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RESUME. Nous avons montré que plusieurs transitions des ions lithiumoides donnent naissance à des inversions de population qui se produisent au cours de la recombinaison de plasmas-laser /1/. La transition 3d-5f située à 105.7 A a fait l'objet d'une étude détaillée qui révèle l'existence d'un gain passant par une valeur maximum d'environ 2 cm^{-1} près de 6 ns après le sommet de l'impulsion laser dont la durée est de 2ns. Cette étude a été récemment étendue à la raie 3d-4f située à 154.7 Å et nous avons observé une valeur de gain similaire avec le meme comportement temporel. De plus, en suivant des prévisions fournies par des calculs effectués pour des ions de Z plus élevé /2/, nous avons étudié la transition 3d-5f de S^{13+} située à 65.2 Å. Nous trouvons pour cette raie une valeur de gain voisine de 1 cm^{-1} ce qui constitue le premier résultat obtenu jusqu'ici à une aussi courte longueur d'onde.

ABSTRACT. We have shown that several transitions of Li-like ions give rise to population inversions during the recombination of laser-plasmas /1/. An extensive study has been made for the 3d-5f transition lying at 105.7 Å. It has shown a gain coefficient with a maximum around 2cm^{-1} occuring about 6 nanosecond after the top of the 2-ns laser pulse. We extended recently this study to the 3d-4f line ar 154.7 Å and we observed a similar value of gain with the same temporal behaviour. Moreover, following calculated predictions for higher-Z ions /2/, we studied the 3d-5f transition of S^{13+} which takes place at 65.2 Å. This study gives the first preliminary evidence of a gain coefficient of about 1 cm^{-1}.

INTRODUCTION: The rapid cooling of hot laser plasmas in fast expansion is henceforth known as able to give rise to amplification of radiation in the X-UV range, due to recombination processes occuring in multicharged ions . The first evidence of such a type of amplification was reported by our group in 1978 /3/. This observation was made on an aluminum line situated at 105.7 Å which was unknown at this time. It was then identified as the 5f-3d transition of Li-like ion /4/. Later on, time integrated, then time resolved measurements have demonstrated gains up to 3 cm^{-1} /1/ in good agreement with the predictions of theoretical calculations using new atomic data and plasma hydrodynamics /2,5,6/. In an aluminum plasma this modeling reveals gain to be expected also for the 4f-3d and 5f-4d transitions situated respectively at 154.6 and 334 Å, in all cases a few nanaoseconds after the top of the laser pulse (the duration of which is of the order of 1 ns), i.e. during the cooling phase of the plama when recombination takes place.

EXPERIMENTS. For achieving a lasing action one must try to obtain the highest possible GxL product, where G is the gain (per unit length) and L the length of the plasma. This latter co ndition strictly depends on the energy available in the laser pulse. Thus we are now able to produce plasmas as long as 2 cm with fluxes higher than 10 GW/cm. This is obtained by mixing the two laser beams with the help of a special optical mounting in the way of doubling the energy available /7/. With regard to the increasing of gain itself one must consider different effects as the duration and the wavelength of the laser pulse or the geometry of the target and of its irradiation. In this paper we shall compare the results we have obtained in two kinds of experiments where quite different experimental conditions have been used. In Palaiseau we use one-sided irradiation at 1.054 μ along a focal line on massive planar targets with laser pulses comprised between 0.6 and 20 ns. Line focus is obtained by using two crossed cylindrical lenses. The 1 m-grazing incidence planar targets with laser pulses comprised between 0.6 and 20 ns. Line focus is obtained by using two crossed cylindrical lenses. The 1 m-grazing incidence spectrometer uses a 3,600 groves/mm grating. But recently a new type of experiment has been developped at Rutherford Laboratory in the frame of a collaboration with our group /8/. There the target, which is constituted by a Carbon fiber 7μ-wide coated with 3500 Å of Aluminum, is irradiated symmetrically at 0.53 μ along a focal line by the 120 ps pulse of the Vulcan laser system. In this case, three 7 mm-long line foci are provided by off-axis reflection from spherical mirrors. Plasma lengths of 14 or 21 mm can be obtained by combination of these lines. The spectrograph is of a flat field type.

Beyond the above mentionned differences both experiments also differ in the way gain measurements are performed. In the first case (fig.1), gain is calculated considering radiation transfer from the intensity ratio between two plasmas of different length (one couple is sufficient). Moreover, by coupling an optical multiplier analyzer at the rear part of the streak camera, data can be treated on line upon a wide enough range of wavelength (3 Å). Thus an absorption-gain curve versus wavelength is obtained extending far beyond the width of the line under investigation. On the other hand, in the Rutherford experiment, gain is deduced by fitting an exponential curve to the variation of the output intensity with the increasing lengths of several plasmas (more than two are necessary). Since here a photographic plate is used behind the streak and due to low resolution of the flat field spectrometer intensity measurements are made only at the top of the lines.

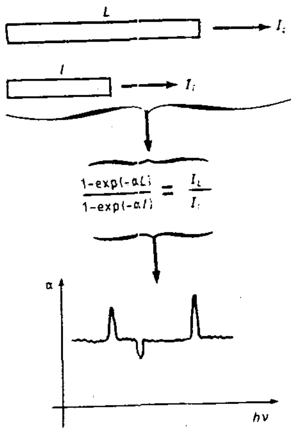
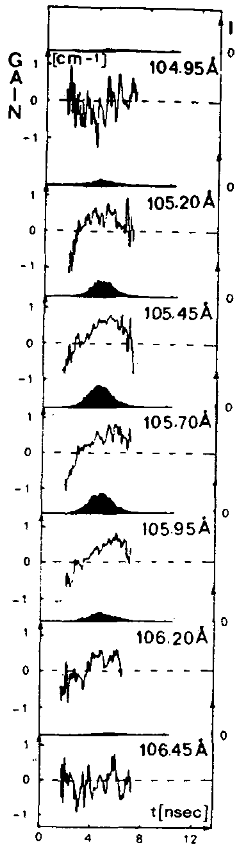


Figure 1. Sketch of the experimental method of absorption coefficient measurement in Palaiseau.

RESULTS AND DISCUSSION. Typical results obtained at 105.7 and 154.6 Å are represented in fig.2 (Palaiseau) and in fig.3 (Rutherford). Both time resolved experiments reveal positive gain values to be obtained as well for the 5f-3d transition at 105.7 as for the 4f-3d at 154.6 Å. But gain values are found generally higher with the thin coated fibre experiment (3 cm^{-1}) than with the massive target one (1 to 2 cm^{-1}). This can be easily understood if one considers that in the first case shorter pulses are used (120 ps). From a theoretical point of view this leads to a faster cooling of the plasma and favourises inversions. Nevertheless, with massive targets, attempts at measuring a gain have always been unsuccessful when using shorter pulses (600 ps instead of 2 ns). Reasons of this discrepancy with theory perhaps can be found in radiation trapping phenomena. Indeed, another feature of the massive target experiment is that values of gain obtained seem to decrease when the plasma length increases. For instance a gain value up to 3 cm^{-1} has been measured with a couple of plasmas of 8 and 3.7 mm whereas, with plasma lengths of 20 and 9 mm, gain is only about 0.8 cm^{-1}. Let us consider the simplified scheme of Lithium-like atomic structure presented on fig.4. It is clear that the strong electric dipole transition $3d_{3/2,5/2}-2p_{1/2,3/2}$ plays an important role in the population inversion scheme by depopulating the lower level lasing transition as far as no other process is able to repopulate this 3d level. As a matter of fact the optical thickness of plasma increases with length and then absorption processes 2p-3d can reduce the effective rate of desexcitation of the 3d level. With this in mind, absence of gain at 600 ps can be explained by the fact that, in this case, simulations show inversions to be present at shorter distances from the target surface than at 2 ns, in a relatively dense plasma zone. Radiation trapping can then outshine inversion. On the other hand in fibre experiments one can expect radiation trapping in 3d level to be avoided, due to a better lateral escape of radiation.



Gain measured is found the same, i.e. 3 cm^{-1}, for both transitions 5f-3d (105.7Å) and 4f-3d (154.6Å) in the Rutherford experiment whereas at Palaiseau, if we compare measurements made in the same conditions of plasma length and of laser energy at 0.6 mm from the target surface, higher gain has been observed at 154.6 Å (1.5 cm^{-1}) than at 105.7 Å (0.8 cm^{-1}). This latter could be qualitatively more coherent with conclusions of theoretical analyses which predict comparable populations for both levels and a higher amplification for the 4f-3d transition at 154.6 Å than for the 5f-3d at 105.6 Å which is less probable. However calculations show that density of inversions depends of many factors and connexion between both experiments is somewhat difficult since they differ on many points.

OUTLOOK TO SHORTER WAVELENGTH. A possible X-ray laser working between 23 Å and 43.5 Å is very interesting for biological purposes. Indeed since water is rather transparent to these wavelengths whereas Carbon is opaque to them one hopes so obtaining microscopic holograms with

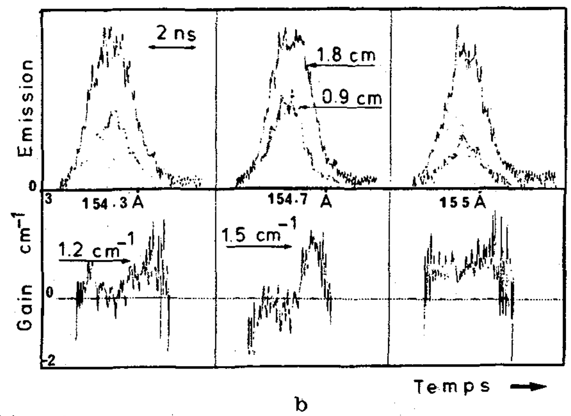


Figure 2. Gain as a function of time for the 5f-3d (a) and the 4f-3d transition (b) in Al^{10+} at 0.6 mm from the target (Palaiseau).

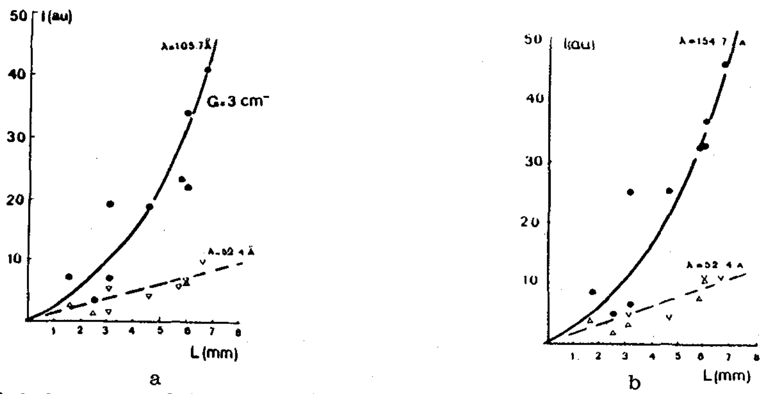


Figure 3. Exponential increase of intensity for the 5f-3d (a) and the 4f-3d transition (b) in Al^{10+} (Rutherford).

good contrast. Considering a given lasing scheme, shorter wavelengths imply to use higher Z elements which will need higher laser flux to be ionized in the proper state. Since fluxes necessary for obtaining a gain in Li-like Al are relatively low (10^{12} W/CM^{-2}) this scheme appears to be a good candidate for progressing towards shorter wavelengths. In this purpose we have planed to study higher Z elements. On the basis of a theoretical study /6/, we have started to investigate the 5f-3d line in Sulfur at 65.2 A. Preliminary results concerning a time integrated experiment are presented here on fig.5. A peak of gain is clearly visible on the recording. Taking into account the effects of time integration and of experimental width a simulation reveals time resolved gain to be about 1 cm^{-1}. Up to now, no time resolved investigation has been achieved due to difficulties in the fabrication of massive sulfur targets able to resist to the sufficiently high number of laser shots necessary to statistics. This number is lower for time integrated measurements.

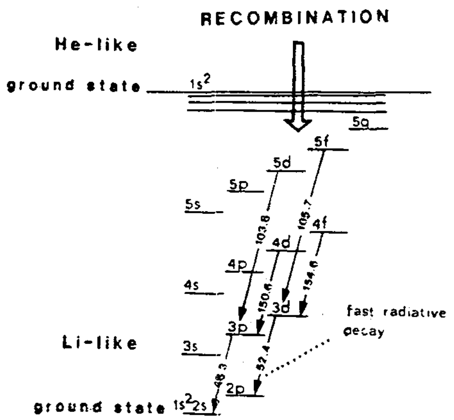


Figure 4. Simplified Lithium-like atomic structure of Al.

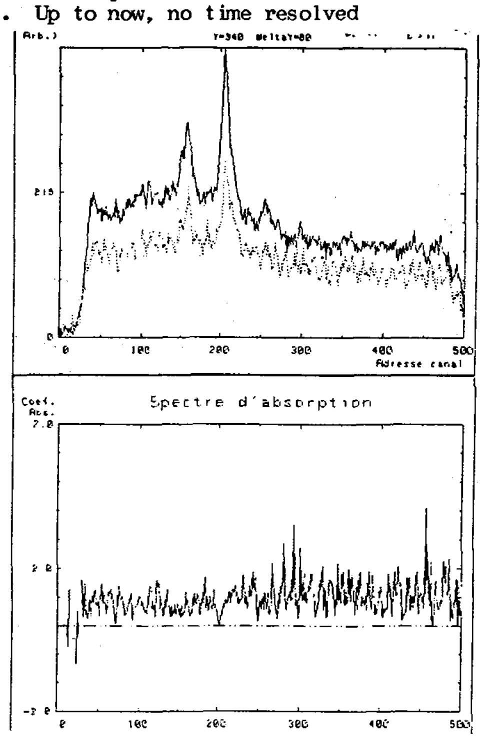


Figure 5. Time-integrated absorption spectrum in a Sulfur plasma, 2 cm-long. (5f-3d transition in S^{13+} at 65.2 Å).

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