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REVIEW OF X-RAY LASER RESEARCH AT CEL-V

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Résumé - Nous présentons l'état actuel des travaux relatifs au laser X réalisés avec le laser Octal. Les résultats récents concernant les inversions de populations pouvant conduire à une amplification sont rapportés. La théorie et les modèles impliqués dans les schémas d'inversion seront examinés.

Abstract - We present the status of X-ray laser experiments using the Octal laser facility. Recent results dealing with population inversion towards X-ray amplification are reported. Theory and modelling of the involved schemes will also be discussed.

Plasmas generated by laser irradiation of solid targets have demonstrated for a long time their non LTE behavior providing numerous states propitious to population inversions. So studying inversions and X-ray amplification is in keeping with the general pattern of the understanding of the plasma state and more precisely of the involved atomic processes. Moreover the recent fruitful experiments on X-ray amplification [1,5] have enforced our interest, if it was not, in theoretical and experimental studies in this new field of investigation.

Theory

Every time an experiment is performed we need estimates of the results and some means for their interpretation. To do this we have first developed a collisional radiative ionization model which provides the mean plasma charge, populations of ionic species and excited levels, and spectra emitted by the plasma medium. For particular transitions investigated in Ne-like ions an improved description lead us to performe new calculations of electron impact collision strengths, not available in the litterature. In the case of high-Z plasmas not highly stripped a real descriptions of levels and population is quite complex due to numerous configurations, so specific simple models have been developed.

The ionization code named LASIX consists of an atomic data base coupled to subroutines solving the time dependent equations of ionic populations and evaluating emission and absorption coefficients. An interesting feature of the code is its flexibility, allowing a rapid comparison of the results of several types of atomic description (average ion, more or less detailed configuration).

An example of the population of H<sub>i</sub>-like ions of Argon in the stationary case at electron density of  $10^{21} \text{ cm}^{-3}$  versus electron temperature is shown in Fig 1. The dashed lines are taken from Stone and Weisheit [6].

FIG 1

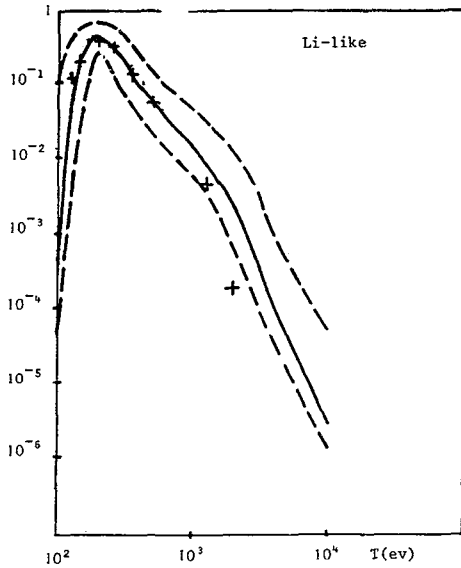
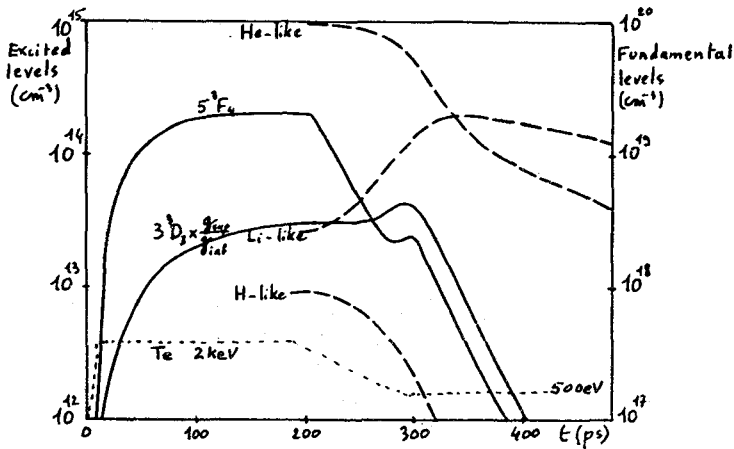


Fig 2 shows the temporal evolution of populations when  $T_e$  varies with time, for an iron plasma at a fixed ionic density of  $10^{22} \text{ g.cm}^{-3}$ . When the plasma is recombining, population inversion are predicted for He-like ions between levels 5f and 3d.

FIG 2

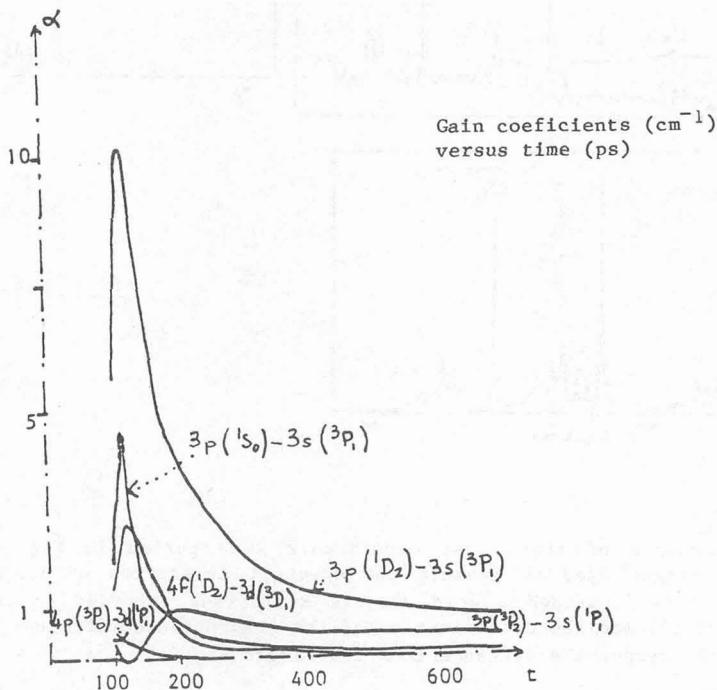


An other interesting application of the code LASIX was its use to interpret the LLNL X-ray laser experiments on Se foil. 8 Ne-like selenium configurations taking into account levels  $n = 4$  have been included.

The main results of this study is the restitution of the LLNL conclusions : as for as the  $3p - 3s$  transitions in Ne-like Se are concerned, the highest gain must be spected for the  $J = 2$  to  $J = 1$  lines.

Nevertheless in the shorter wavelength range lasing transitions exist with smaller gains between  $4p$  and  $3d$ , or  $4f$  and  $3d$  levels (Fig 3).

FIG 3



For high-Z elements, emission spectra are rather complex. Even though some technics exist to diagnose such plasmas, see for example the spotty spectroscopy, their theoretical study is worthwhile for temperature and density diagnostics and for checking of simplified ionization models.

Before building an extensive population model for gold ionized 49 to 52 times, we have studied with a more simple model the effect of accounting for cascades (or dielectronic recombination) and  $\Delta n = 0$  transitions. These transitions allow some understanding of typical feature of experimental gold spectra (Fig 4 a,b,c).

### Experiments

As it has been seen in the previous chapter, our ionization codes are sufficiently reliable to be used to design any experiment involving different types of pumping mechanisms. Although the collisional excitation scheme provides high theoretical gains we preferred for the first step of our research to investigate population inversions and amplification through a recombining scheme of pumping. In a parallel way connected experiments have been performed to qualify the plasma, inferring its macroscopic parameters—electron density and temperature spectral opacity—by means of improved spectroscopic technics.

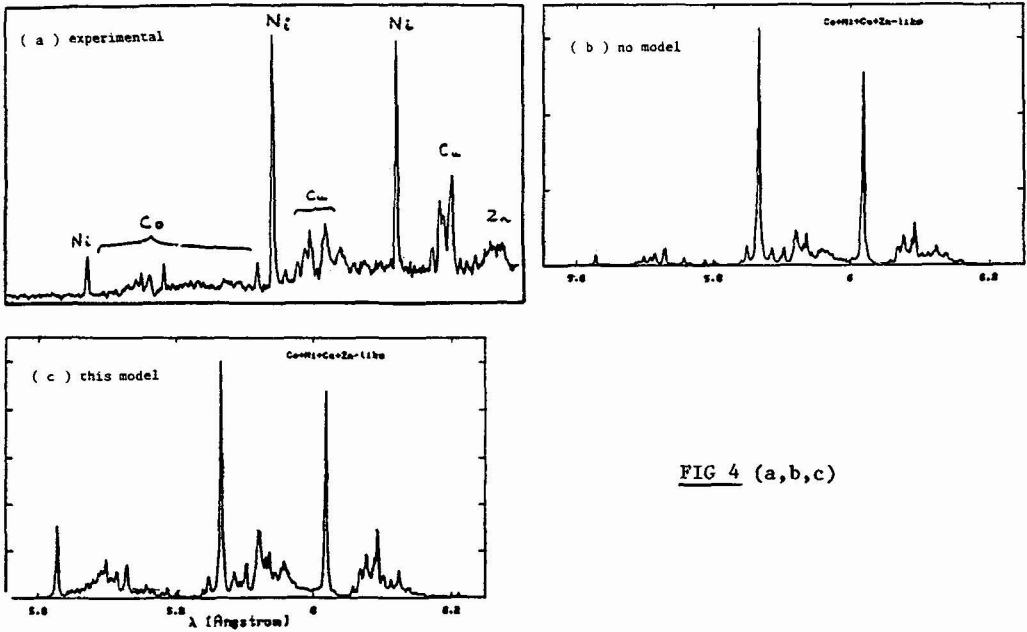


FIG 4 (a,b,c)

An example of these last experiments is reported in Fig 5 representing a multitarget used to measure the spectral absorption of lines emitted by an aluminum plasma through a gold plasma. Radiations recorded in two perpendicular directions allowed the determination of the absorption coefficient wavelengths 7.76 and 7.17 Å, versus the distance from the target Fig 6.

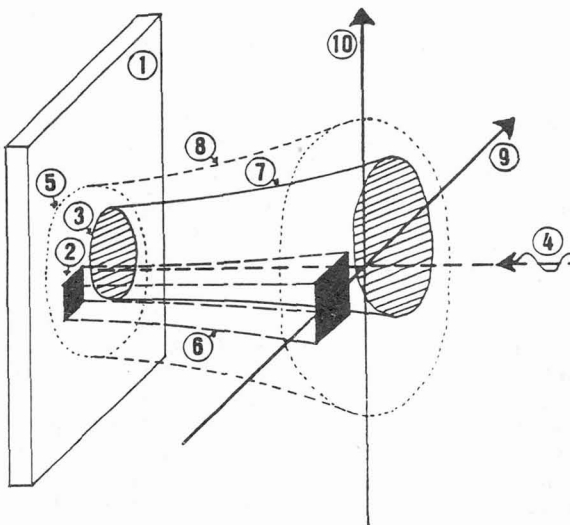
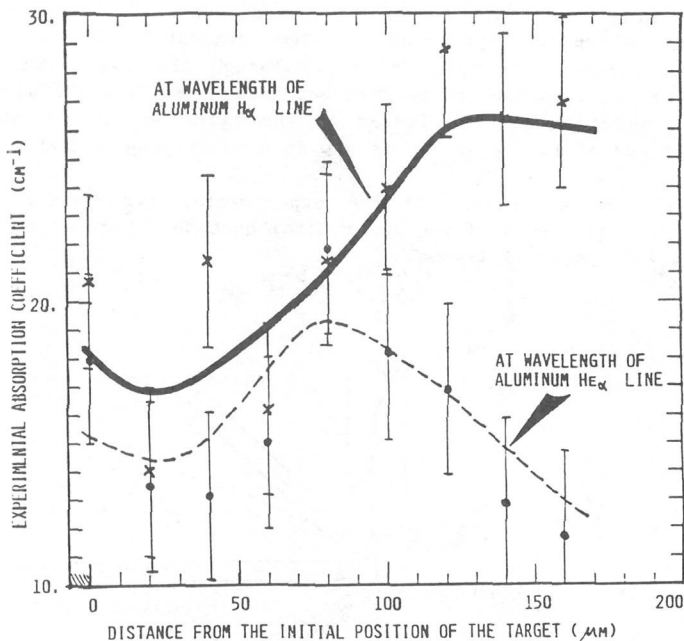


FIG 5

- 1 - Silica substrate
- 2 - Aluminum dot
- 3 - Gold dot
- 4 - Laser beam
- 5 - Focal spot
- 6 - Aluminum plasma
- 7 - Gold plasma
- 8 - Silica plasma
- 9 - Towards longitudinal spectrograph
- 10- Towards transverse spectrograph

FIG 6



Absorption coefficient of Aluminum H-like and He-like lines  
in a gold plasma deduced from experimental measurements

At CEL-V three powerful laser systems devoted to plasma research are routinely operating at the fundamental wavelength 1.053  $\mu\text{m}$  which is generally converted into either the second harmonic or the third. All the main characteristics are gathered in Fig 7.

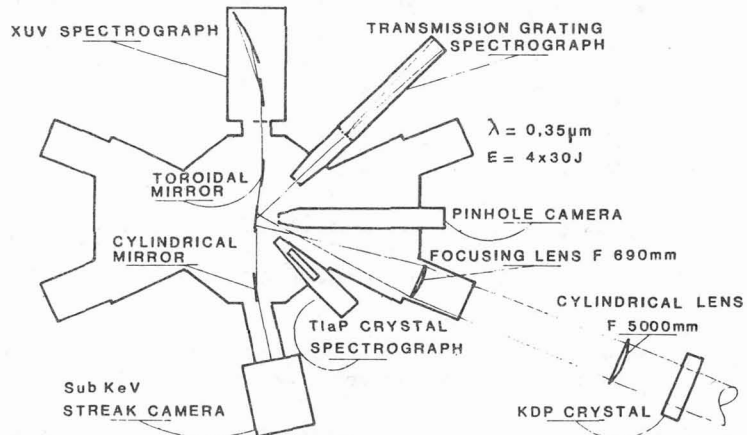
FIG 7

	number of chains	beam diameter	maximum power			pulse duration
			1.05	0.53	0.35	
P 102	1	9 CM rods	0.1 TW	—	0.03 TW	0.05 - 1 ns
OCTAL	8 (2 x 4)	12 CM rods	2 TW	—	0.7 TW	0.2 - 2 ns
PHEBUS	2	74 CM discs	20 TW	13 TW	10 TW	0.2 - 5 ns

The laser P102 is rather used for experiments dealing with specific measurements for a better knowledge of the plasma, such as laser plasma interaction, hydrodynamics of thin foils.... Though the laser Octal is mainly devoted to ICF, it has been used to perform our first X-ray laser studies. The more powerful laser, Phebus, which is similar to the laser Novette at LLNL gave its first shot at the end of last year and is now in a qualifying period.

The schematic representation of the experimental arrangement is shown in Fig 8. Four of the eight beams of the laser Octal have been focused onto targets by both cylindrical and spherical lenses.

FIG 8



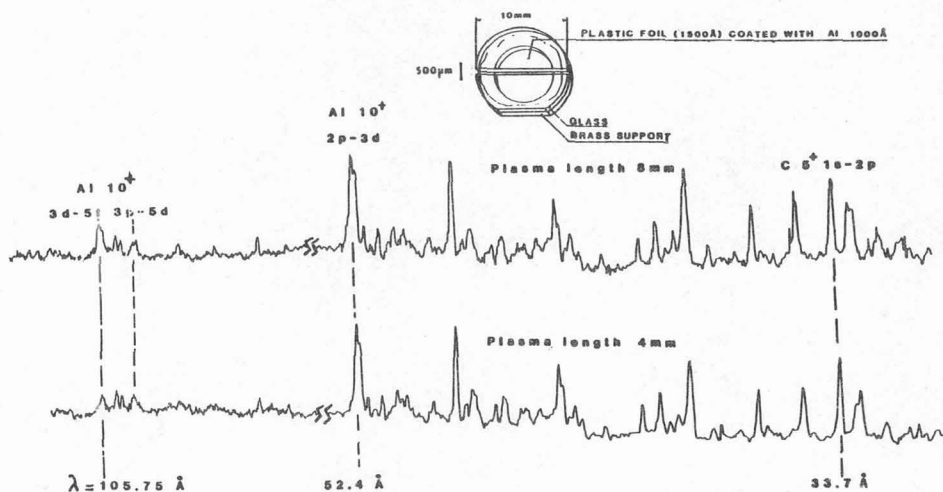
The two main diagnostics were a grazing incidence spectrograph (GIS) with a toroidal collection mirror and a flat TiAP crystal spectrograph (FCS) with a spatial resolution slit (100  $\mu\text{m}$  width). Both have high spectral resolution : respectively  $\frac{\lambda}{\Delta\lambda} = 2.10^3$  for GIS and 400 for FCS. In addition we imaged the plasma in the 1 - 1.5 keV X-ray energy using a pinhole camera (30  $\mu\text{m}$  in diameter).

Typical targets were composed of an aluminum film, 1000  $\text{\AA}$  thick, deposited on one side of a thin plastic substrate (1500  $\text{\AA}$ ). At laser wavelength of 0.35  $\mu\text{m}$ , irradiances about  $5 \cdot 10^{12} \text{ W.cm}^{-2}$  and pulse duration of 0.8 ns no detectable inversion was observed neither in the aluminum spectrum nor in carbon. This is probably due to the too high density of aluminum because of the high critical density.

A same series of experiments has been repeated successfully at fundamental wavelength of the laser OCTAL (1.053  $\mu\text{m}$ ), for which the critical density is an order of magnitude lower than in the previous case.

Targets were irradiated under two different line focus lengths 4 and 8 mm, and a significant increasing of the intensity of the 5f - 3d line of Li-like ions of Al versus the plasma length was observed (Fig 9). This might be the signature of a X-ray amplification as it has been demonstrated by P. JAEGLE in similar experiments at lower laser density.

FIG 9



### Conclusion

First, conditions of inversion and then A.S.E. in laser plasmas are possible with our powerful laser facilities. Second we have developed time dependent ionization and detailed spectroscopic codes sufficiently reliable to allow design and interpretation of X-ray laser experiments. Finally, our first results show, for a same type of target structure, an amplification of the 5f - 3d line of Al  $10^+$  only at long incident laser wavelength.

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