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## RECENT PROGRESS IN HIGH AVERAGE POWER EXCIMER LASERS<sup>(1)</sup>

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### 1. INTRODUCTION

Numerous potential applications, in particular in the fields of material processing and photochemistry, have recently stimulated considerable interest in the scaling of excimer lasers which emit in the near ultraviolet to : a) higher laser output energy per pulse ; b) higher pulse rate frequency and c) higher average laser power (1). There are however presently number of scientific and technical problems to be solved in order to develop UV excimer lasers in the class  $\overline{P_L} \approx 100 - 1000$  Watts and above and PRF  $> 500$  HZ.

Progress are particularly needed in :

- molecular and atomic kinetics,
- discharge stability for long pulse large volume, high PRF,
- energy transfer efficiency of stored energy to laser medium
- fluid mechanics and acoustics
- whole efficiency including needed flow power
- "quality" of laser beam specially at high PRF
- life time of active medium

In a first part of this survey paper, are presented recent progress in high average power excimer lasers in these various fields as they appears in the open literature. A second part concerns a survey of the European program on research and development EUREKA on Excimer lasers (Eurolaser-Excimers). In a last part, very recent results obtained on the 200 watts - 1 KHz LUX XeCl excimer laser system ( $\lambda = 308$  nm) developed at I.M.F.M. are presented.

### 2. RECENT PROGRESS IN PHYSICS OF HIGH AVERAGE POWER UV EXCIMER LASERS

Potential applications of high average power ultraviolet lasers stimulate a large amount of studies in USA, Japan, URSS and Europe with the aim to scale up excimer lasers to higher output energy, pulse rate frequency, average power and efficiency (1)-(7). Thereafter are summarized some significant progress achieved recently in this frame.

#### 2.1 Molecular and atomic kinetics

All the high average power excimer lasers presently use a pulsed discharge excitation for production of the needed excited state rare gas halide molecules (upper laser level). Production of these excited molecules relies on complex plasma processes occurring on the short time scale characteristics of the upper laser state radiative life time ( $\tau_r = 9$  ns and 40 ns for KrF\* and XeCl\* respectively). Despite complexity of these processes where dozens of reactions occurs, efficiency for upper laser level production can be very high (several

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tens per cent). Recent progress have been achieved in identifying key reactions and saturable and non saturable losses in the XeCl laser which is the last known system. In particular quenching of upper laser level and partially saturable absorption by Xe<sub>2</sub>Cl\* has been shown to be an important process (8) (9). Fuel burning effect during long pulses and the added difficulties of long pulse kinetics understanding have been shown (8)-(11). Increased precision in key rate constants have been achieved (11) (12) (13). It has been shown that Ne/Xe/HCl mixture is the most adapted to XeCl discharge laser (1),(2). Modeling of the whole kinetics of excimer lasers gives now good results. Several complete models including excitation circuit, time varying plasma impedance, full kinetics and photon equation have been developed recently and validated by comparison with experience (8) (14) (15). A model which includes the most recent rate constants available has been established at IMFM (Fig1). Modeling gives good agreement (within 30 % for laser power and energy) with experimental results obtained at IMFM (8). It is to mention however that it remain poorly known kinetics related phenomena by example photoabsorption photodetachment and photoionization, specially for the KrF laser.

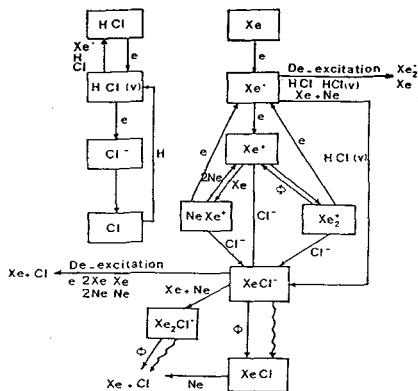


Fig.1. Most important kinetic reactions used in IMFM XeCl model

2.2 discharge stability and energy transfer efficiency

In the high pressure gas halide discharge typical of UV excimer lasers true steady state operation is never achieved. However transient equilibrium can be achieved on a short time scale even though long term equilibrium cannot be reached in the attachment dominated regime typical of rare gas halides. Like all transient phenomena, the quasi-steady state equilibrium of the excimer discharge depends strongly on the initial conditions. Control of the discharge initiation and achievement of long pulses have been keys of much recent excimer laser research progress (16)-(19).

Most commercial lasers currently rely on UV preionization achieved with ultraviolet light from sparks or corona discharges that are generated inside the laser gas before the main discharge is fired. Because UV light is strongly absorbed by the laser medium, only a limited depth of gas can be preionised in that manner. This sets one of the most stringent limit on the size and thus power increase of the excimer laser head. Progress have been achieved, mostly experimentally on threshold needed for preionization density and duration, preionization electrons loss process and time delay between preionization and main voltage application (1) (16)-(19). Nevertheless the mechanism of preionization in fluorine rich mixtures remains poorly understood. In the laboratory and for a few commercial devices, UV preionization has been superseded by X rays preionization which offers much more flexibility and scalability(20). With laboratory X-rays gun it becomes feasible to preionize large volumes with a good homogeneity thus lifting some of the most severe constraints on power scaling. Progress

have been made in the technology of high repetition-rate X rays gun with a particular mention to the very reliable wire ion plasma gun (W.I.P.) recently developed (21) (22). It has also been shown recently that as little as  $10^{-3}$  rad of 40 KV X rays is sufficient for effectively stabilize the discharge of an excimer laser even at high PRF (7) (19). Such low requirement leaves a good possibility for the design of an X rays preionized high PRF industrial excimer laser. Progress have also been achieved recently on understanding and control of discharge stability (16) (17) (23). These progress concern mechanisms of instability, control of the discharge by segmented electrodes connected to inductances, or by circuit allowing and also lengthening of laser pulse duration by modification of working mixture and lowering of power loading. Concerning instability processes two basic processes have been identified : a) the halogen depletion instability (23) ; b) the thermally driven cathode sheath instability (24). As shown later these instabilities are favored by aerothermodynamic disturbances. Laser pulses as long as  $1 \mu s$  have been obtained (17). Pulse rate frequency above 1 KHz are now obtained at the laboratory level with average power near 1 kilowatt and systems of 100 to 200 watts average power with 500 Hz PRF are commercially available. A PRF of 8 KHz has been reached very recently with a no flow XeCl\* laser excited by microwaves (25). The main discharge consists, in most of the commercial and laboratory rep-rate excimer devices in a C-L-C (or transfer type) circuit often associated with a magnetic assistance or a magnetic compression stage (1) (26). This type of device which is now well known is limited to about 2 % efficiency owing to its relatively low energy transfer efficiency. Advanced discharge excitation systems have been proposed recently and are currently studied in several laboratories. They are the double discharge circuit shown on fig. 2 (27)-(29), and the preionization switched circuit shown on fig. 3 (30) (31).

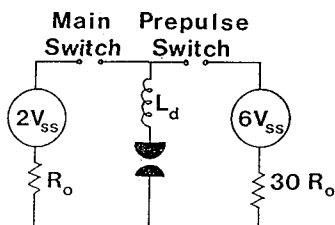


Fig.2. Double discharge circuit

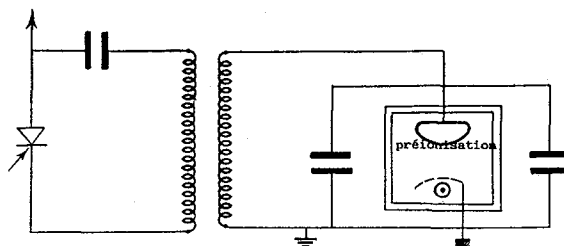


Fig.3. Phototriggered circuit

In the double discharge circuit, functions of gas breakdown and pumping are separated allowing a good impedance matching and so a high energy transfer efficiency during the period of main energy feeding. This concept associated to X-rays preionization and very fast magnetic switching as very recently allowed to obtain with XeCl\* an efficiency of 4.2% with 2.7 J extracted optical energy (3.3 J/l) per pulse at low PRF (28). Work is currently in progress at I.M.F.M. on this type of circuit. This system is very promising for a very high average power high efficiency excimer laser system.

In the preionization switched circuit, the laser head is directly connected to the storage capacitor, without any fast high voltage switch, and loaded to its design voltage with a relatively slow rise time. The triggering of a stable discharge is then obtained by rapid creation (10-20 ns), in the interelectrode spacing, of the required electron density using photoionization either by a corona UV, X rays

or KrF photon flux. Photoionization self switching is also very promising due to its obvious potential in terms of circuit simplicity and laser compactness. However the immunity of this excitation system to the local densities disturbances present in high PRF devices has yet to be demonstrated. Nevertheless relatively high PRF lasing (up to 350 Hz) and high efficiency (2.2 %) at low PRF have been achieved as well as high energy (1.7 joules) in XeCl(30). Selftriggering is best suited for XeCl discharge however progress is still required noticeably for KrF and ArF laser excitation by this method.

### 2.3 FLUID MECHANICS, ACOUSTICS, WHOLE EFFICIENCY AND BEAM QUALITY

Under the high repetition rates and high energy per pulse conditions which are characteristic of future 1 KW (or more) average power excimer lasers, the fluid dynamics of the gas flow loop becomes a central issue. This situation, which is well known in the case of the infrared CO<sub>2</sub> laser, is made much more difficult here due to the short wavelength of excimer lasers and reduced stability of the discharge. Mainly, three problems have to be solved : a) the heated gaz as to be swept out of the laser cavity between two excitations (i.e in 1 ms for 1 KHz PRF) ; b) the acoustic waves inside cavity have to be damped to a level of  $\Delta S/\rho \approx 10^{-4} - 10^{-3}$  in the same time scale from  $\Delta S/\rho \approx 10^{-1}$  immediately after excitation ; c) the flow power needed must not decrease too much system efficiency.

Although they are many closed-cycle pulsed gas lasers presently in operation, several issues pertinent to the design and operation of closed cycle flow systems for excimer lasers systems need further consideration in particular for very high average power systems which need advanced tranverse flow circulators (centrifuge circulator, transverse circulators) (3).

Natural damping of the aerodynamic disturbances due to the heavy excess energy deposit in the discharge volume which occurs during each pulse is not fast enough to insure uniformity in the laser cavity required by optical beam quality and discharge stability (3)(32)-(34). Three types of pressure waves have been identified (3) (32) in excimer laser cavity : one family of longitudinal waves and two families of transverse waves. Longitudinal waves travel in the upstream and downstream directions and can be reflected on the preceeding hot gas column and on any area change present upstream or downstream the cavity. One dimensional unsteady non linear analysis have been used (characteristics method, SHASTA FCT method etc..) with some success to model complete closed-cycle excimer laser flow loops (3) (33). Two dimensional modeling has also been applied locally (33). Broadband passive damping that minimally affect the average flow has been shown to be best achieved with sidewall mufflers. Such mufflers associated with felt nickel dampers have been found to stretch longitudinal waves wavelength to that the net change of refraction index across the optical aperture width become acceptably small. The length of muffler needed for effective damper scale with flow channel diameter. To reduce this length, it has been shown recently that dampers should be located as close to the cavity as possible. Of course, care must be taken to avoid wave reflexion back into cavity. Wave damping by use of active methods (use of destructive interferences) have also been recently proposed (35). The interaction of pressure waves with region of non isentropic flow (screens, honeycombs, heat exchangers...) induce late time density disturbances called entropy waves(3). Several methods have been recently proposed to manage these entropy waves including turbulent mixing. Additional multipulse studies are needed to investigate the cumulated entropy wave effect and more generally possible resonant effects of waves combinations. Transverse pressure waves that propagate along the optical axis have little effect on the optical quality of the medium but must be kept below 1 % at the time of excitation to avoid discharge instability which reduce extracted

laser energy. They can be damped and swept out with sidewall mufflers and tilted walls. Transverse pressure waves that propagate between electrodes are very detrimental to laser beam quality in the far field (34) and very difficult to damp. There too attenuation can be at least partially achieved with dampers set behind electrodes and by tilting of side walls and diffraction from the electrodes themselves (3) (32) use of canted cavity side walls have shown to be efficient). It is to note that recent progress in wave management (both in experiments and in modeling) shows that it is possible to damp to a reasonable level waves in a time scale compatible to 1 KHz PRF. Clearing ratio as low as 2,5 have been recently observed in several laboratories (3) (7). Flow power needed to manage excimer gas flow in the loop has been shown to be a real problem (3). On one side base line flow inside cavity has to be of very good quality ( $\Delta S/g \approx 10^{-4}-10^{-3}$ ); that necessitates very careful design of the loop and relatively high loop pressure drop. On the other side, flow power has to be maintained at a relatively low level to have no detrimental effect on the whole system efficiency. Work is still needed in this field. It is to note that any increase in laser electrical efficiency induce a natural reduction on the induced waves amplitude and so on the needed wave management. Laser beam quality (laser power density in the far field) is very dependant of cavity flow homogeneity. Progress have been made recently which permit to obtain  $\Delta I/I \approx 1$  to  $2 \cdot 10^{-1}$  for typical conditions of the state-of-the-art lasers. However that is not yet true for future 1 KW average power lasers. Methods using non linear optics for beam cleaning (Raman Scattering, Brillouin mirror) seem to be very promising for beam processing as a help to wave management to increase beam quality. Work is in rapid progress in this field (1).

#### 2.4 LIFE TIME OF ACTIVE MEDIUM

Maintenance and reliability of excimer laser systems are obviously an important issue. The problem is related of course to individual components degradation (capacitors, switches, electrodes, optics, bearings etc...) but most importantly excimer laser gas lifetime is presently a strongly limiting parameter. Even if the bulk kinetics predicts a complete recycling of initial gaz compound, gas life time is in fact limited by slow consumption of the halogen component and by discharge generated impurities. In addition these impurities can be deposited on the laser optics or induce photolytic depositions are them. Thus the excimer laser power has a natural tendency to decline during operation. Extensive work has been made recently in several laboratories in order to solve thus problem (36) (37). A very careful choice of material (Nickel, fluorinated compounds etc...) associated to in-line processing of gases and powders present in the loop and computer controlled long term stabilization of laser output has already allowed to obtain XeCl life time ( $\bar{P}_1 \rightarrow \bar{P}_1 / 2$ ) exceeding  $10^8$  shots. A life time exceeding  $10^9$  shots on XeCl can be reasonably expected for the next few years. However the situation is presently less encouraging for KrF and ArF lasers.

#### 3. EUROPEAN PROGRAM EUREKA ON EXCIMER LASERS

Construction of multikilowatt UV lasers is one of the more challenging task currently offered in gas laser development. It is actively pursued within administration sponsored programs in the USA and in Japan. In the frame of the European program on Research and Development EUREKA, a multinational program called "Eurolaser-Excimer" has been started in Europe in 1986 in order to develop in four years an Industrial excimer laser at the 1 to 3 KW average power level (37). The planned basic technology is as follow : XeCl laser transition  $\lambda = 308$  nm, fast flow closed loop, X-rays preionisation, discharge excitation, 500-1000 Hz PRF, 1 to 5 joules per pulse.

The planned calendar for this program is as follow :

- definition phase : September 1986-September 1987
- realisation phase: September 1987-1990

The planned funding includes 50 % from States and 50 % from compagnies for a total amount estimated to 120 MF.

The countries involved in the definition phase of the program are :

FRANCE : CGE, CNRS (IMFM, LPGP, CPAT, GREMI, LPMI), SOPRA, ONERA, CEA,  
RFA : KWU, LAMBDA PHYSICS, FRAUNHOFER ILT, DFVLR, LEYBOLD, LASER OPTIK, ...  
GREAT BRITAIN : OXFORD LASERS, UKAEA, EEV, ...  
ITALIE : ENEA, GALILEO, CNR-IEQ, ...  
NEDERLAND: TWENTE U.,  
GREECE: IESL (Crete), ATHENES U., MIRTEC, ...  
SWEEDEN: PERMANOVA AB,

The program includes :

- applications and marquet analysis
- laser concepts and system aspects
- laser discharges (including aerothermodynamics)
- laser optics

With the EUREKA Eurolaser-Excimer project, Europe, so, is also in position to develop efficiently its own industrial excimer technology.

#### 4. VERY RECENT PROGRESS ON HIGH AVERAGE POWER LASERS AT IMFM

Since 1979 the possibility of X-rays preionised excimer lasers as high average power UV sources is investigated at the Institute of fluid Mechanics of Marseille. Since 1981 a program to investigate both experimentally and theoretically the XeCl laser for conditions of high PRF and high average power has been undertaken. The goals are :

- to improve the knowledge of XeCl laser
- to determine parameters controlling the scaling up of XeCl laser to a) very high average power ( $\bar{P} \approx 1$  KW) and b) very high PRF ( $\approx 1$  KHz)
- to determine limitations of XeCl

Progress have been achieved in 1986-87 at IMFM toward theses goals :

- An advanced XeCl laser system called LUX (for laser ultraviolet preionisé par rayons X), which associates a fast flow subsonic loop, a WIP gun X-rays generator and a thyatron driven high PRF, C-L-C discharge has been constructed and upgraded (7) (22)
- Specific diagnostics have been developed or adapted which allow to study quantitatively key parameters of LUX test bed. They include frame and streak laser interferometry (39) (40) fast piezoelectric pressure gauges coupled to a microcomputer (41) and an home mode electrooptic system which allows temporal and spatial characterisation of LUX laser beam for high PRF conditions (42).
- An average laser power of 200 watts has been obtained from XeCl ( $\lambda = 308$  nm) at 1 KHz PRF in long burst ( 250 shots) with an Ne/Xe/HCl mixture (7) (40). LUX test-bed has been very recently scaled up to study XeCl laser characteristics at the 300-400 watts level. This modification includes sophisticated mufflers in the cavity and its vicinity.
- It has been shown that only a small X-ray dose is needed for preionization of the laser medium even at high PRF (7) (19).
- A complete model of long pulse X-rays preionized self- sustained discharge XeCl laser has been established for transfer capacitor and PFN circuits and Ne/Xe/HCl active medium (8).
- Shot to shot variation at up to 1.5 KHz PRF of various laser parameters for long bursts (250 shots) has been recorded. Theses experiments has already allowed to obtain new data of the repetition rate effects on the fluctuations of peak laser power, energy per pulse and spatial energy density repartition. In particular a strong effect of mixture composition on beam profile has been observed (42).
- A detailed experimental study of induced aerothermodynamic phenomena inside laser head of an excimer laser has been fulfilled for high energy load (100 - 150 J/l in 50 ns) and high PRF (500 - 1000 Hz) in burst mode (250 shots). An interferometric study has allowed to record time and space density variations inside cavity as well as

waves generation and behavior for multipulses conditions at high PRF (Fig.(4)). Enhancement of density heterogeneities inside cavity following a shot after several successive shots at 1 KHz PRF compared to a single shot has been observed and characterised. Pressure versus time at several places near the cavity have been recorded and analysed. longitudinal and transversal waves have been identified and characterised. At last a 1D model developed at IMFM and using the characteristics method has been modified and adapted to simulate present LUX conditions ( fig (5)) (43). A new 1D model using finite difference method (Shasta FCT) has been developed per multipulses simulation and is now operational for the case of a single shot. Results are in good agreement with the model using characteristics method and also with results from LUX experiments (39).

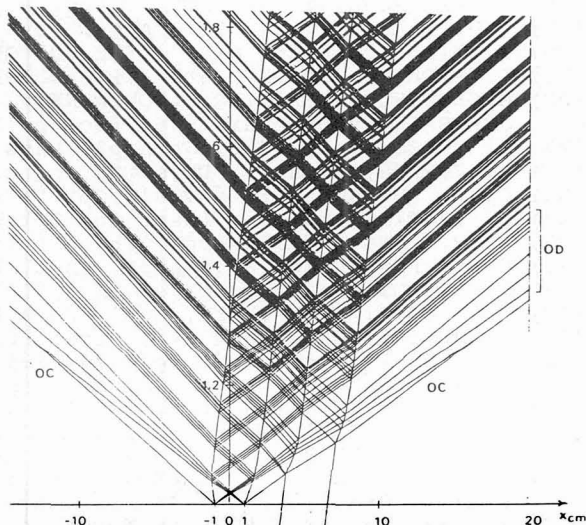
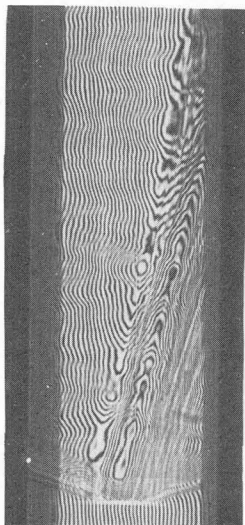


Fig.4. x,t LUX interferogram

Fig.5. x,t wave diagram at 1kHz

#### CONCLUSION

Even if it remain much work to be done, progress achieved recently in various laboratories, following active research on various aspects of high average power excimer laser physics, allow to be optimistic about the future of this class of lasers.

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