PROSPECTS OF THE HIGH POWER IODINE LASER

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Abstract

The characteristic properties of the iodine laser (gaseous laser substance, photolytic pump mechanism, variable stimulated emission cross-section) made it possible in a relatively short time to generate ns pulses in the kJ range.

The Asterix II and III iodine laser systems at IPP are working successfully, and the question arises what prospects are afforded for further iodine laser development. What are the problems that have to be clarified in order to build 10 or 100 kJ systems for laser fusion experiments? According to our experience these can be classified as follows:

1. Short pulse generation and contrast ratio.
2. Pulse shaping in a high-gain laser and amplification in the coherent time range.
3. Non-linear properties at high intensities.
4. Scalable pumping schemes and chemical processes.

Recently, major advances have been achieved in some of these fields. Measurements of the cross-section have shown that it is readily possible to attain a transition bandwidth of 3 x 10^{10} Hz. The pulse lengths obtained in mode-locked oscillators therefore had to be comparable with those of Nd-YAG lasers. So far only 100 - 200 ps has been reached instead of 20 - 50 ps. This has to be ascribed, on the one hand, to the mode-locking mechanism and, on the other, to the iodine laser transition itself. Relaxation processes between the sublevels of the laser transition are only beginning to be understood and investigated. As calculations show, this behaviour is particularly important for the amplification of ultra-short pulses. As a rule, iodine laser systems show a very high total gain, the last amplifier being operated almost in saturation. The accompanying pulse shortening can go so far that coherent effects have to be taken into account. These effects become particularly drastic when a saturable absorber in which iodine atoms act as the absorbing medium are used.

For high-power lasers the optical properties of the laser gas are particularly important at high intensities. Estimates of the non-linear properties still contain appreciable errors. Experiments to date show that at least up to 10^{10} W/cm² no disturbing effects occur in ns pulses.

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*) Invited paper given by K. Hohla at the XIth International Quantum Electronics Conference in Amsterdam.

The substantial clarification of chemical processes has led to the development of a quasi-closed cycle for C_3F_7I lasers. There are nevertheless still a few unknown side effects. To a slight extent these produce non-volatile compounds which in some cases, however, contaminate the laser tube in the long run and reduce the energy yield by approximately 20 %. The detection of this pumping light absorbing layers was responsible for a new design of the 4th amplifier of A III which now has the flashlamps and reflectors outside the active medium and not anymore in direct contact with the active medium as it was the case before. Moreover, by optimizing the laser-tube-flashlamp-reflector geometry it was possible to increase the fraction of the pump light absorbed in the active medium yielding an amount of stored optical energy of now 2.5 kJ compared with 1 kJ in the older version.

CONTENTS

1. Introduction

In a relatively short time the development of the iodine laser has led to laser systems with a performance comparable to the Nd-glass or CO_2 laser /1/. Compared to the personal and financial efforts for the development of the Nd-glass and CO_2 lasers the costs of the iodine laser development so far are rather moderate. Naturally some scientific problems are still to be solved, the solution of which is important for further development of the iodine laser. The main problems are related to the so-called pulse cosmetics, which includes pulse duration, contrast ratio, pulse shaping and nonlinear properties of the medium.

At the same time there exist a number of perspectives of the iodine laser, notably new pumping schemes, which show this system to be an attractive field of research.

2. Short Pulse Generation

The requirements for pulse duration and pulse shape are set by laser fusion experiments /2/. At this time pulse durations with a FWHM of 100 ps seem to be desirable, the risetime being as steep as possible. The contrast ratio has to be extremely high.

First the questions will be discussed how 100 ps pulses can be generated, what is the state of the art, what possibilities show up.

The most prominent method at the moment - because of the lack of useful saturable absorbers - is active modelocking. Acoustooptic and electrooptic methods have been used /3,4,5/. In the experiments of Sandia Laboratories an iodine laser oscillator is Q-switched by means of a Pockels cell and at the same time modelocked with an acoustooptic modulator. Figure 1 shows the pulsewidth, as measured with a streak camera, plotted against the pressure of the laser gas. For the iodine laser the bandwidth of a single line can be varied by means of pressure broadening: The higher the pressure the larger the bandwidth. Comparison with the Siegman-Kuizenga theory gives a dependence

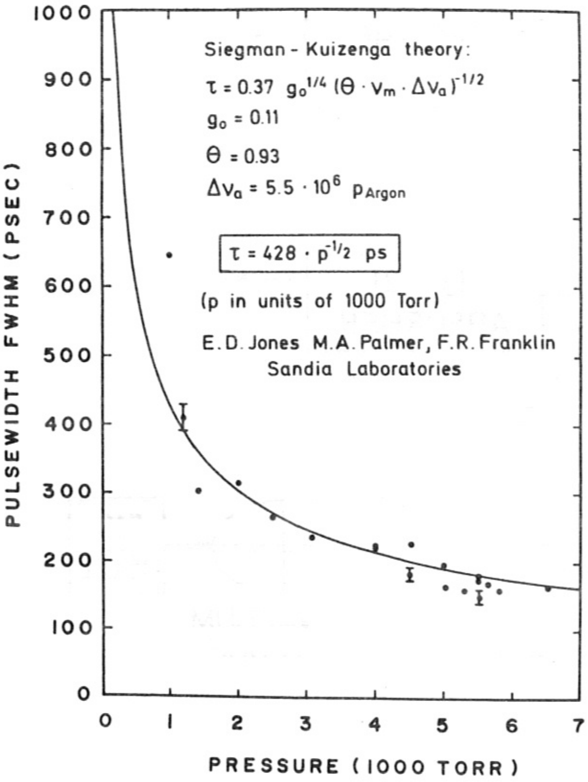


Fig. 1
Pulse duration of a mode locked iodine oscillator. Mode locking was caused by acousto-optical modulation, the pulse duration was measured with a streak camera /4/.

= 428 $p^{-1/2}$ ps plotted in Fig. 1. The good correspondence between theory and experiment makes it possible to draw conclusions on parameters which lead to pulses in the 100 ps range. According to these extrapolations the use of better modulators - resulting in larger Θ - increase of the modulation frequency and lowering of g_o should make pulses of 100 ps possible.

Among the many other methods to generate shorter pulses one possibility deserves special consideration: the method of free induction decay (FID) /6/. It is based on truncating the pulse by optical breakdown and filtering the narrow band frequency components of the original pulse by a narrow band filter.

In Garching the following experiment was performed (Fig. 2) /7/: A 3 ns pulse was focussed into an J_2 cell. Termination of the pulse by optical breakdown is especially fast if the f-number of the focussing optics is small.

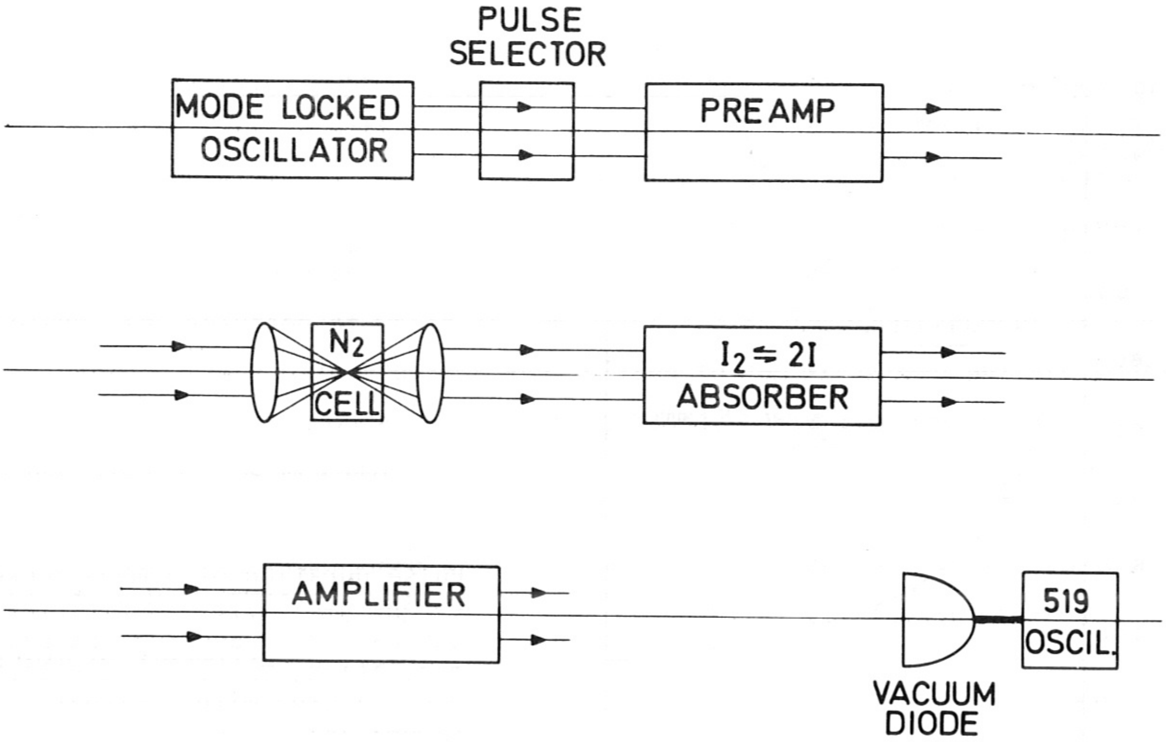


Fig. 2 Set-up for producing a free induction decay pulse (FID-pulse)

The ultrafast fall time of the pulse gives rise to a broad spectrum. In a hot iodine cell, which will be described later on, the narrow band spectrum of the original pulse is absorbed, and only the broad spectrum during the termination is transmitted. Figure 3 shows the time history for this experiment.

The resulting pulse duration is determined by

a) the duration of breakdown,

b) the dephasing time of the absorber and its absorption, whichever is longer.

In case of an ideal switch (termination infinitely fast) a pulse of half width $T_2/\alpha \cdot L$ is obtained, where T_2 is the dephasing time of the absorber and α the absorption per cm and L its length /8/. With typical T_2 times of 800 ps and values of $\alpha \cdot L$ of 10 pulses with a duration around 80 ps are conceivable.

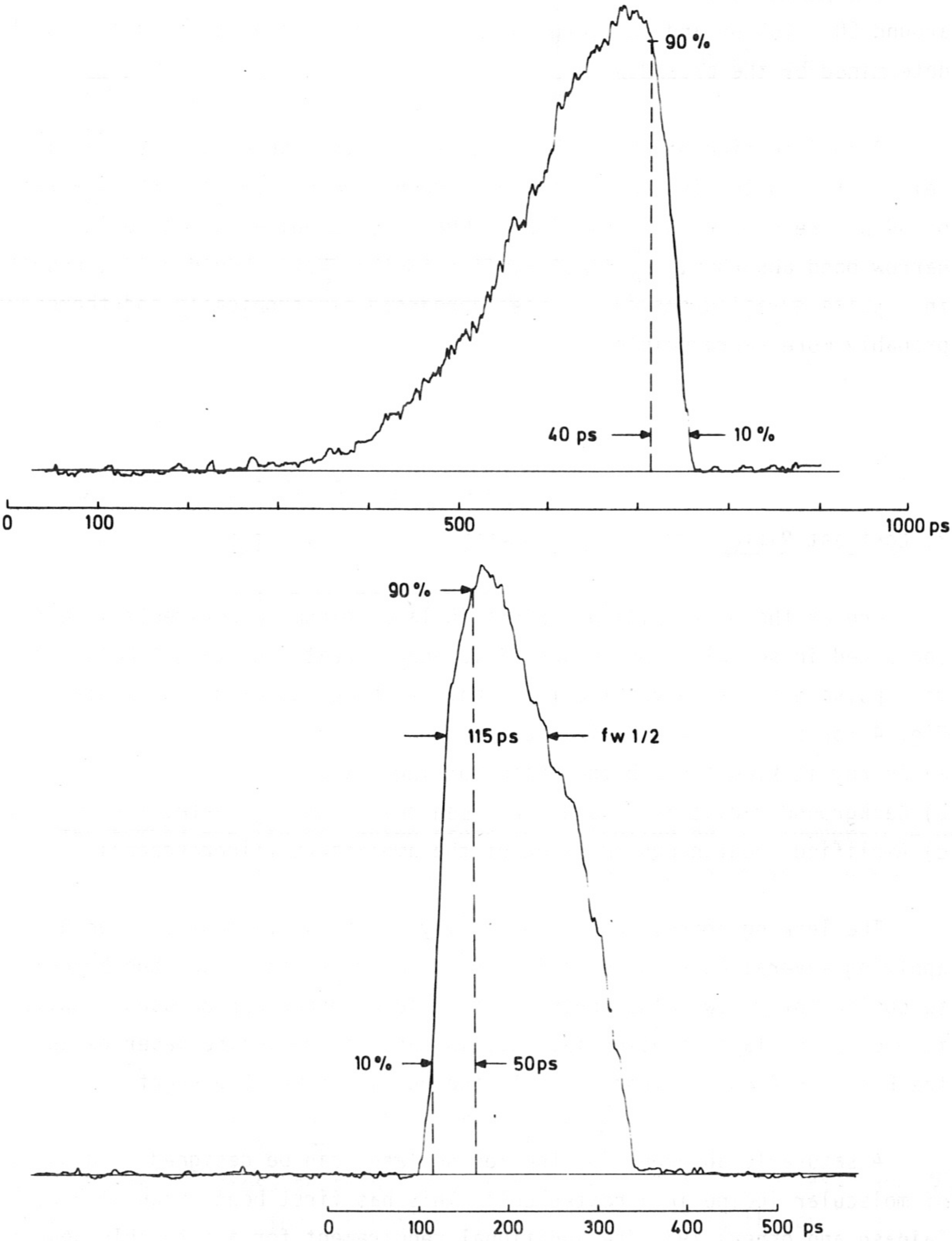


Fig. 3 The upper picture shows the original pulse (FWHM 2 ns) which was truncated by the gas breakdown. The cut-off time of 40 ps is determined by the breakdown. The lower picture shows the same pulse after passing through the absorber. The pulse duration is now mainly given by the dephasing time of the atom in the absorber. (The pictures are densitometer traces of streak camera records.)

The pulses obtained in Garching with an F/2 optics had a duration of around 50 - 100 ps and an energy of ≈ 100 μJoules. The duration is probably determined by the breakdown.

A modification of the method consists in the use of a fast Pockels cell as the switch instead of the breakdown. Pockels cells with rise times of 90 ps are commercially available. When such a pulse is passed in a narrow band absorber, an effect similar to the above should arise, resulting in a pulse duration around 100 psec, produced electronically and therefore probably more reproducible.

3. Contrast Ratio

One of the most critical points in laser plasma experiments is energy contained in so-called prepulses. This energy heats the target before the main pulse hits it. Several effects have to be considered, as displayed in Fig. 4 for a modelocked oscillator.

a) Energy leaking through the pulse cutting system
b) Background radiation passing the open pulse cutting system (precursor)
c) Amplified spontaneous emission of the amplifiers (fluorescence)

The leaking energy can - hopefully - be sufficiently reduced by applying several Pockels cells in series. However, to reduce the precursor to sufficiently low values only a saturable absorber can be used. Amplified fluorescence plays no essential role in case of the iodine laser because the Einstein A coefficient is small and pumping times are short.

A saturable absorber for the iodine laser can be designed by dissociation of molecular iodine in a heated cell. This has first been shown by V.A. Gaidash and others /9/. The additional requirement for a saturable absorber, namely that the relaxation time of the upper level be long compared to the pulse width is fulfilled in case of the iodine cell. Conditions relating to the I_2 cell have been comprised in Fig. 5.

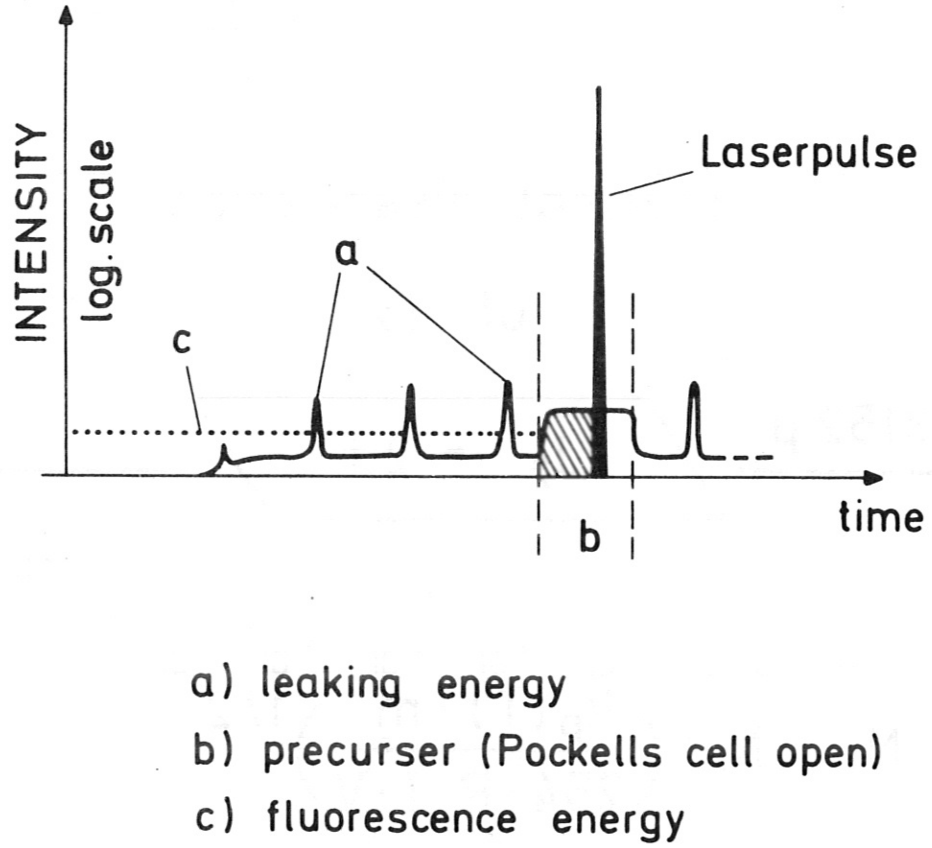


Fig. 4 Reasons for prepulse energy in mode locked oscillator - amplifier device

The number density of iodine atoms is controlled by the temperature of the iodine cell. The cross-section for absorption depends mainly on the line width of the transition. As in the case of the laser it is adjustable by adding a foreign gas or by changing the temperature.

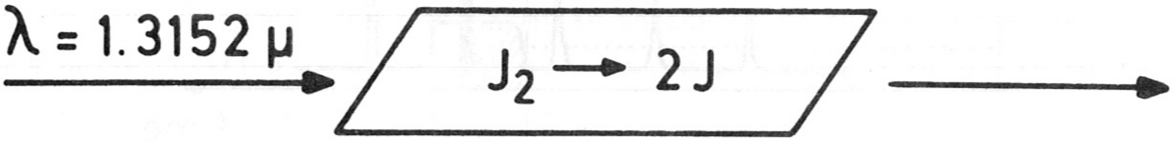
For the iodine cell to act as a saturable absorber its parameters have to be set to fulfill the conditions

$$\left(\frac{\sigma \cdot b}{A}\right)_V \ll \left(\frac{\sigma \cdot b}{A}\right)_A$$

where σ_V is the cross-section for stimulated emission of the laser and σ_A is the cross-section for absorption of the absorber. A is the cross-section of the beam in amplifier and absorber respectively, b is the degeneracy factor.

thermal dissociation

of I_2



$$N_I = N \left(\frac{k_p(T) \cdot m}{254 \cdot R \cdot T \cdot V} \right)^{1/2}$$

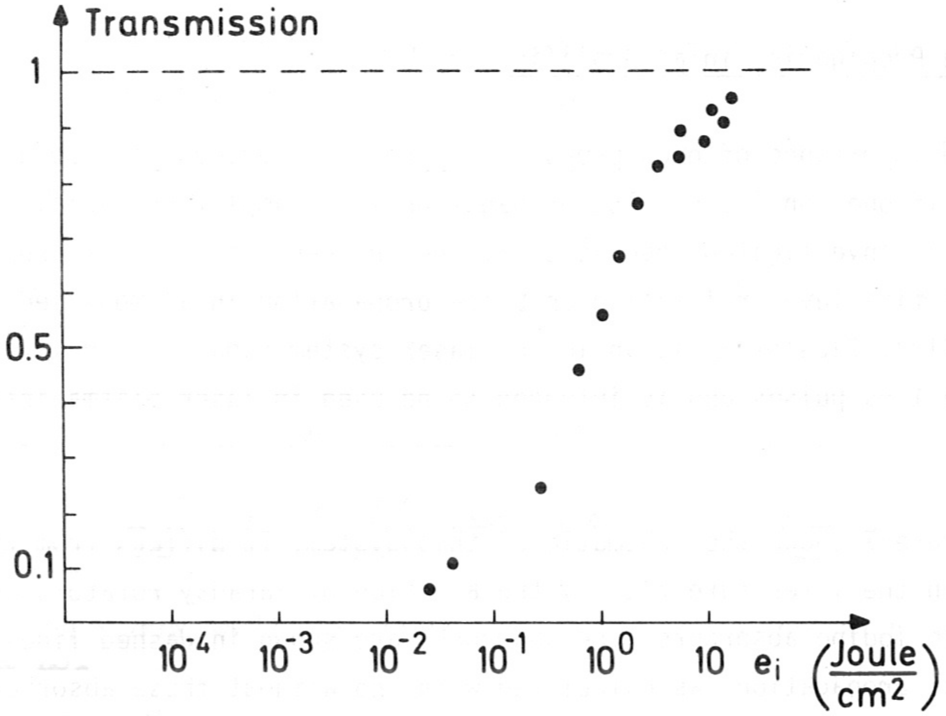
small signal: $e_0 \ll e_s \quad T_s = \exp(-\sigma N_I\, l)$;

large signal: $e_0 \gg e_s \quad T_l = 1 - \dfrac{h\nu \cdot N_I \cdot l}{b \cdot e_0}$;

condition for the absorber :

$$\left(\frac{\sigma \cdot b}{A} \right)_V \ll \left(\frac{\sigma \cdot b}{A} \right)_A$$

Fig. 5 Thermal dissociation of I_2 determines the concentration of ground state iodine atoms. From the equations for small and large signal attenuation the condition for the saturable absorber can be deduced.



$T_S = 10^{-3}$ for $e_i < 10^{-3}$

$T_L \geq 0.9$ for $e_i > 4$

Fig. 6 Transmission of an I_2 cell (length 40 cm, diameter 2,5 cm) filled with 50 mg I_2 heated to 800 °C.

For ns pulses we found a behaviour displayed in Fig. 6. As can be seen the iodine cell is well saturable with energy densities of a few Joules/cm^2. For the contrast ratio (small signal transmission / large signal transmission) values of 10^{-3} and better are obtained. Suppression of prepulses improved by a factor of 1000 could be demonstrated experimentally. Only the future can tell if these results can also be realized for 100 ps pulses.

So far, discussion has centered upon conventional methods of generation of nanosecond pulses. A good deal of the problems would be overcome, if the FID method could be taken into operation. The narrow frequency spectrum of a 100 ps pulse could easily be filtered out with an I_2 cell with no need of saturation for the main pulse. Contrast ratios of 10^{10} seem to be entirely feasible according to calculations.

4. Pulse Propagation in an Amplifier

The importance of good prepulse suppression becomes particularly evident if one considers pulse propagation in an amplifier system /10/. Olsen /11/ investigated theoretically the influence of prepulse suppression and hyperfine level relaxation on pulse propagation in an modified Asterix II system /12/. Plasterix is an iodine laser system capable of delivering 60 - 70 Joule 1 ns pulses and is intended to be used in laser plasma interaction studies.

Figure 7 shows the schematic of this system. It differs from that described in the literature /12/ by the addition of Faraday rotators and two saturable iodine absorbers. The absorbers are shown in dashed lines because the pulse propagation was calculated with and without these absorbers.

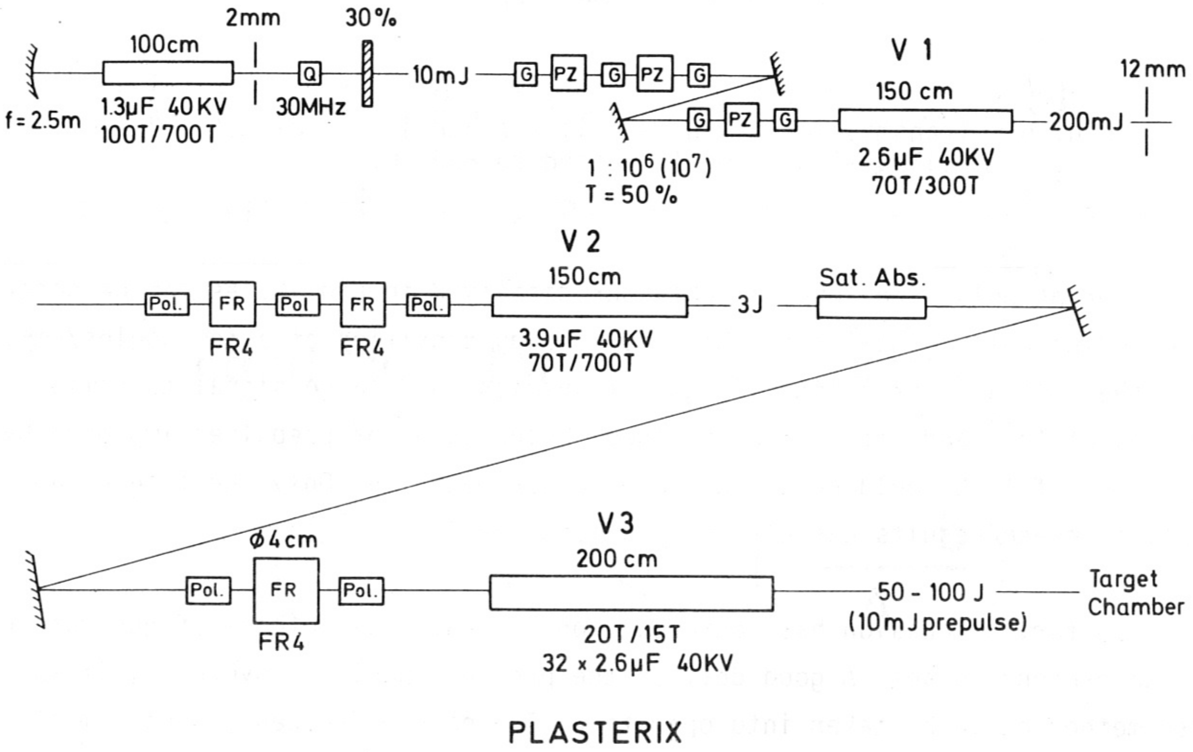


Fig. 7 Schematic set-up of the modified Asterix II system named Plasterix

The theoretical model for the calculation is described as follows: the pulse duration of 1 ns of the entering pulse is taken equal to the dephasing time of the absorber. The same is true for the relaxation time of the hyperfine levels.

For this reason the semiclassical equations, including coherent effects were used.

a) The equation for the electric field envelope:

$$\frac{\partial E}{\partial t} + c\,\frac{\partial E}{\partial x} = 2\pi\omega P - \frac{\gamma\cdot c}{2} E$$

including a very small loss factor γ, and on resonance with the medium $\omega = \omega_0$

b) The equation for the polarization:

$$\frac{\partial P}{\partial t} + \frac{P}{T_2} = \frac{|\mu|^2}{\hbar} N_{34} E$$

containing the dephasing time T_2, and the inversion $N_{34} = n_3 - \frac{7}{9}N_4$ which satisfies

c)

$$\frac{\partial N_{34}}{\partial t} = - \frac{b_{34}\,PE}{2\hbar} + (b_{34} - 1)\frac{N_{4R}}{T_R}$$

where b_{34} is the degeneracy and $N_{4R} = N_4 - \frac{9}{15}N_R$ the density of the lower laser level, coupled to its reservoir:

$$\frac{\partial N_{4R}}{\partial t} = \frac{1}{2\hbar} PE - \frac{b_{4R}\cdot N_{4R}}{T_R}$$

Under the assumption that the incoming pulse has a prepulse of 3 ns duration with a contrast ratio of 1 : 10^4, one obtains the pulse shape shown in Fig. 8b. The Gaussian pulse shape of 1 ns half width is changed very little. At the exit we find a pulse duration of .76 ns and 84 Joules of energy. Because of saturation effects, the pulse is steepened a little towards the front. Particularly noticeable, however, is the growth of the prepulse, whose intensity is now 2 % of that of the main pulse. The pulse shapes, how-

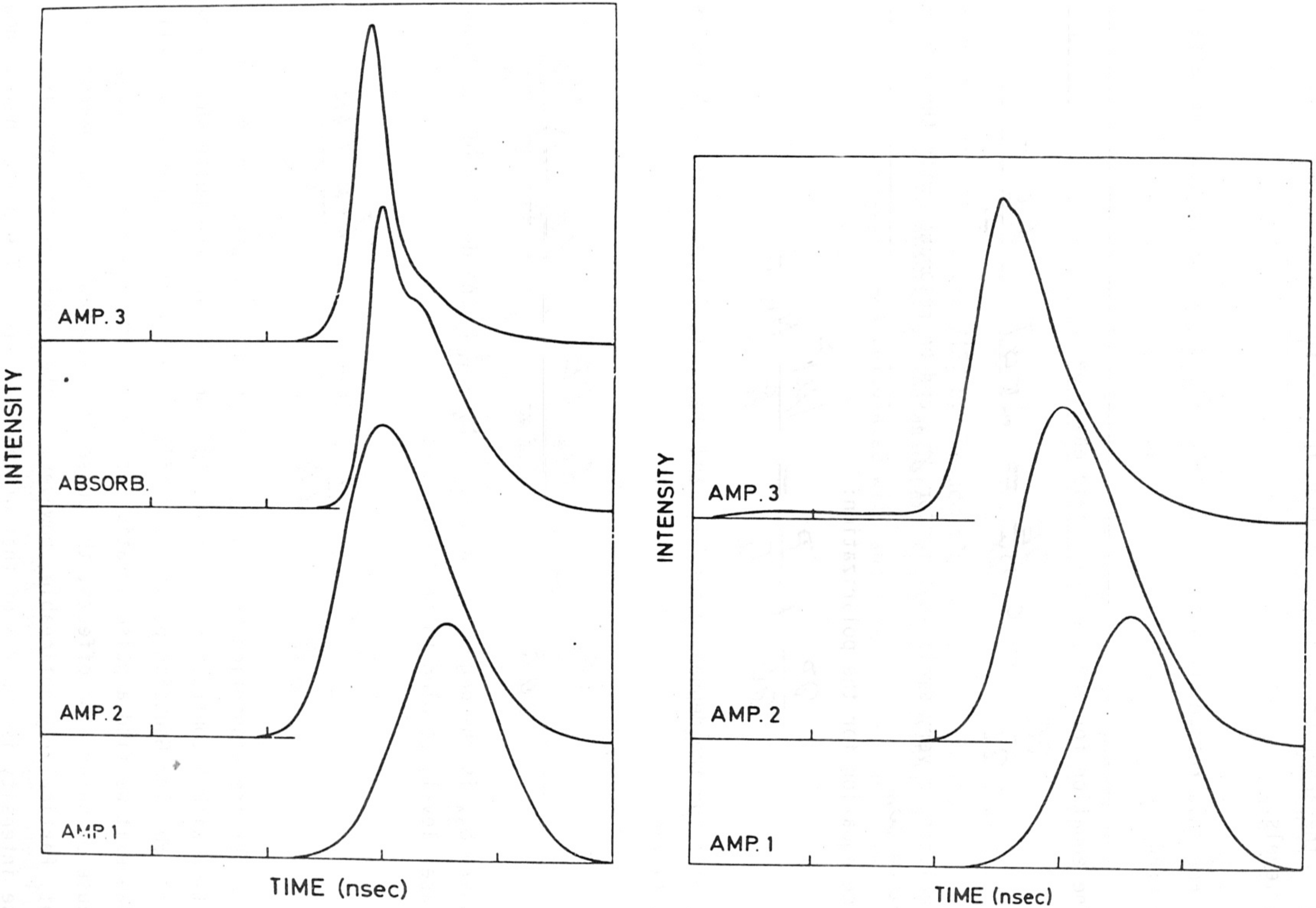


Fig. 8 Calculated pulse forms at various places in the system Plasterix:
a) with absorber placed between amplifier 2 and 3, b) without a saturable absorber

ever, change drastically if one includes a saturable absorber in the amplifier chain. In Fig. 8a one sees a considerable steepening of the pulse. The halfwidth here is about 340 ps and the rise time about 200 ps. The contrast ratio is about 3 x 10^4. If one included two such absorbers, the contrast ratio would improve to 1 : 10^7, a value quite satisfactory for laser target interaction experiments. The absorber reduced the total pulse energy by about 10 %, which is more than compensated for by the power increase.

5. Self Focussing

An often asked question in the iodine laser business relates to self focussing problems. The non-linear index n_2 of the laser gases CF_3I and C_3F_7I has so far not yet been measured. In general, however, gases at 1 atm have n_2's about $10^2 - 1o^4$ times smaller than that of Nd glass. Therefore we assume that n_2 does not play the limiting role in iodine as it does in glass.

Another consideration arises from the anomalous dispersion. If an absorption or gain line saturates, the anomalous index also changes, which leads to an effective energy dependence of the anomalous index in an amplifier. The anomalous index near resonance may be approximated by

$$n_\nu = n_0(\nu_0) + \frac{(\nu - \nu_0)}{2\pi\Delta\nu}\,\lambda\, g(\nu)\,\mathcal{L}(\nu - \nu_0)$$

where $n_0(\nu_0)$ = index in the absence of the resonance

λ = wavelength

$\Delta\nu$ = FWHM

$\mathcal{L}(\nu - \nu_0)$ = Lorentz line shape

$g(\nu)$ = saturable gain in the amplifier

The possibility of self-focussing now comes from the fact that because of inhomogeneities transverse to the direction of propagation, there is more or less saturation in regions across the beam. This leads to transverse variation in the anomalous index, or lensing effects. The maximum index difference possible is

$$\delta n = -\frac{(\nu-\nu_0)}{2\pi\Delta\nu}\lambda\, g(\nu)\, \mathcal{L}(\nu-\nu_0)$$

which can be estimated for the iodine laser with $g = 0.04\ \mathrm{cm}^{-1}$ to be $\delta n = 2 \times 10^{-7}$. The Kelley self-focussing length /13/ is then

$$z_f = \frac{1}{2} a \sqrt{\frac{n_0}{\delta n}}$$

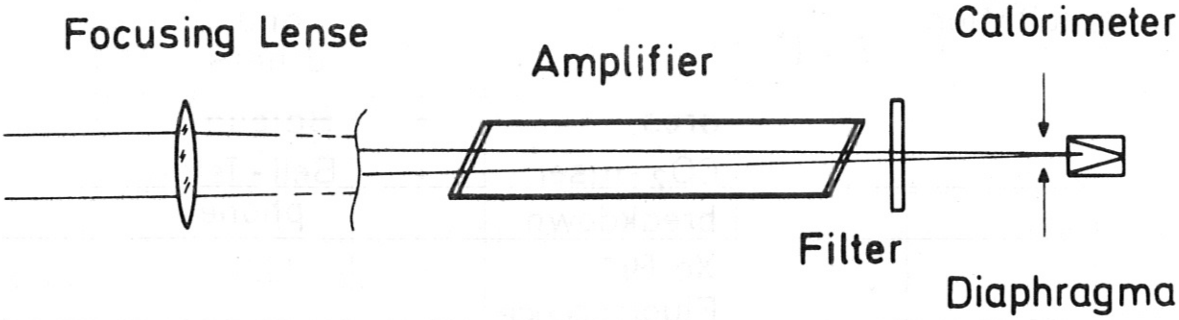
where one must, however, consider that diffraction tends to compensate the self-focussing. The dimension of the diffraction disc from the aperture a at a distance z_f is

$$b = \frac{\lambda}{a} z_f = \frac{\lambda}{2}\sqrt{\frac{n}{\delta n}}$$

and hence independent of a for $n = 1$, and $\delta n = 2 \times 10^{-7}$, one obtains a b of about 1.4 mm. This implies that inhomogeneities larger than 2 mm diameter can become a problem, leading to self-focussing with a focal length of about 2 m.

To investigate this self-focussing mechanism, we carried out the following experiment (Fig. 9). The energy density in the focal spot of a 16 m lens was determined with an iris of variable diameter after a passive amplifier. Then the experiment was repeated with the amplifier in operation. The energy density at the entrance of the amplifier was considerably above the saturation energy density of the amplifier.

In spite of energy densities of up to 6 Joules/cm², corresponding to intensities of about 10 GW/cm² no evidence of self-focussing could be seen.



No selffocusing effect up to:

$$6 \left(\frac{\text{Joule}}{\text{cm}^2}\right) \text{ and } 10 \left(\frac{\text{GWatt}}{\text{cm}^2}\right)$$

Fig. 9 Schematic set-up of the self-focussing experiment

6. Pumping Mechanisms for the Iodine Laser

So far the considerations were mainly concerned with basic problems of a laser for laser fusion. Further development of the iodine laser, however, will mainly depend on the possibilities to build systems in the 10 or 100 kJ region. The question arises, how the iodine laser is scalable, what efficiencies are to be expected.

At the beginning of this discussion Figure 10 gives a survey on pumping schemes presently under investigation /14, 15/.

	Process	Type	Result	Laboratory
Photo-excitation	$RI + h\nu \longrightarrow R + I^*$	Xe-flash	+	Garching and others
		arcs	+	Batelle
		CO_2-laser breakdown	+	Bell-Telephone
		Xe Br*-Fluorescence	+	LLL
		Wire explosion	+	Lebedev
		CW-lamps	0	
Electron-excitation	$RI + e^- \longrightarrow R + I^*$	e-beam	-	LASL
		discharge	+	Westinghouse

Fig. 10 Survey of various pumping schemes

The pumping mechanism most intensively investigated is photoexcitation. For this kind of excitation scaling laws can already be given, because laser tubes up to 30 cm diameter have been investigated. Other types of excitation are still in a too early state of development to be able to derive a scaling law.

The further discussion will be limited to excitation with lamps in general.

Usually iodine lasers are pumped in a time of 10 - 20 µsec, despite of the long lifetime of the excited iodine atoms (~ 130 ms). Two reasons are responsible for this fast excitation:

a) The Xe-plasma of the flashlamps has to be heated fast enough to get the maximum of the emission spectrum into the absorption of the iodide at about 2800 A.

b) The resulting high pumping rates generate a shock wave in the laser gas which destroys its optical homogeneity /16, 17/. To keep the part of the gas disturbed by the shock wave (and therefore the not useful diameter) as small as possible, pumping has to be completed in a time as short as possible. The fast discharges in the flashlamps result in low tolerable energy densities in the discharges to provide long enough lifetimes of the lamps.

In the laser system Asterix III the final amplifier has 64 flashlamps supplied with 250 kJ of electrical energy in a time of 15 µsec. Figure 11 shows this whole unit extending of 8 m with an open diameter of 20 cm. In the set-up shown in Fig. 11 the flashlamps are placed in the laser gas. This concept has lead to considerable difficulties because the high radiation intensity of the pumping light caused thermal decomposition of the laser gas. This resulted in carbon deposits on the lamps, lowering their efficiency.

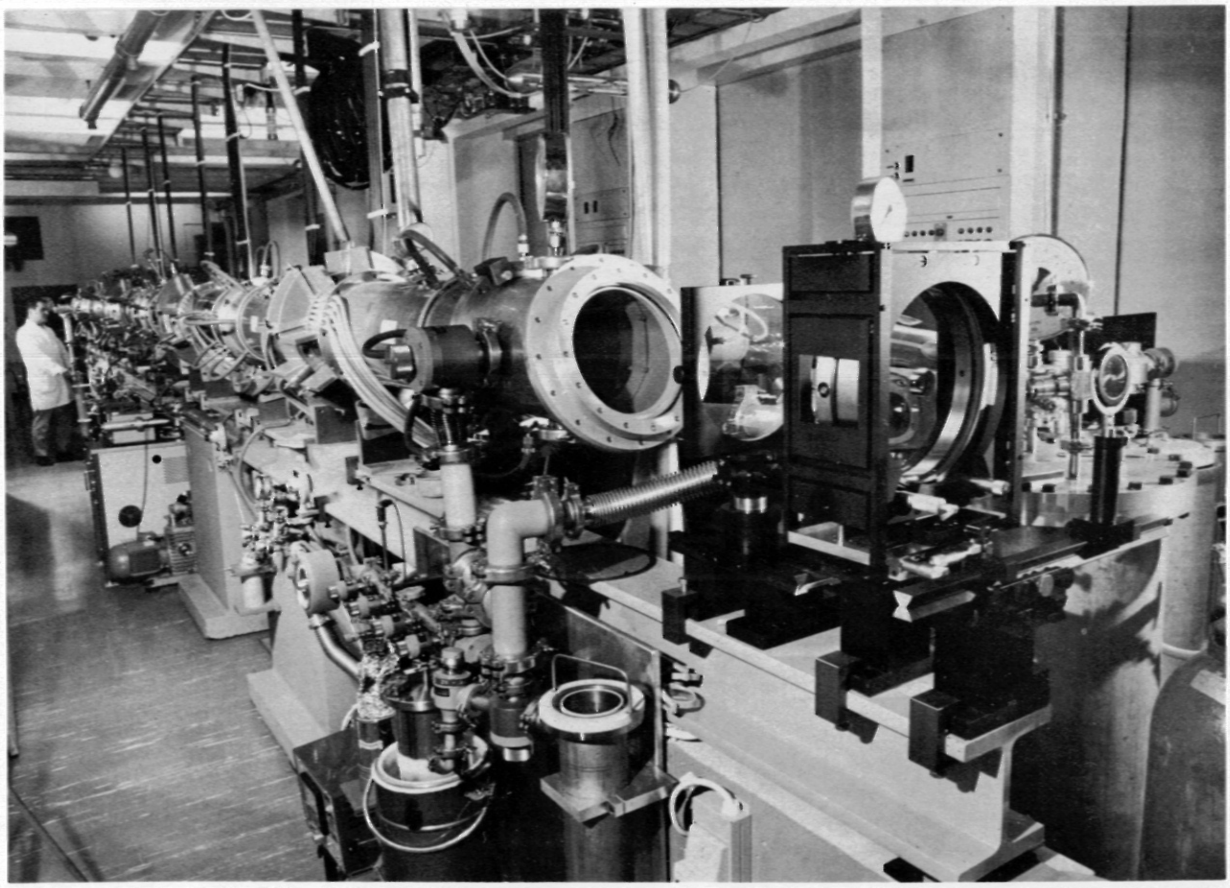


Fig. 11

As a consequence a quartz tube of 18 cm diameter was inserted into the flashlamp housing, so flashlamps are no more in direct contact with the laser gas. This way we got rid of the problem of deposits. The efficiency of the new laser heads increased almost by a factor of 2 and is now 0.9 - 1.1 % as defined by oscillator output/stored electrical energy in the capacitors. This means that in operation as a saturated amplifier ~ 0.5 % efficiency should be possible. The lifetime of the flashlamps (presently run without a simmer current) is around 2000 firings. The construction and testing phase of this new concept is now completed, and Asterix III will go fully in operation soon, expecting energies in the range of 600 - 1000 Joules.

The high loading of the flashlamps leads to a relatively low lifetime of the lamps. To provide a solution to this problem we have developed a new large lamp with an inner diameter of 45 mm and a length of 150 cm, operated at a Xe pressure of only 5 Torr (Fig. 12). Even after several thousand shots these lamps showed no hair cracks or other deterioration of the quartz. The estimated explosion limit is at 60 kJ electrical input; input used in our system was 9 kJ. Development of even larger lamps seems to be possible.

Fig. 12
Super flashlamp
length: 130 cm
inner diameter: 4,4 cm
Xe pressure: 5 torr

7. CW Lamps

Besides the line of Livermore, to use the fluorescence of XeBr for optical pumping, we should like to point out that another source of radiation seems to be applicable: cw mercury lamps. In the spectral range of 2500 - 3100 Å interesting for the iodine laser these lamps have an efficiency of 35 - 40 % /18/. They can also be operated in the so-called simmer mode, in which 10 - 100 pulses per second are emitted with a pulse duration of several milliseconds /19/. If it would be possible to apply this performance to the iodine laser, such a system would come close to the requirements of a fusion laser. Efficiencies of 3 - 5 % together with high repetition rates seem to be feasible. Precondition for this concept is a sufficiently long storage time of the iodine laser, i.e. the excited iodine atoms have to keep the excitation energy for several ms. The radiative lifetime of 130 ms is no limitation.

The influence of various deactivating collisions has been investigated in the past by several groups /20, 21, 22/. It turned out that rare gases as Argon are the only suitable pressure broadening gases. In the case of a noble gas as the buffer gas collisions of the excited iodine atoms with the iodide molecules are responsible for quenching.

To discuss the influence of quenching we should like to base our considerations on the set-up shown in Figure 13.

The laser gas RI and Argon flow perpendicular to the axis of the laser with a velocity v. In a closed circulating system used up iodide is exchanged and again led into the laser tube. UV lamps are placed at the side of the laser vessel, along a width a.

The energy density in the active volume can be estimated to be /23/

$$e = \rho \cdot 10^{-2} \frac{\varepsilon \cdot \alpha}{\beta \cdot k_{RI}}$$

where ε = UV power of the lamps per cm length of lamp

β = lateral size of lamp

α = absorptive cross-section of RI

K_{RI} = desactivation constant

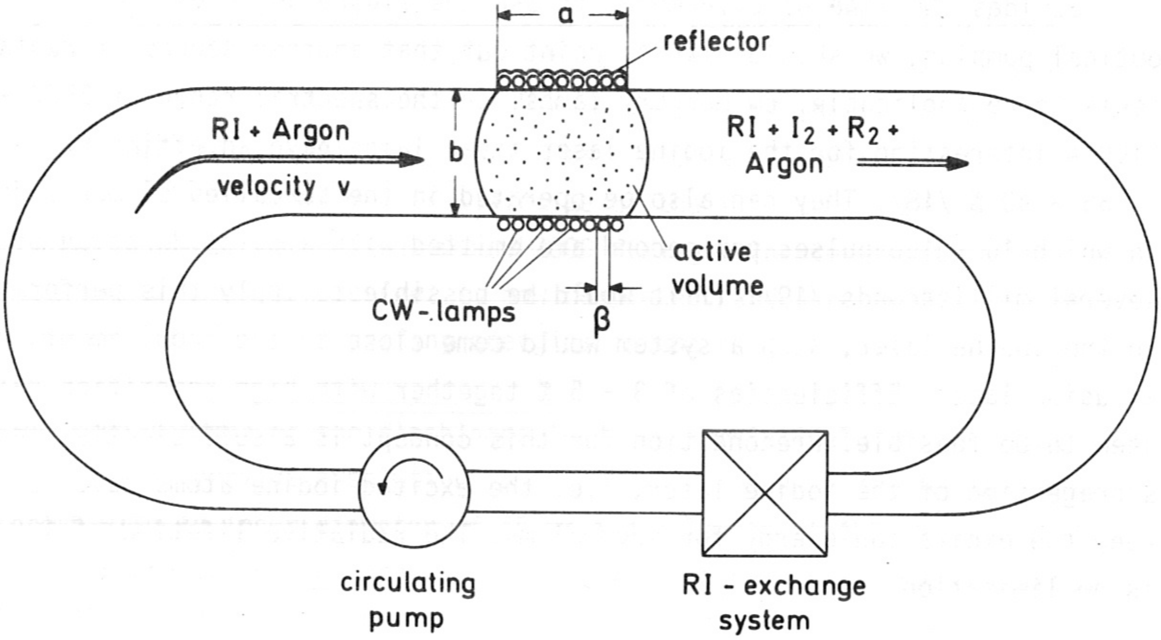


Fig. 13 Schematic set-up of a CW high efficient iodine laser

Here the pumping time was assumed to be 1/5 of the quenching time; the diameter of the laser was chosen to be equal to the absorption length of the UV radiation.

The length l can be calculated from the tolerable energy load ϱ of the mirrors and windows to be

$$\ell = \frac{2\varrho}{\varepsilon} = 25\,\frac{\varrho\,\beta\,K_{RI}}{\varepsilon\,\alpha}$$

For a 10 kJ system, assuming a surface load ϱ of 2 Joules/cm² and CF_3I as the laser gas the following dimensions are obtained (Fig. 14).

l = 20 m; F = 5×10^3 cm²; a = b = 75 cm.

With the assumption of a streaming velocity of 80 m/sec the maximum repetition rate turns out to be $\nu_R = 100$ Hz. To clarify the possibilities and prospects of the concept a detailed kinetic analysis and careful testing of the lamps will be necessary. In any case, it could be a way in the direction of a fusion laser. The dimensions don't seem to be unreasonably large.

At the end of this paper let me repeat the essential points:

1. The investigations of the last years have shown the potential of the iodine laser to generate high power. The variable cross-section for stimulated emission is probably the most important property of the iodine laser.
2. Experiments presently under way are mainly concerned with pulse cosmetics; pulses in the 100 ps range with excellent contrast ratio are being aimed at. Self-focussing could not be detected. The repetition rate for the system Asterix III is about 200 shots per day.
3. Scaling to multikilojoule systems seems possible with common flashlamp configurations. The iodine laser is especially attractive because of the possibility to pump it with lamps of high efficiency. Moreover this opens a way to repetition rates up to 100 Hz.

References

1 G. Brederlow, K.J. Witte, E. Fill, K. Hohla, R. Volk, IEEE Journal of Quantum Electronics QE-12, No. 2 (1976)

2 J.L. Emmett, J. Nuckolls, L. Wood, Scientific American 230, 24 (1974)

3 K. Hohla, W. Fuß, R. Volk, K.-J. Witte, Opt. Comm. 13, 114 (1975)

4 E.P. Jones, M.A. Palmer, F.R. Franklin, Optical and Quantum Electronics 8, 231 (1976)

5 H.J. Baker, T.A. King, J. Phys. E 9, 287 (1976)

6 E. Yablonovitch, Phys. Rev. A10, 1888 (1974)

7 E. Fill, K. Hohla, G.T. Schappert, R. Volk, to be published in Appl. Phys. Lett.

8 E. Fill, K. Hohla, to be published in Opt. Comm.

9 V.A. Gaidash, G.A. Kirillov, S.B. Kormer, S.G. Lapin, V.I. Shemiakin, V.K. Shirigin, ZhETF Letters 20, 243 (1974)

10 N. Skribanowitz, B. Kopainsky, Appl. Phys. Lett. 27, 490 (1975)

11 J. Olsen, to be published in Journal of Applied Physics

12 K. Hohla, G. Brederlow, W. Fuß, K.L. Kompa, J. Raeder, R. Volk, S. Witkowski, K.-J. Witte, J. Appl. Phys. 46, 808 (1975)

13 D.L. Kelley, Phys. Rev. Lett. 35, 1005 (1965)

14 N.G. Basov, V.S. Zuev, Il Nuovo Cimento 31B, 129 (1976); R.E. Beverly III, R.H. Barnes, Peter K.-L. Yin, Opt. Comm. 14, 412 (1975); L.P. Pleasance, L.A. Weaver, Appl. Phys. Lett. 27, 407 (1975); W.T. Silfvast, L.H. Szeto, O.R. Wood II, Appl. Phys. Lett. 27, 593 (1974); J.C. Swingle, C.E. Turner, Jr., J.R. Murray, E.V. George, W.F. Krupke, Appl. Phys. Lett. 28, 387 (1976)

15 M. Pilch, LASL, private communication 1973

16 L.E. Golubev, V.S. Zuev, V.A. Katulin, V.Yu. Nosach, Kvantovaya Elektronika 6, 73 (1973)

17 K. Hohla, MPI für Plasmaphysik, Report IV/33 (1971)

18 G. Brändli, Brown-Boveri-Mitteilungen 5, 62 (1975), p. 202

19 G. Brändli, private communication, May 14, 1976

20 N.Yu. Zalesskii, Sov. J. Quant. Electronics 4, 1009 (1975)

21 W. Fuß, K. Hohla, Z. Naturforsch. 31a, 569 (1976)

22 K. Hohla, K.L. Kompa, Chem. Phys. Lett. 14, 445 (1972)

23 K. Hohla, K.J. Witte, MPG Projektgruppe für Laserforschung, Report IPP IV/90 (1976)