frac{E_o}{e_o}} \quad [\mathrm{cm}]} \tag{4}$$

The pressure p of the alkyl iodide should be adjusted in such a way that the illumination of the cylinder volume is homogeneous. It was found empirically that the relation $p \cdot d = K$ is valid for a wide range of p and d.

$$\boxed{p = \frac{K}{d} \quad [\mathrm{torr}]} \qquad K = 175 \, [\mathrm{torr\ cm}] \tag{5}$$

The length l of the amplifier follows from the relation:

$$\boxed{l = \frac{1}{K\,K'}\,\frac{e_{ST}\,d}{\alpha} \quad [\mathrm{cm}]} \quad K' = 5 \cdot 10^{-3}\ [\mathrm{J/cm^3\ torr}] \qquad (6)$$

with

$$\boxed{e_o = \eta^{*}\, e_{ST}\ [\mathrm{J/cm^2}]} \quad \eta^{*} \leq 0.66 \qquad (7)$$

The stimulated emission cross-section σ has then to be adjusted in such a way that the relation $V \leq V_{TH}$ is satisfied.

$$\boxed{\sigma \leqq \frac{h\nu}{e_{ST}}\ \ln V_{TH} \quad [\mathrm{cm^2}]} \qquad (8)$$

In the pressure range of interest pure C_3F_7J has a σ-value of around $\sigma = 10^{-18}\,\mathrm{cm}^2$. This is a value which is normally essentially higher than that required by formula (8). Therefore σ has to be reduced by adding a foreign gas. In adding CO_2 the empirical formula (9) gives for pressures higher than 100 torr the desired pressure of the foreign gas p^{*} to adjust σ to the proper value.

$$\boxed{p^{*} \geqq C\,\frac{e_{ST}}{\ln V_{TH}} \quad [\mathrm{torr}]} \quad C = 2.4 \cdot 10^{3}\,[\mathrm{torr\ cm^2/J}] \qquad (9)$$

The input energy density e_i necessary to extract the required output energy density e_o from the amplifier follows from equation (10):

$$\boxed{e_i = \frac{e_o}{\eta^{*} b\, \ln V_{TH}}\ \ln\left(\frac{V_{TH}^{\,\eta^{*} b} - 1}{V_{TH}} + 1\right) \quad [\mathrm{J/cm^2}]} \qquad (10)$$

(b - degeneracy factor, b = 1.5)

These scaling laws were used to calculate the parameters and the input energy density of the amplifiers of the iodine laser built at IPP.

In the following table the parameters and the input energy density of the end amplifier of the 1 kJ laser are listed.

Parameters of the end-amplifier of
a 1 kJ laser

specified	calculated
$E_o = 1\,[\mathrm{kJ}]$	$d = 20\ [\mathrm{cm}]$
$e_o = 3{,}2\,[\mathrm{J/cm^2}]$	$P_{C_3F_7J} = 9\,[\mathrm{torr}]$
$\eta^* = 0{,}5$	$l = 7{,}3 \cdot 10^2\ [\mathrm{cm}]$
$V_{TH} = 10^5$	$\sigma = 2{,}8 \cdot 10^{-19}\,[\mathrm{cm^2}]$
	$P^*_{CO_2} = 1{,}1 \cdot 10^3\,[\mathrm{torr}]$
$\alpha = 0{,}1$	$e_i = 1{,}1 \cdot 10^{-2}\,[\mathrm{J/cm^2}]$
	$\epsilon_{ST} = 9 \cdot 10^{-3}\,[\mathrm{J/cm^3}]$

The electrical data of the capacitor bank for the end amplifier, which delivers practically the total laser energy, are given by the total efficiency, which is around 0.5%. Therefore, the capacitor bank should have a capacity of at least 200 kJ.

4. High power laser at IPP.

In 1972 it was decided at IPP to build high power lasers for fusion experiments. Firstly the laser system Asterix II was set up in order to investigate the scaling laws and to gain experience in building high power lasers.

The planned output power of this laser was 100 J in 1 nsec. Until now 60 J has been obtained in 0.7 nsec pulses. The set-up of the system is schematically shown in Fig. 1. This system consists of an oscillator, a pulse-cutting system and two amplifiers.

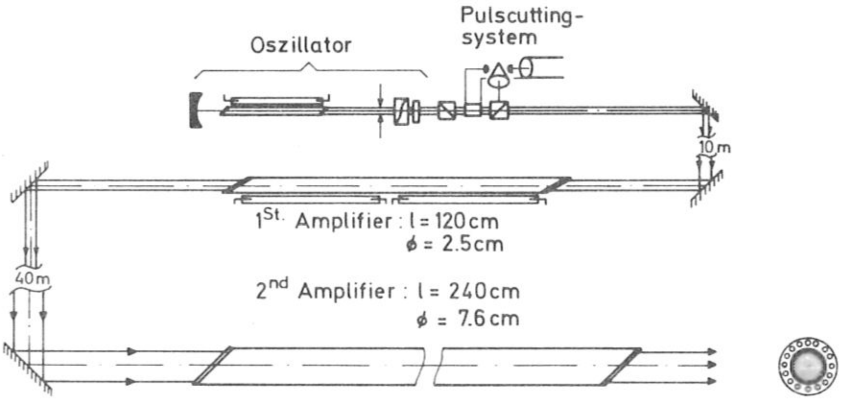

Fig. 1 Schematic set-up of Asterix II

The oscillator and the amplifiers are quartz tubes with the flashlamps mounted outside the tubes. The oscillator delivers a mode-locked pulse train from which a single pulse is cut by means of a pulse-cutting system. The beam divergence is 1.3 mrad in accordance with the TEM_{oo}-mode of the oscillator. The pulse duration is dependent on the gas pressure in the oscillator and varies between 3 nsec and 0.7 nsec. The first amplifier tube is located 10 m behind the oscillator. The distance is chosen such that the beam starting from the oscillator and getting broader owing to its natural divergence fits the diameter of the amplifier tube. The energy at the exit of the first amplifier is 0.6 J.

The gas is a mixture of C_3F_7J and CO_2 at 40 torr respectively 240 torr. The gain factor over the length of 120 cm is 0.08 cm^{-1} ($\sigma = 10^{-18}[cm^2]$). The second amplifier serves as the actual amplifier of the energy. The length is 2.40 m and the diameter 6.6 cm. The pressure is $P_{C_3F_7J} = 23$ torr, $\overset{x}{P}_{CO_2} = 560$ torr. Four flashlamp chambers each with 16 lamps were mounted around the tube. The distance of 40 m between the first and second amplifiers is again chosen such that the beam matches the diameter of the tube. The tube contains a spiral in contact with the wall to prevent the amplifier from expending its energy in parasitic oscillations. With this spiral a small signal amplification of 10^5 was achieved (10^3 without the spiral). As already stated, until now 60 J/0.7 nsec pulses have been obtained. Pulses of 150 J/subnsec are expected.

The 1 kJ iodine laser, Asterix III, which is now under construction, has the same schematic set-up as Asterix II (Fig. 2). The oscillator, pulse-cutting system and first amplifier correspond to those of Asterix II. However, for the optical isolation a Pockels cell and a Faraday rotator will be placed between the first and second amplifiers. A beam expander is needed in addition since the natural divergence of the beam requires too long a light path to expand the beam diameter up to 20 cm.

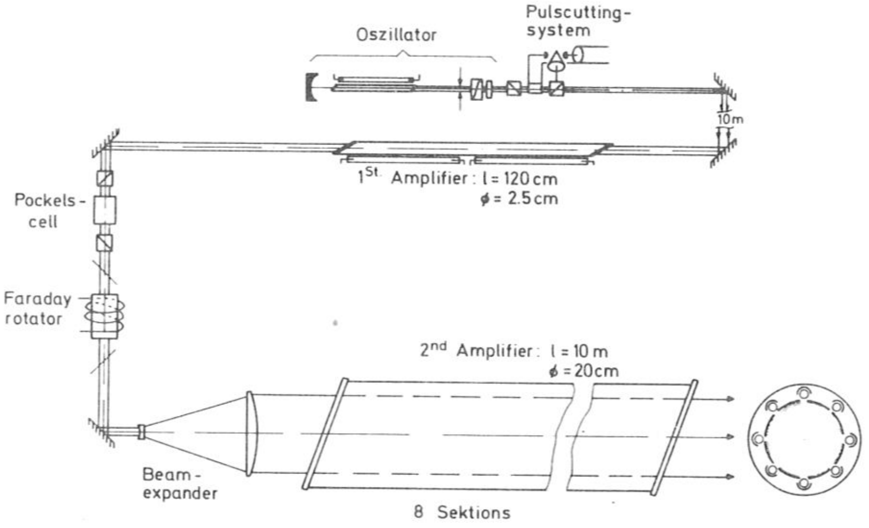

Fig. 2 Schematic set-up of Asterix III

The second amplifier differs completely from that of Asterix II. It consists of a stainless-steel tube 10 m long with an active diameter of 20 cm. This tube consists of eight sections. In each section eight flashlamps, each with an input energy of 4 kJ and backed by reflectors, are mounted inside. To prevent parasitic oscillations and coupling of adjacent sections, an optical sink was mounted along the wall of each section. This optical sink consists of rings fixed at certain distances along the walls. Until now the oscillator, pulse-cutting system, first amplifier and two of the eight sections of the second amplifier have been set up. We are now investigating the stored energy in these two sections. We found values of the order of up to 500 J. With eight sections mounted this energy should be sufficient to give a 1 kJ pulse ($\eta^{*} \approx 0.5$).

4. Conclusion

The iodine laser is still at an early stage of its technical and scientific development and the limits of its capacity have not been reached. Nevertheless we already recognize several advantages of this laser. These are:

1. high flexibility allowing easy adjustment of the laser parameters to obtain optimal laser performance

2. high amplifier extraction efficiency, which is due to the homogeneous line broadening
3. suitability for large beam cross-sections
4. suitability in building large-volume amplifiers, thus allowing a considerable reduction in the number of amplifiers and optical components compared with other laser types
5. high beam quality
6. simple technical structure
7. low construction and operation costs.

For these reasons the iodine laser should become a valuable tool for laser fusion research.