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I. Development at PNC of a high-repetition, high-~~paver~~ power Cu/Cu halide vapor laser

II. Recent developments of laser sources biblio graphic study

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REPORT

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I. DEVELOPMENT AT PNC OF A HIGH-REPETITION, HIGH-POWER Cu - Cu HALIDE VAPOR LASER.

II. RECENT STUDIES OF LASER SOURCES: BIBLIOGRAPHIC STUDY.

by Robert CAPITINI (+)

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Saclay, november 20th 1990

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変更表示

Ⅰ．高繰り返し、高出力ハライド系銅蒸気レーザーの開発

Ⅱ．最新レーザー研究（文献調査）

Robert Capitini

要旨

1989年～1990年まで客員研究員として、核燃料技術開発部先端技術開発室に在籍し、レーザー開発に従事した。本報告書は、この間に実施した試験及び調査についての報告である。

本報告書は2部構成になっており、

Ⅰ部は、先端室で行ったハロゲン化銅蒸気レーザーの特性についての試験報告である。

Ⅱ部は、著者が試験の傍ら、同位体分離に利用できるレーザー源について、最近の文献を収集し、整理したものである。

核燃料技術開発部　先端技術開発室

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REPORT

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510, 6 nm Green
578, 2 nm Yellow

I. DEVELOPMENT AT PNC OF A HIGH-REPETITION, HIGH-POWER, Cu/Cu HALIDE VAPOR LASER.

peak power 約100,000 watts ~~[illegible]~~ 約100 kW

I.1. INTRODUCTION.

10-30 ns
約2kHz

The most powerful and efficient Metal Vapor Laser is the copper vapor laser (CVL) which was operated for the first time by Walter et al in 1966. The copper vapor laser emits short laser pulses (10-50 ns), typically at multi-kHz repetition rates, at two wavelengths 510.6 nm in the green and 578.2 nm in the yellow region of the visible spectrum. The peak power of these laser pulses ranges from hundreds of kilowatts, while the average output power for typical small-scale devices ranges from 3 to 49 Watts. Large scale devices (more than 10 cm tube diameter) have produced output powers in excess of 100 W. A particularly attractive feature of the CVL is its high wall-plug efficiency of typically 1 %. Recently Mitsubishi Heavy Industries has obtained a world record of 1.51 % (see characteristics in Annexe).The CVL is therefore significantly more efficient than the other popular visible gas laser, the Ar+ laser, which has a wall-plug efficiency of approximately 0.04%.

The unique properties of the CVL output have been employed in a large number of practical applications. The CVL is well-suited as a pump source for dye lasers, and this application has provided the incentive for a substantial amount of CVL development work. Two particularly exciting applications for CVL pumped dye lasers are in laser isotope separation and the generation of ultrashort optical pulses. Some other applications are in medicine in microprocessor control and air-cooled, single phase power operation.

Laser operation on the self-terminating laser transitions of copper can be achieved using a large variety of different discharge tube geometries, copper atom production schemes and excitation circuit characteristics. The most successful is the discharge heated longitudinally excited CVL. All current commercial CVLs use this arrangment as does the laser considered in this study.The discharge-heated CVL basically consists of an alumina discharge tube (not in our study as explained in the next chapter), with refractory metal electrodes placed at each end. Pure copper pieces are placed at uniform intervals along this tube, which is filled with a buffer gas. This buffer gas acts to stabilise the discharge and to prevent rapid loss of copper through diffusion from the hot zone. Typically, high pressure neon (30-200 mbar) is used as the buffer gas as it has been found to lead to optimal CVL performance. The discharge tube is thermally insulated, so that the heat evolved from the repetitively pulsed discharge raises the tube temperature and so allows the correct partial pressure of copper vapor to be established. This method of copper vapor production is known as self-heating. The required tube temperature for optimal laser performance is in the range 1400°C-1600°C. Outside this temperature range, CVL performance is degraded because of the non-ideal copper density. The high-voltage excitation pulses are most usually derived from a thyratron-switched capacitance transfer circuit. The requirements for plasma relaxation between excitation pulses means that these lasers generally operate at repetition frequencies of 5-15 kHZ. We will see in our study how it is possible to operate at higher repetition frequencies (40-50 kHz). Without feedback mirrors the CVL produces strong superradiant output because of the high gain of the system (typically 0.1/cm). In normal operation, a plane-plane or hemispherical cavity is used with the CVL, with the optimum output coupling of the resonator exceeding 90 %. The CVL may also be used with unstable resonators, which have the advantage of producing a significantly less divergent output than plane-plane or hemispherical resonators.

The technological difficulties in producing and containing a copper vapor discharge at elevated temperatures (1500°C) led many researchers at this time to investigate schemes for reducing the operating temperature of the CVL.In 1973, Liu et al suggested the use of copper compounds (in particular,copper halides) in place of elemental copper to reduce CVL operating temperatures of the CVL.

At this time, Liu et al successfully obtained superradiant copper emission at 510.6 nm and 578.2nm using copper iodine (CuI) vapor at 600 °C as the source of copper atoms. Later in 1973, Chen et al reported the achievement of laser action using copper chloride (CuCl) at 400 °C as the copper source.This study revealed that two discharges pulses were required to produce laser action in a copper halide, the first pulse dissociates the copper halide to produce free copper atoms and the second pulse excites laser action.

The discovery that copper halides could be employed as the copper source for CVLs initiated a great deal of research interest, particularly in the USA. In 1974 and 1975 respectively, Liberman et al and Chen et al reported the operation of multiplypulsed copper halide lasers. In these devices, each excitation pulse both excites laser action and produces copper halide dissociation for the next pulse. Both these lasers were only small devices but the output power densities obtained (0.28 W/cm^3 and 0.7 W/cm^3 respectively) suggested that large scale devices would rival the performance of large scale elemental CVLs. The development of copper halide lasers culminated in two different devices. Nerheim et al in 1978 optimised the double-pulse CuCl laser to produce about 10 mJ per output pulse. Chen et al optimised in 1979 the multiply pulsed CuBr laser to produce 20 W at a prf of 16.7 kHZ. Difficulties with further scaling of these devices led to a susbsequent decline in research interest. During this intense period of copper halide laser development, the discharge-heated elemental CVL was only examinated once in the USA. But the major impetus for further CVL development was the decision to use CVLs as part of the isotope separation program, known as AVLIS, at Lawrence Livermore National Laboratory (Grove 1982). The AVLIS program, which was geared particularly towards isotope enrichment, required CVLs with higher output power and greater reliability than were available in the USA at that time.

In addition to the use of copper halides, a variety of other low temperature schemes for copper vapor production have been investigated. In 1985, Saito et Taniguchi reported a CVL using a vapor-complex reaction to produce copper vapor. Sputtering of copper atoms in a glow discharge was used as the copper source in the CVL of Anders et al in 1986. Later in 1990, Taniguchi and Saito have studied the transient phenomenon of relaxation oscillation in CVL. Relaxation oscillations were observed in the 510.6 nm laser line of discharge-pumped CuCl vapor lasers under appropriate conditions which are furthermore shown to agree with the theoretical considerations. In 1989, R.Bhatnagar et al have used a self-filtered unstable resonator in order to reduce the beam divergence to 0.19 mrad. This is about two times the diffraction limit. In 1989, S. Cavalieri et al have constructed a small scale selh-heating copper vapor laser. They have reported in detail the analytical design of the thermal isolator. Particular attention has been given to the knowledge of power deposition in the discharge to evaluate the component losses. In the optimized conditions the laser mean power is over 5 W, confirming the expected values. In 1988, high-efficiency CuBr laser with interacting peaking circuits have been obtained by N.Vuchkov et al. This innovation in CuBr laser excitation causes a significant increase of the ouput power and laser efficiency. The novel electrical circuitry consists of two interacting peaking circuits as just mentionned. A comparison of the operation parameters between an ordinary-circuitry excited CuBr laser and the novel-circuitry (interacting peaking circuits) excited CuBr was made showing an efficiency of 1.45 % at 17.4 W average output of the novel-circuitry CuBr laser. Operational efficiency increase in a CVL was shown in 1989 by L.Estep due to the replacement of vacuum jacket Brewster windows with flat windows. The cause of the efficiency increase appears due to a double optical cavity set up by the flat windows. However authors underlined that the variation of the efficiency due to changes in the pulse repetition frequency and buffer gas pressure were less well understood. At PNC, CVL research activities led by N.Sasao and K.Ouchi were confined to experimental studies of high-repetition rate (25-35 kHz), high average power (15 W) copper halide lasers. (CuBr, CuCl, CuI). Details of this study are described in the next chapter. We can mention that these performance has been presented at international congres such as

CLEO 90. The laser used was of conventional self heated longitudinal discharge as explained in the text.

I.2. SUMMARY OF THE RESEARCH AT PNC.

The main goal is to develop a high-power, high-repetition rate, low-temperature copper vapor laser (CVL) using copper halide as lasant.

The subgoal is to investigate power scaling limitations of high-repetition rate copper halide lasers. Observations and conclusions resulting from the parametric study of the laser will be detailed.

I.3.EXPERIMENTAL PART AND PROSPECTS.

Different copper halides (CuCl , CuBr , CuI), as the lasant, have been used into a CVL in order to run at low temperature (~500°c) and, consequently, to use normal pyrex glass for the laser construction.

Characteristics of the pyrex CVL are given in TABLE 1.

Initially, research was confined of measurements of laser power as a function of the discharge parameters, such as, applied voltage, buffer gas pressure, pulse repetition rate and the chemical properties of the copper halide lasant.

The investigations have been completed.

The main results of this preliminary study are briefly described below in taking the case of CuI which has given the best performances.

a). Output laser power versus halide laser medium: determination of the amount of halide to put into the pyrex tube has been determined by an empirical method. Optimum operating temperature were found to be 400°C , 480 °C , 600°C , respectively for Cucl,CuBr and CuI.

TABLE 1

CHARACTERISTICS OF THE COPPER HALIDE USING I (CuI)

-=-=-=-=-

- Pyrex laser tube ....ϕ i = 26 mm.
- Beam diameter .... ϕ i = 16 mm.
- Ni electrodes ... ϕ i = 16 mm.
  (at both ends of the tube)
- Lasing medium ... along the tube.
- Tube temperature ... ~ 500° to 600°C.
- Operation lifetime .... ~ 5 h per each charge (CuI = 3 gr.)
- Laser efficiency .... 0.75 %.
- Optical cavity
  - output coupler ... 15 %.
  - dielectric multilayered mirror .... 99.9 %.
- Thyratron maximum repetition frequency ... 100 KHz.
- Power supply for thyratron. ..maximum 50 KHz.
- Buffer gas Ne ... pressure up to 100 torrs.
- Gas flow rate ..... 1.4 l/min.
- Charging voltage capacity (*) ... up to 25 KV.
- Power supply for discharge circuit ... 10 KW.

(*) rate between laser energy output to electrical energy input (stored in charge capacity).

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As an example, we have obtained a maximum laser power of 12 Watts for a tube-wall temperature of 600°C while using CuI.

At lower temperature, the output laser is strongly decreasing due to a lack of CuI for an available excitation.

At higher temperature, there is too much CuI that reduces electron temperature, in other terms, that reduces excitation of the copper.

The experimental conditions are: charging voltage 11 KV Ne gas pressure 60 torrs and pulse repetition rate 30 KHz.

b). Output laser power versus pulse repetition rate:

The performances of the thyratron are limited by the charge transfer circuit whose maximum repetition frequency is 50 KHz (cf. TABLE 1).

FIGURE 1 shows the output laser power for CuI versus the pulse repetition rate, varying from 25 to 45 KHz. Curve A shows a maximum of about 12 Watts at 45 KHz, instead of being much higher if the pulse energy would remain constant (curve B). Curve C shows that pulse energy is continuously decreasing (3.5 to 2.5 10^{-4} J) when pulse repetition rate varies from 25 to 45 KHz.

In this experiment, the other conditions are: C_s = 1.12 nF, Ne gas pressure 60 torrs, discharge voltage 11 KV.

This decrease of the laser pulse energy with pulse repetition frequency clearly explains limitation of this laser at high repetition rate.

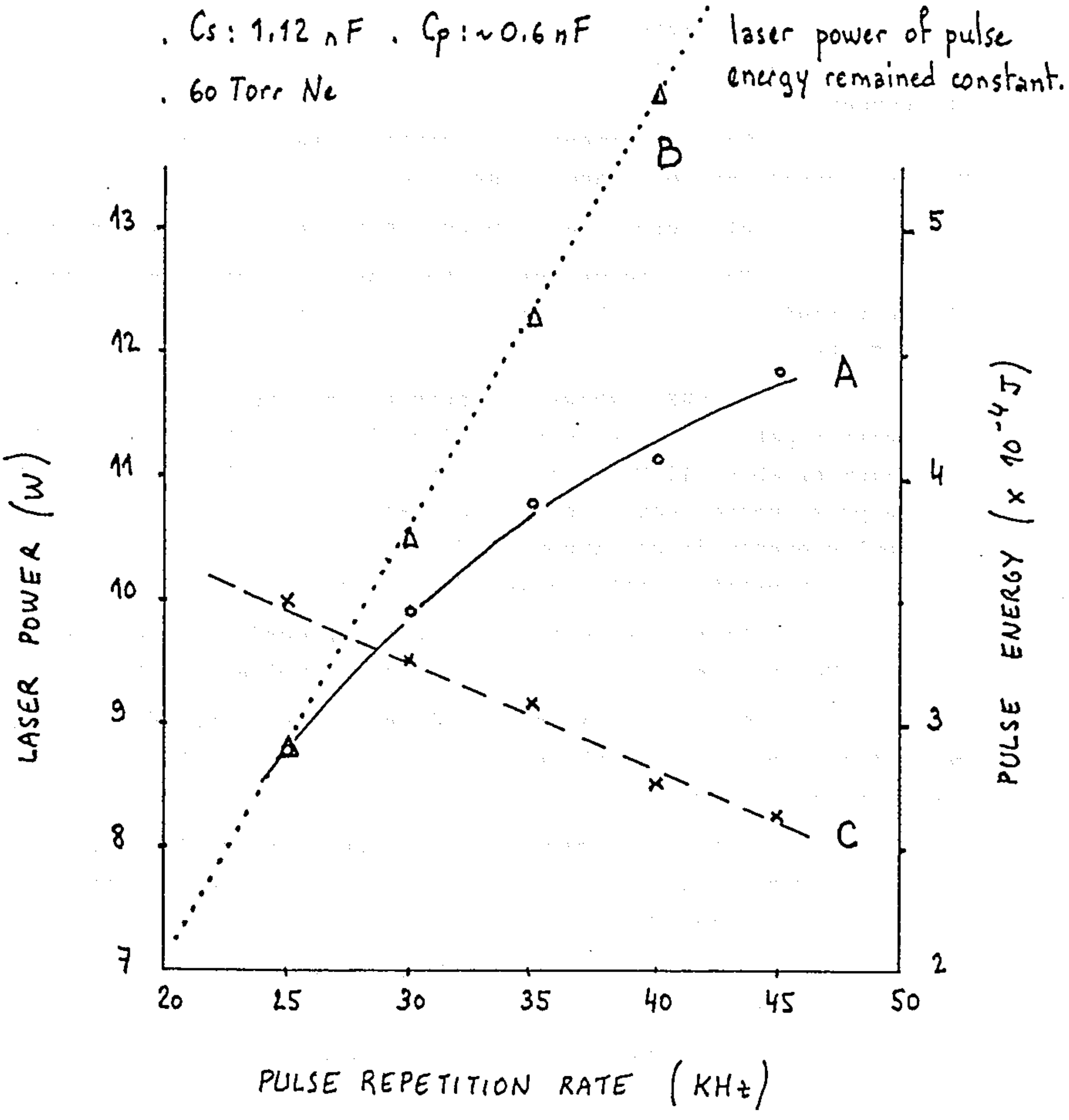
Condensers capacity, or slight degradation, could reduce charging discharge voltage a bit.However,important reason could be due to mechanism of laser action as discussed in Chapter III.

The main goal therefore, is to understand the reasons for this effect.

c). Output laser power as a function of applied voltage:

FIGURE 2 shows the output laser power (in Watts) versus the applied voltage (storage capacity in KV) at 25 KHz (curve A) and 35 KHz (curve B). The only reason for which CuI works better at 35 KHz is due to higher pulse counting rate. The two other curves, respectively show the pulse energy for operation at 25 KHz (curve C) and 35 KHz (curve D).

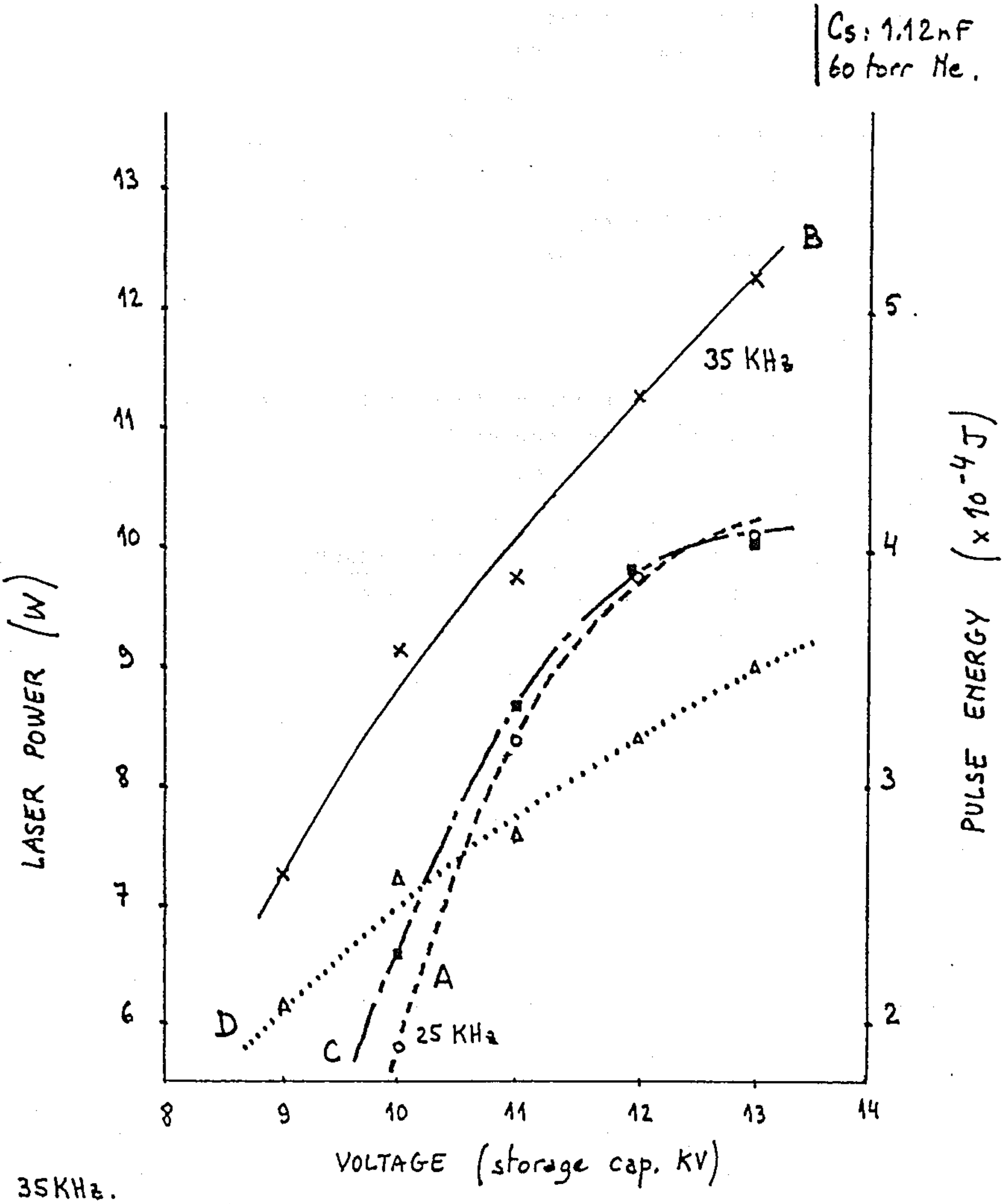
LASER POWER AND PULSE ENERGIES
AS FUNCTION OF P.R.R (KHz)



COPPER HALIDE LASER USING I.

Figure : 1

LASER POWER AND PULSE ENERGIES AS FUNCTION OF APPLIED VOLTAGE.



COPPER HALIDE LASER USING I.

Figura: 2

d). Output laser power as a function of the buffer gas pressure:

FIGURE 3, curve A, shows a maximum of the output laser power at 14 Watts for a gas Ne pressure of 90 torrs. The pulse repetition rate is fixed at 30 KHz.

At 35 KHz, the measurements are scattered but we approximate the dispersed values of output laser power as constant along curve B. This last result needs to be checked once more.

In this experiment, gas flow rate is constant and set up at 1.4 l/min. The discharge voltage is 11 KV and the storage capacity C_s = 1.12 nF as previously.

-=-=-=-=-

In conclusion of this part, we can say that it is possible to run with a pyrex copper laser using halide, at low temperature, high repetition frequency and high output power.

However, unchecked factors are limitating the performances of the CuI-CVL. In particular, FIGURE 1 sums up the problems associated with higher repetition rate operation.

So, to get higher repetition rate operation, it will be essential that we understand kinetics of the discharge.

Programm for this next step is described in the Chapter III. Part of it is in progress.

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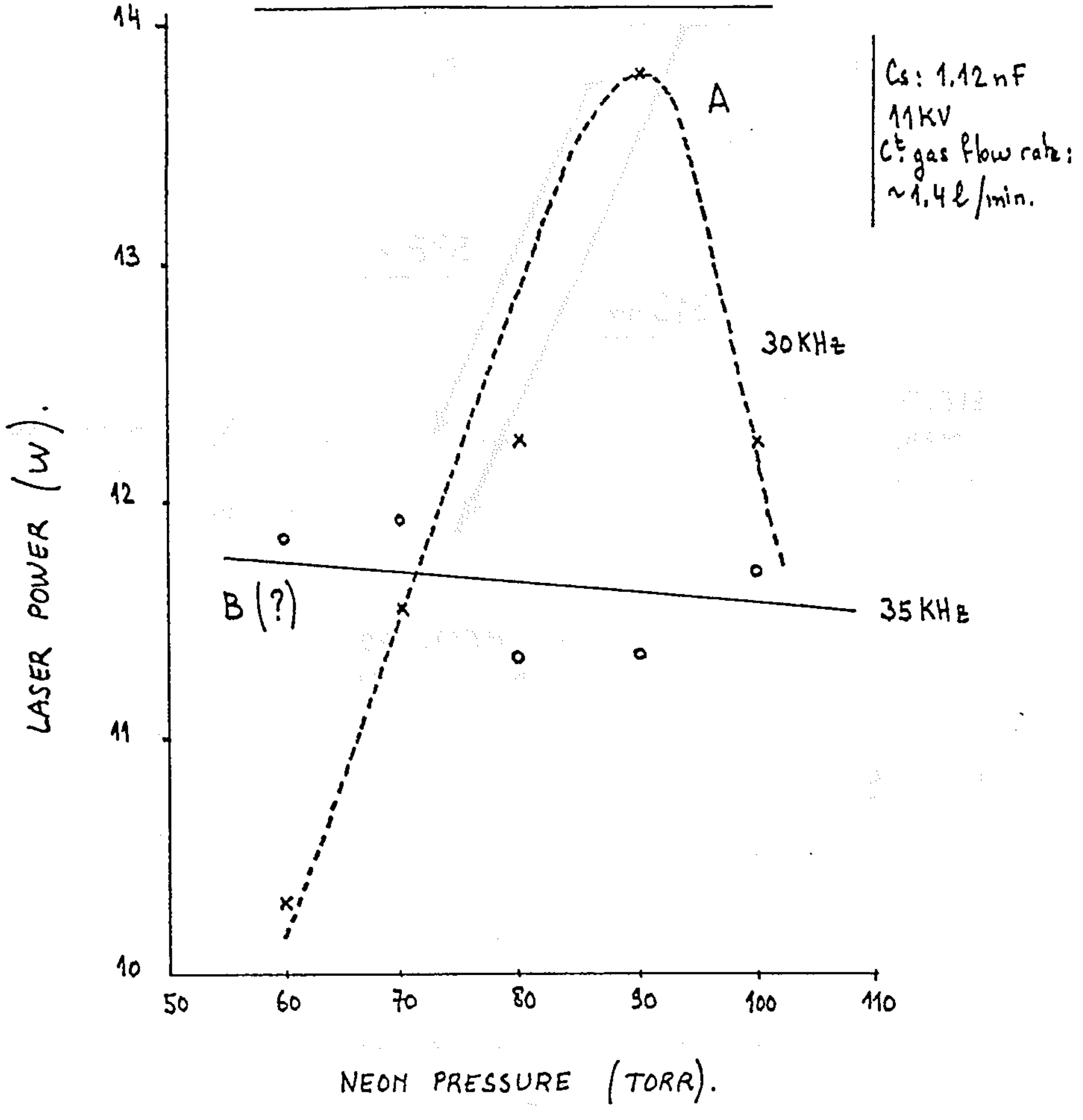
For a better understanding of the kinetic studies involved in the experiments in progress, FIGURE 4 shows the energy levels in CVL which are involved with laser action.

- the 4 s ^2S $1/2$ ground state.
- the 4 p ^2P $1/2$ and 4 p ^2P $3/2$ upper laser levels. They are in resonance with the ground level. Upper levels are populated by discharge electrons. Electrons have large cross sections due to the high optical transition probabilities between upper levels and ground level.
- the 4 s^2 ^2D $3/2$ and 4 s^2 ^2D $5/2$ lower laser levels. These levels are metastable and optical transitions with the ground state are forbidden

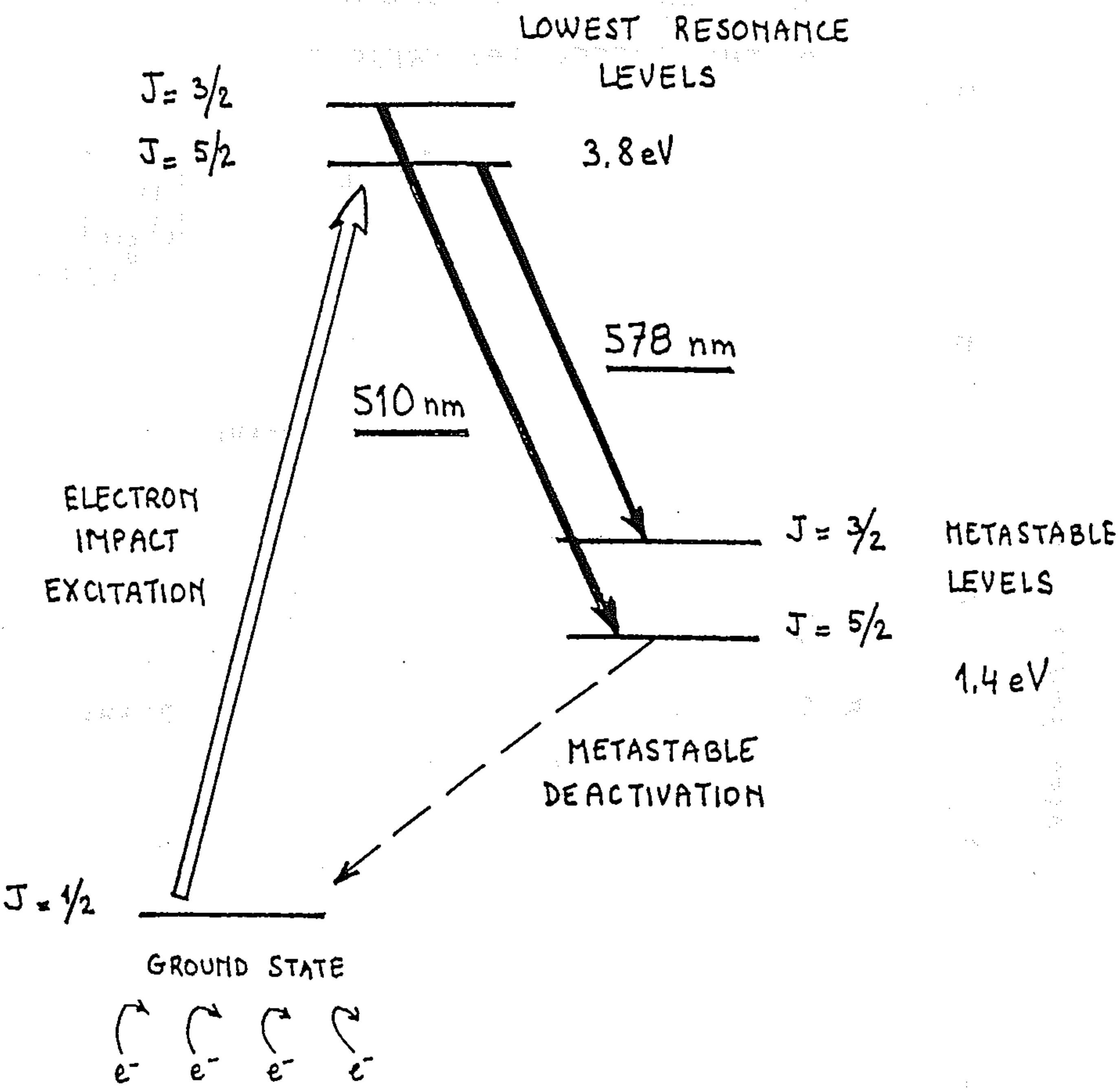
Excitation is a longitudinal discharge excitation. The large cross sections of the upper levels and, consequently, their low



LASER POWER AS A FUNCTION OF THE BUFFER GAS PRESSURE.

COPPER HALIDE LASER USING I.

Figure: 3



MECHANISM OF LASER ACTION IN COPPER VAPOUR.

Figure ; 4

lifetimes, impose to apply a high voltage short pulse to the discharge tube.

High gains can be reached if the temperature of the peak electron Te, in plasma, is greater than 2 eV (3.8 eV - 1.4 eV), FIGURE 4 .

In the particular case of the copper halide laser using CuI, we have assumed, in the Chapter II that the performances limitation could be explained by a better understanding of discharge kinetics.

According the literature of this subject, the study remains unsolved at high repetition rate.

It, mainly, concerns knowledge of:

a). Prepulse electron density (n_e): high n_e density conducts to lower population inversion.

b). Copper metastable density (N_m): high density is problematic at high repetition rate.

TABLE 2 shows the different processes which could be at the origin of the limited performances.

In the goal of understanding the influence of each parameters and, also, to indicate limitation for power scaling in the case of high repetition rate copper halide laser, our study involves investigation of the copper halide plasma using interferometry and absorption technics. In this study, laser pulse energy is limited while working at high repetition rate frequency.

Of a particular interest are the measurements of:

- prepulse electron density.
- copper metastable density.
- plasma temperature.

Plasma gas temperature will be measured using standard broadband absorption technics and prepulse electron density estimated from the electric field penetration time through the plasma.

However, preliminary experiments could be necessary to estimate the line profile of the absorption bands although the broadline of the pulsed dye laser is narrow ($\Delta\lambda = 0.05\ cm^{-1}$).

In addition of this preliminary study, we are starting, first, the experimental set up to determine gas temperature before the absorption measurements as shown FIGURE 5.

In a first time, gas temperature profile measurements

TABLE 2

CAUSES OF PERFORMANCES LIMITATION ON A HIGH - REPETITION CVL

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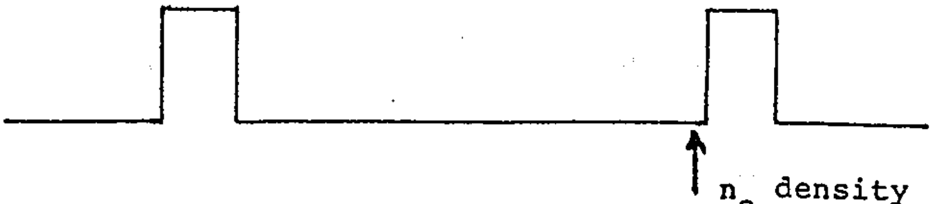

1). ELECTRONS

High pre-pulse n_e --> low impedance

--> reduced discharge V

--> T_e (mean) lower.

--> reduce upper excitation rate

no effect on lower excitation

------> population inversion lower,

harder to obtain.

2). METASTABLE DENSITY

High --> discharge must work harder to create inversion.

--> T_g high --> thermal excitation.

--> decay of metastables level is not sufficiently rapid between pulses --> problem at high pulse repetition frequency.

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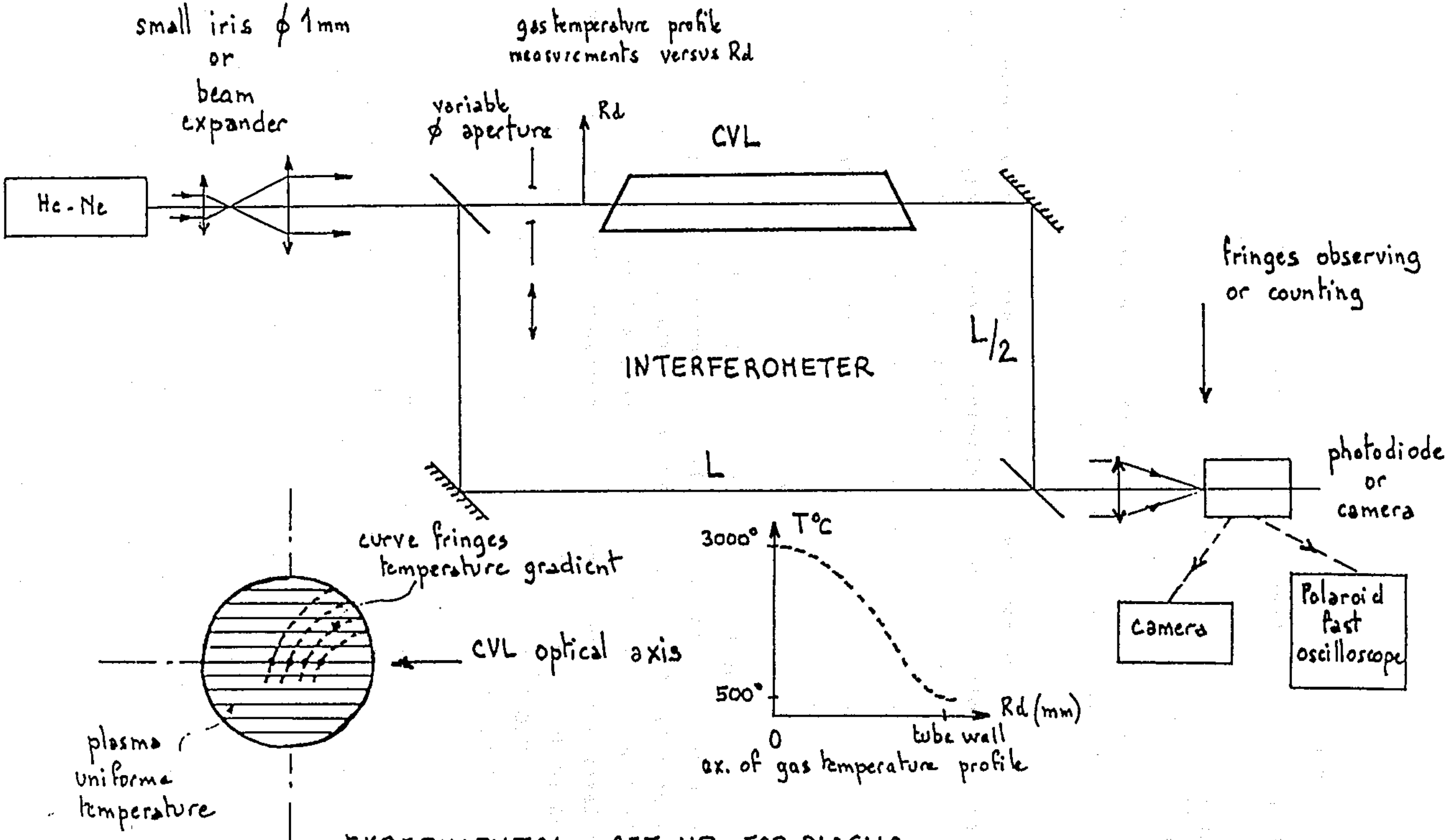


EXPERIMENTAL SET-UP FOR PLASMA
GAS TEMPERATURE MEASUREMENTS

Figure: 5

versus CVL's radius Rd will be done, using a 1 mm diameter laser beam and a photodiode connected to a fast oscilloscope. .

In a second time, plasma gas temperature measurements will be determined using two methods:

- a direct fringes observing, with a beam expander and a camera, in order to count fringes accross the CVL optical axis, as shown in FIGURE 5, and to determine the phase shift from which it is possible to calculate density then temperature.

- an indirect fringes counting. In this case, we will use the 1 mm diameter iris and a photodiode connected to a polaroid fast oscilloscope.

In the two cases, it is necessary to use a steady optical bench and plastic tubes to eliminate, respectively, sources of mechanical vibrations and thermal effects on the interferometer arms.

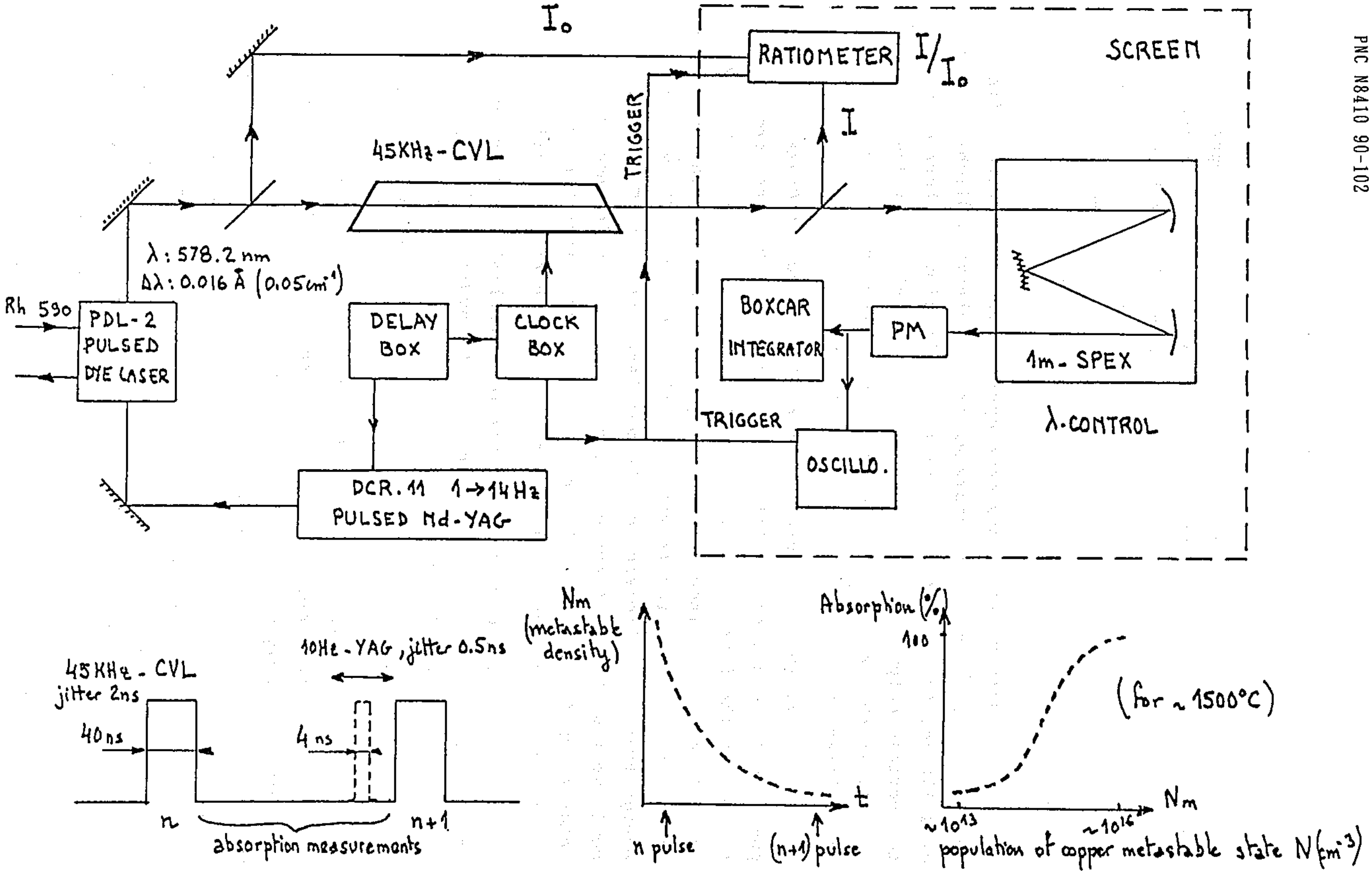
Experimental set up is in progress.

In principle, temperature estimation could be within a few tenth degrees of accuracy (gas temperature: 2.500°to 3.000°C for metal CVL, probably lower for CuI).

Absorption measurements will be done between two consecutive pulses (n and n+1)of the CVL running at 45 KHz. The probe is a 4 ns-pulse from a 10 Hz YAG laser. The absorption wavelenghts are 578.2 nm (metastable levels) and 324.7 nm (ground state) so, a dye laser and a spectrometer are necessary. Timing between 45 KHz CVL and 10 Hz pulsed dye laser will be controlled by delay and clock boxes (cf.FIGURE 6). Jitters have been measured and are, respectively, as 2 ns and 0.5 ns.

To investigate the CVL inter-pulse period ($2\ 10^{-5}$s) with the 4 ns pulsewidth, in order to measure metastable decay rates under various discharge conditions (high voltage, pressure, temperature) measurements will have to be done far and very close of the CVL pulse. Absorption band profile will be checked using a 1m- SPEX spectrometer. Ratiometer method will be used for preliminary absorption measurements . Then, spectrometer and photomultiplier connected to a boxcar integrator will be used for starting absorption measurements. Systematic investigation of the interval period will be done in a second step, with a minimum of 10 points. Measuring apparatus will be put into the screen.

In the continuity of these experiments, study will be extended to the ground state density.



EXPERIMENTAL SET-UP FOR ABSORPTION STUDIES.

Figure: 6

II. RECENT DEVELOPMENTS OF LASER SOURCES: BIBLIOGRAPHIC STUDY

II.1. METAL VAPOR LASERS.

The performance of commercially available copper vapor laser (CVL) continues to improve as the Oxford laser. The average power operating range is above 100 W. This has been achieved due to improvements in head design (60 mm bore ceramic tube) and in switching technology (multiple thyratrons in parallel). The input power required is 12 - 13 kW (prf 5.5 kHz and up to 32 kHz) with 0.9 % efficiency.

HITACHI WORKS has developpd a 100 W-CVL with a discharge tube of 80 mm inner diameter and an electric discharge length of 1,570 mm. Some limitations exist in enlarging the bore of a CVL to increase output power because of causing relatively low power density in the central zone (current suppressed by the skin effect, and relaxation of the lower level by the wall effect).

At the Institute for Laser Technology in Osaka, a CVL pumped with an all-solid-state switch modulator has been demonstrated for the first time in 1989. The solid state switch modulator consists of static induction (SI) thyristors and two stage magnetic pulse compression circuits with saturable reactors. The maximum energy transfer efficiency of the modulator is 67 %. The modulator could work with high transfer efficiency over a wide input energy range by optimization of the rest currents for saturable reactors. The average laser power was 21 W at a 5 kHz repetition rate.

At the Central Institute of Mitsubishi, studies were carried out during 1989-1990 to extend the hydrogen thyratron life time by using parallel or magnetic assist circuits. Energy loss at thyratron is reduced to 50 % and laser power is increased by 10 %.

At Osaka University, density measurements of the laser levels of CVL have been made. Time and spatial profiles of the density were directly measured for the lower level as well as the upper level (2D5/2 and 2P3/2 respectively). The density of the 2D5/2 level reached an equilibrium state with a gas and electron temperature in 30 microseconds. In the other hand, we can mention two other studies for laser isotope separation (LIS) in the same Institute. An experimental and analytical study of S. ADACHI et al on the propagation effects of the laser pulse on atomic LIS was made. Pulse reshaping of a narrow-line dye laser propagating in sodium vapor was observed and compared with calculation based on the adiabatic model. Selectivity and ionization rate in two-step ionization process in atomic Gd isotope separation have been investigated. Gadolinium oxide is added as a burnable poison in a light water reactor fuel. LIS of atomic Gd will be discussed later in the LIS part. At the same Institute, contaminants emission (Mg, H,OH,C_2,CH) from a high temperature discharge CVL tube have been identified by emission spectroscopy of plasma discharge. T.TAKEDA et al have shown that laser output increased by decreasing emission intensity of OH radical. Gas temperature in a plasma tube can be determined on the basis of the rotational spectra of OH radical. Other metal-vapor laser of interest is the He-Cd laser at output powers from CW to 50 mW. Primary output wavelengths are 325 and 441.6 nm but other wavelengths (443 nm) have been reported in 1989. Its low cost lifetime is 2,000 hours, so relatively inexpensive and reliable but it operates with air cooling. Note that the production in Japan of solid state laser is equivalent to the He-Ne production, each represents 2,5 billions of Yens in 1989 and CO_2 3 billions of Yens and excimers 1 billion of Yens. Concerning efficient deep-ultraviolet generation by frequency doubling in β - BaB_2O_4 crystals, enhanced efficiency and sum frequency generation from the two CVL ouputs (511 and 578 nm) was reported by Macquarie University in Australia. Over 460 mW UV output at 255 nm (SHG of 511 nm) and 271 nm (SFG) and up to 300 mW at 289 nm (SHG of 578 nm) were obtained with wall-plug efficiencies up to 0.016 % for a 16 W CVL with a M = 26.5 off-axis unstable cavity. Nonlinear frequency conversion of solid-state lasers covers other variety of crystal-growth techniques, especially KTP and its isomorphs.

The Fujian Institute of Research and the Research Institute for synthetic crystals in Beijing (China) continue to carry studies on the non linear properties of lithium triborate (LiB_3O_5) generally referred to as LBO. LBO is transparent from 160 to 2,600 nm with surface damage threshold as large as 256 W/cm^2 for a 100-psec pulse Nd-YAG laser (3.5 times that of KDP and 1.6 times that of BBO under the same conditions). Conversion efficiencies as high as 60 % have been measured in an 11-mm long LBO crystal when pumped by a 20 nsec Nd:GAG laser pulse.

II.2. GAS LASERS.

MITSUBISHI HEAVY INDUSTRIES and The Industrial Research Institute have succeded in attaining record of output 7 kW over 4 hours using a CO laser, expected to be a next generation laser for industrial and nuclear use. This CO laser is to be used for in-core structure cutting technology tests (MITI contract) on reactor decommissionning. As the wavelength of the CO laser is about 5 μm (one half that of the CO_2 laser), CO laser provides a feature that the minimum spot diameter at the focal point is one half of that of the CO_2 laser and energy density is 4 times up.By comparison with a 3 kW CO_2 laser it is possible to cut up to 20 mm thickness of carbon steel and 16 mm of stainless steel, but the 3 kW CO laser can cut 70 mm thickness of carbon steel and 40 mm of stainless steel. MITI and Nuclear Power Engineering Test Center plan to develop a 20 kW class CO laser.

Electron beam, plasma and ion beam are often employed to simulate the high heat flux applied to the first wall in a fusion reqctor. Irradiation test can be carried out , under atmospheric condition, by using high power CO_2 laser. T.TERAMOTO et al have developped a thermal analysis code to take melting and evaporation behavior into account. The laser absorption coefficient can be raised up to 95 % before melting if special paint is coated on specimen surface and consequently CO_2 laser is quite suitable for use as a heat source to simulate a high heat flux.

TEA CO_2 lasers with high-peak power output are expected for application such as chemical vapor deposition, making and isotope separation, in particular RIMLIS. The major problem for industrial TEA CO_2 making is to achieve high-output energy, high-repetition rate and long lifetime. To overcome these problems, optimum preionize, all-solid-state power supply with switch and magnetic pulse compressor and high-density discharge techniques are required. TOSHIBA has developped TEA CO_2 laser systems with 10 J/pulse output energy and 100 pps repetition rate.

For efficient and stable operation of gas lasers at high repetition rate, such as TEA CO_2 laser, turbulence of a gas flow must be swept out from the discharge region. To realize the ideal cleaning of discharge wastes and heated gas, recovery process of a gas flow after discharges was investigated by H.TASHIRO et al (at RIKEN) with an interferogram method using a high speed video. High repetition rate operation of TEA CO_2 lasers with all-solid-state exciters (ASSE) was experimentally investigated in 1989 by H.HATANAKA, H.TASHIRO et al. At the repetition rate of 1 kHz an average laser power of 250 W was obtained by a 10-J class ASSE. The average laser power increased in proportion to the repetition rate.

We also note that if DC discharge has traditionnally been the main method of conventional excitation for CO_2 lasers, radio-frequency (RF) discharge is however, recently, gaining attention as a new excitation method because this method of excitation is amenable to high pulsing rates (up to 10 kHz).

The CO_2 laser is basically an efficient device, in slow-axial-flow device configurations, if heat is removed from the laser discharge by conduction to the walls of the laser tube. Maximum output of slow-flow devices is limited to below 50-100 W/m. As we will note in the solid-state chapter, CO_2 laser applications have been limited by the lack of suitable materials for fiberoptic components at 10.6 μm. So, the development of kW range CW CO lasers, oscillating in the 5-7 μm range, may offer an alternative approach to flexible IR laser for material processing.

In Japan, 1,300 CO_2 laser have been installed in 1989 which is corresponding to a laser-system market of 45 10^9 Yens (1 Yen = 0.0365 FF). Leqders in the field are MITSUBISHI Electric, MATSUSHITA Electric, AMADA and MAZAK. Together, these 4 companies account for laser-processing machinery produced in Japan. Other companies are NTC, NEC, KOMATRU and TOSHIBA for the most importants.

Concerning excimer lasers, much effort has concerned development of excimer-laser discharges with longer output pulses. Pulsewidths of a few hundred nsec are commercially available. Applications for excimer lasers are expected to be extensively applied in the biomedics, electronics and semiconductors areas. TOSHIBA has achieved a stable laser pulse at a high-repetition rate of 2.5 kHz in a project commissionned by the MITI. Since about 1980, attempts have been made in the USA, France and USSR to achieve high-repetition operation (1-2 kHz) by circulating high-speed gas through the discharge unit. By 1993, TOSHIBA could realize a rate of 5 kHz with an average laser output power of 0.5 kW. Most of the excimer lasers use UV preionization in order to maintain the glow discharge mode. The preionization has a significant effect on discharge stability and laser performance. Because for excimer laser improvement, it is important to investigate the magnitude and distribution of electron density in the discharge volume, S. TAGAKI et al have developped in 1989 a Langmuir probe technique to measure electron densities and temperatures in UV preionized XeCl excimer (and CO_2 laser). The results show that for excimer (and CO_2) laser gases, the electron density decreased to about 10^8 cm^{-3} compared with 10^{10} cm^{-3} in pure He and the electron temperature was constant at 3-6 eV. Also let us note that T.HASAMA et al have designed a 50 J, 85 nsec, discharge -pumped XeCl laser with a wide aperture of 10x10 cm^2. The number density of preionization electrons, distribution electrons is greater than 6.10^9 cm^{-3}. HITACHI Research Laboratory has developped in 1989 a discharge-pumped excimer laser to be applied to photochemical materials processing (semiconductor) because of high-power in UV region. A high average power over 120 W was obtained in a simple capacitor transfer laser with an air-cooled thyratron by employing an efficient UV preionization scheme (total primary and secondary capacitances are 64 and 52 nF respectively with arrays of ceramic capacitors located externally along the discharge tube).

At Tsukuba, the Electrotechnical Laboratory has began operation in 1989 of a high-power KrF excimer laser system (ASHURA project, as Advanced System for High-power Ultraviolet Radiation Applications). The laser has attained 15 MW/cm^2 of focused power density. The Laboratory plans to develop a Raman compression system for ASHURA.

CULHAM Laboratory (U.K. Atomic Energy Authority) is to lead a \$ 22.5 10^6-4 year European project for building powerful excimer lasers (towards a 3 kW UV laser by early 1990s). Already built is a large-scale working model of an excimer laser known as CHIRP (Compact High-Repetition rate laser) as a part of EUREKA program. European project goals are to develop excimer lasers that achieve 10 J/pulse at 100 Hz, 1 J/pulse at 1 kHz and 0.2 J/pulse at 5 kHz. Study to investigate the CO laser is also under an European contract.

Concerning thermical oxygen iodine laser (1.315 μm, COIL) we can note the work of YOSHIDA S. et al for industrial uses with a power level of 200 W and a maximum overall efficiency of

40 %. The advantages of the COIL as an industrial laser include an ideal power transmission through silice fibers, the capacity of yielding extremely high CW output, high efficiency and good beam quality (corresponding to the advantages of both CO_2 and YAG lasers). However, the status of the technology is still immature for realistic industrial uses in terms of stability (degenerating of the fuel solution in the singlet oxygen generator) and running cost.

High-efficiency long-pulse DF and DF CO_2 chemical lasers will wall-plug efficiencies of 130 % and pulselengths of 150 µsec are under development by Los Alamos National Laboratory in USA.

II.3. SOLID-STATE LASERS.

Researchers from AMOCO have recently obtained (1990) simultaneous stable single-frequency emission at 1.064 and 1.319 nm of a Nd:YAG cube laser pumped with diode-laser arrays.

At MIT Lincoln Laboratory has been designed a compact electro-optically tuned single-frequency Nd-YAG laser.

Let us note that Spectra-Physics has obtained more than 70 kW peak-power in a 8.5 nsec pulse from a Q-switched Nd:YLF slab pumped by a diode-laser bar with efficiencies of 33 % (2nd harmonic generation, HG) and 15 % (3 rd HG) using lithium borate.

Collaboration research at CEA Limeil, Saclay and ENST in France have carried out a 50 TW, 1 psec, Nd-YAG using chirped pulse amplification.

Let us note also at Lawrence Livermore National Laboratory the design of a 12 TW, 700 fsec, Nd-glass in which a regenerative amplifier is used.

In Japan, a group from HOYA Corporation has obtained a kilowatt-class slab glass laser. TOSHIBA has developped a 2.4 kW Nd-YAG for industrial applications (weldings, cuttings, drillings, etc..). The utilization of optical fibers helps high power YAG laser systems to be going to replace multi-kW CO_2 lasers. The solid state laser (CW Nd:YAG laser) has a couple of advantages over the CO_2 particularly to allow the use of flexible, high transparency, silica fibers (at 1.06 µm). For instance, a 1 kW power from a YAG laser could be equivalent to several kWs from a CO_2 laser. For that treatment, YAG laser are more convenient than IR lasers because metals absorb more power at shorter wavelengths. The YAG laser light is absorbed 4 times higher than the CO_2 laser light. So, it is possible to have an aera of 11 mm wide by a 0.7 mm deep obtained at 0.12 m/min.

TOSHIBA had developped a high-power alexandrite laser (100 W average). To tune the laser output frequency a birefringent filter is used giving a 70 GHz spectral bandwidth. Using an etalon and a transverse mode selector with the birefringent tuner, the spectral bandwidth was narrowed to 15 GHz and 3 W (150 mJ, 20 Hz) output is obtained. As another application of spikey output, the drilling of Ni base alloy and the marking of plastic IC packages are possible (drilling a 10-mm thick plate with 4-J laser pulses and marking with performance similar to that of a TEA CO_2).

TOSHIBA has been developed a prototype semiconductor laser with the world's shortest wavelength that emits more light than current products on the market. The semiconductor laser offers the potential of replacing He-Ne gas lasers. This compact, reliable and less power-consuming laser emits at room temperature at a wavelength of 638 nm, shorter than devices of 670 nm currently sold in the market.

II.4. LASER ISOTOPE SEPARATION (LIS).

The advance of laser technology has made possible new applications in the field of nuclear energy, such as separation of isotopes.

PNC, as JAERI, RIKEN and other japanese Institutes are developing this technology. For instance, PNC is developing laser photochemistry method to the reprocessing of spent nuclear fuel and wastes, RIKEN is developing shortwave laser and JAERI is continuing research on selective excitation reaction and collecting basic spectral data.

Candidate elements for processing using atomic vapor laser isotope separation (LIS) are: samarium, europium, gadolinium (burnable poison for power reactors), mercury (more efficient fluorescence lamps), zirconium (cladding for nuclear fuel elements), rhodium, palladium, platinum (precious metal recovery from nuclear waste). The world demand is, for each case, of order greater than 1 Mg/year. As an example, PNC is working on the LIS of Pd 107 by using a two-step photoionization process. Significant results have been obtained with Pd 105 todate by H.YAMAGUCHI and N.SASAO which show that this isotopic component can be totally removed (nuclear spin of Pd 107 and 105 are similar). The influenceof the laser linewidth on the selectivity in the two-step selective phtoionisation spectroscopy was shown as non critical by T.ARISAWA et al from JAERI. LIS of Ti 50 by using the same process was demonstrated in JAERI in which a separation factor of around 15 for Ti 50 was obtained.

At RIKEN, $(CF_3)_3CT$ was shown to be one of the most promosing molecules for CO_2 LIS of tritium. The hydrogen isotope exchange between $(CF_3)_3CH$ and HTO was found to be extremely rapid, which is advantageous in the practical LIS cycle for tritium removal from water. At the Institute of Laser Engineering in Osaka, H.NIKI et al have obtained in 1988-1989 absorption spectra of Gd 157 - Gd 155 in the 560-600 nm region by means of laser-induced fluorescence spectroscopy. The absorption spectrum has a complex structure because there are seven isotopes and two of them have hyperfine structures and few data are available so far. LIS with a Q-switched CO_2 laser was obtained on SF_6 32 and $^{12}CF_3I$ at Max-Plank Institute in 1987.

Reactivity enhancement was studied at JAERI in 1983 using a reaction between a laser excited atomic beam and a molecular beam and applied to LIS of lithium. It was found that the specified lithium (6 Li) isotope was enriched in the reaction product LiF, whereas 6-7 LiCl have no selectivity.

II.5. SHORT WAVELENGTH LASERS (UV, VUV, XUV).

A variety of lasers are available that emit in the UV and VUV regions such as:

- Ar+ (351 - 364 nm).
- Rare gas halide excimers: KrCl (222 nm).
- Metal vapor ion lasers: HeCd+ ion laser (325 nm).
- Free-electron lasers (FELs): from 0.5 μm to the far infrared and millimeter regions (Standford, LANL, Univ. Calif. San Bernardo).

In the next few years, several institutions plan to have opereting FELs in the UV and eventually down to 10 nm. FELs based on RF LINAC accelerator, electron storage rings, will be located at Los Alamos, Standford, NBS respectively.

- New short wavelength lasers: one development that shows continuing promise for leading to new VUV oscillators is the laser-produced plasma. Laser-produced plasma are convenient, efficient and short time-scale sources of incoherent soft X-ray radiation. Such plasma sources can be used to photoionize the core electrons of atoms and the resulting ions will decay rapidly and selectively by Auger processes to particular levels. The yields of specific electronic states in certain cases that have been proposed (Zn, Cs, Rb) are as high as 20 %.

As an example, the 108.9 nm Auger laser in atomic Xe was first demonstrated by Falcon et al (Berkeley). The key discovery was that effective plasmas could be created with laser power densities on target of only 5.10^{10} W.cm^{-2}. Other specific atomic and molecular systems under investigations include ionic excimers in alkali halide and rare gas halide compounds, core excited states in potassium and rubidium populated by collisional excitation transfer from electrons beam excited metastable helium and neon atoms, VUV and XUV anti-Stokes Raman lasers in molecular systems such as nitrogen and the rare gas excimers.

- Frequency mixing for generating tunable VUV radiation are:
    - non-resonant frequency conversion in rare gases (conversion efficiency, η 10^{-5}, 10^{-6})
    - resonant frequency mixing, η , 10^{-4}, 5.10^{-3}
    - resonant sum frequency mixing, η , 10^{-5}, 10^{-4}
    - two-photon resonant, difference frequency, conversion in Hg, Kr and Xe.
- Main laboratories in Japan working on VUV, XUV lasers:

a). Electrotechnical Lab. Tsukuba (K.MIYAZAKI et al.)
XeCl 50 J, 85 nsec, preionized with X-rays (collaboration with PNC), generation of coherent VUV by frequency non-linear conversion (FNLC) in Cd vapor, tunable 119.6 to 136.8 nm, coherent VUV by 2 photons resonance in Xe and Kr and FNLC (BBO crystal), 71 and 92 nm, F_2 molecular laser, 8 atmospheres, 110 mJ, 157 nm.

b). Electrotechnical Lab. Tsukuba (T.TOMIE et al.)
glass laser, high-power, mode-locked, internal etalon intra-cavity, 4 psec.

c). Kyushu University, Fukuoka (M.MAEDA et al.), coherent VUV generation by two-photon resonance and frequency mixing in Kr and FNLC (BBO crystal), tunable from 129 to 145 nm.

d). Osaka University (W.SASAKI et al.) Kr excimer laser, high-pressure 15 atmospheres, pumped by electron, 6.6 MW, 145.7 nm. Ar excimer laser, pumped by electrons, stimulated Raman frequency conversion, tunable around 126 nm, 16 MW.

e). Tokyo University (S.WATANABE et al.) XeCl excimer laser, 1 TW, 310 fsec, 7x7 cm aperture, 300 mJ output energy, subpicosecond fluorescence of KrF laser, multi-TW 220 fsec, pumped by electrons.

f). Tokyo University (H.KURODA et al.) plasma of He-Al, XUV generation, adiabatic detente recombination, gain measurements of population inversion.

g). RIKEN (K.MIDORIKAWA et al.) plasma of Xe, laser pumping photoionization, YAG laser and XeCl laser (short pulse generation), study of anti-Stokes high-energy pulse generation for XeCl.

h). Institute of Laser Engineering, Osaka (H.DAIDO et al.) plasma of C, C_8H_8 targets, CO_2 laser for excitation, soft XUV generation, studies of plasma recombinations.

i). Institute of Laser Engineering, Osaka (Y.KATOU et al.) Nd-glass for excitation, high-power, psec pulse, studies of plasma recombinations.

j). Institute of Laser Engineering, Osaka, (N.YUGAMI et al.) plasma generation in Al by using electric impulsion, 40 nsec-impulsion radiation, 20 GW, used for pumping Al/F laser for X-rays generation, studies of plasma recombinations.

By comparison with american laboratories, just let us mention recent results:

k). Lawrence Livermore National Laboratory (R.LONDON et al.) realisation of several optically pumped X-ray amplificators, transition gain measurements down to 18 nm, multilayers for dielectric mirrors (MgF_2 overcoated Al mirror) allowing several forth and back in the amplifier, population inversion demonstration.

1). Standford (M.SHER et al.)
- 2 Hz mirrorless laser, 109 nm emission by photoionisation Xe pumping, output energy optimization, gain measurements at 109 nm.
- Use of VUV chemical converter detector, open microchannel plate (MCP) image intensifier with a photocathode directly deposed on the channels and MCP image intensifier with a MgF_2 window and an S-20 photocathode.

However, note that to extend the applications of VUV pulses to the VUV spectroscopy (study and probing of larger molecules) it is necessary to have a source 10^3 to 10^4 times brighter than is now available. Although existing sources provide intensities adequate for one-photon spectroscopy, more intense VUV lasers are highly desirable for two-photon spectroscopy.